Cold-air pool simulations with AROME

IWCR project report

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Motivation and project goals

In the framework of the TEAMx programme[1] several model intercomparison studies have been initiated, including one on the formation and evolution of cold-air pools (CAPs) in mountain valleys. CAPs have been shown to be particularly challenging for numerical weather prediction (e.g., Holtslag et al., 2013). First, the processes impacting the formation and development of the CAP are local and occur on small spatial and temporal scales so that high horizontal and vertical grid resolution are necessary to properly resolve them, which is not always feasible, in particular for operational weather prediction. Second, CAPs are typically characterized by strong stability, which means that traditional surface-layer parameterizations based on Monin-Obukhov similarity theory may not work well. For the TEAMx model intercomparison study, a case was selected from a multi-day undisturbed period during the PIANO field campaign (Haid et al., 2020) in the Inn Valley, when an approximately 500-m deep nighttime inversion was observed in Innsbruck. The intercomparison study was designed to simulate the full life cycle of the CAP and to allow the evaluation of the models' performance in representing the three-dimensional structure of the CAP, including its strength, depth, and spatial extent.

The goals of this IWCR project were

1. to join the TEAMx model intercomparison study on CAPs with the AROME model run at GeoSphere Austria and
2. to perform a first comparison of the AROME model output with observational data collected during the PIANO field campaign and with the output from the other models participating in the intercomparison study.

Project activities

The project started in October 2023 and ran until June 2024. Two student assistants were employed during this period: (i) Benedikt Wibmer (6 h/week, October 2023–January 2024) set up and performed the AROME simulation following the guidelines for the TEAMx intercomparison study. (ii) Hannes Wieser (8 h/week, January–June 2024) compared the AROME model output with observational data and with the output from the other models participating in the intercomparison study. Both students went to Vienna in January 2024 for two days to visit the model development group of GeoSphere Austria and to discuss the project with Christoph Wittmann.

AROME simulation

An AROME simulation was performed by the student assistant Benedikt Wibmer with support from Clemens Wastl for the selected PIANO case, following the guidelines for the TEAMx intercomparison

[1] www.teamx-programme.org

study. The simulation covers a 24-h period starting at 12 UTC on 15 December 2017, with the analysis focusing on the night 15–16 December. The model domain covers almost the entire Alps with a 1-km grid spacing, identical to the other participating models. Land-cover data, atmospheric data for initial and boundary conditions, and physics parameterizations differ somewhat among the simulations depending on, for example, the availability of specific parameterizations for the respective models. The AROME simulation uses the global IFS model for initialization and for boundary conditions, the ECOCLIMAP-I land-cover dataset, and a 1.5-order PBL parameterization.

Preparing the simulation for submission to the intercomparison study meant not only following the guidelines for the setup, but also ensuring that all the required variables are included in the model output and to adjust the data format according to the guidelines as far as possible.

Model evaluation

The second student assistant Hannes Wieser evaluated the AROME simulation using operational and semi-operational data from Innsbruck as well as data collected as part of the PIANO field campaign. The evaluation included in particular a comparison of the model output with the nighttime radiosounding at the Innsbruck airport, with vertical profiles from a microwave temperature and humidity profiler located at the top of a building of the University of Innsbruck and from four wind lidars at different locations in Innsbruck, with radiative and turbulent fluxes from surface-energy balance stations deployed around Innsbruck during PIANO, and with data from a network of HOBO temperature loggers.

In a second step, the output from the other simulations submitted to the model intercomparison study by different groups were included in the evaluation to produce the first scientific results described in the next section.

Project outcomes

Scientific results

At the time of the project, four simulations had been submitted to the intercomparison study from three different groups and with three different models in addition to the AROME simulation from GeoSphere Austria: a WRF simulation from the University of Innsbruck, a simulation with the Unified Model from the Met Office, and two ICON simulations from the Goethe Universität Frankfurt which differ only in their PBL parameterization. The output from these five simulations was used for the analysis.

Figure 1 shows a comparison of the nighttime temperature profiles at Innsbruck from the simulations with observations from the radiosounding at the airport, from the microwave radiometer at the university, and from a line of near-surface temperature sensors running up the valley sidewall north of Innsbruck. The observed temperature profiles differ somewhat from each other, in particular the fine-scale structure of the vertical profile can only be resolved by the radiosonde and the pseudo-vertical profile along the mountain sidewall shows somewhat lower temperatures than the profiles observed in the free valley atmosphere because of near-surface cooling. The variability among the observed profiles is, however, small compared to the bias between the simulations and the observations. The models reproduce the observed temperature profiles well at higher altitudes, but all five simulations show a strong warm bias near the surface. While the inversion strength, that is, the temperature increase across the depth of the inversion is similar to the observed values, it is in particular the depth of the inversion that is strongly underestimated in the simulations. During daytime, the modeled temperature profiles agree relatively well with observed values. The warm bias forms only with the onset of cooling in the evening and disappears again in the morning together with the erosion of the cold-air pool. Interestingly, the variability among the five simulations is rather small, even though the

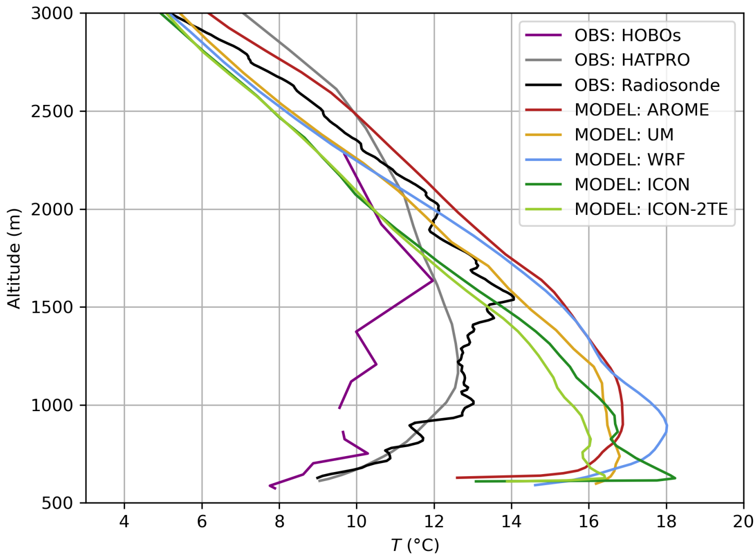

Figure 1: Vertical temperature profiles at 0300 UTC from a line of near-surface temperature sensors running up the sidewall north of Innsbruck (HOBOs), a microwave temperature and humidity profiler at the University of Innsbruck (HATPRO), a radiosounding at the Innsbruck airport, and the five model simulations.

models differ significantly in other parameters, for example, in the vertical humidity and wind profiles.

The analysis performed within this project only started to look into potential reasons for the observed warm bias. Comparing radiative and turbulent surface fluxes with observations showed that the agreement between modeled and observed surface-energy budget components depends strongly on the exact location. While, for example, both AROME and WRF capture the observed magnitudes of net radiation and sensible and latent heat fluxes well for an eddy-covariance station at Innsbruck (surface fluxes were not available for all models), WRF strongly overestimates the sensible heat flux at a steep grass-covered slope site to the east of Innsbruck. Based on these initial results, it was thus not possible to draw any conclusions on the impact of the modeled surface fluxes on the observed warm bias.

The second potential mechanism that was explored briefly in the project is the valley-wind circulation and its impact on turbulent mixing in the valley atmosphere. Observations from the wind lidars in Innsbruck show a pronounced down-valley flow during the selected case study. The daytime up-valley wind transitions to the nighttime down-valley flow between approximately 1600 and 1900 UTC, with weak winds during this period. The down-valley flow then continues throughout the night with maximum speeds of 5–10 m s^{-1} at a height of approximately 300 m AGL. The westerly, down-valley wind direction and the associated jet profile are also visible in the radiosonde profile at 0300 UTC (Fig. 2). While the modeled wind field in the valley varies strongly among the five simulations, all of them underestimate the observed down-valley wind speeds. In particular, ICON and the Unified Model simulate very low wind speeds with a weak easterly up-valley component near the valley floor. WRF and AROME produce a down-valley flow with a jet profile, but still underestimate the observed wind speed by 5 m s^{-1} or more. In addition, the transition from up-valley to down-valley flow occurs too late in the simulations. The delay ranges from about an hour in AROME to three hours in WRF and ICON.

Comparing modeled turbulence kinetic energy (TKE) with observations from a 35-m high university building in Innsbruck also shows that all five model simulations underestimate TKE by a factor of two or more, which may be related to the underestimation of the down-valley flow which contributes to TKE production. Looking at other sites in the valley suggests, however, that the representation of TKE in the simulations is strongly site-dependent, similar to the turbulent heat flux.

A more detailed analysis of the models' warm bias and the reasons behind it is and will be performed in follow-up student theses (see outlook below).

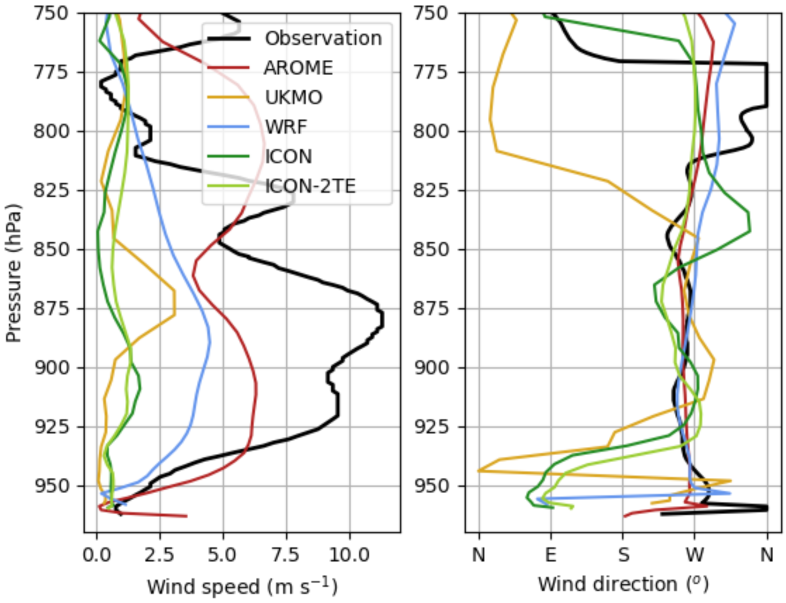

Figure 2: Vertical profiles of wind speed and wind direction at Innsbruck from the radiosounding at the airport and from the five model simulations.

Project output

The following output resulted directly from this project:

1. The AROME simulation was submitted to the TEAMx model intercomparison study. GeoSphere Austria is thus officially participating in the intercomparison study with AROME.
2. A python code package was written to read in the data from the models participating in the intercomparison study at the time of this project and the observational data used for the model evaluation. The package also includes scripts to extract, for example, vertical profiles and cross sections from the three-dimensional model output for visualization and further analysis. The code package is archived on the University of Innsbruck Gitlab repository and is being used by other students continuing to work on the topic.
3. The scientific results from the intercomparison performed in this project were presented at the EMS Annual Meeting 2024 (Lehner et al.: TEAMx cold-air pool model intercomparison study[2]).

Outlook

Subsequent to this project a BSc thesis[3] further quantified the warm bias and the characteristics of the inversion layer (e.g., strength and depth) in the five simulations compared to the observations. An ongoing MSc thesis will focus on the mechanisms leading to the observed model bias.

References

Haid, M., A. Gohm, L. Umek, H. C. Ward, T. Muschinski, L. Lehner, and M. W. Rotach (2020). "Foehn-cold pool interactions in the Inn Valley during PIANO IOP2". In: *Quart. J. Roy. Meteor. Soc.* 146, pp. 1232–1263. DOI: `10.1002/qj.3735`.

[2]https://meetingorganizer.copernicus.org/EMS2024/EMS2024-504.html
[3]Ehrngruber, C., 2025: Representation of a Cold-Air Pool in Numerical Models. BSc Thesis, University of Innsbruck

Holtslag, A. A. M., G. Svensson, P. Baas, S. Basu, B. Beare, A. C. M. Beljaars, F. C. Bosveld, J. Cuxart, J. Lindvall, G. J. Steeneveld, M. Tjernström, and B. J. H. Van de Wiel (2013). "Stable atmospheric boundary layers and diurnal cycles". In: *Bull. Amer. Meteor. Soc.* 94, pp. 1691–1706. DOI: 10.1175/BAMS-D-11-00187.1.