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EVALUATING THE PERFORMANCE OF PALMER DROUGHT SEVERITY INDEX (PDSI) IN VARIOUS VEGETATION REGIONS OF THE ETHIOPIAN HIGHLANDS

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Abstract: This paper focuses on the environment of Ethiopia, a country highly sensitive to droughts severely affecting vegetation. Vegetation monitoring of Ethiopian Highlands requires visualization of environmental parameters to assess droughts negatively influencing agricultural sustainable management of crops. Therefore, this study presented mapping of several climate and environmental variables including Palmer Drought Severity Index (PDSI). The data were visualized and interpreted alongside the topographic data to evaluate the environmental conditions for vegetation. The datasets included WorldClim and GEBCO and Digital Chart of the World (DCW). Research has threefold objectives: i) environmental mapping; ii) technical cartographic scripting; iii) data processing. Following variables were visualized on seven new maps: 1) topography; 2) soil moisture; 3) T °C minimum; 4) T °C maximum; 5) Wind speed; 6) Precipitation; 7) Palmer Drought Severity Index (PDSI). New high-resolution thematic environmental maps are presented and the utility of GMT for mapping multi-source datasets is described. With varying degrees of soil moisture (mean value of 15.0), min T°C (-1.8°C to 24°C), max T°C (14.4°C to 40.2°C) and wind speed (0.1 to 6.1 m/s), the maps demonstrate the variability of the PDSI fields over the country area (from -11.7 to 2.3) induced by the complex sum of these variables and intensified by the topographic effects notable over the Ethiopian Highlands which can be used for vegetation analysis. The paper presents seven new maps and contributes to the environmental studies of Ethiopia.

Keywords: cartography; vegetation; drought; PDSI; precipitation; soil moisture; temperature.

1. Introduction

Drought, severely affecting vegetation, is caused by the shortage in water supply. It has twofold factors: atmospheric origin (precipitation), and soil moisture (surface water). There are many controlling factors which determine the distribution of drought, including atmospheric (precipitation, temperature, intensity and direction of winds), geological (soil moisture, permeability of subsoils), and hydrological (dense of river network and intensity of streams). Visualizing spatial patterns of droughts is crucial for the environmental monitoring of the region with such contrasting climate setting as Ethiopia. Although the duration drought may vary from several days to months or years, its environmental, agricultural and social consequences may have a substantial impact on both nature ecosystems and human existence through the affected agricultural regional economy. Ethiopia is a country with sensitive climate environmental setting, contrasting topography, unique geologic parameters (location of the Afar Triple Junction and distribution of the part of the East African Rift System and Great Rift Valley), **Fig. 1**. The complicated combination of the climatic and topographic factors results in notable drought disasters, recorded in the Somali, the Afar Depression (geological region of the Afar Triple Junction), deserts and lowland regions as the area most affected by droughts. With a focus on visualizing the drivers of drought in Ethiopia, this paper presents a series of maps on current environmental-climate setting of Ethiopia with aim to demonstrate why drought is distributed in a certain correlation with topographic relief, a question which is of interest to the environmental monitoring in Ethiopia. Since humans are dependent upon climate setting, environmental conditions and ecosystems for agricultural production and services, regular updated climate monitoring is essential not only for the physical geographic but also for the social studies, which explains and justifies the actuality of the undertaken research.

Agricultural problems caused by drought include a variety of processes. The most significant agricultural consequences include crop failure (Edossa et al., 2010; Suryabhagavan, 2017), soil and pasture losses (Tora et al., 2021; Mihretie et al., 2021) in vulnerable regions of Ethiopia. The direct economic and social issues include famine and diseases (Gebre et al., 2021), physical and mental health strain and children's health (Bahru et al., 2019; Dimitrova, 2021).

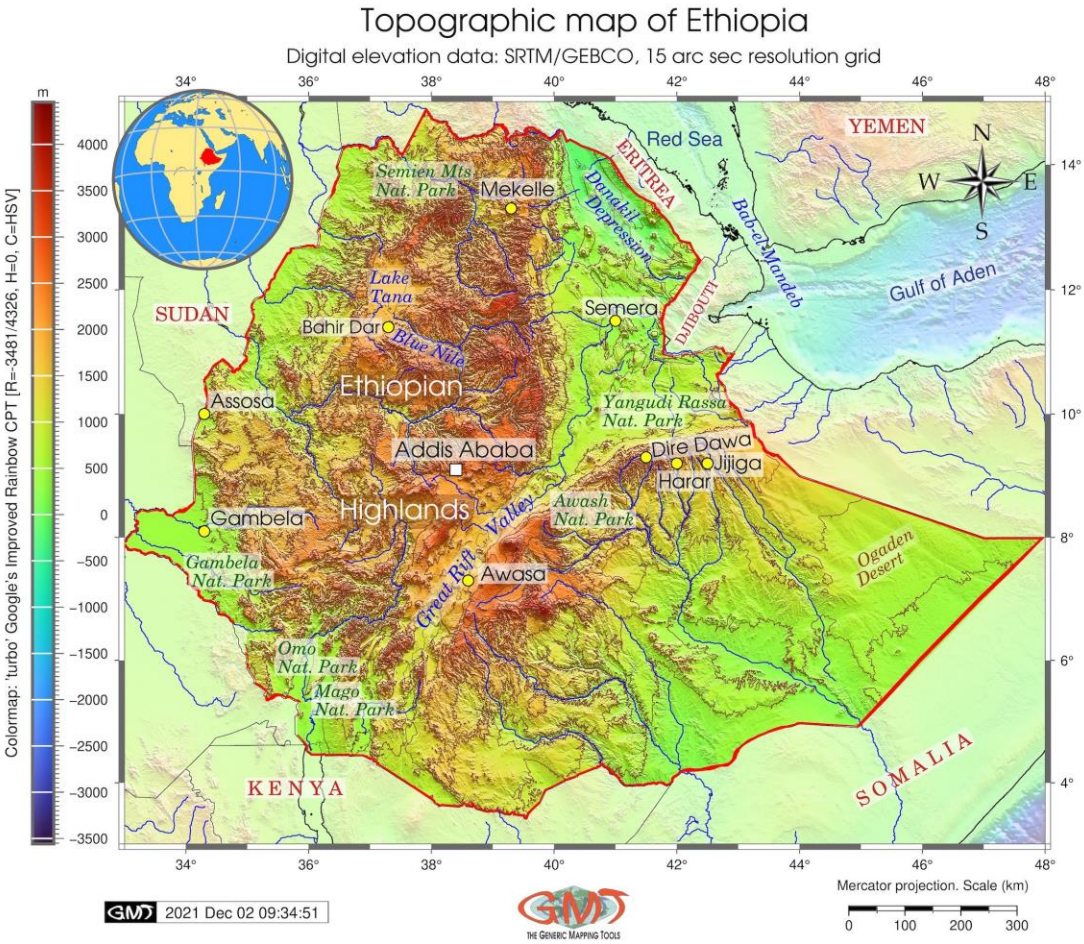

Fig. 1. Map of the study area. Mapping: GMT. Data: GEBCO, DCW. Source: author

Furthermore, drought leads to the increased costs of food for consumers in economic sector and decrease in cattle population (Aragie and Thurlow, 2022). The indirect yet important consequence of drought includes broken supply chains in industry and production: reduced supplies to food processors, demand for fertilizer and farm labor.

The environmental consequences of drought include direct affect on the vulnerable species, such as fruits, flowers, vegetables, tree nuts, and medicinal herbs that are more sensitive to droughts compared to the field crops (Di Falco et al., 2010). Biodiversity consequences include a high risk for losses in species diversity of rare species if the water demand exceeds water supply (Legesse and Negash, 2021). The depletion of water in soils causes significant declines in vegetation productivity and growth of roots (Demelash et al., 2021) that finally affects biodiversity and ecosystems. This is caused by the deficit of water in surface and groundwater that declines during drought period, affecting water availability necessary for normal functionality of plants.

The aim of the present study is to plot a series of maps showing visualized computed index of droughts (Palmer Drought Severity Index, PDSI), and several supporting meteorological, topographic, climate and environmental data of Ethiopia using high-resolution datasets by technical tools of Generic Mapping Tools (GMT) cartographic scripting toolset. Besides environmental assessment and visualization, this paper discusses a GMT-based approach to prepare a series of meteorological maps of Ethiopia using a scripting approach. The presented maps visualize the following environmental variables in Ethiopia in 2018: 1) topography; 2) soil moisture; 3) T °C minimum; 4) T °C maximum; 5) Wind speed; 6) Precipitation; 7) Palmer Drought Severity Index (PDSI). The presented paper serves the threefold research objectives:

i. Contributing to the environmental and climatic studies of Ethiopia through the visualized new seven thematic maps;

ii. Presenting new approaches of scripting tools for technical developing of the contemporary cartography;

iii. Utilizing multi-source datasets from the open repositories showing the application of the multi-source data in the environmental-climate research. The actuality of present study consists in the presented maps visualizing meteorological and climate parameters. Those are necessary for environmental monitoring of the country and assessment of climate change and its possible effects. Among other variables, this paper demonstrates the visualized map of the Palmer Drought Severity Index (PDSI), an index developed by Palmer in 1965 and widely used in various aspects of the environmental monitoring, e.g. as follows:

(a) to assess climate and environmental changes;

(b) to perform ecological monitoring;

(c) to complete climatic divisions for measurements of the hydrologic drought and to indicate severe or extreme drought using PDSI values (Alley, 1985).

The PDSI is the most widely used in climatology regional index of drought which enables to quantify intensity and period of droughts (start/end time) for the global long-term drought analysis (Alley, 1985). In computations of PDSI, we need to estimate the precipitation and temperature for the measurement of dryness (Dai et al., 2004).

Theoretically, the drought should be estimated based on the 'supply-and-demand' properties of soil moisture of the study area which includes such complex parameters as evapotranspiration reflecting the 'demand' of soil, i.e. the need for water (Ficklin et al., 2015).

The PDSI presents an approximated and straightforward model of the drought calculation based only on precipitation and temperature. The PDSI is a standardized measure, ranging from about -10 (extreme drought) to +10 (extreme moisture) and 0 as neutral conditions, of surface moisture setting (Dai et al., 2004).

Practically, the comparative analysis of these values allows to perform spatial analysis of the variability of droughts over the study area. The approaches to asses and calculate drought in climate and environmental studies, are diverse (Tesfamariam et al., 2019). More sophisticated cases of the PDSI calculations include the prognosis of possible drought based on the existing data processed as time series analysis using numerical modelling and visualized graphs (Beyaztas et al., 2018).

Values, nature and spatial distribution of the environmental parameters can be analyzed using various techniques and approaches through data processing, analysis, modelling and visualization (Suetova et al., 2005; Schenke and Lemenkova, 2008; Klaučo et al., 2013; Jain et al., 2015; Lemenkov and Lemenkova, 2021a, 2021b; Lemenkova2019c). Climate data assessment methods use fieldwork records from the local meteorological stations where, for examples, the values of temperature and their statistical extremes, wind speed and direction, frequency and intensity of precipitations are recorded directly. The determined datasets are then stored as data massifs in Climate Centers and Research Units for further data processing (Asfaw et al., 2018). On the other hand, the datasets in tabular formats require detailed and effective mapping for interpretation of the environmental parameters.

Probably the most common approach of cartographic visualization is based on the ArcGIS (Gohl, 2006a, 2006b; Gauger et al., 2007; Lemenkova, 2011; Klaučo et al., 2017; Ghiglieri et al., 2020; Koroso et al., 2020; Kebede et al., 2021), which enables to perform various types of spatial data processing, modelling and visualization. Besides the commercial ArcGIS, the examples of the free open source GIS used for environmental mapping include ILWIS GIS, SAGA GIS and QGIS (Alemayehu et al., 2009; Lemenkova, 2020a, 2020c). While there have been cartographic attempts to present climate mapping of Ethiopia by the traditional GIS approaches, a scripting GMT-based approach enabling rapid data processing of Ethiopian ecosystems using machine learning methods has heretofore been lacking. Compared to the GIS applications, the GMT cartographic data processing obtained using scripting. Due to its console-based approach, the GMT is, to a certain extent, similar to the programming languages applied in geosciences (Lemenkova, 2019a, 2019b).

Retrieval of climate data from available repositories for data processing is very common. These may include government records on climate and meteorological data, field observations and questionnaire surveys (Adgo et al., 2013), census data, crop yield data from surveys (Eze et al., 2020), multi-temporal images (Gebrehiwot et al., 2011). Mapping meteorological variables provides a great importance to analysis of climate change, mitigation its environmental and social impacts and local adaptation (Mera, 2018; Matewos, 2020).

Environmental monitoring, in turn, is useful for evaluating global ecological and social conditions within Ethiopia, a country with extreme climate setting and sensitive ecosystems (Haile et al., 2020). Therefore, the application of the thematic GMT based mapping method for monitoring droughts in Ethiopia, a region with extreme temperatures, prone to droughts, presents cartographic visualization of the high-resolution data provided as a series of

The actuality of this study consists in the added value on environmental data analysis through advanced visualization which may have direct benefits for policy makers and studies on environmental risk assessment using produced maps. Moreover, current research in sustainable agriculture and food systems in Ethiopia has a notable gap between the environmental applications in farming and technical methodologies of mapping and cartographic visualization. At the same time, these are necessary to process geospatial data for possibilities of agricultural activities in various regions of Ethiopia and crop vegetation mapping.

The presented research aims to minimize this gap by presenting a series of thematic maps of Ethiopia prepared using advanced methodologies of GMT for data processing in a semi-automated regime for high-resolution mapping. Environmental mapping of Ethiopia using GMT presented observations of climate variables including PDSI drought index to detect and visualize variability in of climate setting to assess their possible effects on agriculture of Ethiopia. Using scripting methods of GMT and TerraClimate data for environmental mapping is ensured by the large amounts of automation in GMT. The series of the environmental maps may support data analysis in sustainable farming of Ethiopia. Therefore, this research can bring new data to the environmental analysis and support agriculture and public sectors on relevant topics of environment and agriculture of Ethiopia.

2. Materials and methods

Datasets

Data-driven mapping includes visualization of the georeferenced datasets which may vary in reliability, resolution and base maps for developing further environmental analysis using cartographic techniques. source of origin. This necessarily rises a question of the data quality control and assessment. Publicly reknown open data reputable repositories, such as GEBCO, NOAA, USGS, GloVis (well-known sources for the Landsat/Sentinel imagery), or TerraClimate present the reliable source for the input data suitable for mapping. This study captures data from the GEBCO and TerraClimate sources. Specifically, the datasets used in this study utilize on the GEBCO (GEBCO Compilation Group, 2020) used for topographic mapping in **Fig. 1.** and TerraClimate (Abatzoglou et al., 2018) used for **Fig. 2–7**.

High-resolution (4 km) climate data from the TerraClimate WorldClim (Fick and Hijmans, 2017) CRUTS 4.0. sources have been used to visualize and map series of climatic parameters in Ethiopia on 2018: soil moisture; extreme temperatures (T °C min and T °C max), wind speed and precipitation and PDSI. Data processing included five types of actions:

i. data search, selection and capture;

ii. data modeling and numerical processing;

iii. data visualization, elimination and symbolization using cartographic design tools;

iv. data behavior analysis: estimating coherency and finding correlations in datasets (min/max temperatures, soil moisture, topographic elevations, wind speed, PDSI);

v. data interpretation and assessment: explaining trends in spatial distribution of categorical parameters and continuous fields.

Correct, up-to-date georeferenced data about environmental and climate parameters are essential for environmental monitoring of such disasters as droughts, for supporting real-time environmental hazards mapping and climate control, and for performing correlation analyses between geographic variables (for instance, agricultural monitoring, crop mapping, assessment of wildlife habitat distribution). To aid in these efforts, TerraClimate published the set of climate data service to its online portal. The TerraClimate is a global repository of the climate variables, where each data in the NetCDF format contains an estimate of the climate measurements for various years. This study utilities the most recently available, that is 2018, as a case study.

The data from the TerraClimate repository present a useful resource as an input data source to terrestrial environmental mapping of Ethiopia. Clipped from the global original data for Ethiopia using the coordinates of the country borders, TerraClimate data produced a set of robust data layers on Ethiopia that has been adopted as the conceptual and input data for the thematic series in the presented research: temperatures (min/max), soil moisture, wind speed and PDSI. The series of six climate grid from the TerraClimate source and a topographic grid based on GEBCO were handled by the GMT for mapping selected meteorological parameters over the country for 2018 and visualizing the drought-prone areas in Ethiopia. The presented georeferenced data of the climate variables in Ethiopia are visualized, with aim to highlight and compare patterns of data distribution over Ethiopia (temperature extremes, soil moisture, topography, wind speed and PDSI). Thus comparison of the thematic data present new information about the role of topographic location in climate, meteorological and environmental processes driving drought disasters.

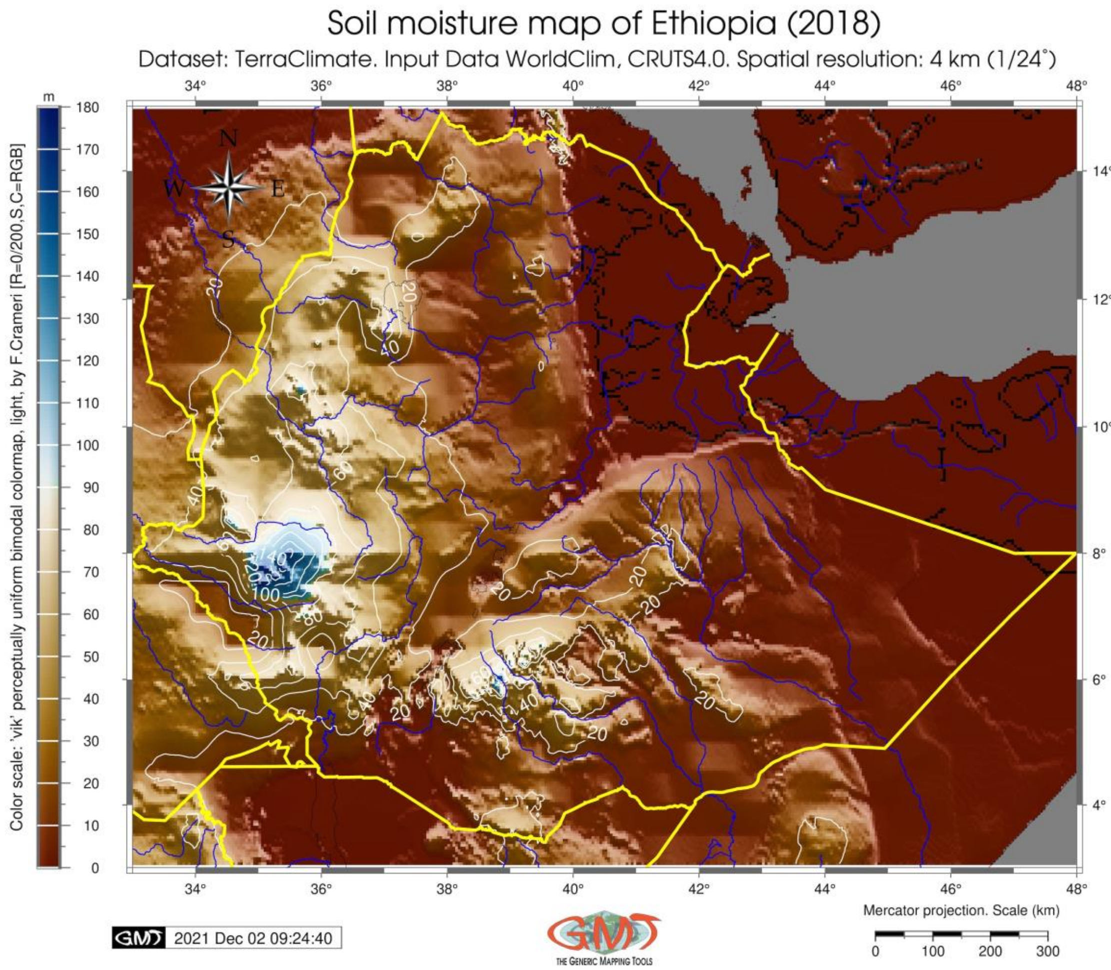

Fig. 2. Soil moisture map in Ethiopia in 2018. Mapping: GMT. Source: author

Research tools

Mapping for all illustrations (**Fig. 1–7**) has been done in Generic Mapping Tools (GMT) cartographic scripting toolset. The GMT based scripting approach applies the principle of programming in terms of console-based generating maps as an efficient cartographic workflow that supports both numerical modelling of the spatial datasets from the tabular formats and aesthetic graphical drawing of maps created for the environmental monitoring of Ethiopia. The regional extent of the study area was applied for Ethiopia, i.e., 33°E to 48°E and 3°N and 15°N.

The data were modelled and interpolated by raster grids using GMT. The datasets were captured from the WorldClim and GEBCO repositories with raster data and Digital Chart of the World (DCW) with vector data for clipping the country to highlight the study area. The mapping process of the GMT based scripting differs from designing a map using Graphical User Interface (GUI) based traditional GIS, such as ArcGIS or QGIS, because the data processing is being performed using script from a console. The mapping includes technically comprehensive and detailed visualization of the distribution of continuous fields of data and categorical environmental parameters in various vegetation regions of Ethiopia.

The input raster images for each of the maps (**Fig. 2–7**) was processed by a set of the GMT modules where each one defines certain map characteristics as described in existing technical papers (Lemenkova, 2020b, 2021a, 2021b).

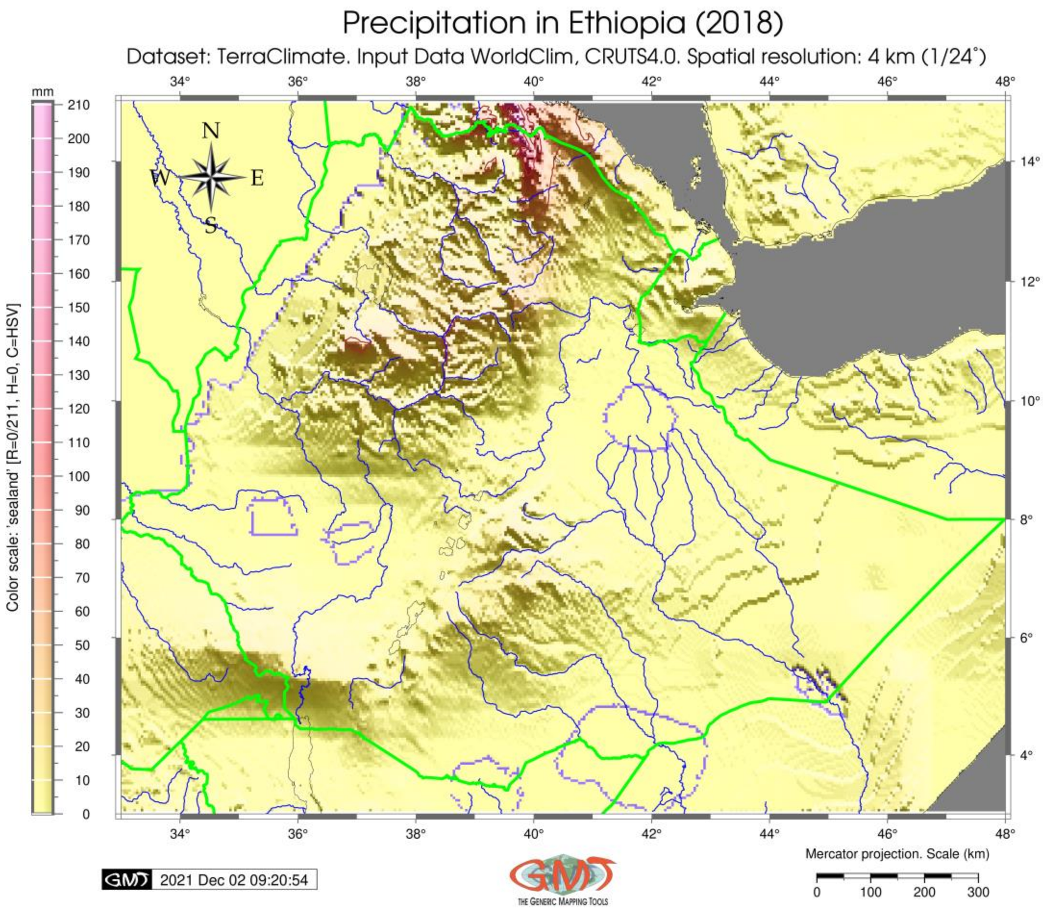

Fig. 3. Precipitation in Ethiopia in 2018. Mapping: GMT. Source: author

The GMT 'pscoast' modules was used for adding general cartographic elements (rivers and country borders) and 'psscale' was used to plot color explanation legend. The 'psbasemap' module was used to plot a title and a cartographic grid with graticule annotations (here the flag '-Bpxg2f0.5a2 -Bpyg2f2a2 -Bsxg1 -Bsyg1' for each map which shows primary and secondary grid annotations and intervals for the ticks).

To facilitate spatial comparison and cartographic visualization, the maps of the presented series (**Fig. 1-7**) were reconciled to the Mercator projection and the same spatial extent covering the country of Ethiopia (33°E–48°E, 3°N–15°N). The output environmental raster grids (**Fig. 2-7**) were recomputed by GMT and the output graphics converted from the PostScript (ps) format to the standard graphical output (jpg) using the fine resolution (720 dpi) as follows: 'gmt psconvert ET_PDSI.ps -A0.5c -E720 -Tj -Z', keeping the same criteria and layout sizes (5.5. inches) used in the implementation of the topographic map (**Fig. 1.**).

Cartographic coherency

The template draft of the GMT script designed for all the seven maps of the thematic series enabled visual cartographic coherency for the overall compatibility of the maps. This facilitated the comparative analysis of the continuous fields represented on the maps. Using identical coordinate extent, projection and orientation enabled to compare how differently the variability of the climate parameters behaved with respect to the topographic features of Ethiopia. The emphasis of the cartographic visualization was on the two steps in a technical mapping workflow:

i. how each flag within a GMT script controls the appearance of the cartographic elements (scale bar, grid image, rivers, DEM hillshade of Ethiopia) and how color palettes on all the maps within a map series;

ii. how sensitive the colour palettes are to climate variability parameters (temperatures, soil moisture, precipitation, PDSI values) demonstrated on the maps.

Therefore, all seven maps were examined how the symbolized environmental variables TerraClimat datasets in one map worked together with other maps of the presented series to enable visual correlation, compatibility and comparability of the maps. The template script of GMT with identical coordinates and map extent was applied for the 7 maps to ensure the iterative technical process of mapping.

3. Results and discussion

The paper presented modelled, visualized and mapped climate and topographic data across the Ethiopia ranges. The data were processed by the GMT methods to display visual cartographic quality through the selected colour palettes and vector properties (graticule, text annotations, legend) and meet the map purpose of modelling drought distribution, while maintaining the environmental goals of the research. The presented study had both theoretical environmental and practical cartographic goals. The environmental goal was to develop a conceptual GMT-based environmental analysis for visualization methods to depict data on a series of climate maps in general and the PDSI map in particular. The practical cartographic goal was to develop and present the cartographic functionality of the GMT scripting tool as a geoinformation visualization device and a scripting framework used for climate datasets.

The geoinformatics and data science approach has been taken to both goals using technical functionality from cartographic semantics and data processing, data visualization and aesthetic design.

In the study presented here, twofold methods of data visualization were presented for comparison of the topography and climate variables of Ethiopia, mapped using GMT: i) separable display of environmental variables achieved through series of the separate seven maps; ii) PDSI mapping demonstrating the integral display of the drought parameters, achieved through visualization of the complex PDSI index of drought over Ethiopia.

The results present a series of seven new maps based on the climatic data on Ethiopia, visualized and interpreted alongside the topography: 1) topography; 2) soil moisture; 3) T °C minimum; 4) T °C maximum; 5) Wind speed; 6) Precipitation; 7) Palmer Drought Severity Index (PDSI). The maps visualize meteorological and climate parameters for ecological monitoring, assessment of climate change, distribution and intensity of droughts.

The precipitation values (**Fig. 3.**) vary from 0 to 211 mm according to the TerraClim dataset checked up by GDAL. Although the maximal values reach higher values, the mean values dominating over the country are 5.167 (mainly light yellow color in **Fig. 3.**) and a standards deviation (StdDev) is 11.294.

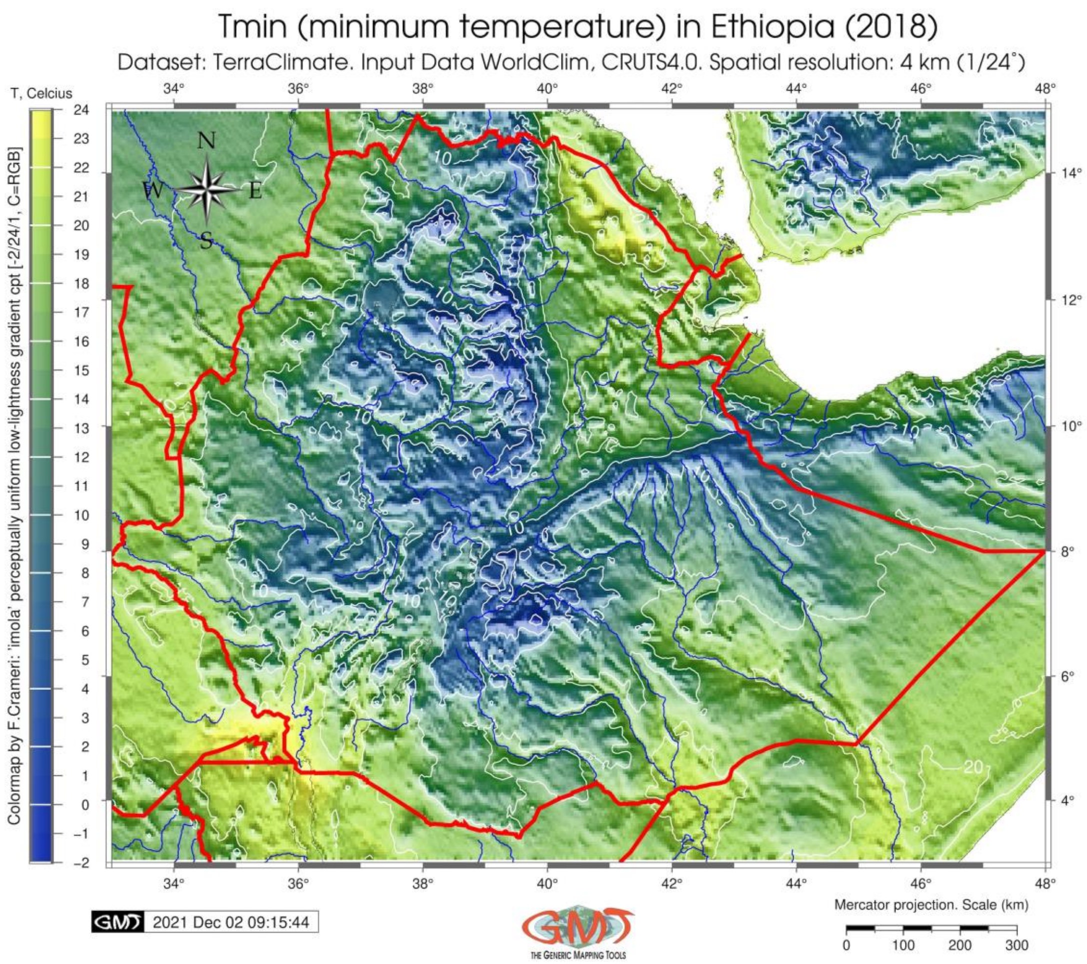

Fig. 4. T °C minimum (tmin) in Ethiopia in 2018. Mapping: GMT. Source: author

According to the data inspection by GDAL, there are three peaks of the higher precipitation in Ethiopia, which location is roughly corresponding to the topographic heights: 1) the Ethopian Highlands; 2) Omo and Mago National Parks; 3) Semien Mts National Park where mean values of the predominant precipitation values exceed 20 mm. Comparison of the presented figures enables to see the variations of climate and meteorological characteristics of the country with main topographic features of Ethiopia.

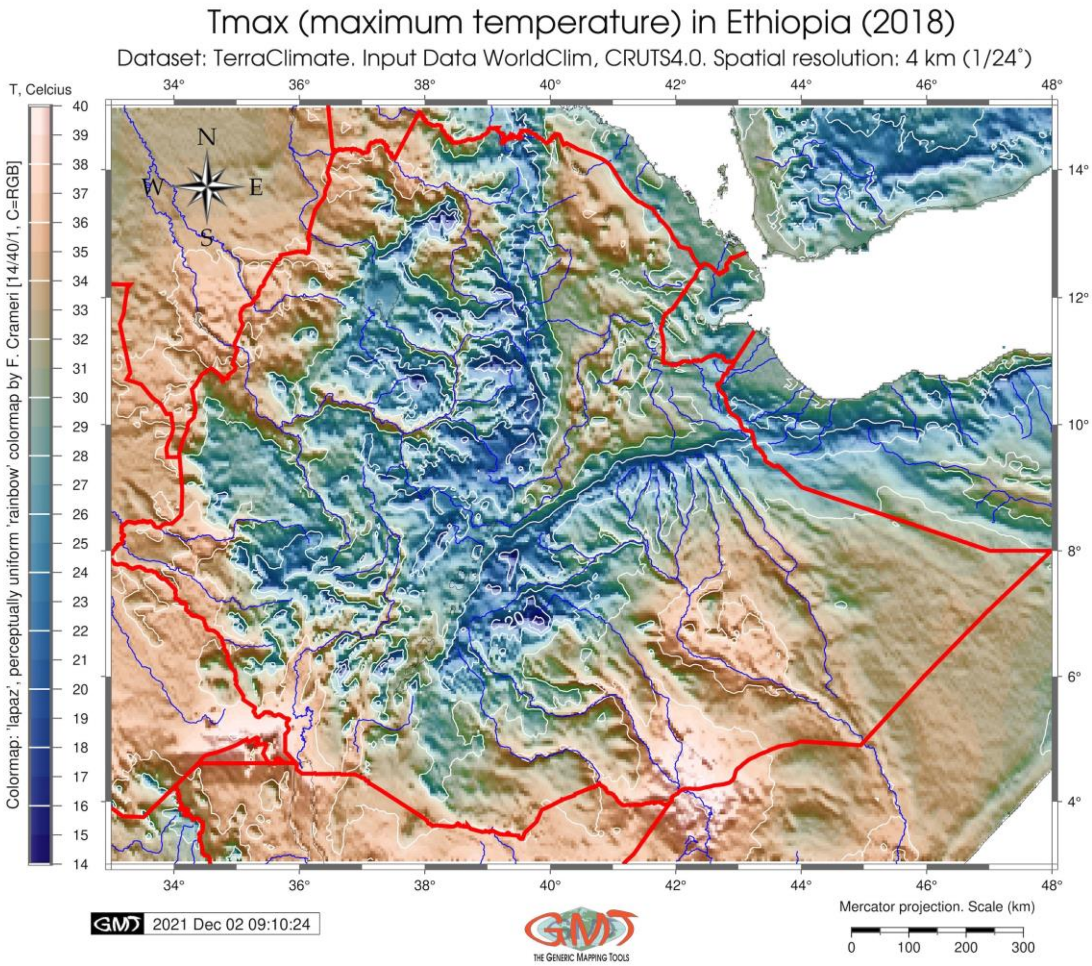

Fig. 5. T °C maximum (tmax) in Ethiopia in 2018. Mapping: GMT. Source: author

The Tmin has values ranging from -1.8 °C to 24 °C, while the Tmax has values ranging from 14.4 °C to 40.2 °C with the maximal areas clearly visible in the SE region of the country and the minimal values primarily concentrated along the Great Rift Valley. The selected color palette is 'lapaz' from the available choice of GMT. A similar pattern of the values distribution can be seen in Figure 4 (Tmin colored by the color palette 'imola' of GMT) showing the lowest values in the Great Rift Valley and over the Ethiopian Highlands (dark blue colors in Figure 4) and highest (up to 24 °C) in the NE region of the country.

It has been observed that the wind speed (**Fig. 6.**) well reflects the surface topography very well with distribution of lower values (0 to 1 m/s, yellow color in **Fig. 6.**) being directed almost in meridian direction which corresponds to the general extent of the Ethiopian

In general, the wind speed has lower values (0.5 to 2.0, which corresponds to the yellow to light aquamarine colors in **Fig. 6.**) in the depressions and topographic lowlands while the lower speed is notable for the higher elevations in the topographic landforms (2.0 to 4.5, which corresponds to the green colors and hues in **Fig. 6.**). The highest values of the wind speed (above 5.0 m/s) are notable along the coasts of Somali (44.0°E–47.0°E).

Along the Ethiopian Highlands higher values are demonstrated by the soil moisture (**Fig. 2.**) which has the highest value of 180 (checked by 'gdalinfo -stats et_soil.nc') Highlands (compare to **Fig. 1.**). According to the data inspection (gdalinfo -stats et_ws.nc), the minimum recorded is 0.100m/s, maximum is 6.1 m/s. The wind speed increases strongly in the depression area which forms a 'delta'-shaped form eastwards of the longitude 39.5°E. decreasing towards the desert areas (Ogaden Desert) representing the rocky and sandy nature of the Triassic deposits. The mean value is about 14.990, standard deviation (StdDev) is 20.056, according to the gdalinfo, which is changing abruptly toward the eastern direction along with the topography of the Ethiopian Highlands (compare **Fig. 1. to 2.**). Another region of higher values in soil moisture is notable around the Awasa city on the right flank off the Great Rift Valley (**Fig. 1.**) with values in the interval 40–60 (blue colors in **Fig. 2.**).

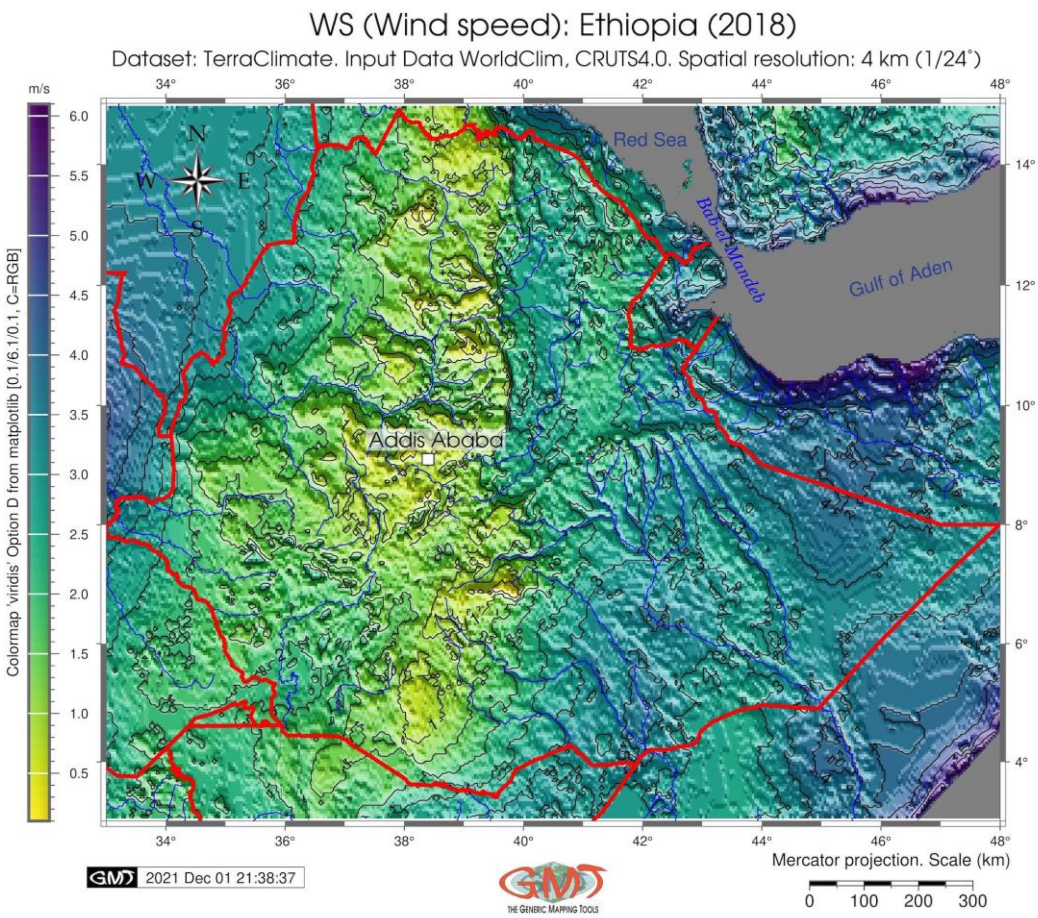

Fig. 6. Wind speed in Ethiopia (2018). Data: TerraClimate. Mapping: GMT. Source: author

The lowest values are notable in the lowlands of the Yangudi Rassa National Park and Semera. A comparison of the presented maps – topographic elevation (**Fig. 1.**), soil moisture (**Fig. 2.**), precipitation (**Fig. 3.**), extremal temperature as minimal (**Fig. 4.**) and maximal (**Fig. 5.**), wind speed (**Fig. 6.**) and the PDSI (**Fig. 7.**)– at the area surface of Ethiopia, shows a great agreement of the datasets proving the dependence of the PDSI on temperature, precipitation, soil-relief parameters and geomorphology of the study area.

The results show the lowest values of the PDSI (-11.7, a moderately moist area) are found in the NW region of Ethiopian Highlands, while the highest values (2.3, an extreme drought: orange to red colors in **Fig. 7.**), are recorded in the south-east off the Ethiopian Highlands (compare **Fig. 7. to 1.**). **Fig. 4.** and **Fig. 5.** are showing the extremal values of the temperature (**Fig. 4.** for the minimal and **Fig. 5.** for the maximal temperature in 2018) have isolines remarkably correlating to the topographic map (**Fig. 1.**) with clearly visible 'delta'-shaped depression area NE to the Greate Rift Valley and the Danakil Depression, where the temperature patterns change accordingly following the topographic relief patterns.

The application of GMT enabled to produce multiple cartographic representations of Ethiopia using several climate grids from a single detailed repository of TerraClimate by scripting approach from a GMT console.

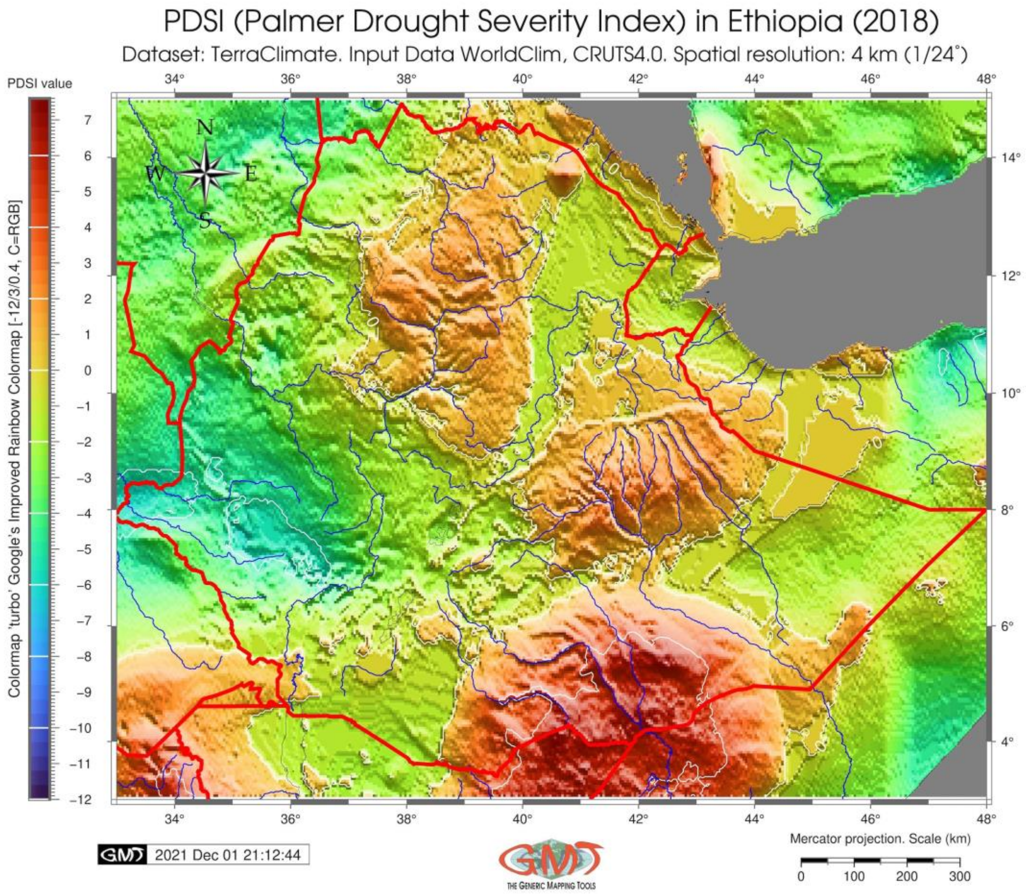

Fig. 7. Palmer Drought Severity Index (PDSI) in Ethiopia. Mapping: GMT. Source: author

Using GMT enables to produce a variety of maps with different purposes, such as geological, geomorphological, climate or environmental maps as scripting method rapidly processes multi-format raw data (IMG, GRD, NetCDF) to high-quality finished mapping outputs. The paper contrasts the existing approaches of the traditional GIS by using more sophisticated approach of GMT based scripting and customized mapping goals to visualization of the environmental parameters of Ethiopia: temperature (minima and maximal), soil moisture, wind speed, topography and the PDSI values.

The presented results explicitly demonstrate the influence of the console-based mapping on the cartographic output by presenting high-quality aesthetic map layouts. The paper shown the cartographic GMT based scripting as an influencing technology that amends cartographic workflow and affects analytical visualization of maps for environmental analysis derived from a multi-source datasets of TerraClimate aimed for multi-purpose environmental and climate assessment of Ethiopia. Comprehensive and detailed maps of the environmental parameters, climate elements and visualization of PDSI are a valuable resource for researchers to assess possible droughts in Ethiopia, a country with a highly contrasting clime and topographic setting.

Discussion

Mapping spatial data has been a subject of longstanding interest in environmental and climate studies, judging by relevant publications. Data visualization through application of various GIS and methods of cartographic data processing can effect changes in visual understanding of the mapped parameters, finding correlations between the phenomena (precipitation, soil moisture, temperature, PDSI) through analysis of their logical topology, geometry and distribution of the fields analyzed along with categorical variables, thus most approaches of mapping are designed to highlight depicted objects and better visualize their characteristics. In the presented multi-source data processing that resulted in a series of maps, projection was pre-established and agreed as the same for all the maps from the series, based on the principle of the best look reflecting the extent and topographic features of Ethiopia.

The guiding principle driving the presented research is to produce a series of the seven new thematic maps on climate settings of Ethiopia with a special accent on PDSI. While preserving identity and logical consistency of maps (projections, spatial extent, location) the maps demonstrate different meteorological and environmental variables over Ethiopia: temperature, soil moisture, precipitation and wind speed. This paper introduced a scripting approach which largely contrasts with the existing GIS-based mapping. Hence, the literature review of the existing publications on climate mapping of Ethiopia shown that the solutions offered to visualize environmental settings and map climate data (PDSI, temperatures, soils moisture etc) have been largely based on the traditional GIS approaches (for instance, ArcGIS) while ignored other cartographic approaches (scripting GMT tools).

The synchronized adjustment of cartographic symbols and elements has been applied for standardization of the maps (**Fig. 1. to 7.**) and achieving cartographic consistency. Pairwise variation in visual categories of the continuous fields using variability on color palettes of temperatures (**Fig. 4. and 5.**), environment (**Fig. 1. and 2.**), meteorology (**Fig. 3. and 7**.) and climate (**Fig. 4. and 6.**) resulted in multiple representations of their elements as a conceptual approach of semantic mapping applying geometric and graphical multiplicities. The presented series of maps focused on the interaction between various environmental, climate and topographic features of Ethiopia aimed to demonstrate and highlight strong correlation between the topographic, climate and meteorological processes, soil moisture and temperature distribution over the area which is finally reflected in PDSI. The map of PDSI, generalizing and summarizing the environmental properties of the country through the computed and visualized index, effectively highlights the regions of Ethiopia prone to drought.

Conclusions

The presented thematic maps of Ethiopia are based on the visualization of the high-resolution datasets used for interpretation of the spatial distribution of droughts (PDSI) and related auxiliary parameters (extreme temperatures (min/max), speed intensity, precipitation, soil moisture, topography) in Ethiopia. The links between the demonstrated environmental and climatic components based on visual comparison and overlay of the cartographic imprints demonstrate interrelations between these factors. The correlations between the soil moisture, precipitation, relief and temperatures point at their environmental associations affecting meteorological variables and drought that can be useful in possible prognosis and modelling of droughts. The cartographic series of the thematic climatic and topographic maps produced using identical spatial extent, projection and view yet using a variety of color palettes for each environmental variable can be successfully used as a reliable source for ecological monitoring in Ethiopia. In this way, this paper contributes to the environmental research of Ethiopia with a special focus and detailed visualization of PDSI map for drought modelling.

The demonstrated results show the predominant distribution of the PDSI values over the Ethiopia Highlands and mountainous areas. The spatial distribution of the PDSI and other climatic datasets covering Ethiopia (as on 2018) obtained as a result of the GMT based mapping reflects the correlation with topography as well as the effects of temperature and precipitation on the variations of the PDSI values. For instance, higher values of the PDSI correlates well with distribution of the areas of the prevailing winds with higher speed. On the contrary, the lower values of the PDSI (severe drought) are found on the sites with low-speed winds. For climate and environmental research, cartographic visualization is a primary technical tool of data processing used to identify geospatial clusters and regular patterns of meteorological continuous fields and to compare these features with patterns of both topographic relief and potential droughts based on PDSI map. Similar situation can be seen on the comparison of maps showing precipitation, temperature and topography with the PDSI values over the country. Thus, regions of higher precipitation coincide with the areas of higher PDSI values (that is, relatively moist regions), while low-level precipitation regions correlate with the PDSI regions showing lower values (that is, extreme drought). The relationship between the occurrence of higher/lower temperature values (min/max as for 2018) in Ethiopia and the PDSI values has also been noticed by the comparison of the respecting maps.

The generated maps are required by the drought assessment and environmental monitoring studies. These maps are proposed for the first time on a GMT-based approach based on scripting techniques and contribute to the existing studies on environment and ecological monitoring of Ethiopia with special focus on climate change, problems of drought and crop harvest (Ntale and Gan, 2003). A series of the climatic variables (soil moisture, extremal temperatures (T °C min; and T °C max), wind speed, precipitation; PDSI) have been visualized based on the existing datasets of WorldClim using scripting approach of GMT to show the reference of the climate to the topographic setting in Ethiopia. The assumption made is that the relief elevation, orientation and steepness should be affecting these parameters and which has been visualized on the series of maps and discussed as interpretation of the map values. A presented series of the GMT-based climate and environmental maps associated with the PDSI index of Ethiopia is useful as the base illustrations in future similar research on the environmental assessment and monitoring of the country.

Scripting cartographic concept implemented in GMT enabled to find out optimal cartographic solutions for data visualization that support effective map production workloads through minimizing human-made routine and increasing automatization. Incorporating various multi-source datasets into the map series, as presented in this research, extends the range of variables for a regional extent of Ethiopia, which in turn increases the volume of information to maintain analysis of correlation between the climate and topographic parameters for the environmental monitoring of Ethiopia.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

1. Abatzoglou J, Dobrowski S, Parks S, Hegewisch KC (2018) TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. Sci Data 5:170191.
2. Adgo E, Teshome A, Mati B (2013) Impacts of long-term soil and water conservation on agricultural productivity: the case of Anjenie watershed, Ethiopia. Agric Water Manag 117:55–61.
3. Aragie EA, J Thurlow EA (2022) Modeling the recovery dynamics of Ethiopia cattle population. Journal of Arid Environments 197: 104664
4. Alemayehu F, Taha N, Nyssen J, Girma A, Zenebe A, Behailu M, Deckers S, Poesen J (2009) The impacts of watershed management on land use and land cover dynamics in Eastern Tigray (Ethiopia). Resources, Conservation and Recycling 53(4):192–198.
5. Alley, W.M. 1985. The Palmer Drought Severity Index as a Measure of Hydrologic Drought. JAWRA J Am Water Resour Assoc 21: 105–114.
6. Asfaw A, Simane B, Hassen A, Bantider A (2018) Variability and time series trend analysis of rainfall and temperature in northcentral Ethiopia: A case study in Woleka sub-basin. Weather and Climate Extremes 19: 29–41.
7. Bahru BA, Bosch C, Birner R, Zeller M (2019) Drought and child undernutrition in Ethiopia: A longitudinal path analysis. PLOS ONE 14(6): e0217821.
8. Beyaztas U, Arikan BB, Beyaztas BH, Kahya E (2018) Construction of prediction intervals for Palmer Drought Severity Index using bootstrap. J Hydrol 559: 461–470.
9. Dai A, Trenberth KE, Qian T (2004) A Global Dataset of Palmer Drought Severity Index for 1870–2002: Relationship with

Soil Moisture and Effects of Surface Warming. J Hydrometeorol 5(6): 1117–1130.

10. Demelash H, Tadesse T, Menamo T, Menzir, A (2021) Determination of root system architecture variation of drought adapted sorghum genotypes using high throughput root phenotyping. Rhizosphere 19: 100370
11. Di Falco S, Bezabih M, Yesuf M (2010) Seeds for livelihood: Crop biodiversity and food production in Ethiopia. Ecological Economics 69(8): 1695-1702.
12. Dimitrova A (2021) Seasonal droughts and the risk of childhood undernutrition in Ethiopia. World Development 141: 105417.
13. Domonkos P, Szalai S, Zoboki J (2001) Analysis of drought severity using PDSI and SPI indices. Idoejaras 105: 93–107.
14. Edossa DC, Babel MS, Gupta AD (2010) Drought analysis in the Awash river basin, Ethiopia. Water resources management 24(7): 1441–1460.
15. Eze E, Girma A, Zenebe A, Zenebe G (2020) Feasible crop insurance indexes for drought risk management in Northern Ethiopia. Int. J. Disaster Risk Reduct 47: 101544.
16. Fick SE, Hijmans RJ (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int J Climatol 37:4302–4315.
17. Ficklin DL, Letsinger SL, Gholizadeh H, Maxwell JT (2015) Incorporation of the Penman–Monteith potential evapotranspiration method into a Palmer Drought Severity Index Tool. Comput Geosci 85 Part A:136–141.
18. Gauger S, Kuhn G, Gohl K, Feigl T, Lemenkova P, Hillenbrand C (2007) Swath-bathymetric mapping. Reports on Polar and Marine Research 557:38–45.
19. Ghiglieri G, Pistis M, Abebe B, Azagegn T, Engidasew TA, Pittalis D, Soler A, Barbieri M, Navarro-Ciurana D, Carrey R, Puig R, Carletti A, Balia R, Haile T (2020) Three-dimensional hydrostratigraphical modelling supporting the evaluation of fluoride enrichment in groundwater: Lakes basin (Central Ethiopia). J. Hydrol. Reg. Stud. 32:100756.
20. GEBCO Compilation Group, 2020. GEBCO 2020 Grid. https://doi.org/10.5285/a29c5465-b138-234d-e053-6c86abc040b9
21. Gebre B, Ayenew H Y, Biadgilign S (2021) Drought, hunger and coping mechanisms among rural household in Southeast Ethiopia. Heliyon 7(3): e06355.
22. Gebrehiwot T, van der Veen A, Maathuis B (2011) Spatial and temporal assessment of drought in the Northern highlands of Ethiopia. Int J Appl Earth Obs Geoinf 13(3): 309–321.
23. Gohl K, Eagles G, Udintsev G, Larter RD, Uenzelmann-Neben G Schenke HW, Lemenkova P, Grobys J, Parsiegla N, Schlueter P, Deen T, Kuhn G, Hillenbrand CD (2006) Tectonic and sedimentary processes of the West Antarctic margin of the Amundsen Sea embayment and PineIsland Bay. Proc 2nd SCAR Open Science Meeting 12–14 July, Hobart, Australia.
24. Gohl K, Uenzelmann-Neben G, Eagles G, Fahl A, Feigl T, Grobys J, Just J, Leinweber V, Lensch N, Mayr C, Parsiegla N, Rackebrandt N, Schlüter P, Suckro S, Zimmermann K, Gauger S, Bohlmann H, Netzeband G, Lemenkova P (2006b) Crustal and Sedimentary Structures and Geodynamic Evolution of the West Antarctic Continental Margin and Pine Island Bay. Expeditionsprogramm Nr. 75 ANT XXIII/4 ANT XXIII/5, 11–12.
25. Haile GG, Tang Q, Leng G, Jia G, Wang J, et al. (2020) Long-term spatiotemporal variation of drought patterns over the

Greater Horn of Africa. Sci. Total Environ 704: 135299.

26. Jain VK, Pandey RP, Jain MK, Byun H-R (2015) Comparison of drought indices for appraisal of drought characteristicsin the Ken River Basin. Weather Clim Extremes 8: 1–11.
27. Kebede YS, Endalamaw NT, Sinshaw BG, Atinkut HB (2021) Modeling soil erosion using RUSLE and GIS at watershed level in the upper beles, Ethiopia. Environmental Challenges, 2: 100009.
28. Klaučo M, Gregorová B, Stankov U, Marković V, Lemenkova P (2013) Determination of ecological significance based on geostatistical assessment: a case study from the Slovak Natura 2000 protected area. Open Geosci 5(1):28–42.
29. Klaučo M, Gregorová B, Koleda P, Stankov U, Marković V et al. (2017) Land planning as a support for sustainable development based on tourism: A case study of Slovak Rural Region. Environ Eng Manag J 2(16):449–458.
30. Koroso NH, Zevenbergen JA, Lengoiboni M (2020) Urban land use efficiency in Ethiopia: An assessment of urban land use sustainability in Addis Ababa. Land Use Policy, 99: 105081.
31. Legesse A, Negash, M (2021) Species diversity, composition, structure and management in agroforestry systems: the case of Kachabira district, Southern Ethiopia 7(3): e06477.
32. Lemenkov V, Lemenkova P (2021a) Using TeX Markup Language for 3D and 2D Geological Plotting. Found Comput Decis Sci 46(3): 43–69.
33. Lemenkov V, Lemenkova P (2021b) Measuring Equivalent Cohesion Ceq of the Frozen Soils by Compression Strength Using Kriolab Equipment. Civ Environ Eng Rep 31(2): 63–84.
34. Lemenkova P (2011) Seagrass Mapping and Monitoring Along the Coasts of Crete, Greece. M.Sc. Thesis. University of Twente, Netherlands. Pp. 158.
35. Lemenkova, P (2019a) Statistical Analysis of the Mariana Trench Geomorphology Using R Programming Language. Geod Cartogr 45(2):57–84.
36. Lemenkova P (2019b) Topographic surface modelling using raster grid datasets by GMT: example of the Kuril-Kamchatka Trench, Pacific Ocean. Reports on Geodesy and Geoinformatics, 108, 9–22.
37. Lemenkova P (2019c) GMT Based Comparative Analysis and Geomorphological Mapping of the Kermadec and Tonga Trenches, Southwest Pacific Ocean. Geogr Tech 14(2):39–48.
38. Lemenkova P (2019d) Geomorphological modelling and mapping of the Peru-Chile Trench by GMT. Pol Cartogr Rev 51(4):181–194.
39. Lemenkova P (2020a) SAGA GIS for information extraction on presence and conditions of vegetation of northern coast of Iceland based on the Landsat TM. Acta Biol. Marisiensis 3(2):10–21.
40. Lemenkova P (2020b) GEBCO Gridded Bathymetric Datasets for Mapping Japan Trench Geomorphology by Means of GMT Scripting Toolset. Geod Cartogr 46(3):98–112.
41. Lemenkova P (2020c) Sentinel-2 for High Resolution Mapping of Slope-Based Vegetation Indices Using Machine Learning by SAGA GIS. Transylv Rev Syst Ecol Res 22(3):17–34.
42. Lemenkova P (2021a) Topography of the Aleutian Trench south-east off Bowers Ridge, Bering Sea, in the context of the geological development of North Pacific Ocean. Baltica 34 (1):27–46.
43. Lemenkova P (2021b) Geodynamic setting of Scotia Sea and its effects on

geomorphology of South Sandwich Trench, Southern Ocean. Pol Polar Res 42(1):1–23.

44. Matewos T (2020) The state of local adaptive capacity to climate change in drought-prone districts of rural Sidama, southern Ethiopia. Clim. Risk Manag 27:100209.
45. Mera GA (2018) Drought and its impacts in Ethiopia. Weather. Clim. Extremes 22: 24–35.
46. Mihretie FA, Tsunekawa A, Haregeweyn N, Adgo E, Tsubo M, Ebabu K, Masunaga T, Kebede B, Meshesha DT, Tsuji W, Bayable M, Berihun ML (2021) Tillage and crop management impacts on soil loss and crop yields in northwestern Ethiopia. International Soil and Water Conservation Research. DOI: 10.1016/j.iswcr.2021.04.006
47. Ntale HK, Gan TY (2003) Drought indices and their application to East Africa. Int J Climatol 23:1335–1357.
48. Schenke HW, Lemenkova P (2008) Zur Frage der Meeresboden-Kartographie: Die Nutzung von AutoTrace Digitizer für die Vektorisierung der Bathymetrischen Daten in der Petschora-See. Hydrographische Nachrichten, 81: 16–21.
49. Suryabhagavan KV (2017) GIS-based climate variability and drought characterization in Ethiopia over three decades. Weather and Climate Extremes 15: 11–23.
50. Suetova IA, Ushakova LA, Lemenkova P (2005) Geoinformation mapping of the Barents and Pechora Seas. Geography and Natural Resources, 4:138–142.
51. Tesfamariam BG, Gessesse B, Melgani F (2019) Characterizing the spatiotemporal distribution of meteorological drought as a response to climate variability: The case of rift valley lakes basin of Ethiopia. Weather. Clim. Extremes 26:100237.
52. Tora TT, Degaga DT, Utallo AU (2021) Drought vulnerability perceptions and food security status of rural lowland communities: An insight from Southwest Ethiopia. Current Research in Environmental Sustainability 3: 100073