Fact Sheet about

The climatological causes of glacier shrinkage on Kilimanjaro since ~1880

A summary from a decade of research by Innsbruck/Massachusetts/Otago universities

On the summit of Kilimanjaro …

Meteorological on-site measurements since 2000 in the summit zone of Kilimanjaro (5600 to 5900 m above sea-level), as well as glacier modeling, have laid the basis for revealing the physics of the glacier-atmosphere interaction. This means today we have a detailed quantitative knowledge about the energy and mass exchanges between glaciers and overlying air. These exchanges are the most direct link between a glacier and the surrounding climate.

Results show that Kilimanjaro glaciers are most sensitive to variability in precipitation (i.e. snowfall at the altitude of the glaciers), because snowfall changes **(a)** affect the most variable energy source on the glacier surface, which is the absorbed solar radiation, by changing the "brightness" of the surface and thus its ability to reflect sunlight; and **(b)** also affect the mass supply of the glaciers directly.

Absorbed solar radiation typically is the dominant energy source for all glaciers, but most glaciers worldwide are still very sensitive to changes in air temperature too. The reason is that many glaciers are situated at altitudes close to the mean 0 °C level and, thus, changes in air temperature largely determine snowfall amount and surface brightness by altering the composition of precipitation: liquid (rain → makes surface darker) versus solid (snowfall → makes surface brighter). In simple words, glaciers on Kilimanjaro lie at too high altitudes to be affected by local air temperature changes of a few degrees Celsius, so precipitation alone "rules" the current glacier response to climate.

Results also show that sublimation, the direct transition of snow and ice to water vapor, is a mass loss process on Kilimanjaro equally important to melting. Thus, calling the observed glacier shrinkage "the melting snows/glaciers of Kilimanjaro" is a strong simplification of the real situation.

Scientific Literature: 2, 6, 7, 8, 10, 14

Another intriguing result was that the glaciers on the summit plateau (left) behave differently from the glaciers on the slope (right). This is because plateau glaciers are margined by near-vertical ice cliffs that show unique energy exchanges with the atmosphere and the surrounding ash surfaces.

Further, unlike a moderately inclined or flat surface these cliffs cannot “capture” snowfall due to their steepness. Thus, whenever we talk about glacier shrinkage on Kilimanjaro, it is important to **(a)** distinguish between the plateau glaciers and the slope glaciers, and **(b)** to realize that it is particularly hard to relate climate change or variability to the size of the plateau glaciers, since their unique characteristics outlined above cause their area to grow only in very wet conditions, or – as soon as ice cliffs are established – to shrink fairly constantly despite concurrent climate variability.

Scientific Literature: 1, 3, 4, 11, 12, 14, 16

Thus, we have chosen a slope glacier to quantify the climate change that can explain observed glacier shrinkage on the southern slope between the late 19th century (onset of modern shrinkage) and the present. The climate change driving modern glacier shrinkage is characterized by a decrease in the annual precipitation sum of 200 ± 40 mm, and by reductions in average cloud cover and relative humidity of 3 ± 1 and 4 ± 2 percentage units, respectively. These values refer to the local climate change, i.e. on the summit of Kilimanjaro.

Scientific Literature: 8

Far away: tracing the large-scale climatic controls …

An agreement between various data sources – historical observations and measurements, global climate modeling, sea sediments, corals, and modern measurements – suggests that there was an abrupt shift in the dynamics of the Indian Ocean (water currents and atmospheric flow above the ocean) in the late 19th century. The change in the dynamics has been responsible for the tendency that inflow of moist air masses from the Indian Ocean to East Africa has become less frequent in the 20th century (glacier loss) than before the late 19th century (when glaciers did not shrink and grew).

While the initial, abrupt change in Indian Ocean dynamics is most probably a natural climatic change, the maintenance of this Indian Ocean state in recent decades is most likely due to global warming. The transition from natural to anthropogenic forcing of the particular Indian Ocean dynamics in question requires further research.

Scientific Literature: 5, 8, 9

Ascending the mountain: the regional climatic controls …

Mountains always pose barriers to air flow and strongly modify approaching air masses. Thus we have employed regional atmospheric models to understand the underlying physics of this modification. Results show that the increased frequency of dry air masses over East Africa in the 20th century complicates cloud formation in high-altitude zones of Kilimanjaro, because air lifting over the mountain has become weaker. Only wet air masses like from the Indian Ocean can form deep clouds all over the tall mountain, but – as we have seen above – these air masses have become less frequent since the late 19th century. This means that the snowfall frequency and amount in Kilimanjaro’s summit area and over the glaciers have decreased in the 20th century, which drives current glacier shrinkage. In simple words, it has become more difficult for moisture to “ascend” the mountain slopes.

Scientific Literature: 8, 9, 13

And what about land cover change?

In the course of these results, the idea arose that the lack of moist air masses over Kilimanjaro could also be a "home-made" problem due to the observed de-forestation on the mountain slopes. Trees generally moisten the air close to the surface, and thus support local formation of clouds. By merging all the measurements and models developed since the start of our research into a new model system, we investigated the contribution of local land cover change and deforestation on Kilimanjaro between 1976 and 2000 to changes in mountain climate and glacier shrinkage. Results show that the reduction of forests has reduced rainfall in the forest belt of Kilimanjaro (roughly between 1700 and 3500 m), but had no critical impact on high-altitude climate and glacier loss.

Scientific Literature: 15

Into the future …

Precise prediction of a possible de-glacierization of the mountain is hard because **(a)** it is uncertain how precipitation on Kilimanjaro's summit will evolve during the 21st century, and **(b)** the role of the vertical ice cliffs is less understood than the slope glaciers. If the present dry climate will persist, our current estimate is that the largest glaciers would not disappear before about 2040. Thus, the publically widely known estimate of complete disappearance between 2015-2020, which was the first modern assessment by scientists in 2002 and has often been quoted (e.g. in Al Gore's movie), is unrealistic. There is no doubt, however, that some of the small ice bodies will be lost within the next few years.

Scientific Literature: 1, 16

So, generally speaking …

We have seen that glaciers on Kilimanjaro are an excellent opportunity to study linkages in the climate system, and how large-scale climatic changes are propagated to high mountains. The direct, local driver of glacier shrinkage is a lack of snowfall at least since the late 19th century. The remote driver is mainly moisture supply from the Indian Ocean, which at least in the most recent decades has been affected by global warming.

The scientific literature in chronological order

(**1**) Mölg T., Hardy D.R., Kaser G. (**2003**): Solar radiation-maintained glacier recession on Kilimanjaro drawn from combined ice–radiation geometry modeling. *Journal of Geophysical Research*, vol. 108: 4731.

(**2**) Mölg T., Hardy D.R. (**2004**): Ablation and associated energy balance of a horizontal glacier surface on Kilimanjaro. *Journal of Geophysical Research*, vol. 109: D16104.

(**3**) Kaser G., Hardy D.R., Mölg T., Bradley R.S., Hyera T.M. (**2004**): Modern glacier retreat on Kilimanjaro as evidence of climate change: Observations and facts. *International Journal of Climatology*, vol. 24: 329-339.

(**4**) Cullen N.J., Mölg T., Kaser G., Hussein K., Steffen K., Hardy D.R. (**2006**): Kilimanjaro Glaciers: Recent areal glacier extent from satellite data and new interpretation of observed 20th century retreat rates. *Geophysical Research Letters*, vol. 33: L16502.

(**5**) Mölg T., Renold M., Vuille M., Cullen N.J., Stocker T.F., Kaser G. (**2006**): Indian Ocean Zonal Mode activity in a multicentury integration of a coupled AOGCM consistent with climate proxy data. *Geophysical Research Letters*, vol. 33: L18710.

(**6**) Cullen N.J., Mölg T., Kaser G., Steffen K., Hardy D.R. (**2007**): Energy-balance model validation on the top of Kilimanjaro, Tanzania, using eddy covariance data. *Annals of Glaciology*, vol. 46: 227-233.

(**7**) Mölg T., Cullen N.J., Hardy D.R., Kaser G., Klok L. (**2008**): Mass balance of a slope glacier on Kilimanjaro and its sensitivity to climate. *International Journal of Climatology*, vol. 28: 881-892.

(**8**) Mölg T., Cullen N.J., Hardy D.R., Winkler M., Kaser G. (**2009**): Quantifying climate change in the tropical mid-troposphere over East Africa from glacier shrinkage on Kilimanjaro. *Journal of Climate*, vol. 22: 4162-4181.

(**9**) Mölg T., Chiang J.H.C., Gohm A., Cullen N.J. (**2009**): Temporal precipitation variability versus altitude on a tropical high mountain: Observations and mesoscale atmospheric modeling. *Quarterly Journal of the Royal Meteorological Society*, vol. 135: 1439-1455.

(**10**) Mölg T., Cullen N.J., Kaser G. (**2009**): Solar radiation, cloudiness and longwave radiation over low-latitude glaciers: Implications for mass balance modeling. *Journal of Glaciology*, vol. 55: 292-302.

(**11**) Kaser G., Mölg T., Cullen N.J., Hardy D.R., Winkler M. (**2010**): Is the decline of ice on Kilimanjaro unprecedented in the Holocene? *The Holocene*, vol. 20: 1079-1091.

(**12**) Winkler M., Kaser G., Cullen N.J., Mölg T., Hardy D.R., Pfeffer W.T. (**2010**): Land-based marginal ice cliffs: Focus on Kilimanjaro. *Erdkunde*, vol. 64: 179-193.

(**13**) Mölg T., Kaser G. (**2011**): A new approach to resolving climate-cryosphere relations: Downscaling climate dynamics to glacier-scale mass and energy balance without statistical scale linking. *Journal of Geophysical Research*, vol. 116: D16101.

(**14**) Hardy D.R. (**2011**): Kilimanjaro. In: Singh V.P., Singh P., Haritashya U.K. (eds.), *Encyclopedia of Snow, Ice and Glaciers*. Dordrecht: Springer, 672-679.

(**15**) Mölg T., Großhauser M., Hemp A., Hofer M., Marzeion B. (**2012**): Limited forcing of glacier loss through land-cover change on Kilimanjaro. *Nature Climate Change*, vol. 2: 254-258.

(**16**) Cullen N.J., Sirguey P., Mölg T., Kaser G., Winkler M., Fitzsimons S.J. (**2013**): A century of ice retreat on Kilimanjaro: The mapping reloaded. *The Cryosphere*, vol. 7: 419-431.

Notes

- All literature cited has been published in international scientific journals, and thus all findings have been reviewed by other scientists. You will find all papers on a Google Scholar search.
- The term “model” signifies a computer model that – based on governing physical laws of a certain system – simulates processes that occur in nature. After a model is tested and confirmed against direct measurements, it allows us to study the sensitivity of the simulated processes, e.g. sensitivity of a system (for instance a glacier) to climate change or land cover change.
- The summarized results and publications represent the most extensive research programme on Kilimanjaro glaciers and climate to date within a collaborating group of scientists.

Authors/Team in alphabetical order

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