Effect of Anthropogenic Forcing on Anomalous Hydroclimate Events in Europe Detected by an Autoencoder

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Introduction

Climate change has widespread effects over the global system, including the intensification of extreme temperature and rainfall events. Large-scale precipitation and record heat waves have occurred more frequently across the globe, and are predicted to increase as a result of global warming by the Clausius-Clapeyron (CC) relation. Recently, Europe has faced particularly devastating impacts of extreme flooding, with these events being labeled a 'climate emergency.'[2] In July 2021, several European countries faced heavy rainfall, resulting in one of the largest flood disasters in Western Europe for decades.[3] In 2023, Europe saw 7% more precipitation,[4] and one third of the European river network saw river flows exceeding the 'high' flood threshold.

Despite the predictions of the CC relation, the mechanism driving these anomalous climate events (particularly in Europe) remains elusive, as recent studies by Martinkova and Kysely (2020) have shown.[4] These studies highlight the importance of circulation changes and anthropogenic forces, and the challenges that these factors pose for separating anthropogenic effects from natural variability.

Recently, deep learning techniques have been applied successfully in Earth system science for objective anomaly detection to address arbitrary thresholds and computational cost.[5] A developed autoencoder utilized over the Japan region found increasing trends in anomalous precipitation events, particularly in Western Japan, with anthropogenic forces showing a significant influence.[6] The objective of this study is to use a developed autoencoder to observations and outputs from large-ensemble simulations with high-resolution over the Europe region to identify trends in the frequency of anomalous precipitation and temperature events and elucidate if trends are attributable to anthropogenic forcing.

Methods and Materials

Observed Data: In this study, we used observations for daily precipitation and daily temperature extremes, minimum and maximum. Daily mean medium-resolution(0.5ºx0.5º) observed data over Europe was obtained from E-OBS for precipitation, daily temp maximum and minimum, from 1971-2023 to avoid uncertainties.

Model and Large-Ensemble Experiments: We used the Seamless System for Prediction and Earth System Research[7] medium-resolution for large-ensemble climate simulations. SPEAR is the current operational modeling system for seasonal to multidecadal prediction/projection, which consists of 0.5º AM4.0 atmosphere model, 0.5º LM4.0 land model, 1º MOM6 ocean model, and the SIS2 sea-ice model.[7] The project conducts two types of multidecadal simulations AllForc (all forcing) and NatForc (natural forcing) using SPEAR. AllForc includes all historical time-varying anthropogenic forcing (e.g. greenhouse gases, ozone, and anthropogenic aerosols) and natural forcing(e.g. volcanic aerosols and solar constant).

Anomalies for the Input of Autoencoder: Since this study focuses on large-scale events of relatively long duration, we analyzed 5-day anomalies of daily mean precipitation, temperature max, and temperature min. We used running-mean for singular precipitation, and fixed mean from 1951-1970 for compound events.[8]

Developing an Autoencoder to Identify Anomalous Events: The model was constructed by training on an input dataset , which learned to reconstruct data while minimizing mean square d errors (MSEs) and determining millions of parameters. If a sample is very rare in the training set, there will be a difficult reconstruction, resulting in a large MSE. We are detecting anomalous events by selecting the events with the highest MSEs, at the 95th percentile.

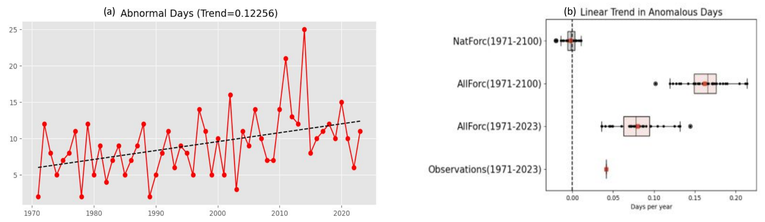


Figure 1: Time series and linear trends of deep learning–detected anomalous precipitation events. (a) Time series of annual frequency (days on y-axis) of anomalous precipitation events in observations (black). The Mann–Kendall significance test was applied, and the p-value< 0.05. (b) Linear trends in anomalous days for observations and models from 1977 - 2015 and 1977- 2050. Red boxes or dots denote statistically significant positive trends for the ensemble means or observations at the 95% level by Mann–Kendall test. Whiskers represent the range of the 10% and 90% quantiles of ensemble members; the vertical lines show the median value; diamonds show outliers; dots show each ensemble member; and squares represent the ensemble mean or observed value.

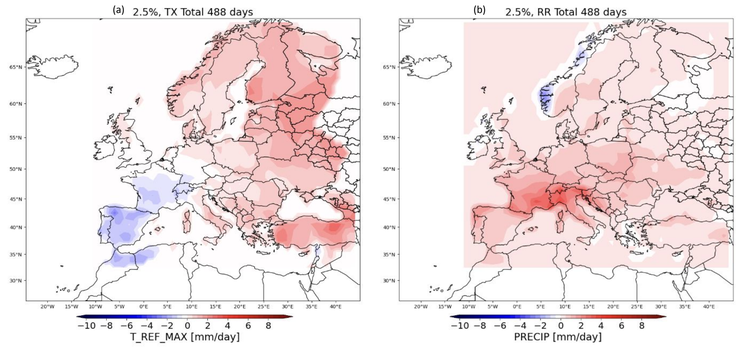


Figure 2: Shaded areas represent composites of the observed local temperature maximum anomalies in (a) and precipitation anomalies in (b) based on the compound anomalous events detected by the autoencoder derived from observed data.

Results

The time series for the observed frequency in anomalous events in Figure 1a shows a statistically positive trend over the period 1971-2023 at the 95% level using the Mann-Kendall test. Figure 1b shows that AllForc experiments by the SPEAR model have statistically significant findings in both the historical period (1971-2023) and the future period (1971-2100). The observed trend in frequency falls within the range of the SPEAR simulation AllForc, whereas there is no significant trend for NatForc. This indicates that AllForc can reproduce trends of the observed data, although the magnitudes of the positive trend have a noticeable difference. Additionally, anomalous events are projected to become more frequent toward the end of the century according to the SPEAR AllForc simulation.

Compound precipitation and surface temperature maximum events show a statistically increasing trend as well. Figure 2 shows the composite map of the maximum temperatures and precipitation for all identified anomalous days of the observed data. In Central Europe, there is a significant number of heavy rainfall events when there are cooler local maximum temperatures. In surrounding regions, there are hotter local maximum temperatures where there are dry events. This suggest that heavy rainfall in Central Europe can cause substantial warming outside the region as a result of some teleconnection that can be further explored.

Results

The colored lines in Figure 3 show the time series of anomalous precipitation events identified under different Socioeconomic Shared Pathways (SSPs). SSP5-8.5 is a climate model scenario representing a high-emissions future where radiative forcing increases, and emissions decrease from SSP3.70 to SSP2.45 to SSP1.19 to NatForc, in which radiative forcing does not increase. As radiative forcing decreases, the frequency in anomalous precipitation events decreases.

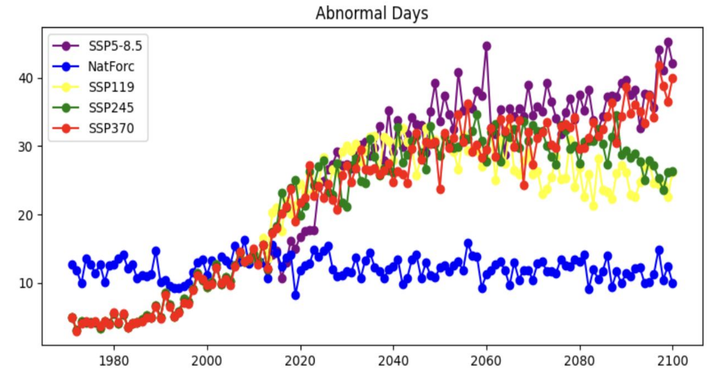


Figure 3: Time series of the frequency of anomalous precipitation events under different Socioeconomic Shared Pathways(SSPs) using SPEAR simulation over the period 1971 - 2100.

Discussion

This study demonstrates the viable success of an autoencoder to detect anomalous precipitation and temperature events. As this deep learning method has previously been applied to Japan, this study fine-tunes the autoencoder over the Europe region with ensembling. The detected anomalous precipitation, surface temperature maximum and minimum temperatures all have a significant positive trend in frequency over the period 1977 -2023. The observed trend in precipitation was significantly pronounced in Western Europe, showing an increase in heavy precipitation.

Compound events – simultaneous extremes in precipitation in surface temperature maximums or minimums — show a significant trend in Central Europe. The autoencoder finds an increasing number of heavy precipitation events at lower local maximum temperatures in Central Europe, but an increasing number of dry events at higher temperatures in surrounding regions. This suggests that heavy rainfall in Central Europe can cause substantial warming outside of the region as a result of some teleconnections. We found that SPEAR reproduced the observed positive increasing trends in anomalous events, although of different magnitudes.

In contrast, the idealized model experiments in which anthropogenic forcing (greenhouse gases, anthropogenic aerosols, and ozone) are not increased over 1971 - 2023, there are no significant trends in the frequency of anomalous precipitation events, suggesting the influence of anthropogenic forcing on the increase of events, beyond internal variability.

Future projections under different Socioeconomic Shared Pathways (SSPs) indicate that frequency and intensity of anomalous precipitation events will continue to rise toward the end of the 21st century. Scenarios with higher greenhouse gas concentrations predict more frequent anomalies compared to lower-emission scenarios. These results highlight the urgent need for global mitigation efforts to reduce greenhouse gas emissions.

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Acknowledgements

I would like to thank Hiro Murakami for his advice, mentorship, assistance.

References

1. Flooding in Europe | Copernicus. (n.d.). Retrieved from climate.copernicus.eu website: https://climate.copernicus.eu/esotc/2021/flooding-july
2. Lehmkuhl, F., Schüttrumpf, H., Schwarzbauer, J., Brüll, C., Dietze, M., Letmathe, P., … Hollert, H. (2022). Assessment of the 2021 summer flood in Central Europe. Environmental Sciences Europe, 34(1). https://doi.org/10.1186/s12302-022-00685-1
3. Nullis, C. (2024, April 19). Europe experiences widespread flooding and severe heatwaves in 2023. Retrieved from World Meteorological Organization website: https://wmo.int/news/media-centre/europe-experiences-widespread-flooding-and-severe-heatwaves-2023
4. Martinkova, M., & Kysely, J. (2020). Overview of Observed Clausius-Clapeyron Scaling of Extreme Precipitation in Midlatitudes. Atmosphere, 11(8), 786. https://doi.org/10.3390/atmos11080786
5. Ettrichrätz, V., Beier, C., Keuler, K., & Trachte, K. (2023). Identification of regions with a robust increase of heavy precipitation events. *EGUsphere*. https://doi.org/10.5194/egusphere-2023-552
6. Murakami, H., Delworth, T. L., Cooke, W. F., Kapnick, S. B., & P.-C. Hsu. (2022). Increasing Frequency of Anomalous Precipitation Events in Japan Detected by a Deep Learning Autoencoder. Earth's Future, 10(4). https://doi.org/10.1029/2021ef002481
7. Delworth, T. L., Cooke, W. F., Adcroft, A., Bushuk, M., Chen, J., Dunne, K. A., Ginoux, P., Gudgel, R., Hallberg, R. W., Harris, L., Harrison, M. J., Johnson, N., Kapnick, S. B., Lin, S., Lu, F., Malyshev, S., Milly, P. C., Murakami, H., Naik, V., & Pascale, S. (2020). SPEAR: The Next Generation GFDL Modeling System for Seasonal to Multidecadal Prediction and Projection. Journal of Advances in Modeling Earth Systems, 12(3). https://doi.org/10.1029/2019ms001895
8. Kikuchi, K., Wang, B., & Kajikawa, Y. (2012). Bimodal representation of the tropical intraseasonal oscillation. Climate Dynamics, 38, 1989–2000. https://doi.org/10.1007/s00382-011-1159-1

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