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An Investigation of Recent Climate Change in Southern Ukraine

Liudmyla Zapukhliak

AN INVESTIGATION OF RECENT CLIMATE CHANGE IN SOUTHERN UKRAINE

by

LIUDMYLA ZAPUKHLIAK

Under the Direction of Jeremy E. Diem, PhD

ABSTRACT

Southern Ukraine is a transition zone between two major climate change "hot-spots" in Europe. However, little is known about how the climate of this region has changed over the past several decades. Understanding climate change impact on agriculture in southern Ukraine, as one of the major producers of grains in the world, is crucial for local and global food security. Based on statistical analysis and visualization of temperature and precipitation datasets for 1981- 2018, this study showed a faster than global mean annual temperature increase (about 1.8-2°C in 37 years) and found signs of the intra-annual precipitation redistribution in southern Ukraine. Precipitation trends show an increase in January (39% - 79%) and a decrease in August (38% - 43%) in parts of the study region. The summer temperature rise is the primary driver of the climate types shift toward warmer climates in the Köppen-Geiger classification and increasing summer soil-water deficit.

INDEX WORDS: Eastern Europe, Ukraine, Climate Variability, Climate Change, Climate Classification.

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LIUDMYLA ZAPUKHLIAK

Committee Chair: Jeremy E. Diem

Committee: Lawrence Kiage

Ricardo Nogueira

Electronic Version Approved:

Office of Graduate Services

College of Arts and Sciences

Georgia State University

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DEDICATION

This thesis is dedicated to my husband, who inspired me to pursue a master's degree at Georgia State University and to my father, who never had a chance to finish college.

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I would like to express my sincere gratitude to my advisor, Prof. Jeremy E. Diem, for his constant support and inspiring guidance. I am also grateful to all the professors in the Department of Geosciences, whose classes provided me with the skills and knowledge necessary to complete this research.

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LIST OF ABBREVIATIONS

CO_2 - Carbon dioxide

CHIRPS - Climate Hazards Group InfraRed Precipitation with Station data

FAO - Food and Agriculture Organization of the United Nations

IPCC - Intergovernmental Panel on Climate Change

NOAA – United States National Oceanic and Atmospheric Administration

WMO - World Meteorological Organization

1 INTRODUCTION

1.1 Background

Climate change is projected to have a significant impact on agriculture. Agricultural crop growth is highly dependent on optimal, stable climate conditions, deviation from which is proven to cause significant loss in crop yield (Olesen and Bindi, 2002; Ray et al., 2019). For instance, variations in average growing-season temperatures of only about 2˚C can lead to up to 50% loss in grain production and significantly impact future global food security (Asseng et al., 2011). A growing season average temperature and precipitation are the major climatic factors that influence agricultural crop productivity (Lobell and Burke, 2010). Thus, climate change is going to play an important role in future food security by increasing temperature and frequency of extreme events, impacting soil erosion and soil fertility, causing changes in the global water cycle, which can lead to a redistribution of the precipitation and water resources (Frederick and Major, 1997; Hegland, 2017).

In Europe, climate change is projected to have both positive and negative effects on agriculture. The temperature increase is projected to have a positive effect on agriculture in northern and western Europe, by increasing yield, enabling expansion of the agricultural areas north, and introducing crops previously unsuitable for these areas (Bindi and Olesen, 2011). In contrast, summer temperature increase together with precipitation decrease in southern Europe will lead to water shortage, increased heat stress, higher frequency and intensity of droughts, and even risk of desertification, especially in Mediterranean region (Alessandri et al., 2014; Jia et al., 2019; Olesen and Bindi, 2002; Spinoni et al., 2015). In general, warm and dry regions of Europe are the most sensitive to climate change adverse effects on crop productivity (Tao et al., 2014; Trnka et al., 2012).

Northeastern Europe and the Mediterranean region were identified as the most responsive to climate change regions across the globe by Giorgi (2006). Analyses of changes in regional mean precipitation, air temperature, and their interannual variability suggest a high possibility of significant summer drying in the Mediterranean region and a significant increase in regional temperature, cold season precipitation, and precipitation interannual variability in North-Eastern Europe (Giorgi, 2006). Based on the projected high impact of those changes on local communities, those regions are highlighted as vulnerable to climate change, which can endanger human security and require the implementation of adaptation policies (de Sherbinin, 2014).

Although Black Sea catchment areas of Eastern Europe exist on the border of two aforementioned climate change hot-spots (i.e., Northeastern Europe and the Mediterranean region), little research has been conducted on climate variability and change of this region, especially in countries outside of the European Union. This lack of research is intriguing, since some European Union Eastern partnership countries, such as Ukraine, play an important role in global food security as world's biggest producers of grains (Fischer et al., 2014; Shiferaw et al., 2011; Shiferaw et al., 2013). According to USDA Annual Agricultural Statistics reports, Ukraine has been among the ten biggest exporters of wheat, corn, barley, and oilseeds in the world over the recent decade(https://www.nass.usda.gov/Publications/Ag_Statistics). Historically, the southern part of Ukraine with the most fertile soil was known as the major producer of grains (Fileccia et al., 2014; Moon, 2013). However, agricultural productivity in this area is unstable and limited by climate variability (Moon, 2016; Trofimova and Adamenko, 2015).

There is a scientific consensus regarding an increasing temperature trend in southern Ukraine, but a disagreement regarding its scale. In the 20th century, the mean annual temperature in this area was increasing faster than the global temperature (Hulme et al., 1995). According to

Odesa weather station data, the average annual air temperature increased by about 2°C over the last 35 years, with higher increase in winter than in summer (Svetlichnyy and Ibragimova (2016). Other studies report mean annual temperature increasing by 0.4-0.6°C per 100 years (Boychenko et al., 2016), mean winter temperature increasing by 1.25 in about 60 years (Bindoff et al., 2013), and mean January temperature increasing by about 0.2-0.3°C per 10 years from 1951 to 2009 (Tuz, 2012), mean annual temperature increasing by 0.2-0.24°C per decade mean winter and spring temperature increasing by 0.24°C per decade, mean summer and autumn temperature increasing by 0.12-0.16°C per decade for the period 1946-2014 (Osadchyi et al., 2018) and mean winter and summer temperature increasing by 1-1.5°C during 1961 - 1990 (Ivanyi, 2015).

The results of precipitation studies are less in agreement with each other than temperature studies. For instance, the Ukrainian Hydrometeorological Institute, the major State research institution in the field of meteorology in Ukraine, report a 15% increase of annual precipitation totals from 1961-1990 compared to 1891-1964 in southern Ukraine, including an increase in all months except in June (decrease by 12%) and October (decrease by 12%) (Barabash et al., 2004). Another local study suggests 15%-30% increase of September and October precipitation and 11% - 15% decrease of winter precipitation during 1961-1990 (Ivanyi, 2015). However, other studies have found no statistically significant trend in annual precipitation in 20th century in southern Ukraine (Villarini, 2012; Yeremeyev and Yefimov, 2003).

All future temperature projections for southern Ukraine suggest an increase in annual temperature by the end of the 21st century. According to the 2013 IPCC report, the mean annual temperature is projected to increase by 1.5°C per each 1°C of global mean temperature increase with more warming in winter than in summer (Stocker et al., 2013). Projections of the Ukrainian scientists are as follows: mean annual temperature in southern Ukraine will increase by 0.5°C by

2030 compared to 1991-2010 and winter temperature will increase up to 3°C by the end of the 21st century (Shevchenko et al., 2014); mean annual temperature can increase by 1,65°C during 2010-2070 in the stabilization emission scenario (RCP 4.5) or by 2,98°C in the high-emission scenario (Prokopenko and Udova, 2017); the higher temperature increase is projected to occur in summer than in other seasons (Gnatiuk et al., 2013).

Compared to temperature projections, precipitation projections for the end of the century are much more variable. Precipitation trends analyses and drought modeling in the region show inconsistent results (Blenkinsop and Fowler, 2007; Feng et al., 2014) with high uncertainty (Bladé et al., 2012; Hartmann et al., 2013; Krakovska, 2018) and high regional precipitation biases (Giorgi and Bi, 2005). According to the 2013 IPCC report, mean precipitation is projected to increase by 3% per each 1°C of global mean temperature change (Stocker et al., 2013). However, local studies report the possibility of a future decrease in precipitation from 5% to 22% in the southern part of Ukraine by 2050 (Boychenko et al., 2016; Loboda and Bozhok, 2016) or by the end of the 21st century (Boychenko et al., 2015; Ivanyi, 2015; Shevchenko et al., 2014; Shvidenko, 2009). European project FP-6 ensembles suggests a significant decrease in summer and increasing in autumn precipitation and by the end of the 21st century (Gnatiuk et al., 2013).

Researchers also have different opinions on the current climate type of southern Ukraine and its possible change in the future. Based on the Köppen-Geiger climate classification, different studies define the current climate type of the region as Dfa (cold, without dry season, hot Summer) in mainland and Dfb (cold, without dry season, warm Summer) in Crimean Peninsula (Peel et al., 2007), Dfb and Dfa in mainland and Cfa (warm temperate, fully humid, hot summer) in the Crimea Peninsula (Kottek, 2006); or Bsk (arid, cold steppe) and partially Dfa (Beck et al., 2018). The region also had been defined as Df (cold, without dry season) based on the Köppen classification.

Based on Köppen-Trewartha classification, some researchers indicate one climate type in the region is Dc (temperate continental) (Belda et al., 2014), but Feng et al. (2014) found four climate types in the same area: DCfa (temperate continental no dry season, hot Summer) and DCfb (temperate continental, no dry season, warm summer) in the mainland and DOfb (temperate oceanic) and DOwb (temperate oceanic, winter dry) in the Crimean Peninsula. The latest IPCC report uses Rivas-Martinez Worldwide Bioclimatic Classification System, and identifies climate of most of the study area as Pluviseasonal-Continental, which is in the Mediterranean group (Jia et al., 2019).

Considering projected changes in temperature and precipitation, climate type shift in southern Ukraine during the 21st century is expected. The projected changes are as follows: Dc (temperate continental) to B (dry) and Do (temperate oceanic) to C (subtropical) on the Köppen–Trewartha classification (Feng et al., 2014); and Dc (temperate continental) to Do (temperate oceanic) (De Castro et al., 2007). According to Beck et al. (2018), the area with Bsk (cold steppe) climate by 2071–2100 is projected to increase. Other researchers suggest that the most southern part of Ukraine mainland currently has Mediterranean climate type, and projects with 70% probability transition of the part that currently has Dfa to Mediterranean climate by the end of the 21st century (Alessandri et al., 2014).

In addition to specific climate types, an important indicator of the relationships between temperature and precipitation is the aridity of the region. The European Union World atlas of desertification describes the current moisture supply of the study area as dry subhumid in the mainland and arid in the flat part of the Crimean Peninsula (Cherlet et al., 2018). It is likely that increasing temperatures with downpour character of rainfall in the future will lead to shifting hydrothermal regime towards aridization in the already dry southern part of Ukraine (Tarariko et al., 2017). Thus, a high risk of an increase in aridity (Groisman and Ivanov, 2009) in the case of global warming over 1.5°C (Park et al., 2018) and moderate risk of desertification (Spinoni et al., 2015) is projected for the study area by the end of 21st century. However, a comprehensive study on global aridity change describes the southern part of Ukraine as a sub-humid area and found no statistically significant trend in aridity change for the period 1960–2009 (Zarch et al., 2015).

The uneven distribution of precipitation over time in the study area leads to periodic droughts. Furthermore, high interannual variability of precipitation, currently present in the study area (Barabash et al., 2004; Moon, 2013), is likely to increase in the future (Giorgi and Bi, 2005). The frequency and severity of droughts have already increased during the last 20 years and are projected to increase further in response to future climate (Loboda and Bozhok, 2020; Prokopenko and Udova, 2017). Increasing temperatures, uneven distribution of precipitation with the tendency to extreme rainfall will prevent soil moisture accumulation and, in extreme cases, can lead to decertification (Adamenko, 2014; Jones et al., 2009; Vyshkvarkova and Voskresenskaya, 2014). Thus, climatic conditions of the study area, that already experience soil moisture deficit during the growing season as the major limiting factor (Fileccia et al., 2014), can become unfavorable for agriculture.

Despite the agricultural importance of southern Ukraine and the high possibility of negative climate-change impacts on agriculture, only a few detailed small-scale scientific studies have been conducted on the climate of southern Ukraine. Some research projects were funded by international organizations and published as the reports on their websites (Adamenko, 2014; Ivanyi, 2015; Jerzy Kozyra, 2017; Shevchenko et al., 2014; Trofimova and Adamenko, 2015), and others conducted by local universities or state institutions, with an unknown peer-review process (Bogdanets, 2018; Krakovska et al., 2017; Polevoy et al., 2007; Romaschenko, 2013; Svetlichnyi, 2018; Svetlichnyy and Ibragimova, 2016). Although global climatological studies may more reliable, they lack regional details (Beck et al., 2018; Debonne, 2019; Rivas-Martínez et al., 2002; Spinoni et al., 2015). Furthermore, studies by European scientists often do not include Ukraine, because Ukraine is not a member of European Union (Ciscar et al., 2014; De Castro et al., 2007). Thus, a small-scale study with a close examination of each climate variable is needed to examine current trends in temperature and precipitation and the possibility of the climate type shift.

1.2 Research purpose and objectives

This study is driven by the lack of scientific consensus regarding the climate of southern Ukraine and current trends in precipitation, noted in the preceding section. The overarching research question is as follows: How has the climate in southern Ukraine changed over the past four decades?

This study aims to attain the following objectives:

1. Examine monthly and annual trends in temperature and precipitation in southern Ukraine;

2. Determine changes in climate types of the study area over the period 1981 - 2018;

3. Assess changes in soil-water budgets in the study area between 1981 and 2018.

2 STUDY AREA

The study area is located in Eastern Europe north from the Black Sea (Figure 1), and includes the following regions of Ukraine: Odesa oblast`, Mykolaiv oblast`, Kherson oblast`, Zaporizhia oblast`, the Autonomous Republic of Crimea, and part of Donetsk oblast` and Dnipropetrovsk oblast`. It is delimited by latitudes from 47.9° N to 45.0° N, and longitudes from 28.025° E to 39.975° E, lying within the Eastern European Plain with a grassland biome. Relief of the study area is mostly flat, with elevations below 200 m, except the Crimean Mountains in the south of Crimean Peninsula, which has elevation up to 1 545 m (Figure 1 and 2.)

The soil of the region is known as one of the most fertile in the World (Moon, 2013). Black (‘chornozem’) and chestnut (‘kashtanovi’) soils were formed during centuries in unique climate conditions under the influence of native steppe vegetation (Moon, D., 2016). However, natural steppe vegetation that used to cover 40% of the Ukrainian territory now remains only on 1% of its land (Parnikoza and Vasiluk, 2011). During the 18th - 20th centuries, parts of Eastern European Plain grassland with the most productive soils and plain relief were almost completely converted to agricultural land (Suttie et al. 2005).

Figure 1. Location of the study area

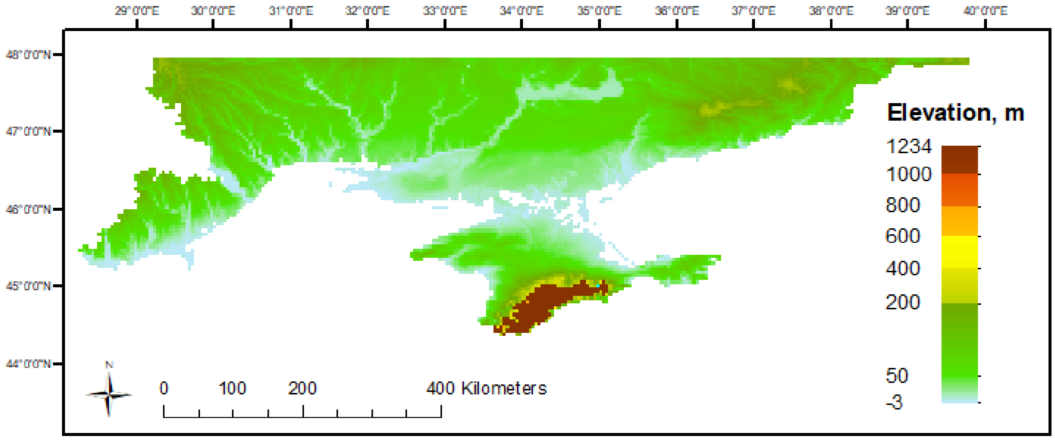


Figure 2. Relief of the study area

The mean annual temperature of five southern regions of Ukraine, that include the study area, was in the range of 8.4°C to 12°C for the period 1961—2014, with mean summer temperature about 22°C, and mean winter temperature from -3°C in the Northern part of the study area to 1°C in Crimea (Shevchenko et al., 2014). Precipitation in southern Ukraine averages between 427 to 528 mm a year (Ivanyi, 2015). Snow cover in winter is present, but not stable. Although there is no distinct dry season, the amount of summer precipitation in the region is insufficient for agriculture, thus agricultural lands often suffer from large soil-water deficit with periodic droughts during the growing season from April to August (Romaschenko, 2013).

Agriculture is one of the major sectors of the economy in southern Ukraine. Based on satellite data, spatial cropland coverage in the study area is between 60 and 85% (Najafi et al., 2018), which is one of the highest indexes of arable land in the World. For example, the cropland area in Odesa oblast` was reported by the local authorities as 62.3 % in 2016 (Shatohina, 2017). A high percentage of cultivated lands together with relatively favorable climatic conditions and fertile black soils with high organic matter content makes Ukraine one of the world's biggest producers of grains (Moon D. 2016). The biggest chank of the agricultural land, about 54,7%, is covered by grains and legumes. The major crops with the most substantial part in gross grain production are winter wheat and corn (Polevoy et al., 2007). Winter wheat covers about 20 - 25 % of the croplands and demonstrates high variability in yield in southern Ukraine (Fileccia et al., 2014; Müller et al., 2016). The other crops with significant representation are sunflower - 19%, corn for grain - 15.3%, barley - 10.5%, and soybeans – 8% of plow land (Jerzy Kozyra, 2017). Inside of the country, the region is known as a producer of vegetables for local use and export to other regions of Ukraine (Gil et al., 2008).

Relatively stable wheat yield and even moderate increase have been reported in southern Ukraine in recent decades (Grytsyuk and Bachyshyna, 2016). However, the yield growth was reached mostly by technology enhancement and was limited by water availability (Najafi et al., 2018). In the future, farming in sub-optimum conditions with a large water deficit during a growing season can be exacerbated by increasing temperatures and decreased rainfall (Bladé et al. 2012). For instance, recent decrease of barley, corn, and sorghum productivity researchers link to changes in climate (Ray et al., 2019). Winter wheat yield in southern Ukraine is projected to decrease by11% at the RCP 4.5 scenario and 18% for RCP 8.5 by 2070 as a possible feedback for climate change (Müller et al., 2016). Thus, changing environmental conditions of the study area may require a change in agricultural practices or switch to other crops, which takes investments unavailable in current economic conditions. However, only about 5-10% of the cropland areas are currently equipped for irrigation (Najafi et al., 2018).

Currently, agriculture production of the study region is already partially dependent on irrigation. The channel system from the river Dnipro allows irrigating potentially around 2 million hectares in southern Ukraine. For example, in Kherson oblast` irrigation is used to grow 30% of grains, 95% of vegetables, 60% of forage crops, and 100% of rice (Gukalova et al., 2015). However, most of the irrigation infrastructure was built in the 1960s and require maintenance or repair (Romashchenko M.I., 2013). In 2014 the ratio of the irrigated land to potentially irrigated in Khersonska oblast` was 70% (291 800 hectares), Odesa oblast` - 19%, Mykolaiv oblast` - 13%. In general, only 610 000 hectares were irrigated according to the Ministry of Agrarian Policy and Food of Ukraine website. Furthermore, development of the irrigation potential in the future will be limited by up to 70% reduction of water resources in southern Ukraine (Loboda, 2010; Loboda and Bozhok, 2016; Loboda et al., 2019; Trofimova and Adamenko, 2015).

3 DATA AND METHODS

3.1 Data

One of the reasons for the lack of regional climate research in Ukraine is the lack of high-quality data from a relatively dense network of stations. The Ukrainian Hydrometeorological Center, which is officially responsible for meteorological data collection in Ukraine, does not provide the temperature or precipitation data to the public. Thus, three publicly available data sources were used for this study:

(1) US National Oceanic and Atmospheric Administration (NOAA) Global Historical Climatology Network (GHCN) summary of the day;

(2) Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS; Funk et al., 2015);

(3) WorldClim 2.1 historical monthly weather data, presented by the Climatic Research Unit, University of East Anglia (Fick and Hijmans, 2017; Harris et al., 2014).

WorldClim 2.1 is a gridded global dataset that combines satellite-based and station data. WorldClim 2.1 historical monthly temperature data were obtained for the period 1981-2018 with spatial resolution 2.5 minutes (about 21 km^2).

3.1.1 NOAA dataset analyses and preparation

The NOAA dataset obtained for the study area contains daily summaries of weather station data from 62 stations for the period 1981 to 2019. First, analysis of the completeness of the stations data was performed. Complete list of the stations with location coordinates and percent of completeness of the dataset is presented in Appendix A. Data sources and quality of the data were analyzed based on metadata provided by NOAA. Besides location, date, temperature and precipitation values, NOAA dataset includes attributes field, that contains coded information about the data source, method of calculations daily precipitation, and data quality check results. Complete list of the stations that failed any of the quality checks is presented in Appendix B. Stations data that filed any of the quality checks was not included in this study. Three stations (Table 1) were selected for this research based on 97 % completeness of the dataset from 1981 to 2012. Three stations have been used: Askania Nova, Lugansk, and Nikolaev.

Table 1. Location and data characteristics of selected weather stations.

Station name	**Lati-tude**	**Longi-tude**	**Eleva-tion, m**	**% non-missing daily data from 1981-2018**	**% non-missing daily data from 1981-2012**	**Attributes: calculation method, quality check, data source**
Lugansk	48.5667	39.25	59	88.2	99.9	B,,S: precipitation total formed from two twelve-hour totals; did not fail quality checks; source: Global Summary of the Day (NCDC DSI-9618)
Nikolaev	46.9667	31.9831	49	84.2	97	,,E: no information on how precipitation total formed; did not fail quality checks; source: European Climate Assessment and Dataset (Klein Tank et al., 2002)
Askania Nova	46.5	33.9	28	92.8	100	,,r - no information on how precipitation total formed; did not fail quality checks; source: All-Russian Research Institute of Hydrometeorological Information -World Data Center. T,,r - trace of precipitation, snowfall, or snow depth; did not fail quality checks; source: All-Russian Research Institute of Hydrometeorological Information – World Data Center. ,,E - no measurement information on how precipitation total formed; did not fail any of quality assurance check; did not fail any of quality assurance check; source – European Climate Assessment and Dataset (Klein Tank et al., 2002)

3.1.2 CHIRPS precipitation dataset preparation and validation

CHIRPS is a quasi-global data set that incorporates in-house climatology, 0.05° resolution satellite imagery, and in-situ station data to provide rainfall data from 1981 to near-present (Funk, 2014). CHIRPS daily and monthly rainfall estimates for the latitudes from 47.975N to 45.025N, and longitudes from 28.025 E to 39.975 E were obtained for a 38-year period (January 1, 1981 to December 31, 2019). The full dataset, that contained gridded rainfall estimates in 14 704 cells, was first cleaned from missing data (indicated by -9999) and cut to the shape of the study area using ArcGIS software. The cleaning phase decreased the number of cells to 7 381. Then, considering that CHIRPS rainfall estimates were not previously used for the high latitudes (Aksu and Akgül, 2020), dataset validation was performed based on the ground-based station data (Diem, 2019).

A validation process shows the ability of the satellite-based products to reproduce ground-based precipitation data. Daily rainfall totals estimated by CHIRPS were compared with rainfall totals at the three weather stations (Askania Nova, Nikolaev, Lugansk) for the period 1981–2012. This validation period was chosen due to the relatively large amount of missing daily rainfall totals after 2012. The nine-cell weighting procedure of calculating CHIRPS rainfall total estimations corresponding to a given gauge was used (Diem et al., 2019a). Weight of the rainfall estimates of the gridded dataset was calculated based on the inverse distance from the weather station to the centroids of each cell. The range in weights for the nine cells across all combinations was 0.053–0.377. The example of distance measurements from a weather station to centroids of the closest nine cells of the gridded CHIRPS dataset, conducted in ArcGIS software, is provided in Figure 3. The example of the nine-cell weighting calculations for Nikolaev station (46.9667N, 31.9831E) is provided in Table 2.

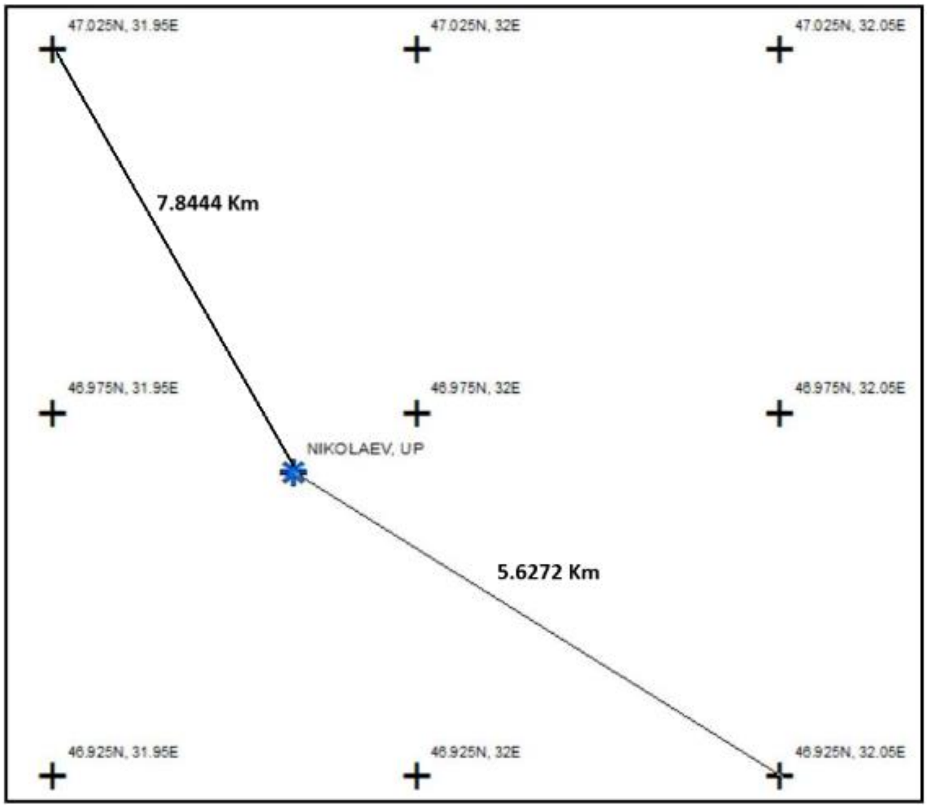


Figure 3. Example of the distance measurements for Nikolaev station

Table 2. Example of nine-cell weighting procedure for Nikolaev station

Cell code	Latitude	Longitude	Distance from the station to the center of each cell, Km	Inverse Distance	Weight
1	47.025	31.925	7.844485	0.127478094	0.053316
2	47.025	31.975	6.510472	0.153598695	0.06424
3	47.025	32.025	7.222437	0.138457421	0.057908
4	46.975	31.925	4.516515	0.221409649	0.092601
5	46.975	31.975	1.109655	0.901180998	0.376906
6	46.975	32.025	3.319307	0.301267704	0.126001
7	46.925	31.925	6.407509	0.15606689	0.065273
8	46.925	31.975	4.676617	0.213829783	0.089431
9	46.925	32.025	5.627284	0.177705621	0.074323

3.2 Detection of temporal change points and adjustment of time series

The homogeneity of CHIRPS satellite-based precipitation estimates was assessed using change-point analysis. The double-mass curves (DMCs) method was used for detecting temporal change points in the precipitation time series. This method of detecting inhomogeneities is based on comparison of cumulative rainfall totals, which makes it less sensitive to outliers (Diem et al., 2019a). The DMC represents cumulative totals of daily CHIRPS precipitation estimates versus cumulative totals of ground-measured daily data. The straight line of the double-mass curve indicates a fixed ratio between the two variables, and change point in the line slope indicates change in relationship between variables (Searcy and Hardison, 1960). Mean cumulative daily totals of Askania Nova, Lugansk, and Nikolaev weather stations for the period 1981 – 2018 were used in this study. Considering that DMC approach requires serially complete data, gaps in Nikolaev station data were filled in using extrapolation from the closest station (Bastanka) and three days with missing rainfall totals in Lugansk station were given the mean rainfall totals of that day based on two other stations (Askania Nova and Nikolaev) to reach 100% completeness of the dataset. Mean daily totals from three stations were used to avoid station-specific effects. Change point significance was estimated based on analysis of covariance ($\alpha = 0.05$). The adjustment of the time series was performed by multiplying CHIRPS satellite-based precipitation estimates before a change point by an adjustment factor - the ratio of the linear regression slopes after and before the change point.

3.3 Precipitation regionalization

Considering that precipitation dataset used for this study has over 7000 individual cells, which is impractical to analyze individually, regionalization was used as a data simplification tool (Diem et al., 2019b). Climate regionalization divides the study area into homogeneous regions with coherent in some respect climatic variables (Badr et al., 2015). Rainfall data were used for regionalization based on the fact that temperature changes in precipitation in the 20th century were the most important factor for shifting of the climate types on a regional scale (Feng et al., 2014). The study area was divided into regions with similar monthly precipitation variability from 1981 to 2018 using the factor analysis method (Bayat et al., 2018; Kachigan, 1991).

3.4 Assessment of multi-decadal trends in precipitation and temperature

CHIRPS gridded satellite-based rainfall data and WorldClim 2.1 historical monthly temperature data for the period 1981-2018 were analyzed for the presence of statistically significant trends. First, monthly precipitation and temperature data were aggregated based on precipitation regions. Then, the presence of the statistically significant multi-decadal trends over 1981–2018 in monthly precipitation and temperature was estimated using Kendall-Tau and Spearman's rank-order nonparametric correlation tests ($\alpha = 0.05$; one-tailed). Both test are widely used by researchers in climatological variables trend analysis (Diem et al., 2019a; Villarini, 2012). The results of these tests show the strength and direction of the association between two variables – time and precipitation, and time and temperature in each of the regions. Nonparametric Mann-Kendall trend test was used for testing the presence of monotonic increasing or decreasing trends and the Sen’s method - for estimating the slope of a linear trend (Gocic and Trajkovic, 2013). Specialized software (MAKESENS 1.0 Mann-Kendall Test and Sen's Slope Estimates for the Trend of Annual Data), provided by the Finnish Meteorological Institute, was used to perform this task. The slope of the linear trend was used to estimate temperature and precipitation values for 1981 and 2018 to determine the climate types and calculate soil-water budgets in the first and the last year of the study period.

3.5 Determination of climate types

Climate classification, as a generalization of the climate conditions, is a convenient tool for analysis of the environmental conditions of the study area. There are multiple climate classification systems developed by different scientists during the 20th century. The first and still dominant quantitative climate classification system was developed by Vladimir Köppen at the beginning of 20th century (Köppen and Geiger, 1923). This system divides climates into five major groups (A – Tropical, B – Arid, C – Temperate, D – Cold, E – Polar) and 16 subgroups, which results in 30 possible climate types. The most common modifications of Köppen classification include revision of the thresholds between C and D climates and aridity determinators (Kottek, 2006; Peel et al., 2007).

In this study, the Köppen-Geiger climate classification was chosen, since it is a commonly used regional climate-type classification scheme (Karki et al., 2016; Kozjek et al., 2017; Rahimi et al., 2020). The Köppen–Trewartha climate classification was considered as not suitable for the study area. Although Köppen–Trewartha classification was developed to account for land cover of the area, it fails to reflect known prevalent native vegetation type of southern Ukraine – steppe grassland (which corresponds to BS climate type in Köppen–Trewartha classification). Literature review shows that published Köppen–Trewartha climate maps that include study area define it as Do, which corresponds to dense coniferous forests with large trees and Dc - Needleleaf and deciduous tall broadleaf forest (De Castro et al., 2007). However, both proposed climate types do not represent the existing biome of the study region.

The climate type of each region was calculated using the criteria in the Köppen-Geiger climate classification (Figure 4) as explained by Kottek (2006). Climate types in 1981 and 2018 were determined based on temperature and precipitation values estimated using multi-decadal trend, explained in the previous section. The possibility of B (arid) climate was identified firs, following by A, C, D, and E climates, as recommended by Peel et al. (2007). The formula for determination of B (arid) climates is Pann <10 x Pth, where Pann – mean annual precipitation, and Pth - Dryness Threshold, calculated as following (Kottek, 2006):

- 2 x Tann, if at least 2/3 of the annual precipitation occurs in winter (cooler six-month period - ONDJFM);

- (2 x Tann) + 28, if at least 2/3 of the annual precipitation occurs in summer (wormer six-month period - AMJJAS);

- (2 x Tann) + 14, otherwise.

Type	Description	Criterion
A	**Equatorial climates**	$T_{min} \geq +18$ °C
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60$ mm
Am	Equatorial monsoon	$P_{ann} \geq 25\,(100 - P_{min})$
As	Equatorial savannah with dry summer	$P_{min} < 60$ mm in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60$ mm in winter
B	**Arid climates**	$P_{ann} < 10\,P_{th}$
BS	Steppe climate	$P_{ann} > 5\,P_{th}$
BW	Desert climate	$P_{ann} \leq 5\,P_{th}$
C	**Warm temperate climates**	-3 °C $< T_{min} < +18$ °C
Cs	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\,P_{smin}$ and $P_{smin} < 40$ mm
Cw	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\,P_{wmin}$
Cf	Warm temperate climate, fully humid	neither Cs nor Cw
D	**Snow climates**	$T_{min} \leq -3$ °C
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\,P_{smin}$ and $P_{smin} < 40$ mm
Dw	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\,P_{wmin}$
Df	Snow climate, fully humid	neither Ds nor Dw
E	**Polar climates**	$T_{max} < +10$ °C
ET	Tundra climate	0 °C $\leq T_{max} < +10$ °C
EF	Frost climate	$T_{max} < 0$ °C

Type	Description	Criterion
h	Hot steppe / desert	$T_{ann} \geq +18$ °C
k	Cold steppe /desert	$T_{ann} < +18$ °C
a	Hot summer	$T_{max} \geq +22$ °C
b	Warm summer	not (a) and at least 4 $T_{mon} \geq +10$ °C
c	Cool summer and cold winter	not (b) and $T_{min} > -38$ °C
d	extremely continental	like (c) but $T_{min} \leq -38$ °C

Figure 4. Description of Köppen climate symbols and defining criteria (image from Kottek (2006)

3.6 Assessment of changes in soil-water budget

Analyzing of the soil-water budget was performed to determine soil-water deficit, as one of the major limiting factors of the crop yield (Webber et al., 2015). WebWIMP version 1.02 Web-based Water-Budget tool (http://climate.geog.udel. edu/*wimp/) (Mather, 1978; Willmott et al., 1985) was used for modeling of the soil-water budgets in the study area in 1981 and 2019. The model estimates potential surplus or deficit of moisture in soil based on precipitation, temperature (which is used to calculate potential evaporation), and the soil water-storage capacity (Diem et al., 2017). Mean monthly air temperature and precipitation, estimated using a multi-decadal trend established in section 3.4, were used as input data for 1981 and 2018 models in each of four regions. A soil water-storage capacity of the soil unit was assumed as 150 mm m^{-1} for all regions and both years, which is acceptable considering that this study is focused on changes in the soil-water budget.

4 RESULTS

4.1 Intra-annual variations in temperature and precipitation

The study region has high intra-annual variations of mean monthly temperature throughout the year (Figures 5). The range in mean monthly temperature for the 1970-2000 period was from -6.5 ˚C in January, the coldest month, to 23.6 ˚C in July and August, the hottest months.

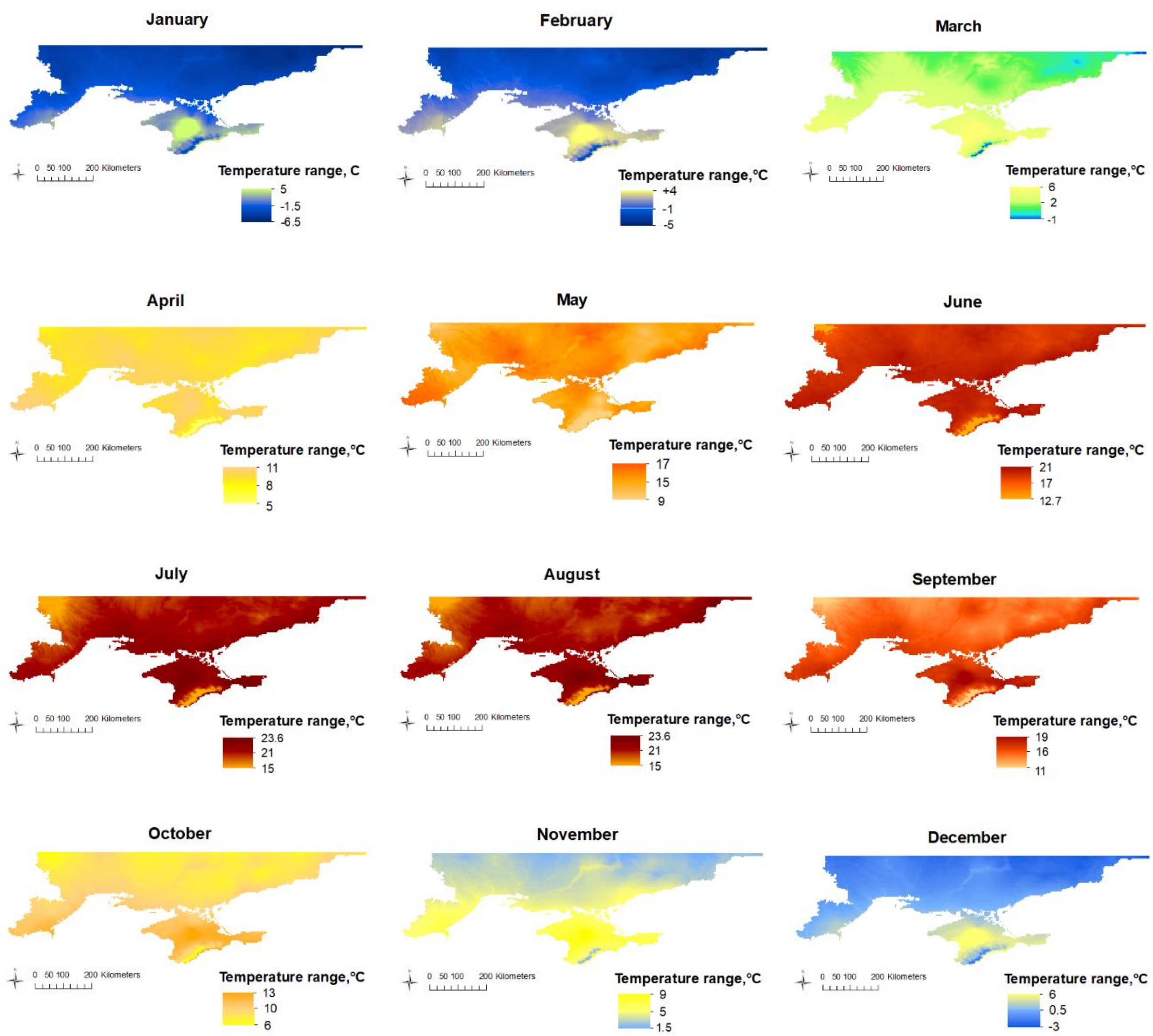


Figure 5. Mean monthly temperature (1970-2000)

Data source: WorldClim version 2.1 climate data for 1970-2000 with 2.5 minutes spatial resolution (Fick and Hijmans, 2017).

The mean monthly precipitation values show no distinct dry season in the study area. The range in mean monthly precipitation over the study area for the 1970-2000 period was from over 100 mm in December over the Crimean Mountains to about 20-30 mm in the majority of the mainland during the year (Figures 6).

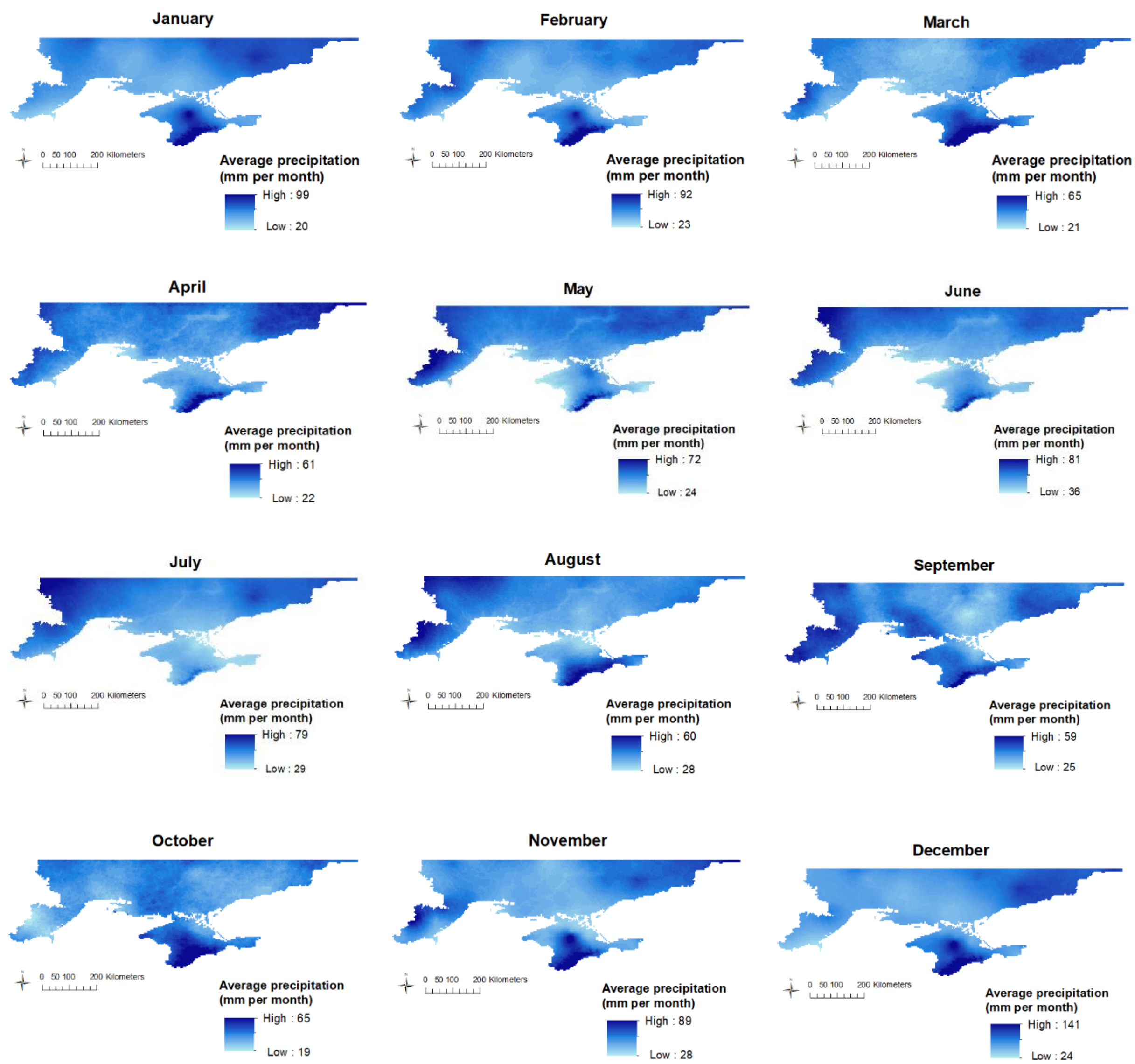


Figure 6. Mean monthly precipitation (1970-2000)

Data source: WorldClim version 2.1 climate data for 1970-2000 with 2.5 minutes spatial resolution (Fick and Hijmans, 2017).

4.1.1 Regionalization

Four regions with homogeneous precipitation variation in 1981-2019 were determined in the study area (Figure 7). Region 1 (R1) includes the western part of the study are, Region 4 (R4) – the Crimean Peninsula and part of the mainland close to it, region 3 (R3) – eastern part, north from Azov sea, and region 2 (R2) – the central part of the study area. A positive correlation of average monthly rainfall between all four regions was found. The strongest correlation is between precipitation patterns in R1 and R2 (correlation coefficient 0.98), R4 and R3 (correlation coefficient 0.86), R3 and R2 (correlation coefficient 0.83). Less similar are regions R1 and R3 (correlation coefficient 0.79), R4 and R2 (correlation coefficient 0.55), R1 and R4 (correlation coefficient 0.53).

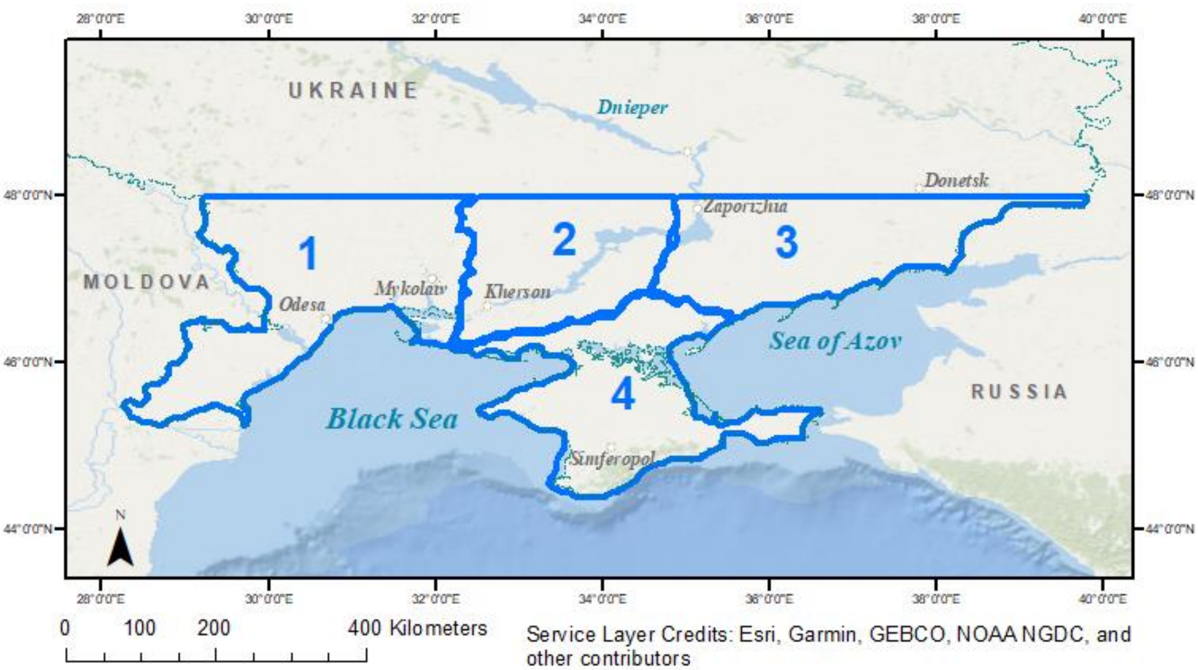


Figure 7. Regionalization results.
R1 - western part of the study area, R2 – central part of the study area, R3 – eastern part of the study area, R4 – Crimean Peninsula and the most southern part of the continental area.

Although no distinct dry season is present in any of the regions, there are some differences in annual precipitation totals and intra-annual variation of precipitation among the regions. The wettest month for all regions is June. The rainfall in June is between 63 mm (R2) and 70 mm (R1). Regions 4 and 3 receive relatively large rainfall in November, December, and January (between 45 and 50 mm). The driest months with rainfall between 30 and 40 mm a month for R1 and R2 from February to April, August and October, for R4 - from February to April, July and September, for R3 - from February to April, and from August to October. The average annual precipitation varies from 509 mm in R2 to 556 mm in R3 (Table 3).

Average annual temperature (Table 4) varies from 9.6 ˚C in R3 to 11.2 ˚C in R4. The average temperature of the hottest month, July, is above 22 ˚C for all the regions, following by August with average temperatures from 21.8 ˚C in R1 to 22.3 ˚C in R3 (Figure 11). The coldest month is January for all the regions, with average temperatures -3.5ºC in R3, -2.4˚C in R2, -2.2˚C in R1 and 0.2 ˚C in R4. Combined average annual temperature and precipitation data (adjusted) is presented in climographs (Figure 8).

Table 3. Average annual precipitation (mm) for 1981-2019 period

R1	R2	R3	R4
519.8	508.7	556.4	520

Table 4. Average annual temperature (˚C) for1981-2018 period

R1	R2	R3	R4
10.1	9.9	9.6	11.2

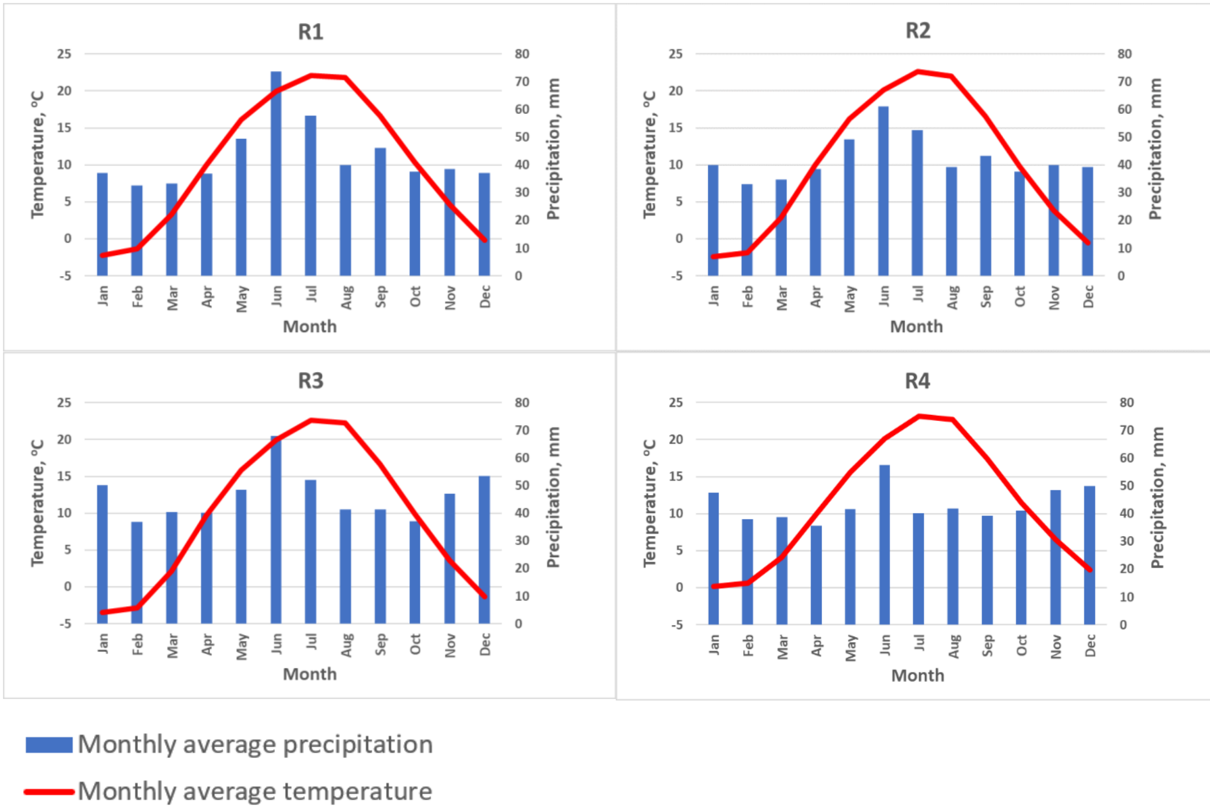


Figure 8. Climograph - a graphical representation of a location's climate (1981 – 2018).

4.2 Multi-decadal precipitation trends

The double-mass curve (Figure 6) shows a significant underestimation of rainfall totals by CHIRPS before November 1999. To reduce this bias of CHIRPS product, estimated rainfall totals from January 1981 to October 1999 were multiplied by 1.163 (Diem et al., 2019a). The slope of the double-mass curve line after November 1999 is close to 1, which indicates good correlation of the CHIRPS estimates to the station data. Considering that the validation process confirmed the ability of CHIRPS to adequately capture precipitation data, corrected CHIRPS rainfall estimates were used as a data source for precipitation trend analysis.

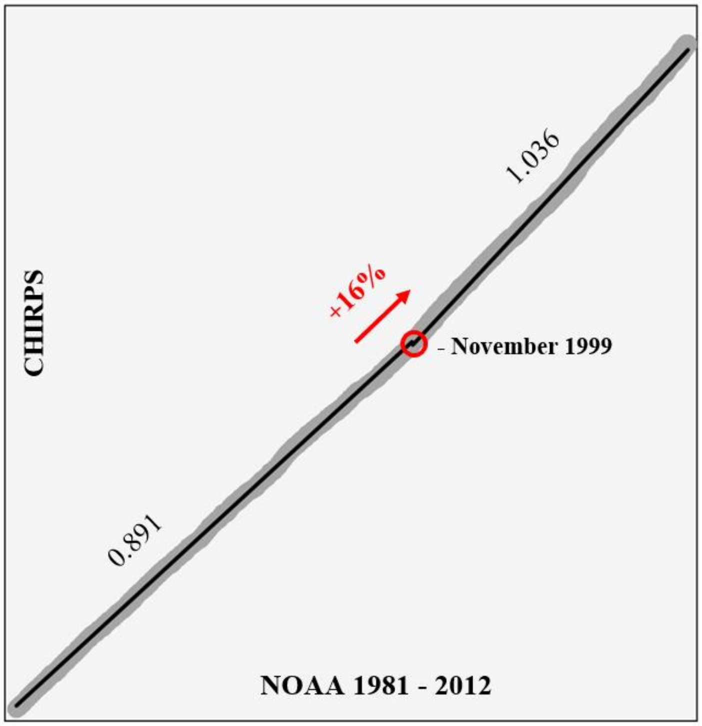


Figure 9. Double-mass curve representing the relationship between CHIRPS rainfall estimates and weather station data in 1981-2012.
Cumulative monthly rainfall measured at the weather station is the x-axis, and cumulative monthly rainfall estimated by CHIRPS is at the y-axis. 0.891 and 1.036 are the slopes of the lines before and after November 1999 – a break point in the relationship between measured and estimated rainfall.

Unadjusted mean annual precipitation trend shows statistically significant at the 0.05 level increase for 37 years (1981-2018) (Figure 10). However, adjusted for CHIRPS bias correction precipitation dataset has no statistically significant trends for any of the four regions (Figure 11). Both annual precipitation time series also show a high year-to-year variability of the rainfall totals.

The mean monthly precipitation trends for the period 1981-2018 show statistically significant increase at the 0.05 level in January precipitation in regions R1 and R4 and statistically significant decrease in August precipitation in regions R1, R2 and R4 (Figures 12, 13, 14). Over 37 years precipitation in January increased in R1 by about 19 mm (79% increase in 2018 compared to 1981), and in R4 for about 17 mm (48% increase). August precipitation decreased in R1 for about 17 mm (39% decrease), R4 - 19 mm (43% decrease), R2 - 17 mm (38%) (Table 5). No statistically significant trends in Region 3 precipitation were determined (Figure 15).

Table 5. Statistically significant change in precipitation over the period 1981-2018.

Month / region	R1		R2		R3		R4	
	Change, mm	Change, %	Change, mm	Change, %	Change, mm	Change, %	Change, mm	Change, %
January	+19	+79	-	-	-	-	+17	+48
August	-17	-39	-17	-38	-	-	-19	-43

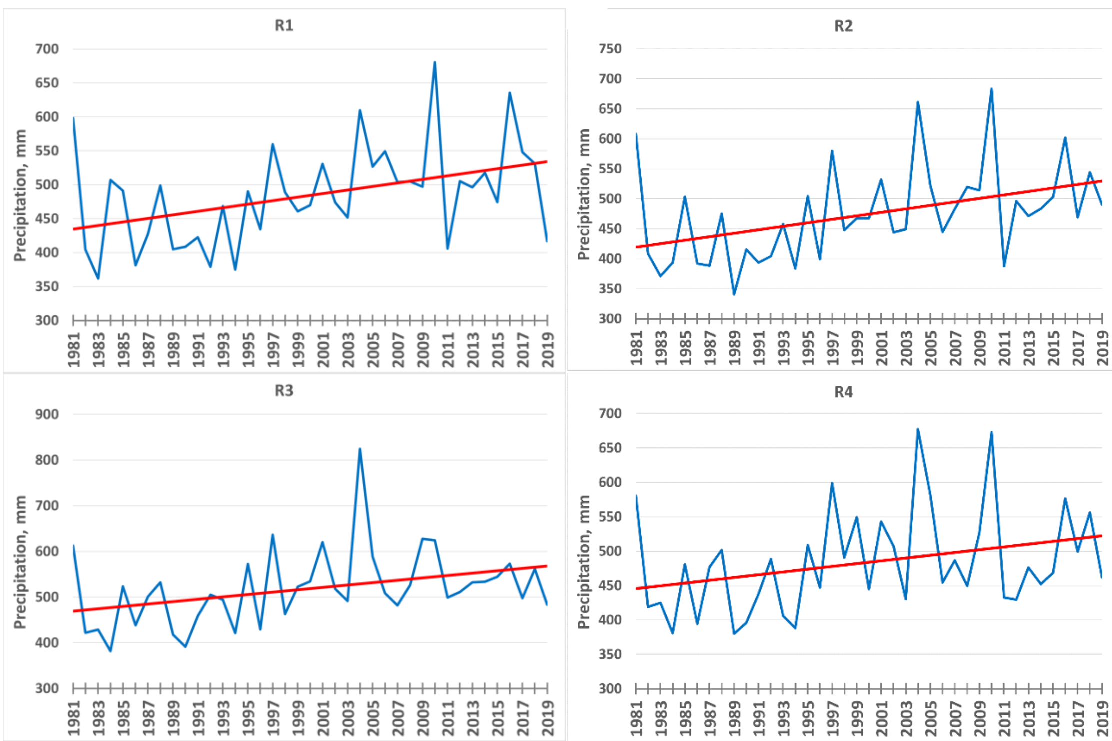


Figure 10. Annual precipitation time series for 37 years (1981-2018) (unadjusted) Red lines represent statistically significant trends (α= 0.05; one-tailed).

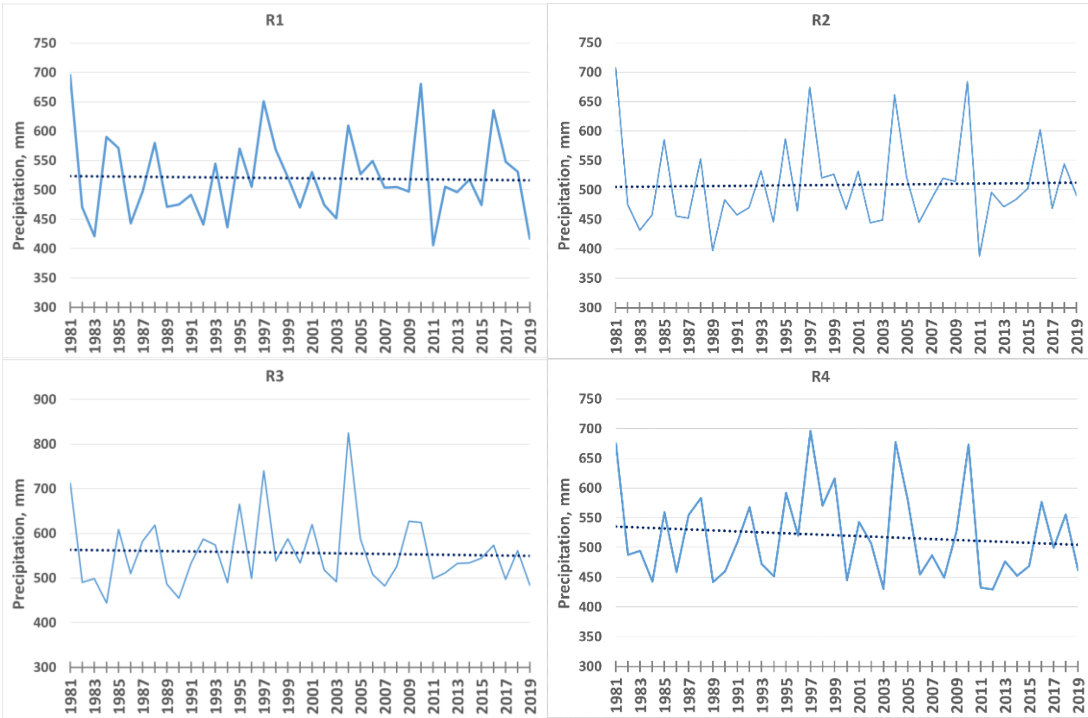


Figure 11. Annual precipitation time series for 37 years (1981-2018) (adjusted for CHIRPS bias correction).
Dash blue line represent statistically non-significant trends

Figure 12. Region 1 mean monthly precipitation (adjusted) over 37 years (1981-2018). Month: 1-January, 2- February, 3-March, 4-April, 5-May, 6-June,7- July, 8-August, 9-September, 10-October, 11-November, 12-December.
Solid dark-blue line represents statistically significant increasing trend (α= 0.05; one-tailed).
Solid red line represents statistically significant increasing trend (α= 0.05; one-tailed).
Dash blue lines represent non-significant trend.

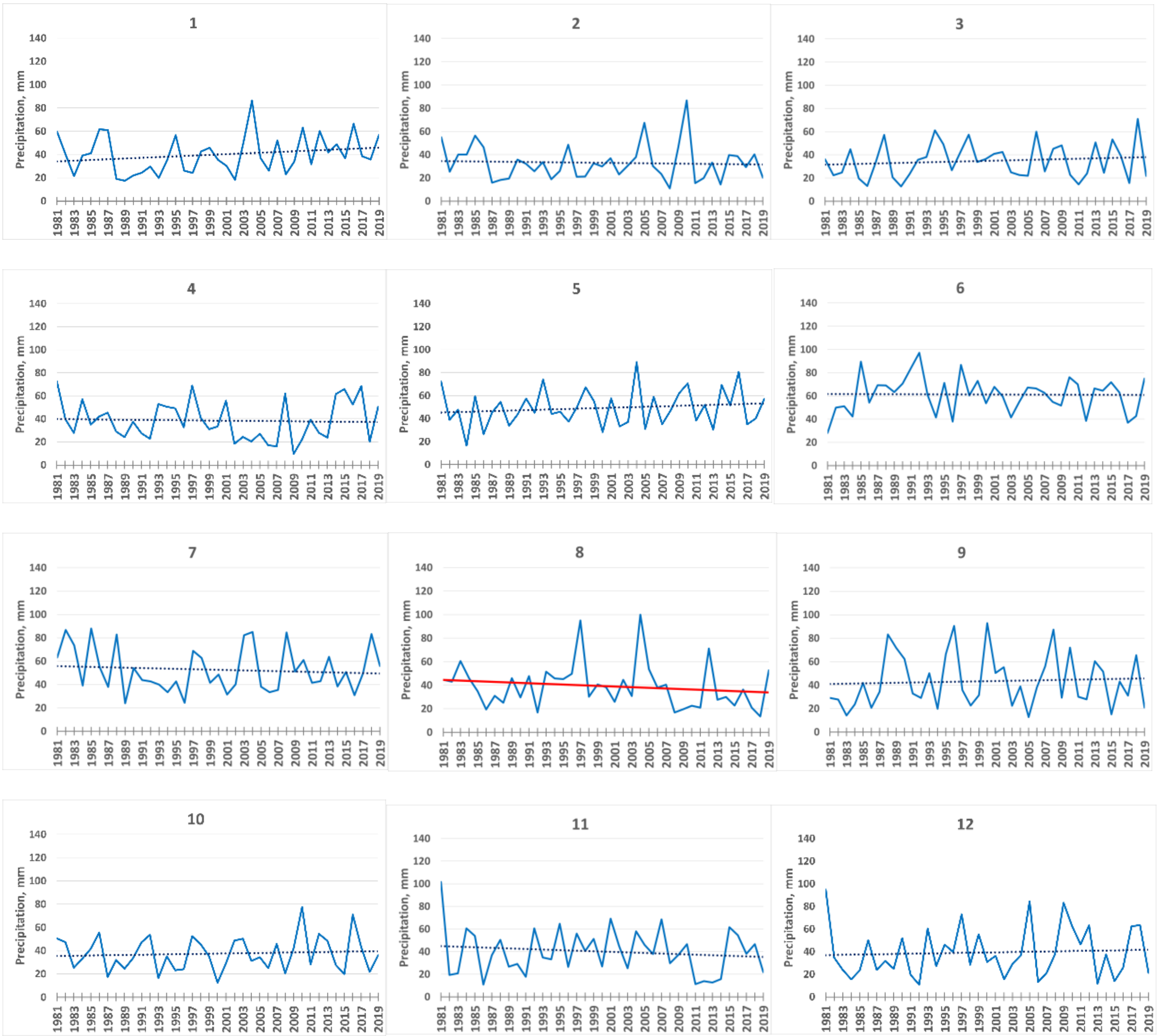


Figure 13. Region 2 mean monthly precipitation (adjusted) over 37 years (1981-2018). Month: 1-January, 2- February, 3-March, 4-April, 5-May, 6-June,7- July, 8-August, 9-September, 10-October, 11-November, 12-December.
Solid red lines represent statistically significant decreasing trend (α= 0.05; one-tailed).
Dash blue lines represent non-significant trend.

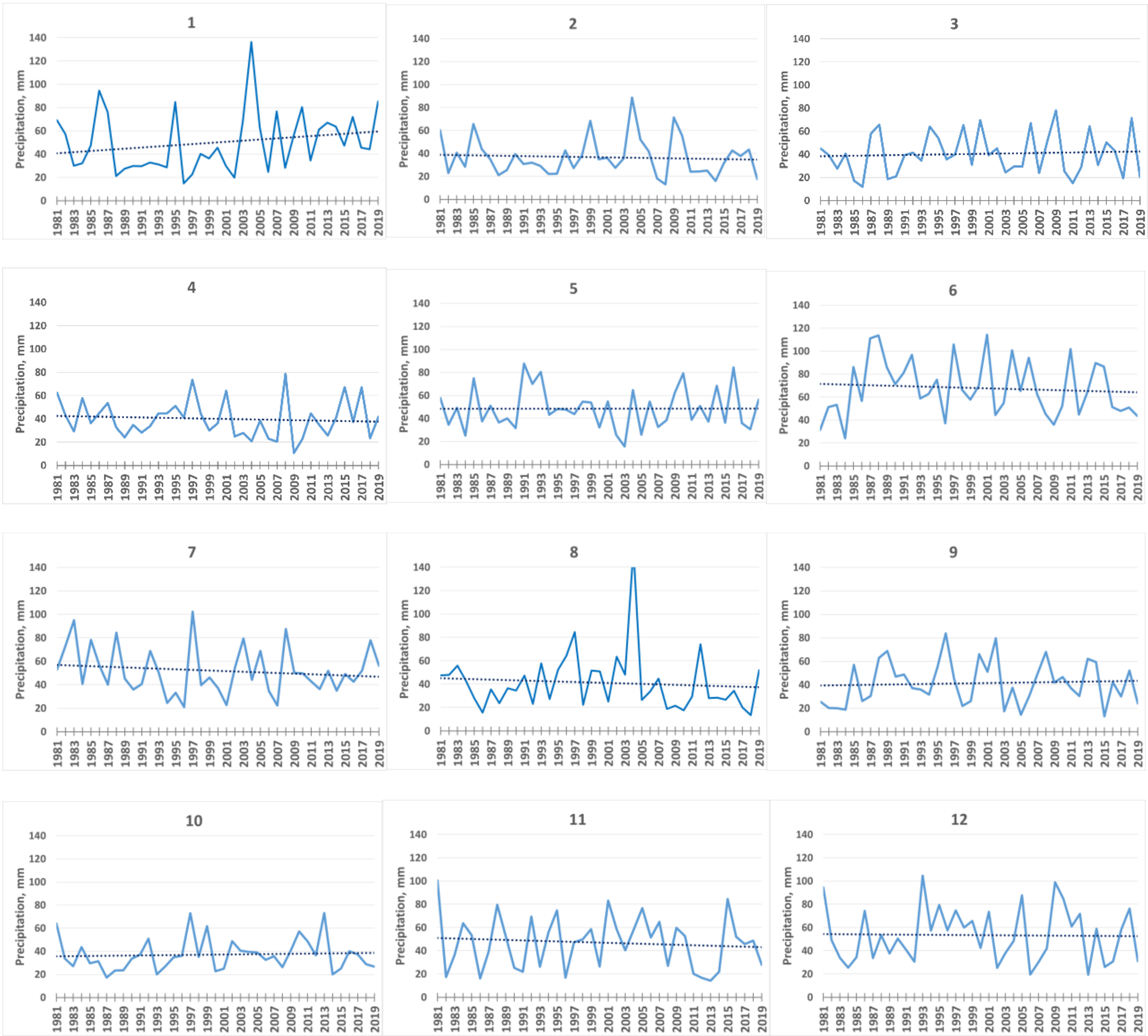


Figure 14. Region 3 mean monthly precipitation (adjusted) over 37 years (1981-2018). Month: 1-January, 2- February, 3-March, 4-April, 5-May, 6-June,7- July, 8-August, 9-September, 10-October, 11-November, 12-December.
Dash blue lines represent non-significant trend.

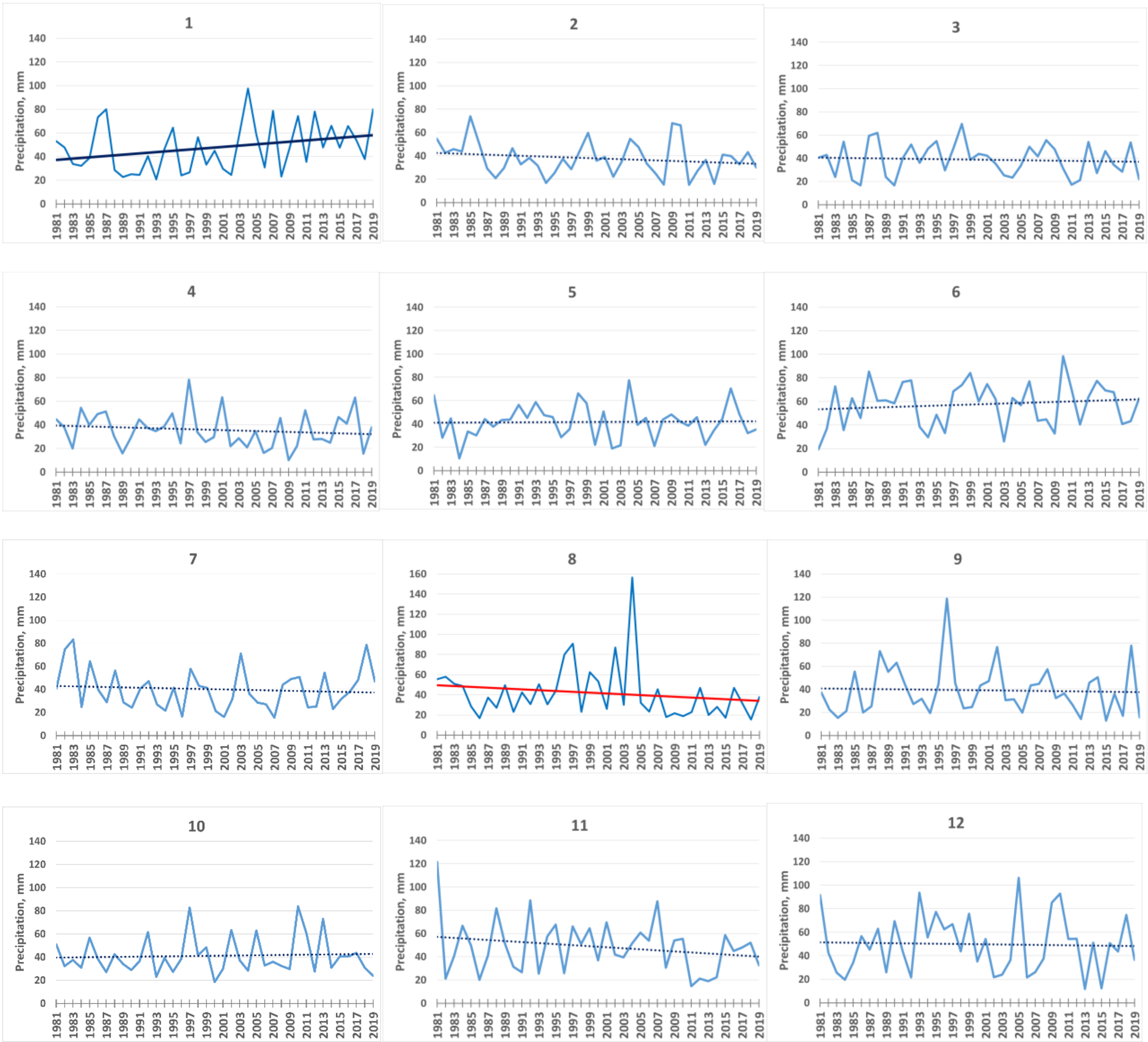


Figure 15. Region 4 mean monthly precipitation (adjusted) over 37 years (1981-2018). Month: 1-January, 2- February, 3-March, 4-April, 5-May, 6-June,7- July, 8-August, 9-September, 10-October, 11-November, 12-December.
Solid dark-blue line represents statistically significant increasing trend (α= 0.05; one-tailed).
Solid red line represents statistically significant decreasing trend (α= 0.05; one-tailed).
Dash blue lines represent non-significant trend.

4.3 Multi-decadal temperature trends

Mean annual and warm season temperature increased in study region over the period 1981-2018. Statistically significant at the 0.01 level increase in mean annual temperature for 1.8-2 ˚C found in all 4 regions (Table 6, Figure 16). The average monthly temperature increased mostly in warmer months. The highest statistically significant warming in the range 3.3 – 3.5 ˚C occurred in August in all four regions. For all the regions the highest statistically significant (at the 0.01 level) increase in temperature was found in Summer and Autumn months: June, July, August, September, and November; significant at the 0.05 level increase also occurred in Spring: in April and May for R1 and in March, April and May for R2, R3, and R4. No significant trend was found in December, January, February and October. The scale of the temperature increase is presented in Table 6.

Table 6. Temperature increase over the period 1981-2018.
Asterisk represents statistically significant increase.
Month: 1-January, 2- February, 3-March, 4-April, 5-May, 6-June,7- July, 8-August, 9-September, 10-October, 11-November, 12-December.

	Temperature increase, ˚C												
Month	1	2	3	4	5	6	7	8	9	10	11	12	Year
R1	-0.5	2.2	2.2	**2.3***	**1.6***	**2.5***	**2.7***	**3.4***	**1.7***	0.6	**3.0***	1.4	**1.8***
R2	-0.7	2.5	**2.3***	**1.9***	**2.0***	**2.7***	**2.7***	**3.5***	**2.2***	0.6	**2.9***	1.6	**1.9***
R3	-0.9	3.2	**2.7***	**1.7***	**2.0***	**2.6***	**2.7***	**3.5***	**2.2***	0.8	**2.8***	1.9	**2.0***
R4	0.0	2.9	**2.3***	**1.6***	**1.9***	**2.6***	**2.6***	**3.3***	**2.3***	0.8	**2.4***	1.7	**1.9***

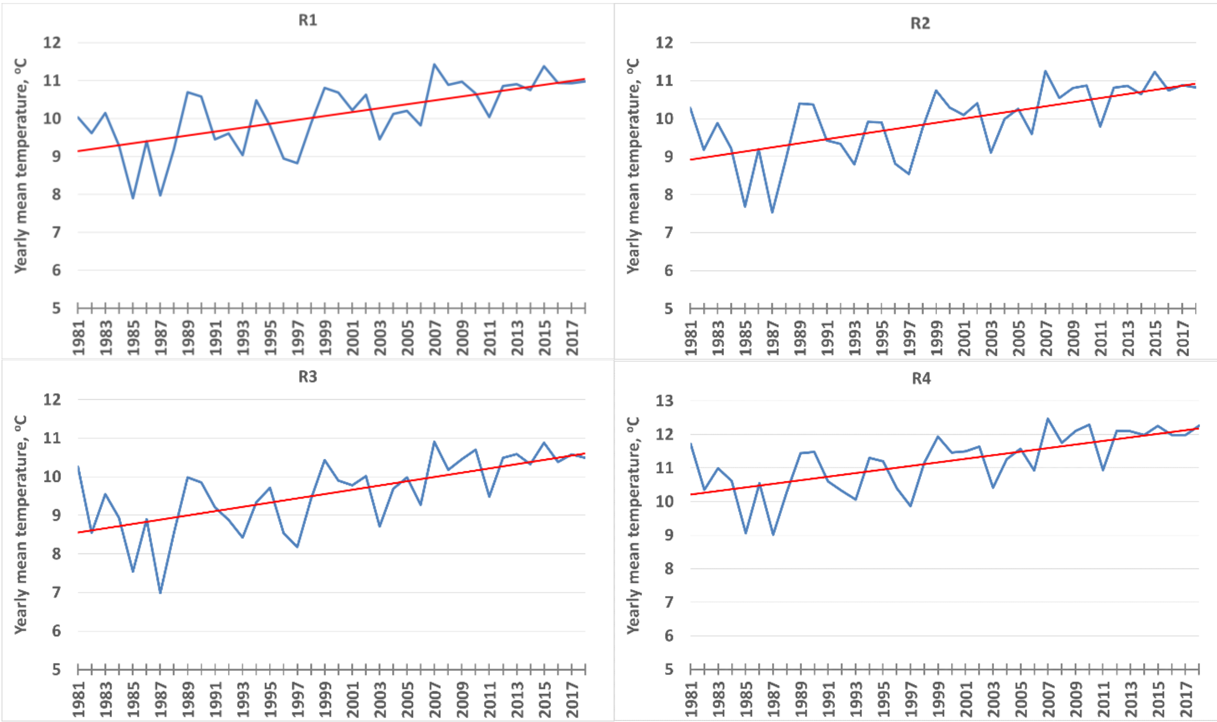


Figure 16. Trend in mean annual temperature for 37 years (1981 – 2018)
Red lines represent statistically significant trends (α= 0.05; one-tailed).

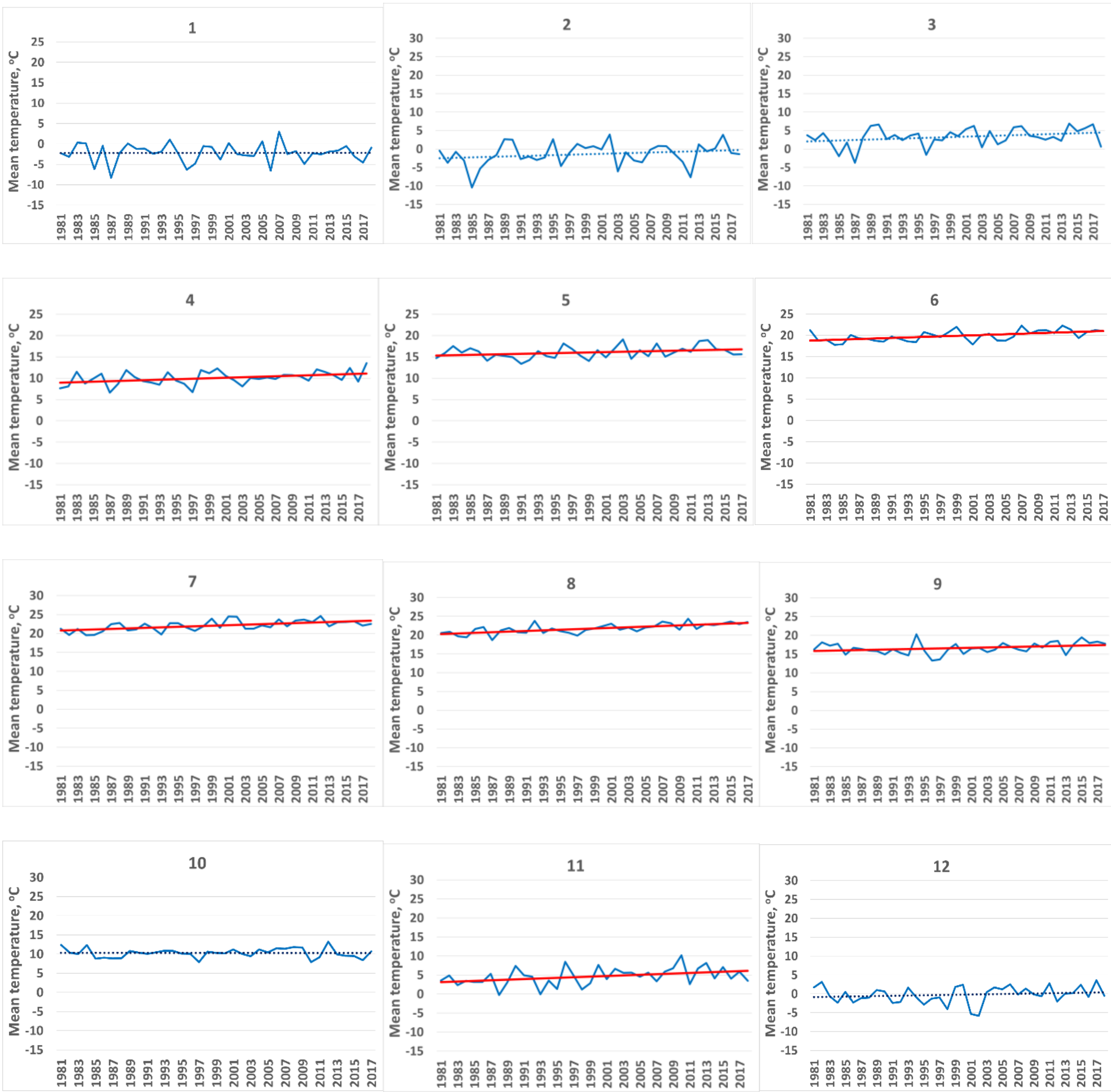


Figure 17. Region 1 monthly mean temperature trends over 37 years (1981-2018). Month: 1-January, 2- February, 3-March, 4-April, 5-May, 6-June,7- July, 8-August, 9-September, 10-October, 11-November, 12-December.
Solid red lines represent statistically significant increasing trend (α= 0.05; one-tailed).
Dash blue lines represent non-significant trend.

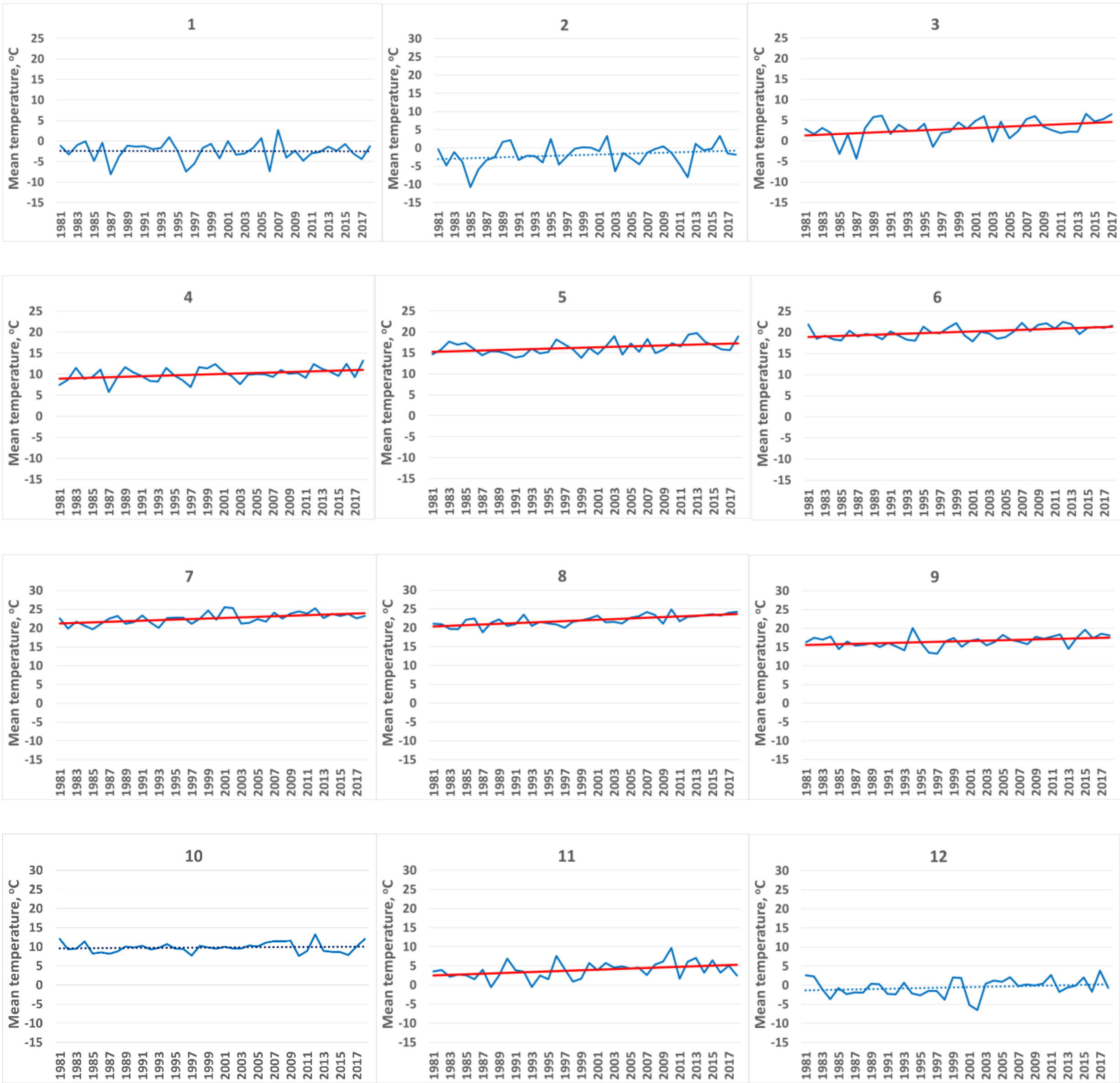


Figure 18. Region 2 monthly mean temperature trends over 37 years (1981-2018). Month: 1-January, 2- February, 3-March, 4-April, 5-May, 6-June,7- July, 8-August, 9-September, 10-October, 11-November, 12-December.
Solid red lines represent statistically significant increasing trend (α= 0.05; one-tailed).
Dash blue lines represent non-significant trend.

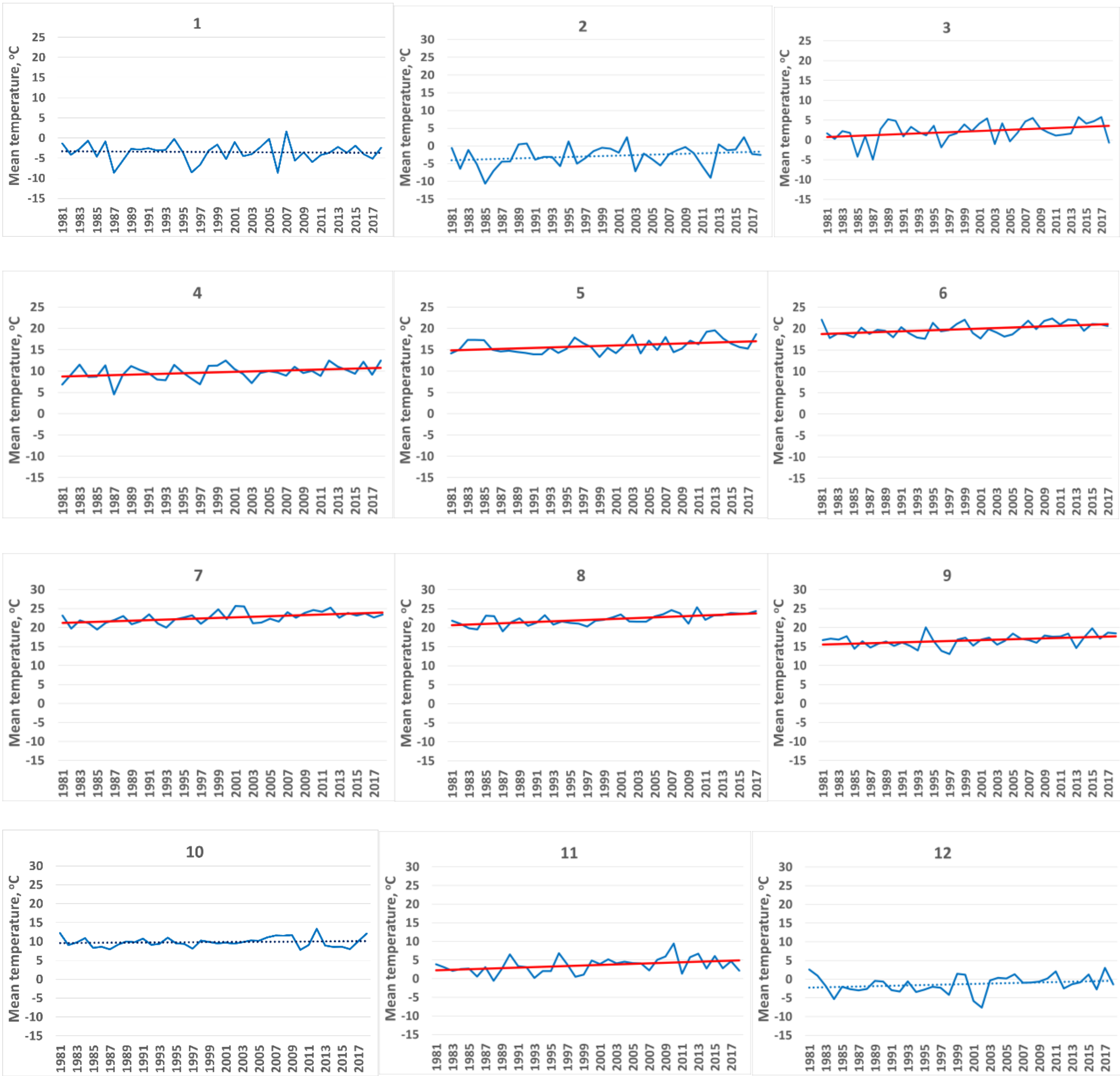


Figure 19. Region 3 monthly mean temperature trends over 37 years (1981-2018). Month: 1-January, 2- February, 3-March, 4-April, 5-May, 6-June,7- July, 8-August, 9-September, 10-October, 11-November, 12-December.
Solid red lines represent statistically significant increasing trend (α= 0.05; one-tailed).
Dash blue lines represent non-significant trend.

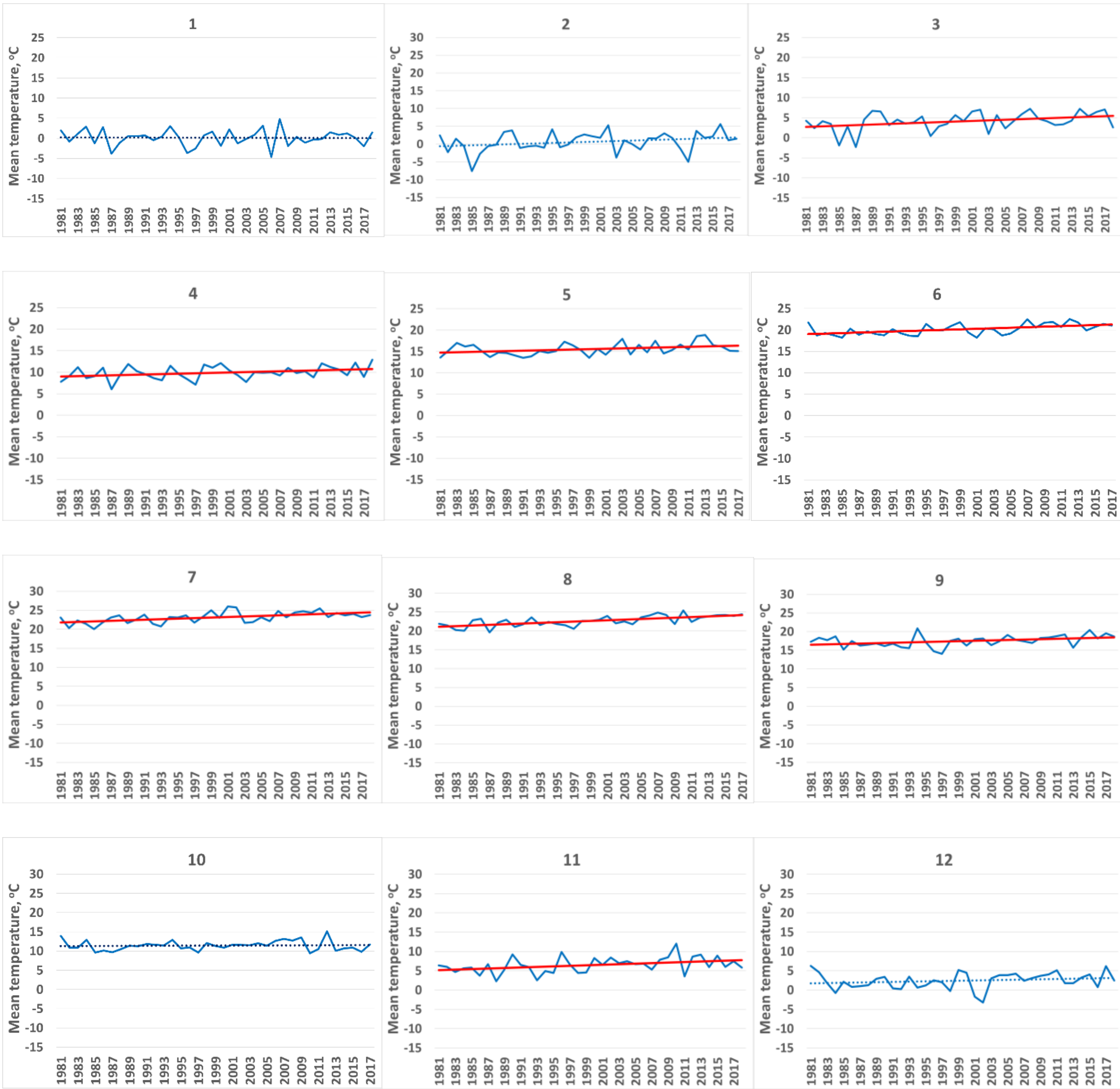


Figure 20. Region 4 monthly mean temperature trends over 37 years (1981-2018). Month: 1-January, 2- February, 3-March, 4-April, 5-May, 6-June,7- July, 8-August, 9-September, 10-October, 11-November, 12-December.
Solid red lines represent statistically significant increasing trend (α= 0.05; one-tailed).
Dash blue lines represent non-significant trend.

4.4 Multi-decadal changes in climate types

All four regions experienced a shift in climate type during 1981 – 2018 period (Table 7). Regions 1, 2, and 4 had Cfb (warm temperate, fully humid, warm summer) climate type by Köppen-Geiger climate classification in 1981, and Cfa (warm temperate, fully humid, hot summer) climate type in 2018. Region 3, the coldest of the regions, had Dfb (snow, fully humid, warm summer) climate type in 1981 and Dfa in 2018 (snow, fully humid, hot summer).

Table 7. Climate type by Köppen-Geiger climate classification in 1981 and 2018

	R1	R2	R3	R4
1981	Cfb	Cfb	Dfb	Cfb
2018	Cfa	Cfa	Dfa	Cfa

Although no B (arid) climates found in the study area, decrease in annual precipitation (Pann) to Dryness Threshold (Pth) ratio (Tables 9 and 10) in all four regions indicate shift toward arid climates.

Table 8. Calculation of the B climate determinators for 1981

1981	R1	R2	R3	R4
Pth	32.3	32.1	31.3	34.7
Pann/Pth	15.4	14.8	16.9	14.8

Table 9. Calculation of the B climate determinators for 2018

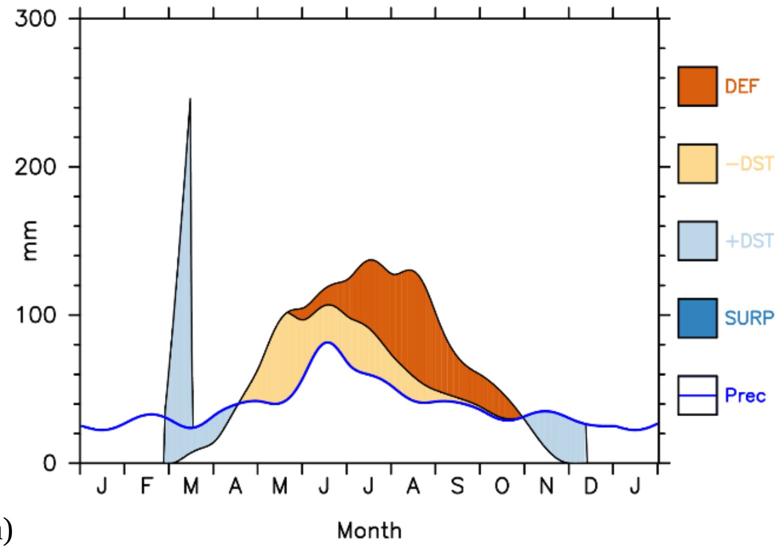
2018	R1	R2	R3	R4
Pth	36.0	35.9	35.3	38.5
Pann/Pth	14.3	13.9	15.4	12.9

4.5 Multi-decadal changes in soil-water budgets

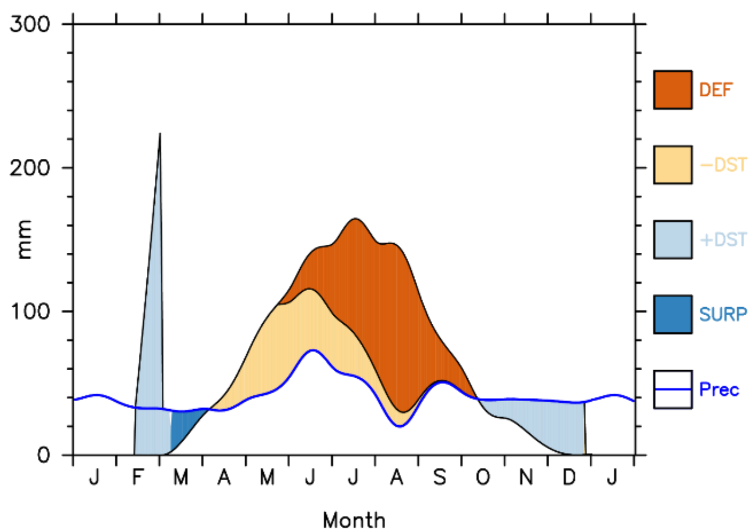
Modeling of the soil-water budgets shows a significant increase in the warm season soil water deficit for all four regions. An increase in water deficit from 1981 to 2018 was in the range of 68 – 88 mm/year^{-1} (Table 10). All four regions had water deficit from June to October both in 1981 and 2018, but Regions 1 and 3 also developed water deficit in May in 2018, and Region 1 May water deficit increased. March water surplus decreased in Region 2, 3, and 4 (Figures 22, 23, 24). In Region 1, an increase in winter precipitation led to water surplus in March in 2019, absent in 1981 (Figure 21); however, it was not enough to change the general drying trend.

Table 10. Soil water deficit by region.

	R1		R2		R3		R4	
Month/Year	1981	2018	1981	2018	1981	2018	1981	2018
Jan	0	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	0
Mar	0	0	0	0	0	0	0	0
Apr	0	0	0	0	0	0	0	0
May	2	3	0	3	0	2	0	1
Jun	14	28	17	28	11	27	15	26
Jul	45	76	58	80	51	85	67	89
Aug	63	100	67	102	66	105	68	111
Sep	29	33	36	37	39	41	41	49
Oct	13	3	9	5	9	4	11	7
Nov	0	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	0
Total	**166**	**243**	**187**	**255**	**176**	**264**	**202**	**283**

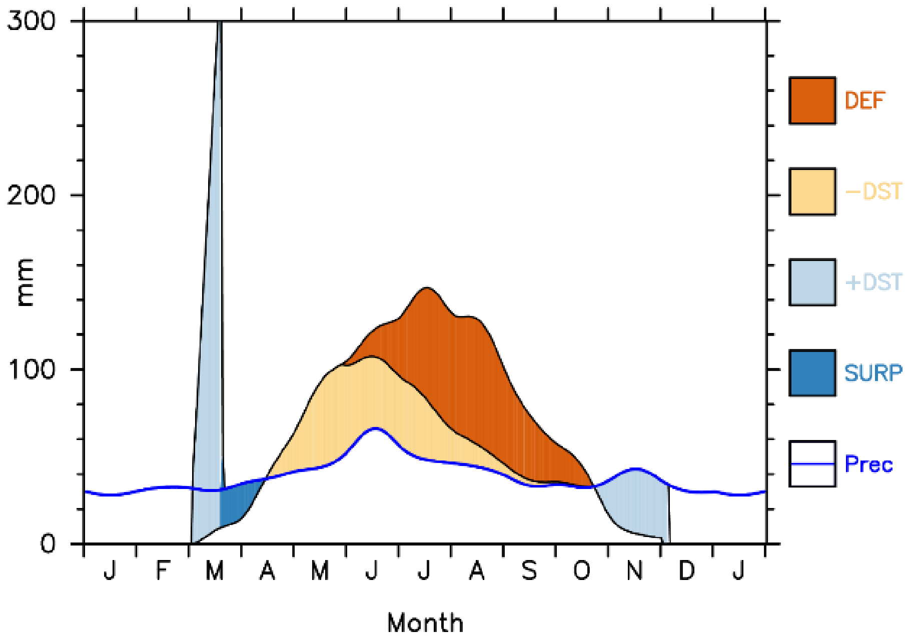


(a)

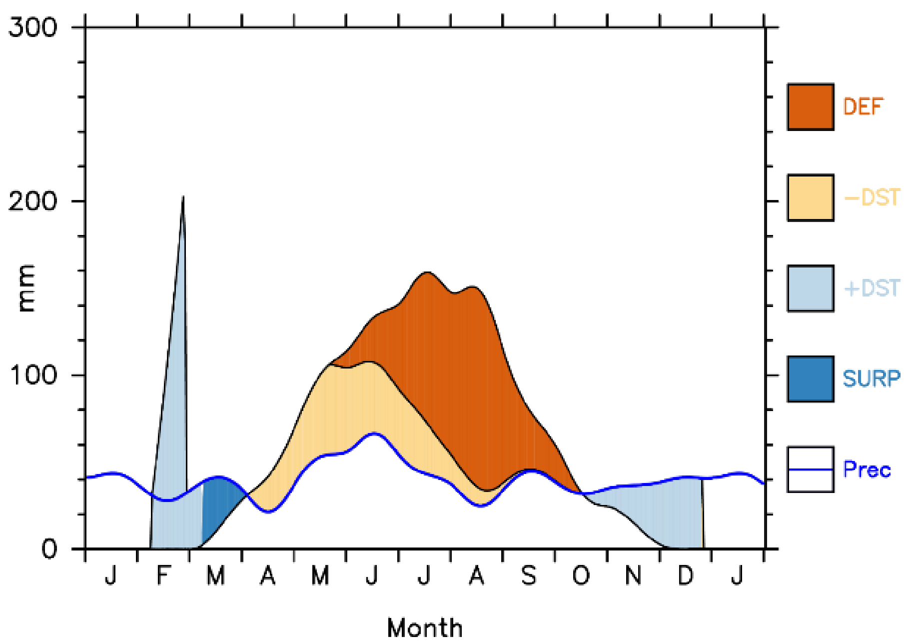


(b)

Figure 21. Region 1 Water-Budget for 1981 (a) and 2018 (b)

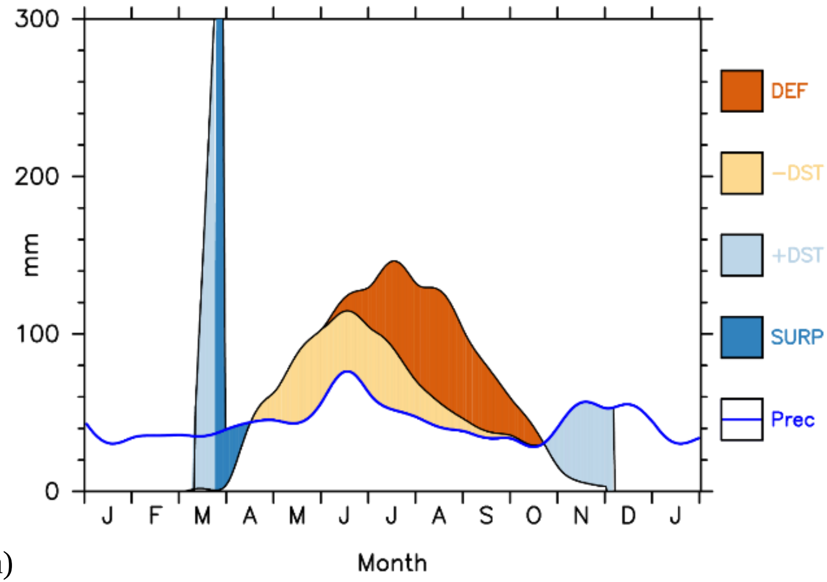


(a)

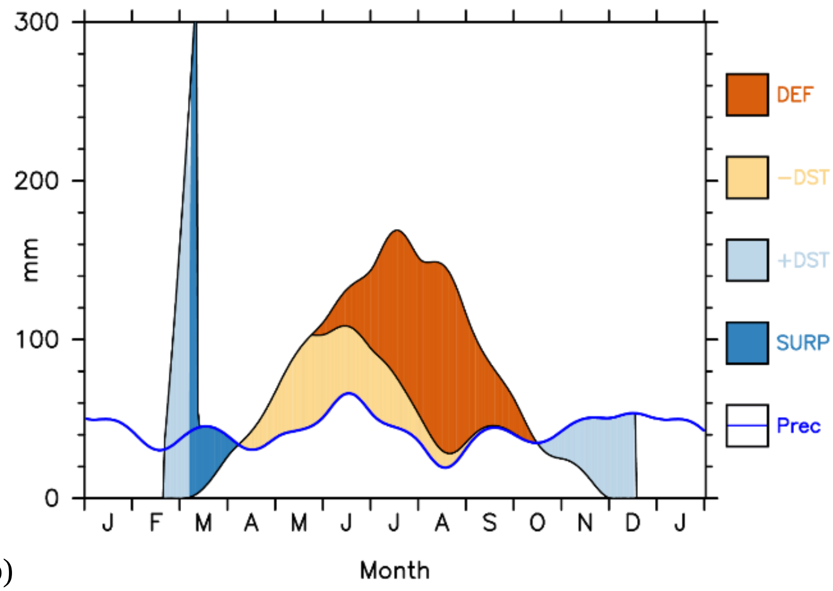


(b)

Figure 22. Region 2 Water-Budget for 1981 (a) and 2018 (b)

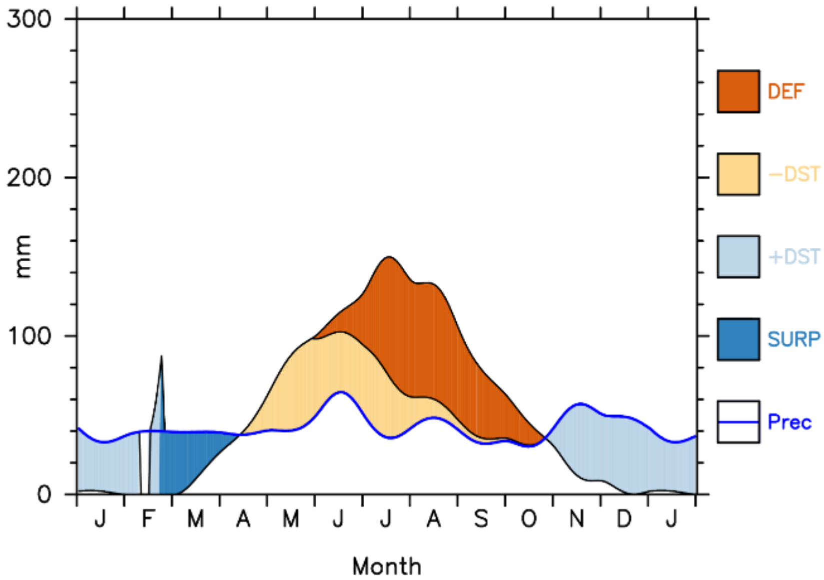


(a)

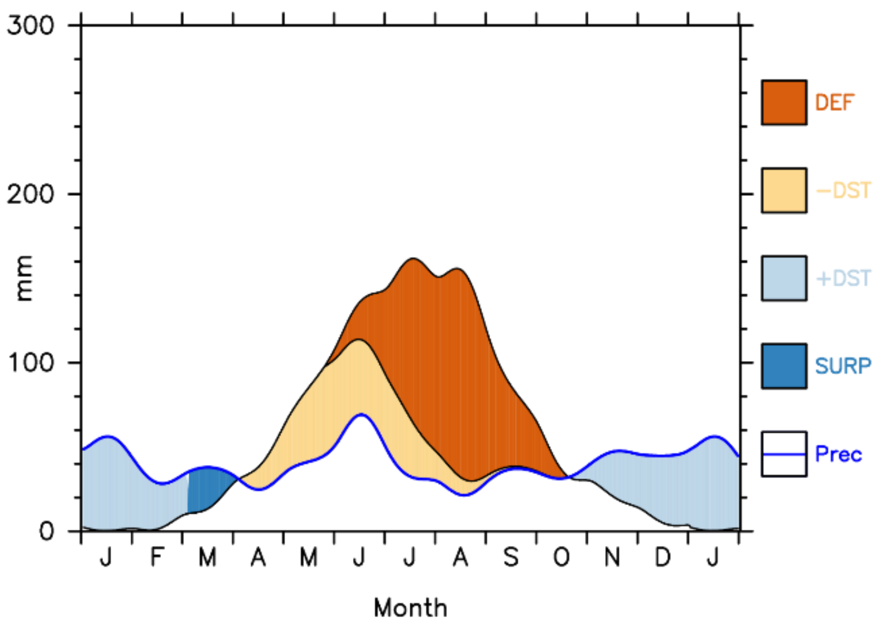


(b)

Figure 23. Region 3 Water-Budget for 1981 (a) and 2018 (b)



(a)



(b)

Figure 24 Region 4 Water-Budget for 1981 (a) and 2018 (b)

5 DISCUSSION

The trends in temperature in the study region confirm the presence of the faster than global increase in mean annual temperature, previously suggested by other researchers; however, it contradicts the previous findings of significant winter warming (Bindoff et al., 2013; Stocker et al., 2013). The mean annual temperature in the study area increased for about 1.8-2 °C from 1981 to 2018 compared to the global annual temperature rate of +0.18°C per decade for 1981 – 2019 (NOAA, 2020). However, this increase occurred mostly due to summer months warming. In the colder half of the year temperature in the study area increased only in November, and no statistically significant trend was found in winter months.

Detailed analyses of local precipitation trends revealed no statistically significant change in precipitation for most of the months except August and January. Summer precipitation decrease in August was found over the study area, except the eastern subregion. Winter precipitation increase in January present only in two of four subregions (wester subregion R1 and the Crimean Peninsula), with no statistically significant change in the central and eastern part. These results contradict with the findings of the other studies that suggest June and October precipitation decrease (Barabash et al., 2004), September and October precipitation increase and winter precipitation decrease during the second part of the 20th century (Ivanyi, 2015). Besides, no mean annual precipitation increasing trend, suggested by 2013 IPCC report (Stocker et al., 2013) and Ukrainian Hydrometeorological Institute (Barabash et al., 2004), was found in the study area. This finding confirms the results of other regional studies (Villarini, 2012; Yeremeyev and Yefimov, 2003).

The designation of the climate types of southern Ukraine in 2018 as Dfa in the eastern subregion and Cfa in the rest of the study area contradicts some global climate classification studies. For instance, classification of the flat part of the Crimea Peninsula as colder climate (Dfb), compared to the mainland part of the study area as warmer climate (Dfa), suggested by Peel et al. (2007), is also incorrect, because the flat part of Crimean Peninsula has the higher summer temperatures (Figure 5). Bsk (arid, cold steppe) climate type of the study area, suggested by Beck et al. (2018), is also not accurate, based on the higher than suggested by Köppen-Geiger climate classification ratio of annual precipitation to Dryness Threshold. Besides, classifying the study region as one of the Mediterranean climate types (Cs), proposed by some researchers (Alessandri et al., 2014), currently is not accurate considering no distinct seasonality in precipitation. The possible reasons for the discrepancies in the climate type determination between different studies are the fact that the study region lies on the boundary between climate types and represents some characteristics of Cold, Temperate, and Arid climates – which makes it so-called "Earth's Problem Climate", that fail to fit into the classical climate classifications (Trewartha, 1961).

Pronounced climate change is the other possible reason of disagreement between researchers regarding the climate classification of southern Ukraine. This study has revealed that climate types shift (from Cfb to Cfa and from Dfb to Dfa) over the recent 37 years was caused mostly by the fast increase of summer temperatures. Intra-annual redistribution of precipitation was not significant enough to impact the climate type. However, considering a rate of increase in January precipitation in regions R1 (west) and R4 (Crimea), and decrease in August in regions R1, R2 (center), and R4, a shift toward Mediterranean climates is possible in the far future. Besides, Pann/Pth ratios are smaller in 2018 than in 1981 for all subregions, which signal increasing aridity, especially in region R4 – Crimean Peninsula. Furthermore, changes in soil-water budgets show massive increase in soil-water deficit in all subregions. This statement supports previous findings of local researchers (Svetlichnyi, 2018), suggesting the future possibility of land degradation and decertification as a climate change response in the study area.

The results of this study suggest an increasing water deficit during the growing season, thereby illustrating the adverse effects of climate change on agriculture of southern Ukraine. Considering the low potential availability of irrigation in the study region, the most important factor in successful agriculture is the timing of precipitation. Precipitation and temperature during the major months for winter wheat (September, October, April, May, June) and spring crops (April, May, June) strongly correlate with crop yield (Grytsyuk and Bachyshyna, 2016). For example, in 2005, the driest September in 28 years delayed crop emergence and caused up to 26% decline in winter wheat production in 2006[1]. Previous research stated that the study region has soil-water deficit from April to August and prone to periodic droughts (Romaschenko, 2013). This research determined that the period of soil-water deficit is longer than it has been in the past. The substantial soil-water deficit from May to October can be exacerbated even more by increasing warm season temperatures with no increase in summer precipitation. Detected summer drying trends and its impact on agriculture suggest that southern Ukraine has similar tendencies as the Mediterranean region – one of the major "climate change hot-spots" (Giorgi, 2006).

[1] https://public.wmo.int/en/bulletin/global-crop-production-review-2006

6 CONCLUSION

This research shows that southern Ukraine is a climate change hot-spot, characterized by the rapid changes in climate conditions and their possible high impact on agriculture. The climate type shift toward warmer climates (Cfb to Cfa, and Dfb to Dfa by Köppen-Geiger classification), that occurred over a relatively short 37-year period, supports the idea of currently present rapid changes in the climate of the region. Multi-decadal trend analyses confirmed faster than global increase in mean annual temperature in the study region from 1981 to 2018 (about 1.8-2^{o}C in 37 years). The highest temperature increase was detected in the warm months from April to September and reached 3.3–3.5°C in August throughout southern Ukraine. However, no statistically significant trend in temperature was found in winter months and October. Significant changes in precipitation over 37 years were determined only in August (decrease by 38% - 43% in three of the four subregions) and January (increase by 39% - 79% two of the four subregions). Winter precipitation growth was not substantial enough to prevent the summer drying trend caused by the higher temperatures. Multi-decadal changes in soil-water budgets show an increase of soil-water deficit severity and duration from May to October, which is the major growing season for the agricultural crops in southern Ukraine.

From the applied research perspective, this study provides valuable insight for the local population and governments of the regions located in the southern part of Ukraine. Considering that agriculture provides a large share of the study region`s gross product and the local rural population relies on small-scale agriculture for their food security, the long-term climate change adaptation policies are necessary for the region. In line with the recommendations of international organizations such as FAO and IPCC, the measures of climate change adaptation on the country level should include implementation of the appropriate sustainability metrics, that can help to analyze socio-economic and ecological factors to build the scientific bases for the posies; targeting the most food insecure groups of people in climate policies and resiliency-building strategies; developing a sound approach for food production and distribution adaptation, that utilizes strengths of the current system and provides for including new sources and building new channels; establishing relevant governance institutions, able to implement climate change adaptation policies and timely address emerging challenges. On the local level, farmers should focus on the implementation of sustainable agricultural practices, such as appropriate crop rotation, using new heat and drought-resistant varieties, and developing irrigation potential.

Further research on the climate of the study area would benefit from analyzing more complete, multi-decadal datasets, performing classification of each pixel, and using more complex models. Considering that the study area represents a transition zone between climate types and experience faster than the global rate of warming, the results of climate classification highly depend on dataset quality and period selected for analyses. Besides, using more variables for factor analyses would help to build a more precise regionalization model. Furthermore, relief, temperature, and precipitation maps suggest that regionalization based on climate classification of each pixel will provide valuable advice for the local population regarding spatial boundaries of climatic zones. For instance, the absence of statistically significant trends in monthly precipitation variability for Region 3 (Crimea) can be influenced by differences in relief in this subregion.

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APPENDICES

Appendix A. Analyses of the completeness of the data from the weather stations located in the study area, provided by the NOAA.

	Latitude	Longi-tude	Eleva-tion	First year of record	Last year of record	Percentage of daily data available
AMVROSIIVKA, UP	47.8	38.517	164	1981	2009	43%
ARTEMIVSK, UP	48.6	37.983	124	1981	2016	44%
ASKANIIA NOVA, UP	46.5	33.9	28	1981	2016	90%
BASTANKA, UP	47.417	32.467	84	1981	2009	53%
BEHTERY, UP	46.3	32.3	6	1981	2009	44%
BELGOROD DNESTROVSKII, UP	46.2	30.4	0	2002	2009	22%
BELOGORSK, UP	45.1	34.6	0	2000	2009	29%
BOBRYNETS, UP	48.067	32.15	143	1981	2016	40%
BOLGRAD, UP	45.667	28.617	81	1981	2009	42%
BOTIEVE, UP	46.683	35.85	19	1981	2016	32%
CHAPLYNE, UP	48.133	36.233	175	1981	2016	44%
DARIVKA, UP	48.083	39.5	302	1981	2015	38%
DEBALTSEVE, UP	48.4	38.4	335	1981	2015	70%
DNEPRODZERJINSK, UP	48.5	34.6	148	1981	1990	98%
DNIPROPETROVSK, UP	48.6	34.967	143	1981	2018	51%
DOLINSKAYA, UP	48.1	32.8	191	1981	2009	42%
DONETSK, UP	48.067	37.767	225	1981	2013	54%
DZANKOJ, UP	45.717	34.4	8	1981	2009	51%
FEODOSIIA, UP	45.0331	35.383	22	1981	2015	72%
GAYVORON, UP	48.35	29.867	175	1981	2016	35%
GORYACHKOVKA, UP	48.367	28.867	0	1981	1989	93%
GULYAYPOLE, UP	47.667	36.25	135	1981	2009	40%
HENICHESK, UP	46.1667	34.816	15	1981	2016	71%
ISHUN, UP	45.9	33.8	2	1981	2009	39%
IZMAIL, UP	45.3667	28.85	28	1981	2016	70%
KHERSON, UP	46.633	32.567	54	1981	2018	47%
KIROVOHRAD, UP	48.517	32.2	171	1981	2018	50%
KLEPININO, UP	45.5	34.2	37	1981	2009	44%
KOMISARIVKA, UP	48.433	33.9	118	1981	2016	43%
KRASNOARMEYSKOE, UP	48.3	36.9	198	1981	2009	43%
KRIVOJ ROG, UP	47.9	33.4	100	1981	2018	47%

KYRYLIVKA, UP	47.333	36.333	221	1981	2016	44%
LIUBASHIVKA, UP	47.85	30.267	183	1981	2018	48%
LOSHKAREVKA, UP	47.9	34.2	83	1981	2009	34%
LUGANSK, UP	48.5667	39.25	59	1981	2014	95%
MARIUPOL, UP	47.1	37.6	8	1981	2018	35%
MELITOPOL, UP	46.833	35.367	34	1981	2016	35%
NIKOLAEV, UP	46.9667	31.983	49	1981	2012	97%
NIKOPOL, UP	47.583	34.45	55	1981	2016	33%
NIZHNI SIROHOZY, UP	46.85	34.4	53	1981	2016	35%
NOVA KAKHOVKA, UP	46.783	33.367	25	1981	2016	42%
NOVODNESTROVSK, UP	48.57	27.45	0	2004	2009	19%
NYZHNIOHIRSK, UP	45.45	34.733	20	1981	2009	41%
OCHAKOV, UP	46.633	31.55	41	1981	2009	41%
ODESA, UP	46.48	30.63	42	1981	2018	70%
OPASNOE, UP	45.4	36.6	2	1981	1990	98%
PAVLOGRAD, UP	48.6	35.9	66	1981	2009	41%
PERVOMAISK, UP	48.05	30.85	103	1981	2016	35%
POMICHNA, UP	48.233	31.4	211	1981	2016	34%
POPELAK, UP	46.2	34.7	30	1981	1989	93%
PRYSHYB, UP	47.267	35.333	88	1981	2016	43%
RAZDOL NOE, UP	45.8	33.5	17	1981	2009	40%
ROZDILNA, UP	46.85	30.083	148	1981	2016	33%
SARATA, UP	46.017	29.667	14	1981	2016	33%
SERBKA, UP	47.017	30.75	73	1981	2016	30%
SIMFEROPOL, UP	44.7	34.133	181	1981	2018	79%
STEREGUSCIJ, UP	45.75	33.217	16	1981	1988	95%
TILIGULO BEREZANKA, UP	46.833	31.4	42	1981	1988	95%
VELIKO ANADOL SKOE, UP	47.7	37.5	236	1981	1990	98%
VELYKA OLEKSANDRIVK, UP	47.317	33.283	56	1981	2016	44%
VOLNOVAKHA, UP	47.617	37.35	267	2016	2016	0%
VOZNESENSK, UP	47.567	31.333	34	2016	2016	8%

Appendix B. NOAA Stations Data that filed any of the quality checks.

Name	Latitude	Longitude	Elevation	Date	Prcp	Prcp_ attributes
ARTEMIVSK, UP	48.6	37.983	124	2/13/1992	103.9	,O,S
BASTANKA, UP	47.417	32.467	84	7/30/1976	300	B,O,S
BASTANKA, UP	47.417	32.467	84	3/22/1994	108	,O,S
AMVROSIIVKA, UP	47.8	38.517	164	12/22/1994	99.1	,S,S
DZANKOJ, UP	45.717	34.4	8	1/4/1973	0	,I,I
DZANKOJ, UP	45.717	34.4	8	1/23/1988	0.3	,I,I
DZANKOJ, UP	45.717	34.4	8	1/22/1992	0	,I,S
DARIVKA, UP	48.083	39.5	302	3/26/1980	1	,I,I
DNIPROPETROVSK, UP	48.6	34.967	143	1/8/1994	140	,O,S
DNIPROPETROVSK, UP	48.6	34.967	143	6/12/1994	240	,O,S
DNIPROPETROVSK, UP	48.6	34.967	143	4/11/1995	150.1	,O,S
DNIPROPETROVSK, UP	48.6	34.967	143	1/20/2006	181	B,O,u
FEODOSIIA, UP	45.0331	35.3831	22	2/4/1986	2.2	,I,r
FEODOSIIA, UP	45.0331	35.3831	22	2/7/1986	0	,I,r
FEODOSIIA, UP	45.0331	35.3831	22	2/13/2004	59	,O,r
DONETSK, UP	48.067	37.767	225	8/13/1976	300	B,O,S
DONETSK, UP	48.067	37.767	225	3/7/1985	0	,I,I
DONETSK, UP	48.067	37.767	225	2/9/1987	2	,I,I
DONETSK, UP	48.067	37.767	225	1/12/1992	80	,O,S
DONETSK, UP	48.067	37.767	225	2/22/1992	101.1	,O,S
DONETSK, UP	48.067	37.767	225	5/24/1994	230.9	,O,S
DONETSK, UP	48.067	37.767	225	3/15/2000	882	B,G,u
GAYVORON, UP	48.35	29.867	175	8/2/1976	307.1	B,O,S
KHERSON, UP	46.633	32.567	54	1/17/1976	89.9	B,O,S
KHERSON, UP	46.633	32.567	54	11/22/1993	80	,O,S
KHERSON, UP	46.633	32.567	54	3/2/1994	103.9	,O,S
HENICHESK, UP	46.1667	34.8167	15	2/16/1986	0	,I,r
KOMISARIVKA, UP	48.433	33.9	118	1/11/1992	102.1	,O,S
KOMISARIVKA, UP	48.433	33.9	118	12/23/1993	101.1	,O,S
KRIVOJ ROG, UP	47.9	33.4	100	1/14/1976	70.1	B,O,S
KRIVOJ ROG, UP	47.9	33.4	100	1/12/1985	0.4	,I,I
KRIVOJ ROG, UP	47.9	33.4	100	10/17/1991	284	,O,S
KRIVOJ ROG, UP	47.9	33.4	100	2/1/1994	101.1	,O,S
KYRYLIVKA, UP	47.333	36.333	221	1/31/1994	101.1	,O,S
IZIUM, UP	49.183	37.3	78	2/7/1973	1	,I,I
IZIUM, UP	49.183	37.3	78	3/13/1976	1	B,I,S
IZIUM, UP	49.183	37.3	78	1/15/1982	0	,I,I
IZIUM, UP	49.183	37.3	78	1/21/1987	1.3	,I,I
IZIUM, UP	49.183	37.3	78	6/24/1991	295.9	B,O,S
IZIUM, UP	49.183	37.3	78	1/28/2000	370	B,G,u

KIROVOHRAD, UP	48.517	32.2	171	3/11/1973	0	,I,I
KIROVOHRAD, UP	48.517	32.2	171	2/27/1976	0	B,I,S
KIROVOHRAD, UP	48.517	32.2	171	1/23/1986	0	,I,I
KIROVOHRAD, UP	48.517	32.2	171	1/17/1994	103.9	,O,S
KHERSON, UP	46.633	32.567	54	1/17/1976	89.9	B,O,S
KHERSON, UP	46.633	32.567	54	11/22/1993	80	,O,S
KHERSON, UP	46.633	32.567	54	3/2/1994	103.9	,O,S
HENICHESK, UP	46.1667	34.8167	15	2/16/1986	0	,I,r
KOMISARIVKA, UP	48.433	33.9	118	1/11/1992	102.1	,O,S
KOMISARIVKA, UP	48.433	33.9	118	12/23/1993	101.1	,O,S
KRIVOJ ROG, UP	47.9	33.4	100	1/14/1976	70.1	B,O,S
KRIVOJ ROG, UP	47.9	33.4	100	1/12/1985	0.4	,I,I
KRIVOJ ROG, UP	47.9	33.4	100	10/17/1991	284	,O,S
KRIVOJ ROG, UP	47.9	33.4	100	2/1/1994	101.1	,O,S
KYRYLIVKA, UP	47.333	36.333	221	1/31/1994	101.1	,O,S
IZIUM, UP	49.183	37.3	78	2/7/1973	1	,I,I
IZIUM, UP	49.183	37.3	78	3/13/1976	1	B,I,S
IZIUM, UP	49.183	37.3	78	1/15/1982	0	,I,I
IZIUM, UP	49.183	37.3	78	1/21/1987	1.3	,I,I
IZIUM, UP	49.183	37.3	78	6/24/1991	295.9	B,O,S
IZIUM, UP	49.183	37.3	78	1/28/2000	370	B,G,u
KIROVOHRAD, UP	48.517	32.2	171	3/11/1973	0	,I,I
KIROVOHRAD, UP	48.517	32.2	171	2/27/1976	0	B,I,S
KIROVOHRAD, UP	48.517	32.2	171	1/23/1986	0	,I,I
KIROVOHRAD, UP	48.517	32.2	171	1/17/1994	103.9	,O,S
NOVA KAKHOVKA, UP	46.783	33.367	25	3/5/1986	0	,I,I
NOVA KAKHOVKA, UP	46.783	33.367	25	2/4/1987	0	T,I,I
NOVA KAKHOVKA, UP	46.783	33.367	25	3/16/1992	113.3	B,O,S
NOVA KAKHOVKA, UP	46.783	33.367	25	2/25/1994	89.9	,O,S
NOVA KAKHOVKA, UP	46.783	33.367	25	6/18/1994	340.1	,O,S
NIZHNI SIROHOZY, UP	46.85	34.4	53	2/6/1995	102.1	,O,S
NIZHNI SIROHOZY, UP	46.85	34.4	53	4/21/2005	120	B,O,u
LIUBASHIVKA, UP	47.85	30.267	183	2/21/1976	0.3	B,I,S
LIUBASHIVKA, UP	47.85	30.267	183	2/3/1984	2	,I,I
MARIUPOL, UP	47.1	37.6	8	8/3/1984	80	,S,S
LUGANSK, UP	48.5667	39.25	59	3/16/1982	0	,I,E
LUGANSK, UP	48.5667	39.25	59	1/7/2003	0	,I,E
LUGANSK, UP	48.5667	39.25	59	2/1/2003	0	,I,E
NYZHNIOHIRSK, UP	45.45	34.733	20	1/17/2000	790	B,G,u
POMICHNA, UP	48.233	31.4	211	1/7/1995	102.1	,O,S
POMICHNA, UP	48.233	31.4	211	4/5/2000	904	B,G,u
POMICHNA, UP	48.233	31.4	211	1/8/2003	117.4	B,O,u
PRYSHYB, UP	47.267	35.333	88	11/7/1993	102.1	,O,S

PRYSHYB, UP	47.267	35.333	88	3/3/1994	71.1	,O,S
PRYSHYB, UP	47.267	35.333	88	2/5/2000	800	B,G,u
SARATA, UP	46.017	29.667	14	12/20/2004	167	B,O,u
VELYKA OLEKSANDRIVK, UP	47.317	33.283	56	3/17/1993	101.1	,O,S