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East African glacier loss and climate change: Corrections to the UNEP article "Africa without ice and snow"

Dear Editor.

The authors of the recent article "Africa without ice and snow" (UNEP, 2013), reproduced from United Nations Environment Programme (UNEP) Global Environmental Alert Service (GEAS) (henceforth UNEP article/authors), undertook a laudable effort to bring the shrinkage of the peculiar glaciers in East Africa to the attention of readers of *Environmental Development*. However, their article contains some major flaws which could have been avoided by considering the current scientific literature on the topic from climatological research. Thus, we feel it is necessary to add this letter—updating readers with the current findings in the relevant scientific field, and providing UNEP with this important information.

Our elucidations below are based on decade-long collaborative research (e.g., Hardy, 2003, 2011; Mölg et al., 2003a, 2003b, 2006a, 2006b, 2008a, 2009a, 2009b, 2012; Kaser et al., 2004, 2010; Cullen et al., 2006, 2007, 2012; Winkler et al., 2010; Prinz et al., 2011; Nicholson et al., 2012) that has aimed to conduct meteorological measurements on the East African glaciers, quantify the local glacier changes, and unravel the climatic drivers of East African glacier changes on local (e.g. Mölg and Hardy, 2004; Cullen et al., 2007; Mölg et al., 2009a; Nicholson et al., 2012), regional (Mölg et al., 2009b, 2012; Mölg and Kaser, 2011) and continental scales (Mölg et al., 2006a, 2009a) from a physically-based perspective. We address three main issues of the UNEP article: the role of East African glaciers as water reservoirs, the modern change in these glaciers, and the climatic reasons for their modern shrinkage.

1. Water reservoirs

In the first paragraph the UNEP article states that glaciers are "one source of the planet's freshwater", and that the reduction of glaciers "will affect agriculture, domestic supplies, hydroelectricity, and industry in the lowlands and cities far away from the mountains". By turning immediately to the three glacierized massifs of East Africa (Mount Kenya, Kilimanjaro, Rwenzori) in the next paragraph, this might suggest to some readers that shrinkage of East African glaciers could have serious hydrological consequences on and around the three mountains. This is, however, fundamentally wrong. It has been emphasized several times in the scientific literature that these glaciers are way too small to act as water reservoirs on the mountain scale (Gilman, 1923; Kaser

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et al., 2004; Mölg et al., 2008b; Hardy, 2011). The most obvious example is given in Mölg et al. (2008b) by a simple calculation: if one was to melt all the glacier volume on Kilimanjaro at once, and distribute the melted water over the entire mountain, the water provided would only amount to 13 l per square-meter (or 13 mm precipitation). Such an amount can easily fall within a few hours during one rainfall event. The same order of magnitude applies to Mount Kenya and Rwenzori. Although some local populations might retrieve water from high elevations, e.g. from glacier runoff on the slopes of Kilimanjaro (Mölg et al., 2008b), the East African glaciers are of negligible importance for the water budget of entire mountain catchments, and even more so for cities far away. A detailed study on Kilimanjaro also finds that the hydrochemical composition of glacial melt water is completely different from those of the lowland springs and rivers (McKenzie et al., 2010), supporting the negligible role of glaciers as water reservoirs.

Only at the end of their manuscript do the UNEP authors state that East African glaciers are unimportant for the mountains′ water budgets, but they argue with the wrong reason (role of sublimation from the glaciers), which we clarify in Section 3. By contrast, the UNEP article's indication that the forest belts of the three mountains are essential water reservoirs for the local and regional populations is supported by scientific evidence: (i) The hydrochemical analysis on Kilimanjaro (McKenzie et al., 2010) also concludes that water re-charge from the forest belt is an essential process in the hydrological system; (ii) the greatest amounts of annual precipitation occur in the forest elevations (Hastenrath, 1984; Hemp, 2006; Mölg et al., 2009b); and (iii) a recent study showed that land cover change on Kilimanjaro on and around the mountain, in particular forest loss on the slopes (e.g. by illegal logging), affects meteorological processes that lead to a decline of rainfall in the forest belt (Mölg et al., 2012). Thus the combination, and interaction, of rainfall and the forest belt control water supply to the lowlands. In a UNEP context, the maintenance of the forest is of utmost importance for regional-scale protection of water resources.

2. Glacier changes

The UNEP authors fail to provide a reliable, scientifically-based overview of glacier changes on the three glacierized mountains of East Africa, since their references are either outdated, for the most part not peer-reviewed and thus not appropriate to cite (e.g., their references "UNEP 2007", "UNESCO n.d.", "Vidal 2012"), or short conference abstracts (their reference "Klein and Kincaid 2007"). To the best of our knowledge, the latest peer-reviewed scientific quantifications of glacier changes are Mölg et al. (2006b) for Rwenzori, Prinz et al. (2011) for Lewis Glacier on Mount Kenya, and Cullen et al. (2012) for Kilimanjaro. These sources should be considered, and Fig. 1 compiles their reported values. While the shrinkage of these glaciers is indeed dramatic, the data do not support the

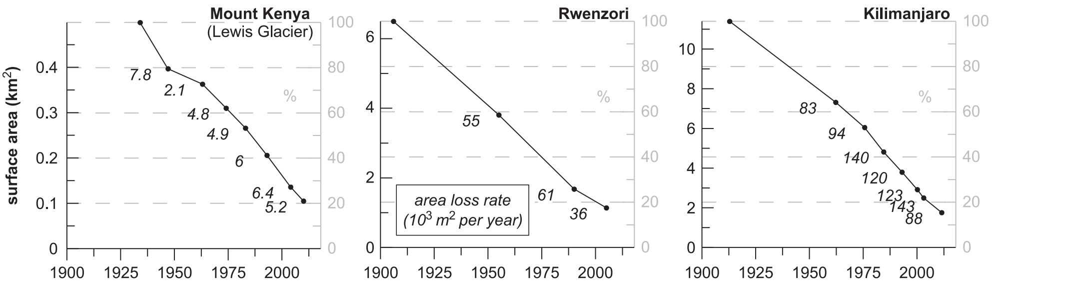

Fig. 1. Changes in glacier surface area over time on Lewis Glacier/Mount Kenya (Prinz et al., 2011), Rwenzori (Mölg et al., 2006b), and Kilimanjaro (Cullen et al., 2012). Right *y*-axes show the amount relative to the first available extent in the record, (in %) and italic numbers along the curves are the mean rates of areal shrinkage (in thousands of square meters per year) between the indicated and previous point in time. Errors of the surface area determinations are typically < 5% (e.g., Mölg et al., 2006b; Prinz et al., 2011) and thus do not impact the trends exhibited.

UNEP article's statement that the glaciers "are now receding at an unprecedented pace". Their recession has been strong throughout the period of the records (Fig. 1).

Another flaw of the UNEP authors in the context of glacier changes is the insufficient distinction between ice and snow. (i) Their Figure 3, for example, compares two images of Kilimanjaro, one with and the other largely without snow cover. Such a pair of images cannot be used to illustrate glacier recession, since the glaciers in one scene ("early 1950s" in the UNEP article) are also covered partially by snow. Thus the reduction of "white surface" in the images gives an incorrect visualization of glacier shrinkage. The same error has been made before with other pairs of satellite images and photos (e.g., initially on the NASA Earth Observatory website; subsequently on the front cover of CLIVAR Exchanges, no. 47), and thus it was also pointed out before that this is a meaningless attempt to document glacier change (Kaser and Allison, 2009). (ii) Figure 9 in the UNEP article is used to support glacier recession in the Rwenzori Range, but the authors indicate "snow cover" in the figure itself, which leaves the reader again with a comparison "apples and oranges". (iii) Also in the satellite image pairs that are Figures 5 and 6 in the UNEP article, it is impossible for readers to recognize the true glacier area. (iv) The confusion of ice and snow in the UNEP article also extends to the title, "Africa without ice and snow". It is indeed a scientific result that East African glaciers could vanish within the next few decades (e.g., Cullen et al., 2012), although uncertainty remains due to the unknown evolution of future precipitation in East Africa, which is a crucial climatic driver of East African glaciers (see below). However, even if the glaciers disappear, snow will continue to fall on the summit of the three mountains during precipitation events. While it is very likely that the complete loss of glaciers on East Africa will impact mountain tourism, the "beauty of the white-topped mountains" (UNEP article) will persist in the aftermath of precipitation events, and thus continue to exist preferably in the wet seasons that are centered around April/May and November/December. "Africa without snow" is therefore a wrong assessment for the 21st century.

3. The climatic drivers of glacier change

The attempt of UNEP authors to summarize why the glaciers on three East African massifs are shrinking lacks one important differentiation. Key in this respect is that glaciers on Kilimanjaro occur almost 1000 m higher than on Mount Kenya and Rwenzori, the two latter of which are situated close to the mean 0 °C altitude (mean freezing level). It is well known from the physics of atmospheric surface layer processes and concurrent surface-air energy and mass exchanges (Van den Broeke et al., 2011) that glaciers located far above the mean freezing level show little sensitivity to air temperature. This and the resultant dominant control of glaciers by precipitation (snowfall amount and frequency and their effect on the glaciers' radiation budget) has been shown in detail for glaciers on Kilimanjaro (Mölg and Hardy, 2004; Mölg et al., 2008a, 2009a). Modern shrinkage of glaciers on Kilimanjaro is therefore driven immediately by reductions in snowfall at the summit since the late 19th century (Mölg et al., 2009a). "A lack of rainfall", as stated by UNEP authors, is certainly not a driver for the glaciers but a misleading reference to the liquid phase of precipitation. Higher air temperatures in the course of the 20th century could only affect the lower-lying glaciers on Mount Kenya and Rwenzori in a quantitatively important way, together with precipitation changes, which Hastenrath and Kruss (1992) showed by simple considerations.

Despite the importance of *regional* and *local* precipitation, all three massifs are potentially sensitive to our *globally* warming climate, since global climate change affects large-scale circulation systems over the tropical oceans (e.g. Held and Soden, 2006; Lintner and Neelin, 2007) that transport moisture to, and thus influence precipitation trends in East Africa (Mölg et al., 2006a, 2009a; Lyon and DeWitt, 2012). The dynamics of the climate system will always result in direct *and* background drivers of an observed change in a local phenomenon. In this regard a summary document of our scientific findings for Kilimanjaro has been produced recently, and is available on the websites of our author team (e.g., http://www.thomasmoelg.info/factsheet_kili.pdf).

A final noteworthy topic about the causes of glacier shrinkage in East Africa concerns sublimation, which the UNEP authors mistakenly call the dominant ice loss mechanism. Only in the very dry, highest glacierized portions of Kilimanjaro does sublimation dominate over melting locally (Mölg and Hardy, 2004; Cullen et al., 2007; Mölg et al., 2008a, 2009a), but lower on the slopes on Kilimanjaro as well as at elevations where glaciers on Rwenzori and Mount Kenya occur, melting removes more mass from the glaciers than sublimation on an annual basis (Mölg et al., 2009a; Nicholson et al., 2012). And again, it is the small size of East African glaciers that prevents their role in the mountain water budgets (see above), not the fact that sublimation occurs on these tropical glaciers, as assumed by the UNEP authors.

In summary, the UNEP article published in *Environmental Development* (UNEP, 2013) only partially provides the reader with the scientific basis of climate and glaciers in East Africa. We hope that our present note helps to emphasize the primary sources of the topic discussed, and are of general relevance to readers interested in East African glaciers and climate change.

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