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Temperature Trends and Evidence for Elevation Dependent Warming on Mount Kenya

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ABSTRACT

Global climate models are important tools for understanding differential impacts of climate change around the world. These models depend on the existence of accurate and timely data for calibration and validation, and in some parts of the world such data is scarce. Tropical mountains are modelled to warm faster than other areas of the globe, due to a theory known as Elevation Dependent Warming. However empirical evidence for EDW is limited, particularly in tropical Africa. The aim of this study is to investigate temperature trends in Mount Kenya, an equatorial mountain in central Kenya, to look for evidence of Elevation Dependent Warming. Three types of datasets- reanalysis datasets, meteorological station data, and in-situ data loggers- were examined. The Reanalysis datasets investigated were TerraClimate- 1958 -2021, ERA5- 1979 - 2022, and CFSR- 1979 - 2022, while the meteorological stations examined included Munyaka Station- 2070 m.a.s.l., Naro Moru Gate Station- 2420 m.a.s.l, and Naro Moru Met Station- 3048 m.a.s.l, all of which had data from 1991 - 2022. Finally, six in-situ temperature loggers were placed at 200 m vertical elevation intervals from 3000 m.a.s.l to 4000 m.a.s.l, and data from these loggers were compared with historical observations at comparable elevations. Results showed that all the reanalysis datasets displayed significant warming, but with widely varying magnitudes, ranging from 0.12°C to 0.48°C/decade. Data from the meteorological stations, on the other hand, did not provide any evidence of warming. In-situ data loggers showed warming of 4-5°C for of absolute minimum temperatures since the 1950s. Despite the differences in the data sources, there was general agreement for lapse rates, which ranged from 0.5°C to 0.55°C/100 m. Each data source had its own shortcomings, and a thorough knowledge of error and conditions of use and is therefore needed before any datasets can be put into research use.

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Introduction

Tropical alpine areas are expected to experience some of the world's highest levels of warming over the next century due to climate change. These areas have been modelled to warm by as much as 4°C by the end of the century [1–4]. This is as compared to global average warming of less than 1.5°C [5]. This warming is known as Elevation Dependent Warming (EDW) and is thought to have something to do with global climate feedback processes such as albedo, water vapour, radiative fluxes, and aerosols, which cause higher elevation areas to warm more rapidly than lower elevations [6–8]. These factors then become more (or less) important in the tropics due to the influence of ENSO (El Niño–Southern Oscillation) cycles [3,9].

Empirical evidence for EDW is limited, however, and conclusions have been mixed [6]. Reviews of EDW have found that the majority of studies do suggest higher warming in mountain regions, though this can vary seasonally, and there remains disagreement over whether tropical mountains are more susceptible than other mountains [6,8]. The uncertainty comes from the paucity of data in these regions and the complexity of these climate systems. Long-term datasets are particularly rare in high elevations worldwide: in the Global Historical Climatology Network (GHCN) of climate stations, only 0.7% are at elevations above 3000 m.a.s.l [6], and those in tropical regions are more scarce yet. This data scarcity is compounded by the complex terrain which requires a high density of stations to accurately capture temperature variations in these regions. Where stations do exist, they are often placed in valleys for logistical reasons; these valleys have their own micro-climate due to down-welling of cold air, and thus do not necessarily reflect the average temperature in the area [6]. Because of this, the majority of evidence for EDW comes from reanalysis datasets [3,10–12]. However satellite data are themselves limited by cloud cover and spatial resolution [6]. What's more, as Global Climate Models are often calibrated by reanalysis datasets, there is the risk of circular reasoning [13–15].

Much of the analysis on tropical alpine warming has been conducted at either a global scale or at a regional scale- particularly in the tropical Andes [16–20]. There have been comparatively much fewer studies on the individual mountains of East Africa [21]. Mount Kenya in central Kenya has some of the most detailed temperature records, but even these are mostly from lower elevations [22]. The ones from high elevations, range at most from a couple days to a few months [23–27]. The objective of this study was to explore the temperature datasets on Mount Kenya, assess their quality, and analyse temperature trends to look for evidence of EDW.

Materials and Methods

Study area

Mount Kenya is an extinct volcano in central Kenya [28]. It is the highest mountain in Kenya (peak at 5,199 m.a.s.l.) and second highest in Africa. It is also one of just three highland areas of Kenya with an alpine climate- occurring at elevations above ~3500 m.a.s.l. - the others are Mount Elgon and the Aberdares [25]. The specific study area is the western slope of Mount Kenya which has three permanent meteorological stations as well as a wealth of historical data on temperature.

Data Sources

There are few remotely sensed datasets for temperature that have global coverage, an adequate spatial resolution to capture topographic variability, and also a long enough temporal record to analyse temperature trends. Three datasets that do meet this criteria are CFSR, TerraClimate and ERA5. CFSR (Climate Forecast System Reanalysis) produces surface temperatures at a spatial resolution of ~38 km, a temporal resolution of 6 hours, and coverage going back to 1979 [29]. ERA5 (European Centre for Medium-Range Weather Forecasts- Reanalysis v5) is another reanalysis product covering the period since 1979. It records 2 m air temperature at a spatial resolution of ~31 km and at an hourly resolution [30]. The ERA5_Ag (Agro-meteorological) product is a summarized dataset providing temperature on a daily time step, but at finer spatial resolution of ~9.6 km [31]. TerraClimate is in itself a combination of several other reanalysis products, combined in such a way as to provide optimum spatial and temporal resolution. It provides surface temperature at a spatial resolution of ~4km, a monthly time step, and a temporal coverage going back to 1958 [32]. These datasets were downloaded for Mount Kenya using the Famine Early Warning System Network's Climate Engine tool [33].

There are three permanent meteorological stations on the west side of the mountain: the Naro Moru Meteorological Station (3048 m), the Naro Moru Gate Station (2420 m), and the Munyaka Station (2070 m) (Figure 1). These are manually operated stations that collect a suite of climatic data including rainfall, wind speed, temperature, and humidity. Data is collected twice a day, and they have been in operation since 1991. Temperature sensors for each of these stations were upgraded after 2008, and in Munyaka, the sensor was changed again in 2018 after the previous one got damaged (Muriungi, M. pers. comm, 2023). Data for these stations were obtained from the Centre for Training and Integrated Research in Arid and Semi-arid Land Development in Kenya [34].

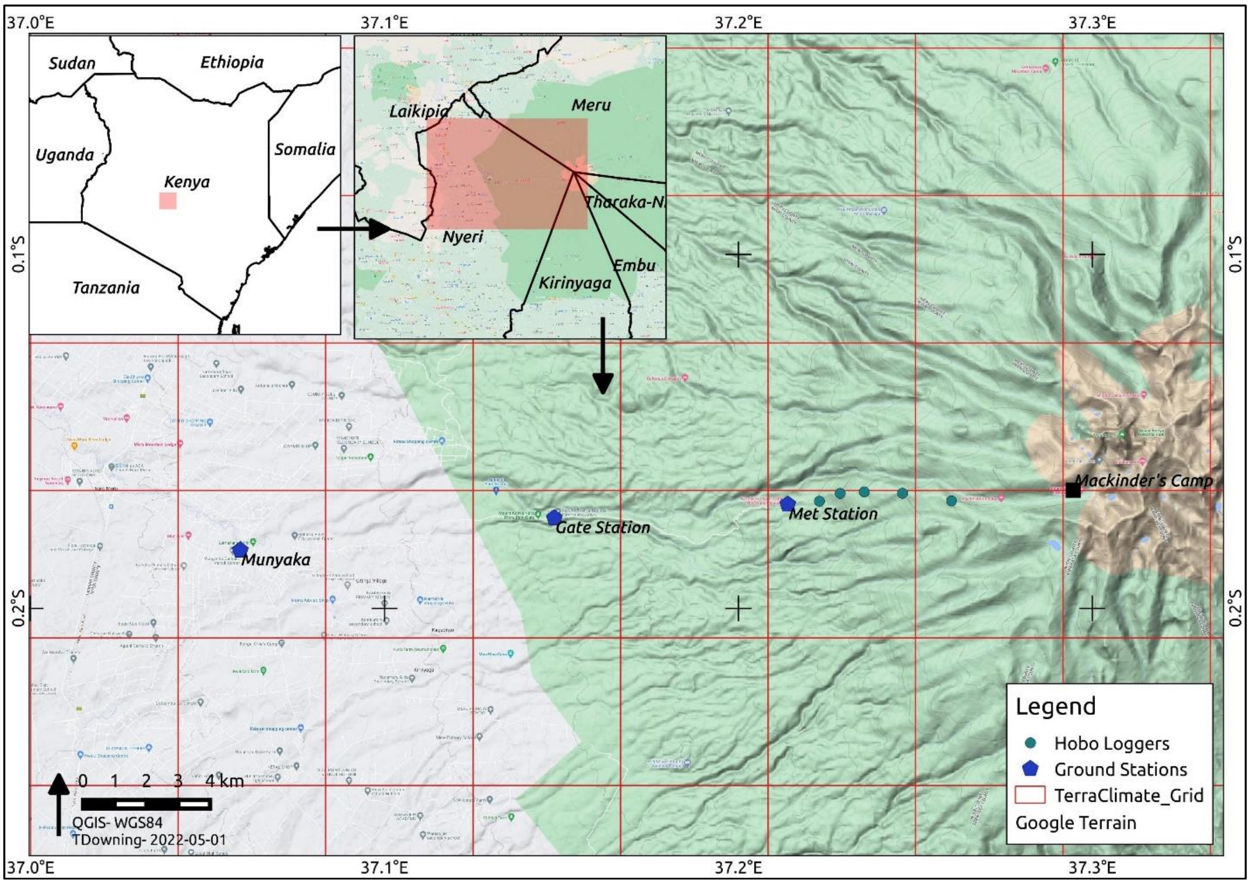

Figure 1: Study area on the western slope of Mount Kenya. Ground station and logger locations used are indicated as well as the footprint of the TerraClimate reanalysis dataset. Map created by author.

In-situ temperature data was also recorded on the western slope of Mount Kenya using Hobo Pendant MX2201 data loggers, accurate to ±0.5°C [35]. Five loggers were set up at 200 m elevation intervals from the 3200 m contour to the 4000 m contour (Figure 1). Loggers were strapped with zip-ties to the bottom of shrubs large enough to provide adequate shade throughout the day. Data loggers can be sensitive to direct sunlight so at the 3600 m contour a second logger was placed immediately next to the first, but encased with an Onset RS1 solar radiation shield [35] to test for impacts of direct radiation. An additional logger was also placed directly beneath the Naro Moru Meteorological Station (hereafter referred to as 'Met Station') for comparison with the other datasets. All loggers were set to record temperature at 30 minute intervals. They were installed on September 21, 2021 and data was downloaded on February 22, 2022.

Data Analysis

The datasets were all compared with the Naro Moru Met Station by comparing average daily means, maximums, and minimums as well as absolute minimum and maximum temperatures over the time period. The averages were compared among the datasets using the student's t-test. At the 3600 m contour, temperatures from the shielded logger were compared to the unshielded logger (but still under the shade) using the student's t-test. Logger data was compared with historic point measurements at similar elevations. As the raw data was not provided in the historic studies, it was not possible to compare these data statistically. However, the absolute maximum and minimum temperatures were provided, which gave some indication of the spread of the data.

Trends for the different datasets at Met Station were compared by plotting the mean temperatures, with 95% confidence intervals, using a lowess (locally weighted scatterplot smoothing) line. This allowed the patterns in the data to be quickly visualized. Significance of trends were assessed using the Mann-Kendall test [36,37]. Trends for the reanalysis datasets (with the longer records) were also statistically analysed by plotting the data as departure from a baseline of 1961-1990. A linear regression line through the data provided the slope by month, which was then converted to an annual rate of change. For the CFSR dataset, the period after 2011 was not included as a change in algorithm after 2011 substantially changed the temperature readings [38]. Finally, lapse rates were calculated for the three datasets using a linear regression of mean temperatures by elevation. The slope of the regression provides the lapse rate as °C/m, which was then converted to °C/100m.

Results

Comparison of data sources at Met Station

The three reanalysis datasets showed general agreement with the meteorological station data over the five months of record (Sept 2021- March 2022), although there were some differences. TerraClimate displayed significantly higher mean (12.34°C vs. 10.17°C, $p<0.01$) and maximum temperatures (18.63°C vs. 15.18°C, $p<0.01$) than the ground station. ERA5_Ag had significantly higher mean temperatures (10.98°C vs. 10.17°C, $p=0.03$), while CFSR had higher maximum temperatures (21.10°C vs. 15.18°C, $p<0.01$). The Hobo loggers had higher maximum temperatures (24.45°C vs. 15.18°C, $p<0.01$), but lower minimum temperatures (4.34°C vs. 5.17°C, $p=0.02$). Hobo absolute maximum temperatures were over 18°C warmer than the ground station data. CFSR displayed the highest variability among the reanalysis datasets, but the mean was closest to the Met Station data (10.89°C vs. 10.17°C) (Table 1).

Table 1: Comparison of temperatures in °C for datasets at the Naro Moru Meteorological Station of Mount Kenya ~3000m; September 2021- March 2022.

Source	**Type**	**Mean**	**Max^**	**Min**	**Abs Max**	**Abs Min**
MetStation	***Automatic weather station***	***10.17***	***15.18***	***5.17***	***19.00***	***2.50***
Hobo	In-situ logger	11.05	24.45*	4.34*	37.19	1.58
CFSR	Reanalysis dataset (38 km²)	10.89	21.10*	2.93	22.65	-0.15
ERA5 Ag	Reanalysis dataset (9.6 km²)	10.98*	16.25	5.43	17.64	4.85
TerraClimate+	Hybrid reanalysis dataset (4 km²)	12.34*	18.63*	6.05	19.10	5.10

^Max and Min are average monthly maximum and minimum temperatures, whereas Abs Max and Abs Min are the absolute minimum and maximum over the time period
+Terra Climate data is only for 2021 (Climate Engine does not have 2022 data)
* Significantly different from Met Station at $p<0.05$ level

Plotting the three reanalysis datasets together with the Met Station since 1980 showed uniform differences between the datasets for the entire period of record; each source is generally outside the 95% confidence limits of the others (Figure 2). TerraClimate and ERA5_Ag showed constant gradual increases, while Met Station and CFSR displayed some unusual patterns as shown in Figure 2. CFSR had a sharp decline in temperature in 2011, which corresponds to the timing of a new release of the CFSR product [38]. Before 2011, the trend was similar to the other reanalysis datasets, but with considerably higher mean temperatures. The meteorological station data similarly showed an abrupt shift at 2008 corresponding to the changing out of the sensors that year.

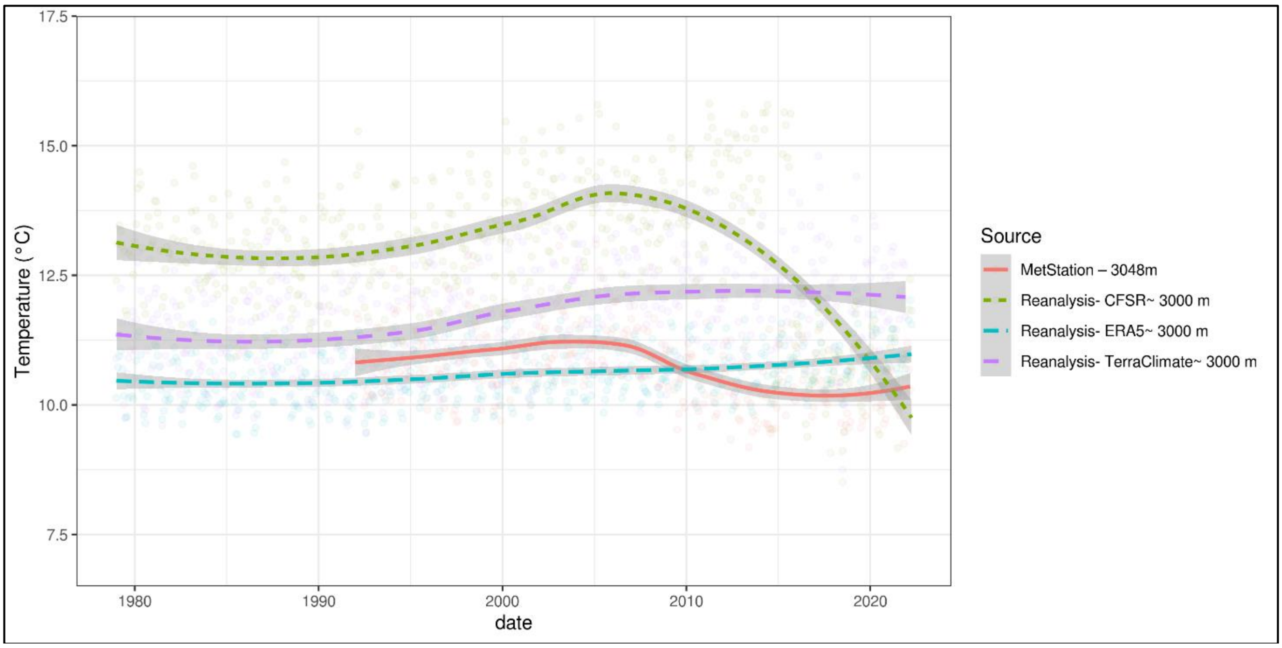

Figure 2: Comparison of temperature datasets at Naro Moru Met Station. Shown here are mean temperatures with a lowess smoothing line and 95% confidence intervals are provided for the three reanalysis datasets as well as the station data

The unusually high maximum temperature readings for the Hobo logger suggested overheating in the sun (see discussion). To test this, data from a Hobo logger with a radiation shield was compared to a logger without a shield (although still in shade). The Hobo logger without the radiation shield produced significantly higher daily maximums than logger with the shield (t(308)= -7.7; p = <0.01). Minimums temperatures, however, were almost identical (t(308)=0.33; p = 0.74). On average maximum temperatures were 3°C warmer as compared to loggers with the shield (Figure 3).

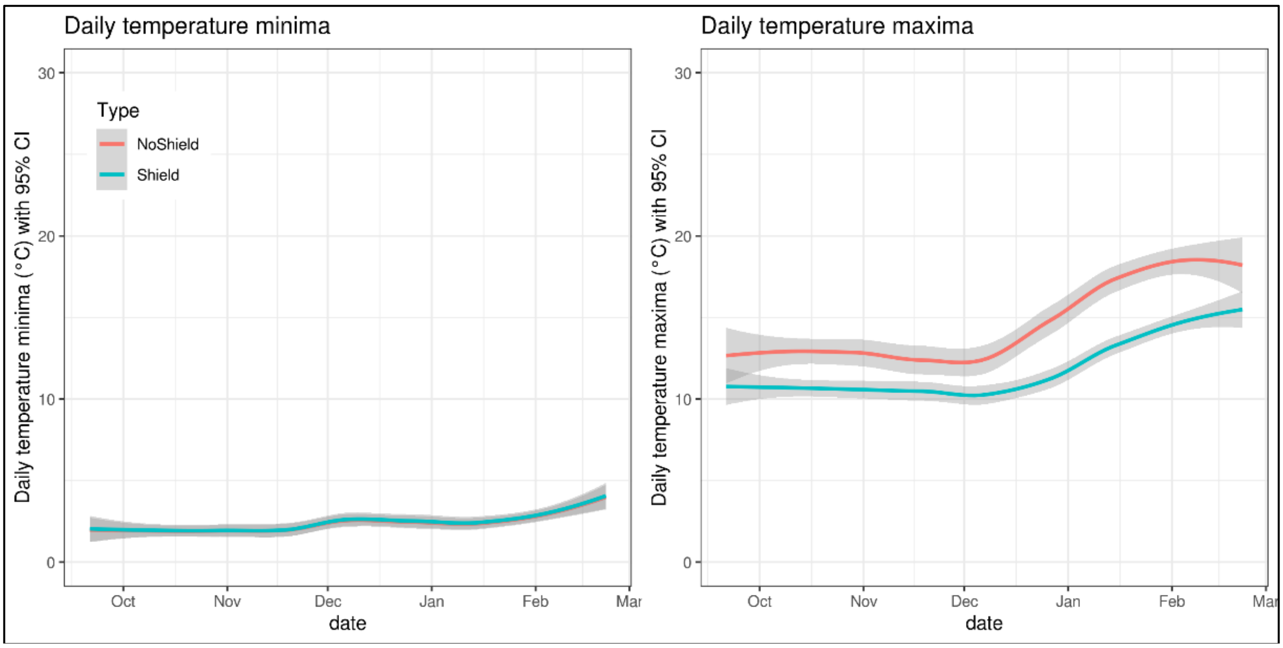

Figure 3: Comparison of minimum and maximum temperatures for Hobo logger with a radiation shield versus without at the 3600 m contour

Data Trends

The reanalysis datasets all show significant temperature increases at Met Station (TerraClimate z= 11.06, p<0.01; CFSR z=10.35, p<0.01; ERA5_Ag z=6.65, p<0.01) using the time period before 1990 as a baseline. The rate of increase, however, varies between the datasets, from 0.012°C/year for ERA5_Ag to 0.048°C/year for CFSR, with TerraClimate right in the middle at 0.024°C /year (Figure 4). For TerraClimate with the longest record (1958-2021), the increase amounts to 1.25 °C as compared to the baseline average from 1961 to 1990 of 11.09°C.

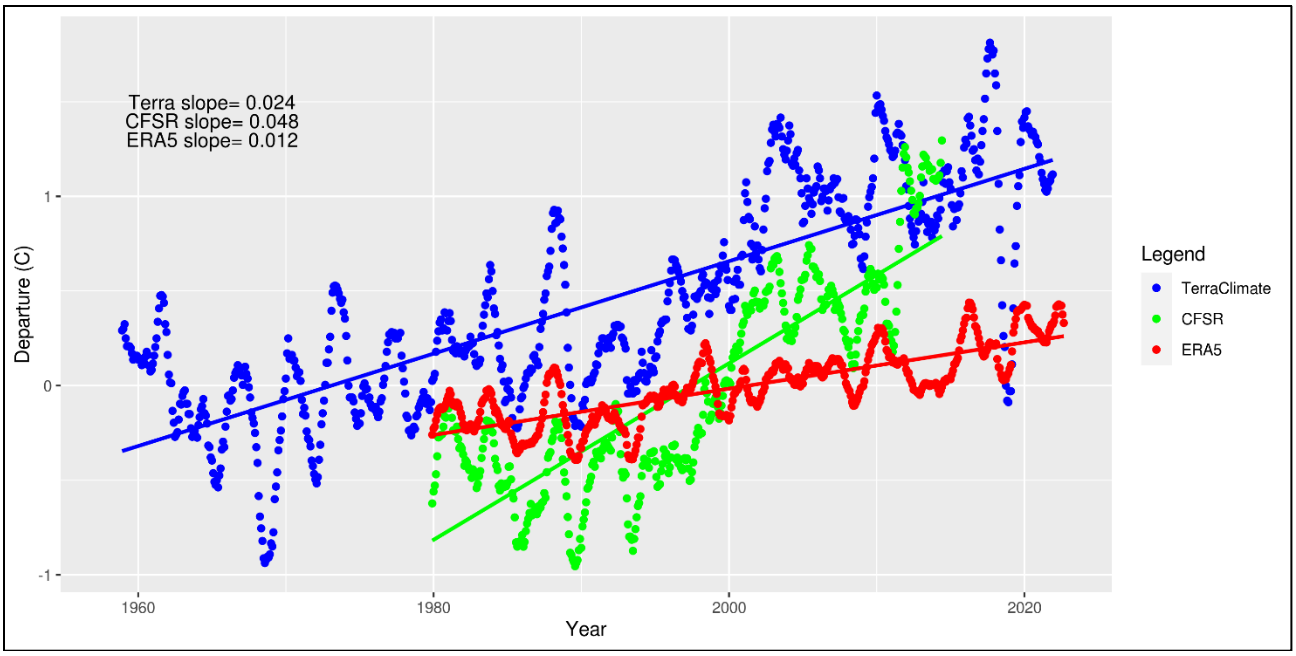

Figure 4: Reanalysis trends at Net Naro Moru Met Station- 1958-2022, displayed as anomalies using the period before 1990 as the baseline

The Ground stations, on the other hand, all displayed significant declines in temperature since 1991 according to the Mann-Kendall test (Met Station: z=-7.39, p<0.01; Gate Station z=-6.77, p<0.01; Munyaka z=-14.35, p<0.01). However, here are considerable anomalies in each time series, which make these trends questionable. In particular, Gate Station reads higher temperatures for much of the time series than Munyaka Station despite being at a higher elevation (Figure 5). The sensor replacement in 2008 is apparent in all three time series, causing an inflection point in each time series.

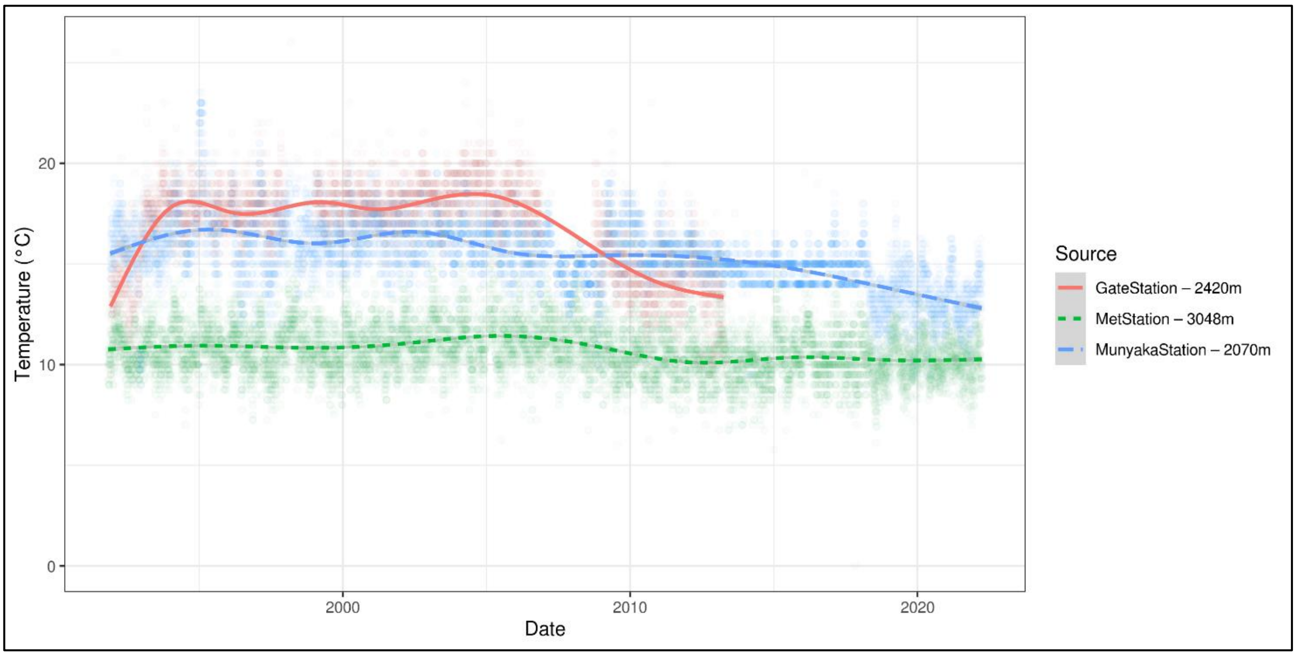

Figure 5: Ground Station trends on Mount Kenya- 1991-2022, displayed as mean temperatures with 95% confidence intervals

The Teleki valley above Met Station has several historic observations of temperature, ranging from 4000 m to 4200 m. The current Hobo logger data from 4000 m is generally within the range of the historic observations for mean and maximum temperature (4.7°C vs. 1.9°C - 6.7°C for mean and 14.5°C vs. 11°C - 18°C for maximum). However, minimum temperature in the current study are 3°C to 5°C higher than the historical data (-1.6°C vs. -5°C to -6.7°C), leading to correspondingly fewer frost days (13% vs. 86-98%) (Table 2). The unusually high maximum value reported by Grab *et al.* (2004) is likely erroneous, caused by direct solar radiation (see discussion).

Table 2: Hobo temperature logger data- in °C- as compared to historical records. Data reported is surface temperature at less than 20cm height

Author	**Elevation (m.a.s.l)**	**Date**	**Mean**	**Abs. Max**	**Abs. Min**	**Frost Days %**	**Duration**
Hedberg, 1964	4200	1948	3.1	14	-6	86	one week, Aug
Coe, 1967	4191	1958	1.9	11	-6.7		one month, Dec- Jan
Beck *et al.*, 1981	4066	1979	5.5	18	-5		3 weeks, March
Grab *et al.*, 2004*	4200	1998	6.7	42.8	-7.2	98	6 months, Aug - Dec
Current Study	4000	2021	4.7	14.5	-1.6	13	5 months, Sept- Feb

*Max temperature is highly suspect- may have been placed in direct sunlight

The lapse rate, for all three data sources- ground station data, Hobo data, and reanalysis data- was similar, ranging from 0.50 to 0.55°C/100 m. The TerraClimate data covered the full elevation range, while the ground station data was confined to the lower reaches of the mountain and the Hobo data just from 3200 to 4000 m (Figure 6).

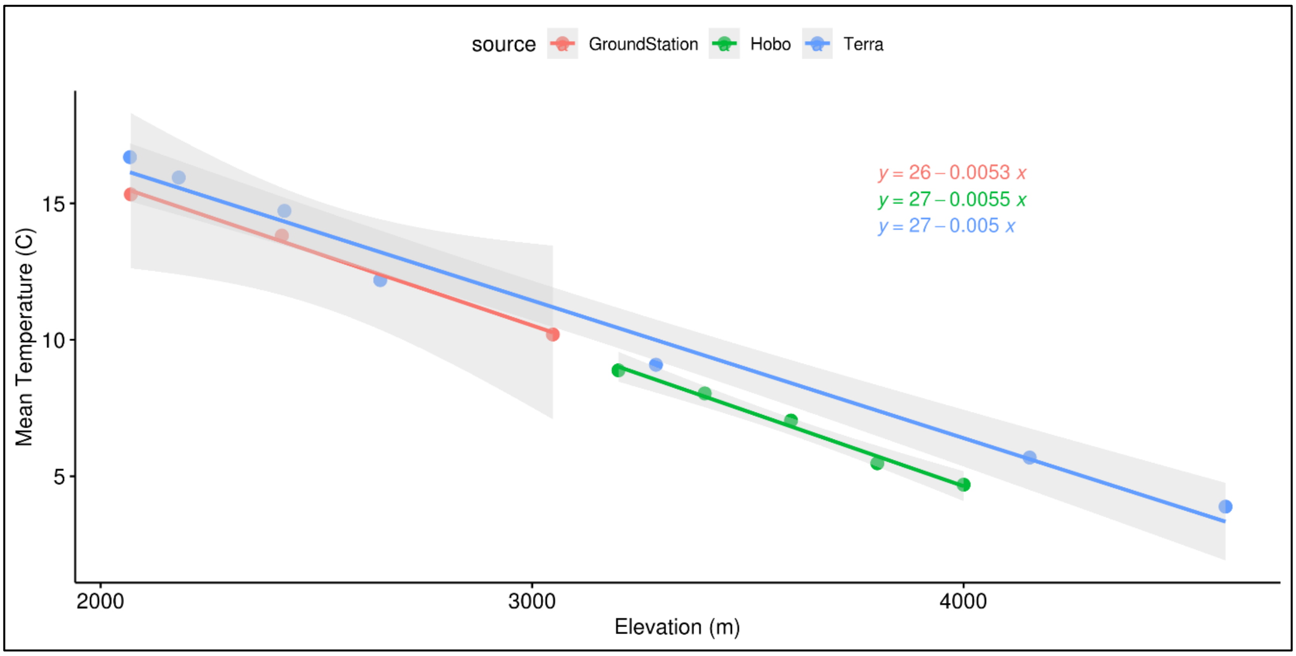

Figure 6: Linear regression for mean temperatures by elevation on the western slopes of Mount Kenya. Comparison of Hobo logger, ground station, and reanalysis dataset

Discussion

The reanalysis datasets provided the best indication of the magnitude of warming in Mount Kenya over the past half century. Although they vary substantially, all three rates (0.12, 0.24, and 0.48°C/decade) fell within the range of observed trends in highland areas around the globe, which range from 0.11°C to 0.34°C/decade [20,39,40]. This is somewhat less than the model predictions for tropical alpine areas, however, which suggest warming of around 4°C by 2080 [3], corresponding to roughly 0.6°C/decade. This gap between model results and observations has been noted before: even where the observations support the model predictions of high rates of warming in high elevation tropics, the scale of this is less than in the model predictions [8,41]. The temperature trends were generally greater than those observed from the rest of Kenya, however, which ranges from 0.09°C/decade to 0.25°C/decade [42–44]. Models project a similar or slightly higher warming in Kenya over the next 50-100 years [45,46].

Some studies have suggested that minimum temperatures will increase faster than maximum temperatures [6,19]. From the few records that do exist for Mount Kenya, it does indeed appear that absolute minimum temperatures (lowest readings over the period of record) have increased substantially. Hedberg (1964) recorded a low of -6°C in just one week of measurement in August, 1948, whereas the current study did not record anything below -1.6°C, over a 5-month period. Coe (1967) recorded an even lower minimum of -6.7°C in December- January 1958/1959. Also the decline in the number of frost days is telling. Hedberg (1964) reported it freezing on 86% of the days at 4200 m. This is much more than the 13% found in this study (Table 2).

A recent paleoclimate temperature reconstruction from sediment cores at Lake Rutundu on the northeast side of Mount Kenya, at 3078 m (comparable to Met Station at 3048 m), found the mean temperature to have fluctuated from 4°C to 15°C over the past 25,000 years [47]. On average, the Last Glacial Maximum (LGM) was 5.5±0.2°C cooler than during the modern period. The authors found that this coincided with a decrease in lapse rate between the two periods from -6.7±0.4°C/km during the LGM to a modern lapse rate of -5.7±0.1°C/km. The lapse rates determined in the current study are somewhat lower than in the Loomis study (-5.0 to -5.5°C/km), and also lower than the commonly reported value in the literature of -6.0°C/km [24,48,49]. A declining lapse rate is consistent with climate change predictions [4], and is also something that is likely underestimated in climate models [47].

Obtaining quality temperate data in hard-to-reach areas can be a challenge. In this study, three different data sources for Mount Kenya were compared- each one having strengths and weaknesses. The reanalysis datasets have the longest temporal coverage- particularly TerraClimate which goes back to 1958 - and they generally provide consistent readings over time. Nonetheless reanalysis datasets are limited by their spatial resolution, the availability of ground station data for calibration, and also changes to the reanalysis models over time. The CFSR dataset, at a spatial resolution of 38 km, should be too coarse of a resolution to characterize mountain temperatures, and yet it had the highest level of agreement with the ground station data. Indeed, this is likely because it was calibrated by the Met Station data: its accuracy would be reduced higher up on the mountain but in the same grid cell. In addition, a new version of CFSR created an abrupt shift after 2011, making analysis of overall trends difficult. After CFSR, ERA5_Ag matched closest with the ground station data over the whole period of record, despite its 9.6 km spatial resolution; again, this may be a function of it being calibrated by Met Station.

Other studies in high elevation areas have noted a cool bias in ERA, with temperatures -3.54 °C cooler than ground observations across several elevations in the Himalayas [50]. Finally TerraClimate, with the longest record and the highest spatial resolution, reads on average two degrees warmer than the Met Station data. The TerraClimate temperature dataset is based on two other reanalysis datasets: WorldClim and CRU (Climate Research Unit) [32]. WorldClim data is known to have a positive elevation bias in the tropics: ground stations used to characterize a grid cell are generally from lower elevations, resulting in higher temperature readings in the high elevations [51]. This explains the warmer minimum and mean temperatures for TerraClimate as compared to the Hobo data and Met Station data.

Ground station data benefit from being direct site-specific readings made by precise instruments. However they are limited by instrument failure from poor maintenance [52–54], as well as siting issues that risk capturing a unique microclimate rather than the general temperature of the area [6]. This is particularly an issue if the station is being used to calibrate reanalysis datasets or climate models. Instrument failures are common, and can be identified by abrupt shifts in the data [55], and indeed this was seen in the ground station data. Personal communication with the station operators revealed that the sensors had been replaced at least twice during the period of record (Muriungi, M., pers. comm., 2023).

In-situ temperature loggers benefit from being cheap and portable and easy to use. When properly used, they also can have a very high accuracy. Unfortunately, they are susceptible to overheating from direct radiation from the sun which can lead to anomalous readings. The experiment with the radiation shield showed that even with an attempt to place loggers in the shade, they were still evidentially receiving some direct radiation, causing readings that were higher than the ambient temperature. In the experiment, maximum temperatures were around 3°C higher in the non-shielded loggers. This somewhat accounts for the difference between the Met Station data and the Hobo data, although the difference was much greater there. Historical in-situ data suffer from the same problem of overheating, and authors rarely recorded in detail where they placed their loggers or the specific tolerances of those loggers. Excessively high maximum temperatures reported on Mount Kenya [56] were almost assuredly caused by overheating due to direct exposure to sunlight. For in-situ data, minimum temperatures are likely the more reliable readings.

A thorough understanding of each dataset is necessary before it can be used for modelling or other purposes. Not knowing the metadata regarding how and when a dataset is to be used, can lead to large errors in interpreting the results. However, while the different datasets had widely different readings, there was a remarkable consistency in the lapse rate. This shows that ratio transformations of the data can be an effective way to utilize different datasets and overall means can be valid even if individual readings are unreliable. Nevertheless, using a combination of datasets and accounting for error in each one is crucial to accurately capture the temperature regimes in these remote areas.

Conclusion

Temperature has increased on Mount Kenya at a rate higher than the global average, which suggests Elevation Dependent Warming may be occurring. However, there is discrepancy as to the magnitude of that warming. Each of the datasets investigated has significant shortcomings, and unless those shortcomings are addressed explicitly, it can lead to misleading results. The TerraClimate temperature record from 1958 to 2021 is likely the most reliable dataset and showed a consistent warming of 0.24°C/decade. This matches with in-situ logger readings showing increases in minimum temperatures of 3°C to 4°C warmer as compared to historical data, and also squares well with warming trends seen in mountain areas around the globe. The other datasets - CFSR, Meteorological stations, and in-situ loggers- all have potential errors that must be addressed before the data can be used appropriately. Even with modern sensors and satellite systems, there can still be anomalies in the data, which are often overlooked. A thorough understanding of the metadata and conditions of use is necessary before making use of any given dataset.

Conflict of Interest:

The authors do not have any conflict of interest to declare.

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References

[1] R.S. Bradley, M. Vuille, H.F. Diaz, W. Vergara, Threats to water supplies in the tropical Andes, Science 312 (2006) 1755–1756. https://doi.org/10.1126/science.1128087.

[2] B. Büchler, R. Bradley, B. Messerli, M. Reasoner, MRI Newsletter 3: Understanding climate change in mountains, Mountain Research and Development 24 (2004) 176–177. https://doi.org/10.1659/0276-4741(2004)024[0176:MNUCCI]2.0.CO;2.

[3] H.F. Diaz, R.S. Bradley, L. Ning, Climatic changes in mountain regions of the American Cordillera and the tropics: historical changes and future outlook, Arctic, Antarctic, and Alpine Research 46 (2014) 735–743. https://doi.org/10.1657/1938-4246-46.4.735.

[4] R. Urrutia, M. Vuille, Climate change projections for the tropical Andes using a regional climate model: Temperature and precipitation simulations for the end of the 21st century, J. Geophys. Res. 114 (2009).

[5] IPCC, Summary for Policymakers, in: An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, Cambridge University Press, Cambridge, UK, 2018.

[6] Mountain Research Initiative, Elevation-dependent warming in mountain regions of the world, Nature Clim Change 5 (2015) 424–430.

[7] A. Ohmura, Enhanced temperature variability in high-altitude climate change, Theor Appl Climatol 110 (2012) 499–508. https://doi.org/10.1007/s00704-012-0687-x.

[8] I. Rangwala, J.R. Miller, Climate change in mountains: a review of elevation-dependent warming and its possible causes, Climatic Change 114 (2012) 527–547.

[9] H.F. Diaz, N.E. Graham, Recent changes in tropical freezing heights and the role of sea surface temperature, Nature 383 (1996) 152–155. https://doi.org/10.1038/383152a0.

[10] R.S. Bradley, F.T. Keimig, H.F. Diaz, D.R. Hardy, Recent changes in freezing level heights in the Tropics with implications for the deglacierization of high mountain regions, Geophys. Res. Lett. 36 (2009) L17701. https://doi.org/10.1029/2009GL037712.

[11] H.F. Diaz, J.K. Eischeid, C. Duncan, R.S. Bradley, Variability of freezing levels, melting season indicators, and snow cover for selected high-elevation and continental regions in the last 50 years, in: H.F. Diaz (Ed.), Climate Variability and Change in High Elevation Regions: Past, Present & Future, Springer Netherlands, Dordrecht, 2003: pp. 33–52. https://doi.org/10.1007/978-94-015-1252-7_3.

[12] D.J. Seidel, M. Free, Comparison of lower-tropospheric temperature climatologies and trends at low and high elevation radiosonde sites, in: H.F. Diaz (Ed.), Climate Variability and Change in High Elevation Regions: Past, Present & Future, Springer Netherlands, Dordrecht, 2003: pp. 53–74. https://doi.org/10.1007/978-94-015-1252-7_4.

[13] D. Maraun, M. Widmann, Cross-validation of bias-corrected climate simulations is misleading, Hydrol. Earth Syst. Sci. 22 (2018) 4867–4873. https://doi.org/10.5194/hess-22-4867-2018.

[14] K. Steele, C. Werndl, Climate Models, Calibration, and Confirmation, The British Journal for the Philosophy of Science 64 (2013) 609–635. https://doi.org/10.1093/bjps/axs036.

[15] S.F.B. Tett, K. Yamazaki, M.J. Mineter, C. Cartis, N. Eizenberg, Calibrating Climate Models Using Inverse Methods: Case studieswith HadAM3, HadAM3P and HadCM3, Climate and Earth System Modeling, 2017. https://doi.org/10.5194/gmd-2016-305.

[16] F. Drenkhan, M. Carey, C. Huggel, J. Seidel, M.T. Oré, The changing water cycle: climatic and socioeconomic drivers of water-related changes in the Andes of Peru, WIREs Water 2 (2015) 715–733. https://doi.org/10.1002/wat2.1105.

[17] N. Michelutti, A.P. Wolfe, C.A. Cooke, W.O. Hobbs, M. Vuille, J.P. Smol, Climate Change Forces New Ecological States in Tropical Andean Lakes, PLoS ONE 10 (2015) e0115338. https://doi.org/10.1371/journal.pone.0115338.

[18] T.A. Seimon, A. Seimon, K. Yager, K. Reider, A. Delgado, P. Sowell, A. Tupayachi, B. Konecky, D. McAloose, S. Halloy, Long-term monitoring of tropical alpine habitat change, Andean anurans, and chytrid fungus in the Cordillera Vilcanota, Peru: Results from a decade of study, Ecol Evol 7 (2017) 1527–1540. https://doi.org/10.1002/ece3.2779.

[19] M. Vuille, B. Francou, P. Wagnon, I. Juen, G. Kaser, B.G. Mark, R.S. Bradley, Climate change and tropical Andean glaciers: Past, present and future, Earth-Science Reviews 89 (2008) 79–96.

[20] M. Vuille, R.S. Bradley, Mean annual temperature trends and their vertical structure in the tropical Andes, Geophys. Res. Lett. 27 (2000) 3885–3888.

[21] T.A. Downing, D. Olago, T. Nyumba, Abstract 421: Temperature trends in the alpine zone of Mount Kenya from in-situ data loggers and satellite derived data, in: Springer, Riyadh, Saudi Arabia., 2023.

[22] J. Schmocker, H.P. Liniger, J.N. Ngeru, Y. Brugnara, R. Auchmann, S. Brönnimann, Trends in mean and extreme precipitation in the Mount Kenya region from observations and reanalyses, Int. J. Climatol. 36 (2016) 1500–1514. https://doi.org/10.1002/joc.4438.

[23] E. Beck, H. Rehder, P. Pongratz, R. Scheibe, M. Senser, Ecological analysis of the boundary between the Afroalpine vegetation types “*Dendrosenecio* woodlands” and “*Senecio brassica- Lobelia keniensis* community” on Mt. Kenya, Journal of the East Africa Natural History Society and National Museum 172 (1981) 1–11.

[24] M.J. Coe, The ecology of the alpine zone of Mount Kenya, Junk, The Hague, 1967.

[25] O. Hedberg, Features of afroalpine plant ecology, Acta Phytogeographica Suecica 49 (1964) 1–144.

[26] K. Mizuno, T. Fujita, Vegetation succession on Mt. Kenya in relation to glacial fluctuation and global warming, J Veg Sci 25 (2014) 559–570. https://doi.org/10.1111/jvs.12081.

[27] T.P. Young, S.V.O. Robe, Microenvironmental role of a secreted aqueous solution in the afro-alpine plant *Lobelia keniensis*, Biotropica 18 (1986) 267. https://doi.org/10.2307/2388496.

[28] B.H. Baker, Geology of the Mount Kenya Area, Republic of Kenya- Ministry of Natural Resources, 1967.

[29] S. Saha, S. Moorthi, H.-L. Pan, X. Wu, J. Wang, S. Nadiga, P. Tripp, R. Kistler, J. Woollen, D. Behringer, H. Liu, D. Stokes, R. Grumbine, G. Gayno, J. Wang, Y.-T. Hou, H. Chuang, H.-M.H. Juang, J. Sela, M. Iredell, R. Treadon, D. Kleist, P. Van Delst, D. Keyser, J. Derber, M. Ek, J. Meng, H. Wei, R. Yang, S. Lord, H. van den Dool, A. Kumar, W. Wang, C. Long, M. Chelliah, Y. Xue, B. Huang, J.-K. Schemm, W. Ebisuzaki, R. Lin, P. Xie, M. Chen, S. Zhou, W. Higgins, C.-Z. Zou, Q. Liu, Y. Chen, Y. Han, L. Cucurull, R.W. Reynolds, G. Rutledge, M. Goldberg, The NCEP Climate Forecast System Reanalysis, Bull. Amer. Meteor. Soc. 91 (2010) 1015–1058.

[30] H. Hersbach, B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R.J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. Rosnay, I. Rozum, F. Vamborg, S. Villaume, J. Thépaut, The ERA5 global reanalysis, Q.J.R. Meteorol. Soc. 146 (2020) 1999–2049.

[31] ECMWF, Global agriculture downscaling and bias correction, (2022). https://confluence.ecmwf.int/display/CKB/Global+Agriculture+Downscaling+and+bias+correction.

[32] J.T. Abatzoglou, S.Z. Dobrowski, S.A. Parks, K.C. Hegewisch, TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015, Sci Data 5 (2018). https://doi.org/10.1038/sdata.2017.191(2018).

[33] FEWS NET, Famine Early Warning Systems Network Climatge Engine, (2022). https://clim-engine-development.appspot.com/fewsNet.

[34] CETRAD, Centre for Training and Integrated Research in ASAL Development, (2022). www.cetrad.org.

[35] Onset, Monitoring Solutions for Every Environment, (2022). www.onsetcomp.com/.

[36] M.G. Kendall, Rank correlation methods, 4th edn., Griffin, London, 1975.

[37] H.B. Mann, Nonparametric tests against trend, Econometrica 13 (1945) 245. https://doi.org/10.2307/1907187.

[38] A.G. Barnston, M.K. Tippett, A Comparison of Skill of CFSv1 and CFSv2 Hindcasts of Nino3.4 SST, Climate Prediction S&T Digest 18 (2013) 11.

[39] B.G. Mark, G.O. Seltzer, Evaluation of recent glacier recession in the Cordillera Blanca, Peru (AD 1962–1999): spatial distribution of mass loss and climatic forcing, Quaternary Science Reviews 24 (2005) 2265–2280. https://doi.org/10.1016/j.quascirev.2005.01.003.

[40] S. Schauwecker, M. Rohrer, D. Acuña, A. Cochachin, L. Dávila, H. Frey, C. Giráldez, J. Gómez, C. Huggel, M. Jacques-Coper, E. Loarte, N. Salzmann, M. Vuille, Climate trends and glacier retreat in the Cordillera Blanca, Peru, revisited, Global and Planetary Change 119 (2014) 85–97. https://doi.org/10.1016/j.gloplacha.2014.05.005.

[41] N.C. Pepin, J.D. Lundquist, Temperature trends at high elevations: Patterns across the globe, Geophys. Res. Lett. 35 (2008) L14701. https://doi.org/10.1029/2008GL034026.

[42] B.O. Ayugi, G. Tan, Recent trends of surface air temperatures over Kenya from 1971 to 2010, Meteorol Atmos Phys 131 (2019) 1401–1413. https://doi.org/10.1007/s00703-018-0644-z.

[43] T.J. Lawrence, J.M. Vilbig, G. Kangogo, E.M. Fèvre, S.L. Deem, I. Gluecks, V. Sagan, E. Shacham, Shifting climate zones and expanding tropical and arid climate regions across Kenya (1980–2020), Reg Environ Change 23 (2023) 59. https://doi.org/10.1007/s10113-023-02055-w.

[44] V. Ongoma, H. Chen, C. Gao, P.O. Sagero, Variability of temperature properties over Kenya based on observed and reanalyzed datasets, Theor Appl Climatol 133 (2018) 1175–1190. https://doi.org/10.1007/s00704-017-2246-y.

[45] G.L. Muhati, D. Olago, L. Olaka, Past and projected rainfall and temperature trends in a sub-humid Montane Forest in Northern Kenya based on the CMIP5 model ensemble, Global Ecology and Conservation 16 (2018) e00469. https://doi.org/10.1016/j.gecco.2018.e00469.

[46] P. Ward, R. Lasage, Downscaled climate change data from the HADCM3 and ECHAM5 models on precipitation and temperature for Ethiopia and Kenya, Institute for Environmental Studies, Vrije Universiteit., Netherlands., 2009.

[47] S.E. Loomis, J.M. Russell, D. Verschuren, C. Morrill, G. De Cort, J.S. Sinninghe Damsté, D. Olago, H. Eggermont, F.A. Street-Perrott, M.A. Kelly, The tropical lapse rate steepened during the Last Glacial Maximum, Sci. Adv. 3 (2017) e1600815.

[48] G. Nigrelli, S. Fratianni, A. Zampollo, L. Turconi, M. Chiarle, The altitudinal temperature lapse rates applied to high elevation rockfalls studies in the Western European Alps, Theor Appl Climatol 131 (2018) 1479–1491. https://doi.org/10.1007/s00704-017-2066-0.

[49] P.W. Rundel, Tropical alpine climates, in: P.W. Rundel, A.P. Smith, F.C. Meinzer (Eds.), Tropical Alpine Environments: Plant Form and Function, Cambridge University Press, Cambridge, 1994: pp. 251–272.

[50] L. Gao, M. Bernhardt, K. Schulz, X. Chen, Elevation correction of ERA-Interim temperature data in the Tibetan Plateau, Int. J. Climatol. 37 (2017) 3540–3552. https://doi.org/10.1002/joc.4935.

[51] R.J. Hijmans, S.E. Cameron, J.L. Parra, P.G. Jones, A. Jarvis, Very high resolution interpolated climate surfaces for global land areas, Int. J. Climatol. 25 (2005) 1965–1978. https://doi.org/10.1002/joc.1276.

[52] P. Brown, B. Russell, Siting and Maintenance of Weather Stations, (2010).

[53] S. Feng, Q. Hu, W. Qian, Quality control of daily meteorological data in China, 1951–2000: a new dataset, Int. J. Climatol. 24 (2004) 853–870. https://doi.org/10.1002/joc.1047.

[54] C.A. Fiebrich, C.R. Morgan, A.G. McCombs, P.K. Hall, R.A. McPherson, Quality assurance procedures for mesoscale meteorological data, Journal of Atmospheric and Oceanic Technology 27 (2010) 1565–1582. https://doi.org/10.1175/2010JTECHA1433.1.

[55] M.J. Menne, C.N. Williams, M.A. Palecki, On the reliability of the U.S. surface temperature record, J. Geophys. Res. 115 (2010) D11108. https://doi.org/10.1029/2009JD013094.

[56] S.W. Grab, C.K. Gatebe, A.M. Kinyua, Ground thermal profiles from Mount Kenya, East Africa, Geografiska Annaler: Series A, Physical Geography 86 (2004) 131–141.