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Wavelet Analysis of the Near-Surface Air Temperature, Cloudiness and Precipitation in Bulgaria

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One of the current problems of our contemporary time is related to the changes in the climate of local, as well as global scope. We offer an analysis of long-term time series of meteorological data from different weather stations in Bulgaria. The data collected so far contains more than 68 000 values for the period 1905 – 2022. There are close to 200 time series from 37 meteorological stations in Bulgaria. In the context of the tendency of global climate change, we made a comparison with data about region which is very different in climatic aspect. We compared the results obtained in Bulgaria with the wavelet analysis results obtained in Eastern Siberia. Observational data for Siberia are provided by RIHMI-WDC (http://meteo.ru/data). Based on data from Bulgarian meteorological stations, we detected a periodicity in long-term variations of the near-surface air temperature, cloudiness and precipitation using wavelet analysis. Results for four meteorological stations are presented. Three of them have the longest time series of yearly mean values with very short gaps. The data from Irkutsk contains monthly average values and have a similar time window with uninterrupted monitoring and correspond to our methods of analysis. The presented results show similarities regarding the periodicity of temperature, precipitation, and cloudiness between Bulgarian and Irkutsk stations. The analytic periods could be related to the influence of El Niño and the North Atlantic Oscillation (NAO). Our first results from the data analysis show the existence of periodical meteorological anomalies with period of 2-6 years. This shows that the influence of NAO, Strong El Niño and La Niña events could be of definitive role for regions of Earth's surface with different climate.

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1. Introduction

We live in dynamic times regarding climate change on Earth in global and local scale due to the influence of different natural phenomena. They could be external with regards to Earth (cosmic factors) or internal (geophysical and geological). These factors could have a rapid impact on climate changes (powerful cosmic collisions or super-volcanoes) or relatively slow and predictable, forming clear trends of changes in course of decades. The role of the Sun as the primary energy source for the Earth and a driver of global climate change is particularly important [1]. In fact, this dynamic should not necessarily be regarded as negative. On the contrary, this means that there is not a determined and definite direction leading to a predefined limit of development of the Earth as well as life on the planet. Here we should agree that we talk about the next tens or hundreds of thousands of years or even millions of years. Of course, in a global aspect, the dynamic of the climate changes now cannot be compared with the dynamical processes, which were taking place tens and hundreds of million years ago, when our young planet was hammered by powerful and rapid geological processes. The last few millennia are a period of relatively calm evolution of our planet and its climate conditions – life on the planet again is proliferating and animal and plant species continue to be the unique face of our planet amongst all we have managed to see and discover in the limitless cosmos.

It is well known that the measurement of the temperature on Earth has begun in the year 1856 when the British Meteorological Society starts collecting temperature data from all over the globe. Until then proxy data from the geological records were used to identify the temperature values such as tree-rings (dendrochronology), pollen spectrum, isotopic data from sediment rocks, etc. The definition of the mean Earth temperature, which is frequently cited, is not based on reliable and direct methodology. These are averaged data for the different continents! This is the same as defining the temperature of a human by averaging the temperature of each human being on a cruise ship with about a thousand of tourists on board. Because of this, the statements of various authors that the mean global temperature will rise with 3-8°C [2, 3] contain a measure of speculation. During the last three decades the measurement of the temperature in global scale are significantly improved in terms of quality, due to various international programs for satellite observations and measurements of the temperature of the Earth's atmosphere. Through the use of more accurate scientific approaches of the analysis of the temperature data, the models show that global temperature rise is within the range of 1-2°C till the end of the century [4]. Of course, we should again underline the responsible attitude and behavior of humankind towards the environment.

The term "global warming" is frequently understood erroneously in the sense that the temperature of all regions on the globe will increase homogeneously and simultaneously. In reality the increase of the mean temperature accelerates the circulation of the Earth's atmosphere, and as a result some areas will have temperatures higher than the global average, while others will have lower. Some regions might even experience cooling instead of warming. We consider to be very important that each local database with various meteorological elements is maintained and analyzed. This could be key to developing models for short-term prediction of meteorological phenomena, which could cause disasters.

When we talk about global changes of the temperature, even simulated data could be used. This data could have a large degree of credibility and often they include real measurement data.

PoS(BPU11)036

For example, simulated data is used by the World Bank (http://climateknowledgeportal.worldbank.org). We think that if we are looking for short-period climate changes with local character, such data could not yield a meaningful result. And that it is very important that local data is compared to similar data for every other possible geographic location. The analysis of the data could show us the eventual short-term temporal variations, caused predominantly by natural geoidal factors. But it is also possible that anomalies caused by clearly local causes including human activity. This justifies analysis of data of very dissimilar geographic characteristics. With the analysis of our meteorological data, we put in focus some basis questions such as what are the changes of the basic meteorological parameters with time; is there any periodicity in the changes; are these local regularities or do they have global character. One established mathematical analytical method is the so called "wavelet analysis", which could give us analytical result related to the questions in focus.

2. Data collection

We have collected meteorological data from the Statistical Yearbook of Republic of Bulgaria, published by the National Statistical Institute. The data is available online (https://www.nsi.bg/statlib/bg/index.php) in the form of PDF (Portable Document Format) files containing images of scanned pages of hard copies of the Statistical Yearbook. The data holds monthly and yearly averages for near-surface air temperature, precipitation, humidity, cloudiness, atmospheric pressure, and sunny hours. We have extracted more than 68 000 values for the period 1905 – 2022 from 37 meteorological stations and have managed to construct 193 time series for each measurement and station. The digitized data is ordered by time for the different meteorological stations and contain all values published in the Statistical Yearbook of Bulgaria (Table 1).

PoS(BPU11)036

Location	**measure**	**Count of values in Statistical Yearbook**
Sofia	cloudiness	1032
	temperature	1031
	precipitation	1030
Varna	cloudiness	995
	precipitation	994
	temperature	983
Burgas	cloudiness	934
	precipitation	934
	temperature	933
Pleven	cloudiness	852
	humidity	852
	precipitation	852
	temperature	852
Sofia	humidity	852
	Pressure	851
Pleven	Pressure	828
Varna	humidity	813
…	…	
UmrukChal	temperature	48
	sunny hours	47
Kneja	pressure	36
Berkovitsa	humidity	24
	temperature	24
Chirpan	pressure	24
LevskiGrad	cloudiness	24
	humidity	24
	precipitation	24
	pressure	24
	temperature	24
Stations count 193		**Total values count 67 261**

Table 1. Digitalized and tabulated data for temperature, cloudiness, precipitation, pressure, sunny hours for 37 stations in Bulgaria. Due to the large size of the table here we present only a sample of the data.

The challenges we had were related to interruptions of publishing meteorological data for different periods of time for different stations, as well as movement of the location of some stations. The time series of yearly mean values for temperature, precipitation and cloudiness for the cities of Sofia, Plovdiv, and Burgas are sufficiently long and have been analyzed. Figure 1 presents time series from selected meteorological stations in Bulgaria.

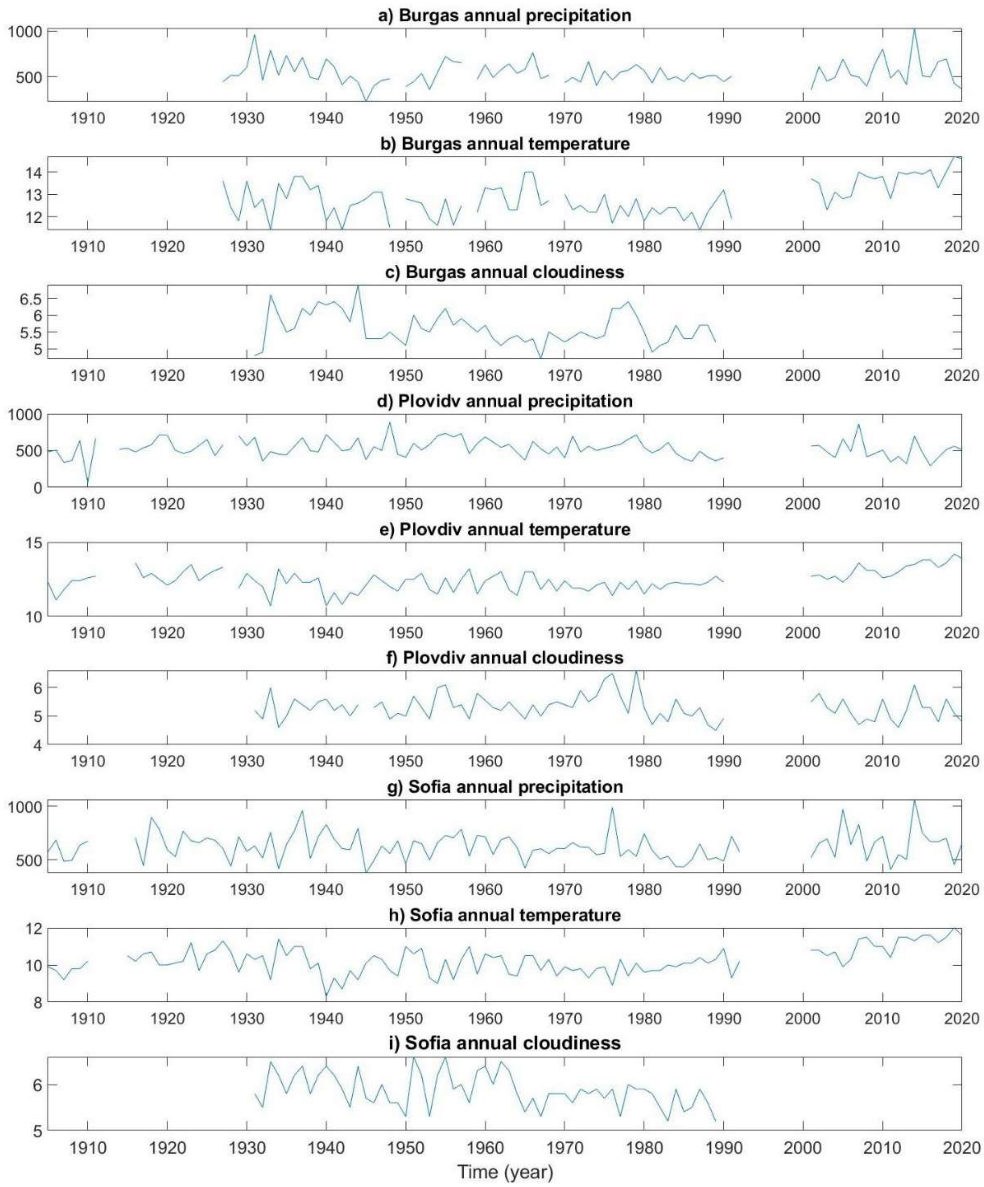

Figure 1. Graphical representation of time series of yearly mean values for precipitation, temperature and cloudiness for Sofia, Burgas, Plovdiv from Statistical Yearbook of Bulgaria. X-axis shows time in years; Y-axis – precipitation (liters), temperature (degrees Celsius), cloudiness (1 to 10, 10 is maximum cloud coverage), respectively.

We use data from 3 meteorological stations in Bulgaria, located in zones with specific climate characteristics (Table 2). These specifics are related to the geographical location of the stations. Sofia is situated in the skirts of Vitosha mountain and is part of a large plain. The Burgas station has clear seashore characteristics and Plovdiv is situated in the central part of southern Bulgaria with some of influence from the Mediterranean Sea. These stations also have the longest, almost uninterrupted series of observations.

Weather station	Coordinates	Altitude	Observation period
Sofia	42°42’ N 23°20’ E	550 m	1905 to 2020
Burgas	42°29’ N 27°29’ E	6 m	1905 to 2020
Plovdiv	42°9’ N 24°57’ E	160m	1927 to 2020

Table 2. Information for the stations, sources of data for the current study.

For a period of one century, the observation series have only up to several (<5) missing data points. We have completed the missing data points using moving average technique to produce a first approximation with the purpose to take advantage of as long as possible time series, which greatly improves the application of wavelet analysis. For completing the missing yearly mean values for temperature and precipitation for the selected stations we have also included data available from The World Bank, Climate Change Knowledge portal, where the historical data, produced by the Climatic Research Unit is published (https://climateknowledgeportal.worldbank.org/country/bulgaria/climate-data-historical).

We compare the results from our analysis with the results obtained by our colleagues for Irkutsk, Russia (Table 3). Irkutsk is located in the center of the Eurasian continent in the south of Eastern Siberia, near lake Baikal. The climate is sharply continental with significant daily and annual fluctuations in air temperature. Winter is harsh and long over 5 months. The Siberian anticyclone sets clear, frosty and calm weather. The coldest month is January. Summer is hot, the warmest month is July.

Weather station	Synoptic index	Coordinates	Altitude	Observation period
Irkutsk observatory	30710	52°18’ N 104°18’ E	467 m	1882 to present

Table 3. Information for meteorological station in Irkutsk, Russia.

3. Methods of data analysis

Our analytical method of choice is Wavelet Analysis, and we have used the commercial product MATLAB to analyze the time series data. Wavelet analysis allows to identify the frequencies of periodic and quasiperiodic phenomena, and to localize them in time. As opposed to Fourier analysis, where we can identify the frequencies of the elementary signals of which the time series is composed, but it does not allow identifying when the phenomena took place. To achieve this, the time series are decomposed in basis of scaled and translated wavelet functions, which are based on a so-called mother-wavelet function. There are various choices of mother-wavelet functions, and for our analysis we used the Morlet wavelet that is a fast algorithm for Gabor filtering, specially designed for multi-scale image representations [5]. This allows comparison of the results of the analysis of the meteorological time series from the selected locations in Bulgaria with analysis of other locations in the world. The significance levels of the wavelet spectra were calculated following the methodology proposed by Torrence and Compo [6].

The results from the analysis of each time series is visualized with three graphs: a) anomaly diagram giving the distance from the mean in terms of standard deviation for the particular element, b) wavelet power spectrum and c) global power spectrum. In essence the wavelet power spectrum is a two-dimensional diagram of time along the x-axis and period (in years) along the y-axis, where the significance contours enclose periodical phenomena which are discernible from the random noise. The wide v-shape line denotes the cone of influence (COI), and it encloses the wavelet coefficient estimates which are reliable. The points outside the COI are not reliable due to edge effects, coming from the fact that the time series is not infinitely periodical. Our wavelet method of analysis shows periodicity values with confidence level 95% according mathematical analysis of long period timeseries [6]. These parameters could be adjusted, and so different quasiperiodic changes of meteorological values, can be identified. The confidence level could be lowered when observational series of natural phenomena are analyzed, due to the usual low signal to noise ratio [7].

Figures 2, 3 and 4 show our results based on the data (cloudiness, precipitation and temperature) from the stations in Burgas, Plovdiv and Sofia, respectively. Data analysis for annual temperature (1882-2019) from Irkutsk, Russia are presented on Figure 5.

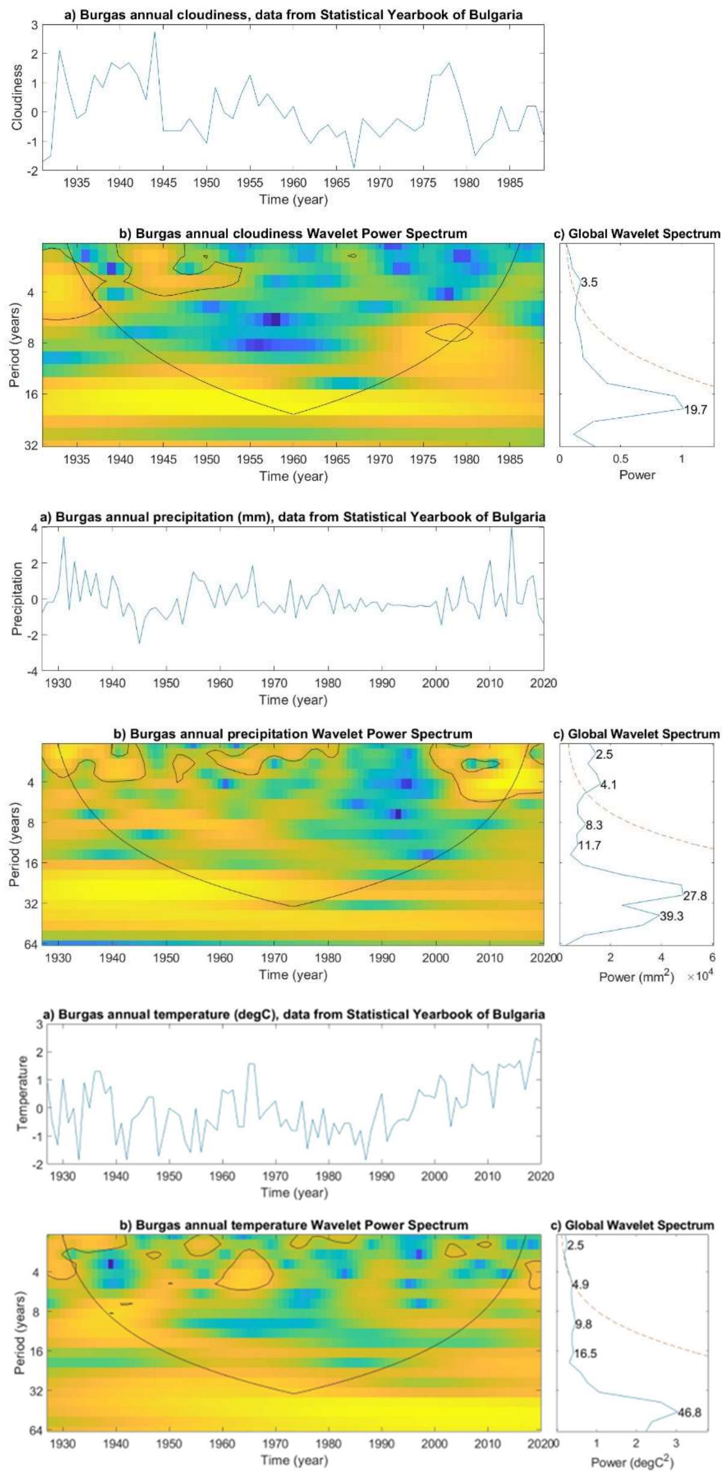

Figure 2. Annual cloudiness, annual precipitation and annual temperature in Burgas. The color-coding represents low to high precipitation, temperature, cloudiness, respectively from blue to yellow. The dotted red line defines 95% significance level.

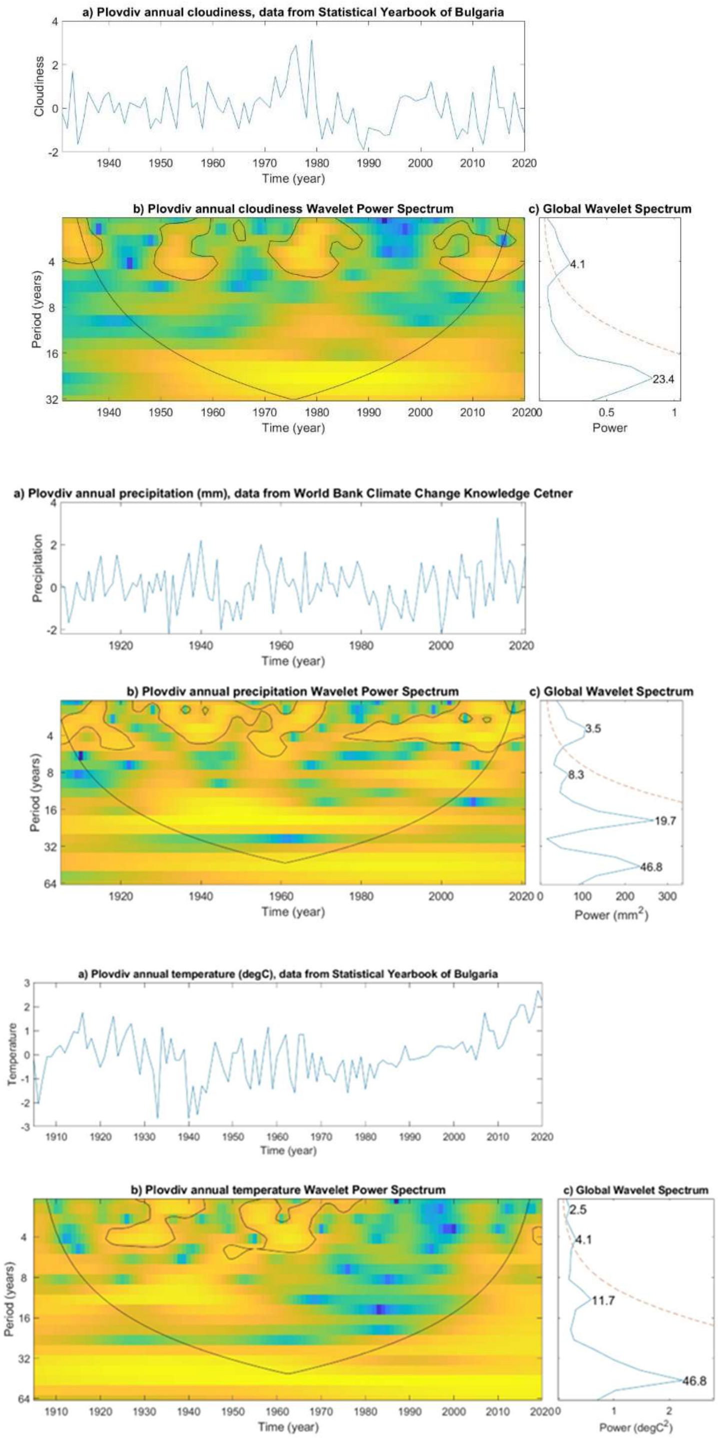

Figure 3. Annual cloudiness, annual precipitation and annual temperature in Plovdiv. The color-coding represents low to high precipitation, temperature, cloudiness, respectively from blue to yellow. The dotted red line defines 95% significance level.

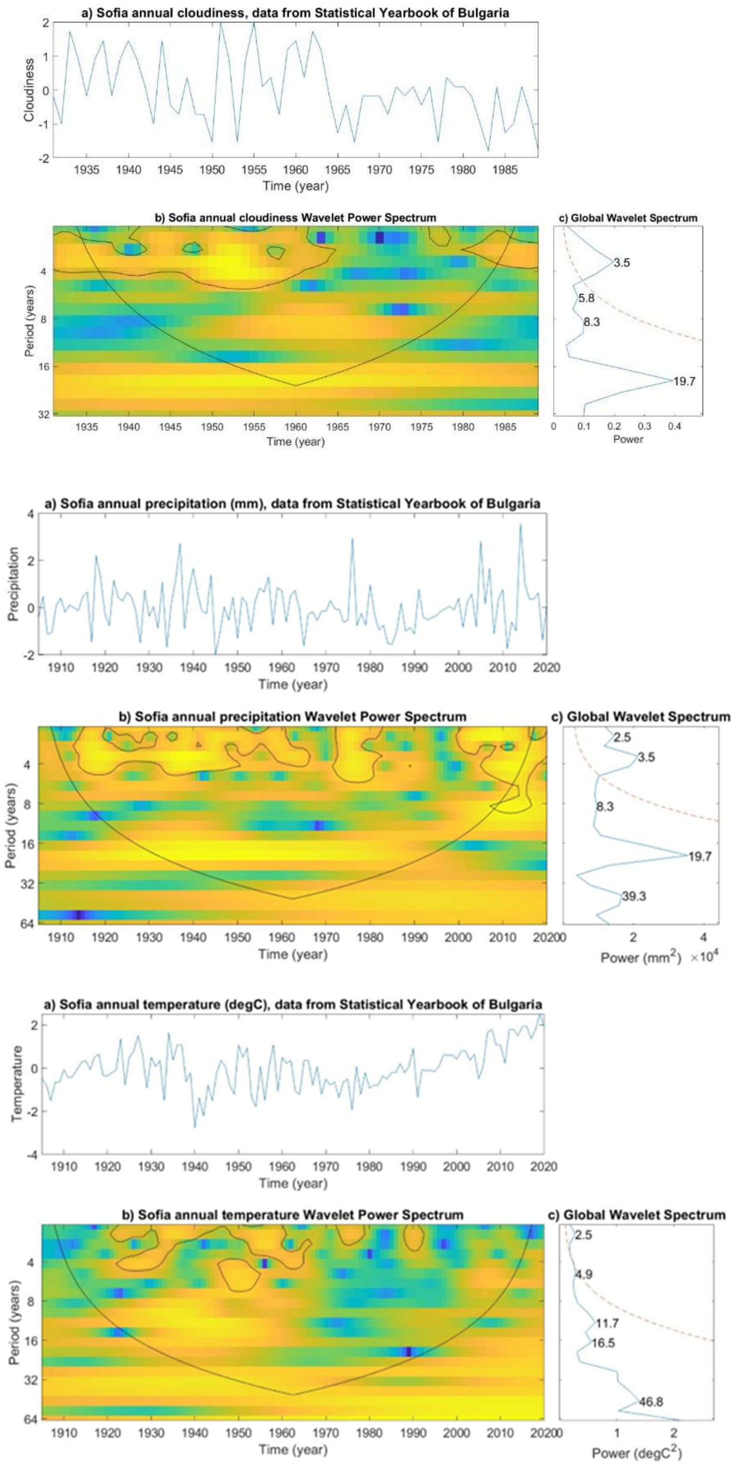

Figure 4. Annual cloudiness, annual precipitation and annual temperature in Sofia. The color-coding represents low to high precipitation, temperature, cloudiness, respectively from blue to yellow. The dotted red line defines 95% significance level.

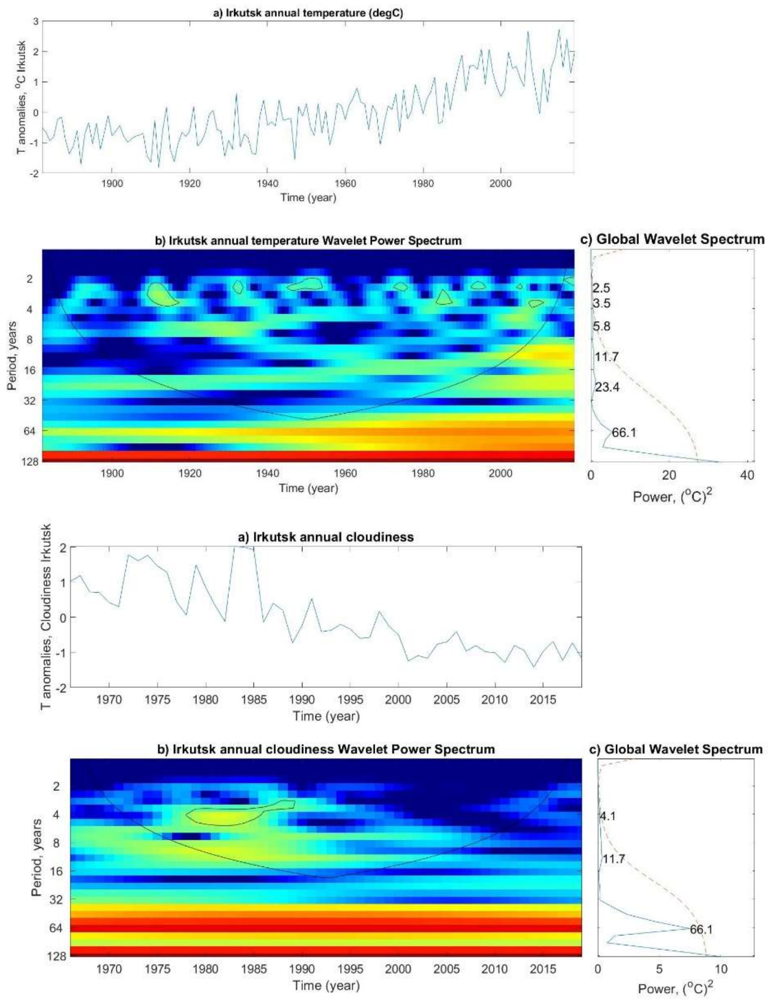

Figure 5. Annual temperature and annual cloudiness in Irkutsk. The color-coding represents low to high precipitation, temperature, cloudiness, respectively from blue to yellow. The dotted red line defines 95% significance level.

4. Results and discussion

Bulgaria is a Balkan country situated in the south-eastern part of Europe. Bulgaria has relatively small territory, but it contains multiple mountains and mountain ranges. This produces regions with specific local climate characteristics [8]. In the last several decades, the clear tendencies of the global climate change, produce their impact on separate territorial areas in Bulgaria [9, 10, 11].

Despite of the specific characteristics of the different geographical regions, the analysis of the digitized meteorological data shows a clear tendency of increase of yearly mean temperatures for each region since 1980. A well-defined tendency for increase or decrease of precipitation is not present, while the cloudiness has general decrease but without a constant gradient in time. These conclusions can be derived from the most complete time series, as well as from the shorter observation series. The performed wavelet analysis of selected observational data from three locations in Bulgaria show possible quasi-periodic oscillations with period between 2 and 6 years.

These probable periods of reoccurrence apply for temperature as well as for the precipitation and cloudiness. We render the existence of periodicity mainly due to the influence of North Atlantic Oscillations, which correlates with the Arctic Oscillation, which describes hemisphere-wide shifts in atmospheric pressure between the Arctic and the mid-latitudes of both the North Pacific and North Atlantic [12]. We made a comparative analysis of the observations in Bulgaria with observational data from Irkutsk, Russia. The temperature and cloudiness time series for Irkutsk have no gaps. This means that the obtained results can be treated as completely credible analytical result. Here we also see the tendency of increase of the mean yearly temperatures since 1980. The cloudiness is also generally decreased with no constant gradient in time. The mathematical wavelet analysis of the data from Irkutsk also exhibits quasi-periodic oscillations with periods between 2 and 6 years.

This initial analysis once more confirms the hypothesis of strong influence of North Atlantic Oscillations as well as the Arctic Oscillation on the average yearly changes mainly of the temperatures of the whole north hemisphere of the Earth [13, 14]. On the other hand, the influence of El Niño on the North Atlantic Oscillation and the Arctic Oscillation, shows us that we have one global climatic dependency on them.

Important next step for us towards a better analysis of the meteorological data is collecting and digitizing the monthly average values for precipitation, temperature, and cloudiness. The data is available in complete and gapless archive, but the digitization and organization of the data in time series database is a time-consuming process. Our database currently contains about 70% of the available on hard copies data. Mathematical analysis of monthly mean values could show eventual temporal oscillations of meteorological measures on seasonal basis, which would lead to a more clear and credible result. We are going to make comparative analysis of data from Bulgaria with as much as possible similar data from other locations on the globe.

5. Conclusions

We show the collected and analyzed data (near-surface air temperature, precipitation, humidity, cloudiness, atmospheric pressure and sunny hours) from 3 major meteorological stations in Bulgaria for the period 1905-2020 and compare the results to the data from 1 Russian station. Our initial analyses show that:

1. There is clearly noticeable tendency of increase of yearly mean temperature for the analyzed three stations in Bulgaria. This process of "warming" begins from 1980. The data of yearly mean temperature for Irkutsk, Russia also shows same rise, but this process seems to decrease or inverse after 2010.

2. Regarding temperature, our analysis shows that there are eventual periods of repetition of increase/decrease in yearly mean values with period between 2.5 and 5 years. The solar cycle is more observed during the temperature decrease. Periodicities with bigger period cannot be affirmed by this analysis, either because of edge effects, and they lie outside the code of influence or they are below the significance level and cannot be discerned from the background noise. This could be improved with longer time series of observational data. Similar periods could be related to El Niño/Southern Oscillation (ENSO) – phenomenon, which manifests as a quasi-periodic fluctuation in sea-surface temperature (El Niño) and air pressure of the overlying atmosphere (Southern Oscillation) across the equatorial Pacific Ocean [15].

3. Regarding cloudiness we do not find significant changes for the time after 1980 (Bulgarian data).

4. The analysis of precipitation does not show a clear tendency of constant change, but there is a quasi-periodicity with period of about 3.5 years. This could also be related to the quasi-periodic fluctuations of ENSO, North Atlantic Oscillations as well as Arctic Oscillations.

We present initial results of yearly mean values for temperature, precipitation and cloudiness of selected locations in Bulgaria, and a comparative analysis of similar data from Irkutsk, Russia. We acknowledge the great inaccuracy of the obtained quasi-periodicity based on the data from Bulgaria, due to the lack of real archive records. This will be improved after the collection and digitalization of the complete data base of monthly average values for meteorological data for Bulgaria.

Acknowledgements

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References

[1] T. Nikolov, N. Petrov, 2014, *Main factors influencing climate change: A review, Comptes rendus de l'Acad´emie bulgare des Sciences* **67**, 11, p. 1455.

[2] S. Manabe, R. T. Wetherald, 1967, *Journal of the Atmospheric Sciences* **24**, p. 786.

[3] R. A. Kerr, 2007, *Global Warming Is Changing the World, Science* **316**, 5822, pp. 188-190.

[4] G. Peters, R. Andrew, T. Boden et al., 2013, *The challenge to keep global warming below 2 °C, Nature Clim Change* **3**, 4–6.

[5] A. Bernardino, J. Santos–Victor, 2005, *A Real-Time Gabor Primal Sketch for Visual Attention,* In: Marques, J.S., Pérez de la Blanca, N., Pina, P. (eds) *Pattern Recognition and Image Analysis. IbPRIA 2005. Lecture Notes in Computer Science* **3522**.

[6] G. Torrence, G. P. Compo,1998, *A Practical Guide to Wavelet Analysis, Bulletin of the American Meteorological Society* **79**, 1, pp. 61-78.

[7] Z. Ge, 2007, *Significance tests for the wavelet power and the wavelet power spectrum, Annales Geophysicae*, **25**, 11, pp. 2259-2269.

[8] D. Topliisky, 2006, *Climate of Bulgaria*, Foundation "Amstels", Sofia *[In Bulgarian].*

[9] S. Mitkov, D. Topliisky, 2018, *Climate change in Bulgaria, represented by complex indices, Annual of Sofia University "St. Kliment Ohridski", Faculty of Geology and Geography, Book 2-Geography*, pp. 25-38 *[In Bulgarian].*

[10] N. Nikolova, D. Yanakiev, 2020, *Climate aridity in southern Bulgaria for the period 1961-2015, Forum geographic, Studii și cercetări de geografie și protecția mediului* **XIX**, 1, pp. 10-17.

[11] L. Bocheva, K. Malcheva, I. Gospodinov, V. Georgieva, E. Hristova, E. Georgieva, 2022, *Brief climate analysis and extreme weather events in Bulgaria during 2020, Bul. J. Meteo & Hydro* **25**/2, pp. 61-71.

[12] R. Lindsey and L. Dahlman L., *Climate Variability: North Atlantic Oscillation*, https://www.climate.gov/news-features/understanding-climate/climate-variability-north-atlantic-oscillation, Reviewed by Tom Di Liberto.

[13] M. H. Visbeck, J. W. Hurrell, L. Polvani, H. M. Cullen, 2001, *The North Atlantic Oscillation: Past, present, and future, PNAS* **98**, 23, pp. 12876-12877.

[14] J. W. Hurrell, C. Deser, 2008, *North Atlantic climate variability: The role of the North Atlantic Oscillation, Journal of Marine Systems* **79**, Issues 3–4, pp. 231-244.

[15] N. Jajcay, S. Kravtsov, G. Sugihara et al., 2018, *Synchronization and causality across time scales in El Niño Southern Oscillation. npj Clim Atmos Sci* **1**, 33.