environmental sciences proceedings

MDPI

Proceeding Paper

Causal Drivers of Mediterranean Winter Climate Variability †

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† Presented at the 16th International Conference on Meteorology, Climatology and Atmospheric Physics—COMECAP 2023, Athens, Greece, 25–29 September 2023.

Abstract: As a significant component of natural climatic variability, teleconnection patterns play an important role in determining regional climate variability and extremes. The mechanisms linking the North Atlantic and the Mediterranean climate variability have not been rigorously demonstrated so far. Traditional statistical analysis of climate variability has vastly exploited concepts based on linear correlations and composites, nonetheless, with several weaknesses. The recently developed powerful concept of causal effect network (CEN) allows the detection of the causal relationships among a set of univariate time series (actors) by removing the confounding effects of autocorrelation, indirect links, and common drivers, retaining eventually only the actual causal links. In this study, we investigate the causal interaction mechanisms linking large-scale atmospheric variability with the Mediterranean winter climate by applying for the first time the CEN analysis. Results reveal causal links among the North Atlantic Oscillation (NAO), Eastern Mediterranean Pattern (EMP), and Eastern Atlantic (EA) teleconnection patterns, while the NAO acts as a causal driver for Mediterranean winter temperatures.

Keywords: teleconnection patterns; climate variability; Mediterranean climate; causal effect network (CEN); causal maps

Citation: Hatzaki, M.; Di Capua, G.; Chaniotis, J.; Patlakas, P.; Donner, R.V.; Flocas, H.A. Causal Drivers of Mediterranean Winter Climate Variability. *Environ. Sci. Proc.* **2023**, *26*, 155. https://doi.org/10.3390/environsciproc2023026155

Academic Editors: Konstantinos Moustris and Panagiotis Nastos

Published: 4 September 2023

1. Introduction

Teleconnection patterns play an important role in determining regional climate variability and extremes, as they constitute a significant component of natural climatic variability. While the spatial and temporal characteristics of the patterns affecting the Mediterranean region have been already evaluated along with their impacts on Mediterranean winter climate variability and extremes (e.g., [1,2]), there are open questions about the underlying dynamical mechanisms that contribute to the development of these patterns, their intra-annual variations, and possible relationships among them. In addition, the mechanisms linking climate variability over the North Atlantic with the Mediterranean intraseasonal variability have not been rigorously demonstrated in previous works. Traditional statistical analysis of climate variability has vastly exploited concepts based on linear correlations and composites; however, it exhibits several weaknesses.

Here, we apply a causal discovery approach using the PCMCI (Peter and Clark algorithm combined with the Momentary Conditional Independence approach; see Section 2) method [3]. The main advantage of causal discovery tools is that they can identify and remove spurious correlations [3–5] and, thus, provide insight into the potential causal relationships [6].

The resulting weighted network representation of causal interdependencies is referred to as a Causal Effect Network (CEN) [7,8]. A CEN detects and visualizes the causal relationships among a set of variables. Finally, we can visually highlight causally related spatial structures, grounded on the concept of causal maps [9].

Here, we applied the PCMCI+CEN approach to a set of teleconnection indices of the Northern Hemisphere that had been found to affect the Mediterranean climate, to investigate their inter-relationship and their links with the Mediterranean climate.

2. Material and Methods

PCMCI is a causal discovery method based on the PC algorithm (named after Peter and Clark) combined with the Momentary Conditional Independence approach (MCI, [3]). Given a set of univariate time series (called "actors"), PCMCI estimates their time series graph representing the conditional independencies among the time-lagged actors. The actors are selected by the user guided by previous knowledge. Assuming linear dependencies, PCMCI uses partial correlations to iteratively test conditional independencies and remove spurious links arising from autocorrelation effects, indirect links, or common drivers. Thereby, PCMCI efficiently conducts partial correlation tests to identify which links cannot be explained by other time-lagged actors [3].

The output of PCMCI is a p-value for each time-lagged causal link. It should be noted that the term "causal" lies on specific assumptions [5]. Adding or removing actors can alter the result, thus, having a robust hypothesis for the choice of the selected actors is important. The causal links detected via the PCMCI algorithm are then visualized in terms of a causal effect network (CEN). Each CEN is composed of circles representing the various actors, with their color indicating the strength of self-influence, and arrows indicating the direction of the detected causal links between the actors.

To explore the causal effects that a specific actor has on a 3D (lat, lon, time) climate variable field, the concept of causal maps was introduced [9]. In causal map visualization, we can directly illustrate the effect of a specific actor on the variable field, considering the influence of autocorrelation, indirect links, and common driver effects due to other participating variables. Causal maps are analogous to correlation maps; however, a causal map shows the path coefficient β from one actor to each grid point of the examined field, conditioning out all remaining actors. For example, for a set of two actors (X1 and X2) and one field Y, we can obtain two causal maps: one from X1 to Y, conditioned on X2 and all autocorrelation effects, and one from X2 to Y, conditioned on X1 and all autocorrelation effects, respectively.

The Northern Hemisphere teleconnection patterns that were selected as actors in the present analysis are represented by the EMP [10], NAO [11], and EA [12] indices. The time-series of NAO and EA were derived from the NOAA Climate Prediction Center (https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml, accessed on 12 June 2023). For the investigation of their causal effects on the Mediterranean climate, we used the ERA5 air temperature and precipitation monthly fields for the period 1959–2021 [13].

3. Results

The resulting CEN for the selected set of indices is plotted in Figure 1 and shows that EA is causally connected to EMP, while EMP is causally connected to NAO, both with a lag of 1 month. Specifically, the red arrow from NAO to EMP indicates a positive link, meaning that an increase in the NAO index will lead to an increase in the EMP index one month later, while the blue arrow from EMP to EA indicates a negative link. The strength of this relationship is seen from the right color bar in Figure 1. Thus, any correlation between NAO and EA is due to an indirect link via EMP (or to a common driver not included in this CEN).

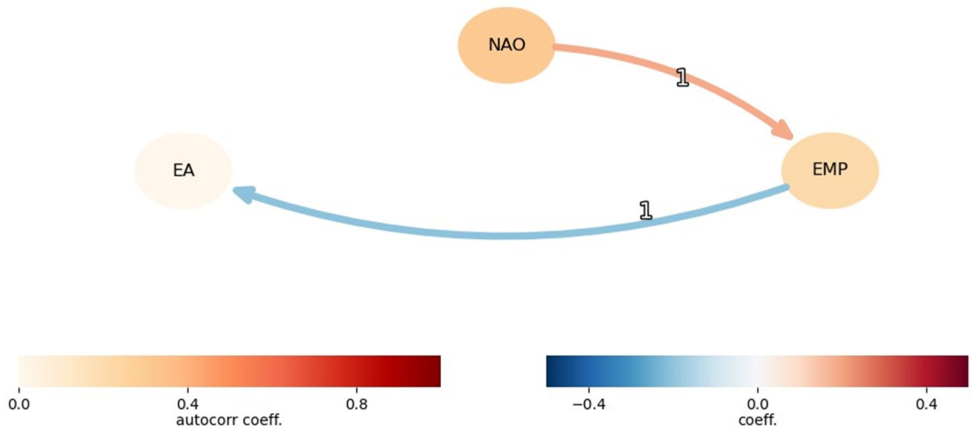

Figure 1. Causal effect network (CEN) built with EMP, NAO, and EA. The strength of the causal links is expressed by the standardized regression path coefficients and shown by the color of the arrows, while autocorrelation path coefficients are indicated by the colors of the circles. All links have a lag of 1 month. The lag is indicated by the respective numbers on the arrows. Only causal links with $p < 0.05$ are presented.

The causal map of Figure 2 shows the path coefficient β for the NAO link on Mediterranean winter air temperature, conditioning out the other actors and autocorrelations. This link is negative over the northern central-eastern Mediterranean. This indicates that an increase in the NAO index will lead to a decrease in winter temperature one month later.

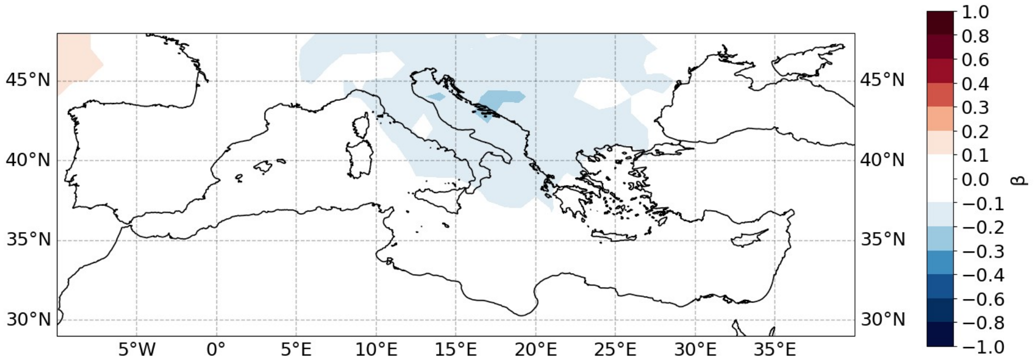

Figure 2. Causal map for NAO influence on Mediterranean winter air temperature (Tair). The map shows the β coefficient for the link NAO on Mediterranean winter temperature with 1-month lag, excluding other factors and autocorrelations. Only path coefficients β with $p < 0.05$ are shown.

The respective analysis for Mediterranean winter precipitation does not result in statistically significant results.

4. Conclusions

In this preliminary study, we apply causal discovery algorithms to analyze the causal links among teleconnection patterns of the North Hemisphere and their influence on Mediterranean climate winter variability.

We find that there are causal links between NAO and EMP and between EMP and EA, with different signs and with a lag of 1 month. NAO is related to the winter air temperature of the northern parts of the central and eastern Mediterranean and specifically, it is found that an increase in the NAO index leads to a decrease in air temperature with 1 month of lag.

The present analysis will be extended employing different sets of actors and higher temporal resolution datasets in order to examine the consistency of the causal effect networks across different timescales and to uncover the underlying mechanism of their links.

Author Contributions: Conceptualization, M.H., G.D.C., R.V.D. and H.A.F.; methodology, G.D.C. and R.V.D.; software, M.H., G.D.C. and J.C.; validation, M.H. and G.D.C.; formal analysis, M.H., G.D.C. and H.A.F.; investigation, M.H., G.D.C. and H.A.F.; data curation, M.H., J.C. and P.P.; writing—original draft preparation, M.H.; writing—review and editing, M.H. and H.A.F.; visualization, M.H., J.C. and P.P.; supervision, R.V.D. and H.A.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: No new data were created.

Acknowledgments: This work has been performed within the context of the IKYDA 2022–2024. Programme for Project-Related Personal Exchange (PPP) between Germany and Greece "Causal drivers of Eastern Mediterranean climate variability and extremes (CauseMED)". G.D.C. and R.V.D. acknowledge financial support by the German Federal Ministry for Education and Research (BMBF) via the JPI Climate/JPI Oceans project ROADMAP (grant no. 01LP2002B).

Conflicts of Interest: The authors declare no conflict of interest.

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