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METEOROLOGICAL MEASUREMENTS IN MOUNT KENYA REGION, IMPORTANCE OF QUALITY CONTROL, PREPARATORY STEPS AND CALIBRATION

Peter K. Musyimi [(1, 2)], Balázs Székely [(1)], Tamás Weidinger [(3)]

[(1)] ELTE Eötvös Loránd University, Institute of Geography and Earth Sciences, Department of Geophysics and Space Science, H-1117 Budapest Pázmány Péter sétány 1/C, Hungary
[(2)] Karatina University, Department of Humanities and Languages, Karatina, Kenya
[(3)] ELTE Eötvös Loránd University, Institute of Geography and Earth Sciences, Department of Meteorology, H-1117 Budapest Pázmány Péter sétány 1/A, Hungary

Abstract. Quality-controlled datasets are a foundation and a conduit for real results from any set scientific objectives. The purpose of this paper was to emphasize the importance of quality checks and preparatory steps of any scientific data in the context of meteorological variables and measurement. The motivation to make measurement was necessitated by a desired effort to develop new database in Kenya, critical for data driven decisions in analysis The instruments were set up in Mount Kenya region at 1998 m, Karatina University weather station, and 3050 m above sea level, Mackinders Campsite at the rainforest biome. After careful examination and interacting with meteorological data from synoptic stations for our study as well as meteorological measurements from Karatina University weather stations, we realised the importance of new effort for climate variables measurements. Data gaps identified required filling in missing data (data filling) and correcting various errors such as values outside the acceptable value limits. Preparatory steps were undertaken to thoroughly check for synop errors and fix data errors identified (data cleaning). Variables measured and undergoing measurement include temperature, relative humidity, soil temperature, and soil moisture data using data loggers as well as Temperature-Moisture-Sensor (TMS) loggers. This made us raise critical questions for scientists to ponder before the start of any analysis which include: should we just analyse raw data without quality check; should we consider meteorological measurement of data enough; how effective are the instruments. However, even though the optimal solution to quality data would be to obtain direct field measurements, quality control, checks, and assurance should be the second-best step in scientific involvement.

Introduction

The quality of data in scientific research is fundamental because it has a direct link and influence on the intended expected outcome and/or results. The WMO[1] (2021) has provided principles and guidelines for quality control of data at the weather station level. Faybishenko et al. (2022) indicate that the accuracy of analysis, results, and predictions are influenced by the quality of collected meteorological data. Even though, the climate parameters and elements vary in space and time, i) a concerted effort and time should be put in place to fill identified data gaps and/or ii) fill missing data (data filling) as well as iii) fix data errors identified (data cleaning) (Cerlini et al., 2020) and iv) correct all errors, uncertainties, and erroneous values identified (Zahumenský, 2004) through data checks after downloading or measurements. The errors should then be flagged before any further processing (Halida & Pramono, 2021).

Data quality, control, and assurance are critical steps that should be available in any scientific process: without these steps of dataset check, quality assurance, etc. expected

[1] World Meteorological Organisation

outcomes and/or results cannot be achieved. According to Bell (2001), it is always important to examine data measurement uncertainties, which helps diagnose probable existing errors as indicated by Andresen et al. (2002), Zahumenský (2004), and Cerlini et al. (2020), which include micrometeorological errors, random errors, and systematic errors, internal consistency, homogeneity, gross error limit check among others. Then, the diagnosis gives room for correcting and filling the gaps. Other sources and types of errors as outlined by WMO (2021) include the start time of the error; the end time of the error; measures taken to mend the error and whether the error has caused any data gaps, and in addition, how the identified errors were dealt. After correction and data gap filling, a quality database is created, which can be considered clean for analysis processes. According to Snyder et al. (2013), poor quality data is less useful, and therefore, without a doubt, quality control of data, and quality assurance is an indispensable step that should form the basis of any step of start-up analysis. Faybishenko et al. (2022) note that there should be data exploration steps that involve the processing of raw datasets, harmonizing datasets of different characteristics, and identifying duplicates, outliers, and extremes. This initiative minimizes errors or instrument errors and eventually helps the researcher to acquire a valid dataset (Halida & Pramono, 2021) that can be subjected to further processing, which can reduce biases (Beele et al., 2022).

Overall, the datasets must be examined through quality control management to serve the scientific and practical purpose and produce expected results that are clear for decision-making and proper planning of fields/sectors of interest, for instance, agriculture, air pollution, water, and climate valuable to progress and prosperity of a countries/nations economic growth. Raw data will be integrated to larger databases and erroneous components (missing values, data expressed in other units, etc.) will decrease the value and usability of the encompassing database and will potentially propagate to derivative works. Comparisons of different datasets can as well form a basis for quality data checks. Comparison of climate parameters can be done, for instance, ERA5 gridded dataset (Hersbach et al., 2020), the synoptic data set [1 – Meteomanz], and field measurement, for instance, the dataset from Karatina University weather station in Kenya. This is indispensable because it forms a system and coordinated system of instrument measurements, hence the development of a commonality of data checks and quality necessities and requirements. This is because according to Andresen et al. (2002), the outcome of the quality control must be disseminated to end-users, and further, the data-driven results would be best in data-driven decision for decision-makers and planning of a country, state, and/or nation economic sectors.

Goal and objectives of the study

The main goal of carrying out meteorological measurements in Kenya was to form a foundation for practical and field work for students pursuing geography and environmental studies at Karatina University and start a meteorological database measurement at Karatina University in collaboration with ELTE Eötvös Loránd University for future collaborative studies on evapotranspiration, soil science, and mountain ecology in understanding microclimate in humid regions of Kenya. This new effort involves dataloggers and soil moisture sensors, where pretesting was done at Lágymányos HMS[2] Station (Budapest) before real measurement at Karatina University weather station at an elevation of 1998 m above sea level and at an elevation of 3050 m above sea level at the Mackinders Camp site at Mount Kenya rainforest biome. The objectives of the study include identification of errors and gaps in meteorological measurements, testing the functionality of the new instruments at Lágymányos HMS Station, compare the results of the new soil moisture sensor with HMS

[2] Hungarian Meteorological Service

data and analyse preliminary results, set up the new instrument at the measurement site at Karatina University weather station and analyse preliminary results as well.

Quality Control, Quality Assurance, Gap Filling and Cleaning of Datasets

Data with 3-hour time resolution was downloaded from arid, and semi-arid conditions in Taita-Taveta County (Voi weather station) and Garissa County (Garissa weather station), and savannah tropical regions in Mombasa County (Mombasa weather station) with elevations between 57 m to 579 m above sea level. Data was also downloaded from humid Kenya highlands (> 1350 m), Trans-Nzoia, Nyeri, and Embu counties (Kitale, Nyeri, and Embu synoptic weather stations) and arranged into datasets from 2000–2022 [1 – Meteomanz]. The methodology of linear interpolation was used to check if the missing measurement periods were shorter than 12 hours. The mean daily course of the meteorological elements combined with the measured variables before and after the data gap was used for longer missing periods. If the lack of data was between 0.5 day and 5 days, then the missing period was replaced with the average daily course from the date of the days (1 or 2 depending on the length of the data gap) before and after the missing period. Of course, it is a semi-empirical method. The measured and gap-filled periods have been aligned during the initial and final 12 hours of the data-deficient period with a linear approximation. Errors in the SYNOP messages (for instance bad digits, time inconsistency) were also filtered in the temperature, relative humidity, pressure, wind speed, direction, and time series from the online database [1 – Meteomanz] based on our Visual Basic macro. The quality-assured database was arranged in Excel tables. After the data set was clean, the next step of analysis begins. The simple steps of the whole procedure shown (*Fig. 1*) can be used as a guide for quality control of data.

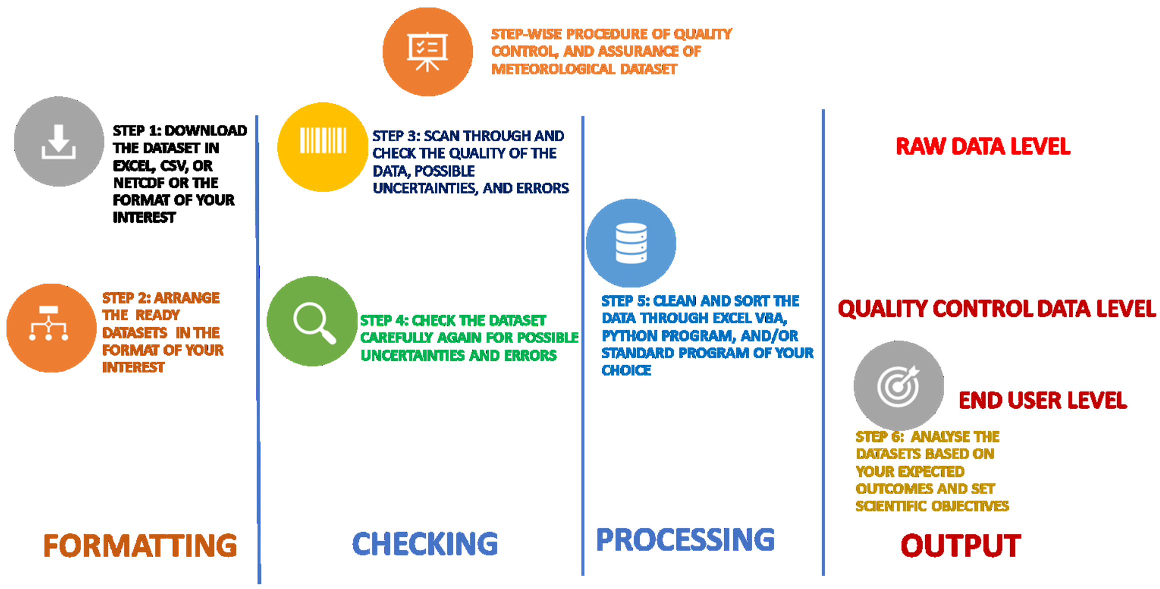

Figure 1: Stepwise procedure (scheme) of quality control of meteorological datasets.

Instrumentation

TMS sensors

The instruments used included one TMS[3] Burial (100 cm) Soil Sensor no. TMS 94249183, and two TMS Long (45 cm) Soil Sensors no. TMS 94249182 and no. TMS 94249181. The

[3] Temperature-Moisture-Sensor

sensors measure soil moisture and temperature in a depth of +15, +2, and –6 cm relative to the ground level for the TMS Long (45 cm) [2 – Tomst]. The soil sensors are equiped with thermometers, which measure temperatures at three mentioned levels that is T3 (Top of the sensor), T2 (Grass surface), T1 (Below the surface) as shown in *Fig. 2*.

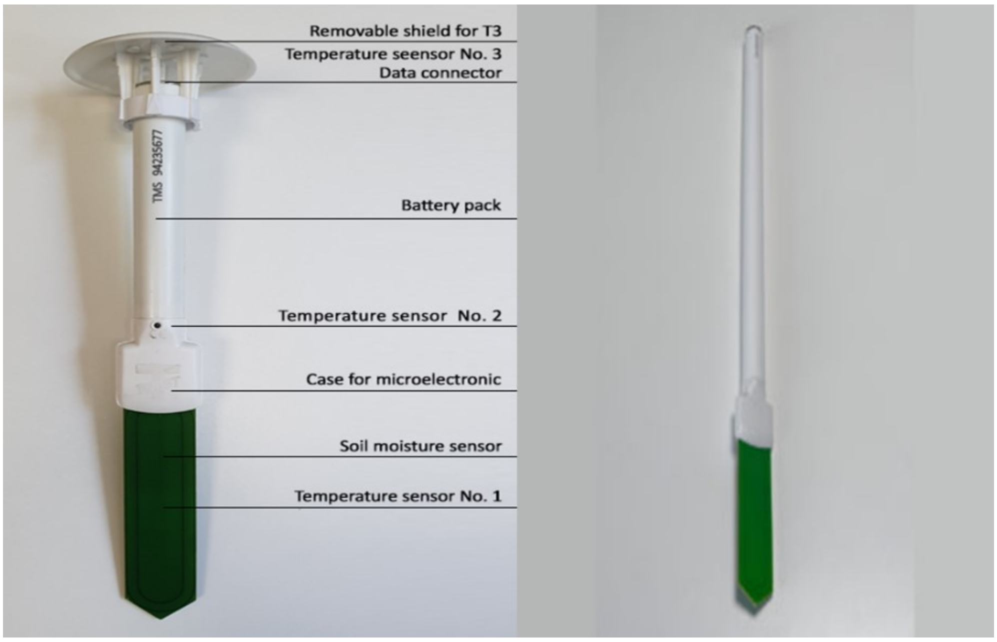

Figure 2: Description of TMS [3 – Tomst].

The TMS data is extracted using the Lolly software [3 – Tomst]. Prior testing was performed at ELTE Lágymányos HMS station (WMO ID no. 44505). After, the planned measurements were carried out at the Karatina University weather station site consisting of two soil moisture loggers, TMS Long (45 cm) and TMS Burial (100 cm), while sensor no. TMS 94249181 (TMS Long) was set up at the Mackinders camp site at Mount Kenya rainforest biome. The TMS is designed for long-term meteorological data acquisition in diverse environmental conditions. As indicated by Wild et al. (2019) and [2 – Tomst] the time is in UTC, a resolution of 0.0625 °C and an accuracy of ±0.5 °C within a range of measurement of −40 °C to +60 °C.

Data logger (DL-121TH)

The measurements of meteorological parameters, as well as field measurement campaigns, were started at Mount Kenya region. This was objectively aimed at stating a consistent database of temperature, relative humidity, and dewpoint. The data loggers manufactured by CONRAD manufacturer, no. DL 121TH (pseudo names P1 and P2) measures the three commonly used climate parameters, which include temperature (ºC), dew point (ºC), and relative humidity (%) within a temperature measurement range of −40 ºC to 70 ºC, temperature accuracy ±1 ºC (0 to 40 ºC), dew point accuracy of ±2 ºC at 25 ºC, and measurement range of 0 to 100% for relative humidity with a resolution of 0.1 ºC for temperature and 0.1% relative humidity. The measuring interval is from 2 s to 24 h. Our data loggers were set at an interval of 30 min to save on battery life.

Preliminary test and real measurements

Preliminary testing of the functionality of the instruments was carried out at ELTE Lágymányos HMS station (WMO ID no. 44505) before they were taken to Kenya for actual measurements. The three soil moisture sensors used were one TMS Burial (100 cm) Soil Sensor (one soil temperature and one soil moisture measuring point), two TMS Long (45 cm) Soil Sensors, and a TMD adapter for data extraction. The instruments were set up at the ELTE Eötvös Loránd University weather station (*Fig. 3)*. The three sensors and two data loggers (temperature/relative humidity) were first placed in the instrument shelter (*Fig. 3A*) and later installed for four days from 2022-12-09 to 2022-12-13 (winter season) and inserted to the ground to acquire initial data.

(*A*) (*B*)

Figure 3: (*A*) Data loggers and TMS sensors in the instrument shelter of the ELTE Lágymányos HMS station (WMO ID No. 44505).
(*B*) a and b are TMS Long (45 cm) sensors, while c is TMS Burial (100 cm) all set in soil for testing of the functionality in data acquisition at the ELTE Lágymányos HMS station (WMO ID No. 44505) (winter season).

Comparisons of grass surface (T2) temperature, and soil temperature at 5 cm deep were made from the data collected from the TMS (45 cm) soil moisture sensors that is T2 (grass surface temperature), and T1, the temperature at –6 cm deep for the soil moisture sensors and –5 cm from HMS station. Thereafter, the instruments were taken to the stations, Karatina and Mackinders campsite in Mount Kenya in Kenya for micrometeorological measurements (*Figs. 4* and *5*).

Figure 4: Karatina University weather station, 1998 m above sea level.

Figure 5: Mount Kenya meteorological station at Mackinders campsite, 3050 m above sea level, the TMS sensor no. 94249181 inside a wire cage (superimposed) set up at Mount Kenya rainforest biome.

Raw soil moisture data was measured in TMS signal raw. Therefore, calibration was performed, which converted the raw counts into VWC[4], in m^3/m^3, the ratio between water volume and total soil volume (Datta et al., 2017; Van der Keijl, 2023). The calibration was performed using Kopecký et al. (2021) equation to approximately convert raw soil moisture counts to VWC as shown in *Eq. (1)*:

$$VWC \approx -1.340 \cdot 10^{-8} \cdot TMS^2 + 2.496 \cdot 10^{-4} \cdot TMS - 0.158 \qquad (1)$$

where *TMS* is the signal raw soil moisture count.

Results and discussions

Identified errors and gaps from synoptic data and field measurement

From the preparatory steps of checking, an exploration of values outside the limits of the acceptable value was identified and hence deemed as erroneous (*Table 1*). Repeated values (*Table 2*) that is temporal repetition (the same/homogenous variable at the same synoptic station measured thrice) were also deemed major errors. As indicated by Zahumenský (2004), consistency checks are also very important in quality check and control of data (Halida & Pramono, 2021). *Tables 3* and *4* show missing data (shaded cells by yellow) from synoptic stations and weather station levels, respectively.

Table 1: Error: higher value of minimum temperature (°C), outside the acceptable limit, is highlighted in red.

Date	Ave. T. (°C)	T. max (°C)	T. min (°C)
2015-12-08	31.8	31.2	32.4

[4] Volumetric Water Content

Table 2: Error: identical values of average temperature (°C), maximum temperature (°C), minimum temperature (°C) [1 – Meteomanz].

Date	Ave. T. (°C)	T. max (°C)	T. min (°C)
2011-07-26	29.4	29.4	29.4
2013-09-28	29.5	29.5	29.5
2015-07-31	29.4	29.4	29.4
2016-04-05	29.5	29.5	29.5

Table 3: Error (shaded by yellow): missing data (requires data filling) of average temperature (°C), maximum temperature (°C), minimum temperature (°C), pressure (hPa), wind speed, and cloud cover (okta) [1 – Meteomanz].

Date	Ave. T. (°C)	T. max (°C)	T. min (°C)	Pressure (hPa)	Wind Speed (Km/h)	Cloud C.
2010-01-15	26.4	31	21.8	1015.5 hpa	9	5/8
2010-01-16						
2010-01-17						
2010-01-18						
2010-01-19	25.9	30.7	21.1	1015.5 hpa	18	5/8

Table 4: Error (shaded by yellow): missing data (requires data filling of climate parameters), Atmospheric pressure (kPa), Precipitation (mm), Solar radiation (W/m^2), Relative humidity (decimal). Source: Karatina University weather station, Kenya.

Date	Time interval	Atmospheric pressure (kPa)	Precipitation (mm)	Solar Radiation (W/m^2)	Relative humidity (-)
2021-07-01	6:50	80.87	0	63	0.639
2021-07-01	6:55				
2021-07-01	7:00				
2021-07-01	7:05	80.86	0	97	0.622
2021-07-01	7:10	80.86	0	104	0.614
2021-07-01	7:15	80.86	0	108	0.675

Furthermore, other identified errors were wrong values automatically detected by TMS sensors specifically when downloading the data. These errors were corrected by our interpolation program using VBA[5] as WMO (2021) indicates that quality control processes may vary in application, manually, automatically, or semi-automatically at each step.

Test results from the ELTE Lágymányos HMS weather station

Preliminary results of the initial data measurements from TMS Long (45 cm) show that the mean temperature was 4.6 ± 1.4 °C, 2.2 ± 2.4 ºC, 1.8 ± 2.8 ºC, for T1(–6 cm, below the surface), T2 (Grass surface), and T3 (Top of the sensor), respectively, while raw soil moisture (TMS) was 2324.0 ± 90.6 (unitless) and VWC was 0.35 ± 0.01 m^3/m^3. The distribution of calibrated soil moisture and trend of VWC is shown in *Fig. 6,* while the distribution of the three temperatures, T1, T2, and T3 is shown in *Fig. 7,* which clearly demonstrates slight variation in skewed distribution.

[5] Visual Basic for Applications

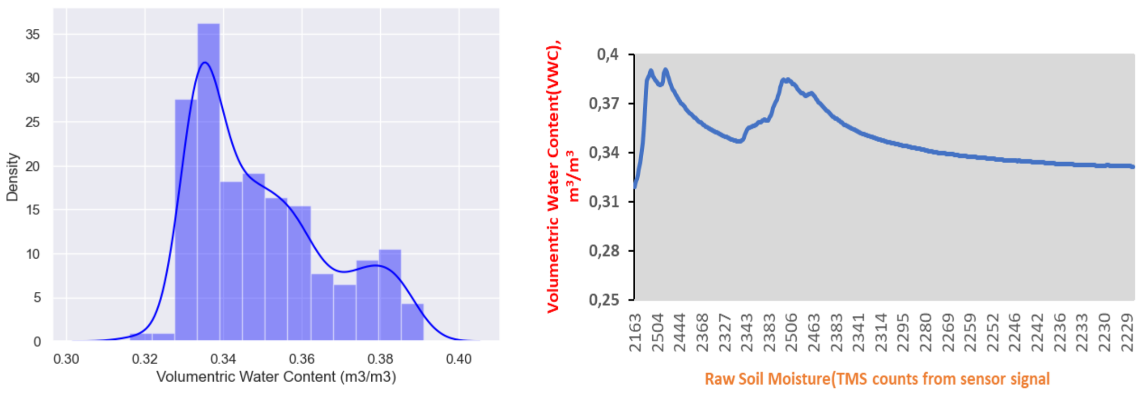

Figure 6: Distribution of soil moisture (left) and the variability of soil moisture, VWC (right) against the raw soil moisture, TMS counts at an interval of 10 min from preliminary testing from TMS Long (45 cm) carried out at ELTE Lágymányos HMS station (WMO ID No. 44505) at an interval of 10 min.

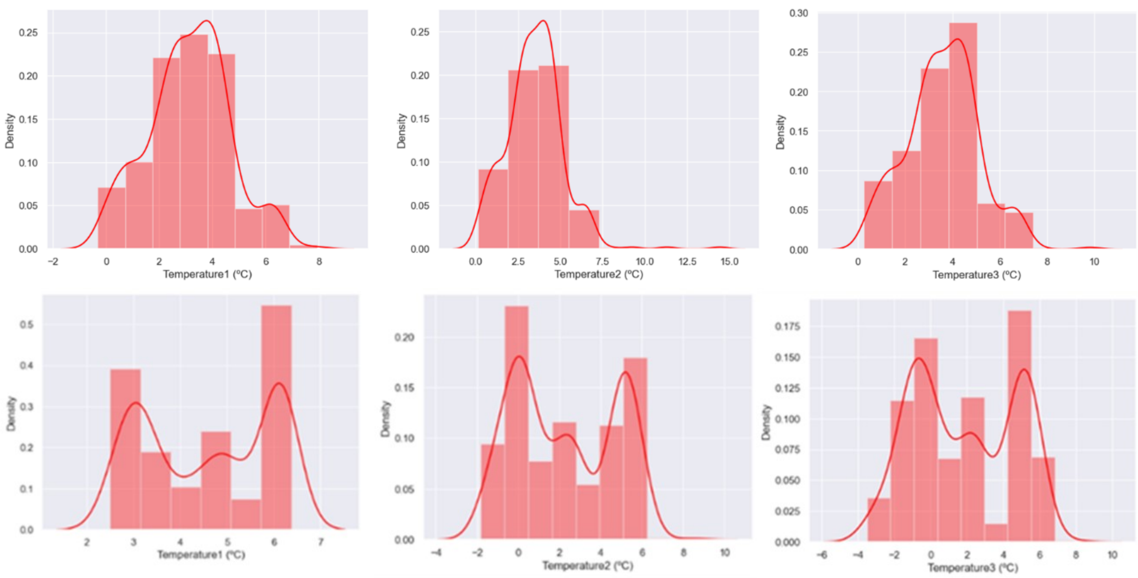

Figure 7: Distribution of T1, T2, and T3 from TMS Long (45 cm) no. 94249182 from preliminary testing of the sensors and the instrument shelter (top panels) and after inserting in the soil (bottom panels) carried out at ELTE Lágymányos HMS station (WMO ID No. 44505) in the winter season.

Comparison of soil temperature data with measurements from Lágymányos HMS Station

Results from the ELTE Lágymányos HMS station (WMO ID no. 44505) indicated that the mean grass temperature was 1.6 ± 2.8 ºC for the grass surface temperature and 4.6 ± 1.4 ºC for the soil temperature at -5 cm deep. The results were of the same dates (four days from 2022.12.09 to 2022.12.13) and the same time interval (10 min), when we installed soil moisture sensors for testing and acquisition of the initial data. The mean actual temperature was 1.8 ± 2.7 ºC. There was a slight variation in the results from TMS (45 cm) long moisture sensors and data from the HMS where the mean grass surface temperature (T2) from TMS Long (45 cm) was 2.2 ± 2.4 ºC, while from HMS was 1.6 ± 2.8 ºC. Soil temperature from the TMS (45 cm) long sensor at –6 cm deep (T1) was 4.6 ± 1.6 ºC, which was also interestingly like the mean soil temperature at –5 cm deep from HMS data with a mean value of 4.6 ± 1.4 ºC. The daily variation from 10 min interval for both T1 and T2 from HMS and from the new TMS sensor is shown (*Figs. 8* and *9*) demonstrates that similar patterns in trend and variation. Similarly, both T1 and T2 from the two data sets shows same direction and strong relationship (*Fig. 10*).

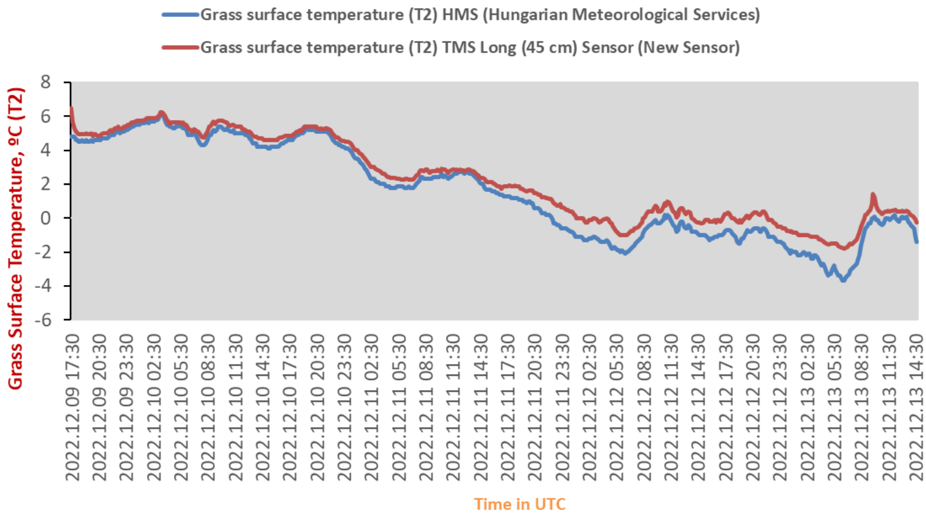

Figure 8: Daily variation of grass surface temperature (T2) from HMS and from the new TMS (45 cm) sensor no. 94249182 now set up at Karatina University weather station.

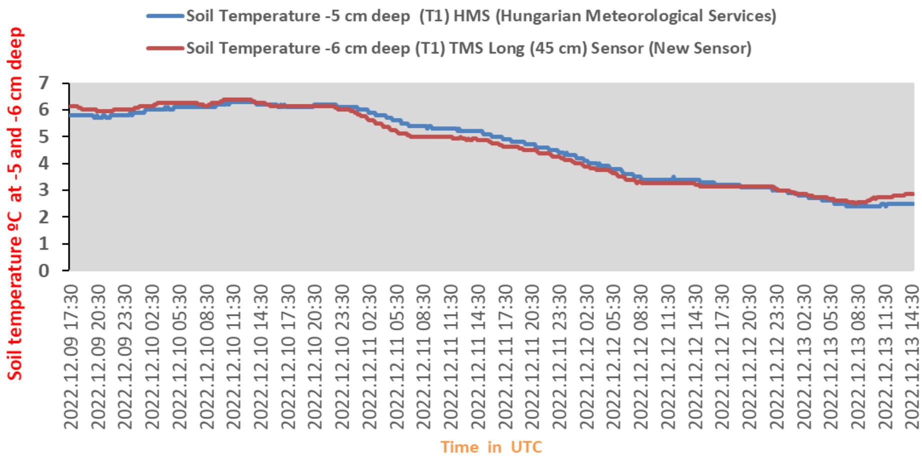

Figure 9: Daily variation of below surface temperature (T1) at –5 cm and –6 cm from HMS and from the new TMS (45 cm) sensor no. 94249182 now set up at Karatina University weather station, respectively.

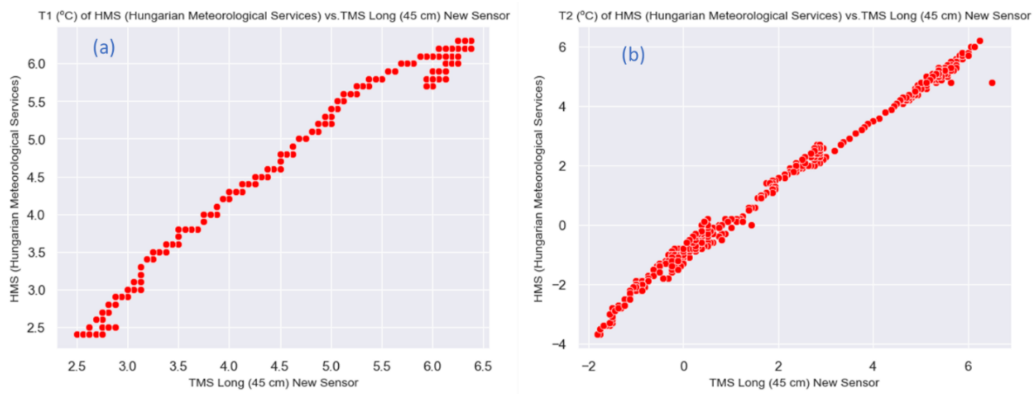

Figure 10: (a) Scatter plots of T1 (ºC) from HMS (–5 cm) vs new TMS (45 cm) sensor (–6 cm) and (b) T2 (ºC), grass temperature from HMS vs new TMS (45 cm) sensor no. 94249182.

Results at Karatina weather station

Preliminary results of the measurements from TMS Long (45 cm) show that the mean temperature (measured with an interval of 10 min) for the period from January 25th to July 20th, 2023, was 18.2 ± 1.5 ºC, 17.2 ±4.1 ºC, 16.5 ±5.1 ºC for T1, T2, T3, respectively, while raw soil moisture was 2210 ± 510.3 (unitless). Results from TMS Long Burial (100 cm) show that the 10 minutes (meteo mode) mean temperature was 17.5 ± 0.7 ºC, T (at –100 cm level), while raw soil moisture was 2124 ± 68.4. The VWC against the raw soil moisture raw counts is demonstrated in *Fig. 11*. The results show that the higher the soil moisture, the lower the temperature, which conforms with Schwingshackl et al. (2017), who indicated that soil moisture plays a great role in indirectly inducing a decrease in surface temperature through incoming net radiation partitioning into latent and sensible heat flux. This may happen mostly during the daytime due to the incoming short-wave radiation since at night soil releases outgoing long-wave radiation, which practically does not influence the latent and sensible heat flux as also observed by Davis et al. (2019). These meteorological measurements are of great importance to solving societal weather-related challenges and overcoming obstacles amicably, for instance, climate adaptation barriers in the current regime of climate change (Wild et al., 2019). Similar measurements, investigations, and studies using the TMS sensors have been carried out in Europe (Koukol et al., 2022), in Arctic tundra-characterized regions (von Oppen et al., 2022), as well as forests of British Columbia, Canada (Smith-Tripp et al., 2022) and in Swedish coniferous forest by Van der Keijl (2023).

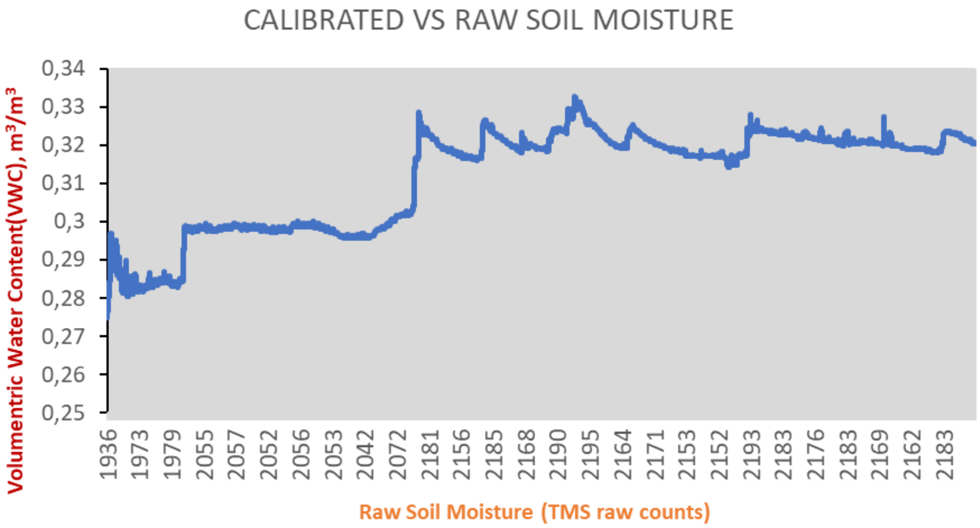

Figure 11: Variability of TMS Long Burial (100 cm) VWC from Karatina University weather station, 1998 m above sea level.

From the TMS Long (45 cm), the relationship and distribution depicted the same patterns as the TMS Long Burial (100 cm) with slight variations. During the dates of downloading of soil moisture data, erroneous values were recorded as shown in *Fig. 12a*. The values below 0.1 m^3/m^3 occurred on 2023-02-24, 2023-04-20, and on 2023-07-20, when the measured data was downloaded. After quality checking and correcting the errors, we were able to plot the VWC (calibrated) against the Soil moisture Counts (Raw signal soil moisture data) (uncalibrated) in *Fig. 12b*, and we demonstrated the seasonal daily variation in *Fig. 12c*.

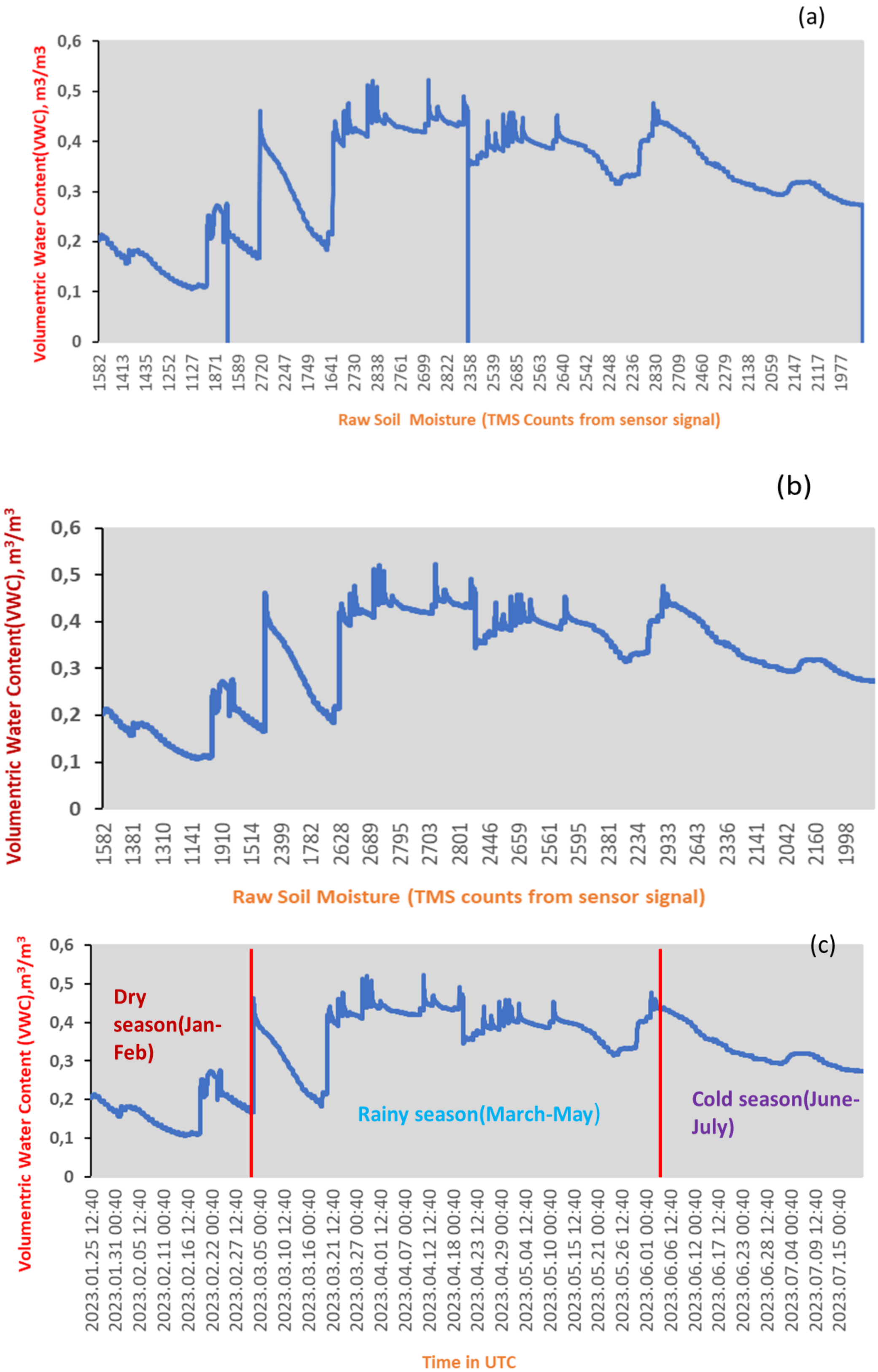

Figure 12: TMS Long (45 cm) data logger/sensor soil moisture taken at an interval of 10 min, a) without quality check, b) after quality control, and, c) seasonal daily VWC variation from Karatina University weather station, 1998 m above sea level.

Results from data loggers, relationship between temperature and humidity

The mean values of 30 min measurements for the period from February 2023 to July 2023 were 16.0 ± 3.3 ºC, 12.9 ± 2.2 ºC, and 83.0 ± 10.4%, for temperature, dew point, and relative humidity, respectively. From *Fig. 13a*, there is an indication that the moisture amount that the air can hold increases as the relative humidity of the air decreases, which concurs with a study by Van der Keijl (2023). This reveals an inverse relationship between temperature and relative humidity. The increase in temperature depicted an increase in dew point (*Fig. 13b*).

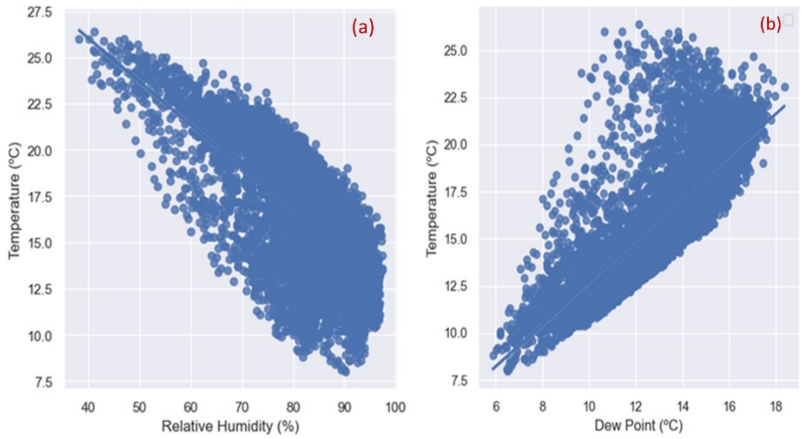

Figure 13: (a) Relationship of temperature (ºC) and relative humidity (%), and (b) the relationship between temperature (ºC) and dew point (ºC) at a height of 2 m from measurements at Karatina University weather station measured at an interval of 30 min, 1998 m above sea level.

The relationship between variables and the distribution of independent variables was examined to understand their variability in the period of measurement (*Fig. 14*).

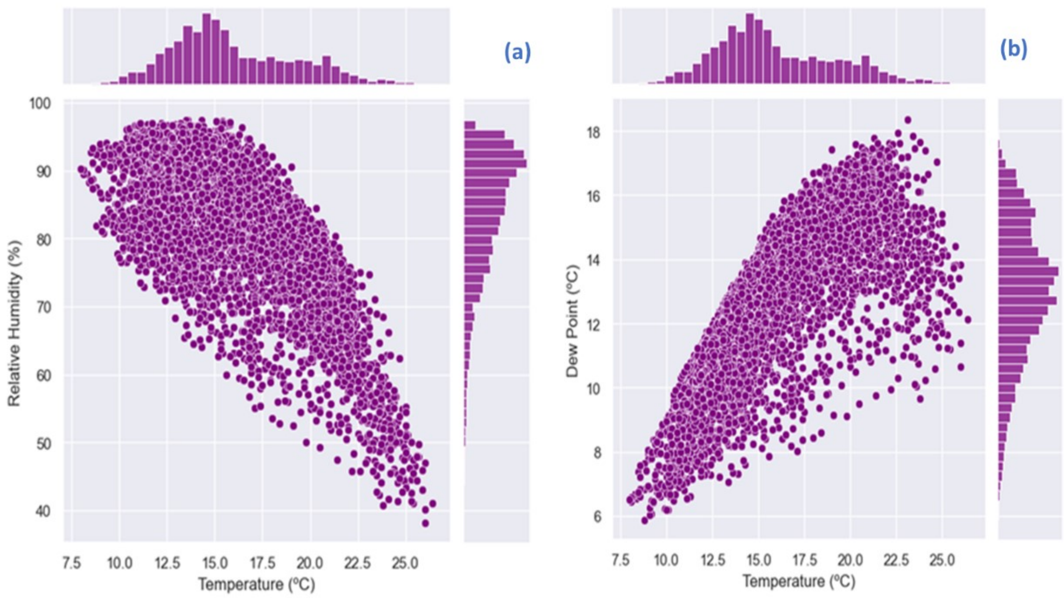

Figure 14: Relationship between the variables, (a) temperature (ºC) and relative humidity (%) together with their distributions, and (b) the relationship between temperature (ºC) and dew point (ºC) together with their distributions, from the measurements at Karatina University weather station measured at an interval of 30 min, 1998 m above sea level.

The distribution of variables, temperature, dew point, and humidity showed temperature varied with relative humidity in an inverse relationship. This observation is critical in every stage of crop growth, because according to Lin (2007) temperature is a key climate parameter for crops since high or low temperatures can influence yield. The plot on top of *Fig. 14a* showed a left-skewed distribution of temperature (i.e. higher frequency with smaller values), while the plot on the right of *Fig. 14a* showed a right-skewed distribution of relative humidity (i.e. higher frequency with higher values).

Conclusions

The paper presents the errors identified from raw meteorological data and field measurements. It emphasizes the importance of quality control of data. It provides an interpolation method that was used to fill in the missing data and correct the extremes, duplicates, and outliers identified using data check and exploration. Furthermore, it provides preliminary results from meteorological measurements started in Kenya as an optimal solution to the scarcity of climate data.

Soil temperature (in Lágymányos ELTE Campus, 2022 December) from the TMS (45 cm) long sensor at –6 cm deep (T1) was 4.6 ± 1.6 ºC, which was also almost the same as the mean soil temperature at –5 cm deep from HMS data with a mean value of 4.6 ± 1.4 ºC. Daily variation and cycles of below the surface temperature and grass surface temperature from HMS and the new TMS sensor demonstrated similar patterns with very slight differences.

Karatina University weather station measurements results from TMS Long (45 cm) show that the 10 minutes mean temperature for the period from January 25th to July 20th, 2023, was 18.2 ± 1.5 ºC, 17.2 ± 4.1 ºC, 16.5 ± 5.1 ºC for T1, T2, T3, respectively, while raw soil moisture was 2210 ± 510.3. Results from TMS Long Burial (–100 cm) show that the 10 minutes (meteo mode) mean temperature for the period from January 25th January to July 20th, 2023, was 17.5 ± 0.7 ºC, T (at –100 cm level) while raw soil moisture was 2124 ± 68.4. Data logger results showed that the 30 minutes interval mean values for the period were 16.0 ± 3.3 ºC, 12.9 ± 2.2 ºC, 83.0 ± 10.4% for temperature, dew point, and relative humidity, respectively.

The paper emphasizes data quality checks for meteorological measurements for any scientific research for geography, environment, and earth sciences-related disciplines for experts, i.e., meteorologists, and climatologists. It can be used to enrich the practical and field work aspects in geographical curriculum, earth science, and environmental studies education.

Acknowledgement

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ORCID

Musyimi P.K. https://orcid.org/0000-0003-4165-8565
Székely B. https://orcid.org/0000-0002-6552-4329
Weidinger T. https://orcid.org/0000-0001-7500-6579