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Comment on "Recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature" by Richard G. Taylor, Lucinda Mileham, Callist Tindimugaya, Abushen Majugu, Andrew Muwanga, and Bob Nakileza

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[1] The focal point – and new contribution to the community – of the study by *Taylor et al.* [2006] is the derivation of recent (1987, 1995, 2003) glacial extent in the central Rwenzori Mountains, Equatorial East Africa (EEA). This is done by a remote sensing technique, which involves analysis of Landsat satellite images, and shows strong shrinkage between 1987 and 2003. Ground-based measurements of two glacier termini retreats (Speke and Elena glaciers) complement the evidence of continuing glacier retreat on Rwenzori.

[2] However, the main conclusion drawn by the authors is that there is a strong link between a climate signal, namely rising air temperature, and recent glacier retreat. In that context, they analyze meteorological station data which contain significant gaps, and have been recorded at low tropospheric levels (i.e., 3000 m or more below the altitude of the glaciers). While we do not doubt the persistently strong shrinkage of the glaciers on Rwenzori in agreement with previous work [*Kaser and Osmaston*, 2002], we show here that *Taylor et al.*'s [2006] main conclusion is based on (a) questionable data and (b) wrong assumptions for the interpretation of these data (items 1–3 below). As the main conclusion is also expressed in the title of the paper ("due to rising air temperature"), we argue that its principal message is misleading and incorrect. In addition, the relevant part of the study (derivation of the new glacier extents) holds methodological deficiencies (item 4 below) that result in significant uncertainties of the reported and therefore predicted glacier extents.

[3] 1. For small and fast-responding glaciers like on Rwenzori and other tropical mountains [e.g., *Kaser et al.*, 2003], surface energy balance (SEB) and mass balance provide the best (and most direct) quantitative link between climate parameters and glacier change. Establishing this link requires a set of meteorological and glaciological measurements directly on (or very near) the glacier [e.g., *Klok and Oerlemans*, 2004], for input to a SEB model resolving all the glacier-atmosphere mass and energy fluxes that determine the surface mass balance. Such measurements and associated SEB modeling have never been performed in the Rwenzori mountains, but on the other two glacierized massifs in EEA; in the 1970s on Mount Kenya [*Hastenrath*, 1984], and presently on Kilimanjaro [*Mölg and Hardy*, 2004]. These studies, and also other SEB studies of tropical glaciers [e.g., *Wagnon et al.*, 1999; *Favier et al.*, 2004], have demonstrated that parameters related to atmospheric moisture (air humidity, precipitation affecting also surface albedo, cloudiness affecting incoming solar radiation) dominate the SEB. Thus, looking at air temperature (T_a) as primary parameter, as done by *Taylor et al.* [2006], represents an oversimplified approach that does not meet the complexity of physical processes at the interface between atmosphere and tropical glaciers.

[4] 2. Still, meteorological records provided by the national weather services can serve as useful basis for the interpretation of how climate may affect glacier mass balance, which *Taylor et al.* [2006] attempt in their section 4. Nonetheless they neglect essentials of atmospheric trend analysis and assume the trends in the available data, which have been recorded between 960 and 1869 m a.s.l. (as said, ~3000 m or more below the glaciers), would also exist at the high, glacierized elevations. This assumption is crude and incorrect for two reasons. First, the term ''thermal homogeneity'' (used in their section 4) does not imply that trends at different tropospheric levels will be the same. It rather describes that – in tropical climate – the annual cycle in T_a is of a smaller amplitude than the diurnal cycle (temporal dimension), and that this seasonally almost constant T_a applies to all regions within latitudes experiencing the sun at the zenith (spatial dimension) [*Kaser and Osmaston*, 2002]. Secondly, trends at lower elevations do not necessarily have to occur in the mid-troposphere, neither in magnitude nor in sign. This has been shown for the tropics many times through observations [e.g., *Gaffen et al.*, 2000] and model simulations [e.g., *Bradley et al.*, 2004]. The authors disregard this finding and persist in relying on the data collected far below the glaciers, which they use unreservedly for their interpretation. Changes of trends due to vertical dimension are ignored. Figure 1 in this comment demonstrates such changes by the widely used NCEP/NCAR reanalysis data [*Kalnay et al.*, 1996], for the grid point almost perfectly

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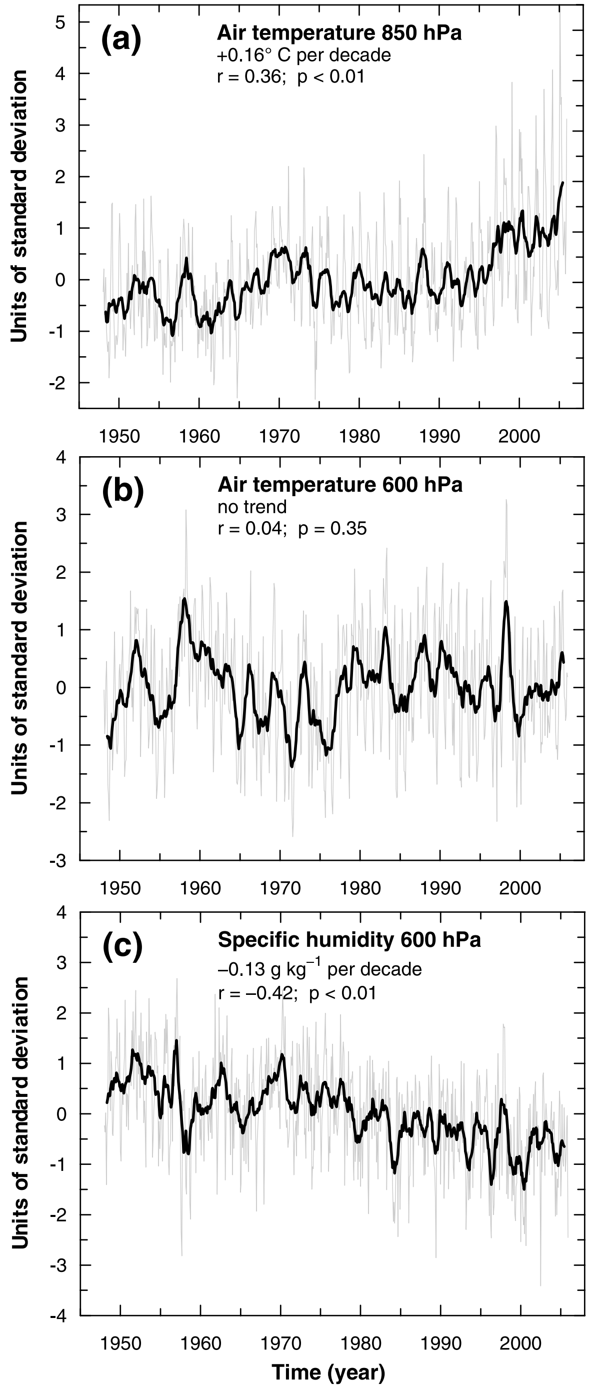

Figure 1. Time series of monthly (a) air temperature at 850 hPa, (b) air temperature at 600 hPa, and (c) specific humidity at 600 hPa from NCEP/NCAR reanalysis data [*Kalnay et al.*, 1996] for 1948–2005 at grid point 30°E/0°N. Bold lines represent the 12-month running mean. Correlation coefficients (r) and significance levels (p) displayed for 1948–2005 are almost identical when calculated for 1960–1998 (the period of station data analyzed by *Taylor et al.* [2006]). The evident trends (positive, none, negative, respectively) are also the same if we analyze data after 1978 (introduction of satellite climatology to the reanalysis [cf. *Kistler et al.*, 2001]), or average the displayed parameters over a larger East African domain (e.g., 25°–40°E; 10°N–15°S).

centered over the Rwenzori Mountains (30° E, 0° N). Since time series analysis with NCEP/NCAR data can be problematic we computed the trends for different time periods and spatial domains (as proposed by *Kistler et al.* [2001]), which yielded consistent results (see Figure 1 caption). Further, it has been shown that NCEP/NCAR free-air temperatures represent observed surface air temperatures well, especially on mountain tops [*Pepin and Seidel*, 2005], but the NCEP/NCAR moisture field may contain errors [*Trenberth and Guillemot*, 1998]. For EEA, however, the derived negative humidity trend (Figure 1c) agrees with the Nairobi radiosonde record [*Hense et al.*, 1988] and – on the other hand – still reflects well enhanced rainfall in EEA as forced by large-scale circulation modes (Figure 2). This suggests that trends in the NCEP/NCAR time series are robust for our region of interest. – – T_a at 850 hPa (Figure 1a), the approximate elevation of the stations considered in *Taylor et al.* [2006], does experience a statistically significant rise over the 1948–2005 period, especially in recent decades. The temperature rise of +0.16°C per decade agrees well with the gridded surface observations used by *Taylor et al.* [2006, Figure 3, bottom], the CRU TS 2.0 data [*New et al.*, 2002] which yield +0.15°C per decade over 1960–1998. However, T_a at 600 hPa, the approximate altitude of the glaciers, does not show any significant trend over 1948–2005 (Figure 1b). Thus, T_a is unlikely to be the main driver of the recent observed retreat. In contrast, specific humidity at 600 hPa (Figure 1c) has significantly decreased over the same period, and this may have several impacts on glacier mass balance. It can increase sublimation [e.g., *Wagnon et al.*, 1999] which is known as a significant mass balance component of tropical glaciers [e.g., *Mölg and Hardy*, 2004]. It also directly affects the energy flux from incoming (atmospheric) longwave radiation, which in turn alters the net radiation budget [*Mölg and Hardy*, 2004]. – Such possibilities are not discussed by *Taylor et al.* [2006], as the commonly used atmospheric data products (Figure 1) were not considered in their study. Thus, the scenario of a T_a-driven humidity increase in East African highlands, and associated accelerated melt, proposed in an early 1990s study prior to the availability of reanalysis data [*Hastenrath and Kruss*, 1992], seems to be outdated and has not been reconsidered by *Taylor et al.* [2006]. However, this is their only causal explanation of how T_a changes would control glacier mass balance on Rwenzori. Moreover, the effect of T_a changes on the accumulation component and its interaction with the ablation component [e.g., *Mölg and Hardy*, 2004] is neglected by *Taylor et al.* [2006].

[5] 3. In addition, station data shown in their Figure 3 seem to have obvious disadvantages for trend analysis, as evident by the long data gaps in the 1970s and 1980s and individual missing years after 1990. Have the stations been relocated after they started to reoperate? Are different instruments in use for the recent period? Has a homogenization procedure (a necessity for trend analyses) been applied to the data? The authors do not address these questions. It is therefore no surprise that the trend calculated from the meteorological stations is unrealistically high and more than three times as large (+0.5°C per decade) as the trend from the homogeneous, complete data sets (CRU and NCEP/NCAR data, see Figure 1a here and Figure 3 (bottom) of *Taylor et al.* [2006]).

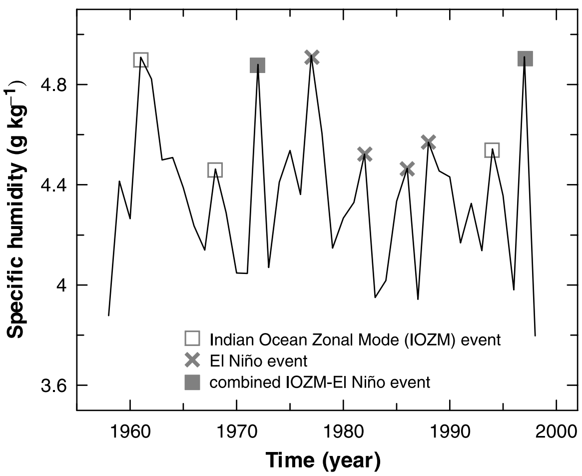

Figure 2. Time series of October–December (OND) specific humidity at 600 hPa from NCEP/NCAR reanalysis data at grid point 30°E/0°N. The peaks correspond to coupled atmosphere-ocean events (as documented by *Saji et al.* [1999] for 1958–1998) that typically control precipitation variability in EEA by causing anomalously high OND rainfall [e.g., *Indeje et al.*, 2000; *Mölg et al.*, 2006].

[6] 4. Regarding the satellite-derived glacier extent, improper separation of transient snow and glacier surfaces, and partial misclassifications of surface types due to insufficient compensation of terrain-induced illumination effects, significantly decrease the accuracy of the glacier surface areas. False color representations or spectral ratios, as applied by *Taylor et al.* [2006], do not allow separating temporary snow fields from perennial, snow covered glacier surfaces [*Kääb*, 2005]. This is obvious in their Figure 1 where the legend of the map (Figure 1b) was changed from "glacier areas" in the original map [*Kaser and Osmaston*, 2002] to "snow cover (1955)" and "snow cover (1990)". Both areas refer in the original publications to glacier extent reconstructed from air photographs (1955) and field mapping and terrestrial photographs (1990) [*Kaser and Osmaston*, 2002]. In Figure 1d, the resulting 2003 snow cover area locally exceeds the 1990 glacier area and even the 1955 glacier area in several cases. Particularly at higher elevations many rock ridges between glaciers are missing. This results in imprecise numbers for the glacier areas of the individual Rwenzori mountains that inaccurately describe the temporal retreat behavior of the glaciers. Therefore the postulated "steady rate of decline in glacial extent" with perfect linear recession in time (r^2 = 0.999) is questionable. We analyzed the glacier areas on the Rwenzori Mountains based on an ASTER image of 21 February 2005 (Table 1). The image is cloud-less, and the ice-free terrain is almost completely free of snow, enabling good delineation of glacier boundaries. Our analysis is based on the visible and near IR bands 1, 2, 3 (15 m spatial resolution), and SWIR band 4 (30 m resolution) of the ASTER instrument operating on the Terra Satellite of NASA (http://asterweb.jpl.nasa.gov/instrument.asp). The analysis was supported by oblique photography made in the field in 2004. The temporal retreat of glacier areas shows clear differences between the three Rwenzori mountains, depending on size and elevation of the glaciers. In particular during the last decades, the larger and higher elevated glaciers on Mount Stanley are retreating much slower (Table 1), as already pointed out by *Kaser and Osmaston* [2002] and by *Mölg et al.* [2003a]. These differences in the retreat behavior are not evident in the numbers given by *Taylor et al.* [2006] because of errors in their glacier maps.

[7] In summary, mapping of the Rwenzori glaciers is of great relevance for climate change studies of the tropics (if ice and snow are properly distinguished by the method chosen), although the analysis presented by *Taylor et al.* [2006] does not fully meet the required accuracy. However, the main flaw with their paper is the climate signal inferred from recent glacier recession on Rwenzori (rising T_a), due to severe deficiencies in using and interpreting climate data (see items 1–3). While rising T_a does control glacier and ice sheet retreat on a global scale, glaciers in EEA seem to behave differently [*Hastenrath*, 2001; *Kaser et al.*, 2004; *Mölg et al.*, 2003a, 2003b; *Mölg and Hardy*, 2004] which must not be neglected in the analysis of tropical climate change. To accurately assess the role of T_a for the mass balance of the Rwenzori glaciers, at least one of the following would be necessary. First, SEB experiments to quantify the climate sensitivity of the glaciers to T_a changes; secondly, simulations of atmospheric dynamics with a high-resolution climate model, to explore a potential link between low- and mid-tropospheric T_a on a local scale (which is possibly not resolved in the present reanalysis system). The retreat for the most recent decade reported by *Taylor et al.* [2006] rather indicates the continuing depletion of accumulation area and, thus, gradual vanishing of the reservoirs supplying mass to the glacier tongues. This depletion originates from a drastic moisture drop in the late 19th century [*Hastenrath*, 2001; *Nicholson and Yin*, 2001; *Kaser et al.*, 2004; *Mölg et al.*, 2006], and has been interrupted only by enhanced precipitation in the early 1960s which led to glacier advance, as noted in *Taylor et al.* [2006]. Since specific humidity seems to be a good proxy for precipitation in EEA (Figure 2) and other parts of

Table 1. Glacier Extents on Mountains Baker, Speke, and Stanley (Central Rwenzori) in 1906, 1955, ~1990, and in 2005 From ASTER Analyses[a]

Year	Mount Baker, km^2 (HE 4873 m a.s.l.)	Mount Speke, km^2 (HE 4891 m a.s.l.)	Mount Stanley, km^2 (HE 5111 m a.s.l.)
1906	1.47 ± 0.07 (100)	2.18 ± 0.10 (100)	2.85 ± 0.14 (100)
1955	0.62 ± 0.03 (42)	1.31 ± 0.06 (60)	1.88 ± 0.09 (66)
1990	0.12 ± 0.01 (8)	0.56 ± 0.02 (25)	1.00 ± 0.05 (35)
2005	0.04 ± 0.01 (3)	0.30 ± 0.03 (14)	0.80 ± 0.06 (28)

[a]Data for 1906, 1955, ~1990 are after *Kaser and Osmaston* [2002]. See item 4 for discussion of ASTER analyses. Values in parentheses are relative to the 1906-extent. "HE" indicates the highest summit elevation of each mountain.

the tropics [*Bretherton et al.*, 2004], its decrease after ~1970 (Figure 1c) may have accelerated the recent decline of the accumulation areas. Still, the higher elevated glaciers on Mount Stanley will very likely outlast the next two decades forecasted by *Taylor et al.* [2006], since they show a much slower decrease than the other glaciers on Rwenzori (Table 1).

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