Trends in compound extremes of air temperature and precipitation in Eastern Europe

Elena Vyshkvarkova (✉ aveiro_7@mail.ru)

Institute of natural and technical systems <https://orcid.org/0000-0002-4890-3247>

Olga Sukhonos

Sevastopol State University

Research Article

Keywords: compound extremes, temperature, precipitation, Eastern Europe, trends, teleconnection patterns

Posted Date: November 23rd, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1085030/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

The spatial distribution of compound extremes of air temperature and precipitation was studied over the territory of Eastern Europe for the period 1950–2018 during winter and spring. Using daily data on air temperature and precipitation, we calculated the frequency and trends of the four indices – cold/dry, cold/wet, warm/dry and warm/wet. Also, we studying the connection between these indices and large-scale processes in the ocean-atmosphere system such as North Atlantic Oscillation, East Atlantic Oscillation and Scandinavian Oscillation. The results have shown that positive trends in the region are typical of the combinations with the temperatures above the 75th percentile, i.e., the warm extremes in winter and spring. Negative trends were obtained for the cold extremes. Statistically significant increase in the number of days with warm extremes was observed in the northern parts of the region in winter and spring. The analysis of the impacts of the large-scale processes in oceans-atmosphere system showed that the North Atlantic Oscillation index has a strong positive and statistically significant correlation with the warm indices of compound extremes in the northern part of Eastern Europe in winter, while the Scandinavian Oscillation shows the opposite picture.

1. Introduction

Simultaneous or consecutive occurrence of several extreme phenomena (events) in climatology is referred to as complex extreme phenomena (events). Over the last decade, these events have been attracting the attention of the academic community due to their increased impacts on nature and society (Zscheischler et al. 2018; Seneviratne et al. 2012; Trenberth et al. 2014; Beniston et al. 2007; AghaKouchak et al. 2020, etc). Extreme precipitation and temperature values, which are two of the key variables in climatology and hydrology, are multidimensional phenomena, and they can occur at different periods (e.g. blocking anticyclones with droughts and heatwaves) (Röthlisberger 2019; Zscheischler 2020). It is crucial to understand various types of compound precipitation types and extreme temperatures to develop proper strategies for reducing the potential impacts on society and ecosystems. Changes in temperature and precipitation are often physically linked.

Droughts and heatwaves 2003 and 2015 in Europe, in 2010 in Russia, and 2012-2014 in California featured extreme events in terms of temperature and precipitation (the lack of thereof) that resulted in significant casualties and economic effects (Fink et al. 2004; Barriopedro 2011; Trenberth and Fasullo 2012; Horton et al. 2016; Diffenbaugh et al. 2015). Extreme precipitation and temperature values are considered independently using monodimensional statistical methods (Cooley et al. 2007; Katz 2010; AghaKouchak and Nasrollahi 2010; Zhang et al 2011; Alexander 2016). There are several approaches to the analysis of compound extremes (Hao et al. 2018). The statistical methods include the following: empirical, multivariate distribution (Estrella and Menzel 2013; Schöelzel and Friederichs 2008, for instance), indicator approach (Gallant et al. 2014), quantile regression (Quesada 2012), and Markov chain model (Shaby et al. 2016) (Hao et al. 2018). The empirical approach to the analysis of compound extremes is manifested in the calculation of the number of simultaneous or consecutive occurrences of several extremes. Beniston (2009) suggested using the combination of air temperature and precipitation

values exceeding the set thresholds (the 25th and 75th percentiles) in the empirical analysis of compound extremes. The joint distribution of the two weather variables like the temperature and the precipitation is a rational indicator of weather conditions and their stability (Beniston and Goyette 2007; Beniston et al. 2011). Joint distributions reflect weather conditions better than the statistics for the temperature or precipitation alone (Beniston et al. 2011; Zscheischler et al. 2018).

Trenberth and Shea (2005) discovered a strong negative correlation between the monthly average temperature and the precipitation rates over continents in the summer in both of the hemispheres. This correlation changes to the opposite inland at high latitudes in winter. Long-term trends for joint quantiles of air temperature and precipitation rates for European cities with different climates (Mediterranean, coastal, and continental) since 1901, as well as their possible changes by the end of the 21st century, were analyzed in the research work by Beniston (2009). Gallant and Karoly (2010) studied the changes in air temperatures and extreme precipitations over Australia using two combined indices and discovered the increase in extreme heat and humidity and the reduction of extreme cold and droughts in all of the seasons throughout the 20th century. Similar research was carried out for other regions, such as North America (Tencer et al. 2014; Martin and Germain 2017; Hao et al. 2018), China (Wu et al. 2019), India (Dash and Maity 2021), Europe (Morán-Tejeda et al. 2013; Arsenovic et al. 2015; Malinovic-Milicevic et al. 2016; Sedlmeier et al. 2018), and on the global scale (Hao et al. 2013).

The purpose of this research work is to analyze compound extremes of air temperature and precipitation based on the reanalysis of E-obs data for 1950–2018 in Eastern Europe, as well as studying the connection between these indices and large-scale processes in the ocean-atmosphere system.

2. Material And Methods

In this work, the authors used the data on daily average air temperature and precipitation amounts over the period of 1950–2018 in Eastern Europe (Central and North-Eastern Europe). The data were retrieved from the reanalysis of E-obs 20.0 (with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$) (Haylock et al. 2008). The study region is located within the following coordinates: $25\text{--}45^{\circ}$ east longitude, $42\text{--}61^{\circ}$ north latitude. The quality control of the initial data was done. The data availability maps for the region were constructed. There is enough data on the air temperature and precipitation rates in the region, the amount of data in E-obs reanalysis mesh points over 1950-2018 is over 80% for the study region.

To characterize compound extremes, combined air temperature and precipitation indices were used (Beniston 2009). The cold/wet (CW) index was calculated as a combination of the number of days with the average temperature below the 25th percentile (T25) and the daily precipitation amount higher than the 75th percentile (R75) at the same time. The same procedures were applied to calculate other indices combining the cold/wet parameters, such as the cold/dry days (CD – T25/R25), warm/dry days (WD – T75/R25), and warm/wet days (WW – T75/R75). This research work does not use so-called extreme percentiles (25th and 75th) to identify a large number of compound extreme events for air temperature and precipitation (Beniston 2009).

The threshold values for air temperature and precipitation were calculated for each of the seasons over the basic climate period of 1961–1990. The compound temperature and precipitation extreme was identified if the specific extremes occurred on the same day in 1950–2018. After that, the total number of such coincidences per month/season/year was counted. It should be noted that the precipitation percentiles were calculated for the series of days in question if the precipitation exceeded 1 mm. Calculations were performed for winter and spring. Summer and autumn seasons did not consider due to the low precipitation during these seasons. Spring corresponds to March, April, and May (MAM) of the current year, while winter stands for January and February of the current year, and December of the previous year.

To analyze the correlations between the compound extreme indices and circulation modes, the North Atlantic Oscillation (NAO), East Atlantic Oscillation (EA), and Scandinavian Oscillation (SKA) over the period of 1950–2018 were used. The indices were taken from the Climate Explorer website (<https://climexp.knmi.nl>).

The values of linear trend coefficients were determined using the least-squares method. The non-parametric test of Mann-Kendall was used to obtain the statistical significance of trends (with a significance level of 95%). To identify the correlations between air temperature and precipitation, compound extreme indices, and circulation modes, the Pearson's correlation coefficient was calculated and obtained its statistical significance using Student's criterion (95% significance).

3. Results

3.1. The occurrence rates of temperature and precipitation combinations

The average number of CD (cold/dry) days in winter for the study region is 1-3 days a year (Fig. 1, left). The number increases to 4 days on the eastern coast of the Black Sea (the Black Sea coast of the Caucasus). The CW (cold/wet) combination occurred up to 1-2 days a year in the entire region, except the Caucasus (up to 5 days a year). The WD (warm/dry) combination amounts to 2-3 days a year up to the 52nd parallel, while northwards it increases to 3-4 days a year. The WW (warm/wet) days are the most numerous in the region during winter. For the south of European Russia, eastern and Northern Ukraine, and Belarus, the number increases to 5 days a year, and in the north of the study region, this number of days with this index is 7-8 per year.

The number of days per year with the compound air temperature and precipitation extremes in spring is lower than in winter (Fig. 1, right). All of the indices occur 1-3 days a year. The CD index occurs more frequently in the Caucasus (up to 5 days a year), the CW index is often observed on the eastern coast of the Black Sea (up to 5 days a year), and the WW index occurs in the northern parts of the region.

Fig. 1 The spatial distribution of average days with compound air temperature and precipitation extremes over the period of 1950-2018 in winter (left) and spring (right)

The repeatability of compound extremes can be partially attributed to the correlations between precipitation and temperatures. The spatial distribution of correlation coefficients for the air temperature and precipitation over the period of 1950-2018 is shown in Fig. 2.

In winter, the positive (statistically significant) correlation is typical of the Crimean Peninsula, the south of European Russia (excluding the North Caucasus), the southeast regions of Ukraine, and all of the region to the north of the 54th parallel (Fig. 2a). A negative statistically significant correlation between the air temperature and precipitation rates can be observed on the western coast of the Black Sea (in Romania, Ukraine, and Moldova).

In spring, the study region shows a negative correlation between air temperatures and precipitation. Statistically significant negative coefficients are observed in the southeast of the Crimean Peninsula (the Crimean Mountains), Bulgaria, and the northeast of the region. The positive statistically significant correlation ($p < 0.05$) was observed on the eastern coast of the Black Sea, in the south of Belarus, and the parts of Russia bordering the Baltic states (Fig. 2b).

The frequency distribution of the WW combination corresponds to the distribution of correlation coefficients of the air temperature and precipitation rates during winter.

Fig. 2 The spatial distribution of Pearson's correlation coefficients for the air temperature and precipitation in winter (a) and spring (b) throughout 1950-2018. Statistically significant correlation coefficients ($p < 0.05$) are shown as black dots

3.2. Compound extreme indices trends

The CD index mainly features negative trends across the region during winters (Fig. 3, left). Positive trends are observed on the western coast of the Black Sea, yet they are not statistically significant. Compound extremes combining cold and wet conditions (CW) show a statistically significant increase in the number of days in central Ukraine, as well as negative trends on the eastern coast of the Black Sea near the Caucasus featuring the greatest negatives of up between -0.7 and -0.8 days /10 years. The linear trends for the wet/dry extreme combination are inhomogeneous. In the north of the region, there is a positive trend with statistically significant values observed in Belarus, Estonia, and some parts of Russia. The statistically significant increase in the WW index is observed throughout the entire region north of the 50th parallel (up to +1 days in 10 years). Negative trends were found near the Caucasus.

The distribution of trends for this index during spring is similar to the winter one, yet the trend values are smaller (Fig. 3, right). The CD index mainly features negative trends across the entire region. The statistically significant reduction of compound extremes is observed in the North Caucasus, eastern Ukraine, and some parts of Russia. A statistically significant reduction of CW extremes is observed near the Caucasus (up to -0.9 days/10 years). The WD demonstrates a mixed structure in the distribution of

linear trend coefficients. The trends for the extremes combining high temperatures and heavy precipitation are positive in the center of the region (they are also statistically significant).

Fig. 3 The spatial distribution of linear trend coefficients for compound air temperature and precipitation extremes in winter (left) and spring (right) over the period of 1950-2018. Black dots stand for statistically significant trends ($p < 0.05$)

3.3 Correlation of compound indices and large-scale processes

The European climate is influenced by large-scale processes in the oceans and atmosphere, such as the North Atlantic Oscillation, East Atlantic Oscillation, etc. The impacts of these signals were covered by many researchers from different regions of the world (Hurrell 1995; Nesterov 2009; Mikhailova and Yurovsky 2016; Mellado-Cano et al. 2019 and many others).

For each of the seasons, we took the season average value of the large-scale signals (NAO, EA, and SKA) and calculated the winter and spring indices. After that, we calculated Pearson's correlation coefficient for the compound extreme indices and the winter and spring signal indices.

The correlation analysis of the compound extreme indices and the NAO index in winter produced the following results (Fig. 4, left). Negative correlations were found between the NAO index and the “cold” CD and CW indices across the region and the 95% statistically significant indices in Belarus, Eastern Ukraine, and the Black Earth Regions. The warm indices (WD and WW) showed a statistically significant positive correlation (up to 0.8) with the winter NAO index above the 50th parallel. A negative correlation was observed between the WW and the NAO indices in the North Caucasus and the Caucasus ridge (up to -0.8).

The correlation between the CD index and the winter EA index is negative throughout the region with little statistically significant areas (Fig. 4, center). The CW index features a mainly positive correlation with the EA index above the 50th parallel, while on the Black Sea coast of the Caucasus the correlation is negative (and statistically significant). The warm compound extreme indices (WD and WW) have a positive correlation with the winter EA index throughout almost the entire region. The WW index features a statistically significant correlation in Belarus, the Baltic, and the northern part of European Russia.

The correlation between the cold indices of CD and CW and the winter SKA index is quite heterogeneous (Fig. 4, right). There are areas with a positive statistically significant correlation on the western coast of the Black Sea (Bulgaria, Romania, Moldova, and a part of Ukraine), as well as in the north of the region. The warm indices (WD and WW) feature a largely negative correlation with the winter SKA index with statistically significant values in the north of the region.

Fig. 4 The spatial distribution of correlation coefficients for compound extreme indices and atmospheric circulation signals in winter. Statistically significant correlation coefficients ($p < 0.05$) are shown as black dots

The spring is characterized by the following results (Fig. 5). Cold indices demonstrate a negative correlation with the spring NAO index throughout almost the entire region. For the CD index, positive correlation coefficients were observed near the Caucasus, and in eastern Ukraine for the CW index. The compound extreme WW index and the NAO index have a statistically significant correlation in Belarus, Bulgaria, and some parts of Russia.

The correlation between the CD index and the spring EA index is negative throughout the region with statistically significant values west of the 36th degree. The CW index has a positive correlation with the EA index in the left-bank region of Ukraine and the northeast of the region. Negative correlation coefficients were found in Romania and Moldova. The WW index is characterized by the positive values of the correlation coefficient across the region with large areas of statistically significant values.

Ukraine, Belarus, as well as the western and eastern coasts of the Black Sea, are characterized by positive correlation coefficients for the spring CD and the spring SKA indices. A negative (statistically significant) correlation between the CW index and the spring SKA index was observed in the southeast of Ukraine, and a positive correlation was observed in central Ukraine. The WW index features a largely negative correlation across the entire region with the areas of statistically significant correlation coefficients in the center and the east of the region.

The distribution of the correlation coefficient between the WD index and the spring indices of large-scale circulation is characterized by great spatial heterogeneity.

Fig. 5 The spatial distribution of correlation coefficients for compound extreme indices and atmospheric circulation signals in spring. Statistically significant correlation coefficients ($p < 0.05$) are shown as black dots

4. Discussion And Conclusions

The overall increase in the frequency and intensity of extreme events associated with air temperature and precipitation requires that this problem should be studied in more detail (Field et al. 2012). Extensive research on the extreme trends in air temperatures and precipitation rates in the study region has been conducted. They include the data on Russia (Vyshkvarkova 2021; Aleshina et al. 2018; Aleshina et al. 2021), Georgia (Keggenhoff et al. 2014), the western coast of the Black Sea (Croitoru et al. 2013; 2016), Ukraine (Boychenko et al. 2016), etc. The research works differ in the methods used and the observation period. However, the key outcome of the majority of works is a statistically significant increase in the air temperature and its extreme values, as well as the heterogeneous precipitation values (Cardell et al. 2020).

We used the empirical approach to define the joint extremes of air temperature and precipitation and analyze their spatial and temporal distribution over 1950-2018 in Eastern Europe. We evaluated the occurrence frequency and trends typical of compound extremes in winter and spring. Positive trends in the region are typical of the combinations with the temperatures above the 75th percentile, i.e., the warm

extremes in winter and spring. Negative trends were obtained for the CD and CW indices (cold extremes). Statistically significant increase in the number of days with warm extremes was observed in the northern parts of the region in winter and spring.

The results obtained correlate with those obtained previously by other researchers. The compound extremes in European countries and regions show that the warm combinations (warm/dry and warm/wet) are growing while the cold combinations are decreasing (Beniston 2009; Morán-Tejeda et al. 2013). Aleshina et al. (2021) used the data from observations and ERA5 reanalysis to demonstrate that the 95th percentile precipitation increases against the growth of temperatures in winter all over Russia. Global research (Hao et al. 2013) based on the CRU data also showed the increase in WD and WW extremes in Russia in the second half of the 20th century. The comparison of compound extremes produced using the CRU data and CMIP5 project models showed correlation, which allows for the further use of the CMIP project results for global climate modeling to assess any possible changes in compound extremes in the future. According to IPCC experts, the occurrence rates and intensity of extremes associated with air temperature and precipitation will increase in the future (IPCC 2014). The analysis performed using various models and scenarios for the European regions confirms this claim (Khlebnikova et al. 2019; Kjellström et al. 2018). The growth of hydrological extremes is predicted in Great Britain by the end of the 21st century (Visser-Quinn et al. 2019), for instance.

The increase in the occurrence rates of the extremes combining high temperature and a lack of precipitation may result in droughts similar to the weather conditions observed in Russia and Central Europe in 2010, 2015, and 2021. Such conditions may provoke forest fires (AghaKouchak et al. 2020) and aggravate their effects, e.g., the smog and air pollution. Positive trends for the WW combination can be attributed to the intensification of cyclonic activity and, as a result, they result in heavy rains and floods. These may include the flood in Krymsk (Krasnodar Territory) of 2015 when 2-5 monthly rainfall fell over a short period, the flooding of the cities on the Black Sea coast of the Caucasus and the east of Crimean Peninsula in 2021, and the 2021 floods in Germany. This kind of research remains vital and requires further efforts due to the ongoing climate change.

We used the NAO, EA, and SKA indices as circulation modes. According to various authors, they impact the air temperatures and precipitation rates in Eastern Europe (Zubiate et al. 2017; Tsanis and Tapoglou 2019; Cioffi et al. 2015; Mikhailova and Yurovsky 2016, etc). The analysis of the impacts of the large-scale processes in oceans-atmosphere system showed that the NAO index has a strong positive and statistically significant correlation with the WD and WW indices of compound extremes in the northern part of Eastern Europe in winter. The correlation with the EA index is similar but its correlation coefficients are smaller. The Scandinavian oscillation features the opposite: there is a negative correlation in the north of the region. The results for spring are less straightforward. The circulation types change and cyclone paths shift during various signal phases, which impacts the occurrence and distribution of compound extremes of air temperatures and precipitation in the Eastern Europe region.

The changes observed in the occurrence and frequency of compound extremes are affecting and shall continue affecting various areas of life including healthcare, agriculture, transportation, infrastructure, power industry, etc. The results obtained can be used to develop adaptations to climate changes, compound extremes in particular.

Declarations

Funding

The study was supported by state assignment of Institute of natural and technical systems (Project Reg. No. AAAA-A19-119031490078-9).

Competing Interests

The authors have no relevant financial or non-financial interests to disclose

Author Contributions

All authors contributed equally to the study concept, design, analysis, and final write up. All authors read and approved the final manuscript.

Availability of data and material

Data and material are available from hyperlinks in text.

Ethics approval

Not applicable, the study does not contain human or animal participants.

Consent to participate

Not applicable, the study does not contain human or animal participants.

Consent for publication

All authors consent to publication if accepted.

Conflict of interest

The authors declare no competing interests.

References

AghaKouchak A, Chiang F, Huning LS, Love CA, Mallakpour I, Mazdiyasni O, Moftakhari H, Papalexiou SM, Ragno E, Sadegh M (2020) Climate Extremes and Compound Hazards in a Warming World. Annu Rev

Earth Planet Sci 48:519–548. <https://doi.org/10.1146/annurev-earth-071719-055228>

AghaKouchak A, Nasrollahi N (2010) Semi-parametric and parametric inference of extreme value models for rainfall data. *Water Resour Manag* 24:1229–1249. DOI 10.1007/s11269-009-9493-3

Aleshina M, Semenov VA, Chernokulsky A (2021) A link between surface air temperature and extreme precipitation over Russia from station and reanalysis data. *Environ Res Lett* 16:105004. <https://doi.org/10.1088/1748-9326/ac1cba>

Aleshina MA, Toropova PA, Semenov VA (2018) Temperature and Humidity Regime Changes on the Black Sea Coast in 1982–2014. *Rus Meteor Hydrol* 43 (4):235–244. DOI: 10.3103/S1068373918040040

Alexander LV (2016) Global observed long-term changes in temperature and precipitation extremes: A review of progress and limitations in IPCC assessments and beyond. *Weather Clim Extrem* 11:4–16. DOI: 10.1016/j.wace.2015.10.007

Arsenovic P, Tosćić I, Unkasevic M (2015) Trends in combined climate indices in Serbia from 1961 to 2010. *Meteorol Atmos Phys* 127:489–498. DOI 10.1007/s00703-015-0380-6

Barriopedro D, Fischer EM, Luterbacher J, Trigo RM, García-Herrera R (2011) The hot summer of 2010: redrawing the temperature record map of Europe. *Science* 332:220–224. DOI:10.1126/science.1201224

Beniston M (2009) Trends in joint quantiles of temperature and precipitation in Europe since 1901 and projected for 2100. *Geophys Res Lett* 36:L07707. doi:10.1029/2008GL037119

Beniston M, Goyette S (2007) Changes in variability and persistence of climate in Switzerland; exploring 20th century observations and 21st century simulations. *Global Planet Change* 57:1–15. doi:10.1016/j.gloplacha.2006.11.004

Beniston M, Uhlmann B, Goyette S, Lopez-Moreno JI (2011) Will snow-abundant winters still exist in the Swiss Alps in an enhanced greenhouse climate? *Int J Climatol* 31:1257–1263. DOI: 10.1002/joc.2151

Boychenko S, Voloshchuk V, Movchan Y, Serdjuchenko N, Tkachenko V, Tyshchenko O, Savchenko S (2016) Features of climate change on Ukraine: scenarios, consequences for nature and agroecosystems. *Proceedings of the National Aviation University* 4(69):96–113. DOI: 10.18372/2306-1472.69.11061

Cardell MF, Amengual A, Romero R, Ramis C (2020) Future extremes of temperature and precipitation in Europe derived from a combination of dynamical and statistical approaches. *Int J Climatol* 1–28. DOI: 10.1002/joc.6490

Cioffi F, Lall U, Rus E, Krishnamurthy CKB (2015) Space-time structure of extreme precipitation in Europe over the last century. *Int J Climatol* 35:1749–1760. DOI: 10.1002/joc.4116

- Cooley D, Nychka D, Naveau P (2007) Bayesian spatial modeling of extreme precipitation return levels. *J Am Stat Assoc* 102:824–840. <https://doi.org/10.1198/016214506000000780>
- Croitoru A-E, Chiotoroiu B-C, Ivanova Todorova V, Torică V (2013) Changes in precipitation extremes on the Black Sea Western Coast. *Global and Planetary Change* 102:10–19. <http://dx.doi.org/10.1016/j.gloplacha.2013.01.004>
- Croitoru A-E, Piticar A, Burada DC (2016) Changes in precipitation extremes in Romania. *Quat Int* 415:325–335. <https://doi.org/10.1016/j.quaint.2015.07.028>
- Dash S, Maity R (2021) Revealing alarming changes in spatial coverage of joint hot and wet extremes across India. *Sci Rep* 11:18031. <https://doi.org/10.1038/s41598-021-97601-z>
- Diffenbaugh NS, Swain DL, Touma D (2015) Anthropogenic warming has increased drought risk in California. *PNAS* 112:3931–3936. [doi/10.1073/pnas.1422385112](https://doi.org/10.1073/pnas.1422385112)
- Estrella N, Menzel A (2013) Recent and future climate extremes arising from changes to the bivariate distribution of temperature and precipitation in Bavaria, Germany. *Int J Climatol* 33:1687–1695. <https://doi.org/10.1002/joc.3542>
- Field CB, Barros V, Stocker TF, Dahe Q, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press p. 582
- Fink AH, Brucher T, Kruger A, Leckebusch GC, Pinto JG, Ulbrich U (2004) The 2003 European summer heatwaves and drought—synoptic diagnosis and impacts. *Weather* 59:209–216. <https://doi.org/10.1256/wea.73.04>
- Gallant AJ, Karoly DJ, Gleason KL (2014) Consistent trends in a modified climate extremes index in the United States, Europe, and Australia. *J Clim* 27:1379–1394. <https://doi.org/10.1175/JCLI-D-12-00783.1>
- Gallant AJE, Karoly DJ (2010) A combined climate extremes index for the Australian region. *J Clim* 23:6153–6165. <https://doi.org/10.1175/2010JCLI3791.1>
- Hao Z, AghaKouchak A, Phillips TJ (2013) Changes in concurrent monthly precipitation and temperature extremes. *Environ Res Lett* 8:034014. [doi:10.1088/1748-9326/8/3/034014](https://doi.org/10.1088/1748-9326/8/3/034014)
- Hao Z, Hao F, Singh VP, Xia Y, Shi C, Zhang X (2018) A multivariate approach for statistical assessments of compound extremes. *J Hydrol* 565:87–94. <https://doi.org/10.1016/j.jhydrol.2018.08.025>
- Hao Z, Singh VP, Hao F (2018) Compound Extremes in Hydroclimatology: A Review. *Water* 10:718. [doi:10.3390/w10060718](https://doi.org/10.3390/w10060718)

- Haylock MR, Hofstra N, Klein Tank AMG, Klok EJ, Jones PD, New M (2008) A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. *J Geoph Res* 113:D20119. doi:10.1029/2008JD010201
- Horton RM, Mankin JS, Lesk C, Coffel E, Raymond C (2016) A review of recent advances in research on extreme heat events. *Curr Clim Chang Rep* 2:242–259. <https://doi.org/10.1007/s40641-016-0042-x>
- Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation regional temperatures and precipitation. *Science* 269:676–679. DOI: 10.1126/science.269.5224.676
- IPCC Climate Change 2014: Synthesis Report (2014) Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC Core Writing Team. Pachauri RK, Meyer LA (Eds). Geneva, Switzerland, 151p.
- Katz R (2010) Statistics of extremes in climate change. *Clim Change* 100:71–76. DOI 10.1007/s10584-010-9834-5
- Keggenhoff I, Elizbarashvili M, Amiri-Farahani A, King L (2014) Trends in daily temperature and precipitation extremes over Georgia, 1971–2010. *Weather and Climate Extremes* 4:75–85. <http://dx.doi.org/10.1016/j.wace.2014.05.001>
- Khlebnikova EI, Rudakova YuL, Shkolnik IM (2019) Changes in Precipitation Regime over the Territory of Russia: Data of Regional Climate Modeling and Observations. *Rus Met Hydrol* 44 (7):431–439. DOI: 10.3103/S106837391907001X
- Kjellström E, Nikulin G, Strandberg G, Christensen OB, Jacob D, Keuler K, Lenderink G, van Meijgaard E, Schär C, Somot S, Sørland SL, Teichmann C, Vautard R (2018) European climate change at global mean temperature increases of 1.5 and 2C above pre-industrial conditions as simulated by the EURO-CORDEX regional climate models. *Earth Syst Dynam* 9:459–478. <https://doi.org/10.5194/esd-9-459-2018>
- Malinovic-Milicevic S, Radovanovic MM, Stanojevic G, Milovanovic B (2016) Recent changes in Serbian climate extreme indices from 1961 to 2010. *Theor Appl Climatol* 124:1089–1098. DOI 10.1007/s00704-015-1491-1
- Martin J-P, Germain D (2017) Large-scale teleconnection patterns and synoptic climatology of major snow-avalanche winters in the Presidential Range (New Hampshire, USA). *Int J Climatol* 37:109–123. DOI: 10.1002/joc.4985
- Mellado-Cano J, Barriopedro D, García-Herrera R, Trigo RM, Hernández A (2019) Examining the North Atlantic Oscillation, East Atlantic Pattern, and Jet Variability since 1685. *J Clim* 32:6285–6298. <https://doi.org/10.1175/JCLI-D-19-0135.1>
- Mikhailova NV, Yurovsky AV (2016) The East Atlantic Oscillation: Mechanism and Impact on the European Climate in Winter. *Phys Oceanography* 4:25–33. DOI: 10.22449/1573-160X-2016-4-25-33

Morán-Tejeda E, Herrera S, López-Moreno JI, Revuelto J, Lehmann A, Beniston M (2013) Evolution and frequency (1970–2007) of combined temperature–precipitation modes in the Spanish mountains and sensitivity of snow cover. *Reg Environ Chang* 13:873–885. DOI 10.1007/s10113-012-0380-8

Nesterov ES (2009) East Atlantic oscillation of the atmospheric circulation. *Russ Meteorol Hydrol* 34:794–800. <https://doi.org/10.3103/S1068373909120048>

Quesada B, Vautard R, Yiou P, Hirschi M, Seneviratne SI (2012) Asymmetric European summer heat predictability from wet and dry southern winters and springs. *Nat Clim Chang* 2:736–741. <https://doi.org/10.1038/nclimate1536>

Röthlisberger M, Martius O (2019) Quantifying the local effect of northern hemisphere atmospheric blocks on the persistence of summer hot and dry spells. *Geophys Res Lett* 46:10101–10111. <https://doi.org/10.1029/2019GL083745>

Schöelzel C, Friederichs P (2008) Multivariate non-normally distributed random variables in climate research–introduction to the copula approach. *Nonlinear Process Geophys* 15:761–772. <https://doi.org/10.5194/npg-15-761-2008>

Sedlmeier K, Feldmann H, Schädler G (2018) Compound summer temperature and precipitation extremes over central Europe. *Theor Appl Climatol* 131:1493–1501. DOI 10.1007/s00704-017-2061-5

Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, Luo Y, Marengo J, McInnes K, Rahimi M (2012) Changes in climate extremes and their impacts on the natural physical environment. In: Field CB, Barros V, Stocker TF, Qin D, Dokken D, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK et al. (Eds) *Managing the Risks of Extreme Events and Disasters to Advance climate Change Adaptation; A Special Report of Working Groups I And II of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge University Press, Cambridge, UK, pp 109–230

Shaby BA, Reich BJ, Cooley D, Kaufman CG (2016) A Markova-switching model for heat waves. *Ann Appl Stat* 10:74–93. DOI: 10.1214/15-AOAS873

Tencer B, Weaver A, Zwiers F (2014) Joint Occurrence of Daily Temperature and Precipitation Extreme Events over Canada. *J Appl Meteor Climatol* 53:2148–2162. DOI: 10.1175/JAMC-D-13-0361.1

Trenberth K, Shea DJ (2005) Relationships between precipitation and surface temperature. *Geophys Res Lett* 32:L14703. doi:10.1029/2005GL022760

Trenberth KE, Fasullo JT (2012) Climate extremes and climate change: the Russian heat wave and other climate extremes of 2010. *J Geophys Res-Atmos* 117:D17103. <https://doi.org/10.1029/2012JD018020>

Trenberth KE, Dai A, van der Schrier G, Jones PD, Barichivich J, Briffa KR, Sheffield J (2014) Global warming and changes in drought. *Nat Clim Chang* 4:17–22. <https://doi.org/10.1038/nclimate2067>

- Tsanis I, Tapoglou E (2019) Winter North Atlantic Oscillation impact on European precipitation and drought under climate change. *Theor Appl Climatol* 135:323–330. <https://doi.org/10.1007/s00704-018-2379-7>
- Visser-Quinn A, Beevers L, Collet L, Formetta G, Smith K, Wanders N, Thober S, Pan M, Kumar R (2019) Spatio-temporal analysis of compound hydro-hazard extremes across the UK. *Advances in Water Resources* 130:77–90. <https://doi.org/10.1016/j.advwatres.2019.05.019>
- Vyshkvarkova E (2021) Changes in extreme precipitation over the North Caucasus and the Crimean Peninsula during 1961–2018. *Idojaras* 125:321–336. DOI:10.28974/idojaras.2021.2.8
- Wu X, Hao Z, Hao F, Zhang X (2019) Variations of compound precipitation and temperature extremes in China during 1961–2014. *Science of the Total Environment* 663:731–737. DOI: 10.1016/j.scitotenv.2019.01.366
- Zhang X, Alexander L, Hegerl GC, Jones P, Tank AK, Peterson TC, Trewin B, Zwiers FW (2011) Indices for monitoring changes in extremes based on daily temperature and precipitation data. *WiRes-Climate Change* 2:851–870. <https://doi.org/10.1002/wcc.147>
- Zscheischler J, Martius O, Westra S, Bevacqua E, Raymond C, Horton RM, van den Hurk B, AghaKouchak A, Jézéquel A, Mahecha MD, Maraun D, Ramos AM, Ridder NN, Thiery W, Vignotto E (2020) A typology of compound weather and climate events. *Nat Rev Earth Environ* 1:333–347. <https://doi.org/10.1038/s43017-020-0060-z>
- Zscheischler J, Westra S, van den Hurk BJJM, Seneviratne SI, Ward PJ, Pitman A, AghaKouchak A, Bresch DN, Leonard M, Wahl T, Zhang X (2018) Future climate risk from compound events. *Nat Clim Change* 8(6):469–477. <https://doi.org/10.1038/s41558-018-0156-3>
- Zubiate L, McDermott F, Sweeney C, O'Malley M (2017) Spatial variability in winter NAO–wind speed relationships in western Europe linked to concomitant states of the East Atlantic and Scandinavian patterns. *Quarterly Journal of the RMets* 143 (702):552–562. <https://doi.org/10.1002/qj.2943>

Figures

Figure 1

The spatial distribution of average days with compound air temperature and precipitation extremes over the period of 1950-2018 in winter (left) and spring (right)

Figure 2

The spatial distribution of Pearson's correlation coefficients for the air temperature and precipitation in winter (a) and spring (b) throughout 1950-2018. Statistically significant correlation coefficients ($p < 0.05$) are shown as black dots

Figure 3

The spatial distribution of linear trend coefficients for compound air temperature and precipitation extremes in winter (left) and spring (right) over the period of 1950-2018. Black dots stand for statistically significant trends ($p < 0.05$)

Figure 4

The spatial distribution of correlation coefficients for compound extreme indices and atmospheric circulation signals in winter. Statistically significant correlation coefficients ($p < 0.05$) are shown as black dots

Figure 5

The spatial distribution of correlation coefficients for compound extreme indices and atmospheric circulation signals in spring. Statistically significant correlation coefficients ($p < 0.05$) are shown as black dots