Tropical Glacier Retreat

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In a previous post entitled **Worldwide Glacier Retreat**, we highlighted the results of a study by J. Oerlemans, who compiled glacier data from around the world and used them to estimate temperature change over the last ~400 years. A question that arose in subsequent online discussion was to what extent Oerlemans had relied on glaciers from tropical regions (answer: he didn't), and what the reasons are behind retreat of glaciers in these regions. Raymond Pierrehumbert, a climate dynamicist at the University of Chicago, kindly offered to write a guest editorial to further clarify what we do and don't know about tropical glacier retreat. Pierrehumbert's editorial follows below. –eric

1. INTRODUCTION

The Tropics, loosely defined as the region from 30N to 30S latitude, make up nearly half the surface area of the Earth; they are home to 70% of its people, and the vast majority of its biological diversity. Moreover, the tropical region is the "accumulation zone" for the Earth's energy balance, with a great deal of excess solar energy being exported to help warm the rest of the planet. Detection and characterization of climate change in the Tropics is therefore a matter of great concern. Assessing the ability of climate models to reproduce this change is an important part of determining the fidelity with which the models can be expected to forecast the way climate will change in response to future increases in greenhouse gas content.

Qori Kalis

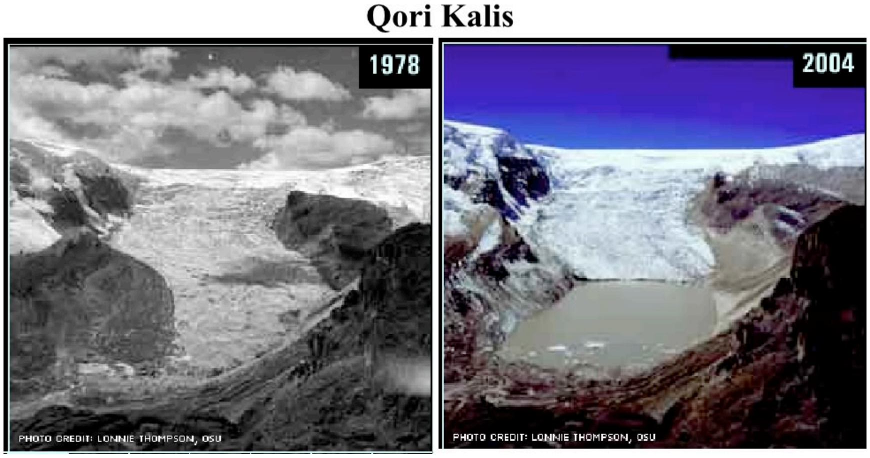

Figure 1: The Qori Kallis Glacier in the Peruvian Andes

Throughout the Tropics, glaciers are in retreat. Well-documented examples include Quelccaya [Thompson, et al. 1993], Huascaran [Byers, 2000; Kaser and Osmaston,2002], Zongo and Chacaltaya [Francou,et al 2003; Wagnon et al. 1999] in S. America; and the Lewis, Rwenzori and Kilimanjaro (more properly, Kibo) glaciers in East Africa [Hastenrath, 1984; Kaser and Osmaston, 2002]. There have been indications of widespread retreat of Himalayan glaciers, including Dasuopu in the subtropics, but a quantitative understanding of this region must await peer-reviewed analysis of the recently completed 46000-glacier Chinese Glacier Inventory. The case of Quelccaya, in the Andes, is especially interesting, because it provides direct evidence of an unusual recent warming trend. When the summit core was first drilled in 1976, the chemical composition of the ice showed well-preserved annual layering throughout its depth, accounting for a time span of 1500 years. When attempts were made to update the record by redrilling in 1991, it was found that the annual cycle had been wiped out over the top 20 meters of the core by percolation of meltwater from extensive melting of the ice surface since 1976. Melting of this sort had not occurred at the summit at any time during the previous 1500 years, and indicates an increase of 150 m, between 1976 and 1991, of the altitude at which significant melting occurs. A vivid animation showing the retreat of the Qori Kalis glacier flowing out of Quelccaya can be seen **here**.

The widespread retreat is all the more notable because tropical mountain glaciers are old. They have survived thousands of years of natural climate fluctuations, only to dwindle at a time when other climate indicators — notably surface temperature — are showing the imprint of human influence on climate. Quelccaya is at least 1500 years old, Dasuopo is 9000 years old, and Huascaran has seen 19000 years. A date for the ultimate demise of these glaciers has not been fixed, but the Northern Ice Field on Kilimanjaro may be gone in as little as twenty years, after having survived the past 11,000 years.

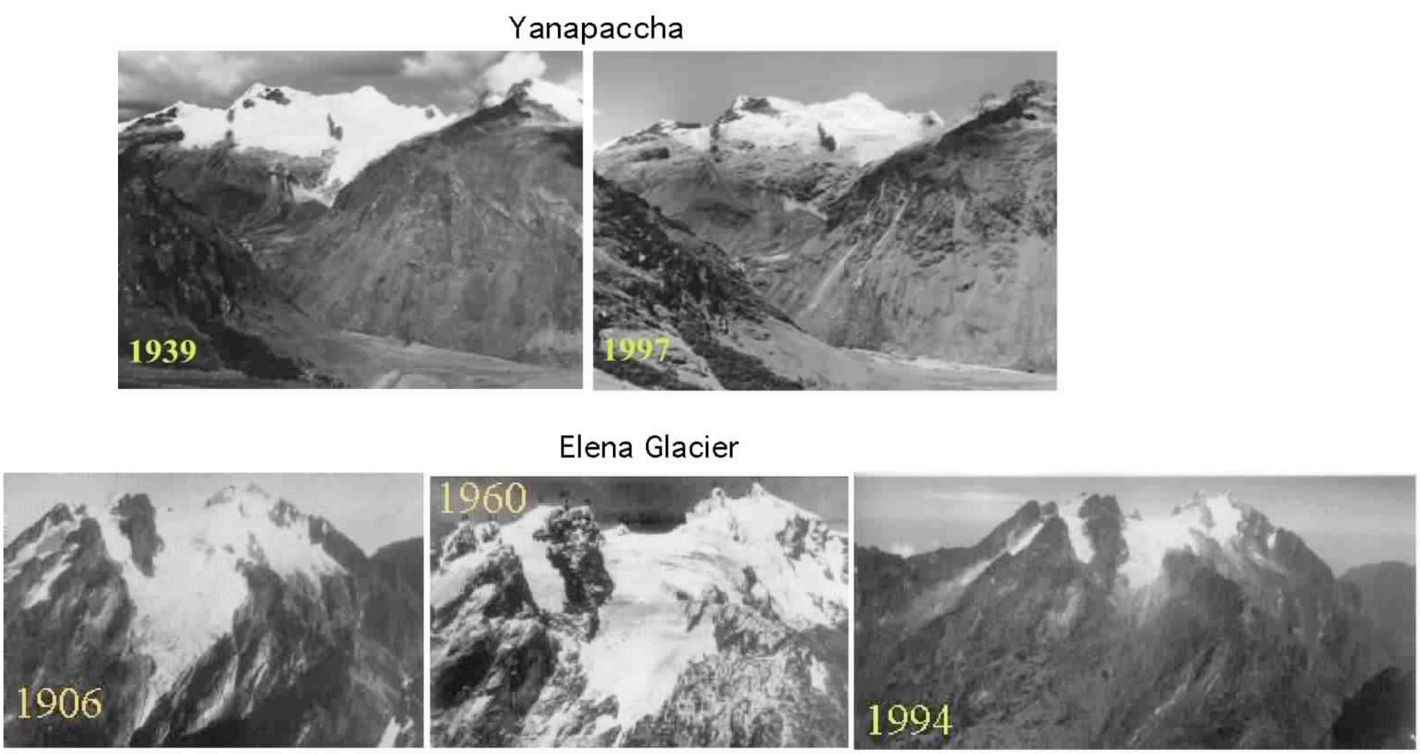

Figure 2. Top: The Yanapaccha glacier in the Huascaran National Park, Peru (from Byers, 2000). Bottom: The Elena Glacier on Mt. Stanley, in the Rwenzori massif near the Congo-Uganda border. (From Kaser and Osmaston, 2002).

The tropical glaciers are certainly telling us that something unusual –and probably unprecedented for centuries or even millennia — has been happening to tropical climate.

The problem at this point is to determine which of the many characteristics of climate change they are indicating, and to what extent these changes can be attributed to the train of events set in motion by anthropogenic increase of greenhouse gases.

2. A PRIMER ON THE PHYSICS OF TROPICAL GLACIERS

The reason there are tropical glaciers at all is that temperature decreases with altitude, as a consequence of the compressibility of air. As warm air rises, it expands and cools. Some of the cooling is offset by the heat released by condensation of water vapor, leading temperature to go down at a rate which is currently a little over 6.5 degrees C per kilometer of altitude. You may be slogging through the steamy lowlands at a temperature of 31C down in Tanga, but meanwhile, up atop Kilimanjaro at an altitude of 5892m, the temperature is a chilly -7 C.

The next ingredient needed to make a tropical glacier is precipitation, which at high, cold altitudes will fall as snow. The rate of snowfall needed to sustain a glacier depends on the rate of removal of glacier ice, called the *ablation rate* .

In contrast to the extratropics, the daily average Tropical temperature varies little throughout the course of the year. Most of the surface temperature variability is on the diurnal (day-night) time scale. On the other hand, the seasonal cycle of precipitation is strong. In the tropics, seasons are characterized by wet vs. dry, rather than cold vs. hot.

Another important feature of tropical climate is that horizontal temperature variations are weak once one goes above a relatively shallow layer near the Earth's surface. This property arises from unassailable dynamic considerations having to do with the weak influence of the Earth's rotation in the tropics, where the local vertical is nearly perpendicular to the Earth's axis of rotation. Without strong Coriolis forces to balance the pressure differences that would be caused by temperature variations, the tropical mass redistributes itself until horizontal temperature gradients are nearly eliminated. [Pierrehumbert,1995; Sobel, et al.,2001] The horizontal homogeneity of temperature is something of an idealization, and becomes less valid towards the edge of the tropics, but temperature is much more uniform than other meteorological fields (precipitation, humidity, and cloudiness) which affect mountain glaciers. Because of the spatial homogeneity of tropical free-tropospheric temperature, when one sees tropical glaciers recede in concert, there is strong reason to presume that air temperature is playing a direct role, temperature being the one thing that is expected to change in lock-step throughout the tropics. For example, the uniform lowering of tropical snowline by about 900 meters during the Last Glacial Maximum is generally attributed to cooling [Porter 2001], and indeed provided the first indication that something was wrong with plankton-based estimates of tropical cooling during the glacial period.

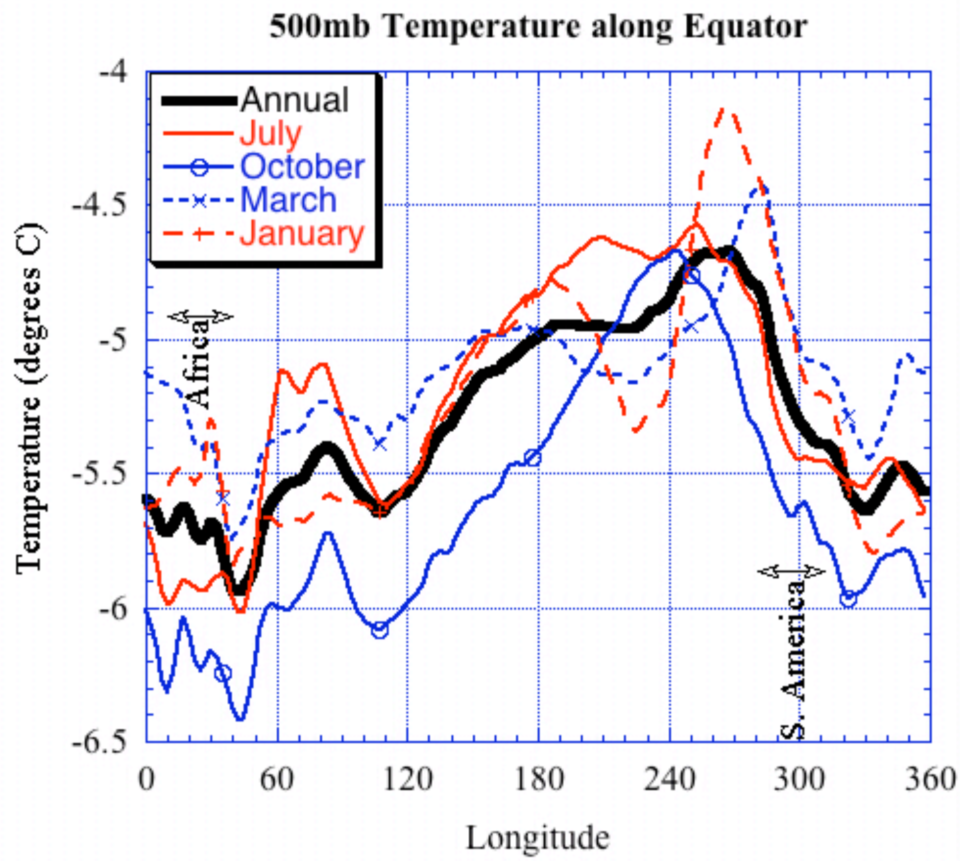

Figure 3. The 1950-1995 climatological mean temperature along the equator at the 500mb level. This level is approximately at the altitude of the summit of Kilimanjaro. Results are based on the NCEP data set. Note that the annual mean equatorial temperature varies by only 1.5 degrees C over the entire globe.

There are two main ways that a body of snow or ice can lose mass: through melting (conversion of solid into liquid) or sublimation (conversion of solid into vapor). Both transformations require energy. It takes 8.5 times as much energy to convert a kilogram of ice into water vapor by sublimation as it does to convert the same kilogram into liquid water by melting. Therefore, if conditions allow the glacier surface to warm to 0 C, the amount of ablation that can be sustained by a given energy input increases dramatically. Sublimated water vapor is always carried away by the air, but the fate of meltwater has a strong effect on ablation by melting. Runoff from steep ice-cliffs, or through subglacial flow driven by water percolating through pores or fractures, will convert a high fraction of melting into ablation. If melt-water percolates into the glacier and re-freezes, the effect on ablation is more limited and indirect.

A detailed description of the way the energy budget determines ablation can be found **here**, but a simplified version of the story goes as follows. In contrast to the midlatitude case, tropical glaciers do not have summertime melt seasons characterized by above-freezing air temperature. Lower altitude portions can be warmed directly by year-round exposure to above-freezing air, but at higher altitudes absorption of sunlight ultimately supplies all the energy which sustains ablation. However, the other terms in the energy balance directly or indirectly affect the amount of absorbed solar radiation which is available for ablation. These terms are sensitive to air temperature, atmospheric humidity, cloudiness, and wind. The daytime glacier surface temperature typically has to be greater than the air temperature in order to close the energy budget; in consequence, melting can occur even when the air temperature remains below freezing. Because melting is so much more energetically efficient than sublimation, the main way that moderate changes in atmospheric conditions

— including air temperature– affect ablation is through changing the number of hours during which melting occurs, and the amount of energy available for melting. In particular, through infrared and turbulent heating effects, an increase in air temperature forces the glacier surface to warm, and makes it easier for melting to occur.

In addition to adding mass to a glacier, precipitation has an indirect effect on glacier mass balance by changing the amount of sunlight the glacier absorbs. This occurs because fresh snow is much more reflective than old snow or bare ice. The reflectivity effect can be almost ten times more important than the effect of mass directly added by precipitation [Moelg and Hardy, 2004]. Because a thin layer of snow is just as reflective as a thick layer, the reflectivity effect depends more on the seasonal distribution of snowfall than the annual average amount.

A healthy glacier has an accumulation zone at high elevations and an ablation zone at lower elevations; ice flow from the accumulation zone continually feeds glacier tongues that penetrate into the ablation zone. The altitude separating the accumulation zone from the ablation zone is known as the *equilibrium line altitude*. Glaciers shrink when climate change causes the equilibrium line to rise, but they stop at a new, smaller equilibrium size. However, if the equilibrium line rises to the summit of the mountain, the accumulation zone disappears altogether and the glacier is doomed. This has happened on Chacaltaya and, according to limited recent observations [Moelg and Hardy,2004], also on the summit glaciers of Kilimanjaro.

3. KILIMANJARO: ICON OR RED HERRING?

A glacier is like your bank account. Whether your wealth is growing or dwindling depends on how much money you deposit vs. how much you withdraw each year. The Kilimanjaro glaciers are nearing bankruptcy, but is this due to excessive withdrawals or insufficient savings? This, in essence, is the question raised (but not settled) in the paper by Kaser et al. [2004]. This paper has played a valuable role in calling attention to important work on the physics of tropical glaciers, that can help in teasing out the record of tropical climate change from glacier retreat data. It has also been widely misquoted and misinterpreted.

The aspect of the paper that has attracted the most attention is the claim that the retreat of the Kilimanjaro summit glaciers can be explained by precipitation reduction, without any compelling need to invoke a warming trend in local air temperature. The arguments are special to the high, cold glaciers of Kilimanjaro, and are not meant to generalize to other tropical glaciers. As the authors point out, even if the whole story comes down to precipitation changes which favor ablation, the persistence of these conditions throughout the 20th century still might be an indirect effect of global warming, via the remote effect of sea surface temperature on atmospheric circulation.

The first major piece of evidence put forth in support of the precipitation hypothesis is that the retreat of the Kilimanjaro glaciers began in the late 19th century — before the beginning of significant anthropogenic warming — and coincided with a shift to drier conditions, as evidenced by a reduction in the level of Lake Victoria. This is indeed a convincing argument in favor of the early phase of the retreat (up to around 1900) being precipitation-driven. It would be a fallacy, however, to conclude that the late 19th century precipitation drop is the cause of the continued retreat, and ultimate demise, over the subsequent century or so. After all, precipitation went down in the late 19th century, and Lake Victoria found an equilibrium at a new, lower level without drying up and disappearing. Why should it be any different for the Kilimanjaro glacier, which is also a matter of finding an equilibrium where rate of mass in equals rate of mass out? The association of the initial retreat with precipitation changes has no bearing on this question.

Most of the field studies cited in support of the dominance of precipitation effects for East African glacier retreat only support the role of precipitation in the initial stages of the retreat, up to the early 1900's. For example, [Kruss 1983] has this to say about the Lewis glacier on Mt. Kenya: "A decrease in the annual precipitation on the order of 150mm in the last quarter of the 19th century, followed by a secular air temperature rise of a few tenths of a degree centigrade during the first half of the 20th century, together with associated albedo and cloudiness variation, constitute the most likely cause of the Lewis Glacier wastage during the last 100 years." This conclusion is repeated in [Hastenrath 1984].

Moreover, if one only looks at the Lake Victoria level since 1880 one gets the mistaken impression that the high precipitation regime in 1880 was somehow "normal" and that the subsequent shift to drier conditions puts the glacier in a much drier environment than it had previously encountered. The fact is that wet-dry shifts of a similar magnitude are common throughout the record. It would be more correct to say that 1880 represented the center of a wet spike lasting hardly a decade — a very short time in the life of an 11,000 year old glacier– and that the subsequent drying represented a return to "normal" conditions, as illustrated in the accompanying long term lake-level graph from [Nicholson and Yin, 2001]. In fact, a few wet years around 1960, and a moderate shift to wetter conditions in subsequent years, restored the Lake Victoria level to within 1.5 meters of its high-stand. This level is comparable to the level in the decade preceding the 1880 wet spike, and considerably greater than the values estimated for the earlier half of the 19th century. Even more significantly, the Kilimanjaro glacier survived a 300 year African drought which occurred about 4000 years ago, as inferred from the ice core record [Thompson et al, 2002]. This drought was so severe that it has even been implicated in the collapse of a number of civilizations that were subjected to it. If the Kilimanjaro glacier has survived earlier precipitation fluctuations, what is different this time around that is causing its imminent disappearance, if not for something associated with anthropogenic climate change?

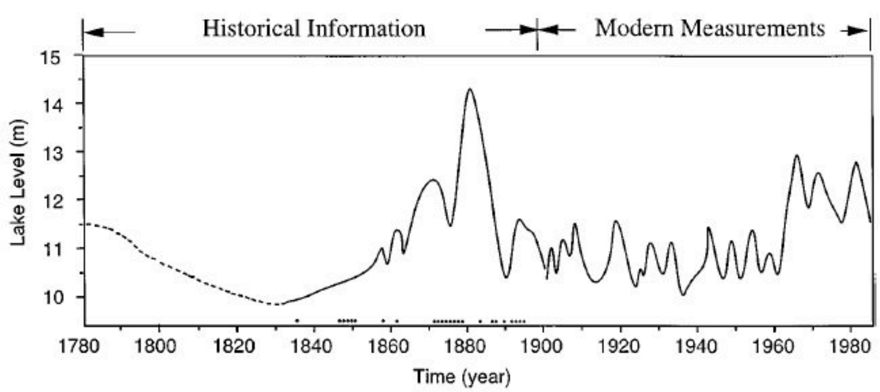

Figure 4: Lake Victoria level data, after Nicholson and Yin (2001). The lake acts somewhat like a huge rain gauge, so that lake level is a proxy for precipitation. Data before 1840 is not based on individual year level measurements, but historical reports of general trends.

Kaser et al also argue that surface and mid-tropospheric (Kilimanjaro-height) temperature trends have been weak in the tropics, in "recent decades." One of the papers cited in support of this is the analysis of weather balloon data by [Gaffen et al, 2000], which covers the period 1960 to 1997. It is true that this study shows a weak (cooling) trend in mid-tropospheric temperatures over the short period from 1979-1997, but what is more important is that the study shows a pronounced mid-tropospheric warming trend of .2 degrees C per decade over the full 1960-1997 period. Moreover, few of the sondes are in the inner tropics, spatial coverage is spotty, and there are questions of instrumental and diurnal sampling errors that may have complicated detection of the trend in the past decade. Analysis of **satellite data** by [Fu et al, 2004] reveals a tropical mid-tropospheric temperature trend that continues into the post-1979 period, at a rate of about .16 degrees C per decade. When one recalls that tropical temperatures aloft are geographically uniform, this data provides powerful support for the notion that East African glaciers, in common with others, have been subjected to the influences of warming. Set against this is the surface temperature record from the East African Highlands, reported by [Hay et al 2002]. This dataset shows little trend in surface temperature over the location covered, during the 20th century. However, surface temperature is more geographically variable than mid-tropospheric temperature, and is strongly influenced by the diurnal cycle and by soil moisture. The large decadal and local variability of surface temperature may have interfered with the detection of an underlying temperature trend (more “noise” less “signal”). It is unclear whether this estimate of temperature trend is more relevant to Kilimanjaro summit conditions than the sonde and satellite estimate.

Because of the great deal of energy needed to remove mass by sublimation, the ablation rate will be very insensitive to changes in conditions — whether air temperature or precipitation-determined surface reflectivity — in circumstances where all ablation is due to sublimation. The discussion in [Kaser et al] is often misread as meaning that the high,cold Kilimanjaro glaciers are only influenced by sublimation. However, there is both theoretical and observational evidence that melting now occurs on the horizontal surfaces of the Kilimanjaro Northern Ice Field, and contributes to ablation [Moelg and Hardy 2004; Thompson et al 2002]. According to [Thompson et al 2002], “Melt features similar to those in the top meter did not occur elsewhere in the NIF or SIF cores.” Thus, there is evidence that the Kilimanjaro glacier has recently entered a new ablation regime. If the melting were solely due to the albedo reduction coming from the 19th century precipitation reduction, it should have shown up much earlier. [Kaser et al] also specifically identify melting as the main mechanism for retreat of vertical ice cliffs. Once melting comes into the picture, ablation rate becomes much more sensitive to air temperature.

Energy and mass balance studies on Kilimanjaro cover barely two years, and define neither trends nor the long term ablation rate. Nonetheless, the studies can be used to provide some preliminary estimate of how much precipitation or temperature change must be invoked to explain the current net ablation of the glacier. According to [Moelg and Hardy, 2004], if air temperature were 1 degree C colder than at present, the potential ablation would be reduced by 14.2 millimeters per month (liquid water equivalent). This is a far from insignificant change, amounting to 32% of the measured net ablation during the short period for which data is available. This sensitivity estimate is not the last word on the subject, because of uncertainties in the approximate formulae used to compute the terms in the energy balance, and neglect of possible effects of water vapor feedback on the surface budget.

As for precipitation, [Moelg and Hardy, 2004] tentatively conclude that the glacier might be in positive mass balance if snowfall were increased to its 1880 maximum rate, even if temperature is held fixed at its present value. In this estimate, only 4 .2mm per month of liquid water equivalent are due to the mass added by enhanced precipitation; the vast majority of the effect (72mm per month of decreased ablation) is due to the effect of precipitation on reflectivity. Concerning this effect, one should note that the measured ablation differed by a factor of two between the two years studied, even though annual mean snowfall was similar in both years. This underscores the fact that ablation (via the reflectivity effect) depends on the seasonal distribution of snowfall. This unpleasant fact undermines efforts to relate glacial history to proxy data like lake-level history, which are sensitive only to annual means. A further point of note is that the calculated sensitivity of ablation to precipitation is as high as it is only because of the occurrence of melting. The sensitivity would be reduced if sublimation were really the only ablation mechanism.

It might well be that the snowfall rate of the 1880's was so large that, if it had persisted, it would have allowed the glacier to survive despite whatever warming it suffered in the 20th and 21st centuries. But what significance is there in the thought experiment of holding precipitation fixed at its maximum 19th century value, given that other parts of that century were evidently no wetter than today? To be convincing, any model used in precipitation vs. temperature attribution studies of Kilimanjaro retreat would have to pass the test of accounting for why previous dry periods in the 11,000 year history of the Kilimanjaro glacier did not cause the glacier to disappear. No model has yet been subjected to this test.

Employing much the same palette of facts and observations as invoked by [Kaser et al], one could paint this rather different picture of what is going on: The Kilimanjaro glacier has waxed and waned since the time of its inception about 11,000 years ago. An unusually wet decade around 1880 put the glacier into strongly positive mass balance, bulking up its mass. Early 20th century explorers found the glacier recovering towards equilibrium from this anomalous state. However, rather than finding a new equilibrium in the 20th century, the glacier has continued to retreat, and is now on the brink of disappearing. Though air temperature has so far remained below freezing, melting has begun to occur, and the glacier is suffering net ablation over its entire surface. Air temperature increases similar to those observed aloft since 1960, amplified by associated increases in humidity, account for a significant portion of the enhanced ablation leading to this strongly negative mass balance, but the exact proportion is highly uncertain because of the short span of energy and mass balance observations. However, changes in the distribution of snowfall through the year, conceivably linked to increases in sea surface temperature, may have reduced the reflectivity of the glacier and played an even bigger role in forcing the retreat than changes in air temperature alone.

4. ENTER THE SKEPTICS

When the interesting and thought-provoking work of [Kaser et al] emerged from the machinery of the skeptics' disinformation operation, it had mutated beyond all recognition. The reports put out by the Heartland Institute (**here** and **here**) are typical. The first of these, which came out under the banner "Global Warming Fears Melting," is headed by a quote from Patrick Michaels starting, "Kilimanjaro turns out to be just another snow job …" and goes downhill from there. All subtlety, tentativeness, context and opposing evidence has been lost. The study is presented as a broadside on one of the central tenets of global warming, in a fashion echoing skeptics' coverage of the **"hockey stick"** issue. Even when the work is quoted directly, it is quoted without the context needed to make sense of the claims. Notably, the quote "Mölg and Hardy (2004) show that mass loss on the summit horizontal glacier surfaces is mainly due to sublimation (i.e. turbulent latent heat flux) and is little affected by air temperature through the turbulent sensible heat flux." is intended to give the impression that air temperature can make no difference, whereas we have seen that the results of [Moelg and Hardy,2004] are compatible with several ways in which air temperature can affect ablation.

The skeptics' press, especially as echoed in Crichton's ***State of Fear*** states that the Kilimanjaro retreat can have nothing to do with anthropogenic global warming, because it began in the 1880's, before any appreciable CO_2 response is expected. The error in this reasoning was discussed in the previous section. This situation here is reminiscent of the ubiquitous **"Little Ice Age"** problem. It is a fact of life for attribution studies that the climate changes associated with the end of the Little Ice Age overlap with the beginning of the era of industrial warming. Thus, a graph will always give the superficial impression that the present trends are just a continuation of something that began before human influences were much in the picture, leading one into the fallacy that the causes of the beginning of the trend are the same as those responsible for its continuation.

The Heartland Institute's propagation of the notion that the Kilimanjaro glacier retreat has been proved to be due to deforestation is even more egregious. They quote "an article published in Nature" by Betsy Mason ("African ice under wraps," Nature, 24 November, 2003) which contains the statement "Although it's tempting to blame the ice loss on global warming, researchers think that deforestation of the mountain's foothills is the more likely culprit." Elsewhere, Heartland refers to this as a "study." The "study" is in reality no scientific study at all, but a news piece devoted almost entirely to Euan Nesbit's proposal to save the Kilimanjaro glacier by wrapping it in a giant tarp. The article never says who the "experts" are, nor does it quote any scientific studies supporting the claim. The Mason news article is what Crichton quotes as "peer reviewed research" proving that it is deforestation, not global warming, which is causing the Kilimanjaro glaciers to retreat. (**George Monbiot's article in The Guardian** documents a similar case of systematic misrepresentation of glacier data by skeptics.)

A November 26,2003 New York Times editorial contributed to the spread of the deforestation legend by repeating Mason's statement verbatim and without attribution. The Times coverage in **Andy Revkin's March 23, 2004 article** was far more balanced and informative, though you'd never know it from the quote concocted by Heartland:

- "Now the pendulum has swung," commented the March 23 New York Times. "The authors wrote that the dry weather both limited the snows that help sustain tropical glaciers and, by reducing cloud cover, allowed more solar energy to bathe the glacier. In dry, cold conditions, the ice vaporized without melting first, a process called sublimation. There was no evidence that rising temperatures had caused the melting."

The omission of the original article's long passage between the two quotes gives the misleading impression that it is the pendulum of scientific opinion in the community of researchers that has swung. In reality, what Revkin was saying was that, so far as activism goes, the pendulum had swung towards the use of Kilimanjaro by global warming skeptics.

Even the admirable Revkin doesn't get it quite right: On horizontal surfaces, observations and modeling show a role for melting in both the baseline ablation and the sensitivity of ablation to precipitation and temperature; melting is the dominant ablation mechanism on vertical ice cliffs; and though Kaser et al find "no evidence" about rising temperatures, it is only because the in situ studies don't cover a long enough period to detect trends. Elsewhere, where Revkin wrote that most scientists agree that "for more than a century, its ice has been in a retreat that is almost assuredly unstoppable and was not caused by humans," it would have been more accurate to state that the agreement is for the most part only that the beginning phase of the retreat was not caused by humans. On the whole, though, Revkin did a fine job with the essential science. A good impression of the main thrust of his article is given by the following intact quote:

- "We have a mere 2.5 years of actual field measurements from Kilimanjaro glaciers, unlike many other regions, so our understanding of their relationship with climate and the volcano is just beginning to develop", Dr. Douglas R. Hardy, a geologist at the University of Massachusetts and an author of the paper, wrote by e-mail. "Using these preliminary findings to refute or even question global warming borders on the absurd." In short, Kilimanjaro may be a photogenic spokesmountain "no matter what the climatic agenda" but it is far from ideal as a laboratory for detecting human-driven warming. The debate over it obscures the nearly universal agreement among glacier and climate experts that glaciers are retreating all over the world, probably as a result of the greenhouse-gas buildup. "These climate skeptics are making generalizations not only to the rest of the tropics but the rest of the world" Dr. Hardy said. "And, in fact, global warming may be part of the whole picture on Kilimanjaro, too."

5. AIR TEMPERATURE ROLE CLEAR FOR OTHER TROPICAL GLACIERS

Generally speaking, lower glaciers which extend below the elevation where above-freezing air temperatures occur, are more sensitive to temperature. [Kaser and Osmaston 2002] calculate that such tropical glaciers are even more temperature-sensitive than midlatitude glaciers. A warming of 1 degree C is sufficient to raise the equilibrium line (below which net ablation occurs) by fully 300 meters. As we've already seen, warming is by no means unimportant to the 20th century retreat of the Lewis glacier (Mt. Kenya) in E. Africa. In other cases, the role of warming is yet more clear.

Data from the tropical and subtropical Andes suggest that changes in precipitation and cloud cover in the latter portion of the 20th century are minor, and that changes in these quantities are unlikely candidates for explaining Andes glacier retreat. (see the discussion in [Francou et al, 2003]). Tropical Andes temperature increased at a rate of at least .1 degrees C per decade since 1939, and the rate has more than tripled over the past 25 years. Specific humidity content of the air has increased, as expected as part of the conventional water vapor feedback, but in fact relative humidity also increased between 1950 and 1990, indicating a stronger water vapor feedback than given by the conventional assumption of fixed relative humidity. Detailed studies of the energy balance and ablation of the Zongo and Chacaltaya glaciers support the importance of air temperature increase, and identify the increase in downward infrared radiation as the main way that the effect of the warmer air is communicated to the glacier surface [Wagnon et al. 1999; Francou et al, 2003].

In the subtropical Himalayas, there is evidence from ice-core isotopic data and from nearby stations for unusual 20th century warming [Thompson et al, 2003]. These are in the outer Northern Hemisphere subtropics. Thus, we have evidence for a warming effect on glaciers over a range of tropical latitudes in S. America, evidence for warming in the Northern subtropics in Asia, some evidence for a role of warming at the Lewis glacier in E. Africa, evidence for general tropical mid-tropospheric warming from sondes and satellites, and a firm theoretical reason to believe tropical free-tropospheric temperature to be geographically uniform. It would take a rather perverse (though not impossible) set of circumstances to leave Kilimanjaro out of the picture.

6. CONCLUSIONS AND PERSPECTIVES

Kilimanjaro has attracted special attention not because it is an unusually important indicator of tropical climate change, but because it is well known through the widely read Hemingway short story. If anything, it is the widespread retreat of the whole population of tropical glaciers that provides the most telling story. Perhaps one can regard the Kilimanjaro glaciers as a kind of "poster child" standing in for this whole population. It is not yet clear whether this photogenic and charismatic poster child is a good choice for the role. Certainly, if Hemingway had written, "The Snows of Chacaltaya," life would be much simpler.

Based on what is now known, it would be highly premature to conclude that the retreat and imminent disappearance of the Kilimanjaro glaciers has nothing to do with warming of the air, and even more premature to conclude that it has nothing to do with indirect effects of human-induced tropical climate change. On the contrary, a study of the glaciers' long history argues powerfully that the recent retreat is happening in an environment significantly different from that which the mountain experienced during past equally dry periods. To better understand what Kilimanjaro and other tropical glaciers are telling us about climate change, one ultimately ought to drive a set of tropical glacier models with GCM simulations conducted with and without anthropogenic forcing (greenhouse gases and sulfate aerosol). There are substantial challenges to doing so: uncertainties in modeling the energy balance terms, general difficulties in modeling regional climate change, and insufficient resolution of mountains and their mesoscale circulation patterns. The time is ripe to make the first attempts at this, and hopefully such efforts will bear fruit within the coming decade. The attempt to reconcile simulated warming patterns with the tropical glacier record will shed a lot of light on the influence of a range of climate feedback factors — including convection, clouds and water vapor — and the ability of models to faithfully represent them. Because of the strong effect of fresh snowfall on the ability of a glacier to absorb sunlight, it is likely that changes in precipitation amount or pattern will prove to be part of the story.

An interesting thing to watch is the effect of precipitation trends over the next decade or two. Most GCM's predict that, while some parts of the tropics get drier in response to anthropogenic greenhouse gas increases, the net tropical precipitation increases. Thus, some areas of the tropics should experience substantial increases in precipitation, which, at high elevations, will come in the form of snow. If tropical glaciers continue to retreat despite an increase in precipitation, that will constitute a powerful case for the role of air temperature. Interestingly, East Africa is one region where IPCC models predict precipitation increases for the coming century. It will be the height of irony if it turns out that the IPCC models are right, but that Kaser et al are *also* right, that the Kilimanjaro glacier therefore begins to advance again AND that proves to help confirm the validity of the global warming forecasts! Keep a close eye on the real-time radar satellite monitoring of the level of Lake Victoria **here**.

More understanding will result as detailed, accurate glacier and regional climate modeling becomes possible. This enterprise will not only help in understanding the nature of modern climate change, but will permit us to decode the record of past climate changes hidden in tropical glaciers. The general understanding of how the climate system responds to natural and anthropogenic forcings will improve as a result. Ultimately this is much more interesting and much more important than whether or not Greenpeace chose wisely in picking a place to unfurl their banner.

Acknowledgements: Many thanks are due to Doug Hardy, Thomas Moelg and Lonnie Thompson for many patient and illuminating discussions concerning theory and observations of tropical glaciers.

References

For a summary of some of the highlights of the work by Moelg and Hardy, and other co-workers of the Innsbruck Glacier Group, see Moelg's comment (#61) to our the RealClimate posting on **Worldwide Glacier Retreat**

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