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O1 Oral Session: Orographic clouds and precipitation: Part 1

O1.1 Orographic convection: progress and challenges

Daniel J. Kirshbaum *(McGill University, Canada)*

Through its ability to generate large-amplitude vertical air displacements that bring moist-unstable airflow to saturation, orography serves a focus for convection initiation. As a result, orographic convection represents as an important forecasting problem and has attracted decades of intensive research. However, the physical understanding and numerical representation of orographic convection remain incomplete and elusive. This study briefly reviews the history of orographic convection research with a focus on recent findings facilitated by intensive observational field campaigns and ever-increasing computational power. It subdivides the problem into two fundamental (but not mutually exclusive) physical mechanisms: mechanically and thermally forced convection. Observational studies have investigated one or both mechanisms in increasing depth and detail over the past few decades, with distinct progress made through the Mesoscale Alpine Programme (MAP), the Convection and Orographically-induced Precipitation Study (COPS), and various others. Over the same period, the emergence of cloud-resolving simulation over large domains has permitted the explicit and systematic investigation of mountain cumuli over a spectrum of background conditions and terrain forcings. While providing critical new insights, these observational and numerical studies have also highlighted the complex interactions between airflow dynamics, cloud microphysics, and surface heat exchange that make orographic convection a highly challenging (and intriguing) problem. The study concludes with a discussion of some prominent obstacles facing the improved understanding and prediction of this problem.

O1.2 Controls on precipitation in thermally driven orographic clouds

Alison D. Nugent *(NCAR, United States of America), Campbell D. Watson, Gregory Thompson, Ronald B. Smith*

Active orographic convection was observed over a small tropical island and yet a negligible amount of precipitation was observed. The generation of precipitation from a cumulus cloud depends sensitively on the nature of the updraft, the updraft aerosols, and the turbulent entrainment of dry air, all of which were observed during the DOMEX (Dominica Experiment) field campaign. Observations suggest aerosol-cloud-precipitation interactions may be important in retarding precipitation formation in thermally driven orographic convection but differences in the observed cloud layer moisture content confound the relationship. Early test simulations also suggest that the island geometry may influence the aerosol impact. This leads to the question of under what circumstances can aerosol-cloud-precipitation interactions impact orographic precipitation?

The WRF model with the aerosol-aware Thompson microphysics scheme is used to further explore the relationships between simulations with and without a surface aerosol source. Idealized cloud resolving 3D simulations with a variable sensible heat flux simulating one thermal day are performed with a set of terrain configurations, wind speeds, and cloud layer moisture contents in addition to the changing surface aerosol source. It is found that aerosols have the largest impact on precipitation when it is struggling to form. A water budget, an aerosol budget, and a close look at microphysical conversion rates from cloud to rain water help to shed light on the processes at work.

O1.3 Sensitivity of orographic precipitation in Switzerland to atmospheric processes – simulations with the high-resolution numerical model COSMO

Nicolas Piaget *(ETH Zurich, Switzerland), Felix Naef, Heini Wernli*

Dimensioning of flood protections is based on the estimation of the probable maximum flood (PMF). A reliable estimate of this quantity can only be made using a realistic estimate of the probable maximum precipitation (PMP) in the considered catchment. However, traditionally used procedures to estimate the PMP are not

well suited for mountainous regions. These procedures typically transfer an extreme precipitation event observed in a nearby area to the catchment of interest with some adaptation for the differing topography. But the complex terrain does strongly affect the precipitation distribution and impose strong nonlinearities for the precipitation resulting from small variations in the atmospheric flow conditions. Therefore an in-depth knowledge of the precipitation characteristics of a catchment is needed to obtain realistic estimates of the PMP and eventually the PMF.

We use the high-resolution numerical weather prediction model COSMO to study small-scale processes induced by topography-flow interactions. A sensitivity analysis is performed to determine the influence of subtle variations in atmospheric parameters such as specific humidity, wind direction, and temperature on the precipitation distribution. For this purpose, various approaches are used to modify either the initial and boundary conditions of humidity and temperature. Simulations are performed for different flood events in Switzerland, including different type of synoptic forcing, such as blocked and unblocked cases, characterized by atmospheric rivers or quasi-stationary cyclone.

The results show that, for instance an increase of the specific humidity of the incident flow does not necessarily produce an increase of precipitation in the target catchment. Indeed, with increased ambient moisture, smaller mountains upstream of the catchment can be more efficient in triggering precipitation and therefore reduce the moisture available downstream. This novel approach with a set of synthetic sensitivity experiments allows estimating, for a particular catchment, the physical limits of the PMP value.

O1.4 Relation between airflow and rainfall orographic enhancement over the Pyrenees: Three heavy precipitation events

Laura Trapero Bagué *(Institut d’Estudis Andorrans, Andorra), Joan Bech, Fanny Duffourg, Jeroni Lorente*

The windward slopes of the Eastern Pyrenees, as other mountainous Mediterranean regions, are regularly affected by heavy precipitation events (HPE). This study benefits from high resolution numerical simulations (with horizontal grid lengths of 2.5 km) of different case studies using the MESO-NH research model. The analysis has a twofold objective: to describe the synoptic environment in which the HPE developed and to identify the mesoscale mechanisms that lead to steady rainfall over the Eastern Pyrenees. Furthermore, the analysis has been extended to include a Lagrangian description of the flow feeding the precipitation systems which were fairly well reproduced by the model.

Results from the simulations of three different conditionally unstable episodes indicate a marked dependence of the precipitation intensity over the Pyrenees on two factors: the intensity of the wind at low and mid levels and the moisture advection towards the Pyrenees in the lowest 3 km of the atmosphere (Q3). According to the simulations, it has been detected three different rainfall intensity regimes ranging from weak to heavy orographic precipitation where Q3 exceeded 550 kg/m•s and a low level jet of 30 m/s was also present. From the backward trajectories based on Eulerian on-line tracers, it has been found that the feeding flow is confined between 0.5 and 3 km of altitude, mainly in the top edge of the conditionally unstable boundary layer (>1000 m), whereas for the precipitating systems close to the coast the flow is confined in the first 1000 m within the PBL.

O1.5 HyMeX IOP2b: observations and numerical simulations of a supercell over the Friuli-Venezia Giulia region (northeastern Italy)

Mario Marcello Miglietta *(ISAC-CNR, Italy), Agostino Manzato, Richard Rotunno*

An analysis is presented here of severe convection affecting the Friuli-Venezia Giulia region (FVG, northeastern Italy) during Intensive Observation Period 2b (IOP2b) in the first Special Observation Period (SOP1) of the HyMeX campaign. This work focuses on the morning of September 12, 2012, during the first of three severe convection episodes that affected the region during IOP2b. In the first episode, a supercell, which produced hail and severe damage to trees and buildings, was observed on the plain of FVG.

The same day has been analyzed already by previous studies, but here the available observations were analyzed together with new WRF model simulations, in order to identify the mechanisms responsible for the severe convection. The WRF model was used in a one-way nesting configuration, using three nested domains with grid spacing respectively of 9, 3, and 1 km.

First, the predictability of the event was analyzed. Six different simulations were performed starting at three different initial times, using respectively the ECMWF and the GFS analysis/forecasts as initial/boundary conditions. A large spread was observed among the simulations. Only a few simulations were able to reproduce intense rainfall on the plain of FVG during the morning, although with significant differences in the rainfall distribution among them. Second, it was found that in this case the GFS-initialized run starting at 12 UTC, 11 September 2012 best reproduces the observed elongation toward Slovenia of the intense rainfall maximum. The characteristics of the cell are consistent with those expected for a supercell and its simulated evolution near the Adriatic coast agrees well with the observations. Finally, the simulated evolution of some relevant instability parameters over the FVG plain and offshore (over the northern Adriatic Sea) is analyzed, finding that during this event the potential instability varies a lot even in small space and time intervals.

O2 Oral Session: Orographic clouds and precipitation: Part 2

O2.1 The OWLeS Orographic Field Campaign: Adventures in Intense Snowstorms on the Tug Hill Plateau

W. James Steenburgh *(University of Utah, United States of America), Leah Campbell, Peter Veals, Theodore Letcher, Justin Minder*

Rising a modest 500 m above the eastern shore of Lake Ontario, the Tug Hill Plateau of northern New York averages up to 750 cm of snow annually and likely experiences the most intense snowstorms in the world. These storms are generated by long-lake-axis-parallel (LLAP) snowbands that develop over Lake Ontario and intersect the plateau's gentle western slope. World-record snowfalls recorded on the plateau include 30 cm in 1 h (Copenhagen, NY, 2 Dec 1966) and 130 cm in 16 h (Bennetts Bridge, NY, 17–18 Jan, 1959). In addition, a remarkable 24-h accumulation of 195 cm was recorded in Montague, NY from 11–12 Jan 1997, but is unofficial because five measurements were made during the period rather than four.

During December 2013 and January 2014, the National Science Foundation sponsored Ontario Winter Lake-effect Storms (OWLeS) project examined lake-effect storms in the vicinity of Lake Ontario. Research platforms included the University of Wyoming King Air Research Aircraft, three Center for Severe Weather Research (CSWR) mobile X-band Doppler on Wheels radars, the University of Alabama at Huntsville Mobile Integrating Profiling Systems, and five mobile sounding systems. Scientists from the University of Utah and State University of New York at Albany operated a transect of profiling K-band radars from the eastern shore of Lake Ontario to upper elevations on the Tug Hill Plateau, as well as lowland (145 m MSL) and upland (385 m MSL) snow-study stations spaced ~20 km apart, providing an unprecedented look at orographic enhancement during lake-effect snowstorms.

During intensive observing periods (IOPs), snowfall rates at the upland site reached 13.9 cm/h, 36.5 cm/(6 h), and 98 cm/(24 h). During the 12-day period encompassing IOPs 1–5, the upland site received 252 cm of snow with a mean water content of only 5.9%. Despite an elevation difference of only 240 m, the mean orographic ratio (i.e., upland/lowland liquid equivalent precipitation) for 6-h periods during which manual cores of fresh snow were collected at both sites was a remarkable 2.1. Analysis of the data collected by OWLeS observing platforms combined with snow and precipitation measurements from the upland and lowland sites provides new insights into the mechanisms contributing to intense snowfall rates during lake-effect storms and a unique perspective on orographic precipitation enhancement over modest topography.

O2.2 Variations in orographic precipitation enhancement during lake-effect storms over the Tug Hill Plateau: Observations from OWLeS IOP2

Leah S. Campbell *(University of Utah, United States of America), W. James Steenburgh, Peter G. Veals, Theodore Letcher, Justin R. Minder*

Orography downstream of large bodies of water, such as the Great Lakes of North America, often enhances lake-effect snowfall, which can be intense, extremely localized, and challenging to predict. Here we examine orographic effects during lake-effect storms over the Tug Hill Plateau, which gradually rises ~500 m above the eastern shore of Lake Ontario and receives nearly twice the annual snowfall as the surrounding lowlands. Our analysis uses data collected during the Ontario Winter Lake-effect Systems (OWLeS) field program, including S-band surveillance radar scans and data from a transect of profiling K-band radars and snow measurement stations that extended inland from the eastern shoreline of Lake Ontario to the upper Tug Hill Plateau. We specifically examine how the morphology and three-dimensional structure of lake-effect convection during OWLeS IOP2 modulates the orographic enhancement of precipitation over and around the Tug Hill Plateau.

IOP2 produced over 100 cm of snow on the western slope of the Tug Hill Plateau in 24 h. During the event significant vacillations in lake-effect morphology were observed. Organized long-lake-axis parallel (LLAP) bands centered over the transect produced the highest precipitation rates and accumulations at both lowland and upland sites, but also the lowest orographic ratios (i.e., the ratio of upland to lowland liquid precipitation equivalent). Rimed crystals and graupel were frequently observed at both sites during LLAP periods. Broad coverage periods, featuring less-organized convective coverage made up of distinct individual cells, produced lower precipitation rates at both sites but higher orographic ratios as cellular convection produced over the lake transitioned to a more stratiform mode with greater coverage and more persistent precipitation over the Tug Hill Plateau. Mixed mode periods, which consisted of broad coverage concomitant with an organized LLAP band, also exhibited broadening and a convective-to-stratiform transition. During these periods there were low orographic ratios between the upland and lowland site when the band was centered over the transect and high orographic ratios when the band was to the north or south of the transect.

Climatologically, organized bands account for 10% of lake-effect hours over Lake Ontario with broad coverage and mixed mode making up the majority of the remainder. Accordingly, this study suggests that the Tug Hill Plateau precipitation maximum may be largely due to the broadening of precipitation coverage and frequency over the uplands rather than the invigoration of LLAP bands over the Tug Hill Plateau.

O2.3 Climatological Characteristics of Lake-Effect Storms over Eastern Lake Ontario and Orographic Enhancement over the Tug Hill Plateau

Peter G. Veals *(University of Utah, United States of America), W. James Steenburgh, Leah S. Campbell*

The Tug Hill Plateau of upstate New York rises ~500m in elevation east of Lake Ontario, observes frequent lake-effect snowfall, and is one of the snowiest locations in the eastern United States. This, in addition to its simple geometry and the weather surveillance radar situated atop it, make the plateau a favorable location to study orographic precipitation. Using a variety of datasets including imagery from the KTYX WSR-88D radar, this work examines the climatological characteristics and orographic enhancement of lake-effect precipitation over the Tug Hill Plateau over 13 cool seasons (16 September 2001 - 15 May 2014).

Lake effect is important to the hydroclimate of the region, with lake-effect days accounting for 61-76% (24-37%) of the mean cool-season snowfall (liquid precipitation equivalent). The greatest lake-effect snowfall occurs over the western and upper plateau, decreasing abruptly in the lee over the Black River Valley.

Wind speed and direction are shown to strongly affect the precipitation distribution over the plateau. Low wind speeds produce a maximum in radar echoes over the lower slopes of the plateau, and increasing speed shifts the maximum to the higher slopes the plateau. During the highest winds, frequent precipitation persists well inland into the western Adirondack Mountains. A pronounced maximum in echo frequency is present over the plateau under westerly winds (260°-280°), but even when more northerly winds (281°-300°) displace the primary lake-effect structures south of the plateau, precipitation nevertheless continues to initiate or intensify over the plateau.

Orographic enhancement is also examined in the context of the morphological characteristics of lake-effect precipitation features. The two most common morphological types, broad coverage and LLAP, account for 72% and 24% of the total time of lake-effect periods, respectively. Broad coverage exhibits greater enhancement over the plateau than LLAP, despite the fact that LLAP bands produce the most intense snowfall. Collectively, these results illustrate the unique characteristics of orographic precipitation enhancement over the relatively modest topography of the study region during lake-effect storms.

O2.4 Mountain Waves and Orographic Precipitation in a Northern Colorado Winter Storm

David Kingsmill *(University of Colorado, United States of America), Ola Persson, Sam Haimov, Matt Shupe*

Gravity waves forced by terrain-induced vertical displacements of stably-stratified air parcels are referred to as mountain waves. There has been considerable investigation of the role of mountain waves in downslope windstorms, clear-air turbulence and orographic drag influence on the general circulation. In contrast, the influence of mountain waves on orographic precipitation has received comparatively little attention in the literature. Most of these investigations have employed a simulation approach using either quasi-analytical linear models or numerical weather prediction models. Observational studies linking mountain waves to orographic precipitation are scarce. Doppler-radar-based studies of mountain waves and orographic precipitation have provided useful insights, but are limited by not describing the field of vertical air motions across the primary barrier through the full depth of precipitating cloud. It is these vertical motions acting in concert with horizontal motions that directly impact the spatial distribution of precipitation relative to the barrier.

The present study addresses these limitations through analysis of a winter storm passing over the Park Range of northern Colorado on 15 December 2010 during the Colorado Airborne Multi-Phase Cloud Study (CAMPS) field experiment. Observations from the W-band Wyoming Cloud Radar onboard the University of Wyoming King Air (UWKA) research aircraft are used to document horizontal and vertical motions along with precipitation structure in a two-dimensional vertical plane that extends across the Park Range near Steamboat Springs from upstream of the windward slope, over the crest and downstream of the lee slope. Additional observations employed in the analysis include those from the UWKA flight-level instrumentation and ground-based observations from the Atmospheric Radiation Measurement (ARM) program mobile facility (AMF2) such as a W-band scanning radar, balloon sounding system and surface meteorology instrumentation. Surface observations from the Desert Research Institute (DRI) Storm Peak Laboratory (SPL) are also incorporated into the analysis.

The winter storm investigated in this study is associated with a general zonal flow over the western continental U.S. and significant vertical wind shear between 700 and 500 hPa. A vertically-propagating wave forced by the Park Range is most evident above 4 km MSL and associated with relatively-wide, upstream-tilted updrafts and downdrafts located above the Park Range windward and lee slopes, respectively. The Park Range also forces a trapped-lee wave that manifests itself as a relatively erect updraft ~15-20 km east of the crest. Smaller-scale trapped lee waves forced by terrain upstream of the Park Range are evident below 4 km MSL and associated with rotor circulations composed of relatively-narrow, updrafts and downdrafts located above the Yampa Valley and the Park Range windward slope. A ~1 km-thick layer of strong vertical shear exists between the mountain waves forced by the Park Range and those forced by upstream terrain. This shear layer exhibits a large vertical displacement over the Park Range, with relatively-strong westerly winds plunging to low levels over the lee slope. While precipitation on the Park Range windward slope is generally enhanced for the event, data analysed for this case surprisingly does not show a spatially and temporally consistent correlation between mountain-wave kinematic structures and orographic precipitation. Transient processes such as frontally-forced mesoscale circulations, precipitation bands, and/or wave-regime interactions may have masked this correlation.

O2.5 A Precipitation experiment in the Kananakis area of the Alberta Rockies

Julie M. Thériault *(Université du Québec à Montréal, Canada), Ronald E. Stewart, Juris Almonte, Stephen Berg, Émilie Bresson, Mélissa Cholette, Ida Hung, Dominic Matte, Émilie Poirier, Paul Vaquer, John Pomeroy*

Major precipitation events occur in the Banff/Calgary area of Alberta that are a critical aspect of the region's water cycle and they can lead to major disasters such as the June 2013 flooding. This extreme event was the most costly natural disaster in Canadian history. Such events can bring rain, snow or both to the area but there has never been an atmospheric-oriented special observation of these events beyond those made with operational networks. The objectives of this field experiment are to better document and understand precipitation and associated atmospheric conditions in the Banff-Calgary region. To study such storm, based on the climatology of the area, intensive observational period were conducted in March and April 2015. These included detailed measurements of precipitation and weather conditions at the surface, vertical Doppler radar observations, soundings, and profiles down a mountainside examined during each weather event. An overview of the weather events and key preliminary findings will be presented using both observations and model information with a special focus on the characteristics of the transition between rain and snow which often occurs in this area in the spring.

O3 Oral Session: Orographic clouds and precipitation: Part 3

O3.1 Scale dependence of the statistics of heavy precipitation in the Alpine region

Luca Panziera *(MeteoSwiss, Switzerland), Marco Gabella, Alexis Berne, Paolo Ambrosetti, Urs Germann*

The continuing increasing size of weather radar archives offers an unique opportunity to investigate the statistical properties of precipitation.

In this study, quality-checked quantitative precipitation estimates produced by MeteoSwiss by combining radar and rain-gauge measurements for the period 2005-2014 are employed to investigate the influence of different spatial and temporal scales on the statistics of heavy precipitation in Switzerland.

Intensity-Duration-Frequency (IDF) curves for precipitation extremes measured over several spatial and temporal scales are shown, and compared with those derived from point rain-gauge measurements. The spatial continuity of regional rainfall distributions and IDF curves in Switzerland is also analyzed, thus permitting to identify regional differences in the behavior of heavy rainfall.

This study constitutes the scientific framework necessary to identify optimal thresholds of precipitation accumulations for a nowcasting system recently developed at MeteoSwiss and specifically designed to issue heavy rainfall alerts over pre-defined geographical regions.

O3.2 Aerosol-Cloud interactions in orographic wave clouds (ICE-L)

Annette K. Miltenberger *(University of Leeds, United Kingdom), Paul Field, Adrian Hill, Ben Shipway*

Ice nucleation and cloud droplet freezing are two of the most poorly constrained cloud microphysical processes in the atmosphere. Orographic wave clouds at mid-tropospheric levels provide an ideal testbed to study these processes by combining aircraft measurements and numerical modeling. In the presented work we investigate wave clouds observed over the Rocky Mountains during the ICE-L campaign using the Unified Model. The thermodynamic and dynamic properties of the wave clouds are extremely well captured in the simulations, which allows us to focus on the representation of cloud and aerosol processes. Cloud microphysics are represented with the newly developed CASIM microphysical scheme, which accounts for aerosol processing and vertical transport. We evaluate the performance of different ice nucleation parameterizations in representing the measured microphysical evolution. In addition the vertical redistribution of aerosol particles due to sedimenting ice crystals is investigated. This comparison provides important insights in our current understanding of cloud droplet freezing and ice nucleation and the role of mid-tropospheric clouds to redistribute aerosol particles.

O3.3 A high-resolution weather station network in a complex terrain catchment to improve hydrometeorological forecast and water supply for the São Paulo megacity.

Thomas Martin *(University of Sao Paulo, Brazil), Jonathan Mota, Helber Freitas, Nilson Neires, Raianny Leite, Miriam Mathias, Ricardo Hallak, Humberto Rocha*

A high-resolution wireless network of automatic meteorological weather stations (Vaisalla WXT520, Finland), about 200m spaced, was installed in a 12 km² watershed, in a hilly landscape, with altitudes varying between 1100 to 1400 m, at Extrema city, MG state, in Brazil, with the purpose to measure the spatio-temporal variability and mesoscale processes, which includes the heterogeneities of air temperature and humidity, and wind circulations controlled by the topography. The catchment is strategically important, located at the headwaters of the Cantareira reservoir system, which provides half the water for the São Paulo megacity. The measurements will help to improve specification of initial conditions in Regional Climate Models designed for weather forecasting, building of hydroclimatological data set used in models of catchment water balance, and investigation of the effect of global climate changes in mountain regions, among others. First measurements suggest the occurrence of 3m/s up-slope wind (1 m/s down-slope), with regimes of temperature 2°C warmer (4°C colder) on the valley during the daytime (night-time). The air humidity is higher down the valley and reaches two maxima at 12am and 7pm, and minima at 6am and 3pm. Despite it is a small watershed, previous data collected during four years with 4 rain gauges show a difference of annual rainfall of about 200 mm/yr higher in the headwaters compared to the mouth of the stream. The basin is North-South orientated, and is affected by differential heating between the West and East slopes of about 1.5°C. We show spatio-temporal patterns of weather variables for different synoptic conditions, specially in pre-cold front, post-cold front systems and along the ZCAS rainy events (South Atlantic Convergence Zone). We run a very high resolution (100m) Advanced Regional Prediction System (ARPS) model, using the Large Eddy Simulation (LES) mode, and compared to observations. The calculations represented well the local wind circulation and the patterns of temperature and humidity within the watershed.

O3.4 Origin and Flow History of Air Parcels in Orographic Banner Clouds

Volkmar Wirth *(University of Mainz, Germany), Sebastian Schappert*

Banner clouds are clouds in the lee of steep mountains or sharp ridges. Previous work suggests that the main formation mechanism is vertical uplift in the lee of the mountain. On the other hand, little is known about

the Lagrangian behavior of air parcels as they pass the mountain, which motivates the current investigation. Three different diagnostics are applied in the framework of Large Eddy Simulations of air flow past an isolated pyramid-shaped obstacle: Eulerian tracers indicating the initial positions of the parcels, streamlines along the time-averaged wind field, and online trajectories computed from the instantaneous wind field.

All three methods diagnose a plume of large vertical uplift in the immediate lee of the mountain. According to the Eulerian tracers the cloudy parcels originated within a fairly small coherent area at the inflow boundary. In contrast, the time-mean streamlines indicate a bifurcation into two distinct classes of air parcels with very different characteristics. The parcels in the first class originate at intermediate altitudes, pass the obstacle close to its summit, and proceed directly into the cloud. By contrast, the parcels in the second class start at low altitude and take a fairly long time before they reach the cloud on a spiralling path. A humidity tracer quantifies mixing, revealing partial moistening for the first class of parcels and drying for the second class of parcels. For the online trajectories, the originating location of parcels is more scattered, but the results are still consistent with the basic features revealed by the other two diagnostics.

O3.5 The Impact of Mountain asymmetry on Banner Cloud Formation at Mount Zugspitze

Isabelle Prestel *(University Mainz, Germany), Volkmar Wirth, Anne Martin*

Banner clouds are clouds that appear on the leeward side of steep mountains and sharp ridges on otherwise cloud-free days. Previous work has shown that the main formation mechanism is strong lifting of air and associated adiabatic cooling on the leeward side of the mountain.

Banner clouds can frequently be observed at mountains like Matterhorn in the Swiss Alps or Mt. Zugspitze in the Bavarian Alps. A few years ago systematic observations were carried out at Mt. Zugspitze. It turned out that banner clouds at this moutain have a preference for south-easterly flow and appear to avoid northerly flow. In addition, numerical simulations with idealized mountains indicated that weak stratification as well as a rather steep mountain are favourable for the formation of banner clouds.

Here we present numerical simulations in order to understand why banner clouds at Mount Zugspitze have a preference for south-easterly flow. To this end we carried out large eddy simulations with a special focus on the shape of the orography. In a first set of simulations we used idealized orography while systematically varying the windward-leeward asymmetry of the obstacle. Banner clouds we readily formed for mountains with a steep slope on the leeward side and a flat slope on the windward side, because in this setup a bow-shaped vortex can form on the leeward side; the latter is important as it produces the vertical uplift and associated adiabatic cooling. In a second set of simulations we used the realistic orography of Mt. Zugspitze and its environment while varying the wind direction of the incoming flow. In these simulations we found that banner clouds do preferably form for south-easterly flow while they tend avoid northerly flows. This result is in qualitative agreement with both the observations and our idealized simulations. It is concluded that the preference of banner clouds for south-easterly flow at mount Zugspitze must be due to the asymmetry of the orography.

O3.6 How does fog formation vary throughout a valley network?

Sian Lane *(Met Office (UK), United Kingdom), Jeremy Price, Amanda Kerr-Munslow*

Radiation fog is a high impact weather type which remains extremely difficult to forecast accurately, despite recent advances in numerical weather prediction. Although the basic requirements for fog formation of high relative humidity, low wind speed, and clear night skies are well known, the more complex local and non-local processes which influence the timing and location of fog formation are not well understood.

In order to better understand these processes, and to improve the fog-forecasting ability of the Met Office Unified Model, a large observational campaign (LANFEX) is currently being undertaken at two locations in the UK, running over two winters. The campaign comprises 13 sites at a variety of hilltop and valley sites in Shropshire, as well as five companion sites in the much flatter Bedfordshire area in eastern England. The six main sites are equipped with comprehensive instrumentation including flux towers, nephelometers, aerosol spectrometers, and dewmeters. Further to this, 15 sites are also equipped with newly developed fog spectrometers for measuring droplet size distributions and the liquid water content of fog.

The sites in Shropshire are located within a small area (largest distance between sites is 27 km) and were chosen to sample contrasting terrain types – particularly with regard to valley geometry and site elevation. Initial results from the campaign will be presented, focusing in particular on the observed differences in fog formation and development between the various sites.

O4 Oral Session: Thermally-driven flows and cold pools

O4.1 Thermally driven up-slope flows: State of the art and open questions

Dino Zardi *(University of Trento, Italy)*

Thermally driven flows over simple slopes are a relevant research topic, not only per se, but also as a source of key concepts for understanding and modelling many other flows over more complex topographies. However, compared to down-slope, up-slope flows have received much less attention in the literature. Indeed, to investigate katabatic winds many extensive and well equipped field measurements were performed in recent years under various research projects, and a series of high-resolution numerical simulations were run. On the contrary, few field experiments have provided detailed datasets documenting the development of anabatic flows, and the analysis of numerical investigations still relies on Schumann's (1990) pioneering LES simulations. Also, analytic solutions - such as Prandtl's (1942) constant-K profiles - reproduce fairly well katabatic flows, but are definitely inadequate to accurately reproduce field data for up-slope flows (Defant 1949).

In particular, some open questions still claim for further investigations, such as the conditions of instability of slope-parallel flow vs. vertical motions, and the related possible occurrence of flow separation, and the similarity analysis of slope-normal velocity profiles of temperature anomaly, wind intensity and turbulence related quantities.

Here a review of the state of the art on the subject is proposed, along with some insights into possible future developments.

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O4.2 The impact of the temperature inversion breakup on the exchange of heat and mass in an idealized valley: Sensitivity to the radiative forcing

Daniel Leukauf *(University of Innsbruck, Austria), Alexander Gohm, Mathias W. Rotach, Johannes S. Wagner*

The breakup of a nocturnal temperature inversion during daytime is studied in an idealized valley by means of high-resolution numerical simulations. Vertical fluxes of heat and mass are strongly reduced as long as an inversion is present, hence it is important to understand the mechanisms leading to its removal. In this study breakup times are determined as a function of the radiative forcing. Further, the effect of the nocturnal inversion on the vertical exchange of heat and mass is quantified. The Weather Research and Forecasting (WRF) model is applied to an idealized quasi-two-dimensional valley. The net short-wave radiation is specified by a sine-function with a amplitude between 150 and 850 W m–2 during daytime and is zero during the night.

The valley inversion is eroded within five hours for the strongest forcing. A minimal amplitude of 450 W m–2 is required to reach the breakup, in which case the inversion is removed after eleven hours. Depending on the forcing amplitude, between 10 and 57% of the energy provided by the surface sensible heat flux is exported out of the valley during the whole day. The ratio of exported to provided energy is approximately 1.6 times larger after the inversion is removed than before. More than five times the valley air mass is turned over in twelve hours for the strongest forcing, while the mass is turned over only 1.3 times for 400 W m–2 . An even smaller forcing amplitude leads practically to a decoupling of the valley air from the free atmosphere.

O4.3 A nested large-eddy simulation study of the Ora del Garda wind in the Alps

Lorenzo Giovannini *(University of Trento, Italy), Lavinia Laiti, Dino Zardi*

High-resolution numerical simulations performed with the Weather Research and Forecasting (WRF) model are analyzed to investigate the atmospheric boundary layer (ABL) structures associated with the development of a lake-breeze and valley-wind coupled system developing in the southeastern Italian Alps, the so-called “Ora del Garda” wind. Three mesoscale domains, forced by reanalysis data field, are used to drive the finest domains, in which the large-eddy technique is used, achieving a final horizontal resolution of 80 m over three different target areas. Model results complement an existing dataset composed of a series of measurement flights and surface observations. The flights explored specific valley sections at key locations in the study area, namely over the lake’s shore, at half valley and at the end of the valley where the breeze blows. Model results display a good agreement with the experimental dataset. In particular, the surface diurnal cycles of radiation, wind and air temperature are satisfactorily reproduced. The typical structure of the valley ABL, characterized by shallow or even absent mixed layers surmounted by slightly stable layers extending up to the lateral crest level, due to compensating subsidence in the valley core, is also well reproduced in the simulated fields. Moreover, the simulations confirm characteristic local-scale features of the thermally-driven wind field suggested by the analysis of the airborne dataset as well as from previous observations in the area. For example, the model shows the development of inhomogeneities in the cross-valley thermal field, caused by the propagation of the lake breeze and by the different heating between the sidewalls of the valley, as well as the formation of a structure resembling a hydraulic jump in the area where the Ora del Garda flows down into an adjacent valley from an elevated saddle.

O4.4 Energetics of idealised valleys in pooling and draining configurations

Gabriele Arduini *(University of Grenoble and University of Hertfordshire, United Kingdom), Charles Chemel, Chantal Staquet*

In urbanised alpine valleys, persistent stable conditions, as they may occur in winter, lead to high pollution levels. Under these conditions, the atmospheric circulation within the valley is most often decoupled from the synoptic winds and the circulation in the valley is controlled by thermal (along-slope and along-valley) winds. In the simplest case of an idealised valley with uniform surface properties, the intensity and direction of these winds are controlled by the variations in the stratification within the valley, which ultimately result from the variations of the underlying terrain. These observations motivate the present study, which aims at investigating the atmospheric circulation and the heat budget of an idealised valley that opens either on a narrower valley (pooling case) or on a larger valley (draining case). The opening of the idealised valley on a plain is used as a reference case. The WRF numerical model is used to quantify the differences in the nocturnal heat budget between these different configurations.

The numerical results show that the down-valley winds are weaker for both the draining and pooling cases than for the reference case. The reason for this reduction in the intensity of the down-valley winds is that the hydrostatic pressure difference close to the surface between two valleys is weaker than between a valley and a plain.

Because the pressure gradient is related to the difference in the thermal structure of the valley boundary layers, we next consider the heat budget equation averaged over the valley and compare the terms of this equation in each valley for the pooling and draining cases.

Interestingly, after a transient stage associated with the growth of the down-valley winds, a quasi steady state is reached in all valleys, with almost the same valley-averaged instantaneous cooling rate.

However, the details of the transient and steady states are different between the pooling and draining cases. For the draining case, the cooling rate is similar to that of the reference case for both the transient and steady states, with only minor differences in the advection contribution due to the weaker down-valley winds. In contrast, for the pooling case the cooling rate during the transient stage is 60% larger than for the reference case because of large differences in the advection contribution. When the steady state is reached, the dynamical contribution (i.e. the sum of the advection and the sensible heat flux contributions) to cooling is almost identical.

After the down-valley winds have developed, we observe that the cooling rate hardly varies along the valley axis for both the pooling and draining cases. This finding is discussed using volume arguments.

O4.5 Large-eddy simulations of sea breezes over a mountainous island

Chun-Chih Wang *(McGill University, Canada), Daniel J. Kirshbaum*

Mountains and coastlines both favor the development of thermally-driven diurnal circulations, including slope flows induced by elevated heating and land/sea breezes generated by differential heating of land and water bodies. Although slope flows and sea-breeze circulations have each been studied intensively using observations and numerical simulations, understanding of the interactions between the two remains limited. In particular, some studies suggest an enhancement of the sea breeze in the presence of coastal orography while others point to a blocking or weakening effect. To gain insight into these interactions, we conduct a series of large-eddy simulations of daytime airflow over an idealized Gaussian-shaped island terrain. We analyze the simulated sea-breeze propagation characteristics and frontal-circulation strength under varying environmental and topographic factors, including island geometry (width, terrain height and steepness), boundary-layer static stability, and ambient winds. The results suggest that inland orography accelerates the sea-breeze front inland but also causes a weakening of the baroclinicity and frontal circulation. Over sufficiently tall mountains, the latter effect causes the sea-breeze front to vanish entirely as it ascends the slope. The mountain effects on the sea breeze are quantified by tracking the frontogenesis terms and along-front vertical motion in a sea-breeze-following reference frame. This analysis suggests that the mountain upslope flow acts much like an onshore ambient wind: it hastens the inland frontal propagation but also induces strong frontolysis, both of which scale with the mountain height. The potential for sea-breeze blocking at the foot of the mountain is also assessed through a simple Boussinesq scaling.

O4.6 Identification and climatology of Alpine pumping from a regional climate simulation

Meinolf Kossmann *(Deutscher Wetterdienst, Germany), M. Graf, K. Trusilova, G. Mühlbacher*

The regional scale thermally driven circulation between the European Alps and the alpine fore-land - named Alpine pumping – occurs regularly under clear and calm weather conditions. While previous studies focused on Alpine pumping impacts on moist convection and transport of air pollutants over the mountains, this study was motivated by its contribution to the ventilation of the city of Munich, located about 50km north of the European Alps in undulating and only slightly inclined terrain where local thermal circulations are weak. Hourly and daily data from a reanalysis driven regional climate simulation using the model COSMO-CLM are used to identify days with Alpine pumping and to determine the mean diurnal variation of the direction, intensity, and extension of the regional thermal circulation. The model domain extends from the foothills of the Swabian Mountains and the Bavarian Forest in the north to the southern side of the Alpine divide. The model simulation for the years 1989 to 2008 consists of 110x112 horizontal grid points with 2.8km resolution and 50 non-equidistant vertical levels with higher resolution near the surface.

Four literature based combinations of meteorological criteria have been tested to identify days favourable for Alpine pumping from COSMO-CLM results. The first criterion selects days with a daily sum of solar radiation greater or equal 20MJ/m2 and has also been used in an earlier observational study. The mean annual number of 60 days fulfilling the criterion in the model simulation compares well to the 67 days per year determined from observations. The other three criteria combinations consider a maximum upper level wind velocity, a maximum daily precipitation sum, and/or a maximum mean cloud cover. The mean annual number of selected days is lower for these criteria combinations and ranges between 20 and 52.

The daily solar radiation sum of 20MJ/m2 is only exceeded during the months from April to September with highest exceedance frequencies from May to August. In contrast the criteria combinations without a radiation threshold occur all year round. In agreement with observations, the simulated regional thermally driven wind field extends up to about 100km north of the Alps, with average near surface wind speeds of around 1 to 1.5 m/s in the Munich area. With increasing distance from the Alps the diurnal cycle of alpine pumping is delayed by up to 3h. The simulated mean depth of the daytime inflow layer derived from meridional vertical cross sections of the wind field through Munich ranges between 500m and 1500m, while the depth of the nocturnal outflow layer typically reaches up to a few hundred meters.

O5 Oral Session: Gravity wave and airflow dynamics: Part 1

O5.1 Mysteries of the Deep: Flying through New Zealand's gravity waves

James D. Doyle *(Naval Research Laboratory, United States of America), Qingfang Jiang, Alex Reinecke, Carolyn Reynolds, Stephen D. Eckermann, David C. Fritts, Ronald B. Smith, Mike Taylor, Andreas Dörnbrack*

The DEEP propagating gravity WAVE program (DEEPWAVE) is a comprehensive, airborne and ground-based measurement and modeling program centered on New Zealand and focused on providing a new understanding of gravity wave dynamics and impacts from the troposphere through the mesosphere and lower thermosphere. This program employed the NSF/NCAR GV (NGV) research aircraft from a base in New Zealand in a 6-week field measurement campaign in June-July 2014. The region near New Zealand was chosen since all the relevant gravity wave sources (e.g., mountains, cyclones, jet streams) occur strongly here, and upper-level winds in austral winter permit gravity waves to propagate to very high altitudes. During the field phase, the NGV was equipped with new Rayleigh and sodium resonance lidars and a mesospheric temperature mapper, a microwave temperature profiler, as well as dropwindsondes and a full suite of flight level instruments providing measurements spanning altitudes from immediately above the NGV flight altitude (~13 km) to ~100 km. The DLR Falcon, equipped with a down-looking Doppler wind lidar and in situ instrumentation, was also available for coordinated flights. The ground based instrumentation included a wind profiler and radiosonde unit on the west coast of the South Island, as well as ground based lidars and high-altitude radiosonde sites.

Highlights of observations of deep propagating gravity waves during the field phase will be presented. During DEEPWAVE, 16 Intensive Observation Periods (IOPs) occurred, which featured 26 NGV and 13 Falcon research flight missions, as well as a comprehensive suite of ground based observations. These observations include cases of topographically generated gravity waves, as well as waves generated by generated by non-orographic sources such as jet streams and cyclones. Examples of coupling between the lower and upper levels will be shown using the in situ and remote sensing observations, as well high-resolution models with deep domains.

Results will be presented from high-resolution and adjoint models with deep domains for cases over New Zealand during DEEPWAVE that feature GW wave propagation. Comparisons will be made with DEEPWAVE observations. These high-resolution models highlight the role of lateral shear from the jet stream that refracts vertically propagating gravity waves generated by regions of high terrain, such as New Zealand. The predictability links between the tropospheric fronts, cyclones, jet regions, and GWs that vertically propagate upward through the stratosphere are quantified using a nonhydrostatic adjoint model. Preliminary results will be presented that quantify the degree to which forecasts of GW launching and characteristics are sensitive to the model initial state and in particular to synoptic-scale and mesoscale characteristics of mid-latitude cyclones.

O5.2 Severe turbulence in a deep valley associated with rotors and interacting cross-mountain and up-valley flows

Lukas Strauss *(University of Vienna, Austria), Vanda Grubišić, Stefano Serafin*

A simple conceptual model of atmospheric rotors in the lee of a mountain range emerged from the first organized glider observations as early as the 1950s, during the Sierra Wave Project, and was refined by in situ research aircraft measurements over the Colorado Rockies in the 1970s. Since then, rotors have been traditionally depicted as turbulent horizontal vortices in the lee of and parallel to mountain ridges, forming in association with large-amplitude mountain waves.

The Terrain-induced Rotor Experiment (T-REX, Owens Valley, California, 2006) was the most recent coordinated effort to study the coupled system of mountain waves, boundary layer and rotors. The comprehensive T-REX observational dataset, consisting of ground-based and airborne in situ and remote sensing measurements, provides the opportunity to reconsider the rotor concept in a deep valley.

In this context, the idealized picture of a rotor proves to be simplistic and needs to be extended taking the characteristics of the valley environment into account. For example, rotor formation may be influenced by factors like the onset of thermally-driven slope and valley flows, terrain-forced flow channelling, the presence of a secondary parallel ridge, or the along-ridge variation of crest height.

A rigorous re-analysis of T-REX cases with a strong flow response to the Sierra (IOPs 1, 3, 4, 6, and 13) has been carried out. The analysis reveals that, at any given time, multiple processes may contribute to the generation of severe turbulence in the valley. For example, at nighttime, both wave-induced pressure gradients and positive buoyancy forces may work in concert to make the flow separate well above the valley floor, leading to enhanced turbulence in the valley that bears similarities in structure and strength to the classical depiction of a rotor but does not extend to bottom of the valley. Beyond rotors, turbulent interaction of cross-mountain wind, intruding into the valley, with strong pressure-driven channelled up-valley flow can give rise to turbulence intensities as large as in rotors. Based on evidence from these and other cases, we propose extensions to the current conceptual model of an atmospheric rotor that are appropriate for a deep valley.

O5.3 Lee rotor onset prediction using linear theory with a boundary layer

Miguel A. C. Teixeira *(University of Reading, United Kingdom)*

Lee rotors are elongated vortices formed beneath trapped lee waves, where the flow stagnates and reverses near the surface, often originating flow unsteadiness and turbulence. These flow structures can constitute a serious aviation hazard, however, they are hard to forecast, because their scale is relatively small (a few km across), therefore being inadequately resolved by both global and even some regional weather prediction models. The nature of rotors, with flow stagnation and reversal, suggests that they are intrinsically nonlinear phenomena. Their accurate forecast is probably only possible using high-resolution numerical simulations, with grid spacings smaller than 1km, and resolving part of the turbulence (e.g. LES), because small-scale structures, and their impact on the large-scale flow, are intrinsically 3D, even when the large-scale flow, and the orography that generates it, are 2D. However, the fact that the near-surface flow stagnation leading to rotors has been observed for relatively modest mountain heights suggests that the flow may be nearly linear outside the boundary layer in many situations of practical interest, and only boundary layer effects induce nonlinearity, with frictional effects facilitating flow stagnation. On the other hand, it was seen previously that linear theory can give valuable qualitative indications about the onset of flow stagnation outside the boundary layer. This suggests the approach used in the present study, where the linear model of trapped lee waves over 2D obstacles developed by Teixeira et al. (2013) is extended to include a very simple representation of the boundary layer, following Smith et al. (2006). The drag calculations of Teixeira et al. (2013) found a significant correlation between trapped lee wave drag and the onset of rotors. Here we will go further by calculating the conditions under which flow stagnation occurs in the lee of 2D ridges. The flow stagnation condition is diagnosed based on the streamwise velocity perturbation (which is closely related to the drag). The existence of a boundary layer promotes flow stagnation by concurrently amplifying this velocity perturbation and attenuating the mean incoming flow. The predictions from this linear model are compared with the regime diagrams of Vosper (2004) and Sheridan and Vosper (2006), showing broad consistency.

O5.4 The impact of mountain width and stratification on wave-induced rotor formation

Johannes Sachsperger *(University of Vienna, Austria), Stefano Serafin, Vanda Grubišić*

The formation of rotors and their coupling to waves aloft is investigated using a numerical model and linear wave theory. The study considers a set of uniformly stratified flows, defined by a range of stabilities and mountain widths, over an isolated mountain ridge. The resulting wave regimes range from weakly to strongly non-linear and hydrostatic to non-hydrostatic. Working in conjunction with surface friction, mountain waves give rise to boundary layer separation and rotors in a broad range of simulated flows and conditions.

The deepest rotors and strongest reversed flows at the ground are found to develop in non-linear and moderately non-hydrostatic cases. This finding agrees with linear theory, which predicts mountain wave amplitudes to be largest in such flows. However, in near-hydrostatic conditions, for which linear estimates of wave perturbations are comparatively small, boundary-layer rotors also form. These rotors do not directly adjust to the flow structure aloft and are decoupled from it by wave breaking

It is shown, by means of linear interfacial wave theory, that an undular bore that forms on a strongly-stratified low-level jet can explain the presence of rotors in hydrostatic flows. Part of the wave energy trapped at the interface can still leak through the evanescent layer that owes its origin to wave breaking. In the process, short-wavelength vertically-propagating modes are generated, which distinctively impact the flow structure of the stratified atmosphere aloft.

Our results suggest that rotors in uniformly stratified flows owe their origin to non-hydrostatic wave modes that are either part of the primary wave field or represent secondary wave motions that are generated by breaking of near-hydrostatic waves.

O5.5 Aspects of inversions and mountain flows

Haraldur Ólafsson *(HI, Iceland), Hálfdán Ágústsson, Marius Opsanger Jonassen, Birta Líf Kristinsdóttir, Sigurður Jónsson, Andréa Massad, Eiríkur Örn Jóhannesson*

Numerous studies have shown inversions to be importan for the creation of perturbations in atmospheric flows in the vicinity of mountains. Here, several aspects of the importance of inversions are presented. They are based on both observations and numerical simulations of features ranging from gravity waves with extreme rotors to weak mountain flow. A preliminary attempt to map the climatology of inversions in Iceland is also presented. The above studies indicate that elements of the flow may be very sensitive to not only the elevation, but also the strength or sharpness of the inversion. A very little temperature change at the inversion may transform the downstream flow pattern, leading to an increased magnitude of vertical velocities by an order of magnitude. Numerical weather prediction models tend to fail in reproduction of the inversions.

O5.6 Virtual and real topography for flows across mountain ranges

Laurence Armi *(University of California San Diego, United States of America), Georg J. Mayr*

A combination of real and virtual topography, as opposed to the real or actual topography alone, describes the essentials of stratified flow over mountain ranges and leeside valleys or plains when a layer capped by a strong density step exists above the topography. This cap acts as virtual topography for the stratified flow aloft and will control its response.

On 14 March 2006 [Intensive Observation Period 4 of the Terrain-Induced Rotor Experiment (T-REX)], a nearly neutral cloud-filled layer, capped by a strong density step overflowed the Sierra Nevada and separated from the lee slope upon encountering a cooler valley air mass. The flow in this lowest layer was asymmetric across and hydraulically controlled at the crest. The density step at the top of this flowing layer formed a virtual topography, which descended 1.9 km and determined the horizontal scale and shape of the flow response aloft reaching into the stratosphere. A comparison shows that the famous, 11 January 1972, Boulder windstorm case was similar: hydraulically controlled at the crest with the same strength and descent of the virtual topography. In both of these cases the layer in contact with the real topography makes a transition from subcritical to critical flow at the crest and becomes supercritical downstream. It becomes subcritical again farther downstream after transitioning through a hydraulic jump. For the less-well-known Boulder case of 18 February 1970 the layer in contact with the real topography was subcritical everywhere with only a slight dip above the crest, typical of subcritical flows. In all three cases the shape of the virtual topography was very different than the real topography.

The response aloft in the troposphere to the virtual topography differed among these three cases. This response can be analyzed with the internal Froude numbers of the troposphere layer and the virtual topography beneath these layers. For the Sierra case the troposphere layer is subcritical and hence decelerates and slows with a decrease in the height of the virtual topography. This is a subcritical response with an associated rise in the elevation of the tropopause. Although the famous 11 January 1972 Boulder case has virtual topography that is similar to that of the Sierra case, the troposphere layer makes a transition from subcritical to supercritical flow. The difference is in the existence of a weak cap aloft bounded by a stagnant isolating layer. The 18 February 1970 Boulder case had no downslope windstorm and no response in the supercritical flow in the troposphere layer aloft, despite the 80 m/s westerly wind component at 10 km.

O5.7 Sub-kilometre simulation of terrain-disrupted airflow associated with aircraft diversion at the Hong Kong International Airport

K. K. Hon *(Hong Kong Observatory, Hong Kong S.A.R. (China)), P. W. Chan*

Situated on an artificial island surrounded by complex mountainous orography, the Hong Kong International Airport (HKIA) is susceptible to the occurrence of terrain-induced airflow disturbances under suitable meteorological conditions. These airflow disturbances are known to bring about windshear and/or turbulence when encountered by landing/departing aircraft, and pose potential aviation safety hazard.

During a particular episode in March 2015, the arrival of an intense late-season northeast monsoon resulted in over 60 reports of windshear encounter at HKIA within a day, necessitating a number of aborted landings and even diversion in some cases. Analysis of wind field around HKIA, as visualised by Doppler LIDAR PPI scans, revealed typical flow patterns conducive to terrain-induced windshear for sustained periods of time, including occurrence of a low-level southeasterly jet aloft the arrival corridor and subsequently frequent shedding of vortices downstream of the Lantau mountains as winds veered south.

This study examines the performance of the Hong Kong Observatory (HKO)'s Aviation Model (AVM) in capturing such terrain-induced windshear features through comparison with aircraft pilot reports, aircraft Quick Access Recorder (QAR) data and LIDAR observations. The AVM is a sub-kilometre implementation of the Weather Research and Forecast (WRF) model by HKO in an operational setting, providing hourly-updated short-term forecasts around HKIA at horizontal resolution down to 200 m. Simulated LIDAR return by the AVM, both in the form of PPI scans and aircraft glide-path headwind profiles, will be studied with a view to identifying the strengths and weaknesses in reproducing the spatio-temporal characteristics of the observed wind features. Sensitivity of the simulated wind features to horizontal resolution of the model domain, as well as predictability of such features, will also be briefly discussed.

O6 Oral Session: Boundary layer processes: Part 1

O6.1 A mesoscale model-based climatography of daytime atmospheric boundary layer heights over complex terrain.

Stephan F. J. De Wekker *(University of Virginia, United States of America), Stefano Serafin, Jason C. Knievel*

Numerical weather prediction (NWP) models are providing weather forecasts at increasingly higher resolutions, allowing boundary layer phenomena to be resolved over areas with mesoscale topography. Multi-year climatographies, constructed from high-resolution NWP model output, can therefore now provide an improved representation of the spatiotemporal structure and other characteristics of these phenomena, including atmospheric boundary layer (ABL) heights. Knowledge of the ABL height variability is important for many studies including the dispersion of air pollution, weather forecasting, and planning of boundary layer field experiments. In this paper, two years of hourly output from an operational forecasting model run with a 1.1-km grid interval are analyzed to construct a daytime ABL height climatography and to investigate the spatiotemporal behavior of ABL heights over an area of complex terrain in northwestern Utah, centered around an isolated mountain. The two year climatography shows considerable variability in ABL heights, which generally increase from west to east and from north to south. The variability cannot be solely explained by gradients in sensible heat flux due to heterogeneities in surface type. Changes in terrain elevation and associated thermally driven circulations are partially responsible for the ABL height variability. Data from intensive observational periods during the MATERHORN field campaign are used to demonstrate the complexities associated with comparing simulated PBL heights to observations. This study demonstrates that climatographies constructed from high-resolution NWP output can potentially provide useful information about ABL height variability for different applications, and can improve our understanding of boundary layer structure over complex terrain.

O6.2 The Passy project: Objectives, underlying scientific questions and preliminary numerical modelling of the Passy Alpine valley

Chantal Staquet *(Université Joseph Fourier, France), Alexandre Paci, Julie Allard, Gabriele Arduini, Hélène Barral, Manuel Barret, Sébastien Blein, Christophe Brun, Frédéric Burnet, Guylaine Canut, Didier Chapuis, Charles Chemel, Florie Chevrier, Jean-Martial Cohard, Alain Dabas, Hélène Guyard, Jean-Luc Jaffrezo, Pauline Martinet, Stéphane Mercier, Grisa Mocnik, Isabel Peinke, Julian Quimbayo, Jean-Emmanuel Sicard, Delphine Six, Florence Troude, Isabella Zin*

Urbanised Alpine valleys experience high pollution levels during wintertime stable conditions. One notable example is the Arve valley around the small city of Passy, located in the French Alps 20 km west of Chamonix, which is one of the most polluted places in Région Rhône-Alpes under such conditions. A key controlling factor of pollution lies in cold air pools that form at the bottom of the valleys. Only recently have field campaigns been specifically focussing on such conditions, e.g. COLPEX (Cold-air Pooling EXperiments) in the Clun valley in England, I-Box (Innsbruck Box) in the Inn valley in Austria and PCAPs (Persistent Cold-Air Pool Study) in the Salt Lake basin in the USA.

A scientific project devoted to the study of the atmospheric circulation in the Passy valley has been under way since January 2014, named the Passy project, in close connection with a programme devoted to the study of PM10 distribution in the same valley (managed by the air quality agency of Région Rhône-Alpes and laboratory LGGE in Grenoble). The Passy project has two main objectives: (I) to characterise the atmospheric circulation and the thermal structure of the inversion layer within the valley during stable conditions; (ii) to quantify their impact on pollutant dispersion. To start with, a field campaign was held in winter 2014-2015, during which extensive meteorological data and supplementary atmospheric composition data (mostly PM10) were collected in the valley. This field campaign along with preliminary results are presented in a companion paper by Paci et al.

The aim of the present paper is to introduce the objectives and underlying scientific questions of the project, and to report about preliminary numerical experiments of the atmospheric circulation in the valley using the WRF model. Nested domains are used for this purpose but such a numerical modelling represents a technical challenge: the valley around Passy is very narrow (few kilometres in width) with steep slopes. Numerical results for the diurnal cycle of a cold-air pool during one of the IOPs will be compared to field measurements, focusing on the height of the inversion layer and on wind profiles. A preliminary picture of the atmospheric circulation in the valley will be proposed, the attention being brought to the ventilation processes inside the cold-air pool.

O6.3 High-resolution numerical modeling of meteorological conditions and associated particulate matter distribution over complex terrain, in the Italian Alps.

Elena Tomasi *(University of Trento, Italy), Lorenzo Giovannini, Luca Ferrero, Dino Zardi, Mariapina Castelli, Marcello Petitta*

High-resolution numerical simulations are performed with the Weather Research and Forecasting (WRF) model and with the CALPUFF dispersion model in order to reproduce meteorological conditions and particulate concentration vertical profiles close to the city of Merano, in the Adige Valley, in the north-eastern Italian Alps. Simulation results are compared against observations recorded both by surface weather stations and by means of balloon soundings performed during a field campaign in March 2010. The soundings recorded temperature and particulate concentrations from the surface up to 800 m above ground level in several moments of the day, to evaluate the temporal evolution of the boundary layer. Interesting meteorological phenomena, able to influence the dispersion of particulate matter, were observed during the field campaign and were also correctly reproduced by the simulations, as for instance the break-up of the early morning ground-based thermal inversion after sunrise and the arrival of strong foehn winds. The observations clearly show that these meteorological phenomena are strictly related with changes in the vertical distribution

of particulate matter: concentrations, indeed, are very high near the ground in the early morning, when thermal inversion, biomass burning for domestic heating and the traffic rush hour act simultaneously. Conversely, particulate matter concentrations diluted with the development of the boundary-layer and strongly decreased at all heights when the foehn wind starts to blow.

O6.4 Comparison of modelled and measured wind fields in an Alpine Valley

Gabriele Rau *(Zentralanstalt für Meteorologie und Geodynamik, Austria), Johannes Vergeiner, Mathias W. Rotach*

Dispersion modelling in an Alpine surrounding has to cope with steep slopes, prolonged periods with low wind speeds and cold air drainage during night-time. Diagnostic wind fields have clear limits in dealing with these aspects, while complex models like WRF (Grell et al. 2005) and INCA (Haiden et al. 2010) should render more realistic wind fields under these conditions. The research-project WAAR focused on the question, which model is to favour and to quantify the impact on next-in-line dispersion models.

The basic dataset used for this evaluation was provided by instruments run in the framework of the “Innsbruck Box” (Stiperski et al. 2012) by the Institute for Meteorology and Geophysics, University of Innsbruck (IMGI). Data from 5 different sites (valley floor and adjacent slopes) around Kolsass (Inn-Valley) were available.

Half hourly wind fields were calculated for two episodes with low windspeeds and two episodes with stronger wind (one foehn event, one frontal passage) with LASAT (Janicke, 2013) and GRAMM (Oettl et al., 2010) , both using the valley-floor data as input and a horizontal resolution of 50 m.

Furthermore the selected episodes were simulated (without taking the locally measured data into account) with the mesoscale prediction model WRF (Grell et al. 2005) and the Analysis and Nowcasting system INCA developed at ZAMG (Haiden et al. 2010) on an hourly basis. INCA is based on the mesoscale prognostic model ALARO; meteorological parameters (i.e. wind, temperature, humidity, precipitation, cloud cover) are provided hourly with a horizontal resolution of 1 km. WRF-CHEM is based on three-hourly data (analysis for 0 and 12 UTC; prognosis for the rest of the time) from the ECMWF-model. The operational grid of WRF-CHEM (Alpine area) has a horizontal resolution of 4 km. Within this grid a nest (100x100 km) with a horizontal resolution of 1 km was centred above the project area. In order to meet the needs of dispersion modelling (LASAT) on a local scale the wind fields simulated by INCA and WRF had to be downscaled (using a bilinear interpolation scheme) to a horizontal resolution of 50 m. These interpolated windfields were used as additional input for LASAT.

Results:

Along the slopes INCA and WRF deliver better results. On the valley-floor (near the measurement site) LASAT and GRAMM/GRAL produce more realistic wind fields.

Against expectations INCA and WRF did not reproduce the two episodes with strong winds very well. There is still some need for an improvement of the interpolation-algorithms, especially for wind speeds in WRF.

For the foehn-event the wind fields are discussed in terms of meteorological plausibility on the valley bottom and on the slopes. A comparison with the i-Box stations and statistical analysis is presented as well and serves to validate the results. The effects on a typical dispersion calculation (i.e. a highway along the valley) are shown qualitatively.

O6.5 The impact of orography on gas dispersion and transportation during the 2014 Holuhraun eruption

Elín Björk Jónasdóttir, ***Guðrún Nína Petersen*** *(Icelandic Meteorological Office, Iceland), Halldór Björnsson, Melissa Anne Pfeffer, Sara Barsotti, Þorsteinn Jóhannsson, Tobias Dürig*

The 2014 fissure eruption in Holuhraun is unique among recent eruptions in Iceland for its high emission rates of volcanic gases. The plume was relatively ash free, but predominantly a bent over vapour plume and its height depended mainly on the atmospheric conditions at the eruption site.

During the first month and a half the preliminary SO2 flux was ~400 kg/s with some days greater than 1000 kg/s. The gas is dispersed from the eruption and was transported by wind, leading to high pollution levels in exposed populated areas in Iceland. During high wind events and when nearby weather systems led to rapid change in wind directions the local population was not been much affected by the emission.

However, during certain conditions, usually light winds and low-level temperature inversions, the concentration of gas build up at the eruption site and then either flowed down from the highlands with katabatic wind or was advected from the eruption site when the synoptic situation changes. Depending on the atmospheric conditions, high concentrations of SO2 were transported in the boundary layer and detected at ground level in populated areas.

Here we describe one such event, the event of 26 and 27 October 2014, when the village Höfn, in southeast-Iceland, experienced gas concentrations exceeding 14000 µg/m3, a concentration considered hazardous to health. We describe the weather conditions prior and during the event as well as the gas dispersion.

O7 Oral Session: Boundary layer processes: Part 2

O7.1 The ScaleX experiment in the TERENO-prealpine observatory

Benjamin Wolf *(Karlsruhe Institute of Technology, Germany), Christian Chwala, Frederik De Roo, Benjamin Fersch, Jakob Garvelmann, Edwin Haas, Wolfgang Junkermann, Nadine Ruehr, Klaus Schäfer, Hannes Vogelmann, Matthias Zeeman, Almut Arneth, Klaus Butterbach-Bahl, Michael Dannenmann, Stefan Emeis, Ralf Kiese, Harald Kunstmann, Matthias Mauder, Peter Suppan, Ralf Sussmann, Hans-Peter Schmid*

Important ecosystem functions, such as the pools and exchange fluxes of carbon, nitrogen, energy and water, or soil fertility, are expected to be altered substantially due to global environmental change. This applies especially for mountain regions which are among the most climate change-sensitive landscapes. The manifold spatial complexity of mountain regions involves variations of terrain, soil types, water availability, vegetation, and land-use across a wide spectrum of scales. The spatial complexity is a challenge for both observation and modeling of ecosystem-atmosphere interactions, boundary layer dynamics, patterns of atmospheric circulation, precipitation, subsurface water movement and nutrient flows.

TERENO is a large-scale integrative observation program designed to determine the long-term ecological and climatic impact of global environmental change at regional scales. The TERENO-prealpine observatory in southern Germany comprises three core grassland sites at different elevations (600, 750 and 860 m a.s.l), which are equipped with eddy-covariance flux towers and chamber-flux/lysimeter clusters. The climasequence arrangement of the core sites along an elevation gradient serves as an in-situ climate change analogy. The complex environment poses a challenging research question: how well can our observations constrain modeling uncertainties of biogeochemical cycles, and close the balances of energy and matter flows? This research question integrates one-dimensional single site approaches, transects along climatic and terrain gradients, and spatially explicit three-dimensional representations of land surface – atmosphere interactions.

The ScaleX campaign in the TERENO-prealpine observatroy is designed to address this overarching research question, and to expand our understanding of energy and matter fluxes from site to regional scale. The scale expansion will be achieved by linking observations of surface fluxes (lysimeter, chamber, EC) to remote sensing techniques (LIDAR, Sodar-RASS, digital and hyperspectral imagery, X-band radar), airborne measurements (ultralight aircraft and unmanned aerial vehicle), and process- to meso-scale modeling (WRF-hydro, WRF-CHEM, LES, L-DNDC). ScaleX is structured into work-packages to examine specific aspects of land surface-atmosphere interactions, including:

• Effects of mesoscale circulations on biosphere-atmosphere exchange processes

• Trace gas budgets in the nocturnal boundary layer for mesoscale model evaluation

• Patterns of precipitation and soil moisture from site to regional scale

• Capability of digital/hyperspectral imagery to scale canopy traits of ecosystem function

• Closure of atmospheric water and energy cycles

• Distributed modeling of energy, water, carbon and nutrient cycles from local to regional scales

We will present preliminary results from the first phase of ScaleX, which will take place during June and July 2015. We will also give an outlook to the second phase, planned for 2016.

O7.2 Flux measurements over complex, forested terrain

Andrew N. Ross *(University of Leeds, United Kingdom), Rosey Grant*

The planar fit method is often used for long-term eddy-covariance flux measurements since it offers a number of advantages over rotating each 15-minute sample into streamwise coordinates. For sites over complex, forested terrain however a single planar fit may not be appropriate since such sites may have very different slopes and forest cover in different directions. There is significant interest in measuring fluxes of momentum, heat and other scalars at such sites to understand the role of complex topography and heterogeneous forest canopies on surface exchange.

We present an alternative to the standard planar fit method where the tilt angle is fitted as a continuous function of the wind direction. This retains many of the benefits of the planar fit method, while at the same time better representing local variations in tilt angle with wind direction. The method is tested for momentum and heat fluxes using data from a field experiment on the Isle of Arran, Scotland studying forest canopy-atmosphere interactions over complex terrain. The 3 tower sites are located over a ridge and there is significant heterogeneity in the canopy cover around them. This makes it a tough test for any coordinate transformation scheme. Results are compared with the traditional planar fit, streamwise rotation and also a sector planar fit method. In most cases the new continuous planar fit method demonstrates better agreement with fluxes obtained from rotating into streamwise coordinates when compared to the standard planar fit method. It also behaves more smoothly than the sector planar fit method, avoiding the discontinuities which can be seen using this method.

O7.3 Challenges when dealing with turbulence measurements in mountainous terrain

Ivana Stiperski *(University of Innsbruck, Austria), Mathias W. Rotach*

Measurement and analysis of turbulence in mountainous terrain are challenging in several respects. Non-ideal terrain makes finding an appropriate coordinate system non-trivial, whereas the abundance of motions on all scales in mountainous terrain raises the question of isolating true turbulence. Still the post-processing methods for analysing turbulence statistics are based to a large extent on the assumptions of horizontally homogeneous and flat terrain.

Here we discuss those aspects of turbulence measurements that require special attention in complex mountainous terrain. We place special focus on coordinate systems and different post-processing options in mountainous terrain. The appropriate choice of post-processing methods is then tested based on local scaling arguments. It is shown that over non-ideal slopes the currently commonly applied planar fit method can be inappropriate, lead to erroneous scaling and underestimates the flux. The reasons for this are studied in detail and a modified planar fit method suggested. We also demonstrate that conclusions drawn from turbulence measurements in complex terrain (e.g., scaling relations) are sensitive to these post-processing choices, thus questioning the results obtained in other studies so far.

O7.4 Evaluating local similarity scaling in the stable, wintertime boundary layer influenced by complex topography

Karmen Babić *(University of Zagreb, Croatia), Mathias W. Rotach, Zvjezdana Bencetić Klaić*

Due to the development (or presence) of internal boundary layers the turbulent characteristics in the lowest meters over heterogeneous surfaces are more complex than above horizontally homogeneous and flat terrain. In this study we investigate the applicability of Nieuwstadt's (1984) local scaling formulation for the stable boundary layer. The data for this study stem from a tall tower within a small forest patch situated in heterogeneous terrain with agricultural land, forested hills and urban surfaces in different upwind sectors. The 62 m tower (levels 20, 32, 40, 55 and 62 m above ground) was situated in the middle of some 120 m x 480 m area of 18 m high trees. Here we only analyze periods with stable stratification from winter 2008/2009 focusing on the influence of the upwind hilly terrain. As turbulent fluxes showed a substantial variation with height, we adopt local scaling approach for which similarity functions and the local stability parameter are based on local fluxes at measurement height. In the data analysis the role of self-correlation is examined. Also an in-depth error analysis applying the Filtering Method allows to estimate the percentage of random errors in the turbulence variables. Using this method it is possible to inspect if the scatter in the measurements is caused by random errors, or by other dynamical factors of the stable boundary layer. Values of scaled standard deviation for wind components in near-neutral conditions are found to be lower at the lowest measurement level and higher at upper levels in comparison to canonical Kansas values. The non-dimensional gradient of wind velocity is also investigated. We compare our results with traditional linear equations for the stable case and also to the empirical non-linear expression proposed by Beljaars and Holtslag (1991). It is found that the stability function for momentum supports the linear equation only up to values of the non-dimensional stability parameter $\zeta \approx 0.5$. Moreover, we find good agreement between our results and the Beljaars and Holtslag function, which increases more slowly with increasing stability. As we observed more strongly stable stationary cases, local z-less scaling is also addressed. Our analysis supports the validity of z-less stratification for very stable conditions ($\zeta > 1$) for scaled wind velocity variances and correlation coefficients for momentum and heat flux. As a preliminary conclusion, based on scaled velocity variances and non-dimensional mean wind shear, it is found that local scaling is promising even over highly non-homogeneous terrain as in our case.

O7.5 On the role of advection for the net ecosystem carbon dioxide exchange of a subalpine grassland

Georg Wohlfahrt *(University of Innsbruck, Austria), Marta Galvagno, Edoardo Cremonese, Umberto Morra Di Cella*

At the majority of FLUXNET sites the net ecosystem exchanges of energy and carbon dioxide are quantified based on a simplified, one-dimensional mass balance, which neglects advective flux contributions. In particular in complex terrain and nighttime conditions, this approach is questionable and thought to cause an underestimation of the true net ecosystem exchange. For carbon dioxide, which typically is taken up during daytime and released during nighttime, this is likely to cause a systematic bias.

Here we report on an experiment at a subalpine mountain grassland in Northern Italy situated in truly complex terrain characterized by slopes of different inclination and exposition. During the month-long experiment we attempted to quantify all terms of the full three-dimensional carbon dioxide mass balance and compared these with concurrent ecosystem respiration measurements by automated chambers.

The main findings of this study can be summarized as follows: (i) the sum of the vertical covariance term and the storage term considerably underestimates nighttime ecosystem respiration as measured by the automated ecosystem chambers; (ii) advection measurements indicate that both horizontal and (less so) vertical advection are important terms of the full mass balance during nighttime; (iii) the net ecosystem carbon dioxide exchange calculated by taking into account all terms, i.e. including advection, closely resembles nighttime ecosystem respiration as measured with the automated ecosystem chambers; (iv) there is substantial spatial variability in the vertical covariance term during nighttime; (v) during daytime, advection appears to make a negligible contribution to net ecosystem carbon dioxide exchange.

O7.6 A factor-separation study of convective boundary layer development over non-uniform land use and topography

Stefano Serafin *(University of Vienna, Austria), Stephan F. J. De Wekker*

Sensible heat fluxes from the ground to the atmosphere cause the planetary boundary layer to become convectively mixed. The spatial variability of mixing heights is known to be determined both by the distribution of heat fluxes and by the shape of the underlying topography, mostly through two distinct physical processes. First, heat fluxes that are either relatively strong or occur at relatively high altitude, e.g. at mountain tops, locally enhance vertical mixing and cause the convective boundary layer (CBL) depth to increase. In addition, the mixing height can be modulated by the lateral redistribution of air masses and heat by breeze systems, generated both by differential heat fluxes and by topographic forcing.

Little is known on which of these factors, land-use differences and topography, has the largest potential impact on mixing height variability. We address this issue by performing a quantitative case study on the area surrounding Granite Peak, in north-western Utah. Granite Peak is an isolated mountain rising approximately 800 m above the surrounding terrain. It separates a flat dry lake (playa) to the west from arid shrubland to the east. The plain east of the peak slopes gently towards the northwest. Upslope winds along the sidewalls of the mountain and lake breezes between the playa and the adjacent plain develop on fair weather days with strong solar forcing.

We perform semi-idealized very-large eddy simulations and use a factor separation approach to assess the pure impacts of topographic effects and of the spatial heterogeneity of land-use on CBL depth. We show that, when synoptic forcing is weak, mixing height variability in this area depends mostly on topographic effects. Beyond quiescent environmental conditions, we examine different prototypical flows with large-scale winds impinging on Granite Peak from the south and the north. Finally, we attempt to quantify how the balance between topographical and land-use effects changes in response to variable strengths of the two factors.

O8 Oral Session: Gravity wave and airflow dynamics: Part 2

O8.1 The second Meteor Crater Experiment (METCRAX II): Introduction and overview of recent results

C. David Whiteman *(University of Utah, United States of America), Manuela Lehner, Sebastian W. Hoch, Matthew O. G. Hills, Norbert Kalthoff, Bianca Adler, Rich Rotunno, Roland Vogt, Iris Feigenwinter, Martina Grudzielanek, Jan Cermak, Thomas Haiden, Nihanth W. Cherukuru, Ronald Calhoun*

The Second Meteor Crater Experiment (METCRAX II) was designed to study downslope-windstorm-type flows (DWF) that occur above the south and west inner sidewalls of the 1.2 km diameter Barringer Meteorite Crater in Arizona. These DWFs occur intermittently within the crater basin on clear, undisturbed nights in connection with a mesoscale drainage flow that approaches the crater from higher terrain to the southwest of the crater. During DWF events a wave descends in the lee of the upwind crater rim, producing a strong and turbulent downslope flow above the slope, which rebounds in a hydraulic jump-like flow feature at the base of the slope. Multiple break-ins of these flows occur on suitable nights, and the individual break-ins vary in strength and duration.

This presentation will provide an overview of the October 2013 METCRAX II field experiment and summarize recent research results. The experiment was supported by the National Center for Atmospheric Research's Earth Observing Laboratory and by other organizations, with an extensive complement of field equipment including a radar wind profiler, 2 radio acoustic sounding systems, three scanning Doppler LiDARs, a vertically pointing LiDAR, instrumented 40- and 50-m towers, 3 surface flux stations, 3 SoDARs, a scintillometer, a ceilometer, automatic weather stations, an array of temperature data loggers, multiple pressure sensors, and visual and thermal IR time-lapse cameras. Seven overnight Intensive Observational Periods (IOPs) were selected during the month on the basis of weather forecasts. Three continuously operated tethersondes and 3-hourly radiosondes provided supplementary vertical sounding data during the IOPs. Forecasts were successful in selecting nights when the DWF phenomenon occurred, and analyses of the extensive data are now in progress. This presentation will summarize recent results, leaving detailed analyses for presentation by other team members in related oral and poster presentations at the conference.

O8.2 Downslope-windstorm-type flows and seiches in the Meteor Crater - responses of the nocturnal crater atmosphere to an impinging katabatic flow

Manuela Lehner *(University of Utah, United States of America), C. David Whiteman, Sebastian W. Hoch, Bianca Adler, Norbert Kalthoff, Richard Rotunno*

The second Meteor Crater Experiment (METCRAX II) field campaign was conducted at Arizona's Meteor Crater in October 2013 to study the regular nighttime occurrence of downslope-windstorm-type flows (DWFs) in the crater basin. The almost circular and approximately 1.2-km wide Meteor Crater is located on a slightly sloping plain, where a southwesterly katabatic flow forms during undisturbed, clear-sky nights. As the southwesterly flow approaches the Meteor Crater, cold air pools upstream of the 30-50-m high crater rim and partially drains into the crater in the form of cold-air intrusions. While part of the katabatic flow diverges around the crater and upstream cold-air pool, part of it flows over the crater, leading to the formation of DWFs along the inner southwest sidewall.

In this presentation, we will look at the response of the basin atmosphere to the upstream katabatic flow that impinges on the crater topography, including the formation of DWFs along the sidewall and the occurrence of seiches in the crater cold-air pool. It is hypothesized that the seiches observed in the surface-based inversion on the crater floor are related to oscillations in the cold-air intrusions down the southwest sidewall and to oscillations in the upstream katabatic flow. On the basis of observations and numerical simulations, variations in the strength and depth of the upstream katabatic flow are identified as key factors that determine the formation and strength of DWFs in the crater basin.

O8.3 Lidar observations during METCRAX-II

Sebastian W. Hoch *(University of Utah, United States of America), Nihanth W. Cherukuru, Ronald Calhoun, C. David Whiteman, Manuela Lehner, Bianca Adler, Norbert Kalthoff, William O. J. Brown*

The second Meteor Crater Experiment (METCRAX-II) was designed to study downslope-windstorm type flows in the lee of the upwind crater rim of Arizona's Meteor Crater. These flows are frequently observed during synoptically quiescent nights when a southwesterly mesoscale drainage flow forming outside of the crater basin interacts with the crater topography.

Three lidars were deployed during METCRAX-II. One lidar was positioned on the upwind side of the crater and was used to monitor and characterize the mesoscale drainage flow approaching the crater. The two other lidars, one on the crater's northern rim and one on the floor of the crater, were positioned on a NNE-SSW transect across the crater topography. Co-planar range-height indicator scans along this transect allowed the retrieval of the two-dimensional wind field of the intruding flows. Flow features such as hydraulic jumps, rotors and flow separation can be resolved from the dataset.

We will show the temporal evolution of the drainage flow outside of the crater topography and its flow response to the topographic obstacle, including flow stagnation near the surface and flow splitting around the crater. Further, we will illustrate the development and evolution of the downslope-windstorm-type intrusions into the crater basin, from shallow cold-air inflows along the inner crater sidewalls to flow separation and the formation of hydraulic jumps, rotors and return circulations.

O8.4 A parameter based approach to idealised numerical simulations of Meteor Crater downslope-windstorm-type flows

Matthew Hills *(University of Utah, United States of America), Dave Whiteman, Sebastian Hoch, Manuela Lehner*

Observations gathered during the METCRAX 2 field campaign show that the incoming flow associated with downslope-windstorm-type flows (DWFs) within Arizona's Barringer Meteor Crater is highly variable in time and space. Such flow complexity can make analysis problematic, with the chaotic structure potentially masking important flow features. In order to improve our understanding of DWFs, we create idealised and semi-idealised simulations of the Meteor Crater environment. These allow us to better understand the flow features that control DWF generation, and their internal dynamics and structure.

Using METCRAX 2 observations as a starting point for the atmospheric structure in our model, fully nonlinear 2D simulations using the real crater terrain are presented. Using a high resolution grid in both horizontal (10 m) and vertical (5 m) directions, we are able to fully resolve the generation of the plunging air into the crater, and the dynamical structure of the wave-like response within the crater atmosphere.

With our approach, we are able to specify the structure and location of the flow features of interest, allowing us to directly determine the impact of an upstream change on the resulting flow. In this manner, we study parameters such as the importance of the speed of the incoming flow, its stability, and its depth and location relative to the crater rim.

Initial simulations show that we can simulate a DWF and warm air intrusion of comparable strength to those in the observations. Associated with this is evidence of boundary layer separation, a hydraulic jump, and a standing wave train - all features observed using LIDAR during METCRAX 2. From our initial work the strength of the cold pool within the Meteor Crater appears unrelated to the generation of DWFs.

O8.5 Do current theories of downslope-windstorm-type flows apply to the Meteor Crater?

Thomas Haiden *(ECMWF, United Kingdom), C. David Whiteman, Manuela Lehner*

Theories of nonlinear lee-side flow amplification have been developed to explain severe windstorms observed downstream of large mountain ranges where the drop in elevation is typically 1-2 km. Observations during METCRAX II of (much weaker) downslope-windstorm-type flows (DWFs) in the Meteor Crater, which is just 150 m deep, raises the question whether existing theory is able to account for such flows as well. One of the main differences, apart from the smaller-scale and curved topography, is the fact that the flow is embedded entirely within the atmospheric boundary-layer, which increases the relative importance of surface friction. Due to the smaller horizontal scale also non-hydrostatic effects may be important. Based on the comprehensive dataset obtained during the METCRAX II field experiment we address these questions by estimating individual terms in the momentum equation. The presence in the crater of a flow feature resembling a hydraulic jump is analysed with reference to the theory of continuously stratified hydraulic flow and the theory of wave amplification in a flow with a stable layer near the surface. It is analyzed to what extent these theories are able to predict the occurrence of DWFs in the crater as a function of upstream flow characteristics.

O8.6 Upstream conditions controlling downslope-windstorm-type flows in Arizona's Meteor Crater

Bianca Adler *(Karlsruhe Institute of Technology (KIT), Germany), Norbert Kalthoff, C. David Whiteman, Sebastian W. Hoch, Manuela Lehner*

During clear and quiescent nights downslope-windstorm-type flows associated with warm air intrusions often occur in the Barringer Meteor Crater in northern Arizona. Their occurrence presumably strongly depends on the upstream flow conditions, particularly on the depth of the mesoscale drainage flow, which regularly forms on the low-angle slope surrounding the Meteor Crater basin. During the second Meteor Crater Experiment (METCRAX II) performed in autumn 2013, comprehensive in-situ and remote sensing instruments were installed inside the crater, on the crater rim and on the slope surrounding the crater.

We investigated the relation between the upstream flow conditions (stability, strength and depth of the mesoscale drainage flow) and the conditions above and inside the crater basin as well as downstream of the crater. Depending on the depth of the upstream mesoscale drainage flow, the flow responses inside and downstream of the crater topography varied When the upstream mesoscale drainage flow was shallow, i.e. about 50 m deep, parts of it intruded into the crater basin along the upstream slope as cold air intrusion. This resulted in an outflow of air over the downstream crater rim. In these cases, no mesoscale drainage flow was observed above or downstream of the crater basin. During some nights the upstream mesoscale drainage flow reached depths of up to 200 m. This was associated with downslope-windstorm-type flows and high turbulence inside the crater. In these cases a flow with similar characteristics as the upstream mesoscale drainage flow was observed downstream of the crater basin.

O9 Oral Session: Gravity wave and airflow dynamics: Part 3

O9.1 Role of Observations in Complex Terrain Research: Recent Progress and Current Challenges

Vanda Grubišić *(National Center for Atmospheric Research, United States of America)*

Observations and physical measurements have traditionally played a pivotal role in complex terrain research. In order to advance understanding of physical processes and phenomena in complex terrain, motivated in large part by an ongoing need to improve forecasting of weather in complex terrain, this field of atmospheric research has been at the forefront in adoption of new technologies and measurement techniques as well as in novel applications of the existing ones.

In this presentation we will offer a retrospective view of some of the key advances in complex terrain research that had been made possible by the technological advances of the day and make an attempt at identifying remaining challenges. Special emphasis will be placed on progress that has been achieved within the context of large observational field campaigns.

O9.2 Gravity wave predictability in the troposphere and stratosphere during DEEPWAVE

P. Alex Reinecke *(Naval Research Laboratory, United States of America), James Doyle, Qingfang Jiang*

Gravity waves play an important role in regulating the momentum budget of the global circulation as they propagate vertically from source regions in the troposphere through the stratosphere and into the mesosphere. Therefore, it is critical to understand the predictive capability of gravity waves in numerical weather prediction. In this talk we will examine the predictability of orographic and non-orographic gravity waves generated over the South Island of New Zealand and Tasman Sea during the DEEPWAVE field campaign. The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) will be used in an ensemble mode to diagnose the characteristics of initial condition perturbation growth in gravity waves as they transit from the troposphere into the stratosphere. Initial results show that compared to the troposphere, perturbation growth rates for orographic gravity waves are suppressed in the stratosphere, and that gravity waves may experience enhanced predictability there. The mechanisms for the decreased growth rates will be explored. The predictability of non-orographic gravity waves in the troposphere and stratosphere will also be presented.

O9.3 An investigation of a midlatitude lower stratospheric gravity wave “valve layer”

Christopher G. Kruse *(Yale University, United States of America), Ronald B. Smith*

The Deep Propagating Gravity Wave Experiment (DEEPWAVE) field campaign was conducted over the New Zealand region to study gravity waves from tropospheric origins to their dissipation at very high altitudes. Preliminary analysis from a season long 6-km resolution WRF simulation suggests about half of New Zealand mountain wave events are strongly attenuated in a lower stratosphere “valve layer” near 15 km. How are mountain waves attenuated in this layer? How are waves modified as they pass through this layer? Does mountain wave attenuation violate PV conservation? These questions are investigated with NCAR Gulfstream V (NGV) aircraft observations and high-resolution simulations of such a valve layer attenuation event that occurred on 24 May 2014 over the South Island of New Zealand. The NGV provided in situ measurements at 12 and 13.5 km and sampled wave breaking along higher flight legs. A microwave temperature profiler onboard the NGV provided remotely sensed 2-D cross sections of temperature 5 km above and below the aircraft. High-resolution (2-km) WRF simulations are compared with the aircraft and AIRS observations and used to study the dynamics of propagation and attenuation through the valve layer. A new 2-D spectral filtering method is used to quantify resolved gravity wave momentum flux and drag within the simulated fields, which suggest the strongest attenuation occurred near 14 km resulting in gravity wave drag of roughly 25 m s-1 day-1.

O9.4 Mountain gravity waves: some new analytical solutions

François Lott *(CNRS, France)*

An almost linear theory of mountain gravity waves present when the incident wind a is (1) null at the ground and upstream the ridge and (2) increasing with altitude is presented. It partly solves the fundamental problem of the “classical” linear mountain wave theories, where the surface winds need to be non-zero at the surface for trapped mountain waves to develop substantially. In these theories, trapped lee-waves occur when there are turning points aloft and providing that the waves reflected toward the surface by these turning points are not absorbed in the boundary layer. These “classical” theories do not take into account that in reality the winds go to zero at the surface, a conceptual difficulty because a zero surface wind corresponds to a critical level for mountain waves, that is a place where gravity waves absorption can be very strong, at least when the flow is stable according to the Miles-Howard criteria. We therefore show that trapped lee waves are favoured when the surface Richardson number is small, bridging a conceptual relation between trapped lee waves and Kelvin Helmholtz instabilities.

We hope that the solutions presented here could help to benchmark Numerical Weather Prediction models that aim at representing mountains and including the smallest scales gravity waves. The solutions proposed can also be used to analyse at a cheap numerical cost the refraction by the gravity waves and the mountains of the infrasounds trapped in the low tropospheric sonic waveguide.

Some details about the mathematical functions used can be found in:

F. Lott, C. Millet, and J. Vanneste, 2014: Inertia-gravity waves in inertially stable and unstable sheared flows, Submitted to J. Fluid Mech.

Lott, F., The reflection of a stationary gravity wave by a viscous boundary layer, 2007: Journal of the Atmospheric Sciences, 64, 3363–3371.

O9.5 NWP modelling of air flow over South Georgia island: an analysis of wake formation and gravity wave activity.

John Hughes *(Leeds University, United Kingdom), Andrew Ross, Simon Vosper*

The South Georgia wave experiment (SG-WEX) combines numerical modelling and observations from radiosonde, meteor radar and remote sensing to investigate gravity wave activity in the vicinity of South Georgia. Located in the South Atlantic, downstream of the Drake passage and collocated with a peak in stratospheric gravity wave activity the island of South Georgia provides an ideal natural laboratory to address key uncertainties in our understanding of the contribution of small islands to gravity wave fluxes and low level drag.

Results from simulations completed as part of SG-WEX will be discussed, with particular focus on validation of the low level flow around South Georgia. Simulations have been completed using the Met Office NWP model in a nested domain configuration centred on South Georgia at 1.5km horizontal resolution and enhanced vertical domain (78km). At this resolution the model is able to resolve gravity wave activity and the low level flow structure around the island. These simulations are then compared against lower resolution global NWP configurations which use an orographic parameterisation scheme to represent the gravity wave and low level drag. The high resolution simulation results are compared with ASCAT scatterometer data of the surface wind structure in the wake and with radiosonde data from the SG-WEX field campaigns in order to assess the performance of the model. Using ASCAT dataset combined with ECMWF ERA-Interim reanalysis a climatology of low level flow regimes around South Georgia is created in order to assess the likely impact of South Georgia on the regional and zonal flow.

O9.6 Spatial distribution and characteristics of foehn conditions over the Larsen Ice Shelf, Antarctica, in observations and Polar WRF.

Jenny Turton *(University of Leeds and British Antarctic Survey, United Kingdom), Amelie Kirchgaessner, John King, Andrew Ross, Alan Gadian, Ralph Burton*

The instability of the eastern Antarctic Peninsula (AP) ice shelves have become a symbol for climate change in the Polar Regions. The northernmost sections of the Larsen Ice Shelf (LIS) collapsed in 1995 and 2002, prompting research into the cause of the disintegration. One theory behind this instability is the ‘föhn hypothesis’. The föhn winds which flow down the eastern slopes of the AP are a feature of the interaction of the mountain range with the prevailing circumpolar westerlies. The theory suggests that the warm, dry conditions which characterise föhn winds are prompting surface melting of the LIS. Investigating the spatial distribution of these föhn winds, and the impact they are having on the remaining Larsen C ice shelf formed part of the NERC funded project ‘Orographic Flows and the Climate of the Antarctic Peninsula’ (OFCAP). As part of this campaign an automatic weather station was installed on Cole Peninsula (-66°51’S, -63°48’W). This station, along with six others provides a network of observational instruments which is complemented with data from the Antarctic Mesoscale Prediction System (AMPS) archive. The AMPS archive holds outputs from the Weather Research and Forecast (WRF) model run operationally over the Antarctic and Southern ocean by the National Centre for Atmospheric Research, USA. Archived model output covering the AP (domain six) from January 1st 2009 to January 1st 2012 is used here.

The occurrence and characteristics of föhn conditions over the LIS, identified from a combination of observational and model data, will be presented here. A north-south and west-east gradient in strength and occurrence of föhn events is apparent, as are other localised spatial variations in conditions. A comparison of the föhn characteristics within the observational and model data shows that there is a good overall agreement between the two datasets. However, there are variations in timing, strength and frequency of the föhn conditions within the data. A number of case studies will also be presented, which highlight the variance in föhn conditions across the shelf.

O9.7 Lagrangian Perspective of Orographic Blocking

Michael Sprenger *(ETH, Switzerland), Nicolas Piaget, Stefan Ruedisuehli, David Leutwyler, Heini Wernli*

In Alpine mountain meteorology, orographic blocking is important because of its impact on: a) lee-cyclogenesis; b) the passage and modification of warm and cold fronts; c) the geographical distribution and intensity of (heavy) precipitation events. Traditionally, orographic blocking is studied with Eulerian methods based on the estimation of the inverse Froude number. Here we present a Lagrangian perspective of orographic blocking, and focus in particular on its impact on precipitation patterns.

Winds are taken from a three-year (2000-2002) reanalysis simulation with COSMO at a horizontal resolution of 7 km. Based on these winds, kinematic forward trajectories are started at a distance of 300 km all around the Alps and at two height levels (750 and 1500 m). The 24-h trajectories are then investigated in their capability to surmount the Alpine barrier, separated into three distinct flow categories, also defined in a Lagrangian way: westerly flow, northerly flow and southerly flow, the latter being restricted to south Foehn cases. As a result a Lagrangian blocking index is available at an hourly resolution between 2000-2002.

For each flow category the percentage of trajectories surmounting the Alps and the percentage of air parcels flowing around the Alps is determined. Furthermore, trajectory densities are calculated to show the different air streams which start from selected upstream positions. Composites of precipitation pattern are shown according to flow category and Lagrangian blocking index.

Finally, an outlook will be given to a new project based on high-resolution COSMO simulations. They will cover whole of Europe at 2-km horizontal resolution during a 10-year time period. A first glimpse on orographic blocking in this data set will be provided.

O10 Oral Session: Numerical weather prediction: Part 1

O10.1 High-resolution simulations of flow over complex terrain: progress and challenges

Fotini K. Chow *(University of California, Berkeley, United States of America)*

The capabilities and complexities of weather forecast models have increased greatly since they were introduced in the 1950s. Operational models are now capable of running at O(1 km) resolution, which means the steepness of the terrain that can be represented has increased dramatically. On the urban scale, models are now capable of simulating flow around buildings at O(1 m) resolution. With any numerical simulation, it is important to understand the role of numerical errors on the solution. These can be discretization errors related to the grid and the numerical methods chosen, or errors from the physical parameterization approaches chosen to represent unresolved turbulence or land-surface forcing, for example. For flow over complex terrain, additional complications can arise. We will discuss errors due to the choice of coordinate system and grid aspect ratio, alternatives to terrain-following coordinates such as the immersed boundary method (IBM), and grid nesting strategies. The importance of physical parameterizations will be emphasized through discussion of turbulence closure models and land-surface models, e.g. illustrating the role of soil moisture variability on flow over complex terrain. A range of domain sizes and grid resolutions will be discussed, encompassing the Reynolds-averaged Navier-Stokes (RANS) and large-eddy simulation (LES) techniques, and the gray zone, where the model resolution is in the intermediate range between LES and RANS.

O10.2 COSMO-EULAG dynamical core for high resolution Alpine weather prediction

Zbigniew Piotrowski *(Institute of Meteorology and Water Management - National Research Institute, Poland), Bogdan Rosa, Damian Wójcik, Michał Ziemiański*

Future very-high resolution mesoscale weather prediction models will require a robust and efficient dynamical core allowing for explicit representation of vigorous convective processes involving close coupling of dynamics and physics, as well as successful handling of steep mountain slopes. Such a core should represent also the basic conservative properties of natural flows.

New EULAG dynamical core for the operational Consortium for Small-scale Modeling (COSMO) model is currently being developed at IMGW within the CELO priority project of COSMO. Recently, its forecasting skills were compared against the reference operational Runge-Kutta dynamical core, within the COSMO framework set close to the operational 2.2 km horizontal resolution setup over the Alps. Within this presentation, an overview of the new dynamical core capabilities, highlights of the verification scores and the projected performance will be presented, including studies at the very high horizontal resolutions up to 100 m.

O10.3 A new vertical grid nesting capability in the WRF model

M. H. Daniels, ***Katherine A. Lundquist*** *(Lawrence Livermore National Laboratory, United States of America), D. J. Wiersema, F. K. Chow, J. D. Mirocha*

As we move toward multi-scale modeling, vertical grid nesting becomes necessary for simulating a wider range of scales. This talk presents a new vertical grid nesting capability we have implemented in the Weather Research and Forecasting (WRF) model based on the interpolation method used by Moustaoui et al. 2007. Vertical grid nesting potentially lowers computational expenses and allows control over grid aspect ratio for improved model stability and accuracy. Grid aspect ratio can be important for reducing errors in large-eddy simulations (Mirocha et al. 2013) and for mesoscale simulations over complex terrain where steep terrain slopes can cause errors in the calculation of horizontal gradients. Idealized simulations are presented which validate the vertical nesting method by showing that solutions from vertically nested and non-nested cases compare well. Large-eddy simulations of the atmospheric boundary layer over flat terrain are presented to demonstrate use of vertical nesting to control grid aspect ratio and improve simulation results when compared to the theoretical log-law solution. Mesoscale simulations over Owens Valley, California are presented and results are compared to observations from the Terrain-Induced Rotor Experiment (T-REX, March-April 2006).

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O10.4 Parametrizing mountain-wave and flow-blocking drag in global models: the "grey zone" in orographic drag

Simon Vosper *(Met Office, United Kingdom), Andy Brown*

Assessing the local momentum budget is important for understanding atmospheric variability on a range of timescales, including the circulation response to climate change. However, the ability of general circulation models (GCMs) to correctly represent the momentum budget is poorly understood, and model circulation is sensitive to the parametrization of drag processes. These drag parametrization schemes are themselves poorly constrained. For example, the partition between orographic drag (due to mountain waves, and low-level flow blocking) and drag due to boundary-layer turbulence is tuneable and varies widely between different models. Furthermore, as the resolution of GCMs increases the drag processes are becoming increasingly (at least partially) resolved. With grid lengths of a few tens of kilometres, we are entering the "grey zone" of orographic drag parametrization. An understanding of how well parametrization schemes can represent the drag, and how well the hand-over between parametrized and resolved drag works across model resolutions is clearly important.

Recent studies have demonstrated how GCMs may also suffer from the so-called "small island problem", whereby the effect of small mountainous islands is neither resolved or parametrized (since they occupy too small a fraction of the GCM grid box). The importance of this problem is unclear, but recent work has suggested that small mountainous islands in the South Atlantic may make significant contributions to the stratospheric gravity-wave momentum flux and that this missing drag may result in systematic errors in the model southern hemisphere stratospheric circulation.

The focus of this presentation is the ability of orographic drag parametrization schemes to represent the drag associated with mountain waves and low-level flow-blocking processes. High resolution numerical simulations of flows over New Zealand and South Georgia Island will be used to determine the drag on the flow, and where possible these simulations will be compared with recent observations from the DEEPWAVE and SG-WEX field campaigns, respectively. The high resolution results will be compared with those from coarse resolution experiments in which the drag is largely parametrized. By varying the horizontal grid length, we will determine the extent to which the total (resolved plus parametrized) drag is invariant across model resolutions. By considering both relatively wide (New Zealand) and narrow (South Georgia) mountain ranges, the importance of mountain width relative to the grid length will be investigated, an issue related to the "small island" problem.

O11 Oral Session: Snow processes

O11.1 Advances in understanding and modelling mountain snow processes

John Pomeroy *(University of Saskatchewan, Canada), Richard Essery, Keith Musselman, Jonathan Conway, Michael Schirmer, Warren Helgason, Nicolas Leroux, Chris Debeer, Chad Ellis*

Recent advances in understanding and modelling snow processes in mountain environments are leading to better assessment of snow accumulation and ablation, and snow-atmosphere energy and mass exchange. One particularly important area of advance is in the coupling of complex terrain windflow with solar irradiance, wind transport, sublimation and melt calculations – this coupling is leading to detailed representations of snow accumulation, turbulent exchange with the atmosphere, albedo and longwave radiation emission in complex terrain. Results from this show that detailed physically based wind flow calculations are necessary to estimate the spatial patterns of alpine snow accumulation and ablation and that these spatial patterns control the areal depletion of snowcover and the persistence of ecologically and hydrologically important snow patches into summer. However, serious questions remain on how to apply stability corrections to turbulent fluxes in complex terrain. A challenge will be to represent this spatial heterogeneity at an appropriate level of complexity in upscaled mass and energy balance calculations for land surface schemes. A second area of advance is in the measurement, understanding and simulation of snow-vegetation interactions at treelines, in shrub-tundra and in discontinuous forest canopies. This has required a better understanding of canopy radiative, aerodynamic and thermal properties and the complex interactions between the atmosphere, discontinuous plant canopies and underlying or adjacent snowcover. Results from these investigations are showing that simple 1-D representations of plant canopies cannot succeed in providing the radiative and aerodynamic exchanges needed for accurate snow ablation calculations and that fascinating relationships between snow accumulation patterns, solar and thermal irradiance and turbulent transfer develop in sparse canopies and dominate snow dynamics in these environments.

O11.2 Modeling elevation-dependent climate warming impacts to snow: effects of temperature lapse rates

Matthew G. Cooper *(Oregon State University, United States of America), Anne W. Nolin, Mohammad Safeeq*

In the mountains of the Western US, shifts in the timing and magnitude of snow water equivalent (SWE) over the past century are well documented and attributed to climate warming, but the magnitude of sensitivity depends on elevation. We estimated the spatial distribution of SWE and its sensitivity to climate warming in the topographically complex, 1500 km2 Upper Deschutes River Basin, Oregon (USA), with a spatially distributed snowpack energy balance model forced by a gridded meteorological dataset. We further compared how these estimates differed across elevations depending on the choice of lapse rates used for spatial temperature interpolation and extrapolation. The 1/16o spatial-scale gridded meteorological forcing data was bias-corrected with PRISM climate data and downscaled to a 100-m spatial-scale digital elevation model using 1) a spatially uniform and temporally constant -6.5oC km-1 lapse rate, and 2) with monthly varying lapse rates computed from long term records of temperature recorded by weather stations in the study region. Model parameters that controlled empirical estimates of incoming shortwave and longwave irradiance and the partitioning of precipitation into rain and snow were estimated independently with each downscaled forcing dataset to optimize the agreement between modeled and observed SWE. We then estimated the sensitivity of the snowpack to +2oC and +4oC warming with each of the four downscaled temperature datasets and optimized parameters. Interdataset differences in modeled SWE during the historical period were largely driven by differences in estimated cloudy-day incoming longwave irradiance, that were in turn driven by differences in prescribed lapse rates. The sensitivity of SWE to +2oC and +4oC warming differed significantly at all elevations between the bias-corrected and original data, but did not depend on choice of lapse rates. At all elevations, SWE sensitivity was largely driven by shifts from snow to rain, but at high elevations increased estimates of longwave irradiance drove increased mid winter snowmelt. Our results revealed a previously unrecognized interaction between prescribed lapse rates and empirical estimates of incoming longwave irradiance, and demonstrate the challenges of modeling SWE with gridded data products in data sparse regions.

O11.3 Modelling mountain snow with large-scale and small-scale driving data

Richard Essery *(University of Edinburgh, United Kingdom)*

The low resolution and simplified processes used in climate models have long been issues for prediction of climate change impacts on snow in mountainous terrain. Upcoming phases of the Snow Model Intercomparison Project (ESM-SnowMIP), the Global Soil Wetness Project (GSWP3) and the Coupled Model Intercomparison Project (CMIP6) will, amongst many other variables, produce global snow simulations for longer periods and at higher resolutions than ever before. In preparation for ESM-SnowMIP, this presentation will review the performance of snow models driven with global driving data at 0.5 degree resolution, with and without downscaling, and in situ meteorological measurements from well-instrumented snow study sites in the Alps and North America.

O11.4 Using snowboards and lysimeters to constrain snow model choices in a rain-snow transitional environment

Nicholas E. Wayand *(University of Washington, United States of America), Adam Massmann, Martyn Clark, Jessica Lundquist*

Physically based models of the hydrological cycle are critical for testing our understanding of the natural world and enabling forecasting of extreme events. Previous intercomparison studies (i.e. SNOWMIP I & II, PILPS) of existing snow models that vary in complexity have been hampered by multiple differences in model structure. Recent efforts to encompass multiple model hypothesizes into a single framework (i.e. the Structure for Understanding Multiple Modeling Alternatives [SUMMA] model), have provided the tools necessary for a more rigorous validation of process representation. However, there exist few snow observatories that measure sufficient physical states and fluxes to fully constrain the possible combinations within these multiple model frameworks. In practice, observations of bulk snow states, such as the snow water equivalent (SWE) or snow depth, are most commonly available. The downfall of calibrating a snow model using such single bulk variables can lead to parameter equanimity and compensatory errors, which ultimately impacts the skill of a model as a predictive tool.

This study provides two examples of diagnosing modeled snow processes at a recently upgraded (Oct. 2012) snow study site located at Snoqualmie Pass (917 m), in the Washington Cascades, USA. We focused on two physical processes, new snow accumulation and snowpack outflow during mid-winter rain-on-snow events, for their importance towards controlling runoff and flooding in this rain-snow transitional basin. 40 years of historical snowboard measurements showed a mean 24hr accumulated snowfall density of 90 kg m-3 below 0°C, with a linear fraction of snow and rain between -1°C and +1°C wet-bulb temperature. Two years of observed snow pit temperature profiles from infrared cameras and manual thermometers found that cold biases in the model snowpack temperature prior to rain-on-snow events could delay model outflow multiple days compared to lysimeter observations. These two examples illustrate the utility of using multiple observations of internal snowpack states to constrain uncertain snow physics options.

O11.5 Identification of snow precipitation mechanisms and accumulation patterns over complex terrain with very high resolution radar data and terrestrial laser scans

Franziska Gerber *(EPFL / WSL-SLF, Switzerland), Rebecca Mott, Jacopo Grazioli, Daniel Wolfensberger, Alexis Berne, Michael Lehning*

Knowledge on changes in seasonal mountain snow water resources are essential e.g. for hydropower companies. Both, snow accumulation and ablation need to be investigated to make precise predictions of water stored in a seasonal snow cover. Only if the processes behind snow accumulation and ablation are understood with sufficient quantitative accuracy, the evolution of snow water resources under a changing climate can be addressed. It is known that different snow precipitation processes and snow redistribution are responsible for snow accumulation patterns in alpine terrain. In a small-scale analysis of radar data in the region of Davos, Mott et al. (2014) could identify different snow deposition patterns for homogeneous precipitation, seeder-feeder mechanism, preferential deposition and a combination of the seeder-feeder mechanism and preferential deposition. In addition to the snow precipitation mechanisms, snow redistribution due to snow-atmosphere interaction is essential to characterize snow accumulation patterns at small scales (Scipión et al., 2013).

In this study we investigate small-scale patterns of precipitation for an extended area over the Dischma valley (Davos, CH) for the winter season 2014/2015. An X-band polarimetric radar was installed on a slope facing the Dischma valley and it conducted plane position indicator (PPI) scans at elevation angles of 7° and 10° (minimum distance to the ground is about 300m and 500m, respectively) and three range height indicator (RHI) scans along the Dischma valley and along the Landwasser valley (i.e. along Davos). These radar products are available with horizontal and vertical resolution of 75 meters and a high temporal resolution of 5 minutes. The specific spatial patterns revealed by the radar measurements allow to characterize the different types of winter precipitation as well as to identify cloud microphysical and dynamical processes that govern the precipitation distribution. The continuous radar measurements are also used to analyze the frequency of certain types of hydrometeors and precipitation genesis processes as well as snow precipitation patters, which are related to specific atmospheric situations. For a few snowfall events, we additionally analyze terrestrial laser scans (TLS) of steep rock faces with different orientations that were performed before and after the snow precipitation events. The results allow us to relate identified accumulation patterns to the identified precipitation patterns and confirm the importance of redistribution processes for accumulation in steep terrain.

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O11.6 Propagation of uncertainty in atmospheric longwave radiation to modeled snowpack and summer evapotranspiration at mountain research sites

Mark Raleigh *(National Center for Atmospheric Research, United States of America), Karl Lapo, Danny Marks, Andrew Hedrick, Gerald Flerchinger, Martyn Clark*

Atmospheric longwave radiation is a key component of the surface energy balance in mountainous catchments, influencing hydrologic process such as snowmelt, snow disappearance, and summer evapotranspiration. Many empirical parameterizations of atmospheric longwave radiation exist in the form of clear-sky emissivity and cloud correction models, and these are typically developed and calibrated at low elevation sites. In most mountainous catchments, it is not possible to evaluate the accuracy of these methods due to a lack of surface measurements. Here, we quantify uncertainty in longwave radiation due to parameterization choice and evaluate how uncertainty in longwave propagates to modeled snow and hydrologic processes. Based on 20 clear-sky emissivity models and 20 cloud correction methods, we examine an ensemble of 400 methods for calculating atmospheric longwave radiation and compare these to surface observations at three well-instrumented mountain research sites spanning maritime, intermountain, and continental climates. We compare and contrast how three physically based models of varying complexity (the Utah Energy Balance, SNOBAL, and the SHAW snow model) simulate snowpack development and ablation across the longwave methods. Using the SHAW model, we examine the linkages between summer evapotranspiration uncertainty and longwave uncertainty, and compare the relative contributions of growing season timing and length (as controlled by longwave-impacts on snow duration), energy availability (as a function of longwave parameterization), and water availability to evapotranspiration uncertainty. Initial results show that longwave uncertainty as a function of parameterization choice is large, with a range typically exceeding 100 Watts per square meter, and with significant impacts on modeled peak snow water equivalent (typically +/- 50%), mid-winter melt occurrence, surface energy feedbacks, and snow disappearance timing (1-2 months). The results highlight the need for robust parameterizations of longwave radiation for model-based assessments of snow and hydrologic processes, especially given the central role of longwave radiation to atmospheric warming associated with climate change.

O11.7 Boundary layer development over a melting mountain snow cover: The Dischma Experiment

Rebecca Mott *(WSL Institute for Snow and Avalanche Research SLF, Switzerland), Sebastian Schlögl, Lisa Dirks, Michael Lehning*

Hydrological and energy balance models typically assume a continuous snow cover. Such approaches neglect that once the snow cover gets patchy in spring, additional boundary layer processes significantly affect the energy balance at the snow surface. Small-scale thermal internal boundary layers develop, involving strong vertical and horizontal flux divergences. Furthermore, the advection of warm air from bare ground towards snow-covered areas can promote strong atmospheric stabilities and boundary layer decoupling above snow that suppress net turbulent heat fluxes close to the snow surface. Neglecting these processes in energy balance models might result in a strong over- or underestimation of snow melt and runoff in spring.

We experimentally investigated the small-scale boundary layer dynamics over snow patches and their effect on the energy balance at the snow surface. A comprehensive measurement campaign, the Dischma Experiment, was conducted during the entire ablation periods of 2014 and 2015. The aim of this project is to investigate the boundary layer development and the energy exchange over a melting snow cover with a gradually decreasing snow cover fraction. Furthermore, the relative importance of different boundary layer processes is quantified on the local and catchments energy balance . For this purpose, two measurement towers equipped with five to six ultrasonic anemometers were installed along the wind fetch over a well-defined long-lasting snow patch. Furthermore, temporally and spatially high resolution ablation rates and snow surface temperatures were determined with a terrestrial laser scanner and an Infrared camera. This data set allows us to relate the spatial patterns of ablation rates and snow surface temperatures to boundary layer dynamics and the changing snow cover fraction. Experimental data reveal that wind velocity, wind fetch distance and topographical curvature control the boundary layer growth, boundary layer decoupling and the efficiency of advective heat transport to contribute to snow ablation. Data from a high density network of meteorological stations was further used to test numerical results from an atmospheric model that revealed a strong dependence of the relative importance of boundary layer processes and the development of local flow patterns on the snow patch size distribution and the synoptic wind forcing. We further verify previous wind tunnel experiments showing that boundary layer decoupling only evolves over snow patches located within a topographical depression and when ambient wind velocities are very low at the same time. The dependence of the advective heat flux and the potential occurrence of boundary layer decoupling to the snow cover fraction, synoptic wind forcing and the local topography will allow the parametrization and consideration of those small-scale effects in high-resolution energy balance models.

O12 Oral Session: Numerical weather prediction: Part 2

O12.1 Progress in weather prediction in mountainous and snow-covered areas achieved with the ICON model

Günther Zängl *(Deutscher Wetterdienst, Germany)*

The ICON (ICOsahedral Nonhydrostatic) model has been developed since 2004 at the German Weather Service (DWD) and the Max-Planck-Institute for Meteorology (MPI-M) in order to achieve a unified modelling framework for global numerical weather prediction (NWP) and climate modelling. In 2012, the Karlsruhe Institute for Technology (KIT) joined the development team in order to incorporate the ART (Aerosols and Reactive Trace Gases) module, which is already coupled to the regional COSMO model. ICON became the operational global numerical weather prediction system at DWD on January 20, 2015, replacing the hydrostatic GME after about 15 years of operational production. Its main advantages over GME are exact local mass conservation, higher efficiency on massively parallel computer architectures, and more advanced physics paremterizations, which is one of the keys towards a better forecast quality.

This presentation will focus on the main improvmenents relevant for mountainous and/or snow-covered regions. From a numerical point of view, a major advantage of ICON over most other models with terrain-following coordinates is that it does not require orography filtering for numerical stability reasons. This allows restricting the filtering to the amount providing the best forecast quality with respect to, e.g., to the low-level wind field or orographic precipitation. Moreover, the previous approach of combining an SSO (subgrid-scale orography) parameterization with an orographic roughness length approach (i.e. enhanced roughness length in the presence of unresolved orography) has been replaced by using an (appropriately retuned) SSO scheme only, which avoids consistency issues between momentum and heat/moisture transfer in the turbulence scheme. The snow parameterization within the land-surface scheme has been revised in several aspects, providing a more realistic representation of snow albedo, snow density and heat conduction through the snow cover. In addition, a tile approach has been introduced in ICON that allows for a better representation of heterogeneous land cover and a partially snow-covered surface. Verification results from various regions of the earth confirm the advances in forecast skills related to these improvements.

O12.2 The future high-resolution NWP systems of MeteoSwiss: COSMO-1 and COSMO-E

Marco Arpagaus *(Federal Office of Meteorology and Climatology MeteoSwiss, Switzerland), Steef Böing, Oliver Fuhrer, Daniel Leuenberger, Guy De Morsier, Jürg Schmidli, André Walser*

MeteoSwiss develops the new numerical weather prediction (NWP) systems COSMO 1 and COSMO E to be operational in 2016. COSMO-1 will provide locally very detailed deterministic forecasts out to +24 hours using a mesh size of 1.1 km and will run 8 times a day, whereas the probabilistic COSMO E will provide an ensemble forecast out to +120 hours using a mesh size of 2.2 km twice a day. Both systems will run for a domain covering the Alpine area. The initial conditions (analyses) for these forecasts will be generated by a new ensemble data assimilation system based on a Local Ensemble Transform Kalman Filter (LETKF) providing analysis uncertainty as well. COSMO 1 as well as COSMO E already run experimentally on a daily basis and demonstrate their benefits mainly in complex topography where high-resolution information and small mesh-size are important for the simulation of atmospheric processes.

The talk will highlight findings from the development of COSMO 1 and COSMO E with emphasis on Alpine meteorology and the benefits of very-high resolution NWP. Results on improved representation of valley winds, idealised simulation of convection over topography, and stochastic physics perturbations will be shown. Additionally, first verification results of the experimental regular runs of the two systems will be presented, providing exemplary evidence that the use of ensemble forecasts (such as COSMO E) in combination to very-high resolution deterministic forecasts (such as COSMO 1) is advantageous for atmospheric processes with limited predictability. Last but not least, first experiences from running these new forecasting systems on a novel GPU-based high-performance computing architecture will also be discussed.

O12.3 Parameterization of NWP WRF in statically stable situations over complex terrain

Goran Gašparac *(Gekom Ltd., Croatia), Amela Jeričević, Branko Grisogono*

The bora wind is downslope wind which blows in a coastal part of Croatia. Due to gusts which are stronger and much often in a winter time, complex orography and land/sea transition in this area, the modelling can be challenging. Within the research with the NWP WRF model, various tests were made with implementation of the new, improved mixing length in MYJ PBL scheme. Turbulence parameterization in MYJ scheme is based on mixing length (ML) scale which is defined as a physical quantity describing the size of the most relevant eddies in a modeled turbulent flow. The new ML is uniformly valid in neutral and static stable airflows. Based on previous research with vertical diffusive schemes in numerical models, the correction of vertical diffusion has been implemented as well. During period from 01 Jan to 31 March of 2011 there have been 17 episodes of bora wind with typical duration longer than 10h. Using high horizontal and vertical resolution the model has been tested and evaluated with measurements from mast tower located in mountainous region in a hinterland on Pometeno brdo as well as with ground measurements from meteorological stations and soundings.

O12.4 A new scheme to represent sub-grid orographic rain enhancement via the seeder-feeder effect

Samantha A. Smith *(Met Office, United Kingdom), P. R. Field, S. B. Vosper, B. Shipway, A. Hill*

A new parameterization scheme to represent rain enhancement due to sub-grid orography via the seeder feeder mechanism will be described. Tests using idealized 2D simulations of the KiD (Kinematic Driver) model, developed at the Met Office, demonstrate that the scheme successfully increases the total rainfall over a low resolution hill towards that produces by a well resolved hill. Simplifying assumptions are made about the nature of the variation of the sub-grid surface height about the grid-box mean, enabling us to estimate the amount of orographic water missing from an NWP grid-box from the sub-grid orographic standard deviation and the grid-box mean RH. This sub-grid orographic water is added to the liquid water mixing ratio used to calculate the accretion rate, thereby enhancing the rain rate. The evaporation of rain is also reduced in the presence of sub-grid orographic cloud. The scheme can be extended to cold cases where snow is present instead of rain.

Currently the scheme is being coded into the Met Office Unified Model in order to test its performance for real cases of orographic rain enhancement. Results from these tests will be shown.

O12.5 Toward Improved NWP Simulations of Utah Basin Persistent Cold Air Pools

Erik Crosman *(University of Utah, United States of America), John Horel, Chris Foster*

Mountainous basins throughout the world are impacted by prolonged episodes of boundary-layer air stagnation or persistent cold air pools (CAPs) during the winter season. These CAP episodes are often associated with poor air quality within urban basins. The detailed meteorological evolution of CAPs are generally inadequately resolved in mesoscale numerical weather prediction (NWP) forecast models, and even small model errors can have large impacts on temperature and air quality forecasts. In this study, we present a number of incremental improvements that have been applied to numerical modeling of these episodes within the Weather Research and Forecasting (WRF) model framework. Simple changes to the specification or parameterization of land use, snow cover, initial atmospheric and surface state, cloud cover, and turbulent mixing have resulted in improved CAP simulations. Several simulated case studies of CAP evolution and sensitivity to surface state during the Persistent Cold Air Pool Study (PCAPS) and Uinta Basin Winter Ozone Study (UBOS) will also be presented.

O13 Oral Session: Weather analysis, forecasting and verification

O13.1 Assimilation of water vapor observations upstream of the precipitation events documented during HyMeX SOP1

Evelyne Richard *(CNRS, France), Nadia Fourrié, Soline Bielli, Cyrille Flamant, Paolo Digirolamo*

During the first HyMeX special observing period (Sep-Nov 2012), the LEANDRE II lidar on board the ATR 42 flew 22 missions aiming at collecting water vapor observations of the marine inflow upstream of heavy precipitation events forecast to hit the Spanish, French or Italian coasts. These lidar observations were assimilated using the 3D VAR assimilation system of the AROME numerical weather prediction mesoscale model.

The assimilation was carried out for the period of 11 September-27 October by running a 3-hour forward intermittent assimilation cycle. In the presentation, the impact of the lidar observations will be assessed, first by comparing the new analyses with the control analyses, then by comparing the precipitation forecasts (obtained with and without the lidar observations) for the 25 rainy days included in the assimilation period. The impact of the assimilation of the water vapor observations is found to be positive up to the first 12 hours of the precipitation forecasts. Special emphasize will be put on the convective line of 24 Sept. for which the location and timing of the system appear very sensitive to the detailed distribution of the upstream moisture.

O13.2 Radar-Based Quantitative Precipitation Estimation and Forecasting in Switzerland.

Ioannis V. Sideris *(MeteoSwiss, Switzerland), Urs Germann, Marco Gabella, Marco Sassi*

Accurate radar precipitation estimation and nowcasting for the Swiss Alps region have always been challenging due to the complexity of the terrain which may impede unobstructed observation. In 2013 MeteoSwiss launched “CombiPrecip”[1,2,3], a sophisticated raingauge-adjustment application of the radar precipitation estimation maps. The main purpose of this application is to produce rainfall estimation as close as possible to the ground-truth. CombiPrecip has been built on the basis of cutting-edge technology originated in the field of geostatistics. It uses co-kriging with external drift to merge spatiotemporal information from a small number of raingauge measurements with the rainfall field observed by the radar and produces a new improved precipitation map. Carefully constructed validation schemes which use a number of skill scores have shown that this improvement is both systematic and important. CombiPrecip is equipped with many novel modules that deal with problems such as convection control in locations and times of low raingauge representativeness, and adjustment over regions not covered by the raingauge network such as out of the country border.

In the field of nowcasting, efforts of MeteoSwiss are currently focusing on a generalization of the “MAPLE”[4], a Lagrangian-persistence-based application, originally developed in McGill University in Montreal. This generalization has been motivated by the fact that in the Alps the evolution of precipitation is strongly influenced by the mountains at several different scales and this influence depends on several aspects such as direction and strength of flow and air-mass stability[5]. Therefore our effort attempts to apply modern statistical learning techniques to numerous multiple-year-recorded variables in order to organize, stratify and eventually recognize repeatable localized weather patterns. Such information can be then coded efficiently and used in an operational scheme. This design is fully probabilistic, but the assignment of probabilities will be based on the history of patterns that have emerged through the statistical supervised learning process.

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O13.3 Performance of a satellite driven nowcasting system and a high resolution NWP AROME-1km model over the Eastern Alpine area

Florian Meier *(ZAMG, Austria), Nauman Awan, Ingo Meirold-Mautner, Alexander Kann, Christoph Wittmann, Yong Wang*

In the framework of the SATIN project, a nowcasting system has been developed and run over an Eastern Alpine domain at ZAMG. It is based on satellite derived precipitation estimates and applies similar algorithms as in the operational INCA nowcasting system, which is normally driven by radar and station observations. Different to the operational version, this satellite INCA system SAT-INCA can be run not only over the Alps, but also in more remote areas, where no radar data and only few conventional data are available. Furthermore, a 1km resolution version of the convection permitting numerical weather prediction model AROME has been tested over the same Alpine area for the first time. For this AROME version also highly resolved orographic data (SRTM), updated land usage data (ECOCLIMAP II) and different boundary conditions were tested. Several case studies in spring, summer and autumn 2014, capturing different synoptic situations like local thunderstorms, wide spread flooding, squall lines were investigated. An inter comparison and evaluation between the new systems, satellite driven INCA and AROME 1km against the operational systems, radar driven INCA , AROME 2.5km and the coarser resolved ALARO 4.8km NWP, has been conducted. Results show, that AROME 1km can better simulate small scale near ground temperature features in Alpine valleys than the coarser models while in flat terrain ALARO is closer to the INCA analysis. There is a very slight positive impact of new orography and new land use data on the precipitation forecast. The highly resolved AROME precipitation simulations are closer to the nowcasting system during the first hours of integration, than the coarser resolved models, but tend to overestimate it later especially over the Alpine Mountain Range. SAT-INCA has its strengths in the rapidly updated analysis which exhibit superior performance than the operationally available NWP fields at that time. Additionally, SAT-INCA nowcasting performs better than the tested NWP models (ALARO, AROME, AROME-1km) in the first hour. For longer integration times, NWP clearly outperforms the satellite based nowcasting.

O13.4 Two novel approaches for precipitation nowcasting in complex terrain within the INCA system

Benedikt Bica *(ZAMG - Central Institute for Meteorology and Geodynamics, Austria), Alexander Kann, Min Chen, Martin Suklitsch, Vera Meyer, Lukas Tüchler, Yong Wang*

In its standard version, the INCA analysis and nowcasting system uses motion vector fields for the nowcasting of precipitation. These fields are based on correlations between patterns in previous precipitation analyses and provide information for a kinematic extrapolation over the first few hours of lead time. By nature, these short range forecasts cannot account for changes in shape and intensity of precipitation structures which occur especially in convective situations.

Two new approaches have recently been implemented and tested at ZAMG, with the goal of improving the nowcasting quality.

1) Superimposing cell-tracking vectors over the motion vector fields: The A-TNT system is a radar-based, object-oriented approach for cell tracking that provides information on cell movement and size. The cell tracking vectors are superimposed over the conventional motion vectors wherever applicable and thus apply modifications to the original extrapolation.

2) Statistical advection: Based on a linear regression approach and calibration data from three convective seasons, predictors such as Lagrange persistence, radar data, convective parameters and others are used to derive modified nowcasting fields.

Objective evaluations using the SAL verification method and standard scores clearly showed improvements in the nowcasting range with both methods. The presentation will show preliminary results as well as further steps towards a refinement of the methodology and adaptations for operational use.

O13.5 MesoVICT – Mesoscale Verification Inter-Comparison over Complex Terrain

Manfred Dorninger *(University of Vienna, Austria), Marion Mittermaier, Eric Gilleland, Barb Brown, Beth Ebert, Laurie Wilson*

The increasing number of spatial verification methods raises the question of their properties and information content. Specific questions like - How does each method inform about forecast performance overall? Does the method inform about location errors? If so, how? Which methods yield identical information to each other? Which methods provide complementary information? – have already been addressed in a spatial forecast inter-comparison project running from 2008-2010 in a more statistical way and over flat terrain.

The second phase, called MesoVICT has been established to further explore the new methods for more realistic meteorological scenarios. MesoVICT has been launched as an official project of the Joint Working Group for Forecast Verification Research (JWGFVR) a working group of the WMO/WWRP. Its test cases include more variables in addition to precipitation, such as winds. Further, the cases represent interesting meteorological events that develop over time rather than single snapshots. The cases also include ensembles of forecasts as well as observations, and, as the name suggests, they are provided on the larger Alpine region, a region associated with complex terrain.

The aims of the project can be summarised as follows:

- To investigate the ability of existing or newly developed spatial verification methods to verify fields other than deterministic precipitation forecasts, e.g., wind forecasts and ensemble forecasts.

- To demonstrate the capability of spatial verification methods over complex terrain, and gain an understanding of the issues that arises from this more challenging situation.

- To encourage community participation in the development and improvement of spatial verification methods, especially for evaluating high resolution numerical forecasts.

- To provide a community test bed where common data sets are available, but also for the sharing of data and code to assist in developing and testing spatial verification methods.

The talk will give some information on the project structure of MesoVICT, data and models used and cases investigated.

O13.6 Evaluation of a High-Resolution Numerical Weather Prediction Model in Truly Complex Terrain

Brigitta Goger *(University of Innsbruck, Austria), Mathias W. Rotach, Alexander Gohm, Oliver Fuhrer, Ivana Stiperski*

Atmospheric processes associated with complex terrain include various phenomena on the meso- and microscale, which contribute significantly to the local weather in mountainous areas of the Earth. Phenomena such as the thermally induced valley wind system, cold pools, foehn winds and channelling of synoptic winds are well-known. However, they still pose a challenge to numerical weather prediction (NWP) models. Several factors, such as the horizontal and vertical grid resolution, input data, initialization, terrain representation and the parameterizations are important for a successful simulation of atmospheric phenomena in complex terrain. Meteo Swiss is currently testing a pre-operational setup of the NWP model COSMO (Consortium for small-scale modelling) on a horizontal resolution of 1.1 km for a domain over the main Alpine range.

In this contribution we assess COSMO's performance with respect to turbulent exchange processes in complex terrain. This is done by using data from the so-called "i-Box" in the Inn Valley, Austria. The "i-Box" consists of six core measurement sites that are located at representative locations in the Inn Valley, and two remote sensing systems (Lidar and HATPRO) in the city of Innsbruck. The long-term measurement set provides a data pool of high-resolution velocity variances, turbulence variables, radiation, soil moisture, and vertical profiles of temperature, humidity, and wind in the lower troposphere.

The model is assessed by the means of case studies of several weather situations representative for the Inn Valley, such as thermally forced flows, stable boundary layer formation, and foehn events. Two case study days will be presented in this contribution. With a process-oriented analysis, we investigate the spatial variability of the surface characteristics, the radiative forcing, the resulting near-surface turbulence structure, and the valley boundary layer development. A special focus is laid on the influence of the terrain representation on the performance of the model for several locations such as valley floor, mountain top, and slopes with different orientation and angle. The results show that the model's performance is indeed dependent on the location (valley/slope/mountaintop), but also on the time (day/night). This allows us to evaluate possible deficiencies of the model setup and to investigate whether the model's physics schemes (initially developed for horizontally homogeneous and flat surroundings) are suitable for truly complex terrain.

O14 Oral Session: Climate analysis and prediction: Part 1

O14.1 The unknown truth: impacts of uncertainties in European precipitation datasets on regional climate analysis

Andreas F. Prein *(National Center for Atmospheric Research, United States of America), Andreas Gobiet*

Precipitation datasets are used to evaluate climate models or to remove model output biases. Especially in mountainous regions, observed precipitation is error prone due to its high spatio-temporal variability and due to considerable measurement errors. Observational uncertainties are usually neglected in climate model evaluation or in bias correction studies. In this study we compare three datasets: the widely used pan-European gridded E-OBS dataset, the pan-European MESAN downscaled HIRLAM reanalysis (HMR), and a set of regional datasets that are based on high station densities and are partly corrected for undercatch. We show that the differences between these datasets can be larger than precipitation errors in the EURO-CORDEX regional climate model simulations. Differences between the observational datasets are especially large in regions where E-OBS and the HMR have low station densities, for low and high temperatures, high latitude, and mountainous regions (the Alps, Scandinavian Mountains, Carpathians, Pyrenees). These results highlight the strong need for using multiple observational datasets for model development, evaluation, and statistical post-processing as well as for impact research focusing on hydrology, agriculture, ecosystem management, or climate extremes. The magnitude of these so far not regarded observational uncertainties can severely affect climate change impact assessment and lead to misguided political decisions.

O14.2 Long series of Swiss seasonal precipitation: Regionalisation, trends and the influence of large-scale flow

Simon C. Scherrer *(MeteoSwiss, Switzerland), Michael Begert, Mischa Croci-Maspoli, Christof Appenzeller*

The knowledge of precipitation trends and variability is vital for many aspects of life and socio-economic sectors. However, confidence in precipitation trends is still limited and merits regular reassessment. Here, seasonal and annual homogenized precipitation series in Switzerland are investigated for the period 1901-2013 in terms of trends, interannual variability and the influence of large-scale European flow patterns. An objective spatial clustering is applied to 305 stations resulting in and 32 distinct precipitation regions. Moving window trend periods from 33 to 113 years length have been analysed on a seasonal and annual basis using Theil-Sen trend estimates and non-parametric Mann-Kendall trend tests (significance limit $p<0.05$).

Of 2720 analysed moving trend windows, 194 (7.1%) show a significantly positive trend, and 10 (0.4%) a significantly negative trend. Most of the significantly positive trends are found for long precipitation series (50+ years) for winter, autumn and annual series. 81 (72)% of the annual (winter) series in the 1901-2013 period show positive trends and for 34 (22)% of the regions the trends are significant. Significantly negative trends are only found in winter for some short time series in the most recent decades. Interannual variability is varying considerably regionally and seasonally. No clear long-term trends could be identified. The same conclusions hold for changes in moderate seasonal extremes.

The influence of large scale flow strongly depends on the season and region. The strongest link between large scale flow and Swiss precipitation variability is found for winter. With the variability of only four major patterns of sea level pressure, precipitation sums of individual years can be reconstructed with a mean relative error of about 15-25% for northern and 25-35% for southern Swiss regions. The most important pattern for northern Switzerland is a Euro-Atlantic blocking like pattern. For southern Switzerland, an Eastern Atlantic like pattern is dominant in winter and a Scandinavian like pattern in autumn. Composites of sea level pressure and near-surface wind anomalies for dry and wet seasons confirm the importance of atmospheric blocking in winter and autumn. In spring, a high pressure anomaly stretching from the mid-Atlantic to central Europe seems to be very indicative for dry years in northern Switzerland.

O14.3 Alpine trends in temperature and precipitation

Johannes Vergeiner *(ZAMG, Austria), Barbara Chimani, Susanne Drechsel, Klaus Haslinger, Gernot Resch, Christoph Zingerle*

In the framework of the Interreg IV project 3P-Clim* trends of temperature and precipitation were examined for the region between Arlberg and the Dolomites. An emphasis was laid on the link between the changes, that have already been observed, and the projected changes.

Homogenised daily data series of 17 selected stations from start of the measurements until end of 2010 build the basis to analyse the already observed changes. The regional climate model (RCM) COSMO-CLM was used to downscale the ECHAM5 global scenario A1B (“realistic scenario”) to a spatial resolution of 10 km in a two-step approach. The climate forecast was utilised for the two thirty year periods 2026 – 2055 and 2071 – 2100.

Results:

It is shown, that the observed temperature trend is spatially quite consistent. The strongest warming in the annual mean temperature occurred in the period from mid 70-ies to about 2003. The warming is most evident in spring and summer, while in winter a more intermittent signal with embedded phases of cooling is seen. The projected temperature evolution basically conforms to the monitored development and predicts an increase of 1 – 2 (3 – 4) degrees for the period 2026 – 2055 (2071 – 2100) compared to the reference period 1981 – 2010. Examples for implications on derived climate indices like number of summer days, frost days etc. are given.

In annual mean precipitation generally high year-to-year variability with little to no significant trend is observed. Nevertheless, a slight tendency to an increase north of the Alpine ridge and a decrease south of it is found. This is in accordance to analysis of the Histalp data-set (Böhm 2008). The RCM predicts less precipitation in the whole area towards the end of the 21st century, with an even more pronounced decrease in the Veneto region. This reduction emerges mostly from the summer months where the decrease is most prominent.

Literature:

Böhm R, 2008: Harte und weiche Fakten zum Klimawandel – ein Überblick. In: Böhm R, Godina R, Nachtnebel HP, Pirker O, (Red.), Auswirkungen des Klimawandels auf die österreichische Wasserwirtschaft. Hrsg. vom BmLFUW und ÖWAV, Wien, 53-70.

* Past, Present and Perspective Climate of Tirol, Südtirol-Alto Adige and Veneto

O14.4 Towards an Alpine Foehn Climatology

David Plavcan *(University of Innsbruck, Austria), Georg J. Mayr*

Foehn is an ubiquitous and yet very local phenomenon in complex terrain. Foehn climatologies in the Alps have been compiled at only few locations and often in a way that one cannot directly compare them.

A new objective, probabilistic and mostly automatic method makes foehn diagnosis so efficient that it can be scaled up for many locations. We present our current standing on the way to an objective and comparable foehn climatology of the whole Alps. Frequencies and characteristics of foehn winds at stations at different locations on both sides of the main Alpine crest will be compared.

O14.5 Future changes of atmospheric cyclone track types with relevance for extreme precipitation events in Central Europe

Michael Hofstätter *(ZAMG, Austria), Annemarie Lexer, Barbara Chimani, Günther Blöschl, Markus Homann, Andreas Phillip, Christoph Beck, Jucundus Jacobeit*

The geographical region from where a cyclone is propagating into Europe appears to play an important role in generating certain weather extremes. Some of the most devastating European floods have been associated with type Vb cyclones, as in August 2002 or with a congeneric type in June 2013 for example. The aim of this work is to assess different propagation paths of atmospheric cyclones in terms of a systematic relation to large scale extreme precipitation events over Central Europe (CE) and examine future changes of precipitation extremes.

Part A: The relevance of cyclone tracks types for heavy large scale precipitation events and the change of cyclone track type frequency under future climate conditions:

Cyclone tracks have been determined form the analysis of vorticity- and gradient fields, derived from sea level pressure and geopotential height. Resulting tracks are then classified into nine types by a new stream-based approach, based on the geographic regions from where cyclones enter CE. The different types are evaluated in terms of a systematic connection to large scale precipitation events afterwards.

Results show very clear differences between different cyclone track-types in terms of their climatological characteristics, as well as in their relevance for large scale precipitation amounts. The exceedance probability for a heavy precipitation event is very different between different sub-domains and between different track types, although the study region covers a rather small part of CE. The most important track types in this respect are Vb, X-N, X-S in the southeastern, as well as ATL and TRZ in the northwestern regions.

Global Climate Model simulations (Echam6, Echam5, EC-Earth) show a good agreement between the observed and modeled track type frequency. Under future climate conditions all models show a clear decrease in the number of cyclone tracks passing Central Europe, especially in summer. Signals for individual track types are not that clear, as differences between models are usually larger than differences arising from different GHG-concentration scenarios, due to the large internal climate variability.

O14.6 Observational Facts of Sustained Departure Plateau Vortexes

Shuhua Yu *(The Chengdu Institute of Plateau Meteorology, CMA, Chengdu, China, People's Republic of), Wenliang Gao, Jun Peng, Yuhua Xiao*

By using the twice-daily atmospheric observation data from 1998 to 2012, station rainfall data, Tropical Rainfall Measure Mission (TRMM) data, as well as the plateau vortex and shear line year book, characteristics of the sustained departure plateau vortexes (SDPVs) are analyzed. Some new useful observational facts and understanding are obtained about the SDPV activities. The following results are obtained. (1) The active period of SDPVs is from June to August, most in July, unlike that of the unsustained departure plateau vortexes (UDPVs), which have same occurrence frequencies in the three summer months. (2) The SDPVs, generated mainly in the Qumalai neighborhood and situated in a sheared surrounding, move eastward or northeastward, while the UDPVs are mainly led by the upper-level trough, and move eastward or southeastward. (3) The SDPVs influence wide areas of China, even far to the Korean Peninsula, Japan, and Vietnam. (4) The SDPVs change their intensities and properties on the way to the east. Most of them become stronger and produce downpour or sustained regional rainstorms to the south of Yellow River. (5) The longer the SDPV sustains, the more baroclinity it has. (6) When an SDPV moves into the sea, its central pressure descends and rainfall increases in all probability. (7) An SDPV might spin over the bend of the Yellow River when there exists a tropical cyclone in the East China Sea. It could also move oppositely to a landed tropical low pressure originated from the sea to the east of Taiwan or from the South China Sea.

O15 Oral Session: Climate analysis and prediction: Part 2

O15.1 Towards Convection-Resolving Climate Modeling

Christoph Schär *(ETH Zurich, Switzerland), Nikolina Ban, Steven Böing, Oliver Fuhrer, Xavier Lapillone, Michael Keller, David Leutwyler, Daniel Lüthi, Linda Schlemmer, Jürg Schmidli, Thomas Schulthess*

Moist convection is a fundamental process in our climate system, but is usually approximated in climate models by using semi-empirical parameterizations. These approximations introduce significant uncertainties and biases, and there is thus a general thrust towards higher resolution and the explicit representation of moist convection. This approach had been pioneered in research-style simulations many decades ago, and has been used in operational numerical weather prediction for a few years. For climate applications, convection-resolving simulations are still very expensive, but they are increasingly becoming feasible and attractive.

Here we present recent results pertaining to the development and exploitation of convection-resolving atmospheric models for climate scenario applications. We discuss the potential and challenges of the approach, highlight validation using decade-long simulations, and present recent results regarding the application to climate change projections. Most examples will be use a 2.2 km horizontal resolution and cover an extended Alpine region from Northern Italy to Northern Germany.

Consideration will also be given to future challenges, as related to the use of filtered governing equations, the representation of turbulence, and the use of emerging heterogeneous many-core hardware architectures. Some preliminary results will be presented of simulations using an extended computational domain covering Europe.

O15.2 Analysis of precipitation extremes using generalized extreme value theory in convection-resolving climate simulations

Nikolina Ban *(ETH Zurich, Switzerland), Juerg Schmidli, Christoph Schär*

Extreme value analysis provides a useful tool for the estimation of the probability of unusually large precipitation events that can cause devastating floods. Climate modeling studies, as well as theory and observations suggest that such extreme precipitation events will intensify with warming. Current projections of extreme precipitation are based on conventional global and regional climate models, which due to the coarse resolution need to parameterize convective precipitation. The use of convection parameterization leads to a poor representation of extreme precipitation especially on the sub-daily time scale.

Here we present an analysis of extreme precipitation events in convection-resolving climate simulations. The simulations are performed with the COSMO-CLM model at a convection-resolving resolution of 2.2 km across an extended Alpine domain. Ten-year long control and scenario simulations (1991-2000 and 2081-2090) are conducted, driven by a CMIP5 coupled climate model (MPI-ESM-LR) under an RCP8.5 greenhouse gas scenario. Generalized extreme value theory is applied to address projections of daily and hourly extreme precipitation events in the winter and summer seasons. We present a detailed intercomparison of convection-resolving model against a conventional (12 km grid spacing) climate model in terms of model performance and difference between climate change signals.

O15.3 Estimating Global-Warming-Induced Changes in Extreme Precipitation over Mid-latitude Mountains

Dale Durran *(University of Washington, United States of America), Xiaoming Shi*

Global-warming-induced changes in extreme orographic precipitation are investigated using a hierarchy of models: a global climate model, a limited-area weather forecast model, and a linear mountain-wave model. We consider the changes produced by a doubling of CO2 in precipitation over idealized north-south mid-latitude mountain barriers at the western margins of otherwise flat continents.

The intensities of the extreme events on the western slopes increase by about 4%/K of surface warming, close to the “thermodynamic" sensitivity of vertically integrated condensation in those events due to temperature variations when vertical motions stay constant. In contrast, the intensities of extreme events on the eastern mountain slopes increase at about 6%/K. This higher sensitivity is due to enhanced ascent during the eastern-slope events, which can be explained in terms of linear mountain-wave theory as arising from global-warming-induced changes in the upper tropospheric static stability and the tropopause level. Similar changes to these two parameters also occur for the western-slope events, but the cross-mountain flow is much stronger in those events, and as a consequence, linear theory predicts no increase in the western-slope vertical velocities.

Extreme western-slope events tend to occur in winter, whereas those on the eastern side are most common in summer. Our idealized climate-model simulations also suggest that changes in extreme precipitation over the mountains will be smaller than that over the oceans or over flat land.

O15.4 Characterization of the Simulated Regional Snow-Albedo Feedback Using a Regional Climate Model over Complex Terrain

Justin R. Minder *(University at Albany, United States of America), Theodore Letcher*

Mid-latitude mountain regions are particularly sensitive to climate change because of an active snow-albedo feedback (SAF). Here, the SAF is characterized and quantified over the complex terrain of the Colorado headwaters (HW) region of North America using high-resolution WRF regional climate model simulations. A pair of 7-year control and pseudo global warming (PGW) simulations are used to study the regional climate response to a large-scale climate change.

Warming is strongly enhanced in regions of snow loss by as much as 5°C. Linear feedback analysis is used to quantify the strength of the SAF within the HW region. The strength of the SAF reaches a maximum value during April when snow loss coincides with strong incoming solar radiation. Simulations using 4 km and 12 km horizontal grid spacing show good agreement in the strength and timing of the SAF, whereas a 36km simulation shows discrepancies that are tied to differences in snow accumulation and ablation caused by smoother terrain.

Energy budget analysis shows that transport by atmospheric circulations act as a negative feedback to regional warming, damping the effects of the SAF. On the mesoscale, the SAF non-locally enhances warming in locations with no snow, and enhances snowmelt in locations that do not experience snow cover change. The methods presented here can be used generally to quantify the role of the SAF in simulated regional climate change, illuminating the causes of differences in climate warming between models and regions.

O15.5 Trends and Multi-decadal Variability in the Hydroclimate of the Tibetan Plateau as Manifested in Paleoclimate, Precipitation and Reanalysis Data 1850-2010.

G. W. Kent Moore *(University of Toronto, Canada)*

Beginning with the work of Blanford in 1884, the Tibetan Plateau has been recognized as having a profound impact on the intensity of the Indian Summer Monsoon. However our ability to fully characterize the changing nature of the plateau's impact on the monsoon has been limited by the lack of observations of the hydroclimate of this remote and data sparse region. The recent availability of atmospheric reanalyses that assimilate only surface pressure data now allows the possibility to extend our knowledge of this relationship back in time. In this presentation, we will make use of the 20th Century Reanalysis from the ECMWF (ERA20C) along with the APHRODITE high-resolution gridded precipitation dataset and an ice core extracted from a high elevation site on the Dasuopu Glacier on Shishapangma, an 8000 meter high peak in Tibet situated just north of the Himalaya, to examine trends and multi-decadal variability in the hydroclimate of Northern India and Tibet since 1850.

In particular we show that over the 20th Century, the ERA20C indicates that there has been a statistically significant decrease in annual mean snowfall over the southern Tibetan Plateau and a concomitant increase in annual mean rainfall over Northern India that extends northwards into the Himalaya. Both of these changes are shown to be associated with the enhanced warming that has occurred over the plateau since the start of the 20th Century. These results are consistent with trends in rainfall and snowfall as recorded in the APHRODITE dataset over the last 50 years. They are also consistent with a long-term trend towards lower snow accumulation in the Dasuopu ice core that began in the middle of the 19th Century. We also use an EOF analysis as well as spatial correlation analysis to examine multi-decadal variability in rainfall and snowfall in the region of interest and the changing nature of the relationship between the two.

O15.6 The evolution of mountain permafrost in Switzerland (the TEMPS-project)

Christian Hauck *(University of Fribourg, Switzerland), Reynald Delaloye, Isabelle Gärtner-Roer, Andreas Hasler, Christin Hilbich, Martin Hoelzle, Robert Kenner, Sven Kotlarski, Christophe Lambiel, Rachel Lüthi, Antoine Marmy, Johann Müller, Jeannette Noetzli, Marcia Phillips, Jan Rajczak, Nadine Salzmann, Michael Schaepman, Christoph Schär, Benno Staub, Ingo Völksch*

Permafrost is a widespread phenomenon in the European Alps and is characterised by temperatures only a few degrees below zero and is therefore particularly sensitive to projected climate changes in the 21st century. To evaluate the sensitivity of mountain permafrost to climatic changes and to assess its future evolution, not only climatic variables such as air temperature, radiation and timing and duration of snow cover have to be considered, but also subsurface characteristics such as ground temperature, ice content, porosity or hydraulic properties. Permafrost monitoring in the Swiss Alps started only 1-2 decades ago, but currently comprises a large set of meteorological, geophysical, kinematic and ground thermal parameters at a large variety of field sites. The large Swiss project cluster TEMPS (The evolution of mountain permafrost in Switzerland), funded by the Swiss National Science Foundation, integrated and analysed this data set for the first time and combined the observations with long-term model simulations using a dynamic process-oriented permafrost model (COUP-model). In combination with results from Regional Climate Model ensembles, TEMPS aimed to create plausible evolution scenarios of mountain permafrost at specific sites and investigated the interactions between atmosphere and permafrost focusing on the evolution of ground temperature, ice content and related degradation and creep processes.

In this contribution we will show the main results of the project by focusing on several Swiss monitoring stations with permafrost temperatures close to the melting point. Long-term simulations with the coupled heat and mass transfer model COUP forced by downscaled GCM/RCM chains from the ENSEMBLES project suggest increasing ground temperatures and permafrost thaw until the end of the century. The projected air temperature increase leads also to a corresponding reduction in snow cover (= decrease of surface insulation leading to a potential cooling effect), however, the latter does not offset the general warming trend of permafrost temperatures in the model simulations. The high variability of surface and subsurface materials in the permafrost regions of the European Alps will strongly modulate any general trend which might already be visible within the coming decades. Furthermore, we will present technical improvements regarding (a) strategies for downscaling and debiasing RCM output data for permafrost analysis on the station scale at high altitudes and (b) new geophysical and kinematic observation techniques for high-mountain areas.

O15.7 Changes in precipitation patterns associated with the retreat and thinning of Vatnajökull ice cap, Southeast-Iceland

Hálfdán Ágústsson *(IMO, Iceland), Haraldur Ólafsson, Helgi Björnsson, Finnur Pálsson*

The Vatnajökull ice cap at the southeast coast of Iceland has a large effect on the spatial distribution of precipitation in Iceland. This effect is quantified based on results from two sets of high-resolution atmospheric simulations. A control simulation employs the current land height and glacial cover while in a sensitivity run the ice caps have been removed and the height of the model surface is based on the bedrock topography of the glaciers. The simulations are done at 8 and 2 km horizontal resolution and are forced with the Interim re-analysis of the ECMWF for two consecutive years 2004-2006.

The simulations indicate that in the absence of the Vatnajökull ice cap, up to 25% decrease in annual precipitation may be expected in large regions covered by the ice cap. The overall decrease for the whole of Vatnajökull may be close to 15% when the glacial cover is removed. The reduced topography height leads to greater spillover, i.e. a larger part of the precipitation associated with lows and fronts approaching from the south and the east reaches the northern and western ice margins. There are, however, only minor changes further into the lee of the ice cap. The results of this study are not only of relevance in general studies pertaining to atmospheric flow and complex terrain, but also in e.g. planning of hydropower availability and harnessing in a warming climate characterized by retreating glaciers.

O16 Oral Session: Statistical post-processing and downscaling

O16.1 Making use of climate model output in the mountains: Recent progress along the continuum of downscaling complexity

Ethan D. Gutmann *(National Center for Atmospheric Research, United States of America), Martyn P. Clark, Roy M. Rasmussen, Jeffrey Arnold, Levi Brekke*

Climate models provide a rich set of information for use in studying the climate system and its possible evolution; however, the size of the grid cells in climate models makes it impossible for them to explicitly represent important alpine processes. As a result, making use of climate change information in alpine environments requires some degree of post-processing of the output. Post-processing options are often viewed as a dichotomy between statistical and dynamical methods, but in reality, there exists a continuum of methods that have developed in recent decades. These methods have traditionally ranged from relatively simple bias corrections designed to mimic statistics of current climate, to complex statistical fits of circulation patterns designed to preserve more physical meaning, and finally to highly complex regional climate models (RCMs) based on first principles. However, an end-to-end physically based method has eluded the applications community due to the tremendous computational cost associated with RCMs. Recently, we have developed the Intermediate Complexity Atmospheric Research model (ICAR) to fill the gap between advanced statistical methods and full RCMs. ICAR shares much in common with a state-of-the-art RCM, but requires less than 1% of the computational cost. Here we compare the climate change signal in the Colorado Rocky Mountains as predicted from methods spanning the downscaling complexity continuum. Finally we discuss the implications of the range of outputs from different methods; how should one make use of this potential glut of information and methods? How can we know which change signals may be more reliable?

O16.2 Diagnosing sub-grid valley cold air pools from numerical weather prediction (NWP) forecasts

Peter Sheridan *(Met Office, United Kingdom), Simon Vosper, Samantha Smith*

Forecasting temperature variation at small scales in complex terrain is important for predicting localised hazards such as freezing temperatures on sections of road, cold damage to crops, and future changes to complex terrain microclimates. Cold air pools which form in valley bottoms on calm, clear nights drive exaggerated low temperature extremes compared to flat terrain. Many valleys in which cold air pools form, however, are unresolved by current operational numerical models, so that predictions of temperature must be derived by using post-processing techniques to downscale the coarse operational model forecast. A scheme used at the Met Office is designed to account for the influence of sheltering on cold air pooling in sub-grid valleys, and can be applied to create fine scale maps of forecast screen temperature. An improved version of this scheme is described, including a component which targets improved upland temperature prediction via a treatment of the interaction between the hilltop boundary layer and the horizontally adjacent atmosphere above the valley floor.

O16.3 A new approach to statistical post-processing of spatial forecasts

Markus Dabernig *(University of Innsbruck, Austria), Jakob W. Messner, Georg J. Mayr, Achim Zeileis*

Statistical post-processing is often used to downscale a global weather prediction model to a particular location, especially in complex terrain like the Alps. When expanded to several stations, the post-processing has to be repeated at every station individually, typically ignoring the available spatial information and thus potentially leading to spatially incoherent forecasts. To maintain spatial coherence, the post-processing is applied to all stations simultaneously. Therefore, site-specific characteristics are eliminated by subtracting a spatial climatology from measurements and numerical forecasts. This results in anomalies on which simple linear regression can be performed for multiple stations simultaneously. Furthermore, since these spatial climatologies are made with generalized additive models for the whole region at once forecasts at any location are possible even where no measurements are available.

O16.4 Probabilistic Predictions in Complex Terrain with an Analog Ensemble

Iris Odak Plenkovic *(Meteorological and Hydrological Service, Croatia), Luca Delle Monache, Kristian Horvath, Mario Hrastinski, Alica Bajic*

The Analog Ensemble is statistical post-processing technique to generate probabilistic forecasts by searching similar past numerical weather predictions (i.e., analogs) across several variables (i.e., predictors) to the current prediction. The measurements corresponding to the best analogs form the analog ensemble (AnEn) with which the probability distribution of the future state of the atmosphere can be estimated. This study explores the application of AnEn for probabilistic short- or medium-range forecasts in complex terrain over

Croatia.

The AnEn is generated with the Aire Limitée Adaptation dynamique Développement InterNational model (ALADIN) run over two nested domains with 8 and 2 km horizontal resolution, respectively. It is tested at several climatologically different locations across Croatia for point-based wind speed predictions at 10 m and 80 m height. Results are verified and compared to the ALADIN model to address the following question: how does AnEn performs at locations in complex terrain over Croatia? The analysis focuses on a group of stations with downslope windstorms occurrences such as bora wind.

The verification procedure includes several metrics (e.g., Brier skill score, ROC skill score, reliability and dispersion diagrams) to optimize the AnEn configuration and to test the probabilistic prediction performances. Different predictors such as wind speed, direction, temperature, Richardson number and Scorer parameter are examined. Skill of AnEn predictions are compared with forecasts generated via logistic regression (LR). This study shows that the AnEn adapts well to different terrain and height. It provides accurate predictions while reliably quantifying their uncertainty and showing satisfactory spread. The AnEn performance is equal or superior than LR, especially for group of stations that are climatologically prone to strong winds. These results encourage the use of AnEn in an operational environment at meteorological station locations, as well as at wind farms.

O16.5 Improving short-range probabilistic forecasts of (intra-)daily precipitation sums

Manuel Presser *(University of Innsbruck, Austria), Jakob Messner, Reto Stauffer, Georg J. Mayr, Achim Zeileis*

Ensemble prediction systems (EPS) attempt to reflect the uncertainty of weather forecasts. To downscale EPS forecasts to point locations, and to correct for systematic errors and missing representativity, they are often statistically post-processed. Precipitation is a challenging quantity, because its distribution is non-Gaussian, bounded at zero, and contains a large fraction of zeros for short accumulation periods (e.g. 3, 6, 24-hourly sums). We present a new statistical EPS post-processing method, which masters these challenges. The idea is to employ a zero-censored Gaussian distribution to appropriately capture the point mass at zero precipitation amounts. Mean and scale of the underlying Gaussian distribution are then linked to the ensemble mean and scale, and estimated by maximum likelihood. Results are presented for the Alto Adige region in the North of Italy for short-range weather forecasts.

P1 Poster Session: Poster Session 1

P1.1 Bayesian Exploration of Multivariate Orographic Precipitation Sensitivity for nearly moist neutral flows

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Recent studies have examined the sensitivity of topographically forced rain and snowfall to changes in mountain geometry and upwind sounding in moist stable and neutral environments. These studies were restricted by necessity to small ensembles of carefully chosen simulations. This research extends the earlier studies by producing a large ensemble of simulations, all of which produce precipitation concentrated on the upwind slope of an idealized bell-shaped mountain. A Bayesian Markov chain Monte Carlo (MCMC) algorithm is used to generate soundings and mountain geometries consistent with a forced upslope rainfall. MCMC-based probabilistic analysis yields information about the combinations of sounding and mountain geometry favorable for upslope rain. The results indicate that many different combinations of flow, topography, and environment can produce very similar rainfall. Exploration of the multivariate sensitivity of rainfall to changes in parameters reveals tipping points in the system, around which a small change in environmental characteristics produces a very large change in rainfall amount and distribution. Detailed examination of model output reveals high sensitivity in the mountain wave breaking behavior to be the cause of these rapid changes in rainfall.

P1.2 The Vertical Structure of Coastal Orographic Feeder Clouds

David Kingsmill *(University of Colorado, United States of America)*

The most commonly documented conceptual model of orographic precipitation enhancement is associated with the seeder-feeder process where water drops in the orographically forced feeder cloud are accreted or collected by larger ice or liquid hydrometeors, respectively, emanating from seeder clouds aloft. Orographic precipitation enhancement has also been attributed to a process that includes a feeder cloud but lacks a significant seeder cloud as manifested by the lack of a radar brightband. In both cases, the orographic feeder cloud plays a critical role in the precipitation development process. The signature of an orographic feeder cloud is increasing total water content (ice plus liquid) with decreasing altitude, which signals the growth of precipitation-sized hydrometeors as they fall in the lowest few kilometers above the terrain. Numerous studies have attempted to document this structure with in situ aircraft observations. Unfortunately, these observations are limited by the constraint that aircraft cannot sample the lowest 500-100 m above ground due to flight restrictions. Scanning and profiling radars have been used as remote sensing alternatives to document orographic feeder cloud structure. While these studies have provided some insights, their relatively small sample size limits the statistical significance of their results. For example, several outstanding questions remain: What is the statistical variation of precipitation growth in orographic feeder clouds? How do these statistics differ, if at all, for orographic feeder clouds associated with and without a seeder cloud? What is the relationship of these statistics with surface rain rate?

This study addresses these limitations with profiling radar data collected in the coastal mountains of northern California over 15 winter seasons during the CALJET, PACJET and HMT-West field campaigns operated by NOAA. More than 2300 60-minute average profiles of reflectivity and Doppler vertical velocity from an S-band precipitation profiler at Cazadero (475 m MSL) are examined. Profiles of rainwater content are calculated from the reflectivity profiles using reflectivity-rainwater content relations derived from collocated raindrop disdrometer data. New findings to date from this effort include:

• The median of the reflectivity (rainwater content) slope distribution is -2.8 dBZe km-1 (57.1 mg m-3 km-1) in the lowest 1 km above the surface.

• Reflectivity and rainwater content slope is steeper (i.e., more negative) for profiles without a seeder cloud compared to profiles with a seeder cloud.

• Reflectivity slope shows no clear correlation with surface rain rate. In contrast, rainwater content slope becomes steeper (i.e., more negative) as surface rain rate increases.

P1.3 Finescale Orographic Precipitation Variability and Gap-Filling Radar Potential in Little Cottonwood Canyon, Utah, USA

Leah S. Campbell *(University of Utah, United States of America), W. James Steenburgh*

Finescale variations in orographic precipitation pose a major challenge for weather prediction, winter road maintenance, and avalanche forecasting and mitigation in mountainous regions. While many have researched orographic precipitation over large or idealized mountain barriers, small-scale (~1–10 km) precipitation gradients and structures over highly three-dimensional terrain are still poorly understood.

Here we examine the structure and evolution of a winter storm over the complex three-dimensional topography surrounding Little Cottonwood Canyon, which cuts orthogonally eastward into the central Wasatch Mountains of northern Utah and is flanked by steep ridges that rise ~2000 m above the canyon mouth. The upper canyon receives an average of ~1250 cm of snowfall per year, but radar beam-blockage and complex terrain limits forecasters' ability to accurately monitor and forecast snowfall in the canyon. Improving forecast skill along the canyon is critical because State Route 210, which runs the length of Little Cottonwood Canyon, services two of Utah's most popular ski resorts and has one of the highest snow avalanche hazard indices of any major road in North America. Ground-based X-band radar observations collected during intensive observing period 6 (IOP6) of the Storm Chasing Utah Style Study (SCHUSS) are used to highlight finescale variations in orographic precipitation during the event. A mobile GRAW GPS-sounding system used over the adjacent Salt Lake Valley and the University of Utah HYVIS snowflake imager provided additional storm data.

Precipitation during the weakly stratified prefrontal storm stage featured a wavelike barrier-scale reflectivity maximum over upper Little Cottonwood Canyon that extended weakly westward along the transverse ridges flanking the canyon. Hydrometeor-type analyses using the X-band radar dual-polarization products and images from the HYVIS snowflake imager suggest the presence of heavily rimed snow crystals and small graupel over the upper canyon. The precipitation pattern appeared to reflect a veering wind profile, with southwesterly flow over the transverse ridges but cross-barrier westerly flow farther aloft. Sublimation within dry subcloud air further diminished low-level radar reflectivities over lower Little Cottonwood Canyon. In contrast, the cold-frontal stage was associated with stronger reflectivities over the lower canyon and the adjoining north- to northwest-facing canyon wall, consistent with shallow, northwesterly upslope flow.

The evolution of these small-scale precipitation features poses a challenge for operational weather prediction, avalanche mitigation efforts, and winter road maintenance in Little Cottonwood Canyon and demonstrates the potential for improved analysis and forecasting of precipitation in Little Cottonwood Canyon and other regions of complex topography using a gap-filling radar.

P1.4 Sea-effect precipitation processes and orographic enhancement over Hokkaido Island, Japan

Leah S. Campbell *(University of Utah, United States of America), Yasushi Fujiyoshi, Yoshinori Yamada, Masayuki Kawashima, W. James Steenburgh*

Throughout much of the winter, cold air from the Asian continent moves across the impressive fetch of the Sea of Japan (~400 km), producing seemingly omnipresent sea-effect snowbands that impact the west coast of Japan. These snowstorms can bring heavy snowfall to both urban and rural areas, impacting local transportation, utilities, education, and commerce. Weather forecasters and numerical weather prediction models currently struggle with accurately predicting the magnitude, timing, and spatial distribution of both snowfall amount and snow crystal type, which is further complicated by the presence of complex terrain. On Hokkaido Island, these snowbands impact coastal mountain ranges that rise to 1000–2100 m above sea level, as well as the major urban center of Sapporo. Sapporo is located on the Ishikari Plain, a broad alluvial plain that is ringed by mountains on its southern, eastern, and northern edges.

Here we integrate observations from operational radars, which enable dual-Doppler synthesis over the Ishikari Plain, with Weather Research and Forecasting (WRF) simulations to examine the orographic influences during a sea-effect event that impacted Sapporo and the western coast of Hokkaido Island. This event, which formed in cold postfrontal flow on 12 January 2014, was unique in that it was dominated by transverse-mode snowbands, a less-well-understood subset of sea-effect bands. In transverse-mode snowbands, convective cells move perpendicular to the mean flow direction and parallel to the boundary-layer wind shear vector. This results in sub-bands oriented transverse to the parent band. During the event, transverse bands impacted the Ishikari Plain and surrounding mountain ranges for about four hours.

Radar observations show that over the mountains each sub-band, oriented perpendicular to the prevailing flow and the parent transverse band, intensified briefly and broadened slightly when it crossed high terrain before weakening in the lee. In addition, radar observations and WRF simulations suggest that the transverse bands intensified as they clipped the mountains on the south side of the Ishikari Bay, resulting in an

Ishikari Plain precipitation maximum located near the shoreline. When WRF simulations were run where the mountains were reduced to the elevation of the Plain, the precipitation maximum produced became smaller in magnitude and horizontal extent and was located farther east from the coast. This work explores the impact of complex terrain on sea-effect snowstorms and suggests that the coastal mountains of Hokkaido Island influence the structure, intensity, and spatial distribution of precipitation produced by transverse-mode snowbands.

P1.5 Lake-effect snow at Lake Constance, Austria: Case studies of winter precipitation over complex terrain

Lukas Umek *(University of Innsbruck, Austria), Lukas Lehner, Alexander Gohm, Susanne Drechsel*

On a few days in recent years, heavy snowfall affected the area on the southeastern shore of Lake Constance, located between Austria, Germany and Switzerland. The precipitating clouds were organized as rather stationary bands that were aligned along or in extension of the lake. This pattern caused strong horizontal gradients in accumulated snow in the region. The snow bands reached a length of about 15 to 40 km and a width of 4 to 10 km. They produced heavy precipitation in the area of the town of Bregenz, located at the southeastern shore of Lake Constance and occasionally over the adjacent mountainous region of the Bregenzerwald.

Typically, these events occurred after the passage of a cold front resulting in a lower air temperature than the lake surface temperature. Therefore, it is assumed that the lake has a significant impact on destabilizing and moistening the planetary boundary layer and the formation of precipitation. Hence, a lake effect, comparable to that over the Great Lakes in Northern America but at a smaller scale is supposed to happen at Lake Constance. Furthermore, orographic lifting over complex terrain may contribute to the formation of stationary precipitation. The height of the topography rises from about 400 m MSL at the shore to about 1000 m MSL east of Bregenz. This study tries to understand the processes and governing factors which determine the formation of these precipitation bands.

Case studies of three events were conducted to clarify the synoptic situation leading to the formation of stationary snow bands over and downstream of Lake Constance. They are mainly based on data of automatic weather stations and ECMWF model analyses. All events occurred during northwesterly flow on the rear side of a synoptic-scale trough, leading to the advection of cold air in the region of Lake Constance. During these three events, the weather station at Bregenz measured daily accumulated precipitation ranging from 37 to 65 mm. These values exceed the 90th percentile of daily precipitation at Bregenz (which is 27 mm for the period from 1972 to 2014). The wind field measured by automatic weather stations shows that a convergence line formed between the northern and southern shore of the lake during the periods of heavy precipitation. Additionally, a weak down-valley flow, emanating from the Rhine Valley, may have caused an intensification of the convergence.

In order to study the phenomenon in more detail, high-resolution numerical simulations of one specific event (17 January 2013) are performed. For that purpose the Weather Research and Forecast Model (WRF-ARW) is used with a mesh size of 900 m to explicitly resolve the snow band. Additionally, sensitivity simulations with modified terrain and lake characteristics (e.g. lake size and temperature) will be performed and presented at the conference to clarify the impact of the lake and the complex topography on the formation and distribution of precipitation. Further, the sensitivity of the simulated precipitation on the initial conditions will be assessed.

P1.6 Lake-effect precipitation at Lake Constance, Austria: Climatology and forecasting

Lukas Lehner *(University of Innsbruck, Austria), Lukas Umek, Alexander Gohm, Susanne Drechsel*

In the past, heavy precipitation events occurred at the southeastern shore of Lake Constance (Austria) that have not been predicted by numerical weather prediction models and human forecasters. These events occurred especially on winter days when distinct convection is typically rather rare. The highest amount of 24-hour accumulated snow in the town of Bregenz (400 m MSL) was 52 cm on 08 February 2013. Hence, the interest in the mechanisms and prediction of this local phenomenon is high. The stationarity and banded structure of observed precipitation is evocative of lake-effect snow events that frequently occur over the Great Lakes, North America, and which have been intensively investigated over many years. For Lake Constance such research is missing. The lake is located at the tripoint of Austria, Germany and Switzerland close to complex terrain, has a length of 60 km, and, hence, is much smaller than any of the Great Lakes. Nevertheless, we suspect that a combination of lake and orographic effects was the reason for the generation and enhancement of precipitation observed in this region during such events.

Here we present an inventory of cases that serve as the basis for a climatology, the analysis of governing factors, and the compilation of a decision tree for the prediction of such events. With the aid of weather station data and images of radar reflectivity, 30 events with potential lake-effect precipitation have been identified for the period 2001 to 2013. During the last five years of this period, five events occurred on average per year. Two-thirds of all detected cases happened in the autumn and winter seasons with a maximum frequency in November. Typically, these events occurred after the passage of a cold front resulting in a lower air temperature than the lake surface temperature. The cold air was frequently advected from northwesterly directions for which the fetch of the northwest-southeast orientated lake is maximal. The residence time of the air over the warmer water body is thereby maximal. Sensible and latent heat fluxes as well as mesoscale convergence and orographic lifting over complex terrain are supposed to be significant factors for the development of lake-effect precipitation at Lake Constance.

Based on the climatology, a decision tree was compiled for human forecasters which should facilitate their decision whether or not to account for enhanced precipitation due to lake effects. It considers the most relevant factors leading to heavy precipitation at the southeastern shore of Lake Constance. The decision nodes ask the user for the stability of the incoming air mass, the flow direction in the lower troposphere and the sign of the sensible heat fluxes between the water surface and the adjacent air mass. A thorough verification of the decision tree will be an important future step.

P1.7 The missing link between Alpine potential-vorticity banners and banded convection: A case study of a severe Alpine snow storm

Simon Siedersleben *(University of Innsbruck, Austria), Alexander Gohm*

On 01 Februar 2014, the southern side of the Alps was affected by a heavy snow storm with widespread orographic precipitation causing authorities to issue the highest level of avalanche risk in parts of Austria. The northern side of the Alps was mostly dry. Nevertheless, quasi-steady convective cloud bands developed over the northern Alpine foreland with a remarkable length of several hundreds of kilometres. This study tries to illuminate the mechanisms of these cloud bands based on high-resolution numerical simulations with the Weather and Research and Forecasting (WRF-ARW) model.

The storm was associated with a deep synoptic-scale trough that caused south-westerly flow over the Alps with winds exceeding 40 m/s, orographic precipitation on the southern side, and foehn-like subsidence on the northern side of the Alps. Orographic potential vorticity (PV) banners developed on the leeward side of the mountain range. They were aligned parallel to the impinging flow and emanated from small-scale topographic features. The cloud bands formed in the area of negative PV. A simulation with a smoothed model terrain indicates that the size and structure of orographic PV banners determines the size and structure of these cloud bands. This result supports the hypothesis that the small-scale topography has an impact on clouds and precipitation also on a larger scale. Analysis of trajectories of air parcels originating from areas of negative and positive PV will be performed and presented at the conference to uncover the link between negative PV and banded convection.

P1.8 Sensitivity Tests and Ensemble Simulations for a Heavy Precipitation Event over Corsica

Phillip Scheffknecht *(Université Toulouse, France), Evelyne Richard, Dominique Lambert*

The island of Corsica, located in the western Mediterranean, is susceptible to heavy precipitation events (HPE). Especially during the fall, the island is often exposed to episodes of heavy rain and flooding. Despite the advances in weather forecasting and the progress in mesoscale modelling, such events remain a challenge to forecasters.

In the framework of the Hydrological Cycle of the Mediterranean Experiment (HyMeX), we present a study of a HPE which occurred over Corsica on 23 October 2012. In the morning, the southeast of Corsica was struck by a convective system which caused localized flooding in the coastal area in the southeast of Corsica around Porto-Vecchio. The convection was associated with an upper level cyclone located west of Corsica.

The event is simulated using the Meso-NH model on a domain with a horizontal grid spacing of 2.5 km with an additional test including a nested domain with a grid spacing of 500 m. The model captures the event well. It places a precipitation maximum over the area where the flooding occurred with a delay of only one hour. To understand the mechanisms involved, a series of sensitivity tests is conducted.

An ensemble of nine simulations with random perturbations on parameters of the model microphysical scheme is used to test the sensitivity model microphysics. These tests show little sensitivity of the precipitation over the southeast of Corsica, where the flooding occurred, but higher sensitivity over the sea. Simulations are conducted with flattened Corsican orography and without the island. In these tests, precipitation organizes along a continued band consistent with the large scale forcing. The inflow of cool air into the Mediterranean basin from the north is blocked by increasing the height of the mountain chains in Italy north and northeast of Corsica. This test results in a longer event and higher precipitation, indicating that the inflow of cool air might have reduced the availability of warm and moist air to the event.

For the studied event, (i) synoptic conditions favored the development of convection west of and over the south of Corsica in the morning of 23 October, (ii) the northerly flow in the boundary layer was split around Corsica and converged southeast of the island where convection was initiated over the resulting convergence line, and (iii) the balance between the converging flows allowed the formation of a stationary convergence line over the southeast of Corsica, resulting in localized high precipitation.

P1.9 Simulations of a long-lived supercell over complex terrain

Phillip Scheffknecht *(Université Toulouse, France), Stefano Serafin, Vanda Grubišić*

We study the convective event of 2 August 2007, when a supercell formed over the east of Switzerland and moved along the Alpine main ridge for more than eight hours. It was part of a series of convective storms ahead of a cold front approaching from the northwest. The supercell passed over several mountains with heights exceeding 2000 m and through multiple valleys, ultimately dissipating in Lower Austria after covering a distance of more than 450 km.

The WRF model was used to simulate the event, in order to gain a better understanding of the mechanisms involved in its evolution. The simulation has a grid spacing of 833 m in the innermost of three domains. The storm is well reproduced in terms of qualitative development, since the simulation produces a supercell with a life time of over six hours on a track very similar to the observed one.

Three idealized simulations were performed, to test hypotheses about the formation of the supercell and its uncommon longevity. In the first test, all fine-scale features were removed from the Alpine topography. A supercell still develops in the simulation, however its life cycle is considerably shorter (only about 90 minutes) and it forms further south, close to higher terrain. In the second test, the Alps are replaced by a plateau at 400 m above sea level. In this simulation no supercell develops and convection organizes along a line instead. In the third test, the Alpine topography is preserved but the surface sensible heat flux is deactivated. The resulting convective system lacks any long lived cell and no supercell occurs.

These results indicate that two important mechanisms are probably at play. First, the alpine ridge as a whole modified the synoptic flow to create the wind shear favorable for the formation and maintenance of a supercell. Second, small scale features contributed to the longevity of the storm by redistributing moisture along ridges and their slopes, providing the storm with warm and moist air along its path. The latter mechanism is not yet fully understood.

P1.10 On the uncertainty of altitudinal precipitation gradients

Michael Kuhn *(University of Innsbruck, Austria)*

The change of precipitation with altitude in Alpine valleys (φ) is seasonally and locally variable and is difficult to measure or to determine indirectly, which implies that basin precipitation in the Alps is an uncertain quantity. This paper addresses the uncertainty first from errors of measurements at individual stations, then presents examples of the simultaneous effect of screening (rain shadowing) and altitude on φ in the Eastern Alps. Basin precipitation (P) is then treated as the residual in the balance of runoff, evaporation and storage in snow and ice, and φ results from assuming a linear increase of precipitation with altitude. The uncertainty of the annual basin precipitation is determined by that of the other terms of the balance. The uncertainty of the mean annual φ depends further on the representativity of the low altitude reference station. Seasonal or monthly values of φ are less constrained, they are subject to possible equifinality of uncertainties in vertical temperature gradients and degree day factors in the storage term. These may temporarily compensate one another and may give the right annual φ at the cost of wrong monthly values. This uncertainty is, however, reduced by the expected different seasonal course of φ, temperature gradient and degree day factor, respectively. The balance has been solved for 80 basins in the Eastern Alps, yielding seasonal values of φ in a range from 5 to 10 % per 100 m with lower values in summer.

P1.11 Analysis of the Recent nivometric conditions in Emilia Romagna territory (Northern Adriatic Italy)

Massimiliano Fazzini *(University of Ferrara, Italy), Cesare Govoni, Sandro Nanni, Valentina Pavan, Francesco Russo*

The understanding of the spatial distribution of precipitations in the Mediterranean basin is extremely complex, especially where the topography is varied. The physical territory of Emilia Romagna is limited to the south by the mountain range of ’Apennines - which covers about 25% of the total area – at north of it, stretches a hilly strip, with a similar extension; finally more to the north, dominates the Po plain. The Apennine presents several peaks rising above 2000 m. with the most prominent high in Monte Cimone, 2165 m while in the north-eastern part of the Po plane, are some areas under sea level. The climate varies from continental cold of the Apennines to the sub continental in plains and hilly; only on the southern partition of coast there are a sub littoral climate. The analysis of snow cover was conducted on over 25 stations manual detection, for the 1981-2012 time span. The series, homogeneous and continuous, they belong to monitoring networks of ARPA Emilia Romagna, service Meteomont of State Forestry and the Meteorological Service of the Air Force. They are located at altitudes between 2 and 2150 m. Were analyzed, on a monthly time, the variables "height of fresh snow" and "permanence of snow on the ground". Were defined also snow regimes. The snowpack is sporadic and not very durable in low and middle plains and is characterized by remarkable cumulated and persistence on the ground over 1000-1200 meters. Furthermore, a evident decrease of fresh snow below 800-1000 meters and especially in the last decade is observed. Finally, a statistical relationships between snowfalls and climatic index NAO and SCAND have been searched. The climatic analysis is completed by the description of the weather types which bring the most abundant snowfalls in different areas of the territory.

P1.12 Time and space distribution of precipitation in the Marche Region (Central Italy): preliminary observations.

Matteo Gentilucci *(University of Camerino, Italy), Carlo Bisci, Massimiliano Fazzini, Carmela Vaccaro*

The data collected at 111 rain gauges in the Marche region and in its immediate neighbor during more than fifty years have been analyzed in order to depict the spatial distribution of precipitation. The available records have been regionalized and analyzed separately for the 1950-1989 and 1991-2007 time spans (103 and 100 recording stations, respectively), in order to individuate time variations connected with global climate change.

The study area covers about ten thousand square kilometer and belongs to the Adriatic side of Central Italy; exception made for a small sub-basin draining to the Thyrrhenian Sea (the Nera River sub-basin of the Tiber River), it is characterized by elevations progressively decreasing moving eastwards (i.e. from the Apennine belt to the Adriatic Sea). There, all the major rivers quite strictly follow the regional altitudinal gradient. The area is mostly hilly (ca. 69%) and subordinately mountainous (ca. 31%, to the west); the maximum elevation is that of the Vettore Mt (2'476 m a.s.l.), located at its SW boundary.

Looking at the raw data, it is evident that for both periods precipitation in every month show a marked increase moving from the coast upstream (i.e. increasing the elevation), with a minimum in the SW portion of the region.

To interpolate the sparse data, multiple regressions have been calculated (by means of GIS and Statistic packages) using various independent variables derived from a detailed DEM and digital topographic maps: elevation, latitude, distance from the sea, slope aspect, distance from rivers, distance from divide and local relief (i.e. local difference of elevation between the divide and the river). The method allowed to describe more than 70% of the overall variance, exception made for the summer records of the most recent period.

The successive step was to individuate and explain the outliers, in order to increase the accuracy of the interpolation.

Finally, the resulting mathematical model has been used to regionalize the rain gauge records, thus obtaining three maps (one for each period and one depicting the difference among them) for annual values and for each seasonal ones.

Observing them, beside the already said observation regarding the vertical gradient of precipitation, it is possible to notice that recent pluviometric changes are not homogeneously distributed, even though a general trend toward more dry climate emerges.

This research is preliminary to a more detailed one, aiming to give the basis for a more strict description of the regional climate of the Marche Region and of its recent variation and short time trends, as well as to test the validity of the method and the relative significance of the different regressors.

P1.13 THORBEX - The Thorbjörn precipitation field experiment in SW-Iceland

*Guðrún Nína Petersen, Hálfdán Ágústsson, **Haraldur Ólafsson** (HI, Iceland), Þórður Arason*

During the autumn of 2014, precipitation was observed by a dense network of automatic raingauges covering the 243 m high and steep mountain in the Reykjanes peninsula in SW-Iceland. The experiment is backed by continous radar observations of winds and precipitation, radiosondes every 12 hours at the nearby Keflavik airport and a number of automatic weather stations. In the presentation, the observed precipitation pattern will be shown under different atmospheric flow conditions.

P1.14 An Analysis of an extreme Rainstorm Caused by the Interaction of the Tibetan Plateau vortex and the Southwest China vortex during the Intensive Observation Period

***Xiaolong Cheng** (Institute of Plateau Meteorology, CMA, Chengdu, China, People's Republic of), Yueqing Li*

Abstract

A rainstorm caused by the coupling of the Tibetan Plateau Vortex (TPV) and the Southwest China Vortex (SWCV) in eastern Sichuan during 29 June–2 July 2013, is analyzed by using conventional weather station data, plus the in-situ intensive observation data for SWCV during flood season. The results show that: under the control of a large transverse trough in Eurasia region at mid-high latitude, the westerly flow in northern China leads TPV eastward movement. And SWCV moves northward and merges with TPV, finally form a major synoptic system resulting in heavy rainfall. In addition, the water vapor from both the Bay of Bengal and the South China Sea provides the sufficient condition for heavy rainfall. The intensive observation clearly reflects the nascent state of TPV and SWCV, the effect of cold advection, the evolution of two vortices, as well as the two vortices merging process that induces rainstorm. But, it's hard to identify the vortices activities and the precipitation variations only by using conventional station data. When the two vortices merge and strengthen, there exists a phenomenon that cold tongue and warm flow meet together. The structure is similar to front: rainfall regions are mainly distributed in the high gradient areas of average temperature deviation. Only relying on conventional observation data, it cannot effectively exhibit the abnormal structure and different characteristics. So, improving intensive observations, augmenting scientific experiment and focusing on meticulous study are conducive to reveal the evolution of SWCV and TPV, as well as their precipitation.

Key words: Intensive observation, Tibetan Plateau Vortex, Southwest China Vortex, Coupling effect, Rainstorm

P1.15 Analysis on Environmental Field and Causes for the Abnormal Track of Tibetan Plateau Vortex after Its Moving out of the Plateau

*Shuhua Yu, **Nini Tu** (The Chengdu Institute of Plateau Meteorology, CMA, Chengdu, China, People's Republic of), Jun Peng*

By using NCEP/NCAR reanalysis data, historical synoptic charts, tropical lows data, and Tibetan Plateau Vortex and Shear Line Yearbooks and based on the investigation into the activities of sustained departure plateau vortexes (SDPVs) which last over two days every time during 1998-2013, this paper contrasts and analyzes various physical fields in mid-troposphere in different stages of the SDPVs when they spin over the west and the east of Hetao region. The results show that the impact weather system of the spinning SDPVs in the west of Hetao is the transverse shear flow field, while that for the spinning of SDPVs in the east of Hetao is the longitudinal shear flow field or the deep trough. The spinning of SDPVs over Hetao region is mainly caused by typhoons or tropical lows on the ocean area to the east of Chinese mainland,

which make the eastward movement of the weather system that affects SDPVs be hindered. The possible causes for the spinning activity of SDPVs over the Hetao region are: (1) Typhoons or tropical lows affect the environmental wind field of SDPVs, and the environmental wind field can change the wind structure of SDPVs. The asymmetric wind structure of SDPVs influences the anomaly of the vortex moving trend. (2) Variation of environmental field where the spinning SDPVs in Hetao region live leads to the change of the moving trend of positive vorticity zone, affecting the vortex moves toward the area which is beneficial for its development, and affecting the vortex moving trend. The research also reveals main differences between the mid-troposphere environmental fields that affect the spinning activities of SDPVs over the western and eastern parts of Hetao region. These findings would provide some references for forecasting rainstorm and flooding triggered by abnormal tracks of plateau vortexes after they move out of the Tibetan Plateau.

P1.16 Observing layout, field experiment of Southwest China vortex and its applications in weather research and forecast

Yueqing Li *(Institute of Plateau Meteorology, CMA, Chengdu, China, People's Republic of)*

Abstract

The Southwest China vortex (SCV) is a very important influence system for the precipitation weather of China, specially, during summer half year. The torrential rain caused by SCV is the second after it caused by typhoon in intensity, frequency and coverage. And the torrential rain of SCV is also a much complex and distinctive torrential rain in China. SCV and its torrential rain are always a key scientific problem in weather science. But, it is not very clear about SCV and its severe weather because of the absence of meteorological station and the sparse of observing data. The research and the understanding are seriously restricted on SCV and its torrential rain.

Based on the situation of scientific research and operational forecast for SCV, this paper discuss the Observing layout, field experiment of SCV and its importance for the basic data. And the intensive observation scientific experiment of SCV has been carried out in summer from 2010 to 2013. The intensive observation data for SCV activities and its weather processes has been obtained, and using the multi-source data from the surface, radiosonde, radar and satellite observation, the basic feature and anomalous mechanism of SCV have been deeply and refinedly researched, which further reveal the structural feature, development process and weather influence of SCV. Furthermore, the radiosonde data assimilation, from the intensive observation scientific experiment of SCV, obviously improves the operation ability of the numerical weather forecast in Southwest China. In a word, it is necessary to optimize the observation network, reinforce the field experiment and expand data application for the research and forecast of SCV and its torrential rain.

P1.17 The correlation between aerosol and large-scale precipitation in autumn in Sichuan Basin

Pengping Wu *(Institute of Plateau Meterology, CMA, Chengdu, China, People's Republic of), Changchun Zhou*

The objective of this study is to identify the correlations between aerosols and low clouds and rainfall in autumn in Sichuan Basin. In this paper, the re-analysis assimilates total aerosol optical depth(AOD) and low cloud cover(LCC), and large-scale precipitation(LSP) (stratiform precipitation) are used here to estimate the correlations over the period 2003–2012. The re-analysis data was provided by the European Centre for Medium-range Weather Forecast (ECMWF) for the Monitoring Atmospheric Composition and Climate (MACC) project. At present, the data includes 2003-2012 year. The re-analysis assimilates total aerosol optical depth retrieved by the Moderate Resolution Imaging Spectroradiometer (MODIS) to correct for model departures from observed aerosols.

Method used here is canonical correlation analysis (CCA). CCA have the advantage of selecting pairs of spatial patterns that are optimally covariated and correlated respectively. The dominant CCA pair gives the highest canonical correlation, followed by the next pair and so on, with the condition that successive canonical coefficients are orthogonal to the previous one. To estimate the correlations between fields of predictor variables (here is AOD) and predictand variables (here is LCC or LSP), the heterogeneous correlation patterns are calculated and plotted to map. The “heterogeneous” correlation maps provide information on the extent to which LCC or LSP is susceptible or which AOD is influential. Prior to conducting the CCA, the standardized predictor and predictand data are separately condensed using standard empirical orthogonal functions (EOF) analysis. The EOF analyses reduce large numbers of original variables to much fewer essential variables, filtering out noise. The number of EOF time series (TS) used was judged by their sum of variance, here is 80%. NCL (The NCAR Command Language) is used to calculate CCA and EOF.

The first pairs EOF may explore the main features of spatial variability. And the first 2 pairs of all variables explain more than 50%. The value of EOF1 of 3 variables are all negative, describing a same sign of spatial patterns of variability. Thus, EOF1 should be the long term climatic stage for 3 variables. The AOD over middle of Sichuan basin is highest, and gradually decrease around that. LCC is highest over southern of Basin and lowest over middle northern. High LSP’s center locates western Basin like daily LSP mean distribution. The EOF2 of 3 variables look similar, presenting two branches: the northwest branch over Sichuan province, with a high value belt; and southeast branch over Chongqing City. According to what dictated by the corresponding TS, the northwest branch is associated with high burden of variables in early autumn, mainly in September; in the later period, the high burden location moves into the southeast branch.

The first 7 AOD and LCC TS will be retained for CCA to explore the correlations between AOD and LCC for 3 different time lags: 0 day later, 1 day later and 2 days later. The heterogeneous correlations between first 3 canonical variate and other variate field in 3 different time lag were also plotted, and the correlations above 0.195 or down -0.195 are statistically significant at the 95% level. For “0 day later” time lag, the r<Y,a> and r<X,b> maps of CCA1 are similar to the EOF1 of LCC and EOF2 of AOD respectively. AOD over most Basin are high correlation with LCC: the high AOD, like in middle and eastern Basin, are positive correlation; the low AOD, from middle to western Basin, are negative correlation. That means that increasing AOD can enlarge LCC, the decreasing AOD can reduce LCC. The r<Y,a> map of CCA2 is similar to EOF2 of LCC. The regions of LCC along the diagonal between southeastern and northwestern of Basin, are strongly correlated with AOD in same region. The r<X,b> maps of CCA2 is the composition of AOD’s EOF2 and EOF4. The smaller sensitive region is similar the the northeast center in early autumn in AOD’s EOF4, and the bigger region like northwestern branch of AOD’s EOF2.

For “1 day later” or “2 days later” time lag, the CCA maps are similar to those for “0 day later” time lag, but the canonical correlation coefficients are all smaller. The square of sensitive regions shrink, even disappear at all. The influence of AOD over LCC have faded much after 1 day.

In general, the influence of AOD on LCC is strongest in same day, and both of highest and lowest LCC are susceptible to AOD. Due to that r<Y,a> map of CCA1 are all similar to LCC’s EOF1 for all 3 time lag, which LCC could be influenced by AOD mainly depends on LCC own climatology distribute. While r<X,b> maps for first 2 time lag are similar to AOD’s EOF2, hence, season cycle of high AOD burden locations changing is primary factor that influent LCC. Furthermore, in the regions along western diagonal southeastern-northwestern where AOD is often high, LCC is aways strong correlatted to AOD both in CCA1 and CCA2. That indicates the AOD over here often cause the change of local LCC.

The first 7 LCC’s and first 5 LSP’s TS were retained for CCA to explore the correlations between LCC and LSP for 3 different time lags. Only for “0 day later” time lag, the regional change of LCC can influent the local LSP. The r<Y,a> and r<X,b> maps of CCA1 for the time lag are similar to each other and to LCC’s EOF2: the sensitive regions are middle northern, western, southern and eastern basin, like the two branches of LCC’s EOF2. When LCC changes its center from western to eastern due to season cycle, local LSP changed correspondingly. The r<Y,a> map of the CCA2 is similar to LSP’s EOF2, and includes only one sensitive region over northwester. The r<X,b> map of the CCA2 looks like a deformed EOF2 of LCC: southeastern branch and north part of northwestern branch. The sensitive regions is over up-western Basin where LCC is not enough high. The correlations coefficients of CCA2 maps are same over entire research domain. That said, the adjustment of LCC on LSP is very slight, or it is long term climatic relationship.

Due to there is interact between AOD and LSP, and local LSP responds the regional change of LCC only in same day, the time lag used to analyze correlation between AOD and LSP is only “1 day later”. First 5 TS of AOD and LSP were used to conduct CCA. The r<Y,a> or r<X,b> maps of CCA1 are similar to LSP’s or AOD’s EOF2 respectively. Both of their sensitive regions are the northwestern branch in early autumn, and correlations between AOD and LSP over here are positive. The sensitive regions in r<Y,a> map of CCA2 are 2 centers, northeastern and southwestern. The r<X,b> map of CCA2 like the composition of AOD’s EOF3 and EOF4. There are 3 small sensitive regions in r<X,b> map: 2 over middle and northeast are positive correlation with LSP, one over northwest is negative correlation with LSP. The middle and northeast regions are similar to the northeast high burden region in middle autumn in AOD’s EOF3, while the northeast region is similar to the northeast center in early autumn in AOD’s EOF4. It’s clear that only high AOD is strong correlated to LSP, change of high AOD, like as spatial shift of high burden due to season cycle, can influence effectually LSP.

Since the so-called “effect of such possible spatial precipitation shift”, change of AOD mainly influent downwind (northwestern) LSP after 1 day, e. g. LSP’s sensitive region are more northwest than AOD’s and the downwind of AOD in CCA1 maps.

It’s no doubt there are strong correlations between AOD and LCC, and AOD and LSP in autumn in Sichuan Basin. Their r<X,b> maps are similar suggest AOD can influent LSP by changing LCC. More work will be done by follow to explore the machine impact of aerosol on precipitation in Sichuan Basin, like analysis of precipitation cases or numeric simulation study.

P1.18 Newly installed soil moisture monitoring network at middle and high elevation in Switzerland: setup and first results

Cécile Pellet *(University of Fribourg, Switzerland), Christian Hauck*

Soil moisture is a key factor controlling the energy and water exchange processes at the soil-atmosphere interface as well as the physical properties of the subsurface such as heat capacity, thermal conductivity, etc. In mountain environments it is a particularly crucial factor since it can affect the stability of slopes and modify the characteristics and behaviour of periglacial landforms. In 2010 soil moisture was classified as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS) and has thus to be continuously and globally monitored.

In spite of its importance, the technical challenges and its strong variability prevented the soil moisture from being measured operationally at high and/or middle altitudes. The newly launched SNF-project at the University Fribourg (SOMOMOUNT) intends to fill this data gap with the installation of soil moisture stations distributed along an altitudinal gradient between the Jura mountains and the Alps. Within the framework of this project, six entirely automated soil moisture stations were installed and four of them at location of already existing permafrost monitoring ones.

The standard instrumentation of each station comprises gravimetric soil sampling and the installation of Frequency Domain Reflectometry (FDR) and Time Domain Reflectometry (TDR) sensors for long term monitoring. Additionally, repeated geophysical surveys as well as spatial FDR (S-FDR) measurements were performed in the vicinity to assess the spatial distribution of soil moisture. Finally the data collection is completed with meteorological data available at all sites either from official MeteoSwiss weather stations or from PERMOS (permafrost monitoring of Switzerland) ones. The instrumentation as well as the network set up (measurement interval, calibration process, data processing, etc.) was designed to be compatible with SwissSMEX, which monitors soil moisture at low elevation throughout Switzerland (Mittelbach et al., 2011).

In this contribution we will present a detailed description of the SOMOMOUNT soil moisture station's instrumentation, monitoring strategies and calibration procedures. Additionally the data collected during the two first years of the project will be reviewed and discussed in relation to their altitudinal distribution. Clear differences in soil moisture patterns are visible between sites and can be related to several factors such as the thermal regime of the ground (frozen versus unfrozen conditions), the subsurface composition (organic versus mineral), the elevation, the topography, etc.

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P1.19 Soil water content distribution and influence on the thermal regime of the permanently frozen ground at Schilthorn (Swiss Alps)

Cécile Pellet *(University of Fribourg, Switzerland), Adrian Wicki, Christin Hilbich, Christian Hauck*

Soil moisture is a key factor controlling the energy and mass exchange processes at the soil-atmosphere interface. In permanently frozen ground it strongly affects the thermal behaviour of the ground by influencing its physical properties such as ice content, thermal conductivity and heat capacity. It also influences other processes like evaporation, infiltration, refreezing rate, runoff and modifies the electrical and electromagnetic properties such as electrical conductivity and permittivity that are used in indirect geophysical and remote sensing methods.

In mountainous terrains the spatial variability of the substrate and therefore variable soil moisture can lead to differences in ground temperature even at small spatial scale. At the Schilthorn permafrost monitoring station in the Swiss Alps, two boreholes installed 15m apart exhibit significantly different thermal behaviour in the uppermost meters of the ground.The analysis of repeated Electrical Resistivity Tomography (ERT) measurements in the vicinity suggests that difference in soil moisture is the main explanatory factor (Hilbich et al., 2011).

In this contribution we first assessed the overall spatial variability of soil moisture at the Schilthorn using several spatially distributed ERT profile lines around the boreholes as well as the 16-year long time series from the ERT monitoring system. Additionally, in-situ soil moisture sensors installed at several locations near the boreholes were used to calibrate a well-known electrical mixing rule called Archie's law to enable the calculation of water contents from the measured apparent resistivity data.

In a second step, the one dimensional coupled heat and mass transfer model COUP (Jansson, 2012) was used to model the soil columns at the location of each borehole using the available temperature and measured soil moisture data for calibration/validation. Finally, sensitivity experiments were performed to test the response of the thermal regime to soil moisture variation in permanently frozen terrain. The work presented here is part of the SNSF-project SOMOMOUNT, which among others aims at installing an operational soil moisture monitoring network at high elevation in Switzerland and understanding its influence on the thermal regime of seasonally and permanently frozen ground.

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P1.20 Thermally-driven circulation and convection over a mountainous tropical island

Chun-Chih Wang *(McGill University, Canada), Daniel J. Kirshbaum*

Observational data from the 2011 Dominica Experiment (DOMEX) and cloud-resolving numerical simulations are exploited to gain a better understanding of controlling parameters of thermally-driven convection over a mountainous tropical island. A "golden" case from DOMEX with a clear diurnal cycle in cumulus convection and quasi-steady large-scale conditions is studied using observations and cloud-resolving numerical simulations. The simulations are quasi-idealized in that they use full model physics and the real Dominica terrain, along with a horizontally homogeneous initial flow based on a single observed sounding. Simulations at different grid resolutions reveal that large-eddy resolution (~100 m) provides the most accurate representation of the in-situ measurements from DOMEX and the radar-derived island precipitation. However, regardless of grid resolution, the simulations robustly under-predict the island diurnal cycle and over-predict the precipitation, which stem from biases in land-surface and subgrid microphysics parameterizations. Sensitivity tests reveal the importance of key factors including island terrain height, land-surface type, cloud-radiative feedbacks, moist stability, and background wind velocity in controlling the thermally-driven convection.

P1.21 Interaction of a sea breeze and a moist convection over the northeastern Adriatic coast: an analysis of the sensitivity experiments using the high-resolution mesoscale model

Gabrijela Poljak, ***Maja Telišman Prtenjak*** *(University of Zagreb, Croatia), Marko Kvakić, Kristina Šariri, Željko Večenaj*

The study investigates the sensitivity of the high-resolution mesoscale atmospheric model in the model reproduction of the combined large-scale wind and thermally induced local wind (i.e. sea breeze) on the moist convection development. The area of the interest is Istria, the largest peninsula in the north-eastern Adriatic. The three chosen cases were simulated by the Weather and Research Forecasting (WRF-ARW) model at three (nested) model domains, where the innermost domain involved 1.5 km horizontal grid spacing. The sensitivity tests were accomplished by modifying: (i) the model setup, (ii) the sea surface temperature (SST) distribution and (iii) the model topography. The first set of the simulations (over the 3 summer 1.5-day periods) were carried out through the modification of the model setup, varying microphysics and the boundary layer parameterizations. The SST distribution has two representations in the model: a weakly time-varying SST field (every 6 h) from the ECMWF skin temperature analysis and a varying SST field provided by hourly geostationary satellite data. The same events were simulated with the modified topography where the mountain heights in Istria were reduced to 30% of the initial height.

A comprehensive set of the numerical experiments was statistically analyzed in a several ways: by the standard statistical measures, the image moment analysis approach and the spectral method. The results of the each model setup were compared with available measurements, which were provided by the standard station and radar measurements and each of these approaches showed optimal combination of the model schemes. The SST variations revealed the effect on the boundary layer and on the evolution of the turbulent fluxes, sea breeze cells and cumulonimbus clouds. The modified topography exposed variations in the origin, timing and the amount of the convective activity as well as on the sea breeze evolution and its dimensions.

P1.22 The impact of downslope winds and the urban heat island on fog formation over the Zagreb area

Maja Telišman Prtenjak *(University of Zagreb, Croatia), Martin Klaić, Joan Cuxart, Marko Kvakić, Karmen Babić, Darko Koračin, Amela Jeričević*

This study investigates fog development over a wider Zagreb area. According to the climatological data, haze and fog occur frequently over the Zagreb-airport area and cause severely low visibility that can last for several days. Zagreb airport is located in a flat terrain south of Zagreb near the Sava river at a height of 108 m above sea level (asl). To the north, the city of Zagreb (~120 m asl) is a main source of urban pollution including condensation nuclei. There are heavy traffic roads around the airport which also generate pollutants. North of Zagreb, the Medvednica mountain rises up to 1000 m asl in a relatively short distance of about 10 km, with a very well defined downslope forest area.

We focus on a case study of a long-lasting fog event that took place during 6-8 November 2013 to understand of the dynamic processes of fog development and fog persistence. The selected case was analyzed by means of available measurements and numerical simulations performed by the WRF-ARW high-resolution numerical model in several model setups. The model was able to reproduce this fog event with small differences among the various model runs. The results revealed the roles of: (i) the downslope wind which usually occurred over city when the net radiation over the Medvednica slopes becomes negative and (ii) the effect of urban Zagreb area which adds pollution to the downslope flow and consequently decreases fog duration over the city. The effect of the downslope flow was not apparent in the surface layer over the airport because it occurred above the thermal inversion contributing to the fog persistence. The influence of the Sava river has been also estimated and discussed. This comprised an additional calculation of backward trajectories and simulations of the water vapor dispersion (a passive scalar in the atmosphere) by the FLEXPART Lagrangian particle dispersion model driven by the WRF output.

P1.23 Slope and valley flows at the Cerdanya valley in the Pyrenees

Daniel Martínez-Villagrasa *(University of the Balearic Islands, Spain), Laura Conangla, Davidde Tabarelli, Maria A. Jiménez, Josep R. Miró, Dino Zardi, Joan Cuxart*

The Pyrenees are a mountain range running in the east-west direction. Most of their valleys are oriented in the north-south direction on both sides of the range. A significant exception is the Cerdanya valley, in Catalonia, which is a graben with NE-SW orientation , roughly 35 km long and 15 km wide with the bottom about 1000 m asl, surrounded by the main axis of the Pyrenees at the north (peaks above 2900 m asl) and by the Cadi range at the south (maximum high 2648 m asl). The valley bottom is covered essentially by pastures, whereas the slopes at its southern side are very steep and covered by forests of conifers, and the slope at the northern side consists mainly of pastures with trees at the bottom of the valleys, less steep than the southern side and with longer river valleys in the N-S direction.

This area is very dynamic in an economical sense: divided between Spain and France, it includes many ski stations, and the valley is a major touristic spot, even in summertime. In the valley center, at the municipality of Das, there is a private aerodrome where an official weather station has been very recently supplemented with a full energy budget station and a Windrass by the Meteorological Service of Catalonia.

For this reason, in order to get a preliminary characterization of local circulations in view of future experimental campaigns, a study of the recently available data was performed and is presented here. These data originate from seven meteorological stations, at different heights, belonging to the meteorological services of France, Spain and Catalonia. The analysis covers the period 1/9/2010-31/8/2014. Conditional filtering allowed to isolate the cases when local circulations prevail and to provide a first explanation of the valley and slope flows as seen by the statistics at the surface level. A particular case, which occurred on 1-4 October 2011, was selected for a more detailed study, since at this time of the year there is no snow over the mountains and the diurnal temperature range is very large, usually above 20°C, with similar duration of daytime and nighttime. An episode of 4 days has been studied, combining meteorological data, satellite information and a high-resolution simulation for the valley, and the preliminary results are shown. This analysis describes the valley and slope wind circulations generated by the local topography, as well as the accumulation of cold air over the valley bottom at night, favouring the establishment of a strong surface inversion of temperature.

P1.24 Revisiting Albert Defant's (1909) seminal paper "Mountain and valley winds in South Tyrol" - A tribute to a pioneering contribution in mountain meteorology

*Dino Zardi, Massimiliano De Franceschi, **Lavinia Laiti** (University of Trento, Italy), Lorenzo Giovannini*

Albert Defant (Trento 1884 - Innsbruck 1974) is nowadays best known as a pioneer in modern oceanography (Siedler 2007). However, at an early stage of his scientific career - after the doctoral degree in meteorology at the University of Innsbruck, Institute for Cosmic Physics in 1906 - his interests focused on the dynamics of lakes and on mountain winds. In particular, after studying the periodic seiches of Lake Garda, he investigated the diurnal thermally-driven winds developing in the valleys of the South Tyrol region, blowing from the Po Plain towards the Alps, and their influence on the oscillations of the lake water level. In his work Defant carefully calculated the pressure gradients between the Po Plain and Bolzano in the Adige Valley on a seasonal basis, performing a harmonic analysis of their diurnal cycles to evaluate amplitude and phase, i.e. intensity and time of onset and offset of the local valley winds. Special attention was paid to the Ora del Garda circulation, which blows over the northern edge of Lake Garda, also thanks to the analysis of lymnograms taken at the northern shoreline of the lake. On the basis of pressure and temperature diurnal cycles, Defant also proposed a first explanation of the differential heating mechanisms associated with mountain and valley winds, including slope winds as a factor determining the production of along-valley temperature and pressure gradients. Moreover, he also described the wind observations collected at six stations, discussing the wind patterns characterizing the Sarca and Adige valleys. The analysis of daily periodic winds developing in the area of Lake Garda has been further pursued in recent years, on the basis of nowadays available approaches, thus leading to new findings. Therefore in the present work we revisit Defant's work in the light of more recent investigations and results on the subject.

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P1.25 A climatological analysis of diurnal winds in the Adige valley in the Alps

***Lorenzo Giovannini** (University of Trento, Italy), Lavinia Laiti, Stefano Serafin, Dino Zardi*

The Adige Valley is one of the main corridors connecting the Po Plain with the inner Alps. It displays a gradually sloping floor along the 150 km path connecting the valley outlet into the plain, near the city of Verona (91 m AMSL), to the upper valley at Merano (330 m AMSL).

Several weather stations are operated along the Adige Valley, providing regular measurements of the main atmospheric variables, such as air temperature, atmospheric pressure, wind speed and direction. A climatological analysis was performed on time series of these data for the years 2009-2014, based on a selection, by means of objective criteria, of days in which favorable weather conditions allowed a full development of valley winds.

Mean daily cycles of along-valley wind speed were evaluated at each station in the valley. Although amplitude and phase of local wind strength turn out to be strongly affected by local topography and land cover, the typical cycle of diurnal up-valley winds - peaking in the afternoon - and nocturnal down-valley winds - weaker but persisting throughout the night - is clearly observed at all the stations. This daily wind cycle is associated with a corresponding cycle of horizontal pressure distribution, as shown by the mean daily oscillation of surface-level pressure at the stations along the valley, from the plain (Verona) to the upper valley (Merano). The amplitude of the surface pressure cycle displays an increase in up-valley direction, with the smallest value in Verona and the largest in Merano, causing a daily periodic reversal of the pressure gradient. However this behavior is locally altered by geometrical irregularities of the valley, which presents narrower and wider parts, and by the presence of some major urban areas, which affect the temperature field in the lower atmospheric layers, especially during nighttime. As a consequence, close to urban areas a pressure counter-gradient may occur, causing a wind convergence over the city center during nighttime.

P1.26 Evaluation of the climatological wind speed simulated by the WRF model over complex terrain

Lorenzo Giovannini *(University of Trento, Italy), Gianluca Antonacci, Dino Zardi, Lavinia Laiti, Luca Panziera*

Wind speed over complex terrain is strongly influenced by mechanical and thermal local effects induced by the topography, which make the wind field strongly variable in both space and time. For this reason the simulation of wind speed over complex terrain with numerical meteorological models is still not an easy task, which requires adequately fine spatial resolutions to be reached in order to properly capture the spatial variability of the wind field. On the other hand, good simulations of the climatological wind speed can be potentially utilized to estimate the wind energy production, in substitution of long and expensive field campaigns.

The objective of this work is the assessment of the ability of the WRF model to reproduce the climatological wind speed over complex terrain. In particular the study evaluates how complex terrain influences the performance of the model. Moreover the benefits of using four dimensional data assimilation (FDDA) are highlighted.

Simulations with the WRF model are run for a ten-year-long period over the Trentino region, in the Italian Alps. Four one-way nested domains are used down to a resolution of 1.2 km. The simulations take advantage of FDDA of both quality-checked surface observations and radiosoundings, to better capture local processes as well as synoptic events. Radiosoundings data are assimilated in the three outer domains, while wind observations from surface weather stations are assimilated in the inner domain. Model results are validated against independent data from surface weather stations, not assimilated by the model. In particular, the validation focuses on the comparison between observed and simulated wind probability density functions (PDFs).

The comparison between model results and observations from surface weather stations highlights that the WRF model, with the setup adopted in this work (including the FDDA), is generally able to capture the main characteristics of the observed wind PDFs. In particular the model is able to simulate with good accuracy the development of thermally-driven winds in the warm season. However, larger errors are found in areas with particularly complex terrain, where orographic features are not well resolved by the model.

The results of this work demonstrate that the WRF model is a suitable tool to evaluate the climatological wind speed over complex terrain. Accordingly, results from WRF simulations can be used to identify potential locations for the installation of wind-energy farms.

P1.27 Influence of along-valley terrain heterogeneity on exchange processes over idealized valleys

Johannes S. Wagner *(Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany), Alexander Gohm, Mathias W. Rotach*

Idealized numerical simulations of thermally driven flows over various valley-plain topographies are performed under daytime conditions. Valley floor inclination and narrowing valley cross sections are systematically varied to study the influence of along-valley terrain heterogeneity on the developing boundary layer structure, as well as horizontal and vertical transport processes. Valley topographies with inclined valley floors of 0.86° increase

upvalley winds by about 100% due to smaller valley volumes (volume effect) and by about 62% due to additional upslope buoyancy forces. Narrowing the valley cross section by 20 km per 100 km along-valley distance increases upvalley winds by about 75%. Vertical mass fluxes out of the valley are strongly increased by about 57 to 84% by narrowing the valley cross sections and by 22 to 32% by reducing the valley volume (e.g., by inclining the valley floor). Trajectory analysis shows intensified horizontal transport of parcels from the foreland into the valley within the boundary layer in cases with inclined floors and narrowing cross sections due to increased upvalley winds.

P1.28 The impact of embedded valleys on daytime pollution transport over a mountain range

Moritz N. Lang *(University of Innsbruck, Austria), Alexander Gohm, Johannes S. Wagner*

Idealized large-eddy simulations were performed to investigate the impact of different mountain geometries on daytime pollution transport by thermally driven winds. The main objective was to determine interactions between plain-to-mountain and slope wind systems, and their influence on the pollution distribution over complex terrain. For this purpose, tracer analyses were conducted over a quasi-two-dimensional mountain range with embedded valleys and a flat foreland in cross-mountain direction. The valley depth was varied systematically. It was found that different flow regimes develop dependent on the valley floor height. In the case of elevated valley floors, the plain-to-mountain wind descends into the potentially warmer valley and replaces the opposing upslope wind. This superimposed plain-to-mountain wind increases the pollution transport towards the main ridge by additional 20% compared to the regime with a deep valley. Due to mountain and advective venting, the vertical exchange is 3.6 times higher over complex terrain than over a flat plain.

P1.29 Model simulations of inversion buildup and cold-air outflow in a small Alpine sinkhole

Manuela Lehner *(University of Utah, United States of America), C. David Whiteman, Manfred Dorninger*

The Grünloch basin is a small, approximately 1-km wide and 150-m deep sinkhole on the Hetzkogel Plateau in the eastern Alps of Austria. Previous measurements collected in the Grünloch found extreme wintertime minimum temperatures and a frequent occurrence of strong nocturnal basin inversions, which are embedded within the larger-scale inversion over the Hetzkogel Plateau. The strongest part of the basin inversions is typically confined to the lowest approximately 50 m above the basin floor, below the height of the Lechner saddle that connects the Grünloch basin with the Lechner gorge to the northwest. A flow through this gap in the topography was noticed suggesting an outflow of cold air on top of the inversion layer. We use a numerical model to simulate the cold-air buildup in the basin, comparing the modeled temperature structure with observational data. The model output is then used to characterize the vertical and spatial structure and the timing of the cold-air outflow and its effects on the basin inversion. Calculating horizontal pressure gradients and mass budgets, we look at the forcing of the outflow and the origin of the air that leaves the basin over the saddle.

P1.30 Global climate change and extreme low temperatures in a sinkhole – a simple relationship?

Manfred Dorninger *(University of Vienna, Austria), Benedikt Bica*

The 150-m-deep Grünloch basin (1270 m MSL) in the eastern Austrian Alps is known for having recorded the lowest temperatures in Central Europe (-52.6°C in February 1932). In 14 consecutive winters between 1928 and 1942, the overnight temperature minima dropped at least eight times below -50°C.

In 2001 we started again to measure winter temperatures in the basin and since 2004 continuous measurement are being made throughout the whole year, thus giving again a data set of 14 years. Within these 14 consecutive winters the minimum temperature never dropped below -50°C - a typical sign for climate change?

One of the major parameters to reach extreme low winter temperatures is, besides clear sky conditions, calm winds and a deep snowpack, the prevailing air mass. The Sonnblick observatory (Salzburg, Austria, 3106 m MSL) provides one of the longest time series in the Alpine region, with climate observations ranging back as far as 1886. From Sonnblick observatory, a comprehensive set of observations of the free atmosphere is available for the thirties of the last century down to the present day.

Correlations of the overnight Grünloch temperature minima and air mass properties as derived from the Sonnblick data results in correlation coefficients higher than 0.8.

In the presentation we will oppose the historic and the newer data set, describe the change in correlation and discuss the question if climate change can explain all the changes in the overnight temperature records in the basin.

P1.31 A case study of cold air pool evolution in hilly terrain using field measurements

Bradley Jemmett-Smith, ***Andrew N Ross*** *(University of Leeds, United Kingdom), Peter Sheridan, John Hughes, Simon Vosper*

A case study investigation of cold air pool (CAP) evolution in hilly terrain is conducted using field measurements made during IOP 16 of the COLd air Pool EXperiment (COLPEX). COLPEX was designed to study cold air pooling in small scale valleys typical of the UK (~100-200m deep, ~1km wide). Despite their relatively small size, such valleys can exhibit temperatures up to 10degC colder than surrounding hilltops during strong CAP events with a large impact on local road icing and fog formation. The synoptic conditions during IOP 16 are indicative of those required for CAPs to form during the night with high pressure, clear skies and low ambient winds. Initially a CAP forms around sunset then grows uninterrupted for several hours. However, some 4hrs after sunset this pattern changes with the CAP and drainage flows being disturbed intermittently – but not eroded – for the remainder of the night. Three episodes are highlighted using LIDAR measurements and the cause of disruption attributed to; (1) gravity wave activity, (2) rapid increases in the ambient wind, (3) the development of a nocturnal low level jet (NLLJ). A weakly stable residual layer provides the conditions for gravity wave activity during Episode 1, which is eroded by a developing NLLJ from top down during Episode 2. The sustained increase in winds at hill top levels, caused by the NLLJ, continue to disrupt the CAP through Episode 3. The NLLJ may play a role in CAP breakup, which occurs ~3.5 h after local sunrise. This case study highlights how even in apparently ideal conditions for CAPs to form, a number of meteorological phenomena can disrupt the CAP evolution. These processes are unlikely to be sufficiently represented by current operational weather forecast models, therefore, highlighting the need to further investigate nocturnal boundary-layer evolution and related phenomena with a view to improve their representation in weather prediction models.

P1.32 Observations of radiative cooling and heating under clear sky and fog conditions

Sebastian W. Hoch *(University of Utah, United States of America), E. R. Pardyjak*

The contribution of radiative heating and cooling to the total cooling in the lowest ten meters of the atmosphere was investigated during clear and foggy nights in connection with the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program. Carefully calibrated up- and downfacing pyrgeometers were mounted at two heights above the surface (approximately 2 and 8 m) on meteorological towers and nearby sawhorse-type structures. Two sites, one on the floor of the Salt Lake Valley, the other on the floor of a smaller, high-elevation valley in Heber, Utah, were instrumented. Radiative heating (radiative flux convergence) and cooling rates (radiative flux divergence) are calculated from the differences in the incoming, outgoing and net longwave fluxes. Initial results from the 2014-2015 winter campaign will be reported, and the magnitude of radiative heating and cooling will be related to sky condition, ground cover (grass or snow) and the formation and development of fog.

P1.33 Forecasting ice formation on roads: Application of a nocturnal cooling model to road surface temperatures for minima prediction in the Adige Valley (Trentino, Italy)

Claudia Di Napoli *(Autonomous Province of Trento, Italy), Andrea Piazza, Roberto Apolloni, Ilaria Pretto*

Forecasting minimum temperatures for road surfaces is crucial in the management of salt as de-icing substance during winter road maintenance operations [1]. It is well known from literature that ice forms on road pavements when surface temperatures are below 0°C and are lower than dew point temperatures. If this condition occurs, i.e. the humidity content in the air above the road is sufficiently high, predicted temperatures below -1°C or -2°C might cause ice formation on roads, leading to potentially dangerous conditions for drivers. Spreading de-icers such as sodium chloride to prevent icy roads is nowadays common practice but an excessive, uncontrolled use might be hazardous for the environment and cost-demanding for local road maintenance agencies [1].

Have a good forecast for road temperatures is therefore imperative. For this reason we have implemented an automatic system based on Reuter's nocturnal cooling model. Originally developed for frost forecasts on agricultural grounds, Reuter's model predicts minimum ground temperatures as a function of ground temperatures at sunset and the time passed since then [2]. We have applied this forecast system to road surface temperatures measured by road weather information system (RWIS) stations installed on a test route along the Adige Valley (Trentino, Italy). In this presentation we show and discuss some preliminary results for the 2014-2015 winter season. Using a contingency table approach, skill scores have been evaluated for forecast verification and temperature thresholds correspondingly estimated. The importance of these critical parameters is discussed within an operational context, i.e. for the planning, management and minimization of ice-related effects by road maintenance decision makers.

This study is funded by the EU/LIFE+ project CLEAN-ROADS. Through a cross-disciplinary approach, the project aims to assess the environmental impact of salt de-icers used for winter road maintenance activities in Trentino mountainous region.

[1] Pretto I. et al., SIRWEC 2014 conference proceedings, ID:0019 (2014)

[2] Reuter H., Tellus, 3:141–147 (1951)

P1.34 Topoclimatological investigation of surface inversions over complex terrain

Klemens Stemberger *(University of Vienna, Austria), Reinhold Steinacker*

This study focuses on the establishment of a robust relation between night time surface inversion formation and topographic features like slope angles, concavity or convexity and elevation variations, land type, etc. at different scales. For that purpose observed surface temperatures and additionally temperature data from ERA Interim at several pressure levels have been used to obtain a statistic of inversion strength at each surface station location in Austria. The correlation between inversion strength and the topographic and land type characteristics is used, to estimate the inversion strength on a fine grid along the topography in the whole Alpine region for each season. This high resolution patterns are used as "fingerprints" for the downscaling procedure of surface temperature fields with the VERA (Vienna Enhanced Resolution Analysis) scheme. Some results and improvements of the methodology will be shown and discussed.

P1.35 Nocturnal winds in joining shallow valleys of different sizes – Observational and numerical studies based on the field experiment KASCADE

Gert-Jan Duine *(University of Toulouse, France), Pierre Roubin, Thierry Hedde, Pierre Durand*

Nocturnal valley winds in South-Eastern France have been studied by means of observations and numerical simulations.

The field measurement campaign KASCADE (KAtabatic winds and Stability over CAdarache for Dispersion of Effluents) has been conducted during the winter of 2013 and revealed the frequent occurrences of downslope winds during stable stratification periods in two cross-oriented valleys with gentle slopes, the Durance valley (DV) and its smaller side valley, the Cadarache valley (CV). The valleys are embedded in a region susceptible to stable stratification periods during which the orography modifies the flow and the ensuing impact of potential pollutants released to the surroundings of Cadarache, a research centre of the Commissariat à l’Energie Atomique (CEA). On the observational part, it has been shown that the two valley winds behave differently in terms of timing (onset and cessation), flow depth and wind strength.

It is found that the thermally driven flow within the CV sets in just after sunset, and ceases about two hours after sunrise, and, according to above-valley wind conditions, extends over a depth of 50 m or so. The occurrence of the drainage CV-wind has been related to a threshold on the vertical temperature-gradient observed on a permanent tower.

The DV-wind depends on larger scales and due to the complexity of the regional orography, the timing for its onset and cessation at the Cadarache-site is more difficult to establish. Possible governing factors for the DV-wind onset are drainage from the Durance valley itself, the Southern Alps and a sloping plateau on the east bank of the valley. Generally, the wind arrives with a delay of 6 – 9 hours after sunset at the Cadarache-site and ceases with an approximate delay of 4 to 5 hours after sunrise. The valley wind depth can be related to the valley height, although deeper DV-winds have been observed occasionally. Generally, the low level jets are at around 175 – 225 m.

Numerical simulations with the WRF-ARW model at 1 km resolution have proven successful to capture the timing and depth of the DV wind. Modeling of the CV-wind however is currently out of reach with such a resolution, due to the valley small size. The most prominent results of observational and modelling studies are detailed in the presentation.

This work is in the frame of the PhD-thesis entitled “Dispersion of pollutants in stable boundary layer conditions in the middle valley of the Durance”, financed by the CEA (MRISQ project) and jointly supervised by CEA and Laboratoire d’Aérologie (LA), Toulouse. It takes place in a wider context of R & D work performed at CEA to characterize the site specific atmospheric conditions, with a view to improve the knowledge of the impact of the potential release of pollutants.

P1.36 The Passy-2015 field experiment: An overview of the campaign and preliminary results

Alexandre Paci *(Meteo-France & CNRS, France), Chantal Staquet, Julie Allard, Gabriele Arduini, Hélène Barral, Sébastien Barrau, Manuel Barret, Joel Barrié, Anne Belleudy, Sébastien Blein, Thierry Bourrianne, Gilles Bouhours, Christophe Brun, Frédéric Burnet, Guylaine Canut, Didier Chapuis, Charles Chemel, Florie Chevrier, Jean-Martial Cohard, Alain Dabas, Jean-Marie Donier, Thierry Douffet, Jean-Michel Etcheberry, Rémi Guillot, Hélène Guyard, Jean-Luc Jaffrezo, Yann Largeron, Olivier Garrouste, Dominique Legain, Pauline Martinet, Griša Mocnik, Eric Moulin, Isabel Peinke, Bruno Piguet, Julian-Andres Quimbayo-Duarte, William Maurel, Marie Mazoyer, Stéphane Mercier, Jean-Emmanuel Sicart, Delphine Six, Quentin Rodier, David Suquia, Florence Troude, Diane Tzanos, Isabella Zin*

Wintertime anticyclonic conditions lead to the formation of stable boundary layers which may induce severe air pollution episodes in urban or industrialized area, particularly in mountain regions. In the Arve Valley near Chamonix, the area of Passy is very sensitive to this phenomenon. This place is indeed one of the worst place in France regarding air quality, the concentration of fine particles and Benzo(a)pyrene (a carcinogenic organic compound) regularly exceeding the EU legal admissible level during winter.

Besides air quality measurements, such as the ones presently carried in the area by the local air quality agency Air Rhones-Alpes or in the DECOMBIO project led by LGGE, it is very important to improve our knowledge of the atmospheric dynamics and processes at the valley scale under these stable conditions in order to improve our understanding on how it drives pollutant dispersion.

These issues motivated the Passy-2015 field experiment which took place during the winter 2014-2015 in the Northern Alps in the Arve Valley around Passy. A relatively large set-up of instruments was deployed on a main measurement site in the valley center and four other satellite sites. It includes several remote sensing instruments, a surface flux station, a 10 m instrumented tower, a large aperture scintillometer, a fog monitoring station. Most of the instruments were present from early January to the end of February. During two intensive observation periods, 6-14 February and 17-20 February, the instrumental set-up was completed on the main site with high frequency radio-soundings (up to one per 1h30), a tethered balloon, a remote controlled drone quadcopter and a sodar.

The field campaign, the instruments, the meteorological situations observed and preliminary results complementary to those reported in the Staquet, Paci et al. companion paper will be presented.

This field experiment is part of the Passy project funded by LEFE/ADEME and Meteo-France. The project involves teams from LEGI, CNRM-GAME, LGGE, Air Rhones-Alpes, LTHE and NCAS. The field experiment was led by CNRM-GAME while LEGI is the principal investigator of the LEFE project. See the ICAM 2015 companion paper by Staquet, Paci et al. for more details on the project.

P1.37 Observing Spatial and Temporal Variations in Air Quality in the Salt Lake Valley Using a Light Rail Vehicle Platform

Erik Crosman *(University of Utah, United States of America), Logan Mitchell, John Horel, John Lin, Alex Jacques*

Light rail electric vehicles are an advantageous measurement platform because they have no in-situ fossil fuel emissions and provide repeated and automated transects through an urban corridor. A light rail vehicle instrumented with meteorological and air quality measurement capabilities was recently installed in Utah's Salt Lake Valley. The primary goal of this project is to provide improved understanding of the spatial and temporal characteristics of greenhouse gases and primary pollutants–particulate matter and ozone–within the Valley. This platform also allows us to examine the effects of thermally- and terrain-driven flows on spatial and temporal variations in pollutants. Preliminary case studies showing the impact of lake breezes, canyon and slope flows, terrain-channeled flows, and boundary-layer depth on the spatiotemporal evolution of pollutants within the Salt Lake Valley will be presented.

P1.38 PANDONIA: ESA Ground-Based Air-Quality and Satellite Validation Network

Martin Tiefengraber *(University of Innsbruck, Austria), Alexander Cede*

In preparation of validation activities for ESA's Sentinel 5 precursor and EarthCARE missions (both to be launched in 2016) gaps in current and expected validation infrastructure have been identified. Currently, there is no standardized measurement and processing system in Europe capable of providing a homogeneous validation dataset for tropospheric air-quality, aerosol and cloud products retrieved from these missions. PANDONIA will close these gaps being a homogenous ground-based remote sensing network ready for monitoring trace gas amounts and aerosol properties. Counteracting the intrinsic difference in the field of view between satellite and ground data, the network will be designed to provide long time series in many locations (strong statistics) by employing cost efficient (quasi-)autonomous instrumentation. The main network instrument, the Pandora-2S, will be a modified, two spectrometer version of the established Pandora instrument. Full direct sun/moon irradiance and sky radiance observation capabilities will provide both independent vertical column amounts and profile information. The major data products delivered by the network will be total O3, total NO2, their separation in a stratospheric and tropospheric column, as well as spectral aerosol optical depth over the UV, visible and short-wave infrared region. Centralized data processing and instrument performance control are geared towards data product availability in near real time. The publicly accessible PANDONIA web portal will offer the data including visualizations and satellite validation results.

P1.39 Influence of an Idealized Valley on the Carbon Budget

Matthias Reif *(University of Innsbruck, Austria), Mathias W. Rotach, Georg Wohlfahrt, Alexander Gohm*

In this project we investigate the effect of complex topography on land-atmosphere exchange of carbon dioxide (CO2). On a global scale the budget of CO2 bears the largest uncertainty in terrestrial exchange processes, which are commonly calculated as the residual from the better known contributions in the budget equation, i.e. concentration increase (atmospheric reservoir), oceanic uptake, anthropogenic fossil fuel emissions and land use changes. The hypothesis is that, on the meso-scale, topography adds additional atmospheric mechanisms that modify the biospheric exchange of CO2 at the surface.

The effect of complex topography on the CO2 budget is studied using the atmospheric numerical model Weather Research and Forecasting with an additional chemistry package (WRF-Chem) coupled to the photosynthesis from the Community Land Model (CLM) while a simple parametrization for respiration is added. A 20 km wide idealized sine shaped valley run at 1km horizontal resolution is compared to a simulation over a plain surface using the identical model to imitate a coarse global model which is not able to resolve fine scale topography. The model set-up is taken equally to idealized valley circulation simulations in the literature and thus reproduces what is currently state of the art in this respect. The differences of moisture and temperature induced by valley circulations determines the intensity of carbon flux by the plants.

The so called topography CO2 effect is calculated as the difference between the mean CO2 exchange through the surface of the valley and the flat domain for one day, respectively. On average, for one day the valley concentrations are on the order of 5% (of the total plant CO2 sink) lower than over the plain, hence the valley acts as a CO2 sink in this ensemble of model runs. However, in this set-up systematic variation of initial conditions show that the sign and magnitude of the CO2 exchange are mainly dependent on the CLM plant functional type, the initial temperature, the initial relative humidity, the ambient CO2 concentration, the latitude and the area height distribution of the topography.

P1.40 On the combined impact of boundary layer height, near-surface meteorological conditions and nocturnal CO concentration on CO diurnal cycle patterns at a low mountaintop site: A case study using simultaneous lidar and in-situ observations

Sandip Pal, Temple R. Lee, ***Stephan F. J. De Wekker*** *(University of Virginia, United States of America)*

Evaluation of trace gas measurements over mountaintop sites and their application in inverse transport models to estimate regional scale fluxes are oftentimes challenging and not straightforward due to unusual and complicated influences associated with atmospheric transport. In mountainous regions, terrain-induced atmospheric processes can modulate the diurnal cycle patterns of trace gas mixing ratios. For instance, flows along the valley and slopes are generated on regular basis due to horizontal temperature gradients arising from heating and cooling of valley atmospheres and the atmosphere adjacent to sloping terrain. These flows are directed upvalley and upslope during the daytime and downvalley and downslope at night.

We hypothesize that the patterns and features of the diurnal cycles of CO at low mountaintops such as Pinnacles depend on the nocturnal CO concentrations at the site before the arrival of adjacent valley air due to upslope flow and onset of convective boundary layer (CBL) development at the mountaintop. Later, the pattern of CO diurnal cycle is influenced by near-surface thermodynamics and boundary layer height evolution. We use simultaneous measurements of lidar-derived atmospheric boundary layer (ABL) height, standard meteorological variables, and CO concentration at Pinnacles, a mountaintop monitoring site in the Appalachian Mountains to investigate the CO concentration variability during and after the morning transition period till late afternoon due to: (1) two different CBL development regimes (shallow and deep) over the mountaintop, (2) impact of CBL growth rate during the morning transition period, (3) combined effect of deep CBL with and without diurnal wind shift often observed at the site on clear sky days, (4) nocturnal CO concentrations.

To this end, we discuss two different scenarios: (1) a diurnal cycle of CO concentrations, starting to increase in the morning and peaking in the afternoon, in agreement with previous studies, and (2) a diurnal cycle, starting to decrease in the morning with a minimum in the late afternoon, similar to the CO variability observed atop tall towers in flat terrain. The high resolution time series of the lidar-derived ABL depths illustrate the ABL regimes present over the site. In both cases, we find that the CO concentration in the morning, before the CBL air reaches the ridge top, plays an important (and decisive) role modulating the CO concentration variability during the remaining (or at least major) part of the entire diurnal cycle. These findings help develop a conceptual framework that could explain and differentiate the two regimes in the CO concentration variability over a ridge top site affected by upslope flows and provide new roadmaps for monitoring and assimilating mountaintop CO measurements in transport models.

P1.41 The impact of the planetary boundary layer height on the diurnal variability and representativeness of CO mixing ratios at a low mountaintop in the Appalachian Mountains.

Temple R. Lee, Sandip Pal, ***Stephan F. J. De Wekker*** *(University of Virginia, United States of America)*

Trace gas mixing ratios measured at mountaintops are oftentimes assumed to represent background values, but are sometimes affected by air within the valley planetary boundary layer (PBL). In particular, the height of the afternoon PBL relative to the ridgetop is important for investigating the influence of valley PBL air on mountaintop trace gas mixing ratios. In the present study, we investigate the impact of the afternoon PBL height over the adjacent valley on 1) the diurnal variability of trace gas mixing ratios at a nearby mountaintop and 2) the degree to which these measurements are regionally-representative. We do this study using carbon monoxide (CO) mixing ratios measured at Pinnacles (38.61 N, 78.35 W, 1017 m above mean sea

level), a monitoring site in the central Appalachian Mountains, from 1 Jan 2009 – 31 Dec 2012. We find that the mean diurnal CO cycle has a daytime increase of 9.5 ppb on days when the afternoon valley PBL height is below the ridgetop because of upslope transport of polluted valley PBL air. There is a daytime CO decrease of 6.2 ppb on days when the afternoon valley PBL height exceeds the ridgetop because vertical mixing and dilution overwhelm the influence of upslope pollutant transport. To investigate how PBL height affects the degree to which the measurements are regionally-representative, we perform simulations with the Weather Research and Forecasting (WRF) model and FLEXPART Lagrangian particle dispersion model (LPDM) for three days with similar meteorological conditions but with different afternoon PBL heights: 23 October 2010, 18 July 2011, and 9 April 2009, which had afternoon PBL heights of 1000 m msl, 1800 m msl, and 3000 m msl, respectively. The LPDM simulations indicate that near-surface emissions immediately upwind of Pinnacles have the largest influence on Pinnacles' trace gas measurements on the afternoons of 23 October and 18 July, but measurements are more regionally-representative on 9 April. On these afternoons with deep PBLs, trace gas mixing ratios can be used like trace gas mixing ratios measured on tall towers over flat terrain in applications requiring regionally-representative measurements.

P1.42 Effects of intermittent turbulent events on air pollutant dispersion

Mireia Udina *(Universitat de Barcelona, Spain), Maria Rosa Soler, Miriam Olid*

Dispersion phenomena, aside from pollutant emission and photochemical processes, are decisively influenced by atmospheric processes. During day time turbulence generated by both, thermal and shear effects, and mesoscale circulations control or strongly influence air pollutant dispersion. However, during night time air pollutant concentrations can not only be driven by terrain forced circulations but also by intermittent turbulence events generated by different coherent structures, as density currents, low level jets and solitary waves, which can modify the pollutant transport and dispersion.

In this study we analyze the effects on pollution dispersion of a sequence of eight atmospheric density current fronts registered in consecutive days at the CIBA (Research Center for the Lower Atmosphere) 100 m tower, located northwest of the Iberian Peninsula. They were observed in the late evening during the INTERCLE experiment in July 2003. The arrival of the density current at the CIBA site produced a sudden decrease in air temperature, an abrupt change in wind speed and wind direction, an increase in water vapor mixing ratio and a fast increase in turbulence intensity and turbulent heat fluxes. Specific days also revealed the formation of gravity waves after the establishment of the density current. The Weather Research and Forecasting (WRF) mesoscale simulations showed that the origin of the current was a combination of a Cantabric sea breeze entrance developed during daytime and the katabatic flows originated at the surrounding mountain ranges. To analyze the effects of the density current arrivals and the generated intermittent turbulence on air pollutant dispersion, the WRF meteorological outputs are coupled with the photo-chemical model Community Multiscale Air Quality (CMAQ) model. We use a point source emitting a passive tracer located at the CIBA site, to explore the effects of the sudden variation of the meteorological fields on the tracer plume concentrations.

P1.43 Atmospheric dispersion modelling with AERMOD for comparative impact assessment of different pollutant emission sources in an Alpine valley

Elena Tomasi *(University of Trento, Italy), Gianluca Antonacci, Lorenzo Giovannini, Dino Zardi, Marco Ragazzi*

High-resolution simulations are performed with the AERMOD model to assess the impact on air quality of different pollutant emission sources in the area surrounding Vipiteno, a town in the northeastern Italian Alps. In this area the environmental burden of pollutant emissions is particularly high because of both its complex terrain and the presence of specific pollutant sources. In this study the effects of the main sources are analyzed and compared: the A22 motorway, which leads to the Brenner pass, the town of Vipiteno, characterized by intensive use of biomass for house heating, three major plants with high emission rates, and a big parking lot, offering park spaces for up to 260 trucks and 50 cars. To assess the impact of these pollution sources, the AERMOD model is run with a spatial resolution of 25m and with different meteorological input data, such as annual series of standard meteorological variables from local weather stations and a set of vertical soundings. During the simulations the motorway is modeled as a linear source, the town as a diffuse source, the local companies as point sources and the parking lot is modeled as a composition of a diffuse source, representing the idling vehicles, and of a linear source, representing the access routes to the park. For each source, specific emission factors are chosen, and hourly and seasonal emission patterns are set, with particular attention to the analysis of idling vehicle emission factors. The annual means and hourly maxima of NO2 and PM10 concentration from the simulations are compared with the limits set by legal provisions and the values measured at a permanent air quality station operated by the local environmental agency. The contribution of each source is then analyzed, highlighting the relative relevance of each source on the air quality of the area.

P1.44 Problems of atmospheric transport simulation for mountain observatories

Petra Seibert *(Universität für Bodenkultur Wien (BOKU), Austria), Anne Philipp, Radek Hofman*

Many important trace gas monitoring stations are located on mountain peaks or at least nearby, for example Jungfraujoch, Zugspitze, Sonnblick, or Schauinsland. Simulating transport to these stations, or calculating source-receptor sensitivities for their measurements, is not trivial. Such simulations usually have to rely on operational weather-forecast models for the generation of wind and other fields, and for many applications these are even global fields. They don't resolve thermal circulations such as slope winds which can be relevant for the observed atmospheric composition. In addition, the smoothed model topography will in general be lower than the real one, so that the question arises whether one should use receptors at model ground or at the station height above sea level, or something else. These issues will be discussed with experiences from past projects as well as with a new study for the simulation of transport of radioactice Xe-133 from the medical isotope production facility in Fleurus, Belgium, to the Schauinsland station (Black Forest, Germany) of the Comprehensive Nuclear Test Ban Treaty Organisation with its seat in Vienna. The representativity of 0.125 degree ECMWF fields is investigated with temperature and humidity measurements a the station.

P1.45 Improving the quality control of observational data in complex terrain

Birgit Eibl *(University of Vienna, Austria), Reinhold Steinacker*

Analysing meteorological data in complex terrain is a challenge for operational models. Whereas the resolution of prognostic and diagnostic models is steadily enhanced, the con-ventional observing network is not improving correspondingly. Therefore accurate reproduc-tion of meteorological information between observation points by interpolation requires scru-tinizing of observational data pertaining to its necessity of rejection, correction or acceptance of the data. With the model independent approach of VERA (Vienna Enhanced Resolution Analysis), where minimized first and second spatial derivatives are used for error estimates and grid point values, analysis fields are of considerable quality, which can be proofed by cross validation.

The latest improvement dealt with the smoothing condition of the temperature field which may be applied for large scale patterns but not for the high resolution “rough” patterns imposed to the fields by orography. Therefore each observational value is split on the one hand into a large scale “synoptic” part which succumbs the smoothing condition and on the other hand into a physically explained high resolution part described by the so called “fingerprints”. Only the synoptic part is then quality controlled amongst other things by the smoothing condition. Subsequently both parts are merged again so as to be calculated as final analysis.

The aim of the study is a lower correction of observational data and preserving the rough character of meteorological parameters in complex terrain. First results will be shown and discussed, showing an improved preservation of high resolution information and a wanted smoothing of the large scale part of the field.

P1.46 The National Centre for Atmospheric Science Atmospheric Measurement Facility for Mountain Meteorology

Victoria Smith *(National Centre for Atmospheric Science, United Kingdom), Barbara Brooks*

The National Centre for Atmospheric Science (NCAS) Atmospheric Measurement Facility (AMF) operates and facilitates access to strategically located observatories and laboratories, as well as specialist cutting edge instrumentation for both ground based and airborne atmospheric observations. Long-term measurement programs are also supported, with the data freely available through the British Atmospheric Data Centre (BADC). NCAS - AMF is committed to excellence in measurement and this poster will describe the extensive instruments and data that are relevant to the mountain meteorology research community, and how access can be gained through a transparent and straight-forward application process.

P1.47 Using Google Earth for visualization of meteorological data in complex terrain

Lukas Strauss *(University of Vienna, Austria), Stefano Serafin, Vanda Grubišić*

Google Earth (GE) offers unprecedented 3D visualization capabilities to the modern geoscientist. Recently, the tool has gained in popularity for science outreach activities that aim at raising public awareness of geoscientific problems of societal and economic relevance (e.g., “Google Earth 4 degrees” by UK Met Office, 2013) and of advanced airborne geoscience observations (e.g., NCAR EOL real-time flight tracking system). At the same time, it appears that Google Earth’s potential for quantitative scientific analysis has not been fully exploited by the mountain meteorology research community. This seems particularly true in view of the advancement of modern meteorological instrumentation, such as fast-scanning remote sensors, which has brought about new challenges in the analysis of spatial and temporal high-resolution data products, especially for scientists working in topographically complex environments.

The aim of this contribution is to draw attention to potential applications of Google Earth for the analysis of measurements distributed over complex terrain in time and space and to show that these are generally easily accessible, with a few helper tools at hand to create KML files for input into GE. Visualization examples will be given using data from the comprehensive dataset of the Terrain-induced Rotor Experiment (T-REX, Sierra Nevada, California, 2006). There, complex 3D interactions between cross-mountain and along-valley flows combined with rapid changes of weather conditions proved to be a particularly demanding aspect of the analysis.

Beyond observational datasets, meteorological applications of Google Earth have already been extended to visualizations of satellite data and even high-resolution numerical model output (cf. recent publications in Elsevier Computers & Geosciences). Developments to visualize output from the Weather Research & Forecasting (WRF) model are currently under way.

P2 Poster Session: Poster Session 2

P2.1 Lagrangian analysis of foehn air warming in a dry and a moist event over the Swiss Alps

Annette K. Miltenberger *(University of Leeds, United Kingdom), Silvia Reynolds, Michael Sprenger*

High temperatures in foehn valleys is one very prominent manifestation of foehn flows. The underlying physical mechanisms have been an issue since the early days of foehn research, but are still not well constrained and understood. By performing Lagrangian investigations of two foehn events in the Swiss Alps with a focus on the Rhine valley, we gain new insight into this topic. To this end, we performed simulations with the high-resolution numerical weather prediction model COSMO with an online trajectory tool and a two-moment microphysical scheme. The high-resolution trajectories illustrate the complexity of the source regions for air parcels arriving in the foehn valley. A budget analysis of potential temperature changes along the trajectories shows that the warming is to the first order determined by adiabatic descent, but in addition there are significant diabatic processes leading to a net cooling and heating of up to 6 Kelvin. These diabatic temperature changes can be attributed to turbulent mixing with other air masses on both sides of the Alps and microphysical processes. The budget analysis of the latent heating due to phase changes of water substance along the trajectories reveals a significant cooling due melting of ice. Besides shedding new light on the temperature changes involved in foehn air warming and the driving physical mechanisms, this study illustrates the added value of the Lagrangian perspective and the use of trajectory data at very high temporal and spatial resolution for understanding flow over complex terrain.

P2.2 Nature and climatology of Pfänderwind

Alexander Gohm *(University of Innsbruck, Austria), Maria Siller, Julius Bär*

The characteristics and climatology of Pfänderwind, a largely unknown downslope windstorm near the town of Bregenz (Austria) at the entrance of the Rhine Valley, are investigated based on an eleven-year dataset of weather station observations and ERA-Interim reanalyses. The goal is to clarify the inconsistency in the definition of this phenomenon, to illuminate its dynamics, and to quantify its frequency of occurrence. It is shown that Pfänderwind has similarities to foehn but does occur for different synoptic-scale conditions. Moreover, two types of Pfänderwind have to be distinguished: Type 1, or classical Pfänderwind, is associated with easterly to northeasterly large-scale flow that crosses the Pfänder mountain range, descends in a foehn-like manner and causes moderate to strong winds in the town of Bregenz and its vicinity. The temperature anomaly induced at the surface by adiabatic warming is small as a result of weak low-level stability. Type-1 events occur on average 12 times per year, preferentially in spring, and most frequently between the afternoon and midnight. Type 2, or southeast Pfänderwind, is associated with westerly to southwesterly ambient winds near the main Alpine crest level. The Rhine valley is filled with cold air and in most cases south foehn is not present. However, the synoptic and meso-scale pressure gradient favours southerly ageostrophic flow in the Rhine Valley especially near the top of the cold-air pool. This flow passes the Gebhardsberg, the southwestern extension of the Pfänder mountain range, descends on its leeward side and causes strong foehn-like warming at the surface. However, southerly to southeasterly near-surface winds at Bregenz are rather weak. Type-2 events occur on average 40 times per year, most frequently between the evening and the early morning, and exhibit a weak seasonal dependence. More than half of all type-1 and type-2 events last only one or two hours.

Reference: http://dx.doi.org/10.1127/metz/2014/0648

P2.3 Climatology of north foehn in southern Switzerland

Cecilia Cetti, ***Matteo Buzzi*** *(MeteoSwiss, Switzerland), Michael Sprenger*

North Foehn is a characteristic weather phenomenon on the Alpine south side, affecting both southern Switzerland and the neighboring Italian regions. The lack of a comprehensive climatology of north Foehn and the growing amount of automatic weather stations in these regions motivated us to compile a new climatology for the period 1993-2014.

The identification relies on the automatic measurements and accordingly is based on an objective algorithm to identify Foehn. Basically, it is based on threshold criteria for several meteorological parameters within the Alpine valleys and additionally at one station at the Alpine crest. The parameters are: wind direction and speed (both mean winds and gusts), relative humidity and potential temperature difference between station in the valley and station at the Alpine crest. A combined application of all threshold criteria results in an hourly climatology of north Foehn. Having established the hourly climatology, distinct Foehn epsiodes are determined, which hence describe a Foehn epsiode from its beginning until its end.

Based on the hourly and epsiode-based climatologies, several questions will be discussed: (i) How often does north Foehn occur?; (ii) Does it depend on the distance from the Alpine crest?; (iii) Is the seasonal cycle of nort Foehn frequencies similar to the one of south Foehn?; (iv) What is the diurnal cycle of north Foehn?; (v) Which intensities, expressed as mean wind speeds and gusts, can be observed?

P2.4 Nowcasting of North Foehn wind gusts in Switzerland using AdaBoosting

Matteo Buzzi *(MeteoSwiss, Switzerland), Daniele Nerini*

Foehn is a dry, warm wind on the lee side of a mountain range. In Switzerland it occurs during southerly and northerly wind flow conditions. While providing alpine and pre-alpine valleys with sunny weather, it also frequently produces strong wind gusts. Foehn events may thus represent a serious hazard for aviation, navigation, cause damage to infrastructure and trees and increase the forest fire danger. Since high resolution NWP models are yet unable to accurately forecast Foehn timing and intensity in valleys, new modelling approaches are explored to try to improve the forecast of such events. The challenge is even greater given the high spatial and temporal variability of the phenomenon. The presentation shows the potential of the AdaBoost machine learning algorithm for wind gust nowcasting during North Foehn events in southern Switzerland. The results will be compared with an high resolution numerical weather prediction model, with another system based on analogue cases in the past as well as with the performance of the manual forecaster based system at MeteoSwiss.

P2.5 New Insights Into Dimmerfoehn in the Alps

Klaus Burri *(Alpine Research Group Foehn Rhine Valley/Lake Constance (AGF), Switzerland), Bruno Dürr, Patrick Hächler, Daniel Gerstgrasser, Alfred Neururer, Michael Sprenger, Richard Werner*

Internationally, the technical term «dimmerfoehn» is often defined incompletely, sometimes even wrongly. Furthermore, the current official WMO-definition of dimmerfoehn does not seem appropriate anymore. In fact, in the definition any reference to precipitation and cloudiness is missing. This poster offers some overviews, facts and new insights in order to illustrate its forthcoming new WMO-definition.

Some historical views will show that the meteorological characteristics of this type of foehn can even be found in 200-year-old travel reports. But it was not until 1933 when Streiff-Becker published the first scientific paper on this topic. This poster will show that the understanding of the term dimmerfoehn has remained astonishingly coherent since then.

The current status of dimmerfoehn diagnostics will be presented with the help of some case studies on this foehn-phenomenon in the Alps. It will be shown that precipitation leeward of the mountain ridge seems to be the main important property of a dimmerfoehn: It differentiates this foehn type distinctively from the «normal» one and can be measured easily. However, defining further distinctive and measurable properties seems to be more complex.

P2.6 150 years foehn station Altdorf, Switzerland – a climatology

Hans Richner *(ETH Zurich, Switzerland), Stephan Bader, Bruno Dürr, Thomas Gutermann*

In Altdorf in the Reuss Valley, an operational weather station was installed in 1864. At this station, special foehn observations were made three times daily, producing a homogeneous time series with monthly means of morning, noon, and evening observations. These triple observations were discontinued in 2008, however, using an objective, automated foehn detection method available since 1981, the original observations can be simulated, thus allowing the continuation of the long, homogeneous time series.

To celebrate the 150 year anniversary of the station, a study of foehn climatology was initiated. In addition to basic statistical features of the total time series, so-called normals for the five 30-year periods are compared, allowing a characterization of each period. Since there are three observations per day, also the diurnal variation of foehn frequency for each month can be extracted. For the periods where data is available, a comparison of weather classifications with actually observed foehn frequency is presented.

Since 1955, the onset and breakdown of each foehn event is being recorded to the nearest hour. A statistical evaluation allows to characterize foehn events by their length, the day-time of their onset and breakdown, as well as the length of pauses between intermittent foehn events.

P2.7 Numerical simulation and analysis of the gap flow emanating from the Oštarijska Vrata Pass at the onset of Bora

Tanja Trošić *(Meteorological and hydrological service, Croatia), Živko Trošić*

The gap flow emanating from the Oštarijska Vrata Pass, locally called the Bora of Pag's ribs, can strongly affect the safety of maritime traffic in the Pag island area, Croatia due to the fact that strong and weak winds are sharply separated. Two cases with severe Bora have been selected for the analysis at the start of Bora. According to the measurements from automatic stations, the MM5 numerical model was successful in the 10-min mean wind speed prediction. The vertical analysis of the wind speed and potential temperature also gave satisfactory results for both cases. The model has proved successful in predicting the characteristics of the Bora of Pag's ribs, and in the second Bora case the gap flow rotation was also successfully predicted. The vertical cross-sections through the centre of the gap point out a permanent hydraulic-like flow. The highest modeled turbulent kinetic energy was found in the jump-like region above the inversion and within the boundary layer, along the lower boundary. In both cases it was concluded that the dissipation in the hydraulic jumps and the wave breaking regions are the reasons for potential vorticity generation.

P2.8 Numerical analysis of microscale properties of a bora windstorm over the eastern Adriatic

Kristian Horvath *(Meteorological and Hydrological Service, Croatia), Branko Kosović*

Downslope windstorms are frequent phenomena in complex terrain worldwide. Bora downslope windstorms along the eastern Adriatic coast are well known for their strength and turbulence intensity, which reduce security of land, marine and air traffic as well as have a major effect on the wind energy production in the region. In this work, we study origin of wind speed pulsations and turbulence in bora flows as well as different contributions to the turbulence kinetic energy budget, as inferred using the multiple nested WRF model simulations.

The event chosen for analysis was a moderate downslope anticyclonic bora windstorm that took place on 28 Apr 2010. Numerical analysis of the event was performed used the WRF model with realistic initial and boundary conditions and multiple nested computational domains in three configurations. The first and the second used a mesoscale setup at a grid spacing as low as 333 m and a MYJ and MYNN planetary boundary layer scheme respectively and the third used a multiscale setup at a grip spacing as low as 33 m using explicit simulation of large turbulent eddies. Considerable differences with regards to evolution of the simulated bora event were present in the two mesoscale simulations. Nevertheless, sub-mesoscale bora wind variability, including wind speed pulsations, which was the largest in the multiscale simulation, was found also in both mesoscale model simulations. The strongest wind speed pulsations were found to be of periods of 7 – 11 minutes and originated near the primary mountain gravity wave. It was found that those pulsations propagated farther away from the formation point during the daytime convective boundary layer than during the stable nighttime conditions. Furthermore, numerical analysis suggested that a significant contribution to turbulence kinetic energy originated from advected non-local turbulence arising from wind speed pulsations. We also assessed contributions of other sources and sinks to turbulence kinetic energy, and pointed out differences between mesoscale and multiscale simulations.

P2.9 On the near-ground Bora turbulence

Petra Lepri *(Meteorological and Hydrological Service, Croatia), Željko Večenaj, Hrvoje Kozmar, Branko Grisogono*

Bora is a strong, temporally and spatially very variable downslope wind. While the average Bora wind velocity is not that significant, the Bora gusts can be very hazardous creating considerable difficulties for traffic, structures and human activities. In particular, during the gusts, the Bora wind velocity can reach velocities up to five times the average values. In order to elucidate Bora wind characteristics more closely, unique 3-level, high-frequency Bora wind measurements carried out on a meteorological tower near the city of Split, Croatia, are analyzed. Vertical profile of the Bora wind velocity for the main wind direction as well as the Bora near-ground turbulence is studied. A good agreement between the average wind velocity profile with the power-law and logarithmic-law approximations is observed. A decrease in the power-law exponent and aerodynamic surface roughness length, and an increase in friction velocity with increasing Bora wind velocity indicate a rural-like velocity profile for larger wind velocities and an urban-like velocity profile for smaller wind velocities. These results are interesting because in the engineering community it is commonly accepted that the aerodynamic characteristics at a particular site remain nearly the same during various wind regimes. The thermal stratification of the atmospheric surface layer proves to be near-neutral indicating that the Bora near-ground turbulence is predominantly generated mechanically due to an intense mixing, while the thermal effects are considered to be negligible. For mean wind velocities larger than 5 m/s, turbulence intensity and Reynolds shear stress appear to be constant, i.e. not dependent on the meandering of the mean wind velocity. An increase in turbulence length scales with increasing Bora wind velocity and vice versa is observed.

P2.10 Bora-induced near-surface layer turbulence scales

Zeljko Vecenaj *(University of Zagreb, Croatia), Danijel Belusic, Branko Grisogono*

The town of Senj settled at the north-eastern Adriatic coast (44.99°N, 14.90°E, 2 m above MSL) is famous for frequent occurrence of bora wind, which makes it to be perfect natural laboratory for investigation of bora. While large- and mesoscale features of bora are intensively investigated in the past few decades and nowadays well understood, there is still insignificant amount of knowledge about its turbulence characteristics. Thus, from March 2004 to June 2006, single point 3D high frequency wind measurements were conducted in Senj using WindMaster ultrasonic anemometers (Gill Instruments) mounted 13 m above the ground. This instrument recorded the data with a sampling frequency of 4 Hz. It was continuously operational for more than two years recording all kinds of airflows. Using very basic criteria to define a bora event (wind of azimuth between 30° and 90° blowing at least for 3 h), we sorted out 294 bora events from these dataset with cumulative duration of almost 7000 h.

Usually, one of the first steps in investigation of turbulence is to obtain spatial/temporal scale(s) within which the turbulence will be defined in an observed flow. Regarding the scales of turbulence, one can find variety of different definitions in the literature. Most frequently used are the spectral gap scale at mesoscale derived from Fourier spectrum, the integral scale derived from autocorrelation function and the scale at which normalized Fourier spectrum achieves its maximum value. In this work we estimate these scales and show that they significantly differ for bora flows in Senj. While the spectral gap scale seems to converge to 30 min, integral and maximum spectrum scales show pronounced dependence on mean bora wind speed. Among other reasons, estimations of these scales are important for numerical model evaluations, turbulence parameterization scheme improvements and various engineering applications.

P2.11 Characteristics of bora wind at the Dubrovnik airport

Zeljko Vecenaj *(University of Zagreb, Croatia), Endi Keresturi, Zeljka Pogacic, Jadran Jurkovic, Igor Kos, Branko Grisogono*

Dubrovnik airport (DA, 42.56°N, 18.27°E) is settled approximately 20 km southeast of the town of Dubrovnik on the 160 m ASL plateau. The runway is 3.3 km long and is oriented parallel to the coast (NW-SE), 1.5 km away from the sea to the southwest and 1 km away from the Sniježnica Konavoska ridge (≈1200 m ASL) to the northeast. Due to this kind of geographical setup, the runway is directly impacted by bora wind which causes many difficulties in the air traffic flow at DA. Therefore, accurate and precise forecasts of bora wind for DA are of the essential importance, primarily for safety reasons and overall tourism.

In this work we analyze METAR reports data logged at the Dubrovnik airport in the period from 28 November 2007 to 30 April 2014 and outputs from the numerical model ALADIN for the same period. We report occurrence of two types of bora wind at DA: 1. standard type (ST) in which bora flow exists only in the lower troposphere and 2. opened type (OT) in which bora flow extends throughout the whole troposphere. The ST bora mostly follows the hydraulic theory which makes it much more predictable than the OT bora whose behavior is more erratic and less understood. In the observed period we found 209 ST and 88 OT bora events. We investigate relationships between the measurements and numerical simulations in order to improve forecasts of bora at DA. We also compare the wind measurements between NW and SE end of the runway in order to investigate which of the two points would be more suitable for taking off/landing during a bora event.

P2.12 Extreme winds in Iceland: combined effects of cyclonic activity and complex topography

Guðrún Nína Petersen *(Icelandic Meteorological Office, Iceland)*

Iceland is a fairly windy country, due to its location adjacent the North Atlantic storm track. The orography of the island is rugged, mountains are steep and fjords and valleys narrow, and this impacts local winds. The resulting wind pattern is complicated; mountain wind phenomena are common, e.g. low level jets, gap winds, down-slope wind storms, mountain waves and wind wakes.

To increase our knowledge of the behaviour of wind in Iceland an extreme value analysis was conducted based on observations from 61 automatic weather stations, applying the Peak Over Threshold (POT) technique on maximum daily wind speed and maximum daily wind gust at each site. The time series included at least 10 years of data and the threshold was chosen as the 0.9 quantile of maximum mean wind speed/maximum wind gust at each location. The results highlight how the local orography has larger impact on the extreme wind gusts compared to the mean wind. With extreme value models in place, a few significant weather events were selected from recent years and the observed wind speeds compared to the models in order to evaluate how extreme the events were and how large area they impacted.

An automatic system has been set up, running once an hour, comparing observed wind measurements to the extreme value models and producing maps of the return periods for all sites. This system gives us the possibility to, on a daily basis, evaluate the extremeness of each situation and simultaneously increase our knowledge of extreme wind behaviour in Iceland. This work is a foundation for studying changes in extreme winds in Iceland.

P2.13 Wind speed frequency distribution in various terrain

Guðrún Nína Petersen *(Icelandic Meteorological Office, Iceland), Haraldur Ólafsson*

A dataset consisting of 10 years of wind speed observations with a temporal resolution of 1 hour at 72 automatic weather stations in Iceland has been explored. The Weibull distribution is commonly used as an approximation to the wind frequency distribution characterized by two parameters, a shape factor and a scale factor.

For each site the Weibull parameters are calculated. The shape factor ranges between 1 and 2 and the scale factor from 3 to 9, giving large variability in the apparent frequency distributions of the wind speed. While the Weibull distribution represents the wind speed distribution well away from steep mountains it is not always suitable. For example the Weibull distribution is more representable in summer than in winter as many sites have two peaks in winter wind speed distribution: the first on for very low wind speeds due to e.g. high pressure situations and the latter at higher wind speeds due to cyclonic activity. Also, many sites are sheltered for high wind speeds from certain wind directions.

P2.14 The Advection of Mesoscale Atmospheric Vortices over Reykjavík

Hálfdán Ágústsson *(IMO, Iceland), Haraldur Ólafsson*

On 12 August 2009, a series of satellite images revealed asymmetric shedding of atmospheric vortices in the lee of Mt. Snæfellsjökull, and their passage a distance of 120km across Faxaflói Bay and over the city of Reykjavík in West Iceland. After landfall, the vortices were detected by a network of surface weather stations. These observations are presented and with the aid of a numerical simulation, they are discussed in view of existing theories of orographic wakes and vortex shedding. In general, the flow is in line with existing knowledge, but there is a remarkable absence of vortices with anticyclonic rotation. Atmospheric conditions for vortices of this kind are most often favorable in late winter and spring and they are a forecasting challenge.

P2.15 The impact of Vatnajökull ice cap on mesoscale atmospheric flow

Hálfdán Ágústsson *(IMO, Iceland), Haraldur Ólafsson, Helgi Björnsson, Finnur Pálsson*

The Vatnajökull ice cap at the southeast coast of Iceland has a large effect on the meso- and finescale flow in the region. This effect is quantified based on results from two sets of high-resolution atmospheric simulations. A control simulation employs the current land height and glacial cover while in a sensitivity run the ice caps have been removed and the height of the model surface is based on the bedrock topography of the glaciers. The simulations are done at 8 and 2 km horizontal resolution and are forced with the Interim re-analysis of the ECMWF for two consecutive years 2004-2006.

The simulations indicate that in the absence of the Vatnajökull ice cap, annual mean winds near the ice cap will increase due to the reduced topography height and weaker atmospheric blockings. Mean winds in the region covered by the ice cap itself will decrease, due to the higher surface roughness of non-glaciated surfaces and the lower topography. There is furthermore an indication of a decrease in the frequency of strong wind events near the ice cap and significant changes changes to patterns of diurnal winds near the ice margin. The key results are relevant for studies of flows in complex terrain as well as in studies of the impact of retreating glaciers on atmospheric flow in a rapidly warming climate.

P2.16 The impact of resolution on the representation of southeast Greenland barrier winds and katabatic flows

G. W. Kent Moore *(University of Toronto, Canada), I. A. Renfrew, B. E. Harden, S. Mernild*

Southern Greenland is characterized by a number of low-level high wind speed weather systems that are the result of topographic flow distortion. These systems include barrier winds and katabatic flow that occur along its southeast coast. Global atmospheric reanalyses have proven to be important tools in furthering our understanding of these orographic winds and their role in the climate system. However, there is evidence that the mesoscale characteristics of these systems may be missed in these global products. Here we show that the Arctic System Reanalysis, a higher resolution regional reanalysis, is able to capture mesoscale features of barrier winds and katabatic flow, including the downslope acceleration associated with the excitation of mountain waves, that are missed or under-represented in ERA-I, a leading modern global reanalysis. This suggests that our understanding of the impact of these wind systems on the coupled climate system can be enhanced through the use of higher resolution regional reanalyses or model data.

P2.17 Progress in the observations and simulations of the fine scale structures of airflow over Bergen

Haraldur Ólafsson *(HI, Iceland), Jan Asle Olseth, Birgitte Rugaard Furevik, Olafur Rögnvaldsson, Ole Edvard Grov*

Continuous progress is being made on the fine-scale network of meteorological observations and simulations of the atmosphere in the complex terrain of Bergen, Norway. Here, the status of the system is presented together with selected cases of flow with substantial spatial variability.

P2.18 Mapping of the impact of the strength and the height of inversions on the low-level flow field in the vicinity of an isolated mountain

Marius Opsanger Jonassen, ***Haraldur Ólafsson*** *(HI, Iceland), Hálfdán Ágústsson*

Using the WRF model, many simulations of flow past an idealized 3D mountain have been carried out. The key variables are the height and strength of a tropospheric temperature inversion. Important elements of the simulated flow perturbations above and in the vicinity of the mountain are presented in the form of flow diagrammes.

P2.19 Incorporating vertical velocity and balloon trajectory data into radiosonde gravity wave analysis: Orographic sources in New Zealand during the DEEPWAVE campaign

Tyler Mixa *(University of Colorado, United States of America), Lakshmi Kantha, David Fritts, Andreas Dörnbrack, Sonja Gisinger*

Conventional analysis of gravity waves from radiosonde data (e.g. Eckermann 1996, Murphy et al. 2014) assumes that the sonde balloon ascent is vertical. It also ignores vertical wind information that can be derived from sonde vertical motion, thus using only temperature and zonal/meridional wind perturbations to extract wave properties. Sonde-derived profiles have been treated as vertical profiles in applications such as long-term climatology, where the desired background temperature and wind fields exhibit self-similarity over sufficiently large horizontal scales to approximate the measurements as vertical profiles. However, the sonde balloon drifts with the winds, and strong horizontal winds can carry the sonde sufficiently far away from the launch site to cause significant errors in the deduced "vertical" wave characteristics.

The vertical component of the wind is another metric of gravity wave activity in the troposphere and lower stratosphere. Wave analysis based on only temperature and horizontal wind perturbations does not account for this. Some recent studies (e.g. Zhang et al. 2012) have tried to incorporate vertical wind measurements into wave analysis, but the derived wave characteristics may lack dynamical consistency.

We propose an alternative analysis technique that incorporates sonde vertical wind measurements and trajectory data to map regions of significant orographic wave activity. The data were collected during the DEEPWAVE field campaign, where a comprehensive suite of ground-based and airborne sensors were deployed, along with radiosondes, to measure gravity wave propagation up to 100 km altitude over the South Island of New Zealand during the 2014 austral winter. Using the resulting sonde data, we investigate the source characteristics of orographic waves measured concurrently by airborne and remote sensors, and compare them to those derived from conventional radiosonde analysis to assess the utility of the technique.

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P2.20 Gravity wave characteristics derived from radiosonde observations at Lauder (45 S 169 E) during DEEPWAVE-NZ

Sonja Gisinger *(DLR, Germany), Andreas Dörnbrack, Benedikt Ehard, Bernd Kaifler, Natalie Kaifler, Markus Rapp, Markus Garhammer, Martina Bramberger, Tanja Portele, Maria Siller*

The field phase of DEEPWAVE-NZ (DEEP propagating gravity WAVE experiment over New Zealand) took place in June and July 2014 on the southern island of New Zealand. One goal of DEEPWAVE-NZ was to explore the propagation of gravity waves into the middle atmosphere which were excited in the troposphere by the flow across the southern island. Airborne measurements with the NSF/NCAR GV and the DLR Falcon research aircraft were complemented with ground-based measurements at various stations on the southern island.

At Lauder (45 S 169 E), long-lasting upper stratospheric and mesospheric observations were taken by the DLR Rayleigh lidar and the University of Utah Advanced Mesospheric Temperature Mapper and Airglow Imager. To provide data in the lower atmosphere up to 30 km altitude, radiosonde measurements were conducted in periods of mountain wave activity.

On ICAM we present wave properties and propagation characteristics determined from 98 soundings reaching a mean height of 31.3 km. Therefore, different analysis methods such as rotary spectra and wavelet analysis are used. For selected cases those findings are combined with results from other instruments (e.g. ground-based lidar) and are related to the prevailing meteorological situation based on high-resolution ECMWF analyses.

P2.21 Does strong tropospheric forcing cause large amplitude mesospheric gravity waves? A Deepwave Case Study

Martina Bramberger *(University of Innsbruck and DLR, Germany), Andreas Dörnbrack, Sonja Gisinger, Bernd Kaifler, Tanja Portele, Markus Rapp, Ivana Stiperski*

The DEEPWAVE (deep-propagating wave experiment) campaign was designed for an airborne and ground-based exploration of gravity waves from their tropospheric sources up to their dissipation at high altitudes. It was performed in and around New Zealand from 24 May till 27 July 2014, being the first comprehensive field campaign of this kind. A variety of airborne instruments was deployed onboard the research aircraft NSF/NCAR Gulfstream V (GV) and the DLR Falcon. Additionally, ground-based measurements were conducted at different sites across the southern island of New Zealand, including the DLR Rayleigh lidar located at

Lauder (45.04 S, 169.68 E).

We focus on the intensive observing period (IOP) 10 on the 4 July 2014, when strong WSW winds of about 40 m/s at 700 hPa provided intense forcing conditions for mountain waves. At tropopause level, the horizontal wind exceeded 50 m/s and favored the vertical propagation of gravity waves into the stratosphere. The DLR Rayleigh Lidar measured temperature fluctuations with peak-to-peak amplitudes of about 20 K in the mesosphere (60 km to 80 km MSL) over a period of more than 10 hours. Two research flights were conducted by the DLR Falcon (Falcon Flight 04 and 05) during this period with straight transects (Mt. Aspiring 2a) over New Zealands Alps at three different flight-levels around the tropopause (approx. 11 km MSL). These research flights were coordinated with the GV (Research Flight 16) where the largest mountain wave amplitudes at flight-level (approx. 13 km MSL) were measured during DEEPWAVE. Additionally a first analysis of Falcon's in-situ flight-level data revealed amplitudes in the vertical wind larger than 4 m/s at all altitudes in the vicinity of the highest peaks of the Southern Alps.

Here, we present a comprehensive picture of the gravity wave characteristics and propagation properties during this interesting gravity wave event. We use the airborne observations combined with a comprehensive set of ground-based measurements consisting of 13 radiosoundings (1.5 hourly interval) together with the DLR Rayleigh lidar. To cover the altitude range from the troposphere to the mesosphere, high-resolution (1 hourly) ECMWF analyses and forecasts are used to estimate the propagation conditions of the excited mountain waves. The goal of our investigation is to find out whether the large amplitude mesospheric gravity waves are caused by the strong tropospheric forcing.

P2.22 Mountain Wave Propagation under Transient Tropospheric Forcing - A DEEPWAVE case study

Tanja Portele *(University of Innsbruck and DLR, Germany), Martina Bramberger, Andreas Dörnbrack, Sonja Gisinger, Alexander Gohm, Bernd Kaifler, Markus Rapp*

The deep-propagating wave experiment (DEEPWAVE) was the first extensive measurement program observing especially orographically induced gravity waves from creation to destruction. The field campaign took place in and around New Zealand from 24 May till 27 July 2014. To gain new insights into gravity wave dynamics, comprehensive airborne and ground-based measurements were conducted. These observations provide different sensitivity to various gravity waves sources and their propagation up to higher altitudes. Among these are airborne measurements with the NSF/NCAR Gulfstream V (GV) and the DLR Falcon. The University of Innsbruck and the DLR operated two radiosonde stations at Lauder (45.038 S, 169.684 E) in the lee of the Southern Alps. There, the DLR Rayleigh lidar provided temperature profiles from 30 to 80 km MSL.

In this study, we investigate one particular case which was observed during the intensive observing period (IOP) 9 from 29 June till 30 June 2014. The goal of this IOP was to explore the deep wave response to a transient tropospheric forcing. Flight-level in-situ data will be analysed and related to the ground-based lidar data. The lidar observed propagating gravity waves in an altitude range between about 40 to 60 km MSL from 10 UTC to 18 UTC on 30 June 2014.

During this IOP, the DLR Falcon and the GV conducted four consecutive flights to cover the whole period of the transient tropospheric forcing. These airborne observations were complemented by 15 radiosondes launched at Lauder every 3 h. The first Falcon flight FF01 was flown under amplifying, the second flight FF02 under significant but decreasing orographic forcing. Here, particularly the horizontal wind at forcing level (700 hPa) was weakening and the wind direction was slightly turning from NW-NNW to WNW-NW from 29 June to 30 June. Due to this gradual change, amplitudes of vertical wind at flight level decreased from up to about 4 m/s on 29 June to up to about 2 m/s on 30 June.

We concentrate on the impact of changing forcing conditions on the propagation of gravity waves across the tropopause into the stratosphere. The observations of this event are documented and analysed. In addition,

the findings are compared with high-resolution (1-hourly) ECMWF analyses and forecasts. Furthermore, the potential of gravity waves to propagate into the mesosphere over the southern island of New Zealand is studied based on the observations.

P2.23 Mountain waves over the Pyrenees: real and ideal simulations using the WRF model

Mireia Udina *(Universitat de Barcelona, Spain), Maria Rosa Soler, Ona Sol*

Mountain waves are buoyancy oscillations produced in a stably stratified flow by the disturbance of an air current that encounters a mountain barrier. They influence the dynamics of the atmosphere and they can be a source of turbulence at different scales, from wave breaking in the middle and upper troposphere to downslope winds and low level turbulence regions in the planetary boundary layer.

Several mountain wave events were identified at the downwind side of the Pyrenees located at the border between France and Spain, in southwest Europe when there is a strong northerly flow in a stable stratified layer. In this study we have selected a specific mountain wave event and we have explored the Weather Research and Forecasting (WRF) mesoscale model predictability and the influence of certain model parameters to resolve the generated waves.

Results show that the model is able to capture fluctuations, in vertical and horizontal wind components, humidity and temperature, generated above the crestline and downwind of the mountain range. In addition, a flow reversal zone in the valley after the first crestline is also reproduced by the mesoscale simulations indicating a possible rotor formation. It is also found that the horizontal grid resolution is more crucial in resolving the mountain waves than the resolved topography or the vertical grid spacing. The wavelength discrepancies between the satellite imagery and the generated waves in WRF simulations can be due to the underestimation of the wind speed upstream of the Pyrenees. To confirm this hypothesis, two-dimensional idealized simulations were performed with a realistic underlying terrain showing that the wave wavelength strongly depends on the upstream conditions.

P2.24 Equatorial Mountain Torques, Equatorial Angular Momentum and Cold Surges in a GCM

Sylvain Mailler, ***Francois Lott*** *(CNRS, France)*

The dynamical relations between equatorial atmospheric angular momentum, equatorial mountain torques and cold surges are analyzed in a General Circulation Model (GCM). First we show that the global equatorial atmospheric momentum budget is very well closed in the GCM, which is a clear benefit when we compare with results from the NCEP reanalysis. We then confirm that the equatorial torques due to the Tibetan plateau, the Rockies and the Andes are well related to the cold surges developing over East-Asia, North America, and South-America respectively. For all these mountains, a peak in the equatorial mountain torque component that points locally toward the pole preceeds by few days the development of a cold surge, yielding a potential predictive interest to our results.

We also analyze the contributions to the torques of the subgrid scale orography (SSO) effects that are parameterized and find that they contribute substantially. In experiments without SSO drags, we find that the explicit pressure torques change substantially to compensate the reductions in the parameterized torques, and that the cold surges are not much affected. This shows that the cold surges can be well captured in GCMs, provided that the synoptic conditions prior to their onset are well represented. The compensation between torques is nevertheless not complete and some weekening of the cold surges is found when the mountain forcings are reduced. This illustrates how the exact torques are needed at a given time to produce the correct synoptic scale dynamics at a later stage.

P2.25 The momentum flux profiles in hydrostatic mountain waves over elliptical mountains

Miguel A. C. Teixeira *(University of Reading, United Kingdom), Chau L. Yu*

Current orographic drag parametrizations, for example at ECMWF or at the UK Met Office, represent the mountain ranges at the global scale as one representative idealized mountain per grid box, with an elliptical horizontal cross-section and a prescribed shape, with shape parameters (orientation, height, width, aspect ratio) derived from statistics of the real, high-resolution orography within the grid box. However, these parametrizations currently ignore vertical wind shear effects on the surface drag, and shear effects on the wave momentum flux profile are treated in a crude way. Typically, the momentum flux is depleted based on the conditions for breaking of gravity waves with a spectrum comprising just a few harmonics. This is inconsistent with the treatment of the surface drag, which assumes a continuous wave spectrum. Shutts and Gadian (1999) developed calculations for the momentum flux associated with a full spectrum of mountain waves in the case of flow over an axisymmetric mountain, in the limit of very high Richardson number (Ri). These calculations, which assumed hydrostatic flow, were extended to lower Ri by Teixeira and Miranda (2009) using a WKB approximation. In the present study, the treatment of Teixeira and Miranda is extended further to mountains with an elliptical horizontal cross section. This model provides a closed consistent theory for the wave drag and momentum fluxes in directionally sheared flows over elliptical mountains. It incorporates both shear effects on the surface drag, which may lead to its increase or decrease, and partial or total absorption of the momentum flux at critical levels. For monotonic wind profiles with a single critical level for each wavenumber, the wave momentum flux at a given height is expressed in terms of the drag in the absence of shear at the surface, and, due to the hydrostatic approximation, this relation does not depend on the detailed shape of the orography apart from its horizontal aspect ratio. The resulting momentum flux divergence is expressed in a closed analytical form and approximately satisfies the extension to 3D of Eliassen-Palm's theorem. In the case of multiple critical levels, the atmosphere is split into various layers, and the momentum flux at a given level may be expressed in terms of its value at the bottom of each layer. This theory could form the basis for a more consistent orographic drag parametrization scheme.

P2.26 Drag produced by 3D trapped lee waves in two-layer atmospheres

Miguel A. C. Teixeira *(University of Reading, United Kingdom), Pedro M. A. Miranda*

Mountain wave drag must be parametrized in weather and climate prediction models. As the resolution of these models increases, non-hydrostatic waves become progressively more important among the waves that need parametrization. It is usually assumed that non-hydrostatic waves give a modest contribution to the global drag compared to hydrostatic waves. For this reason, non-hydrostatic waves, which include trapped lee waves, are usually neglected in parametrizations. However, trapped lee waves have been shown to have a significant impact in some parameter regimes, under specific atmospheric conditions conducive to resonance: i.e. for the atmospheric profiles of Scorer (1949), where the atmosphere has a stably stratified layer near the surface and a less stable layer aloft, and of Vosper (2004), where the atmosphere is stably stratified aloft but near the surface has a neutral layer, capped by a temperature inversion. Teixeira et al. (2013) calculated explicitly the drag produced by trapped lee waves for these idealized two-layer atmospheres, in flow over a 2D mountain ridge (the type of orography originally considered by Scorer and Vosper). In this study, these calculations are extended to the simplest possible case of 3D orography: an axisymmetric mountain. Unlike in the 2D case, where the spectrum of trapped lee waves contributing to the drag is discrete, in the 3D case, this spectrum, like the spectrum of vertically propagating waves, is continuous, corresponding to a "ship-wave" pattern originating above the obstacle instead of a train of monochromatic trapped lee waves. Consequently, the form taken by the drag component due to trapped lee waves is no longer a closed analytical expression, but rather a 1D integral. Because of additional directional wave dispersion effects, the drag enhancement in resonant conditions is less pronounced than in the 2D case. However, the drag may

still take values well above the hydrostatic limit valid if the upper stably stratified layer extended down to the surface, with a sizeable contribution coming from trapped lee waves. The results obtained from linear theory are validated against numerical simulations of similar flows. These results may be straightforwardly extended to a mountain with an elliptical horizontal cross-section, which would increase their relevance to drag parametrization.

P2.27 Drag produced by trapped lee waves and upward propagating mountain waves in directional shear flow

*Chau L. Yu, **Miguel A. C. Teixeira** (University of Reading, United Kingdom)*

In non-hydrostatic flow, the drag produced by mountain waves receives contributions from waves that propagate vertically and waves that are trapped near the surface. This complicates the evaluation of the drag, because the trapped lee waves arise due to singularities in the wave spectrum, corresponding to discrete modes, at least in flow over 2D orography. Existing calculations of the drag due to trapped lee waves have focused on very simple atmospheric profiles, where the static stability or the wind-speed are piecewise constant (Teixeira et al., 2013a, 2013b). However, one of the most common wave trapping mechanisms is vertical shear, when the wind magnitude increases with height. The present study addresses the gravity wave drag produced in a two-layer atmospheric flow with constant static stability over an axisymmetric mountain, where the wind varies linearly in the lower layer and is constant aloft. Many configurations are possible: unidirectional flow with positive or negative shear, or flow with directional shear of various types. The drag behaviour is determined by partial wave reflection at the shear discontinuity, wave absorption at critical levels (both of which exist in hydrostatic flow) and total wave reflection at levels where the waves become evanescent (an intrinsically non-hydrostatic effect), which produces resonant trapped lee-wave modes. As a result of constructive or destructive wave interference, the drag oscillates with the thickness of the constant-shear layer and the Richardson number within it (Ri), generally decreasing at low Ri and when the flow is strongly non-hydrostatic. Critical-level absorption, which increases with the angle spanned by the wind velocity in the constant-shear layer, shields the surface from reflected waves, keeping the drag closer to its hydrostatic limit. Although, for the parameter range considered here, the drag seldom exceeds this limit, a substantial drag fraction may be produced by trapped lee waves, particularly when the flow is strongly non-hydrostatic, the lower layer is thick and Ri is relatively high. In directionally sheared flow with Ri = O(1), the drag may be misaligned with the surface wind in a direction opposite to the shear, a behaviour found to be totally due to non-trapped waves. The trapped lee-wave drag, whose reaction force is felt on the atmosphere at low levels, may therefore have a distinctly different direction from the drag associated with vertically propagating waves, which acts on the atmosphere at higher levels.

P2.28 Analogies between wave trapping- and interfacial wave theory

***Johannes Sachsperger** (University of Vienna, Austria), Stefano Serafin, Vanda Grubišić*

The horizontal propagation of internal waves in stratified fluids is often explored in the context of Scorer's theory of wave trapping in a two-layer atmosphere, where a discontinuity in the Scorer parameter - with evanescent conditions in the upper layer - gives rise to trapped lee waves. The frequency dispersion relationship (FDR) of these waves suggests that their horizontal wavelength depends on the value of the Scorer parameters in both layers as well as on the depth of the lower layer.

Horizontal wave motion can also occur in form of interfacial waves riding along a density discontinuity in the interior of a fluid, similar to surface waves on a free water surface. The wavelength of interfacial waves is defined by the height and strength of the discontinuity and by the horizontal wind speed.

We modify Scorer's wave trapping theory by applying a boundary condition that accounts for a density jump between the two stratified layers. In this case, wave resonance is possible along the density jump even if the lower layer is neutrally stratified. Therefore, both interfacial waves and trapped lee waves are supported. The resulting linear theory can be applied to boundary layer flows over complex terrain, where part of the mountain wave energy is trapped along the inversion that caps the boundary layer.

We show that, under certain combinations of parameters, trapped lee waves behave exactly as pure interfacial waves, i.e., they obey the identical FDRs. Since trapped lee waves and interfacial waves have transcendental FDRs that cannot be solved analytically, we also discuss the implications of the shallow- and deep-water approximations on the wavelength of the resonant mode.

P2.29 Observations of lee wave and rotor development over double ridges in a stratified water tank

Ivana Stiperski, Hálfdán Ágústsson, Peter G. Baines, Anne Belleudy, Vanda Grubišić, Kristian Horvath, Christoph Knigge, Alexandre Paci, Johannes Sachsperger, ***Stefano Serafin*** *(University of Vienna, Austria), Lukas Strauss*

We present an overview of water tank experiments designed to investigate lee waves and rotors in flows over single and double two-dimensional topographic obstacles. The water tank size and the obstacle towing speeds allow us to simulate flows with high Reynolds number, in a reasonably close dynamical similarity to atmospheric flows.

The experimental setup consists of a two-layer flow with a lower neutral and an upper stable layer separated by a sharp density discontinuity. This type of layered flow over terrain is known to generate a variety of possible responses in the atmosphere, from hydraulic jumps to lee waves and highly turbulent rotors. The latter have been linked to the separation of the boundary layer on the lee side of the obstacle due to the pressure gradient induced by the wave field aloft.

Observations of boundary-layer separation, rotors and mountain waves in the lower troposphere have been recently reported in the literature. However, the existing observational studies are restricted to a small number of cases that provide limited insight into the phenomenon. Using high-resolution reconstructions of the velocity and density fields in two spatial dimensions and in time, our set of experiments extends the exploration of rotor formation to a broader range of flow regimes.

The experiments were focused on boundary layer separation and rotor formation in stratified flow over double ridges. Constructive or destructive interference of lee waves is expected in such flows and depends on the ratio of the ridge separation distance to the horizontal lee wavelength. Here we present preliminary results on the comparison between laboratory experiments and the theory of trapped lee wave interference, and seek the optimal conditions for rotor formation.

P2.30 Estimating the convective boundary layer depth during a fair weather day in the Owens Valley, CA

Nevio Babic, Erin Dougherty, Kelsey Everard, Seth Garland, ***Stephan F. J. De Wekker*** *(University of Virginia, United States of America)*

The convective boundary layer (CBL) represents the lowest part of the daytime boundary layer driven primarily by thermally buoyant forces.The boundary between the CBL and the free atmosphere aloft is usually accompanied by a capping inversion, which sets the upper limit of the influence of the surface- driven turbulent mixing processes and represents the CBL depth. Compared to flat and homogeneous topography, estimation of the CBL depth over complex, mountainous terrain, through either observations or numerical simulations, represents a challenging endeavour. It is well known that the spatio-temporal evolution of CBL over complex terrain is highly variable, mainly due to non-linear interactions of thermally-driven and terrain forced flows. Our limited knowledge of these interactions is reflected in poor numerical weather prediction (NWP) forecasts of winds, temperature, water vapor, and pollutant concentrations over mountainous terrain. To improve our understanding of CBLs over complex terrain, it is often desirable to estimate CBL heights from several different observation, analytical, and numerical approaches. Only by having a complete, multi-aspect picture of the processes affecting CBLs over complex terrain, we can aim to improve our understanding of their complexity. This study presents preliminary results from a single, fair-weather day analysis, based on observations conducted during the Terrain-Induced Rotor Experiment (T-REX) in late April 2006. The measurements were taken in the center of Owens Valley, CA. CBL depths are estimated using several approaches including the bulk-Richardson method using high-resolution soundings, aerosol backscatter information from a ceilometer, and the peaks in the weighted and nondimensionalized velocity spectra of the horizontal wind speed components computed using high frequency sonic anemometer data. The use of this latter approach is justified by the better scaling of these spectra with the CBL depth than with height above the ground. We use these observation-based estimates of the CBL depth to validate simple analytical boundary layer growth models. Finally, we use the Weather-Research and Forecasting (WRF) model to complete our multi-aspect picture of the CBL over a valley during a clear, fair-weather day.

P2.31 Investigating the boundary layer structure in a valley using an instrumented multi-rotor copter

Stephan F. J. De Wekker *(University of Virginia, United States of America)*

Recent advancements in electronics are allowing the development of low-cost unmanned aerial systems for studying atmospheric structure and dynamics. While previous emphasis has been on the development of fixed wing unmanned aircraft for atmospheric investigations, the use of multi-rotor copters is unexplored. The two main objectives of this poster are 1) to demonstrate the potential of a multi-rotor copter in atmospheric boundary layer (ABL) research and 2) to show some first results from using the multi-rotor copter to investigate the local dynamic and thermodynamic structure of the nocturnal ABL in a small valley. We are developing a quad- and hexacopter with fast-responding temperature and humidity sensors and are investigating various methods to accurately capture winds using the copter. The copter measurements are compared with state-of-the-art meteorological instruments installed on a 10-m. We plan to show initial results from the copter measurements made during the the evolution of a nocturnal boundary layer in a valley and the subsequent development of local downslope and downvalley flows.

P2.32 The nature of turbulence in the atmospheric boundary layer over an isolated mountain during the Mountain Terrain Atmospheric Modeling and Observations Program

Mark Sghiatti, Sandip Pal, George. D. Emmitt, ***Stephan F. J. De Wekker*** *(University of Virginia, United States of America)*

Turbulence fluxes of momentum, heat and moisture are well investigated over flat terrain but they still remain poorly defined over complex terrain. The objective of this study is to investigate spatial variability of turbulent kinetic energy (TKE) over an isolated mountain. Turbulence observations were made using in-situ airborne measurements performed during the first field experiment of The Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program at Dugway Proving Ground (Utah, USA)). The in-situ airborne measurements were made at 10 Hz over seven flights in October 2012 over Granite Peak, a steep isolated mountain with a horizontal and vertical scale of about 10 km and 1 km, respectively. The temporal and spatial variability of turbulence is analyzed by comparing turbulence statistics as a function of height, location upwind and downwind of Granite Peak, and ambient conditions. Analysis of TKE, calculated from airborne in-situ observations on a day with moderate winds, shows TKE values of about 1.0 to 1.5 m2s2 across a region from several kilometers to the east of Granite Peak (Sagebrush) to the eastern slope of Granite Peak (Eastern Slope). The results also show a distinct increase of 0.5-2.0 m2s2 from the surrounding plains to the eastern slope of Granite Peak. The origins of the observed turbulence spatial pattern are examined by determining the relative contributions of shear and buoyancy generated turbulence. Additionally, the nature of turbulence is explored using spectral analysis to determine the dominant turbulence scales.

P2.33 On the state of the i-Box

Ivana Stiperski *(University of Innsbruck, Austria), Mathias W. Rotach, Brigitta Goger, Eleni Sfyri*

Boundary layers in mountainous terrain are at the very forefront of boundary layer research. Challenging because of their non-homogeneity, terrain complexity, multitude of scales of motions and general lack of long-term datasets, they have yet to be fully understood.

To fill in this gap i-Box is designed as a platform for studying atmospheric boundary layer processes in truly complex, mountainous terrain. Based on both long-term turbulence measurements at 6 stations and surface-based remote sensing located in the Inn Valley, Austria and high-resolution numerical modeling, i-Box aims at answering the burning questions of boundary layer turbulence in mountainous terrain.

Here we give an overview of the current state of i-Box measurement and modeling efforts. We present the dataset as well as the challenges and advances in the measurement strategies. Additionally, some recent results on topics such as local scaling, energy balance closure etc, and modeling of boundary layer characteristics are presented.

P2.34 Scale interactions of atmospheric flows over mountainous terrain

Ivana Stiperski *(University of Innsbruck, Austria), Mathias W. Rotach*

Mountainous terrain is the source of motions on all scales. Motions in the atmospheric boundary layer are thus disturbed by mesoscale influences not relevant in flat terrain. In situations with weak synoptic forcing valley/slope wind systems are the dominant mesoscale driver, while under strong synoptic forcing downslope windstorms can develop and disturb the boundary layer. Gravity wave formation on different scales on the other hand is prevalent irrespective of the forcing when the valley atmosphere is stably stratified. These mesoscale and sub-mesoscale motions can have a significant contribution to the total exchange of heat and momentum, especially in stable boundary layers.

Here the characteristics of submeso and meso motions are studied using observational data from several stations within the i-Box project, under the conditions of both weak and strong synoptic forcing. We examine the frequency of occurrence of different organized motions, their structure and contribution to the total flux of momentum and heat at different scales and compare these contributions to the purely turbulent transport. In this respect the importance of these motions on the energy balance closure is examined.

P2.35 Towards a local similarity framework for scalar turbulence in very complex terrain

Eleni Sfyri *(University of Innsbruck, Austria), M. W. Rotach, I. Stiperski, F. Obleitner*

Near-surface turbulence characteristics are assessed in very complex terrain. Individual turbulence measurements are obtained from 6 sites of different surface characteristics (slope, orientation and surface type) in very complex terrain, using the Eddy Covariance method (EC). The study area is a Boundary-Layer study platform, the i-Box (Innsbruck Box), located at the Inn Valley, in Austria. The non-dimensional standard deviations of temperature and humidity ($\sigma\theta/\theta$* and σq/q*) as a function of local stability are studied at each i-Box site from two years of observations, applying different post-processing methods, in terms of averaging period, coordinate rotation and quality control. The objective of this study is twofold: firstly to describe the scaling behavior of these variables in terms of near-surface local scaling in very complex terrain, deriving appropriate similarity functions and secondly to assess the dependence of this behavior on the local-terrain characteristics, the applied post-processing method and quality control. The best-fit curves for stable and unstable conditions are discussed and the derived local scaling coefficients are compared with those from previous studies in complex terrain, as well as with the reference from flat and homogeneous terrain (i.e. the corresponding Monin-Obukhov similarity theory). The results show that the local scaling is a promising approach for turbulence in complex terrain and that the scaling of the studied variables strongly dependents on the selected post-processing method.

P2.36 Spectral turbulence characteristics of the stable boundary layer over non-homogeneous terrain

Karmen Babić *(University of Zagreb, Croatia), Mathias W. Rotach, Zvjezdana Bencetić Klaić*

The turbulence characteristics of flows over heterogeneous and patchy vegetation still present an ongoing issue, mainly due to the lack of experimental results. In this study we focus on turbulence spectral characteristics of the wintertime, nighttime boundary layer over heterogeneous terrain. Measurements were performed on a tall mast which was situated in a small area of walnut forest. Measurements at five levels above the canopy height (approximately h=18 m) were influenced by the upwind conditions which represent different types of surfaces, namely, agricultural land, forested hills and urban surfaces. We performed an analysis of the spectral structure, local isotropy and dissipation rates of turbulent kinetic energy. Results showed that horizontal and vertical velocity spectra have the predicted -5/3 slope in the high-frequency range indicating the existence of the inertial subrange at the upper four levels (z>1.5h), whereas the lowermost level (just above the canopy) is clearly influenced by the roughness elements showing that on average there is no well-defined inertial subrange. Testing the local isotropy hypothesis more thoroughly resulted in a ratio of the horizontal spectral densities (Sv/Su) approaching the 4/3, while the ratio of the vertical to the longitudinal spectral density (Sw/Su) was less than 1 for all levels indicating an anisotropic turbulence above the canopy. Spectral peaks of wind components showed clear height dependence with an apparent shift toward higher frequencies moving from the lowest to the highest level. Moreover, spectra of all velocity components exhibited strong stability dependence with a tendency for a peak shift to higher frequencies as stratification becomes more stable. Spectra normalized by the local friction velocity showed a good collapse in the inertial subrange for the three highest levels, suggesting that far from the canopy height the flow has reached a local equilibrium. The distinct features that we observed in our results might be attributed to different dynamic forcing caused by surfaces of different roughness that influenced the flow.

P2.37 Wind regime and filtering turbulent data in the CividatEX Experiment

Marco Falocchi *(Università degli Studi di Brescia, Italy), Stefano Barontini, Lorenzo Giovannini, Dino Zardi, Roberto Ranzi*

Results regarding the wind regime and filtering the turbulent data collected during Summer 2012 and 2013 in the framework of the CividatEX Experiment, are presented. The CividatEX Experiment, kicked off in July 2012 and still ongoing (Negm et al., 2013), aims at quantifying the mass and energy fluxes exchanged at the soil-atmosphere interface in an Alpine valley with complex terrain. A micro-meteorological station, equipped with standard meteorological devices, four TDR probes, soil heat-flux plate, soil thermometers and an eddy-covariance system (sonic anemometer and gas analyser), was installed on the valley floor of Valle Camonica at Cividate Camuno (274 m a.s.l., Oglio river basin, Central Italian Alps).

The experimental site is a gentle-sloping Technosol lawn, covered by common grass and surrounded by a steep hill (E and S) and by an anthropized landscape (W and N). Such complex terrain conditions affect the wind regime that is mainly characterised by thermally-driven local winds. Their occurrence, especially during fair weather conditions, is highly regular. The main drainage conditions are the Óra del Sebino wind

(WSW, speed ranging from 2 to 4 m/s), a coupled system of up-valley wind and lake breeze which rises the valley from Lake Iseo (Sebino) in the afternoon; and a katabatic flow with small speed (from 0.5 to 1.5 m/s) blowing down the hillslope (directions ranging from E to SE) since the evening to the sunrise. In addition two less recurrent winds can be recognised: a down-valley wind in the early morning (NE, from 0.5 to 1.5 m/s) and an anabatic up-slope flow (W, from 0.5 to 1.5 m/s) in the late morning.

The problem related to the separation of the surface-layer turbulence from the measured signal was faced. Three different separation approaches, i.e. the block average, the linear detrending and a digital recursive-filtering technique, were compared. The obtained dimensionless standard deviations of the wind velocities and of the temperature fluctuations were analyzed in the framework of the Monin-Obukhov similarity theory by checking their thickening on the similarity relationships. Due to the presence of meaningful unsteadiness during the investigated time-windows, the block average and the linear detrending proved to be less effective than the recursive-filtering procedure at separating the turbulent fluctuations from the mean-flow.

P2.38 Katabatic drainage flow characteristics on a low-angle slope around Arizona's Meteor Crater

*Norbert Kalthoff, **Bianca Adler** (Karlsruhe Institute of Technology (KIT), Germany), Manuela Lehner, C. David Whiteman, Sebastian W. Hoch*

A nocturnal katabatic drainage flow develops regularly on the low-angle slope (~1°) around the Barringer Meteor Crater in northern Arizona. Its characteristics are decisive for the occurrence of downslope-windstorm-type flows in the Meteor Crater basin. During the second Meteor Crater Experiment (METCRAX II) performed in 2013, comprehensive in-situ and remote sensing instruments were installed on the slope surrounding the crater.

Two different drainage flows formed typically on the slope and approached the crater basin – a shallow southerly local drainage and a deeper southwesterly mesoscale drainage flow. The local drainage flow was less than 20 m deep and was controlled by the small-scale terrain gradient. Above this flow layer the mesoscale drainage flow prevailed most of the night. It was caused by the large-scale terrain gradient, with the plain sloping gently towards the southwest. The depth of the mesoscale drainage flow varied during the different nights, probably depending on the ambient wind speed and stability. When the two drainage flows approached the crater rim, which extends about 35-50 m above the surrounding plain, the local drainage flow split and flowed around the crater, while at least parts of the mesoscale drainage flow passed the crater rim and intruded into the crater basin.

P2.39 Visualization of high-resolution surface temperature data collected in the Barringer Meteor Crater during METCRAX II

***Iris Feigenwinter** (University of Basel, Switzerland), Roland Vogt, Mathias Müller, Eberhard Parlow, Martina Grudzielanek, Mateja Maric, C. David Whiteman, Manuela Lehner, Sebastian W. Hoch*

The second Meteor Crater Experiment (METCRAX II) was conducted at Barringer Meteor Crater in Arizona in October 2013 to examine downslope-windstorm-type flows (DWFs) that occur when a mesoscale drainage flow forming outside the crater basin interacts with the crater topography. Three infrared (IR) cameras (two VarioCAM hr research (640x480 pixels) on the North-Rim and one VarioCAM High Definition (1024x768 pixels) on the South-Rim) looked into the crater and recorded the surface temperatures during several intensive operational periods (IOPs). A method to project the 2D infrared images onto a digital elevation model (DEM) with 1 m resolution is presented. The intersection between virtual lines of sight, which can be produced knowing the field of view and the position of the cameras, gives the information about the location of each pixel. This allows the visualization of the surface temperatures in the crater from bird's-eye view. Other measurements, e.g. radiative fluxes at the crater floor and near-surface air temperatures from automatic data loggers, can be compared with the georeferenced IR data. Surface temperature fluctuations are visualized by animations and correlated with the incoming DWFs from the southwest.

P2.40 Infrared imaging for air flow analyses in the Barringer Meteor Crater, Arizona, as part of METCRAX II

A. Martina Grudzielanek *(Ruhr-Universität Bochum, Germany), Roland Vogt, Jan Cermak, Iris Feigenwinter, Mateja Maric, C. David Whiteman, Manuela Lehner, Sebastian W. Hoch, Mathias G. Krausz, Christian Bernhofer, Andrea Pitacco*

In October 2013 the Meteor Crater Experiment II (METCRAX II) took place in the Barringer Meteor Crater, Arizona, USA. Downslope-windstorm-type flows (DWF), the main research object of METCRAX II, were measured by a comprehensive meteorological measurement setup that was installed in and around the crater. In addition, we installed five infrared (IR) cameras (VarioCAM® hr research & VarioCAM® High Definition, InfraTec) to measure the craters surface temperatures from different views. Measuring the surface IR temperatures inside the crater with 0.5 Hz sequenced IR data helped identify and understand the airflow dynamics and revealed fluctuations in inversion strength and depth. Hence, it was possible to detect coherent structures, warm air intrusions and flow regimes. The method was evaluated by comparing IR with other measurements of surface and air temperature data. In this presentation we discuss the potential of IR data visualization to improve understanding of airflow processes. The limitations of the IR method and the possibilities for combining IR with meteorological data to improve flow analyses in complex terrain are briefly discussed.

P2.41 Evaluation of infrared imaging for measuring near-ground flow dynamics at the Barringer Meteor Crater as part of METCRAX II

Mateja Maric *(Ruhr-Universität Bochum, Germany), A. Martina Grudzielanek, Roland Vogt, Jan Cermak, Iris Feigenwinter, C. David Whiteman, Manuela Lehner, Sebastian W. Hoch*

During the second Meteor Crater Experiment (METCRAX II) at the Barringer Meteor Crater in Arizona five infrared (IR) time lapse cameras (VarioCAM® hr research & VarioCAM® High Definition, InfraTec) were installed around the crater rim. In addition to the extensive measurement setup of METCRAX II the IR cameras observed crater surface temperatures from different viewpoints on the crater rim. Changes in high resolution surface temperatures are indicative of air temperature changes induced by flow dynamics inside the crater, including the downslope-windstorm-type flows (DWF) that were the main research focus of METCRAX II. By correlating IR temperature data with meteorological data obtained with other instruments during the Intensive Observational Periods, the applicability of this IR method of representing flow dynamics can be assessed. We present the evaluation workflow, discuss the limitations of the method, present the evaluation results and draw conclusions relative to the application of this method for observing air flow dynamics.

P2.42 Parameterization of subgrid wind speed sheltering/exposure in complex topography

Nora Helbig *(WSL Institute for Snow and Avalanche Research SLF, Switzerland), Henning Löwe, Adam Winstral, Tobias Jonas*

Complex topography is known to have a significant influence on the surface energy balance in mountainous terrain. This is mainly caused by the coupling to the turbulent wind field. Wind fields are altered by the topography giving rise to sheltering in lee directions or by the speed-up of the flow in windward directions of mountain slopes. Large wind speeds provoke turbulent heat and vapor exchange and can considerably increase snow ablation. In view of the prediction of snow depth distributions in complex terrain, a geometrical non-local terrain parameter was previously suggested to capture the effect of wind sheltering and allow for

simplified calculation schemes.

Given the similarity of the wind sheltering parameter to the geometrical terrain parameter used to capture the effect of shadowing we investigated non-local horizon terrain parameters on random topographies covering a wide range of terrain characteristics. Based on an analytically derived terrain sheltering/exposure approximation we obtained a parameterization for the spatially averaged terrain sheltering/exposure in complex topography. In coarse grid cells of large-scale meteorological or hydrological models subgrid topographies are mostly unresolved and a scaling of subgrid processes is required. The parameterization for the spatially averaged terrain sheltering/exposure solely requires easy to obtain subgrid terrain parameters in the grid cell of the coarse-scale model. We validated parameterized wind speeds, derived from numerically exact horizon slopes and measured or predicted exposed wind speeds, with measured sheltered wind speeds of surface measurement stations in Switzerland.

P2.43 Parameterization of orographic effects on surface radiation in AROME

Clemens Wastl *(ZAMG, Austria), Alexandre Mary, Yann Seity, Laura Rontu, Christoph Wittmann*

Complex topography has a significant influence on radiation fluxes at the earth's surface. As a consequence, slope angle and direction, sky view and shadowing by nearby mountains do also have a big impact on e.g. the temperature, local circulation, formation of clouds or triggering of convection in such areas. With increasing spatial resolution of weather forecast models, these effects gain also importance for numerical modeling. For a better representation of these topographic influences and thus for an improvement of the model performance over complex topography, a new parameterization of orographic effects on radiation has been introduced to the High Resolution Limited Area Model AROME. The formulation of the basic equations follows the approach of Müller and Scherer (2005). They suggested to modify the downward longwave (LWR) and the direct and diffuse shortwave radiation (SWR) fluxes by taking into account the different slope angles and directions, relief shadows (for direct SWR) and restricted sky view (diffuse SWR and LWR). The orographic correction of the surface radiation fluxes is based on three quantities: the slope parameter δsl, the shadow fraction δsh and the sky-view factor δsv. These parameters were calculated by using high resolution orography data from the Shuttle Radar Topography Mission (SRTM) with a horizontal resolution of three arcseconds (about 90m in Central Europe). All necessary fields are calculated and stored only once, to be used by the actual forecast run by the model. To avoid much preprocessing and storage of large amounts of time-dependent data, the concept of slope fractions was introduced following Senkova et al. (2007). Within each AROME grid square, slopes given by the high-resolution source data are classified into directional sectors according to the direction they are facing to.

First tests with the new orographic radiation parameterization scheme are quite promising. For selected test cases (clear-sky winter case, summer case with convection, autumn case with fog in valleys, etc.) the strongest effects could be observed in small Alpine valleys and at south-facing slopes, where the scheme simulates a heating of more than +1°C. On the other hand, the temperatures at the northern edges of the Alps are up to 1.0°C lower than in the reference AROME experiment. Intensive testing is ongoing at the moment, also over longer test periods. Not only the direct effect on the temperature fields, but also secondary influences on for example the formation of clouds, onset of convection, changes in the local wind system or effects on the development and dissolving of elevated fog due to the new radiation parameterization scheme is investigated.

P2.44 Olympic HARMONIE 2014

Laura Rontu *(Finnish Meteorological Institute, Finland), Sami Niemelä, Alexander Mary, Yann Seity, Clemens Wastl*

The winter Olympic Games 2014 in Sochi offered a testbed for the high resolution limited area numerical weather prediction (NWP) systems, applied over complex topography. 12 deterministic and ensemble forecasting systems with a horizontal resolutions from 250 to 2500 metres from 8 national weather services provided operational weather predictions during the Games in February-March 2014. WMO Forecast and Research in the Olympic Sochi Testbed (FROST) 2014 focused on validation and intercomparison of the models by utilizing the observations of the enhanced surface-based weather station network over the Olympic domain at Caucasian mountains and Black Sea coast. According to the validation, the one-kilometer resolution deterministic HARMONIE (Hirlam-Aladin Regional Meso-scale Operational NWP in Europe) applying AROME physical parametrizations and ALADIN nonhydrostatic dynamical core, produced mostly good wind, temperature and fog forecasts. However, a large night-time cold bias at the mountain sites was revealed.

The present study focuses on evaluation of the influence of orography representation in the HARMONIE forecasts. HARMONIE relies on a terrain-based vertical coordinate, which is based on smoothed mean orography. The data assimilation, postprocessing and verification of any NWP system use surface-based observations, located at certain elevation, which may differ from the model's smoothed surface elevation. For the parametrizations of orographic effects on near-surface momentum and radiation fluxes, additional subgrid-scale variables are derived from the high-resolution surface elevation data. In the Sochi HARMONIE, the surface elevation was based on the Global 30 Arc-Second Elevation (GTOPO30) data, representing topography with 30 arc second (ca. 1 km) horizontal resolution. The resolution was thus practically the same as in the model itself, excluding the sub-grid-scale orographic parametrizations. In the present study, we replaced the GTOPO30 surface elevation with Shuttle Radar Topography Mission (SRTM) of 3 arc second (ca. 90 m) data.

We introduced new parametrizations for the orographic effects on radiation and momentum fluxes. Both the mean orography for model dynamics and the subgrid-scale orographic parameters, such as the variance of the surface elevation for small-scale orography effects on momentum fluxes or the slopes and sky view factor for radiative fluxes, were derived from SRTM data. We test the influence of the updated orography representation and parametrizations against the FROST 2014 temperature and wind observations during February 2014. To understand the relations of the various parametrized process we also perform sensitivity tests using MUSC, the single column version of HARMONIE.

P2.45 High-resolution forecasts of the thermal comfort in the urban area of Trento

Lorenzo Giovannini *(University of Trento, Italy), Dino Zardi*

A forecasting system composed of the Weather Research and Forecasting (WRF) model coupled with a single-layer urban canopy parameterization scheme is implemented to perform high-resolution forecasts of the human thermal comfort inside the urban area of Trento, a medium-sized city located in the Italian part of the Alps. Simulations with the WRF model are routinely performed at 1-km resolution over the Province of Trento, to provide suitable meteorological upper boundary conditions to the urban canopy model. The single-layer urban parameterization scheme is used to downscale the WRF forecasts inside the urban area, taking into account the local characteristics of the city, and to calculate indexes for the bio-meteorological assessment of the thermal environment. Gridded maps of urban canopy parameters (UCPs) and anthropogenic heat emissions are utilized as input for the urban canopy model. UCPs are obtained with GIS techniques from LIDAR maps with an horizontal resolution of 1 m, while anthropogenic heat emissions from detailed energy consumption and vehicular traffic data. Results from the modeling system are validated against measurements from different field experiments. The validation involves both the forecasts with the WRF model, which are particularly challenging in a region characterized by highly complex terrain, and the thermal field inside the city calculated by the urban parameterization.

P2.46 Prognostic deep convection interaction with mountains in 2-8 km resolution

Martina Tudor *(Meteorological and Hydrological Service, Croatia), Stjepan Ivatek-Šahdan, Antonio Stanešić*

The schemes that parametrize the contribution of deep moist convection assume that the convective cells occupy a small portion of the grid cell as long as the model resolution is above the so called grey zone usually taken to be in the range from 3 to 8 km or similar. It is further assumed that models that run with grid meshes lower than 3 km fully resolve motions associated with deep convection and that the parametrization of deep convection is not needed in high resolution. However, convective motions associated to atmospheric fronts are large and organised so that they can be resolved with horizontal grids larger than 8 km. On the other hand, moist convective motions that result in precipitation can have horizontal extent of less than 3 km and are not resolved with models using that horizontal resolution. The extent of the grey zone is therefore dependent on the weather. A scheme that parametrizes deep convection in a way that the above assumption is not needed has been implemented in the ALADIN model. The scheme is modular multi-scale micro-physics and transport (3MT) scheme. It is used for operational forecast in the Croatian Meteorological and Hydrological Service. Both moisture convergence and CAPE closure are available as well as a combination of them, the first one performs better for most cases of severe convection, while using the other is better for cases with light sub-grid showers. The combined closure is the one used operationally since it allows optimal forecast in both weather patterns and tuning of the schemes performance. The operational turbulence scheme uses prognostic TKE and interacts with deep convection in multiple ways through closure and fluxes. The scheme also parametrizes contribution of shallow convection. The prognostic deep convection scheme is used for operational forecast in CMHS with horizontal resolution of 2, 4 and 8 km. Over flat terrain, precipitation amount moves from the convective to the resolved precipitation with increasing resolution. But this is not generally valid over mountains, especially in cases of severe torrential rain, when higher resolution model also resolves more details, mountain tops and ridges raise higher and this affects the triggering of precipitation and the total amount forecast by the model.

P2.47 The overview of the operational forecast using ALADIN model with NH dynamics

Martina Tudor *(Meteorological and Hydrological Service, Croatia), Stjepan Ivatek-Šahdan, Antonio Stanešić*

The nonhydrostatic and hydrostatic primitive equation versions of the dynamical kernel are implemented in the ALADIN model as a single package activated through a logical switch. Since both can be used with the same horizontal and vertical discretization, time-stepping and advection schemes (there is a choice for each of these schemes in ALADIN), it is possible to distinguish the differences in the model forecast due to introduction of nonhydrostatic component in the context of operational numerical weather prediction. Operational numerical weather prediction in the Croatian Meteorological and Hydrological Service relies on a high resolution dynamical adaptation of wind field that has proven to be essential for the prediction of severe wind events in mountainous terrain along the Adriatic coast. In the operational suite, a 2 km resolution 24 hour forecast was established since 1 July 2011, that uses non-hydrostatic (NH) dynamics and the full parametrization set, including radiation, microphysics and convection schemes. It runs on the same domain as the hydrostatic dynamical adaptation. The NH run uses semi-implicit semi-lagrangian scheme to solve the dynamical and advection terms and semi-lagrangian horizontal diffusion. ALADIN uses a simple microphysics scheme with prognostic cloud water and ice, rain and snow and a statistical approach for sedimentation of precipitation. The operational radiation scheme that describes the transfer, scattering, absorption and reflection of the shortwave solar radiation and longwave thermal radiation of the Earth's surface and clouds is simple and computationally cheap since it uses only one spectral band for long-wave and one for short-wave radiation computations. The turbulent exchange coefficients are computed using prognostic values of turbulent kinetic energy (TKE). The surface scheme used in the operational forecast is ISBA (Interaction Soil Biosphere Atmosphere). The parametrization of convection is used even in the 2 km resolution forecast since its formulations disables double counting for the convection in the resolved and stratiform part. The deep convection is a prognostic mass-flux scheme where convective processes are treated with the use of prognostic variables for updraft and downdraft vertical velocities and mesh fractions. The NH run has been able to predict short duration events of severe bura as well as calm periods in the long bura events that were not predicted by other runs in the operational suite. However, its forecast also yields errors due to wrong timing of such events (by few hours). The errors in the model forecast have revealed the need for better representation of the surface characteristics especially in the mountainous terrain.

P2.48 Verification of extreme weather warnings in Austria

Christoph Zingerle *(ZAMG, Austria), Simon Hölzl*

One of the core duties of the national weather service of Austria (ZAMG) is to alert civil protection services of extreme weather events and issue warnings the general public. Based on model guidance, meteorological experience and knowledge about local effects of topography, duty forecasters identify regions where a significant amount of precipitation or high wind speed is likely to exceed warning thresholds. Depending on the forecasted amount of precipitation or the expected level of wind speed, the warning system decides autonomously on the level of alert in each community. This decision is taken based on the return period of the forecasted event: the higher the return period, the higher the level of alert.

Due to the topography of the Alps, the influence of local effects on the general circulation is high. A dense observational network is beneficial to observe and resolve these local effects. Providing data from 250 automated weather stations every 10 minutes, the observational network of the Austrian weather service is one of the densest in the world. It is, however, not able to catch extreme weather for all communities in Austria. This is mainly due to representativeness of stations with respect to extreme events. Especially when observing extreme wind events, a relatively high number of station needs to be blacklisted and thus excluded from the verification process. Keeping data of non-representative stations would gravely deteriorate verification results.

For the verification of extreme weather warnings a framework will be presented, that is capable to account for a number of forecast and observation uncertainties. Inherent to the warning process it is impossible to decide on exact event start and end time. A similar problem exists when forecasting the precipitation amount or wind gust for each community individually. Furthermore, warning levels are exact numbers and an observation close to the warning level would be verified as NO-event if it does not exceed the alert level. An even more advanced problem is the fact, that defining observations for a certain warning event provides only hits and false alarms in the contingency table. Missed events and correct negatives need to be determined applying a separate algorithm based on forecasters experience. Given this high grade of uncertainty, the verification system allows a certain inaccuracy or fuzziness of timing and expected extremeness of an event.

P3 Poster Session: Poster Session 3

P3.1 Wind Forecast Verification during Various Bora Events at Dubrovnik Airport

Jadran Jurković *(Croatia control ltd, Croatia), Igor Kos*

Several airports are situated in the lee side of the Dinaric Alps where the bora flow is well-known. Bora reduces air traffic operations especially if its direction is perpendicular to the runway direction as is the case at Dubrovnik airport.

Terminal Aerodrome Forecast (TAF) is important in decision making during the flight planning process. TAF wind forecasts are verified compared to observed METAR reports in the period 2009-2014. Climatology shows that the frequency of hours with NE wind greater than 7.5m/s (15KT) is 10-15% in winter time. Bora is dominantly driven by large scale dynamics, hence it is forecasted well. The diagnostic verification results are shown according to lead time, issue time, months. Additionally, profiles from ALADIN model are used to determine the type of flow (shallow, deep or nocturnal downslope flow).

P3.2 Scale dependent evaluation of mesoscale low level winds obtained with ALADIN MNWP model

Mario Hrastinski *(Croatian Meteorological and Hydrological Service, Croatia), Kristian Horvath, Iris Odak, Stjepan Ivatek-Šahdan, Alica Bajić*

In the complex terrain of the eastern Adriatic where wind climate is governed by regional and local winds, it is beneficial to utilize a chain of numerical models to refine wind predictions. Verification of these mesoscale flows is a challenging task for which adequate approaches still need to be revised and defined. Traditionally used statistical scores (MBIAS, RMSE, MAE, etc.) seem to be insufficient for that purpose since small spatial and temporal errors of generally well simulated phenomena can profoundly change the verification results. Therefore, besides moment-based verification, we used spectral analysis as a supplementary verification method to provide a scale dependent measure of model performance, with emphasis on understanding the sources of prediction errors through relating various aspects of physical and spectral verification measures.

The verification was performed on wind forecasts obtained by Aire Limitée Adaptation dynamique Développement International (ALADIN) MNWP model with 8 km horizontal grid spacing in period 2010-2012. These forecasts were further refined to 2 km grid spacing using: i) full-physics based model and ii) so-called dynamical adaptation method (DADA) over subdomain that covers broader area around Croatia. Major objectives of this study were to: i) determine whether an increase of model horizontal resolution and/or complexity improves the accuracy and ii) quantify the importance of different sources of errors and inspect the potential correlation of moment-based measures with various spectral scores.

Based on variety of statistical and spectral scores, it is suggested that the results generally improve with increasing the model horizontal resolution and complexity. The largest portion of root-mean square errors (RMSE) can be attributed to phase errors (PHE), while the most significant increase of accuracy was found for diurnal and sub-diurnal periods of motions. Furthermore, we found a significant correlation between the share of the bias of the standard deviation (BSD) in RMSE and model ability to properly simulate the ratio of modeled and measured power in individual spectral range. For bora dominated coastal stations a considerable correlation exists between the share of measured power within individual spectral ranges and the share of individual sources of errors (PHE, BSD and the bias of the mean-BM). Finally, it was shown that simplified DADA forecasts were valuable in forecasting wind properties on a majority of stations, except for those near the very coast and steep terrain where full-physics based model was more successful in representing regional/local wind systems.

P3.3 The Turb-i-Sim project: Evaluation of COSMO-simulated diurnal valley winds in the Swiss Alps

Jürg Schmidli *(ETH Zurich, Switzerland), Steven Böing, Oliver Fuhrer*

Thermally driven wind systems, such as the diurnal slope and valley winds, have a large influence on mountain weather and climate. These wind systems are not only a key component of the wind climate in mountain valleys, but they also influence the formation of orographic clouds and convective storms. In current numerical weather prediction (NWP) models (with a grid spacing of 2 km) these winds are often poorly represented. The next generation of NWP models will run with a grid spacing of about 1 km. As part of the Turb-i-Sim project, a collaborative effort between ETH and MeteoSwiss, this study investigates the diurnal wind system in the Swiss Alps in the km-scale NWP model COSMO. Of particular interest is the influence of grid resolution and land surface datasets on the accuracy of the simulated diurnal valley winds. COSMO simulations at 2.2

and 1.1 km resolution are conducted for a fair-weather summer period in July 2006. This episode is characterized by strong daytime up-valley flows, weak nighttime down-valley flows, and the formation of shallow convection over the mountains, which transitions to precipitating convection in some areas. For most locations, the valley wind in the 1.1 km simulation is much closer to the observations, as might be expected. Nevertheless, there are large differences in the model skill for the different locations and for some locations the skill is not improved with the higher resolution. Detailed sensitivity experiments are undertaken in order to investigate the causes of these differences and more generally to investigate criteria for an accurate simulation of real-world diurnal valley winds.

P3.4 The impact of assimilating data from a remotely piloted aircraft on simulations of weak-wind orographic flow

Hálfdán Ágústsson *(IMO, Iceland), Haraldur Ólafsson, Marius O. Jonassen, Ólafur Rögnvaldsson*

Orographic winds near a 914 m high mountain in Southwest-Iceland are explored using unique observations made aloft with a small remotely piloted aircraft, as well as with traditional observations and high-resolution atmospheric simulations. There was an inversion well above mountain top level at about 2 km with weak winds below. Observed winds in the lee of the mountain were indicative of flow locally enhanced by wave activity aloft. Winds descended along the lee slope with a prevailing direction away from the mountain. They were relatively strong and gusty at the surface close to the mountain, with a maximum at low levels, and weakening and becoming more diffuse a short distance further downstream. The winds weakened further aloft, with a minimum on average near mountain top level. This situation is reproduced in a high-resolution atmospheric simulation forced with atmospheric analysis as well as with the observed lee-side profiles of wind and temperature below 1.4 km. Without the additional observations consisting of the lee-side profiles, the model fails to reproduce the winds aloft as well as at the surface in a region in the lee of the mountain, as was also the case for the operational numerical models at that time. A sensitivity simulation indicates that this poor performance is a result of the poorly captured strength and sharpness of the inversion aloft. The study illustrates, firstly, that even at very low wind speed, in a close to neutral low-level flow, gravity waves may still be a dominating feature of the flow. Secondly, the study presents an example of the usefulness of lee-side atmospheric profiles, retrieved by simple model aircraft, for improving numerical simulations and short-term weather forecasting in the vicinity of mountains. Thirdly, the study confirms the sensitivity of downslope flow to only moderate change in the sharpness of an upstream inversion.

P3.5 Spatial and temporal variability in snow surface temperatures induced by boundary layer processes

Lisa Dirks *(WSL Schnee- und Lawinenforschungsinstitut SLF, Switzerland), Sebastian Schlögl, Rebecca Mott*

Latest assessments of snow pack models showed weaknesses in modeling snow melt in the later ablation season when the snow surface becomes patchy. These weaknesses could be caused by boundary layer processes which are not considered in the model but considerably contribute to the ablation patterns and the total magnitude of snow melt. Thus the aim of the presented work is to identify boundary layer processes driving the spatial and temporal variability of snow surface temperatures, finally proceeding in ablation patterns.

The influence of boundary layer processes, such as thermally-driven flows or the formation of stable internal boundary layers, on the spatial and temporal variability in the snow surface temperature is investigated in the Dischma valley (Davos, CH) during the ablation season 2015. Information on the wind circulation system is provided by transects of meteorological stations equipped with anemometers (Sensorscope) and two towers with sonic anemometer profiles. High resolution (temporal and spatial) surface temperature measurements are obtained by a thermal infrared camera (VarioCam HD, Infratec GmbH). The camera has a spatial resolution in the range of centimeters and is capable of measuring with a frame rate of 15s^(-1). The infrared data is georeferenced and processed regarding to incidence angle of the measurement and the snow surface structure. For further evaluation the temperature patterns are compared to model results from the radiation module of the Alpine 3D energy balance model run for the Dischma field site and to ablation rates obtained by terrestrial laser scanning.

Preliminary results show a considerable influence of boundary layer processes (i.e. cold-air pooling, advective heat transport) on local ablation rates (not only accelerating but also slowing down ablation). Furthermore, local topographic parameters play a crucial role for the observed surface temperature patterns. The spatial and temporal highly resolved measurements on snow surface warming lead to a better process understanding of the snow cover ablation as a function of snow cover fraction.

P3.6 Validation of bulk-transfer parameterizations of sensible heat flux over snow in complex terrain

*Mathias Dusch, Marc Olefs, Ivana Stiperski, **Friedrich Obleitner** (University of Innsbruck, Austria)*

SNOWGRID is an operational snow cover model which is currently developed by ZAMG. The model is driven by output from the nowcasting system INCA and calculates the spatial distribution of snow height and water equivalent in high spatial and temporal resolution across Austria. An energy balance approach is used to model the snow evolution and the associated processes. The radiation components come from a complementary model development (STRAHLGRID) and the turbulent heat fluxes are parameterized using a bulk-aerodynamic approach driven by windspeed and air temperature derived from INCA model output.

We present an investigation of the skill of the used parameterization of wintertime sensible heat flux in complex terrain thereby also studying the effect of differently derived input parameters. The calculated fluxes are compared to eddy covariance data measured at two sites in the Inn Valley during winter 2013/2014. We here consider two sites located at the valley bottom and at a slope and

the available data are evaluated applying state of art procedures concerning e.g. quality control, coordinate rotation or corrections.

The validation results show that at the valley bottom the straightforwardly calculated sensible heat fluxes compare to the measured one with moderate skill only (RMSE=61W/m2; r2 =0.27 using INCA input). For comparison, the same parameterization yields RMSE=33W/m2 (r2 =0.71) if forced with measured input data. Fluxes tend to be underestimated generally and the validation results are strikingly worse at the slope site.

Sensitivity studies reveal that the gross uncertainty comes from inadequately simulated surface temperature, which is true for both sites and indicates directions of corresponding model improvement. At the slope site, uncertainty in input wind speed plays a critical role as well, which is attriuted to frequently occuring katabatic winds. The correspondingly low-lying wind maximum questions the applicability of the MOS-framework and challenges the representativeness of the directly measured fluxes, respectively. The outcome of this study is not only valuable to correspondingly improve SNOWGRID itself. However, it may be also relevant for other models (atmospheric or snow) treating the energy balance over snow in complex terrain.

P3.7 Contribution of the turbulent heat fluxes to the summer melt of Saint-Sorlin glacier in the French Alps

*Maxime Litt, **Jean Emmanuel Sicart** (IRD, France), Delphine Six, Warren D. Helgason*

On mountain glaciers, large errors may affect turbulent surface heat fluxes measurements, which may lead to uncertainties in estimating melt from surface energy balance (SEB) methods. We study the role of turbulent surface heat fluxes and their measurement biases on the modeled melt of the small Saint-Sorlin Glacier (French Alps, 45N, 68E, 3km2) during the summers of 2006 and 2009 characterized by contrasted wind conditions. Air-temperature and wind-speed vertical profiles and high frequency turbulent data, collected in the surface layer, are used to characterize the wind conditions, the turbulence and the turbulent fluxes in the surface layer and their links with the valley circulation and the large scale forcing. In weak synoptic forcing, local thermal effects dominate the wind circulation. On the glacier, weak katabatic flows with a wind-speed maximum at low height (2-3 m) are detected 70% of the time and are associated to weak turbulent fluxes. When the large scale forcing is strong, the wind in the valley aligns with the glacier flow, intense downslope flows are observed, no katabatic wind-speed maximum is visible below 5 m, and the turbulent fluxes are high. For both regimes turbulent kinetic energy relates poorly to the mean temperature and wind-speed gradients in the surface layer, probably because of the interaction of large-scale orographic disturbances with the surface layer flow when the forcing is strong, or low frequency oscillations of the katabatic flow when the forcing is weak. As a result the bulk aerodynamic method tends to underestimate the fluxes. During the 2006 melt season when weak synoptic forcing conditions were frequent, the bias on the surface energy balance calculation is negligible because turbulent fluxes remain weak. During the 2009 melt season when strong large scale forcing is frequent, the induced biases on the surface energy balance lead to a significant underestimation of the melt.

P3.8 Radiative properties of clouds over a tropical Bolivian glacier: seasonal variations and relationship with regional atmospheric circulation

Jean Emmanuel Sicart *(IRD, France), Jhan Carlo Espinoza, Louis Quéno, Melissa Medina*

At low latitudes, strong seasonal changes in cloud cover and precipitation largely control the mass balance of glaciers. Measurements of shortwave and longwave radiation fluxes reaching Zongo glacier, Bolivia (16°S, 5060 m asl.), were analyzed from 2005 to 2013 to investigate cloud radiative properties. Cloud shortwave attenuation and longwave emission were greater in the wet summer season (DJF) than in the dry winter season (JJA) probably because most DJF clouds were low warm cumulus associated with local convection, whereas JJA clouds were frequently altostratus associated with extra-tropical perturbations. Solar irradiance was high all year round and cloud radiative forcing on down-welling fluxes was strongly negative; with monthly averages ranging from 60 to 110 W m-2 from the dry to the wet season, respectively. In the wet season, high extraterrestrial solar irradiance and low shortwave transmissivity caused very negative cloud forcing despite the high longwave emissivity of convective clouds. ERA-interim reanalysis of wind and geopotential height anomalies and NCAR/NOAA outgoing longwave radiation satellite data were used to characterize the regional atmospheric circulation causing large cloud covers (10% thickest clouds) during the dry (JJA), transition (SON) and wet (DJF) seasons. Around 87% [80%] of cloud events in JJA [SON] occurred during the incursion of low-level southern wind from southern South America to the Bolivian Andes, which caused 2-3 days of cold surge episodes in the Cordillera Real. Around 13% of cloudy days in JJA were associated with high-level low pressure conditions over the Chilean coast around 45°S, including cut-off lows. In SON, 20% of cloudy days were associated with summer conditions, characterized by an active Bolivian High and moist air advection from the Amazon basin. In the wet season, only 46% of large cloud events were associated with low-level southern wind incursions, the other events being associated with the South American Monsoon.

P3.9 The energy and mass balance of tropical Lewis Glacier, Mount Kenya, and its sensitivity to climate

Rainer Prinz *(University of Innsbruck, Austria), Lindsey Nicholson, Wolfgang Gurgiser, Thomas Mölg, Georg Kaser*

Glaciers in the tropics can provide information about regional climate, its dynamics, and its evolution over decadal and centennial time scales, if their interaction with the atmosphere is understood, and their changes are documented or reconstructed. The glaciers on Mount Kenya capture a climate signal from the mid troposphere at about 5 km a.s.l., where our knowledge of climate change is scarce and controversial.

We use in-situ meteorological and glaciological observations to optimize and validate a physically-based, process-orientated energy and mass balance model to quantify the exchange processes between the glacier surface and the atmosphere above and to explore the sensitivity of energy and mass exchanges to changing climatic conditions. Atmospheric reanalysis data and long term glaciological observations provide a baseline against which the results of the sensitivity study are interpreted over climatological time scales.

P3.10 Simulation of snow dynamics at different scales in a high-elevation catchment

Michael Engel *(Free University of Bozen-Bolzano, Italy), Giacomo Bertoldi, Claudia Notarnicola, Stefano Endrizzi, Georg Niedrist, Francesco Comiti*

The availability of fresh water in mountain regions is governed by snow cover distribution, snow amount and timing of melt, which depend on local climatic conditions. Particularly in complex terrain, meteorological conditions and topography control the spatial heterogeneity of snow cover and call for the use of physically-based distributed hydrological modelling of snow covered area (SCA) and of snow water equivalent (SWE). However, the inherent complexity of such advanced modelling requires an accurate evaluation of model results against ground observations and satellite products both at point and at catchment scale before their operational use.

In this context we evaluate the capability of the new model GEOtop 2.0 to simulate snow dynamics at point and at catchment scale in the upper Saldur catchment (61 km²) in the Eastern Italian Alps. At point scale, simulated snow depths and SWE from the period 2009 – 2013. were calibrated against measured snow depth data from measuring sites at different elevations (1930 m - 3035 m a.s.l.) within and close to the Saldur catchment. The statistical indices (R^2 and mean absolute error) were calculated to evaluate the performance of different model parameterisations within a manual sensitivity analysis of 11 key parameters controlling the snowpack and the meteorological input data. We found that SWE and snow depth were mostly controlled by key parameters related to albedo, snow water saturation and by the accuracy of the input precipitation and the estimation of its phase partitioning.

At catchment scale, simulated SCA of the upper Saldur catchment was validated against the daily composite EURAC MODIS SCA at 250 m resolution. The pixel-based overall accuracy and the kappa coefficient were calculated to identify spatial and temporal accuracies between simulated and observed SCA. These accuracies were then related to topographical characteristics of the catchment. The analysis highlights that the largest uncertainties in winter are associated with forested areas, where the MODIS product tend to underestimate SCA. In autumn major differences are associated with elevations between 2500-3000m a.s.l. covered by rocks with a high surface roughness indices between -0.25 and 0. Differences could be likely related to small scale snow redistribution processes induced by wind and gravity. Uncertainties in Spring 2013 could not be related to single topographical characteristics but could result from incorrect spatial precipitation interpolations confirmed also by the findings at point scale. Results underline the key role of an accurate and fine spatial scale representation of the spatial distribution of meteorological parameters, and in particular precipitation, radiation and wind, in order to properly model SCA and SWE with physically-based distributed hydrological models.

P3.11 Potential of the use of high-resolution meteorological forecasts for snowpack modelling in the Pyrenees

Louis Quéno *(Centre d'Etudes de la Neige, CNRM-GAME, France), Vincent Vionnet, Ingrid Dombrowski-Etchevers, Matthieu Lafaysse, Fatima Karbou, Samuel Morin*

A major challenge of avalanche hazard forecasting and mountain hydrology is to take into account the high spatial variability of the snow cover in mountains. This variability depends on the regional climatology, geographical location within the mountain range, orography (altitude, slope, aspect) and microscale processes. High-resolution meteorological forecasts at kilometre scale over mountainous terrain offer new potential for the atmospheric forcing of snowpack models in order to represent the regional snowpack variability.

In this study, high resolution forecasts from the NWP system AROME are used as inputs to the snowpack model SURFEX-ISBA/Crocus (hereafter Crocus) for snowpack simulations at 2.5-km grid spacing in the Pyrenees, during four very contrasted winters (from 2010/2011 to 2013/2014). AROME-Crocus is evaluated in terms of snow depth through comparisons with both daily in-situ observations of 55 stations in France and Spain, and reference simulations forced by SAFRAN reanalyses (provided at various elevations for geographical areas assumed to be meteorologically homogeneous and including a precipitation analysis). This first study highlights an overestimation of snow depth simulated by AROME-Crocus. The spatial distribution of the bias is analyzed through a comparison with the reference simulations, and shown to be associated with specific synoptic patterns.

We focus then on daily snow depth variations, to prescind from the cumulative errors during one season. Their distribution by category shows an underestimation by AROME-Crocus of strong accumulation days, although they are better represented than by SAFRAN-Crocus. The positive bias is mainly due to the underrepresentation of strong ablation days. This category includes non-simulated small scale processes like wind-induced erosion, but the models also underestimate strong melting days.

Finally, the potential of AROME-Crocus is studied for high impact events. The AROME microphysics scheme enables forecasting of freezing rain events, like the one of 6th January 2012 that created a 5-cm thick ice layer in the Pyrenees and caused numerous accidents and 9 fatalities. We study it starting from the diagnostic of freezing rain to the formation of an ice layer within the snowpack model.

P3.12 Trend analysis of snow water equivalent in the Alps

Anna-Maria Tilg *(WSL - Institut für Schnee- und Lawinenforschung SLF, Switzerland), Christoph Marty, Tobias Jonas, Michael Kuhn*

Snow water equivalent (SWE) is an essential property to describe the temporal storage of water in the snow cover. Therefore, information about the regional and annual variability of SWE is important as it impacts for example water supply in numerous areas of the world. Additionally, the hydropower industry is interested in SWE to forecast the discharge for an efficient energy production. Snow load codes are also determined with information about the maximal amount of SWE.

We analysed long-term variability and trends of SWE measurements to determine how climate change impacts SWE. The used stations are located in Austria, France, Germany, Italy and Switzerland between 500 and 3000m asl., whereby some stations have 60 or more years of data. The number of available stations varies between 20 and 66 depending on season and length of time series. The results of the trend analysis show that most of the time series have a non-significant negative trend, independently of the region or the altitude of the station. The percentage of significant negative trends is higher for spring SWE than for mid-winter SWE. Additionally, relative decreases of significant trends are stronger for low-elevated stations than for higher stations.

P3.13 Snow melt frequency in a mountainous temperate maritime environment

Michael Spencer *(University of Edinburgh, United Kingdom), Richard Essery*

Predicting snow melt potential is important for managing water resources and hazard. Knowing which areas are likely to have the highest snow melt allows us to target hydrological observation equipment and plan for societal resilience to natural hazards. A degree day snow accumulation and melt model has been developed for Scotland. This model is driven using historic Met Office station data and interpolated grids and calibrated with snow observations from ground based and remotely sensed records. The model has been run for over 30 years allowing account of rare snow melt events to be made. Statistical analysis of these extreme snow melt events has defined a recurrence magnitude relationship, i.e. how often do we get what size of snow melt event? Our poster summarises input data, the modelling process and maps the spatial variability of snow melt in Scotland.

P3.14 Snow depth extremes in Austria: Spatial modeling with extremal coefficients

Harald Schellander *(ZAMG, Austria), Naomi Auer, Tobias Hell, Stefan Rainer, Claudia Schmuck, Christoph Zingerle*

There is great need for a spatially coherent estimation of extreme snow depths in a number of applications. Simple interpolation after pointwise estimation leads to inaccurate results that in addition lack the possibility to infer uncertainties. Two widely used statistical approaches (smooth spatial modeling, max-stable processes) compete for accuracy and spatial dependency. By taking into account a measure of extremal spatial dependency between all stations as additional covariate (extremal coefficients), the other two possibilities are both outperformed by a better representation of the shape parameter of the extreme value distribution. In addition the new model is not only able to obtain but also to reduce uncertainties of snow depth extremes. We show extreme snow depth maps of Austria computed with the new model.

P3.15 Spatial validation of an operational snow cover model over the eastern Alps using remote sensing data

Marc Olefs *(ZAMG, Austria), Gabriele Bippus, Elisabeth Ripper*

We use fractional snow cover (FSC) products generated from MODIS data covering the Alpine area and lowlands to perform a spatial validation of the results of the operational snow cover model SNOWGRID used at the Austrian national weather service ZAMG. The SNOWGRID model calculates total snow depth and total snow water equivalent (SWE) with a temporal and spatial resolution of 15 minutes and 100 m, spanning a rectangular domain around Austria with 28 m points. For the validation of the SNOWGRID products the FSC products from MODIS data are interpolated to the SNOWGRID model domain. The fractional snow cover and snow depths from EO data and the model, respectively, are converted into binary snow information by applying thresholds on each of the products. For the comparison and calculation of quantitative performance measures contingency tables such as the hit rate or the Kuiper's skill score are used. We show detailed results of this comparison for the extended 2013/14 winter season (Sept-May), during which more than 60 days with cloud cover less than 50% over the model domain allowed a statistically significant comparison. The results demonstrate that snow products from EO data have great potentials for assessing the spatial performance of such a model, to detect its weak points and to improve specific processes in the model such as the snow line depression effect in Alpine valleys which is included in the model. The SNOWGRID model results are already tested and operationally used by Austrian avalanche warning, hydrological and road maintenance services as well as hydro power companies as a supporting tool, and are thus highly relevant to specific users as well as the general public.

P3.16 Proposal for avalanche risk management on the access road to the ski area of Campitello Matese (mountain massif of Matese - Molise region - Central Italy)

Antonio Cardillo *(Agenzia Regionale Di Protezione Civile, Italy), Massimiliano Fazzini, Sandra Scarlatelli*

The mountain massif of Matese is one of the most important "water castles" of the Italian peninsula, thanks to its geographical location and characterization physiographic media. Located on the border between the regions Molise and Campania region. The main axis is about 35 km long and is oriented NW - SE, with maximum odds over 2000 meters. The massif is equidistant between the Tyrrhenian Sea and the Adriatic Sea, favoring the forced lifting of air masses from both West that from the East, and thus generating abundant annual rainfall, exceeding 1800 mm.

The intense precipitation events and morphology extremely complex, favor flowslides snow in many areas of the massif, in fact, the analysis of the time series nivometrica, spanning more than 20 years, shows a regime nivometrico type "balanced or Etale" with abundant snowfall total in relation to the share albeit characterized by considerable variations intraseasonal.

Monitoring and Avalanche avalanche is ensured by the Service of the State Forestry Meteomont who runs the snow field manual in Campitello Matese at an altitude of about 1400 m above sea level In recent years this type of survey has been joined to automatic type managed by the Regional Civil Protection.

The proposed work suggests a methodology of intervention to manage the risk of avalanches on the stretch of road link between the village of San Massimo and the ski resort of Campitello Matese, by morphometric analysis of the channels of power and the use of technologies wireless mesh type network, for reporting of events and the safety of the site.

The aim is to manage the avalanche risk, systems with low coast and ensure access to the ski resort, particularly popular from the point of view of tourism, with a few million visitors per year, waiting to carry out works passive and active commissioning safe slope and stabilization of the snowpack.

The hypothesis technology is to employ wireless sensors (WSN) with accelerometers and ropes tear that, in case of an event, activate both signal lights, both the Authorities concerned, is a special plan of civil protection for the safety and the reclamation of the area subject to avalanches.

P3.17 Study on snow, snow avalanches and danger levels in Bucegi and Făgăraş Mountains-Southern Carpathians (Romanian Carpathians). Preliminary results

Mircea Voiculescu *(West University of Timisoara, Romania), Narcisa Milian, Dana Micu*

Snow avalanches are common in mountain environments and often threaten man’s activities (tourism practices, especially), settlements, housing, roads and life and cause numerous fatalities and injuries. This natural hazard is very present in the Bucegi and Făgăraş Mountains-Southern Carpathians (Romanian Carpathians), here registering the highest number of losses in human lives. Therefore, these mountain areas are recently monitored by the Programme of Nivometeorology within theNational Administration of Meteorology (PN-NAM), founded in 2003-2004 winter season within the National Administration of Meteorology in partnership with Météo France, Centre d’Études de la Neige-Grenoble. The main purpose of the programme is to study snow and its future evolution as well as avalanche triggering conditions. The PN-NAM has one nivometeorological laboratory in Făgăraş massif and two laboratories in the Bucegi Mountains.

In examining the snow depth, the snow avalanche activity and the snow avalanche events, two different periods can be defined: from 1979 to 2004 for Făgăraş Mountains, and from 1961 to 2004 from Bucegi Mountains (year of founding of PN-NAM) and from 2004 to 2013, for the months December through to May.

The purpose of this study is: (i) to supplement previous researches on snow and on snow avalanche activity in these two mountainous areas; (ii) to obtain better knowledge on snow avalanche accidents; (iii) to provide a description and how the snow depth and temperature controls snow avalanche activity.

We use for our study the meteorological data from three automatic weather stations, and the database from PN-NAM on the location of snow avalanches, on all number of days with snow avalanches and on the issuing of snow avalanche danger levels. Our research was supplemented by the Mountain Rescue Public Services (MRPS) and by the Sibiu Regional Weather Forecasting Service (RWFS) databases on snow avalanche accidents. To determine the relationship between snow avalanches and severity of winter we used the Winter Standardized Index (WSI).

Our analysis demonstrates that the monitoring of snow evolution and of snow avalanches by PN-NAM reduced the number of accidents in the last 10 years and the vast majority of snow avalanches occurs in normal and cold winters.

P3.18 Studies of snow climatology at the local scale: examples of the Fiemme Valley (Trentine Dolomites) and in Monte Cimone massif (Northern Apennines)

Massimiliano Fazzini *(University of Ferrara, Italy), Francesco Fanari, Vincenzo Romeo, Sergio Zeni*

Aim of the present study is to analyze the snowmaking on the local scale in two confined areas identified with the Val di Fiemme (Trentino Dolomites) and the emilian Apennine mountain massif of Monte Cimone. These two areas are particularly suitable for a study at the local scale, thanks to the extensive network of local monitoring existing and aimed at monitoring the evolution of the snow cover in relation to to the risk of avalanches. In the Fiemme valley, with different exposures, eight monitoring manual and automatic nivometric stations in an area of approximately 250 sq km - are present, a altitude between about 1500 and 2200 meters. In the Monte Cimone, there are four stations - located in the northern slope - between 1000 and 2150 meters. In the two areas under study, five series temporally extended from 1981 allow to analyze the nivometric trend, while the other sites of detection are characterized by a extremely variable length of the available data. In both areas, in relation to the altitude, the snow is usually very abundant but snowfalls are caused by different meteorological situations between the two massifs. The identification of a statistically valid relationship between morphological variables at the local scale and snowmaking (height of fresh snow, number of snowy days, permanence of snow on the ground, volume mass of the snow) allowed to better understand the spatial and altitudinal distribution.

P3.19 The incorrect information of extreme weather events: the case of the "record snowfall" in the mountains of Abruzzo and Molise of March 2015

Antonio Cardillo, Claudio Cassardo, ***Massimiliano Fazzini*** *(University of Ferrara, Italy), Sandra Scarlatelli*

Over the last years, the increasingly frequent extreme weather events have encouraged the development of a "public" debate on issues relating to prevention, forecasting, management and outcomes of these events and generally the hydrometeorological associated risk. In Italy, the absence of a national weather service does not allow an adequate and correct dissemination of meteo-climatic information. In this regard, the creation of a complex structure formed by personnel of Air Force, National Civil Defence and University is in an advanced phase of development. The above mentioned situation favours the increasing popularity of more or less professional meteorological sites – rarely "ethical" – that tend to amplify or directly use the signals from weather prediction models, and magnify the outcome of the most significant weather events, describing them as exceptional phenomena, often using scientifically incorrect data. This analysis concerns the snowfall occurred during March 5th-6th, 2015, in the mountainous area between the southern Abruzzo and high Molise – central Adriatic Italy – as a result of a dynamic cyclonic circulation that caused heavy rainfall, with snowfall over 500 meters, combined with stormy northeastern winds. Some sources of information (websites) mentioned snow depths in about 18 hours of 256 cm in Capracotta town (1421 m) and 240 cm in Pescocostanzo town (1395 m). These cumulated would have exceeded the world record of accumulated snow in 24 hours, occurred in April 14th-15th, 1921 in Silver Lake (Colorado, USA). Many major international networks, such as CNN and BBC, picked up such incorrect news, causing a massive diffusion. In truth, evidently, the strong wind activity has redistributed the snowfall, characterized by low density, in an extremely

irregular way causing exceptional thickness in zones favourable to eolic accumulations. The analysis of meteorological data, monitored by the networks of Civil Protection of the Molise region, the service Meteomont the State Forestry Corps and the National Weather Service, have shown that the cumulated fresh snow has never exceeded 100 cm/36 hours. It was the bora winds – that have repeatedly exceeded 100 km/h – that led to the formation of huge accumulations reported in the news. A comparison with other snow events occurred in March also showed that the episodes occurred on March 15th, 1987, March 2nd-3rd, 2005, and March 9th-11th, 2010 produced similar snow depths. A detailed analysis of meteorological conditions responsible for this event completes this study.

P3.20 Permafrost modelling to estimate the future evolution of mountain permafrost in the Swiss Alps

Christian Hauck *(University of Fribourg, Switzerland), Antoine Marmy, Jonas Wicky, Nadine Salzmann, Martin Hoelzle*

Permafrost, defined as lithospheric material whose temperature remains below 0 °C for two or more consecutive years, occurs in many high-mountain regions of the European Alps. To evaluate the sensitivity of mountain permafrost to climatic changes and to assess its future evolution, both, climatic variables such as air temperature, radiation and timing and duration of snow cover have to be considered, as well as subsurface characteristics such as ground temperature, ice content, porosity or hydraulic properties. Within the large Swiss project cluster TEMPS (The evolution of mountain permafrost in Switzerland), funded by the Swiss National Science Foundation, a hierarchy of different climate and subsurface models were employed to estimate the sensitivity and future evolution of mountain permafrost, as well as to improve the process understanding of the complex interaction between atmosphere and frozen subsurface. Here, we will present results from the sub-project TEMPS-D focusing on process studies regarding the energy transfer between the atmosphere and the blocky surface layer of many Alpine permafrost sites, as well as regarding the energy transfer within the different subsurface layers. The results were incorporated into climate impact simulations using the subsurface model COUP and downscaled outputs of various ENSEMBLES GCM/RCM chains as forcing data.

The results of transient COUP model simulations until the end of the century for six different permafrost sites in the Swiss Alps show a direct reaction of (a) snow cover duration at all sites and (b) ground temperature to the projected air temperature increase from the downscaled 16 GCM/RCM scenarios. Consequently, a strong permafrost degradation is simulated for all sites, to a varying degree depending on the initial ground ice content. This degree of degradation depends hereby on the interplay between snow cover decrease (loss of insulation), necessary melt energy for ground ice loss, and the ability of the soil to refreeze completely in winter - the latter being a necessary condition for sustained permafrost conditions. Further site-specific permafrost processes, such as air convection in the porous blocky surface layer and 2-dimensional air circulation in deep blocky talus slopes were analysed by additional process models and compared to the dominant processes in the long-term simulations.

P3.21 Monitoring tree growth in alpine regions in Tyrol

David Leidinger *(BOKU Vienna, Austria), Herbert Formayer, Sonja Vospernik, José Groff, Kurt Nicolussi*

In 2012 a large number of increment cores were sampled and a network of dendrometers and soil temperature sensors was installed in Tyrol, Austria. The objective is to use forest growth data sampled along altitudinal gradients with different aspect as proxy data to validate a climate interpolation model in terms of its predictions of temperature, precipitation and solar radiation. The focuses on Norway spruce and Swiss pine at 4 high altitude regions near alpine barrier lakes in Tyrol. Using this data altitudinal temperature gradients and the duration of snow cover are determined. The gradients are compared to gridded datasets (HISTALP, INCA). The ring-width, latewood width and a subsample of interannual density was measured from the increment cores and a cronology was constructed.

P3.22 Near-surface wind climatology over the eastern Adriatic coast in an ensemble of RCM simulations

Andreina Belušić *(University of Zagreb, Croatia), Ivan Güttler, Maja Telišman Prtenjak*

The eastern Adriatic coast is characterized by the complex coastline, strong topographic gradients and specific wind regime. The most famous typical winds along the Adriatic coast are bora and sirocco (mostly during the wintertime) and sea/land breezes (dominantly in the warm part of the year) as a part of the regional Mediterranean wind system. This represents excellent test area for the latest generation of the regional climate models (RCM) applied for the European domain. In this study, near-surface (i.e. 10 m) wind simulated by six RCMs (CLMcom-CCLM4-8-17, DMI-HIRHAM5, IPSL-INERIS-WRF331F, KNMI-RACMO22E, SMHI-RCA4, DHMZ-RegCM4) from the EURO-CORDEX initiative are compared against surface station observations and forcing ERA-Interim reanalysis for the period 1996-2008. Our analysis reveals strong sensitivity of the simulated wind flow and wind pattern to the RCM horizontal resolution (12.5 km vs. 50 km). Additionally, the skill of the RCMs (among others measured by e.g. Brier and Perkins skill scores) in reproducing the observed flows is a function of both season and location analysed. Several methodological aspects related to the interpolation approaches when comparing RCMs and observations (or RCMs at two different resolutions) are also discussed.

P3.23 Climatic Maps of the Tatra Mountains

Zbigniew Ustrnul *(Jagiellonian University, Poland)*

Thanks to bilateral cooperation between Polish and Slovak climatologists, climatic maps of the entire Tatra Mts. (the highest range of the Carpathians) have been constructed. The set of maps contains all basic climate elements and weather phenomena. The special attention was paid to the solar radiation, air temperature, precipitation, snow cover and wind speed. Most of the maps are based on homogenous daily values originated from the period of 1981-2010. All the mentioned maps have been created using GIS techniques including different spatialization methods. Some charts and figures have been also devoted to extreme phenomena and particular case studies. Finally long-term variability of main climatic elements have been presented.

P3.24 Influence of surface-based temperature inversions on extreme low minimum temperature over the Western Carpathians

Angelika Palarz *(Uniwersytet Jagiellonski, Poland)*

Temperature inversion, which is defined as a phenomenon of increasing air temperature with altitude, seems to be an important element of mountain climates as well as a critical factor affecting air quality, formation of fog and deep frost. The primary goal of this study is to investigate the influence of surface-based temperature inversions on extreme low minimum temperature over the Western Carpathians. In order to fulfill this main objective, regions with relatively high frequency and intensity of temperature inversions were delimited, and multi-annual and annual variability of air temperature inversions was analyzed. Moreover, an attempt was made to determine the relationship between large-scale atmospheric circulation and extreme low minimum temperature occurring during inversion episodes. The study is based on data derived from the high resolution gridded data set – CARPATCLIM and some in situ measurements. The meteorological data consist of daily mean, minimum and maximum air temperature as well as daily mean relative humidity from

the years 1961-2010. Simultaneously, two classifications of atmospheric circulation types – Grosswetterlagen and Niedźwiedź's approach have been applied. The results confirmed high impact of surface-based inversions on minimum temperature which are strongly associated both with seasonal variability of weather and local relief.

P3.25 Is it possible to characterize the climate of an Alpine region by means of synoptic circulation types?

Luca Panziera *(MeteoSwiss, Switzerland), Lorenzo Giovannini, Lavinia Laiti, Dino Zardi*

A comprehensive data set of surface temperature, rainfall, solar radiation and wind measurements was setup to investigate the relation between synoptic circulation types and the climate of Trentino, a mountainous region in the South-Eastern Alps.

Synoptic patterns are classified over different levels by means of an existing classification method based on the direction of the flow impacting over the Alpine chain.

Distinct seasonal anomalies of mean daily temperature, total daily rainfall, daily solar irradiation and mean daily wind intensity are associated with most circulation types. However their magnitude varies not only between weather types, but also within the same type for different levels and seasons. Moreover, extreme meteorological events occur with preferential circulation types, since the frequency of occurrence of extremes for each synoptic pattern rarely coincides with the climatological value. Finally, the reference level of the classification scheme which better resolves the variations of the meteorological quantities strongly depends on the season and on the atmospheric variable.

The findings of this study are encouraging in view of developing analogue-based techniques for long-range regional ensemble forecasting in the Alps.

P3.26 A high-resolution solar radiation atlas for the Trentino region in the Alps

Lavinia Laiti *(University of Trento, Italy), Lorenzo Giovannini, Luca Panziera, Dino Zardi*

The accurate assessment of the solar radiation available at the Earth's surface is essential for a wide range of energy-related applications, as well as in the fields of climatology, hydrology, ecology and agriculture. The characterization of solar radiation is particularly challenging in complex-orography areas, where topographic shadowing and altitude effects, together with local weather phenomena, greatly increase the spatial and temporal variability of this quantity. In this contribution a high-resolution (200 m) solar radiation atlas for the Trentino region in the Alps (Italy) is presented. The atlas was recently developed on the basis of hourly observations of global radiation collected at the local radiometric stations during the years 2004-2012. Careful quality controls were applied to the dataset, and a locally-calibrated decomposition model was applied to estimate diffuse and direct radiation components. Moreover, the HelioMont satellite dataset of MeteoSwiss (resolution: 2 km) was used for missing data reconstruction on daily basis. Finally, monthly and annual diffuse, direct and global irradiation maps were obtained by combining the use of a GIS-based clear-sky radiation model (r.sun of GRASS GIS) and of geostatistical interpolation techniques (kriging). The results are then compared with existing solar resource datasets to evaluate the accuracy of the different data sources available for the region of interest.

P3.27 Fog and low stratus over the Swiss Plateau - a climatological study

Simon C. Scherrer *(MeteoSwiss, Switzerland), Christof Appenzeller*

The occurrence of fog and low stratus (FLS) clouds is a common phenomenon over the Swiss plateau during the winter half years. Classical fog observations using horizontal visibility are of limited use for climatological analyses of persistent FLS situations. We present a simple method for determining long climatological series of days with FLS lasting at least a half or a full daylight day. The method relies solely on high quality relative sunshine duration measurements at two stations, a Plateau station below or within the FLS layer (e.g. Zürich/Fluntern) and a nearby peak station above the FLS layer (e.g. Säntis). The analysis for the period 1901–2012 shows that full day FLS are a typical phenomenon of the months November to January, whereas the half day FLS also often occur in October and February. There is substantial interannual and decadal variability. The total number of Zürich full FLS days varies between 4 and 31 d (mean: 17 d) and between 10 and 49 d (mean: 28 d) for at least a half FLS days in the September to March period. The foggiest decade in the 1901–2012 record was 1984–1993; the least foggy decade was 1999–2008 with roughly 40–45% less FLS occurrence than only 15 years before. In the most recent years a return towards the climatological mean can be observed. The long term data series does not show any significant long-term trends for the occurrence of full nor for half day FLS events. The reconstructed FLS occurrence is well correlated with the number of days with cold air pooling. They show very similar decadal variability and long term trends.

Reference: Scherrer SC, Appenzeller C, 2014: Fog and low stratus over the Swiss Plateau - a climatological study. Int. J. Climatol., 34(3), 678–686. doi:10.1002/joc.3714.

P3.28 Moderate extremes of hourly precipitation: Trends and relation to temperature in observed Swiss data

Simon C. Scherrer *(MeteoSwiss, Switzerland), Mischa Croci-Maspoli*

We investigate moderate extremes of hourly precipitation from 59 automated MeteoSwiss stations for the 34 years from 1981–2014. We compute least-square and Theil-Sen trends for different quantiles and compare them with the trends in mean hourly precipitation. Using the correlation with the mean trend as a measure for the robustness of the trend, we find that a trend analysis is useful only up to the 95th quantile (q95). The trends are very random for higher quantiles (q99 or higher). The q95 trends are positive for 61% of the stations (compared to 52.5% for the mean) and the trends significant ($p<0.05$) for 18.6% of the stations.

We also analyse the relation between different quantiles of extreme hourly precipitation and daily mean temperature (Tmean) for different climate regions in Switzerland. For the 99th sample quantile (q99), the highest (lowest) intensities are found for Mountain (Plateau) stations up to Tmean of 17°C (9°C) and for southern Alpine (inner Alpine) stations for Tmean>17°C (9°C). An approximate Clausius-Clapeyron (CC) scaling of 7% precipitation intensity increase per Kelvin Tmean is found for most regions and temperatures below ~10 (southern Alps) to ~13°C (Plateau) and super-CC scaling for ~10°C<Tmean<~18°C (southern Alps) and ~13°C<Tmean<~19°C (Plateau). For Tmean>18-19°C, there are some indications for a levelling off (possibly due to moisture limitations). For inner Alpine stations the intensity increase is much smaller than 7% per K for the large temperature range -2°C < Tmean < 18°C. Here, limitations might be caused by rain-shadow effects and limited water availability.

P3.29 Long-term air temperature and precipitation trends in Swiss Alps and Polish Carpathians

Agnieszka Wypych *(Jagiellonian University, Poland), Zbigniew Ustrnul, Dirk Schmatz, Niklaus E. Zimmermann*

Mountain regions are proved to be most susceptible to potential climate change due to immense sensitivity of mountain ecosystems to changes in temperature and precipitation as mountain catchments characteristics favor rapid discharge.

The main aim of the study is to evaluate temperature and precipitation variability in Swiss Alps and Polish Carpathians since the 19th century in the context of ongoing climate change.

Data from the period 1851-2010 were used considering both in-situ and gridded databases. The analyses were conducted for the whole period with a few sub-periods, i.e. 1851-1930, 1931-1970 and 1971-2010, defining annual and seasonal temperature and precipitation variability in different vertical climatic zones.

The multi-annual changes of analyzed parameters for both regions were referred to the variability of atmospheric circulation defined by Grosswetterlagen classifications.

The comparative study conducted for Swiss Alps and Polish Carpathians proved local and regional differences concerning both climate variability and the role of atmospheric circulation. They manifest themselves in the magnitude of recognized changes as well as the relationships between temperature and precipitation characteristics and the circulation and environmental variables. The obtained results confirm the local diversity of climate conditions as well as the complexity of factors that can control these differences.

P3.30 Cross-scale conditioning of rare extreme precipitation events in the south-eastern Alpine forelands

Katharina Schroeer *(University of Graz, Austria), Gottfried Kirchengast*

While trends of precipitation changes in general are disparate, the “frequency or intensity of heavy precipitation events has likely increased in North America and Europes” (IPCC, 2013: Summary for Policymakers), and extreme intensities of short precipitation events on the daily to sub-hourly scale seem to increase unambiguously as temperatures rise (e.g. Trenberth et al., Clim. Res. 47, 123-138, 2011; Berg et al., Nat. Clim. Change 13, 181-185, 2013; Kendon et al., Nat. Clim. Change 4, 570-576, 2014). Statistical studies on extreme precipitation contribute substantially to the research field. They usually define thresholds to classify extreme events out of a given sample, where methods, such as peak-over-threshold or percentile values, are affected by the sample properties. We term such extreme events statistical extreme events - “SEEs”. Such thresholds can be described user-defined or constructed. Probability density functions (PDFs) are sought, fit and applied to describe frequency, magnitude and recurrence intervals of extreme precipitation events (e.g. Yilmaz et al., Hydrol. Earth Syst. Sci. 18, 4065-4076, 2014; Papalexiou et al., Hydrol. Earth Syst. Sci. 17, 851-862, 2013).

While these studies respond to the needs of engineering practice in e.g. infrastructure design, or trend analysis of precipitation in climate studies, they a) often ignore outliers because of practical or statistical/data limitations (i.e. left out as “residual risk”) and b) tell us little about the underlying processes of the climate and weather system causing these outliers. We term these outliers that can only be attributed to the distribution tails via large uncertainty ranges as rare extreme events - “REEs”.

The main focus of this study is to identify and physically assess those processes that differentiate REEs from SEEs under the hypothesis that REEs are caused by a conjunction of specific conditions on different scales. We differentiate spatio-temporal circumstances of large-scale/long-term and regional/seasonal preconditioning that combine with specific local/short-term event conditions.

In this initial study, we primarily examine precipitation records of high temporal resolution of the ZAMG (National Weather Service of Austria) and Austrian Hydrographic Service (eHyd) meteorological station networks over the climate-sensitive south-eastern Alpine region for the extended summer season (Apr-Oct). The approx. 50 most extreme events found in the period 1990-2014 are then systematically analyzed in depth, using a large pool of auxiliary data. For each event, the preconditioning is evaluated making use of extended climate and weather information such as atmospheric analyses and synoptic observations; complemented by a desk review of peer-reviewed scientific literature, extreme event reports, retrospects of weather services and others. This approach overcomes limits of data-sparse statistics by systematically exploring the processes and uncertainties of REEs on a per-event basis. We find that identifying specific patterns of REEs preconditioning and actual event conditions helps to understand extreme precipitation uncertainties and also delivers valuable information for evaluating precipitation in climate model simulations, as in that respect cross-scale processes still pose a significant source of uncertainty.

P3.31 Projected changes in precipitation extremes in mountain regions of Europe

Jan Kysely *(Institute of Atmospheric Physics AS CR, Czech Republic), Ladislav Gaal, Romana Beranova*

Mountain regions and areas with complex orography are particularly prone to heavy precipitation and floods, and uncertainties in possible changes associated with climate change may be enhanced due to complexity of interactions between orography, atmospheric circulation, and local processes. The study examines possible changes in high quantiles of precipitation amounts in scenarios of the late 21st century climate in an ensemble of regional climate model (RCM) simulations over Europe. The projected changes are evaluated in winter and summer seasons and on a wide range of time scales from hourly to multi-day amounts. The region-of-influence method is applied as a pooling scheme when estimating distributions of seasonal maxima of precipitation, which leads to spatial patterns of high quantiles that are smoothed compared to the local analysis. We focus on a comparison of results (scenarios) for several mountain regions of Europe (the Alps, the Carpathian region, the Pyrenees), and evaluate altitudinal dependence of the projected changes of precipitation extremes. Specific attention is paid to the performance of the pooling scheme, particularly how the regional homogeneity criterion is met in areas with complex topography. Uncertainty of the projected changes due to inter-model variability is also assessed and compared for the selected regions.

P3.32 Daily precipitation in a changing climate: lessons learnt from Swiss national climate change scenario initiatives

Andreas Fischer *(MeteoSwiss, Switzerland), Mark Liniger, Elias Zubler, Simon Scherrer, Denise Keller, Jan Rajczak, Christoph Schär*

Precipitation is a key variable in the climate system that affects many aspects of the hydrological cycle such as river runoff, snow amount, or droughts. Climate change projections of precipitation and related impacts are therefore of fundamental concern for multiple sectors in many regions. Within the Swiss national climate change initiatives CH2011 and CH2014, several precipitation-dependent impacts were quantitatively assessed. This included consideration of projections of the mean annual cycle, as well as changes in extremes, wet-day frequency, and spell lengths. To better understand the needs of the primary and intermediary users of climate model data in Switzerland, a dialogue between the climate modeling and impact communities was established over recent years. In this presentation, we like to report about our experience with these needs, and on the steps we undertook to approach the emerging challenges regarding changes in precipitation.

In our work beyond CH2011, the multi-faceted characteristics of precipitation change over Switzerland are investigated based on the joint analysis of several regional climate model (RCM) simulations from ENSEMBLES at the A1B emission scenario. In some seasons, changes in precipitation frequency and intensity compensate each other, in other seasons just one of these two components changes. Yet, extreme daily precipitation events are projected to intensify in most seasons. In summer, a reduction of frequency yields an augmented risk of more multi-day dry spells and meteorological summer droughts. It is also in summer, when the model simulations exhibit an elevation-dependent shift in precipitation type toward more convective precipitation.

To accommodate the common need of many end-users in obtaining quantitative future projection data at multiple stations, we use a stochastic multi-site precipitation generator as main downscaling technique. In the presentation, we will present first results thereof and discuss, how end-users can handle changes in daily precipitation statistics for climate change scenarios.

P3.33 3PClim – a comprehensive study of past, present and perspective climate in the region of Tyrol, South Tyrol, Trentino and Belluno

Christoph Zingerle *(ZAMG, Austria), Silke Adler, Manfred Bauer, Reinhard Böhm, Barbara Chimani, Giovanni Cenzon, Andrea Crepaz, Francesco Domenichini, Susanne Drechsel, Georg Erlacher, Andrea Fischer, Manfred Ganekind, Günther Geier, Klaus Haslinger, Johann Hiebl, Anita Paul, Gianni Marigo, Vera Meyer, Johanna Nemec, Andrea Rossa, Gernot Resch, James Rudolph, Harald Schellander, Bernd Seiser, Philipp Tartarotti, Mauro Tollardo, Werner Verant, Johannes Vergeiner*

For a wide range of tasks in technical planning, energy- and water management, civil protection, forestry and agriculture, tourism, education and science, accurate and up to date knowledge of the climate is of great value. Within the alpine sub-region of Tyrol, South Tyrol, Trentino and Belluno, the state of the climate was last described in a comprehensive way by Fliri (1975), based on data from 1931 to 1960. Since then, only local scale studies have been carried out. Today's measurement systems and methods of remote sensing, together with computing power allow advanced methods for geo-statistical interpolation, trend analysis, detection of convection or climate projections. Within the framework of the Interreg IV Italy-Austria program, the Austrian Central Institute for Meteorology (ZAMG) has joined forces with the Hydrographical Office of Bozen/South Tyrol and the Regional Environmental Agency of Veneto (ARPAV) to elaborate a climatography describing past, present and perspective climate of the region in a comprehensive way.

In this presentation an overview of the activities and results is given.

The period of 1981 to 2010 was selected as the present climate normal period. As the quality of results is determined by the quality of underlying meteorological data, extensive consistency and quality checks have been applied to meteorological data provided by different institutions.

From the high density network, 160 maps of temperature, precipitation, snow and radiation as well as a number of derived parameters (such as frost and summer days, days with snow cover, heating days, . . .) were derived at a resolution of 500x500 m, applying state-of-the-art geo-statistical methods.

Seventeen representative stations with daily precipitation and temperature data available before 1981 have been selected for homogenization and trend analysis of the past and present climate (see Vergeiner et al, Alpine trends in temperature and precipitation).

The definition and format of glacier related data, as for other data, depend on the institution responsible for their acquisition. Within the project, a homogenous data catalogue was compiled, providing glacier properties such as location and size, images, and whenever available length- or areal changes and mass balances.

Within the latest 10 to 15 years, radar and lightning detection became commonly used to detect and track convective activity. The complex topography of the Alps, together with individual scanning strategies at different radar stations and the changing (improving) quality of the lightning detection system, create serious difficulties for automated storm tracking systems. Nevertheless, a comprehensive storm database was set up. Regions of preferred storm initiation and decay as well as typical storm life cyles are presented (Meyer et al, A Convection Climatology in the Alpine Region).

For the climate projection throughout the 21st century, the most likely scenario (A1B) was applied downscaling from ECHAM5 to COSMO CLM (10x10 km). Climate prediction of temperature and precipitation show a distinct change in temperature and temperature dependent parameters respectively, while the development of precipitation based parameters is much less clear.

After presenting the most relevant results, the media for the dissemination of the results are shortly discussed, i. e. the book "Das Klima von Tirol – Südtirol – Belluno", a data DVD and the project web-page www.3pclim.eu.

P3.34 A Convection Climatology in the Alpine Region

*Vera Meyer, James Rudolph, Giovanni Cenzon, Francesco Domenichini, Luciano Lago, Mauro Tollardo, **Christoph Zingerle** (ZAMG, Austria)*

The generation of a convection climatology in mountainous regions poses a true challenge since the main data source for a comprehensive monitoring of deep convection, the weather radar, suffers significantly from beam blockage. Within the INTERREG IV project 'Past, Present and Perspective Climate of Tirol, South Tyrol-Alto Adige and Veneto' (3PClim) a convection climatology for the region of Western Austria and North Italy has been generated from five years radar and lightning data.

The analysis time covers April through October of years 2009 to 2013. Radar data comprise the Austrian radar network (Rauchenwarth, Feldkirchen, Zirbitzkogel, Patscherkofel, Valluga), the Veneto radar network (Teolo, Concordia Sagittaria) and the Bozen Radar (Mt Macaion). Lightning data are provided by the European lightning detection network EUCLID (www.euclid.org).

The Austrian thunderstorm nowcasting tool (A-TNT) has been employed to identify and track convective cells in the target regions. The algorithm monitors strong convective storms by identifying regions of intense precipitation and electrically active regions following the method of the thunderstorm tracking and nowcasting algorithm ec-TRAM [1]. By using radar and lightning data as complementary information source continuous storm monitoring is supported in areas with reduced radar visibility and occasional data gaps are overcome. A-TNT is run with a temporal resolution of 5 minutes on a 1 km X 1 km grid.

A selection of project results will be presented. It includes a study about preferred storm initiation locations, travel distance, travel direction as well as a diurnal cycle of cell initiation and dissipation. More results can be found on the project website www.3pclim.eu.

Since the data basis does not cover the required time basis of at least 30 years, this study is not a climatological study in its proper sense. But the analysis of five convective seasons already provides interesting insights in the characteristic of deep convective processes in the target region, which can be refined and complemented in subsequent studies.

[1] Meyer, V. K., Höller, H., and Betz, H. D.: Automated thunderstorm tracking: utilization of three-dimensional lightning and radar data, Atmos. Chem. Phys., 13, 5137-5150, doi:10.5194/acp-13-5137-2013, 2013.

P3.35 Radar-based severe storm climatology for Austrian complex orography related to vertical wind shear and atmospheric instability.

***Rudolf Kaltenboeck** (Austro Control, Austria), Anderas Lanzinger, Martin Steinheimer*

Thunderstorm development in Austria is highly influenced by orographical forcing especially in summer. The further development toward local severe storm formation depends on the strength of instability and vertical wind shear which interact with mesoscale influences. For closer insight, the temporal and spatial distribution of severe thunderstorms as a function of CAPE and deep vertical wind shear are examined. A five year period of C band weather radar data is exploited over the complex orography of Austria and linked to ECMWF ERA-Interim data for classification of synoptic flow, vertical wind shear and instability.

A minimum of severe storms over the Alpine crest in high altitudes of the Southwest region is observed which corresponds to lightning data. Westerly and southerly flow classes are associated with more widespread intense thunderstorm development. One of the key results is that the strong deep-layer shear environment leads to organized, line oriented pattern over wide areas of Austria. These preferred areas for severe storm occurrence can be well used for nowcasting. Especially during low CAPE conditions the magnitude of deep-layer shear is very important for the spatial arrangement, maximum size of the convective system, and time of occurrence. For the eastern part of Austria and the Alps, high deep-layer shear tends to produce larger cell cores in terms of high radar reflectivity. For the Alps during low CAPE conditions and for the eastern part of Austria for all CAPE classifications, the strong deep-layer shear increases the frequency of severe storms and shifts the peak of occurrence from afternoon toward the evening.

P3.36 Climatological Characteristics and Inland Penetration of Atmospheric Rivers over the Western United States

W. James Steenburgh *(University of Utah, United States of America), Jon Rutz*

Narrow corridors of intense water vapor transport known as atmospheric rivers (ARs) contribute to extreme precipitation and flooding along the Pacific coast, but knowledge of their influence over the mountainous interior of the western United States is limited. Here we use ERA-Interim analyses, Climate Prediction Center (CPC) precipitation analyses, and Snowpack Telemetry (SNOTEL) liquid precipitation equivalent (LPE) observations from mountainous regions to describe the characteristics of cool-season (November–April) ARs across the western United States, including their modification by major topographic barriers. AR frequency and duration exhibit a maximum along the Oregon–Washington coast, a strong transition zone upwind (west) of and over the Cascade–Sierra ranges, and a broad minimum that extends from the "high" Sierra south of Lake Tahoe eastward across the central Great Basin and into the deep interior. East of the Cascade–Sierra ranges, AR frequency and duration are largest over the interior northwest, while AR duration is large compared to AR frequency over the interior southwest. The fractions of cool-season precipitation and top-decile 24-h precipitation events attributable to ARs are largest over and west of the Cascade–Sierra ranges. Farther east, these fractions are largest over the northwest and southwest interior, with distinctly different large-scale patterns and AR orientations enabling AR penetration into each of these regions. In contrast, AR-related precipitation over the Great Basin east of the high Sierra is rare.

We differentiate between inland-penetrating and non-penetrating ARs using low- (950-hPa) and mid-level (700-hPa) forward trajectories initiated within cool-season ARs as they approach the west coast of North America. These trajectories are then classified as coastal decaying, inland penetrating, or interior penetrating based on whether they remain within an AR upon reaching selected transects over the western U.S. At initiation, interior-penetrating AR trajectories are associated with a more amplified trough-ridge pattern over the northeastern Pacific and western U.S., more southwesterly (vs. westerly) flow, and larger water vapor transport (qu), particularly west of the Sierra Nevada. Such interior-penetrating AR trajectories most frequently originate along the Oregon coast, but the greatest fraction of trajectories that eventually penetrate into the interior is found along the coast of the Baja Peninsula. Due to large water-vapor depletion and other orographic effects, Inland- and interior-penetrating trajectories rarely pass over the "high" Sierra, helping to explain the reduced frequency and influence of ARs east of this range.

These results indicate that water vapor depletion over major topographic barriers is a key contributor to AR decay, with ARs playing a more prominent role in the inland precipitation climatology where lower or less continuous topography facilitates their inland penetration.

P3.37 Large scale heavy precipitation events in terms of climate change in Central Europe

Annemarie Lexer *(ZAMG - Zentralanstalt für Meteorologie und Geodynamik, Austria), Michael Hofstätter, Barbara Chimani, Günther Blöschl, Markus Homann, Andreas Phillip, Christoph Beck, Jucundus Jacobeit*

The geographical region from where a cyclone is propagating into Europe appears to play an important role in generating certain weather extremes. Some of the most devastating European floods have been associated with type Vb cyclones, as in August 2002 or with a congeneric type in June 2013 for example. The aim of this work is to assess different propagation paths of atmospheric cyclones in terms of a systematic relation to large scale extreme precipitation events over Central Europe (CE) and examine future changes of precipitation extremes.

Part B: The development of a precipitation model – using ERA-40 reanalysis data and a specially created precipitation data set – for modelling precipitation sums of cyclone track events over Central Europe and the change in heavy precipitation events in quantity and frequency in terms of future climate change:

For the period 1951-2007 gridded precipitation data has been aggregated within Central Europe on a daily basis and assigned to different regions with specific patterns of precipitation on an annual and seasonal basis. Since precipitation events strongly vary according to the season in which they occur, the number and size of the specified regions also changes. Precipitation totals for each region and track event have been used to determine changes in heavy precipitation amounts and empirical exceedance probabilities for fixed thresholds.

The results show clear differences between the various regions of the study area in terms of their relevance in large scale heavy precipitation amounts. Especially three defined precipitation regions – all in the area of the Alps – show the highest precipitation amounts in all periods under investigation.

To asses future changes in quantity and frequency of extreme events, three different Global Climate Model simulations (ECHAM5, ECHAM6, EC-Earth) have been investigated, using a multiple linear regression on an annual and seasonal basis. Although uncertainty is large due to internal variability, results show a moderate increase of heavy precipitation amounts and frequency for almost all model runs on the annual basis. Contrary to this, there is a strong variability in seasonal changes with a clear decrease of heavy precipitation amounts during summer for almost all model runs.

P3.38 Multidecadal precipitation patterns in a densely glaciated region of western Himalaya: A pointer to orographic control and large scale meteorological phenomena

Arindan Mandal *(Jawaharlal Nehru University, New Delhi, India, India), Al. Ramanathan, Thupstan Angchuk, Jose George Pottakkal, Mohd. Soheb*

Himachal Himalaya in western part of the Himalayan arc is one of the most glacierized regions in High Asia. Long term in-situ precipitation data from three stations from two different subbasins of Indus coming under the western Himalaya were analyzed in this study. A decadal cyclic pattern in fluctuation of precipitation from more than 40 years' data from Bhuntar, Manali and Koksar meteorological stations has been observed. Strong seasonal variability in precipitation prevails in the study area. Most pronounced precipitation seasons are winter DJF months on the orographic interior and summer covering JJA months on the orographic front of Pir Panjal range. DJF contributes maximum to the annual cycle of orographic interior. February accounts for the highest precipitation in winter controlled by MLW, while in summer July experiences the highest amount of precipitation from ISM. Average annual daily precipitation is found to be 2.65, 3.56 and 2.95 mm day-1 respectively. Precipitation gradient is found to be 0.39 m km-1 within Beas basin (Bhuntar to Manali), while it varies from -0.13 m km-1 (Manali to Koksar) and 0.06 m km-1 (Bhuntar to Koksar) between Beas to Chandra subbasins. A homogenized precipitation gradient valley-wide or region-wide cannot be established in high altitudes of western Himalayas especially in regions above 3000 m a.s.l. due to complex orography. Long-term linear trends show a decreasing trend of annual precipitation in Manali, while an increasing trend is observed in Bhuntar and Koksar stations. Trend analysis of annual rainy days intensity has been observed and found to be decreasing in Manali and Koksar, while increasing in Bhuntar station. Annual precipitation followed Ocean Niño Index in most years, but a large variability is observed across seasons. It has been observed that increased precipitation has little impact on the glacier mass budget of this region. However, we need many more long-term continuous datasets from well distributed gauging networks for a concrete conclusion.

P3.39 Investigating potential precipitation changes and related impacts on peasant agriculture and rural life in mountain villages, Cordillera Blanca, Peru

Wolfgang Gurgiser *(University of Innsbruck, Austria), Irmgard Juen, Georg Kaser, Katrin Singer, Martina Neuburger, Marlis Hofer, Simone Schauwecker*

Peasants on the slopes above the city of Huaraz in the Peruvian Cordillera Blanca attribute recent challenges in agricultural production, in part, to seasonally decreasing precipitation. Local climate is characterized by a strong seasonality in precipitation. While the driest conditions prevail in June and July, precipitation increases gradually towards the October to April wet season.

For farm land without access to river-fed irrigation, on-site precipitation is a crucial prerequisite for any kind of cultivation. Because seeding occurs soon after the core dry months, crops in the early stage of growth are highly vulnerable to potential alterations in the transition period from dry to wet conditions. However, there are several other factors for abandoning farm land complicating the attribution of precipitation change: There is evidence for intense deforestation, there are indications for the transition from traditional to industrial seed products, etc. . The resulting impacts on farming may be similar to those of altered precipitation characteristics.

Within our work we focus on potential precipitation changes whereas the availability of meteorological information for proving precipitation trends is generally very poor for this region. We currently investigate the potential of connecting ground measurements with the output from a global atmospheric circulation model.

P3.40 A review on regional convection-permitting climate modeling: demonstrations, prospects, and challenges

Andreas F. Prein *(National Center for Atmospheric Research, United States of America), Wolfgang Langhans, Giorgia Fosser, Ferrone Andrew, Nikolina Ban, Klaus Goergen, Michael Keller, Merja Tölle, Oliver Gutjahr, Frauke Feser, Erwan Brisson, Stefan Kollet, Schmidli Jürg, Nicole Van Lipzip, L. Ruby Leung*

Regional climate modeling using convection-permitting models (CPMs; horizontal grid spacing <4 km) emerges as a promising framework to provide more reliable climate information on regional to local scales compared to traditionally used large-scale models (LSMs; horizontal grid spacing >10 km). CPMs no longer rely on convection parameterization schemes, which had been identified as a major source of errors and uncertainties in LSMs. Moreover, CPMs allow for a more accurate representation of surface and orography fields. The drawback of CPMs is the high demand on computational resources. For this reason, first CPM climate simulations only appeared a decade ago. In this study, we aim to provide a common basis for CPM climate simulations by giving a holistic review of the topic. The most important components in CPMs such as physical parameterizations and dynamical formulations are discussed critically. An overview of weaknesses and an outlook on required future developments is provided. Most importantly, this review presents the consolidated outcome of studies that addressed the added value of CPM climate simulations compared to LSMs. Improvements are evident mostly for climate statistics related to deep convection, mountainous regions, or extreme events. The climate change signals of CPM simulations suggest an increase in flash floods, changes in hail storm characteristics, and reductions in the snowpack over mountains. In conclusion, CPMs are a very promising tool for future climate research. However, coordinated modeling programs are crucially needed to advance parameterizations of unresolved physics and to assess the full potential of CPMs.

P3.41 An evaluation of regional climate model simulated fractional snow cover using high-resolution satellite data (with implications for the simulated snow-albedo feedback)

Justin R. Minder *(University at Albany, United States of America), Theodore Letcher*

Snow cover often exhibits large spatial variability. This is particularly true over mountainous regions where large variations in factors such as elevation, aspect, vegetation, winds, and orographic precipitation all modulate snow cover. Under climate change, reductions in mountain snow cover are likely to substantially amplify regional warming via the snow-albedo feedback. To capture this important feedback it is crucial that regional climate models (RCMs) adequately simulate spatial and temporal variations in snow cover.

Snow cover simulated by an RCM over the central Rocky Mountains of the United States is evaluated. RCM simulations are conducted using the Weather Research and Forecasting (WRF) model at high-resolution (4 km horizontal grid) forced by reanalysis boundary conditions. Seven years of RCM output is compared with high-resolution (~500 m) gridded satellite analyses of fractional snow cover derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) using the MODIS Snow Covered Area and Grain size (MODSCAG) retrieval algorithm.

Results reveal that the RCM is generally successful at reproducing the observed seasonal cycle and interannual variability of snow extent over the high terrain of the Rockies. However, the sub-grid scale fractional snow covered area of RCM grid cells containing snow is systematically too high compared to observations, often exceeding observations by more than 0.2. We quantify how this bias in fractional snow cover translates into a bias in the strength of the snow-albedo feedback under climate change scenarios. The sensitivity of our results to land surface model (LSM) parameterization is examined by comparing RCM simulations using the simple Noah LSM and the more sophisticated Noah-MP LSM.

P3.42 Orographic errors in dynamic downscalings of atmospheric flows

Andréa Massad, ***Haraldur Ólafsson*** *(HI, Iceland), Guðrún Nína Petersen, Hálfdán Ágústsson, Ólafur Rögnvaldsson*

Extended periods of flow over Iceland has been simulated with the WRF model at resolution of 3 km. A detailed analysis of the simulations reveals that most of the largest errors in the wind field eminate from resolved topography. This does of course underline the non-stationary nature of some orographic disturbances, but it also points towards inaccuracies in the representation of the vertical profiles in the simulated flow.

P3.43 The influence of spectral nudging in simulating Vb-events with COSMO-CLM

Ivonne Anders *(ZAMG, Austria), Manuela Paumann*

In previous studies certain European cyclones have been investigated in terms of related extreme precipitation events in Austria. Those systems passing the Mediterranean are of special interest as the atmospheric moisture content is increased. It has been shown in recent investigations that state-of-the-art RCMs can approximately reproduce observed heavy precipitation characteristics. This provides a basic confidence in the models ability to capture future changes of such events under increased greenhouse gas conditions as well.

In this contribution we focus on high spatial and temporal scales and assess the currently achievable accuracy in the simulation of Vb-events. The state-of-the-art regional climate model CCLM is applied in a hindcast-mode to the case of individual Vb-events in August 2002 and Mai/June 2013. Besides the conventional forcing of the regional climate model at its lateral boundaries a spectral nudging technique is applied. This means that inside the model area the regional model is forced to accept the analysis for large scales whereas it has no effect on the small scales. The simulations for the Vb-events mentioned above covering the European domain have been varied systematically by changing nudging factor, number of nudged waves, nudged variables, and other parameters. The resulting precipitation amounts have been compared to E-OBS gridded European precipitation data set and a recent high spatially resolved precipitation data set for Austria (GPARD-6). Varying the spectral nudging setup in the short-term Vb-cases helps us on one hand learn something about 3D-processes during Vb-events e.g. vorticity and formation but on the other hand identify the model deficiencies.

The results show, that increasing the number of nudged waves from 1 to 7 as well as the choice of the variables used in the nudging process have a large influence on the development of the low pressure system and the related precipitation patterns. On the contrary, the nudging factor or the definition of the uppermost pressure level for the nudging are of low impact on the results.

P3.44 Mesoscale atmospheric models forcing strategies for glacio-hydrological studies in complex terrain

Fabien Maussion *(University of Innsbruck, Austria), Emily Collier*

Mesoscale atmospheric models can be used to simulate meteorological variables in remote high-altitude catchments where in situ observations are scarce in space and time. For such simulations spanning years to decades, several methods exist to reduce the model drift from the large-scale driving data: spectral and analysis nudging (in which the model is internally nudged during the simulation time) or daily reinitialisation (in which the model is reinitialised every 24 hours). In a case study of the Langtang catchment in Nepal, we compare these different strategies to drive the Weather Research and Forecasting (WRF) Model, configured with two nested domains of 25- and 5-km resolution centered over the study area, for a one-year period (June 2012 – June 2013). Using a high-altitude observational network for model evaluation we compare the simulations' performance as well as their representation of severe weather events, with a focus on glaciological and hydrological applications.

P3.45 Atmospheric Downscaling for Glaciated mountain environments: DoG starting up

Marlis Hofer *(University of Innsbruck, Austria), Mathias W. Rotach, Ben Marzeion Und Georg Kaser*

Understanding and quantifying the response of mountain glaciers to changing climate and weather conditions is a pressing task for climate scientists and glaciologists all over the world. To date, models that relate glacier mass and dynamics to atmospheric variations are well established. It has remained as a major challenge, however, to accurately describe the past, present and future atmospheric states that affect the glaciers. Recently, a new project (DoG) has started to systematically investigate the following research hypothesis: "The uncertainty in global and regional glacier simulations can be reduced significantly by reducing the uncertainty in the atmospheric drivers of the glacier simulations."

To test this hypothesis - in a first instance, regarding the past state of the atmosphere -, DoG focuses at the development, application and rigorous validation of a state-of-the-art downscaling framework for glaciated mountain environments situated in a diversity of climatic and geo-environmental settings. This downscaling framework contains elements of the most modern statistical, as well as so-called hybrid downscaling techniques applied to reanalysis data predictors, for all atmospheric target variables required in process-based glacier mass balance models. The performance of the available global reanalysis data sets will be assessed for the purpose of glacier mass modelling, on a regionally differentiated view. Using in situ observations from stations near to- and on the glaciers, the transfer of the downscaling framework to glaciated mountain sites in various topographic and climate settings will be validated. This validation procedure pays particular attention to appropriately consider the pitfalls of short or patchy observation records that are often the only data source in remote mountains. Glaciologists all over the world with interest in including their study site in the DoG experiment are invited to get in contact with Marlis.Hofer@uibk.ac.at.

P3.46 Synthetic future daily weather time-series over Switzerland in consistency with RCM projections

Denise Keller *(Federal Office of Meteorology and Climatology MeteoSwiss, Switzerland), Andreas Fischer, Mark Liniger, Simon Scherrer, Christof Appenzeller, Reto Knutti*

Given the expected changes in the climate system over the 21st century, the need for future climate data with high resolution in space and time is continuously growing. This is especially true for impact modelers that require daily input data of several variables. Regional climate models (RCMs) typically provide information on possible future climatic changes at a spatial resolution of 10-50 km, which is often too coarse for direct use in climate impact models requiring realistic spatio-temporal structures. Hence, further statistical downscaling is necessary. In this regard, stochastic multi-site weather generators (WGs) are an appealing technique that allow the simulation of synthetic weather series consistent with the locally observed weather statistics across several stations and its future changes.

Here, we present results of stochastically simulated future daily weather time-series (precipitation, minimum and maximum temperature) with a spatio-temporal correlation structure similar to present-day in-situ observations. For this purpose, a multi-site WG recently developed by the authors has been perturbed with WG parameter changes from RCM projections of the ENSEMBLES project. The multi-site WG is calibrated over a network of Swiss measurement stations from MeteoSwiss over the time-period 1980-2009 and run under future climate conditions for the time-period 2070-2099.

The RCM analysis reveals that largest deviations from present-day precipitation time-series are expected in summer, consistent with the seasonal mean results from the Swiss climate scenario initiative CH2011. Both the number of wet days and the chances of two consecutive wet days is reduced in a future climate, while the likelihood to remain in a dry state given a preceding dry day increases. Concerning temperature, the temporal analysis of daily maximum temperature reveals, that future summers are characterized by more frequent and more persistent warm spells at the end of the 21st century. The time-span in which summer days are expected to occur in the future will increase by 1-3 months. These changes are not uniform across Switzerland and exhibit a pronounced altitude-dependence. Even though the expected future temperature increase will result in a general decrease of snow days, it is still likely that some future winters fall within the range of present-day interannual variability.

P3.47 High-Resolution Spatio-Temporal Precipitation Climatologies in Complex Terrain

Reto Stauffer *(University of Innsbruck, Austria), Nikolaus Umlauf, Jakob Messner, Georg J. Mayr, Achim Zeileis*

A new spatial climatology for precipitation based on a novel statistical model will be presented for the region of North Tirol, located in the Eastern Alps. Current precipitation climatologies are mostly based on monthly means or sums. This may be related to the fact that many common spatial-statistical models assume a normally distributed response. However, the distribution of daily precipitation sums is strongly skewed and contains a large fraction of zeros. The physical limitation to positive precipitation values can be captured in the statistical model by a left-censoring of the observed distribution.

We developed a novel spatio-temporal additive statistical model which allows to estimate mean and scale for censored normal distributions to effectively create high resolved gridded climatologies returning the full distribution estimates on a spatial resolution down to a few hundred meters, and a daily temporal resolution.

P3.48 A statistical post-processing for ECMWF-derived 6-hours maximum rain in NE Italy

Agostino Manzato *(ARPA FVG, Italy)*

Friuli Venezia Giulia (FVG) is the northeasternmost region of Italy and has a very complex orography, comprising the Adriatic Sea on the south side and the Julian and Carnic Alps on the north side. The annual rainfall reach values as high as 3200 mm in the Julian Prealps.

A network of 104 raingauges placed around the FVG territory has been analyzed to extract the absolute maximum rain accumulated every 6 hours (0-6, 6-12, 12-18 and 18-0 UTC) during the period between 15 February 2006 and 15 February 2015.

ECMWF 6h forecasts in 18 grid-boxes (spaced at 0.25 deg) above the FVG region have been analyzed for the same period, to find the maximum 6h rain forecasted by the ECMWF deterministic model from +6 to +48 hours of time lag. The domain is then divided in four more homogeneous subareas. In general, it has been found that ECMWF forecast is underestimated, in particular in the Prealpine region (highest BIAS).

Hence, a linear regression between different ECMWF-derived predictors and the observed 6-h rain has been performed (developing the statistical model on a training sample and verifying it on a test sample), using a stepwise forward selection algorithm.

Candidate predictors are

1. ECMWF rain (both as absolute values than as anomalies or standardized values) in different areas and time lags (+-6 hours);

2. instability indices derived by ECMWF pseudo-sounding above Udine (located in the middle of the FVG plain).

The instability indices has been introduced in particular to improve the forecast during the convective season, when the model skill was lower.