and -0.6°C, when compared to the 1901-1960 reference period. This is substantially lower than the anomaly of -0.23°C for the coldest decade of 1901-1910 in the period of modern instrumental observations and, I think, matches the values of the coldest Little Ice Age decades (e.g. 1450's or 1690's).

In paleoclimatology, the ESA period is generally considered to have been cold and humid. Indeed, positive anomalies of annual mean precipitation prevailed in most of the Northern Hemisphere and occasionally reached substantial values, in excess of 150–200 mm/yr, in western Africa and eastern China (Fig. 2). The whole Sahara was considerably more humid than now and there is historical evidence that men could easily cross what is now the world's greatest desert (Hennig, 1944). At the same time, only negative precipitation anomalies were observed in high latitudes on all the continents. Another vast drier zone spanned tropical areas of Asia, Africa, and Central and South America.

According to my estimates, the precipitation anomaly, averaged over the Northern Hemisphere, was 14 mm/yr or ca. 1.5% higher than the present-day value. Hence, the ESA cold epoch was actually humid. This indicates that the relationship between zonal and hemispheric temperature and humidity is not merely nonlinear, which is well known, but nonmonotonous, i.e. humidity might increase with slight cooling. This is probably related to the fact that some decrease in the moisture content of the atmosphere is completely compensated by stronger westerlies in temperate and subtropical latitudes.

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The Behavior of Modern Low-Latitude Glaciers

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Around 1990, glaciers on low-latitude high mountains—in the South American Andes between Venezuela and Northern Chile, on the East African mountains Kenya, Rwenzori and Kilimanjaro, and on Irian Jaya (New Guinea)—covered an area somewhat less than 2,500 km^2. More than 99% of this area was in the Andes (Kaser, 1999; Kaser and Osmaston, 2002). These glaciers have all, following the global trend, retreated from their Little Ice Age extent after 1850 (Table 1) (Hastenrath, 2001). Secondary to the general retreat, and embedded in the global trend again, advances were observed around 1900, in the 1920's and in the 1970's (Kaser, 1999; Hastenrath, 2001). In the Cordillera Blanca, as most probably throughout the Peruvian Cordilleras (Albert, 2004), a more or less continuous snow cover on most of the glacier surfaces from October 1998 until May 2002 led to an interruption in the general retreat and even to tongue advances of some glaciers. Still, detailed information is scarce and the overall picture is all but complete. Nevertheless, the general retreat was strong and in some areas glaciers have vanished or are close to disappearing (Ramírez et al., 2001; Thompson et al., 2002). Glacier remnants on Irian Jaya (New Guinea) are about to disappear, as revealed by recent IKONOS satellite images from June 2002, showing that there are only two small glaciers left (Klein, pers. comm.).

Table 1: Modern retreat of low-latitude glaciers (after Kaser, 1999); (1) Thompson et al., 2002, (2) Georges, 2004.

	Year: glacier surface area (km^2)			
Irian Jaya	**1850**:	19.3	**1990**:	3.0
Mount Kenya	**1899**:	1.6	**1993**:	0.4
Kilimanjaro	**1850**:	20.0	**2000**:	2.6 *(1)*
Central Rwenzori	**1906**:	6.5	**1990**:	1.7
Cordillera Real	**1920**:	28.6	**1975**:	25
Cordillera Blanca	**1850**:	870	**2000**:	600 *(2)*

The impact of climate on low-latitude glaciers can be described with common glaciological laws but—because of the particular climate in the tropics and subtropics—various parameterizations have to be re-evaluated from several simplifications successfully applied to mid- and high-latitude glacier studies. If mechanical processes like avalanches and calving are excluded, the mass balance of a glacier is composed of accumulation of solid precipitation and ablation due to melting and sublimation. All these processes are related to solar radiation at the top of the atmosphere, air temperature, and atmospheric moisture content, only the first being entirely independent from the others. The atmospheric moisture content influences atmospheric emissivity and determines cloudiness, precipitation, and air humidity.

Relations between glacier mass balance and atmospheric moisture content are complex. The crucial role of sublimation from the glacier surface is noteworthy. Sublimation is driven by the vapor pressure gradient between the glacier surface and the overlying atmosphere. In contrast, melting has no driving force and happens passively only if there is a surplus of energy. Consequently, air humidity controlls the separation of available energy for sublimation and melting. In the mid and high latitudes, air temperature determines the climate's seasonality with positive temperatures representing the availability of energy for ablation (e.g. Ohmura, 2001) and negative temperatures the potential occurrence of solid precipitation. Sublimation, though varying with the degree of aridity, is rather constant as a mean over longer time periods. For these reasons, ablation correlates highly with the sum of so called "positive degree days" in the mid and high latitudes and, moreover, glacier fluctuations reflect fluctuations in air temperature very well (Ohmura, 2001).

This is different in the low latitudes, where seasonal temperature variations are small and the climate's seasonality is primary due to changes in air humidity, advection of moisture, and precipitation. Cloudiness, precipitation, albedo of the glacier surface, the resulting available and effective solar energy, and sublimation vary more or less markedly throughout the year. Thus, not only trends in air temperature but to a much higher degree variations in the seasonality of moisture govern the fluctuations of low-latitude glaciers (Wagnon et al., 1999; Kaser, 2001). The effect of air humidity on glacier ablation is impressively shown in a series of energy balance measurements taken by Wagnon et al. (1999) over the ice surface of Glaciar Zongo in Bolivia (Fig. 1). There, the year-round constant energy from solar radiation is primarily consumed by sublimation during the dry season. Sublimation dissipates 8.5 times the energy of melting when removing the same amount of ice mass. Thus, during the dry season, ablation (and melting) on Glaciar Zongo's surface are markedly reduced.

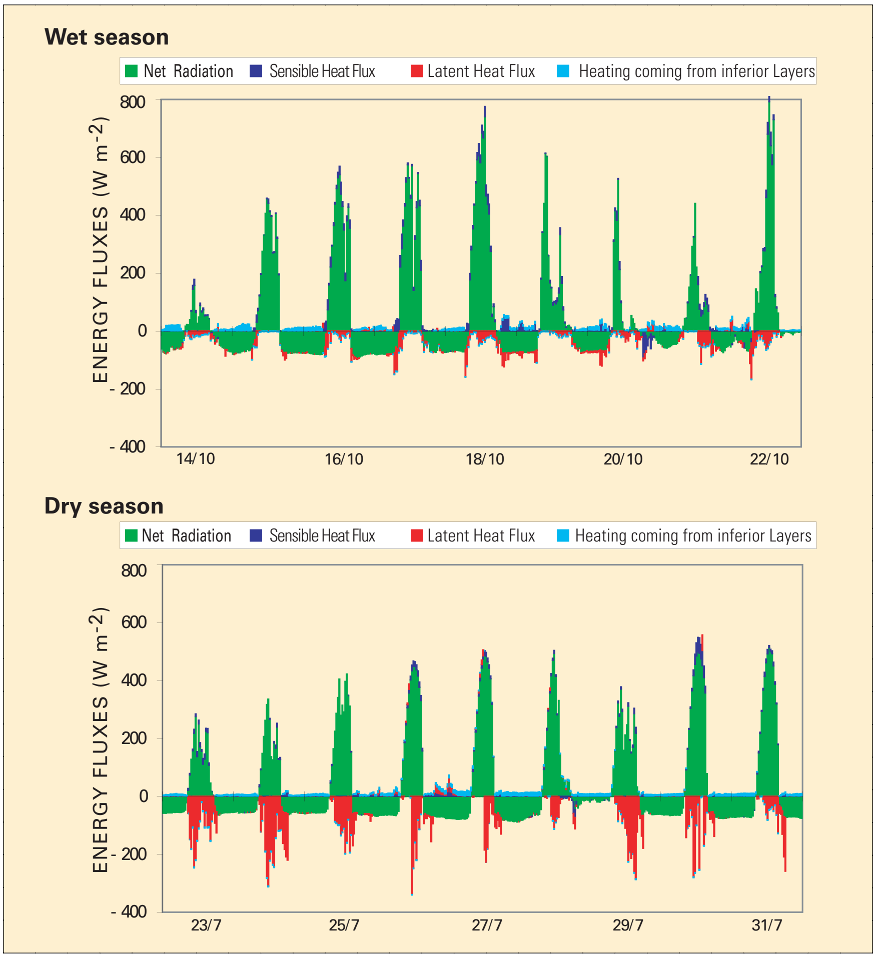

Fig. 1: Half-hourly values of the different energy balance terms measured close to the mean equilibrium line at Glaciar Zongo, Cordillera Real, Bolivia (5150 m asl) (after Wagnon et al., 1999) during a selected 9-day period of the dry (July 23–31, 1996) and wet seasons (14. – 22.10.1996). In both seasons, net radiation is the main energy source at the glacier surface but is almost totally consumed by the strong sublimation (i.e. the latent heat flux) during the dry season.

Beyond the importance of sublimation, another strong effect of a varying hygric seasonality, the short wave albedo of the glacier surface, has been described recently as a key factor on low-latitude glaciers (Wagnon et al., 2001; Francou et al., 2003; Kaser et al., 2004). Related to hygric variations, a highly mass consuming scenario can be imagined as follows: If, after a dry season, the onset of the wet season occurs rather gradually, air humidity may rise, quickly turning sublimation into melt. Also, the atmospheric emissivity may increase and ablation will become considerably higher. At the same time, the reduction of solar radiation, due to increasing cloud cover, is comparatively small but the absorption of solar radiation by the glacier is strongly enhanced due to low-albedo bare ice at the glacier surface. The extreme ablation rates will, therefore, only be stopped by precipitation and consequent albedo increase. Hence, the immediate occurrence of snowfall at the beginning of the wet period can be crucial for the positive mass balance of a low-latitude glacier. In general, this means that any climate interpretation deduced from glacier fluctuations in the low latitudes as well as any prediction, e.g., in terms of water availability from glacier runoff, must consider changes in hygric seasonality, including the occurrence of solid precipitation (Kaser, 2001). Several detailed analyses of 20th century glacier retreat in the low latitudes indeed reveal that the multiple effects of a drier climate dominate over increased air temperature (Kruss and Hastenrath, 1987; Kaser and Georges, 1997; Mölg et al., 2003a).

Although these considerations are also valid when looking at the glaciers on Kilimanjaro's Kibo cone, which have recently attracted broad interest (Thompson et al., 2002), they are a special case. There, the existence of vertical ice cliffs at the margin of the glaciers on the summit plateau and other ice features, such as penitentes or sharp edges, rules out available energy from pos-

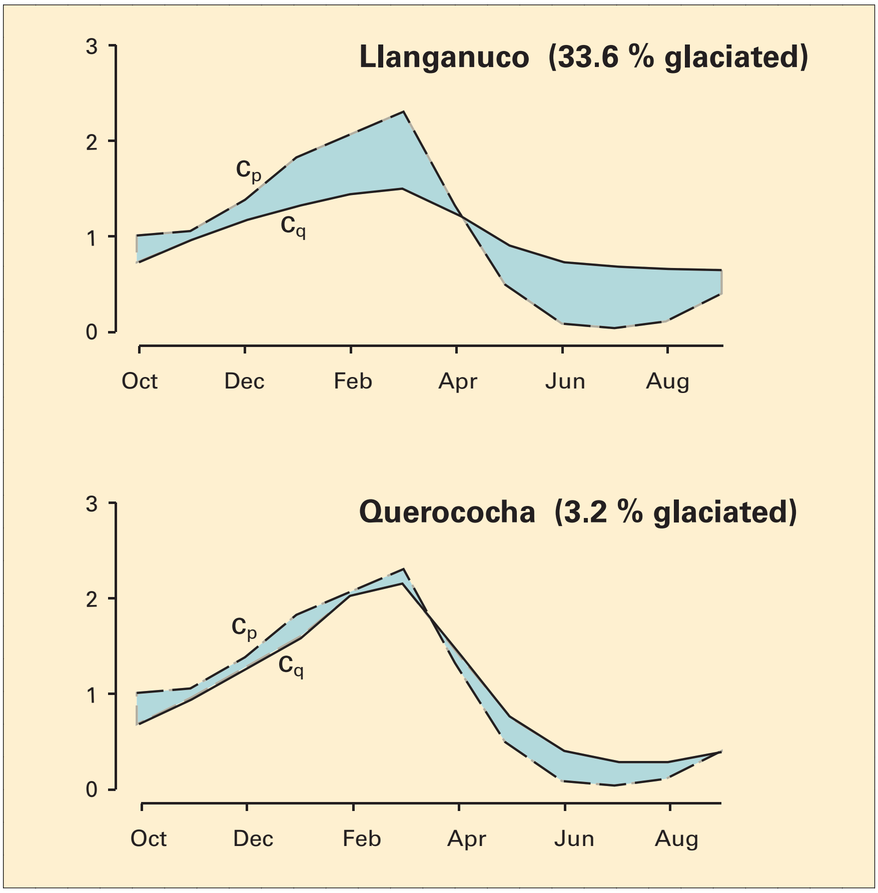

Fig. 2: Mean seasonal precipitation and runoff shown as dimensionless coefficients c_p (for precipitation) and c_q (for runoff) for two differently glacierized catchment areas in the tropical Cordillera Blanca, Peru (after Kaser et al., 2003). Coefficients indicate the ratio between the long-term mean for each month and the overall long-term monthly mean. Note that a coefficient value of zero is equivalent to zero as an absolute value. Glaciers determine the availability of water during the dry season.

itive air temperatures (Kraus, 1972). Rather, it is persistently dry and cold conditions that have formed these features. On the cliffs, only ablation driven by solar radiation can occur (Mölg et al., 2003b). Thus, summit glaciers on Kilimanjaro will disappear if mechanisms of extensive moisture transport to the summit plateau continue to be absent. The spatial distribution of today's largest ice remnants, the Northern and the Southern Icefields, clearly reflects the seasonal cycle of solar incidence, which is strongest during the solstitial periods and weakest when equinoctial cloud cover protects the mountain (Mölg et al., 2003b). The convex shape of the slope glaciers, which are dynamically independent from the plateau ice masses and currently descend to about 5,000 m on Kibo's flanks, illustrates that they are near to equilibrium with the present dry climate. Yet, permafrost found at 4,700 m indicates that these slope glaciers could extend to much lower elevations if only precipitation was more abundant (Kaser et al., 2004). Twentieth century glacier recession on Kilimanjaro is an adjustment to a climate that abruptly "switched" from more humid to persistently drier conditions around 1880 (Hastenrath, 2001; Nicholson and Yin, 2001).

Additionally, any impact of Kilimanjaro's glaciers on the hydrology of the surrounding foothills and lowlands has to be rejected because:

- sublimation plays a substantial role in glacier ablation,
- melt water evaporates directly to a large extent from the dark ashes, and
- any possible melt water runoff would be radially distributed from the mountain cone over concentrically, and therefore rapidly increasing, areas.

Runoff from Kilimanjaro glaciers has hardly ever played a role in the water supply to the lowlands (Lambrechts et al., 2002), which will also be unaffected when the plateau glaciers disappear. However, the water issue is completely different for glacierized mountain ranges in the Andes. There, in many cases, glaciers provide the primary source of runoff during the dry period and reduce the amount of runoff variability in proportion to the degree of glacial cover (Figure 2). Any major retreat or vanishing of glaciers will modify runoff until it exclusively depends on rainfall (Kaser et al., 2003). In such a scenario, some highly populated areas will face serious problems with their water supply.

Studying low-latitude glaciers is essential both in terms of regional water management and in providing a highly valuable tool for detecting climate change on a global scale beyond a temperature-orientated view. Understanding how snow ever accumulated on top of Kilimanjaro—to take a prominent example—and formed glaciers there requires looking at large-scale atmospheric dynamics, as well as the vertical structure of the tropical atmosphere.

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