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A review of the modern fluctuations of tropical glaciers

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Abstract

The tropical climate is characterized by a homogeneous atmosphere without frontal activity, a lack of thermal seasonality, and by one to two differently pronounced precipitation seasons. Consequently, tropical climate has a characteristic impact on tropical glaciers, with glacier–climate interactions different from those of the mid- and high-latitudes.

The glaciers of tropical South America, Africa and New Guinea had a general maximum extent during the Little Ice Age (LIA) and have receded since the second half of the 19th century. Since then the fluctuations have been differently pronounced in different regions, but their general behaviour has been largely synchronous. The retreat from the LIA extent slowed on many glaciers at the beginning of the 20th century, some of them even readvanced almost to the LIA extent. The 1930s and 1940s brought a marked loss of ice masses and were followed by a moderate retreat. Around 1970 the recession generally slowed. Some glaciers even advanced. The last decade was again characterized by a pronounced glacier recession on all tropical mountains which are under observation. The modern fluctuations of tropical glaciers are also quite synchronous to those of the glaciers in the mid-latitudes.

A reduction in air humidity with all the consequent changes in energy and mass balance is suggested to be a major reason for the general recession of tropical glaciers since the end of LIA. The rise in air temperature explains only part of the glacier recession. The accelerated recession since the 1980s is most probably caused by increased air temperature and increased air humidity. Nevertheless, the knowledge of tropical glaciers is still scarce compared to those of the mid and high latitudes. This contribution reviews present knowledge of the fluctuations of tropical glaciers. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

From a glaciological point of view, the following delimitations give a useful definition of the Tropics (Kaser, 1995, 1998; Kaser et al., 1996a): they must be within (1) the astronomical tropics (radiative delimitation); (2) the area where the daily temperature variation exceeds the annual temperature variation (thermal delimitation) and (3) the oscillation area of the Inter Tropical Convergence Zone (ITCZ) (hygric delimitation) (Fig. 1). Thus, tropical glacier regimes can clearly be distinguished from those of higher latitudes. Within these boundaries, outer tropical conditions with one wet and one dry season may be distinguished from the inner tropical conditions with

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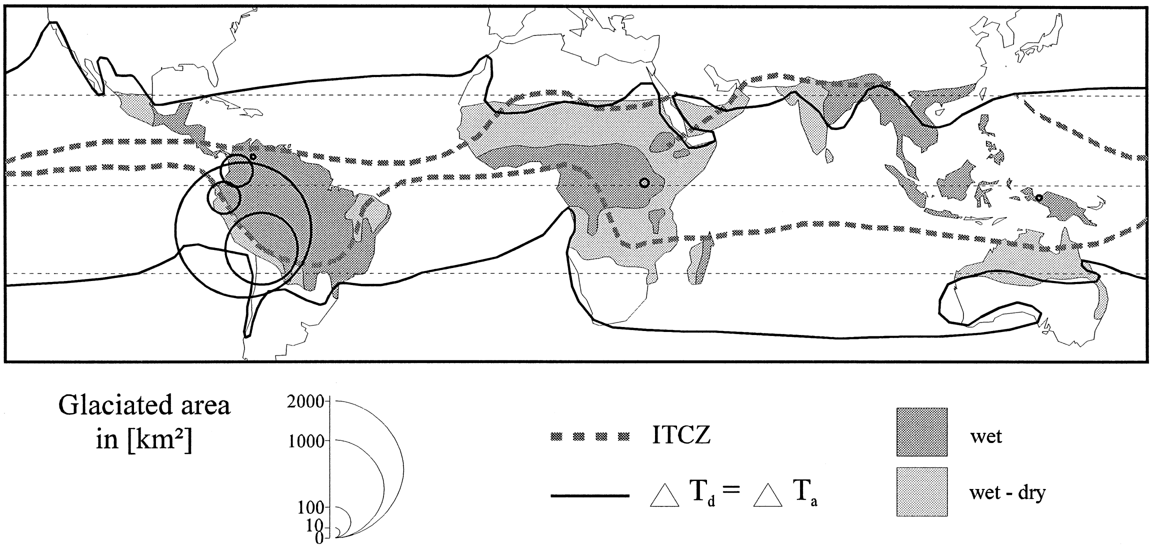

Fig. 1. The Tropics and their delimitations from a glaciological point of view, and the distribution of the glacier areas according to countries' ITCZ (after Kaser, 1998 and Kaser et al., 1996a).

more or less continuous precipitation. In addition, the thermal homogeneity of the tropical atmosphere, including a fairly constant height of the 0°C-level, provide advantageous boundary conditions for the interpretation of the glacier–climate interactions (Kaser, 1995, 1998; Kaser et al., 1996a).

Following these delimitations, tropical glaciers occur in Irian Jaya (Indonesian New Guinea), on the East African Mt. Kenya, Kibo (Mt. Kilimanjaro), and Rwenzori, and in the South American Andes between Venezuela and Bolivia. The distribution of glacier surface areas according to countries is shown in Fig. 1 and in Table 1.

The absence of thermal seasonality leads to special behaviours of some glaciological key values. The vertical mass budget gradient on the glacier

Table 1
The areas of tropical glaciers (after Kaser, 1998)

	km^2	%	Year	Sources
Rwenzori	1.7	0.06	1990	Kaser (1998)
Mt. Kenya	0.4	0.01	1993	Hastenrath (1995)
Kibo (Kilimanjaro)	3.3	0.12	1989	Hastenrath and Greischar (1997)
Africa	**5.4**	**0.19**	**ca 1990**	
Irian Jaya	**3.0**	**0.11**	**1988**	Peterson and Peterson (1994)
Colombia	108.5	3.92	ca. 1950	after Jordan (1991)
Venezuela	2.7	0.10	ca. 1950	after Jordan (1991)
Equador	112.8	4.08	ca. 1970	after Jordan (1991)
Perú	1.972.0	71.28	1970	after Jordan (1991)
Bolivia	562.0	20.32	ca. 1980	after Jordan (1991)
S America	**2.758.0**	**99.70**	**ca. 1950–ca. 1980**	
Total	**2.766.4**	**100**	**1950s–1990**	
Estimated total surface area for 1990: $< 2.5 \times 10^3$ km^2				

tongues is weaker than in the mid-latitudes (Kaser et al., 1996a); therefore, the accumulation area ratio AAR is higher, and the reaction of the terminus to a shift of the equilibrium line altitude (ELA) is greater. Moreover, the sensitivity of ELA to climatic disturbances is generally less with the exclusion of the effect of temperature deviations. A change in temperature affects both the ablation due to the sensible heat flux, and the accumulation due to a shift of the 0°C-level. (Kaser, 1998).

The focus of this condensed review article is on the modern glacier fluctuations in the Tropics and their climatological interpretation. The period in question (''modern'') is from the end of the Little Ice Age (LIA) in the middle of last century till today. A large glacier extent at the end of LIA is reported or at least suggested for all tropical areas (e.g., De Filippi, 1909; Kinzl, 1942; Schubert, 1972; Allison and Peterson, 1976; Hastenrath, 1981, 1984, 1995; Patzelt et al., 1984; Osmaston, 1989a,b; Thompson, 1995; Thompson et al., 1986, 1995) but the date of the beginning of the retreat is not always clear. However, consensus exists about the general marked shrinkage of the tropical glaciers since the end of LIA.

Glaciological observations are scarce for the Tropics and they vary (changes of area, of length, but seldom of volume or masses) (Kaser et al., 1996a). Additionally, they deal with different time periods and often have uncertain dating before the middle of the 20th century. The attempt to compile modern glacier fluctuations in the Tropics, therefore, is done by using information which differs in quantity as well as in quality. Information regarding the changes in surface areas is most complete.

2. Modern glacier fluctuations in the Tropics — a synthesis

The knowledge of surface area extents refers to single years of investigation which are different for the different areas and, in most cases, from a glaciological point of view, arbitrarily chosen. Only the surface areas reconstructed from moraine extensions indicate quasi stable conditions which are relevant for a glacier–climate interpretation. Table 2 shows the reported changes of glacier areas on tropical high mountains.

The relative changes are additionally shown (italic in table) to make the different areas comparable, regardless of absolute glacier size. The level from 1900 to 1920 is used as a reference (bold in the table) for these relative changes. Under the assumption that the glacier extent around 1920 was smaller than at the end of the Little Ice Age, the earlier extent was arbitrarily set at a reference level of 110% for Irian Jaya. This is, however, no suggestion to the real variations between the end of LIA and the reference period. In addition to large glacier areas of the different mountain regions in Table 2, the single Lewis glacier (Mt. Kenya) is listed as the tropical glacier which is best studied by far.

Table 2 shows that tropical glaciers have drastically retreated since the end of the Little Ice Age. The small glaciers — and those in Irian Jaya which extend only over a small altitude range — had the highest relative area losses, whereas the large glaciers in the Cordillera Blanca and in the Cordillera Real have had relatively small losses. This can be expected because of the year-round ablation below the equilibrium line of tropical glaciers. The respective strong vertical balance gradient leads to a substantially high sensitivity of the tongues to a rise of the ELA. Glaciers with a small altitudinal extent are obviously most effected (Kaser, 1995, 1998).

Beyond this erratic picture produced from the quite limited amount of discrete information regarding the extent in surface area for some mountain regions, additional notes of individual expeditions and visitors facilitate the formation of a puzzle which roughly indicates a more continuous concept of modern glacier fluctuations. The fluctuations of the Cordillera Blanca and the Rwenzori glaciers have been investigated comprehensively by the author (Kaser, 1998). The following Section 2.1 and Section 2.2 are summaries of these reviews. Other areas refer to the available literature (Section 2.3).

2.1. Modern glacier fluctuations in the Cordillera Blanca

In addition to the glacier area changes in the sub-massifs of Huascarán–Chopicalqui and Santa

Table 2
Absolute (km^2) and relative (%) (italic) — area changes in the Irian Jaya (I.J.), on Mt. Kenya, the Kibo (Mt. Kilimanjaro), the Rwenzori (Rw.), the Huascarán–Chopicalqui Massif (H–C) and the Santa Cruz–Pucahirca range (SC–P) in the Cordillera Blanca, for selected glaciers of the Cordillera Real (Bolivia) and on Pico Bolivar (Venezuela). Lewis glacier (Mt. Kenya) is added as the tropical glacier which is best studied by far. Arbitrarily set reference values, usually but not always = 100%, are shown in bold

	I. J.[a]	Kenya[b]	Lewis gl[bc]	Kibo[de]	Rw.[f]	H–C[g]	SC–P[h]	CR[i]	PB[j]
ca. 1850	**19.3** *(110)*		0.69 *(111)*	20.0 *(165)*					
1899		**1.563** *(100)*	0.63 *(102)*						
1906					**6.509** *(100)*				
1910									**2.85** *(100)*
1912				**12.1** *(100)*					
ca. 1920			**0.62** *(100)*			**71.0** *(100)*	**93.7** *(100)*	**28.58** *(100)*	
1934			0.50 *(81)*						
1936	13.0 *(74)*								
1947		0.874 *(56)*							
1953				6.7 *(55)*					
1950						59.3 *(84)*	84.2 *(90)*		
ca. 1955					3.808 *(58)*				
1958			0.38 *(61)*	6.5 *(54)*					
1963		0.765 *(49)*	0.37 *(60)*					26.63 *(93)*	
1970				4.9 (40)		58.2 *(82)*			
1972	6.9 *(49)*								0.57 *(20)*
1974			0.32 *(52)*						
1976				4.2 *(35)*					
1975								25.03 *(88)*	
1978			0.31 *(50)*						
1983			0.28 *(45)*						
1987		0.495 *(32)*	0.24 *(39)*						
1989				3.3 *(27)*					
1990			0.23 *(37)*						
ca. 1990	3.0 *(17)*				1.674 *(26)*				
1993		0.413 *(26)*	0.20 *(32)*						

[a] Allison and Peterson (1976), Peterson and Peterson (1994).
[b] Hastenrath (1991, 1995), Hastenrath et al. (1989).
[c] Patzelt et al. (1984).
[d] Osmaston (1989a).
[e] Hastenrath and Greischar (1997).
[f] Kaser (1998).
[g] Kaser (1998), Kaser et al. (1996b).
[h] Georges (1996), Kaser (1998), Kaser and Georges (1997).
[i] Finsterwalder (1987).
[j] Schubert (1972), Jordan (1991).

Cruz–Pucahirca (Table 2) early reports, arial and terrestrial pictures, data regarding the changes of the lengths of a few tongues over the most recent decades, and analyses of Glaciar Yanamarey (Hastenrath and Ames, 1995a,b) and Glaciar Uruashraju (Ames and Hastenrath, 1996) are available.

Sievers (1914) observed a general glacier retreat in the Cordillera Blanca and also in other areas during his journey through Perú and Equador, carried out in 1909. The start of this retreat is difficult to determine. Broggi (1943) quotes information from A. Raimondi according to which the retreat in the Cordillera Blanca had started in 1862. This indicates that the glaciers of the Cordillera Blanca started their retreat from the highest level of the LIA just after the middle of the century.

The glaciers in the aerial pictures of 1948 and 1950 had clearly withdrawn behind the youngest moraines which are still not overgrown by vegetation and seem very distinct. These fresh moraines lie within the thick moraine walls which are covered with slightly developed and low vegetation on their inside, but are already covered with bushes on their outside. Kinzl (1942) has described this sequence of moraines and attributed the thick moraine bastion to a maximum glacier extent over centuries which retreated only towards the end of the 19th century. He found the most recent fresh moraines in many places on top of this bastion and attributed them to an advance lasting only a short time that had taken place shortly before he visited the area in 1932, 1936, 1939, and 1940. The date of this advance can be delimited due to an observation made by the miners of the Mina Atlante on the eastern side of the Cordillera Blanca. According to them Glaciar Atlante advanced in 1923–1924. Up to 1939, the glacier had retreated by more than 100 m (Kinzl, 1942). At the time of the advance of the Glaciar Atlante, miners in other Peruvian mines had problems with advancing glacier tongues (Oppenheim, 1945).

The retreat following in the 1930s was drastic and can be extensively and quantitatively derived from the aerial pictures, as shown for the abovementioned sub-massifs (Table 2). The evaluations made for the Huascarán–Chopicalqui Massif indicate rather weak changes between 1950 and 1970.

Since the beginning of the 1970s the changes of the lengths of the tongues have been measured on single glaciers and were examined by Kaser et al. (1990) up to 1987. Older tongue extents were reconstructed from maps. The tongues have moderately retreated since 1948 and partly had a slight advance between 1974 and 1979. A following, advanced retreat was slowed down again from 1985 to 1986. Ames and Francou (1995) have extended the curves up to 1993 showing an advanced retreat again.

In summary, the glaciers of the Cordillera Blanca have retreated since the end of the highest level of the Little Ice Age in the middle of the 19th century, which cannot be dated exactly. The temporary minimum ice extent, and eventual intermediate advances before an advance around the middle of the 1920s, is not known. The 1920 advance reached almost the same extent as the LIA extent. Between 1930 and 1950, a striking retreat took place that became again much weaker later on. In the 1970s, a few glaciers advanced only to retreat again faster.

2.2. Modern glacier fluctuations in the Rwenzori mountains

Since Abruzzis expedition in 1906 (De Filippi, 1909), various information on the extent of the Rwenzori glaciers has been available showing the following picture of their modern fluctuations.

- In 1906 the glaciers of the Rwenzori were already retreating from a highest level, although it is not known when this started. However, the forefield was still free of lichen (Roccati, 1909). An indication of how quickly lichen colonize snow-free rocks is given in an observation by Humphreys in 1927. When he visited **Elena Glacier** the cairns of the Abruzzi expedition were already covered with lichen. Therefore, it has to be assumed that the last maximum extent could not have been much before 1906. There is no indication whether this was the comparatively late retreat from the LIA or a readvance at the end of the 19th century.
- ‘‘ ...(It was after Humphreys’ expeditions (1926 and 1927) that the general retreat of the Rwenzori ice became apparent, although no detailed work was undertaken at that time’’ (Whittow et al., 1963)
- In the ‘‘past 30 years’’ (about 1930–1958) Whittow et al. (1963) assume an increasingly strong retreat of **Speke Glacier**.
- Five photographs, which show **Speke Glacier** from a similar angle — one from 1952 (Bergstrøm, 1955), one from 1960 taken from the archives of J.B. Whittow (Kaser, 1998), one around 1967 (without date in Temple, 1968), one from 1974 (Hastenrath, 1984) and one photograph from 1977 (Lichtenegger and Lichtenegger, 1978) — show that the retreat was small between 1952 and 1974 and that the area of Speke Glacier did not decrease up to 1977. However, the serac zones in the middle of the glacier seem to be less and less ragged. This gives the impression of a decreasing volume. However, the varying thickness of the snow cover can distort the picture.
- Temple (1968) published changes of the lengths on Elena, Speke, and Savoia Glacier which had been measured between June 1958 and January 1967.

They show a small advance which had taken place on **Elena Glacier** between June 1959 and March 1962 and on **Speke Glacier** between July 1961 and March 1962. On Speke Glacier, this phase of slight tongue changes left a thin wall of large rocks as frontal moraine.

· Kaser and Noggler (1991) have summarized the changes of the length of the tongue of **Speke Glacier** between January 1958 and January 1990. After a short advance in the early 1960s and a following weak retreat, an increased recession took place in the 1980s.

· The latest measurements show that the strong retreat of the tongue of **Speke Glacier** continues (Talks, 1993).

· Whittow et al. (1963) summarize for **Savoia Glacier**:

- From comparison of photographs: 1906 (De Filippi, 1909)–1927–1931 (Humphreys, 1927, 1933)–1934 (Synge, 1937) slight retreat
- 1934–1943 (Firmin, 1945): strong retreat
- 1943–1948 (photograph P. Jenkins, archives Mountain Club of Uganda): disintegration of the middle part of the tongue.
- 1948–1958: no changes
- 1958–1961: slight retreat

In summary, before 1906 the glaciers of the Rwenzori had retreated from a highest level not too long ago. Up to the end of the 1930s the total retreat was low. However, nothing is known of the course during that time. Between the 1930s and the 1950s the glaciers of the Rwenzori underwent a generally strong retreat. In the beginning of the 1960s a number of glaciers slightly advanced (Whittow et al., 1963; Temple, 1968). Up to the end of the 1970s a further retreat took place which only caused slight area changes, as a series of a few photographs indicate. Since then the glaciers have melted heavily.

2.3. Modern glacier fluctuations in other tropical mountains

In addition to the glacier extents on **Mt. Kenya** shown in Table 2, various information about **Lewis Glacier** is available. It is the most intensively studied tropical glacier. Besides a two decade time series of mass balances (among others Hastenrath, 1984, 1991) and frequent determinations of the ice extent (Patzelt et al., 1984, Hastenrath, 1991; 1995; Table 2) some additional information is available:

· Different assumptions have been made about the beginning of the retreat of the Lewis Glacier on Mt. Kenya. While Kruss (1983) and Hastenrath (various publications) assume that the glacier only retreated towards the end of the 19th and at the beginning of the 20th century, Patzelt et al. (1984) derive from detailed field evidence that a retreat had already taken place earlier, and that between 1890 and 1920 several advances and possibly even an increase in the elevation of the glacier surface had taken place. They describe clearly a marked moraine outside the one which was built around 1890. Because of the fresh and uneroded appearance of the moraine, these authors suggest that it is the result of a culmination in the middle of the 19th century. Hastenrath (1995) reports that the glaciers on Mount Kenya were stable at the beginning of the 20th century.

· Immediately afterwards it suffered its highest volume and area losses (Table 2).

· Patzelt et al. (1984) determined a basic increase of the thickness in the upper area of Lewis Glacier between 1958, 1963, and 1974.

· The ice retreat has accelerated in the 1980s and 1990s (Hastenrath, 1995)

For the **Irian Jaya** glaciers little is known in addition to the extents listed in Table 2. However, even though it could not be dated exactly, the largest modern ice extent in the Irian Jaya mountains is to be assigned to the LIA (Hope et al., 1976). Hastenrath (1995) assumes that the beginning recession from it might have been around the middle of the 19th century.

Hastenrath and Geischar (1997) present a reconstruction of the glaciation on **Kibo**, Mt. Kilimanjaro for various years which supplements the data given by Osmaston (1989a). No additional useful information is available. The strong retreat from the LIA until the early 20th century might be related to the particular relief of the mountain (Kaser, 1998).

There is no sufficient information from other tropical high mountains which would allow the reconstruction of their modern glacier fluctuations.

Considering the fact that different glaciers within an area as well as glaciers of different tropical mountains respond with different delay and magnitude to climatic disturbances, the few information indicate a certain synchronosity of the general features of the fluctuation of tropical glaciers since the beginning retreat from the LIA:

- A distinct highest level determined on all tropical glaciers that were investigated is to be assigned to the LIA. It had its end around the middle of the 19th century.
- After the general retreat over the second half of the 19th century some advances occurred around the turn of the century. Little detail is known about this period.
- A distinct advance or at least a quite stable situation was reported around 1920.
- After this, a marked retreat took place mainly in the 1940s and 1950s.
- The period up to the 1970s is characterized by rather small changes and minor advances of single glaciers.
- Afterwards, an accelerated retreat occurred on all tropical glaciers.

These general features of the modern fluctuations of tropical glaciers largely meet those of the glaciers in the mid and high latitudes. This is shown in Table 3, which is a summary of observed culmination of advances in different mountain areas. It is mainly based on a table which was presented by Porter (1986). Information from the Austrian Alps (Patzelt, 1973, 1985), the Cordillera Blanca, the Rwenzori mountains, and from Lewis Glacier (Patzelt et al., 1984) are added. One has to keep in mind that almost no information from tropical glaciers existed until the beginning of our century and that phases of general recession are not shown explicitly in Table 3.

3. Possible climatic reasons for glacier fluctuations in the tropics

The global synchronosity of the general features of modern fluctuations of mountain glaciers leads to the assumption that their causes are also of a global scale. Thus, two primary climatic input key variables have to be considered to be the initial causes for the glacier fluctuations: the air temperature and the content of water vapour expressed as the vapour pressure in the atmosphere, e.g., all other factors which contribute to the accumulation as well as to the ablation of snow and ice depend on these two parameters which, in turn, both result from the energetic state of the earth–ocean–atmosphere system.

Table 3
Recorded culminations of advances of glaciers in different mountain areas of the world. (X) The Lewis Glacier did not advance, but a thickening of the upper areas was observed (Bhatt et al., 1981). ? It is not known when the LIA maximum ended in the Rwenzori mountains and whether there was an additional culmination at the end of the 19th century. A maximum extent is assumed shortly before 1906

Area	1850–1860	1860–1880	1880–1890	1890–1900	1900–1910	1910–1915	1915–1930	1930–1960	1960–1980
W Alps	x		x		x		x		x
Austrian Alps[a]	x		x		x		x		x
N Scandinavia	x		x		x		x		x
Norway		x			x		x		
Iceland	x		x		x				
Canad. Arctic			x		x		x		
Can. Rockies	x		x						x
S Alaska	x		x		x		x		x
Cascade	x		x		x		x		x
Centr. Caucas.	x		x		x	x	x	x	x
Asia	x	x	x		x				
Cord. Blanca[b]	x						x		x
Rwenzori[b]	?		?		?				x
Lewis[c]	x		x		x		x		(x)

[a] Patzelt (1973, 1985).
[b] Kaser, 1998; Section 2.1 and Section 2.2. in this article.
[c] Patzelt et al. 1984; all others: Porter (1986) ref. to different authors.

These two parameters and their changes have a distinctly different variation in space as well as in time. This is best pronounced in the Tropics where it can be assumed of the air temperature that, over large areas, it changes homogeneously. This is true for the horizontal extent as well as for possible changes of the vertical temperature gradient. However, this is different for the amount of humidity in the atmosphere. Due to the short residence time of water vapour in the atmosphere the horizontal distances between its sources and sinks remain within a few thousand kilometers (e.g., Hense et al., 1988). In addition, the consequences of changing air humidity are highly dependent on the starting conditions.

Considering changes in air temperature and air humidity as the input variables when attempting to explain glacier fluctuations on a large scale, several combinations and different consequent effects for the mass balance of a glacier are discussed in detail elsewhere (Kaser, 1998). Whereas, with regards to the spatial distribution, a change in temperature will affect all respective mass balance components uniformly, changes in air humidity have different effects in dry and humid areas. For example, in a climate as found on outer tropical glaciers during the dry season, a rise in air humidity might reduce sublimation as well as increase the long-wave radiation budget and contribute to a more negative mass balance. In a humid area, mass loss might be caused by a decrease in air humidity and subsequently by increasing insulation as well as decreasing precipitation. However, glacier fluctuations which show marked spatial diversities are attributed to changes in air humidity rather than in air temperature. Hence, because of the thermal homogeneity of the tropical atmosphere, tropical glaciers are particularly suitable for investigating glacier–climate relation in terms of global change.

Different probable reasons for the fluctuations of tropical glaciers and for different time periods are offered by various authors. Some are based on numerical modeling, when demanded input data were available (Allison and Kruss, 1977; Kruss, 1983; Hastenrath and Kruss, 1992). Others are determined from reconstructed shifts of mean equilibrium lines or just by comparing observed glacier fluctuations with observed climatic conditions. The authors each compare their model results with independent climatological evidence. Table 4 gives the respective results.

Most of the data in Table 4 does not refer to periods with a glaciologically homogeneous character, but to periods delimited by available data of glacier extents. Nevertheless, they suggest a roughly generalized run of the glacier–climate interaction since the end of the LIA.

Tracing the results shown in Table 4 back to changes in air temperature and air humidity, and

Table 4
Probable reasons for the fluctuations of tropical glaciers as reported by different authors. δt = changes in air temperature, δp = changes in precipitation, δh = changes in air humidity, and δG = changes in global radiation

Area	Periode	Reasons	References
Irian Jaya	LIA-1970	$\delta t = +0.6$°C/century ev. other reasons too	Allison and Kruss, 1977
Mt. Kenya	LIA-beg. 20th century	$\delta p =$ "−"	Patzelt et al., 1984
Mt. Kenya	1899–1963	$\delta p = -160 \pm 70$ mm a^{-1} (= −15%) $\delta t = +0.35 \pm 0.2$°C	Kruss, 1983
Rwenzori	general retreat	$\delta h =$ "−"	Kaser and Noggler, 1991, 1996 Kaser, 1992
Cord. Blanca	1930–1950	$\delta t = +0.12$°C $\delta h =$ "−" ⇒ $\delta p = -155$ mm a^{-1} (= −10%) $\delta G = +0.4$ MJ m^{-2} d^{-1} (= +3%)	Kaser and Georges, 1997 Kaser (1998)
Rwenzori	advances in 1960s	$\delta p =$ "+"	Temple, 1968 Kaser and Noggler, 1991
Cord. Blanca	advances in 1970s	$\delta p =$ "+"	Kaser et al., 1990
Mt. Kenya	1963–1987	$\delta t = +0.2$°C $\delta h = +0.3$ g kg^{-1}	Hastenrath and Kruss, 1992

assuming a global or at least an intertropical character of the suggested climatic changes, the following picture results. Between the end of the LIA and the turn of the century, decreased atmospheric vapour caused the steady retreat. There is no information about the advances around the turn of the century and those in the 1920s. The accelerated retreat in the 1930s and 1940s was due to increased temperatures but mainly by drier conditions. For the Cordillera Blanca it is suggested that only one-third of the glacier retreat can be attributed to the change in air temperature, and two-thirds to the variables which changed due to decreased air humidity (Kaser and Georges, 1997). The scattered small advances in the 1960s and 1970s coincide with respective increased precipitation. Since the 1980s, increased air temperature as well as increased atmospheric vapour seem to cause the accelerated retreat which is observed all over the Tropics.

4. Summary and concluding remarks

Tropical glaciers are highly expressive indicators of tropical climate, which is mainly characterized by homogeneous thermal conditions, and which dominates about one third of the globe. As a result, the fluctuations of tropical glaciers can be directly traced to disturbances of simple climate parameters in which complex synoptic patterns have no bearing.

The retreat of tropical glaciers since the end of the Little Ice Age was frequently interrupted by advancing or stagnant conditions. Even if there are still some differing opinions about the beginning of the retreat from the LIA, but also taking into account that glaciers generally react individually differently on climate impact, the observed tropical glaciers are fairly synchronised among each other. Moreover, their behaviour also generally parallels that of mid and high latitude mountain glaciers. Thus, a global character of the possible climatic reasons is postulated. It is suggested that the main phases of these glacier fluctuations are, to a distinct extent, caused by changes in the hydrospheric conditions. A rise in air temperature can only partially explain the general retreat.

It has to be clearly stated that this review paper tries to give a synthesis of what has to be considered still very poor knowledge on glacier and climate history in the Tropics since the end of the Little Ice Age, and to compile a probable picture in this regard. Measured and reconstructed glaciological and climatological evidence needs to be increased. Some of the supposed assumptions need further proof.

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References

Allison, I., Kruss, P., 1977. Estimation of recent climate change in Irian Jaya by numerical modeling of its tropical glaciers. Arct. Alp. Res. 9 (1), 49–60.

Allison, I., Peterson, J.A., 1976. Ice areas on Mt. Jaya. Their extent and recent history. In: Hope, G.S., Peterson, J.A., Radok, U., Allison, I. (Eds.), The Equatorial Glaciers of New Guinea. Results of the 1971–1973 Australian Universities' Expeditions to Irian Jaya: Survey, Glaciology, Meteorology, Biology and Paleoenvironments. A.A. Balkema, Rotterdam, pp. 27–38.

Ames, A., Francou, B., 1995. Cordillera Blanca, Glaciares en la Historia. Bull. Inst. Fr. Études Andines 24 (1), 37–64.

Ames, A., Hastenrath, S., 1996. Mass balance and iceflow of the Uruashraju Glacier, Cordillera Blanca, Perú. Z. Gletscherkd. Glazialgeol. 32 (2), 83–89.

Bergstrøm, E., 1955. The British Ruwenzori expedition, 1952. J. Glaciol. 2 (17), 468–476.

Bhatt, N., Hastenrath, S., Kruss, P., 1981. Ice thickness determination at Lewis Glacier, Mount Kenya: seismology, gravimetry, dynamics. Z. Gletscherkd. Glazialgeol. 16 (2), 213–228.

Broggi, J.A., 1943. La desglaciación actual de los Andes del Perú. Boletín de la Sociedad Geológica del Perú XIV/XV, 59–90.

De Filippi, F. (Ed.), 1909. Der Ruwenzori. Erforschung und erste Ersteigung seiner höchsten Gipfel. Von L.A. v. Savoyen, Herzog der Abruzzen, F.A. Brockhaus. In: Beilage: Topographische und geologische Karte der Ruwenzori-Kette 1: 40.000.

Finsterwalder, R., 1987. Der Gletscherrückgang in der Cordillera Real (Bolivien) seit 1928 im Vergleich zu dem in den Ostalpen. Z. Gletscherkd. Glazialgeol. 23 (2), 143–153.

Firmin, K., 1945. Ruwenzori: the mountains of the Moon. East Afr. Ann. 1944–1945, 25–35.

Georges, Ch., 1996. Untersuchungen zu den rezenten Gletscherschwankungen in der nördlichen Cordillera Blanca, Perú. Diplomarbeit, Institut für Geographie, Innsbruck.

Hastenrath, S., 1981. The Glaciation of the Ecuadorian Andes. Balkema, Rotterdam.

Hastenrath, S., 1984. The Glaciers of Equatorial East Africa. Dordrecht, etc.. D. Reidel Publishing.

Hastenrath, S., 1991. Glaciological Studies on Mount Kenya 1971–1983–1991. University of Wisconsin, Madison.

Hastenrath, S., 1995. Glacier recession on Mount Kenya in the context of the global tropics. Bull. Inst. Fr. Études Andines 24 (3), 633–638.

Hastenrath, S., Ames, A., 1995a. Recession of Yanamarey glacier in Cordillera Blanca. Perú, during the 20th century. J. Glaciol. 41 (137), 191–196.

Hastenrath, S., Ames, A., 1995b. Diagnosing the imbalance of Yanamarey glacier in the Cordillera Blanca of Perú. J. Geophys. Res. 100 (D3), 5105–5112.

Hastenrath, S., Geischar, L., 1997. Glacier recession on Kilimanjaro. East Africa, 1912–1989. J. Glaciol. 43 (145), 455–459.

Hastenrath, S., Kruss, P., 1992. The dramatic retreat of Mount Kenya's glaciers 1963–1987. Greenhouse forcing. Ann. Glaciol. 16, 127–133.

Hastenrath, S., Rostom, R., Caukwell, R.A., 1989. Variations of Mount Kenyas glaciers 1963–1987. Erdkunde 43, 202–210.

Hense, A., Krahe, P., Flohn, H., 1988. Recent fluctuations of tropospheric temperature and water vapour content in the tropics. Meteorol. Atmos. Phys. 38, 215–227.

Hope, G.S., Peterson, J.A., Radok, U., Allison, I. (Eds.), The Equatorial Glaciers of New Guinea. Results of the 1971–1973 Australian Universities' Expeditions to Irian Jaya: Survey, Glaciology, Meteorology, Biology And Paleoenvironments. A.A. Balkema, Rotterdam.

Humphreys, G.N., 1927. New routes on Ruwenzori. Geogr. J. 69 (6), 516–531.

Humphreys, G.N., 1933. Ruwenzori flights and further exploration. Geogr. J. 82, 481–514.

Jordan, E., 1991. Die Gletscher der Bolivianischen Anden. Eine photogrammetrisch — kartographische Bestandsaufnahme der Gletscher Boliviens als Grundlage für klimatische Deutungen und Potential für die wirtschaftliche Nutzung. Franz Steiner Verlag, Stuttgart.

Kaser, G., 1992. Le fluttuazioni dei ghiacciai del Ruwenzori (Africa Orientale) dalla spedizione del Duca degli Abruzzi (1906) sino agli anni '90. Geogr. Fis. Dinam. Quat. 15 (1–2), 121–125.

Kaser, G., 1995. Some notes on the behaviour of tropical glaciers. Bull. Inst. Fr. Etudes Andines 24 (3), 671–681.

Kaser, G., 1998. The Nature of Tropical Glaciers. International Hydrological Series. UNESCO-Cambridge Univ. Press (accepted and in preparation). English version of: Kaser, G., 1996. Gletscher in den Tropen-ein Beitrag zur Geographie der tropischen Hochgebirge. Habilitationsschrift, Universität Innsbruck.

Kaser, G., Georges, Ch., 1997. Changes in the Equilibrium Line Altitude in the Tropical Cordillera Blanca (Perú) Between 1930 and 150 and Their Spacial Variations. Annals of Glac. 24, papers of the International Symposium on Changing Glaciers held in Fjærland, Norway, 24–27 June 1996: 344–349.

Kaser, G., Noggler, B., 1991. Observations on Speke glacier, Ruwenzori Range, Uganda. J. Glaciol. 37 (127), 313–318.

Kaser, G., Noggler, B., 1996. Glacier fluctuations in the Ruwenzori Range (East Afrika) during the 20th century. A preliminary report. Z. Gletscherkd. Glazialgeol. 32, 109–117.

Kaser, G., Ames, A., Zamora, M., 1990. Glacier fluctuations and climate in the Cordillera Blanca, Peru. Ann. Glaciol. 14, 136–140.

Kaser, G., Hastenrath, S., Ames, A., 1996a. Mass balance profiles on Tropical glaciers. Z. Gletscherkd. Glazialgeol. 32, 75–81.

Kaser, G., Georges, Ch., Ames, A., 1996b. Modern glacier fluctuations in the Huascarán–Chopicalqui massif of the Cordillera Blanca, Perú. Z. Gletscherkd. Glazialgeol. 32, 91–99.

Kinzl, H., 1942. Gletscherkundliche Begleitworte zur Karte der Cordillera Blanca (Peru). Z. Gletscherkd. 28 (1–2), 1–19.

Kruss, P., 1983. Climate change in East Africa: a numerical simulation from the 100 years of terminus record at Lewis glacier, Mount Kenya. Z. Gletscherkd. Glazialgeol. 19 (1), 43–60.

Lichtenegger, J., Lichtenegger, B., 1978. In der Wetterküche des Ruwenzori. Die Alpen 54 (3), 119–126.

Oppenheim, V., 1945. Las glaciaciones en el Perú. Boletín de le Sociedad Geológica del Perú 18, 37–43.

Osmaston, H., 1989a. Glaciers, glaciations and equilibrium line altitudes on Kilimanjaro. In: Mahaney, W.C. (Ed.), Quarternary and Environmental Research on East African Mountains. Brookfield, Balkema, Rotterdam, pp. 7–30.

Osmaston, H., 1989b. Glaciers, glaciations and equilibrium line altitudes on the Ruwenzori. In: Mahaney, W.C. (Ed.), Quarternary and Environmental Research on East African Mountains. Brookfield, Balkema, Rotterdam, pp. 31–104.

Patzelt, G., 1973. Die neuzeitlichen Gletscherschwankungen in der Venedigergruppe, Hohe Tauern, Ostalpen. Z. Gletscherkd. IX (1–2), 5–57.

Patzelt, G., 1985. The period of glacier advances in the Alps, 1965 to 1980. Z. Gletscherkd. 21, 403–407.

Peterson, J.A., Peterson, L.F., 1994. Ice retreat from the neoglacial maxima in the Puncak Jayakesuma area, Republic of Indonesia. Z. Gletscherkd. Glazialgeol. 30, 1–9.

Patzelt, G., Schneider, E., Moser, G., 1984. Der Lewis gletscher, Mount Kenya. Begleitwort zur Gletscherkarte 1983. Z. Gletscherkd. Glazialgeol. 20, 177–195.

Porter, S.C., 1986. Pattern and forcing of Northern Hemisphere glacier variations during the last millenium. Quat. Res. 26 (1), 27–48.

Roccati, A., 1909. Übersicht der geologischen, petrographischen, mineralogischen, sowie der zoologischen und botanischen Beobachtungen. In: De Filippi, F. (Ed.), Der Ruwenzori. Erforschung und erste Ersteigung Seiner höchsten Gipfel. Anhang C. pp. 433–452.

Schubert, C., 1972. Geomorphology and glacier retreat in the Pico Bolívar area, Sierra Nevada de Mérida, Venezuela. Z. f. Gletscher. Glazialgeol. VIII (1–2), 189–202.

Sievers, W., 1914. Reise in Peru und Equador, ausgeführt 1909, Wissenschaftliche Veröffentlichungen der Gesellschaft für Erdkunde zu Leipzig, Band 8. Duncker and Humbolt, München, Leipzig.

Synge, P.M., 1937. Mountains of the Moon. Drummond, London.

Talks, A., 1993. East African Hot Ice 1993. Sir Roger Manwood's School Expedition to Kenya and Uganda. Sir Roger Manwood's School, Internal Report.

Temple, P.H., 1968. Further observations on the glaciers of the Ruwenzori. Geografiska Annaler, Ser. A 50 (3), 136–150.

Thompson, L.G., 1995. Late holocene ice core records of climate and environment from the Tropical Andes, Perú. Bull. Inst. Fr. Études Andines 24 (3), 619–629.

Thompson, L.G., Mosley-Thompson, E., Dansgaard, W., Grootes, P.M., 1986. The ''Little Ice Age'' as recorded in the stratigraphy of the Quelccaya ice cap. Science 234, 361–364.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Lin, P.N., Henderson, K.A., Cole-Dai, J., Bolzan, J.F., Liu, K.B., 1995. Late glacial stage and holocene Tropical ice core records from Huascarán, Peru. Science 269, 46–50.

Whittow, J.B., Shepherd, A., Goldthorpe, J.E., Temple, P.H., 1963. Observations on the glaciers of the Ruwenzori. J. Glaciol. 4 (35), 581–616.