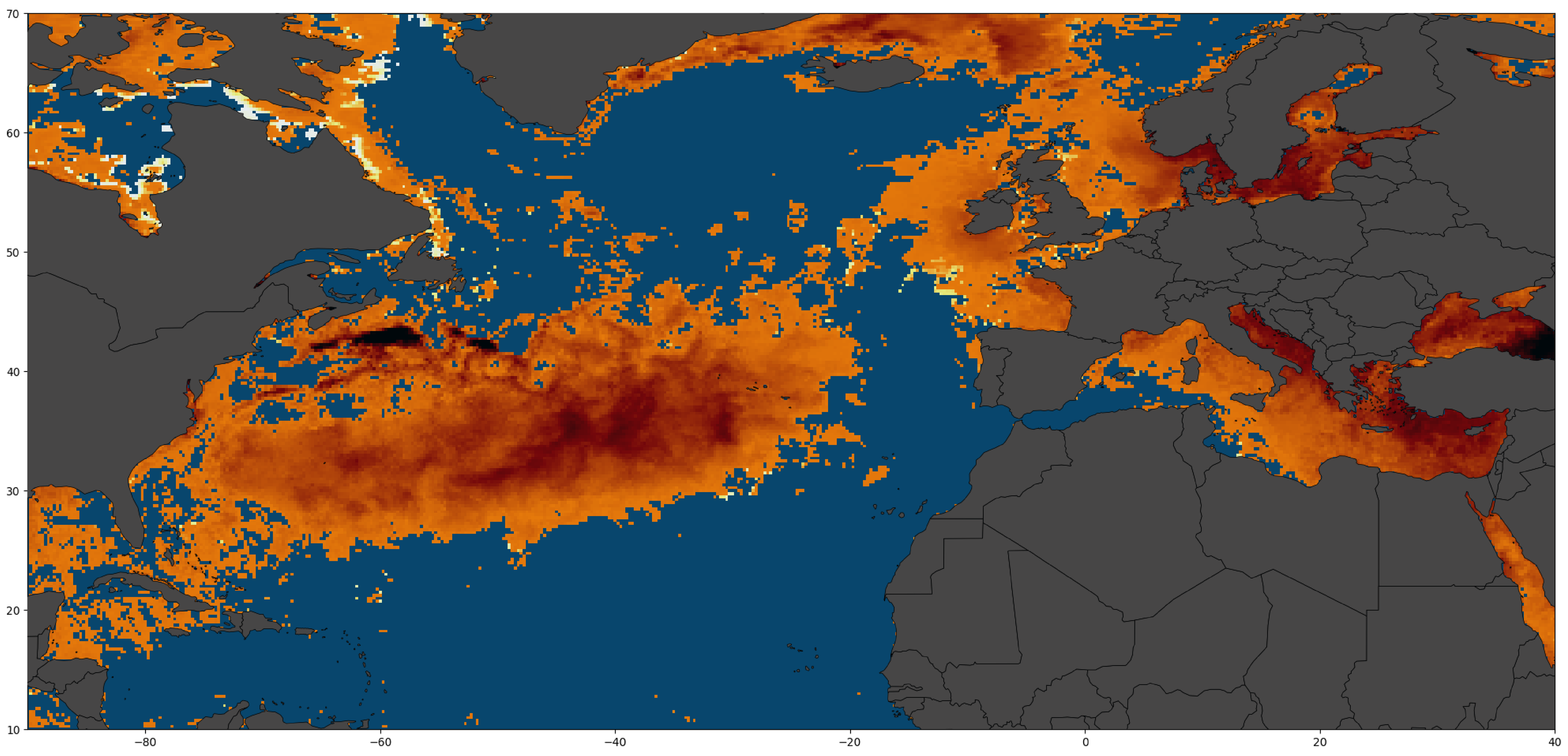
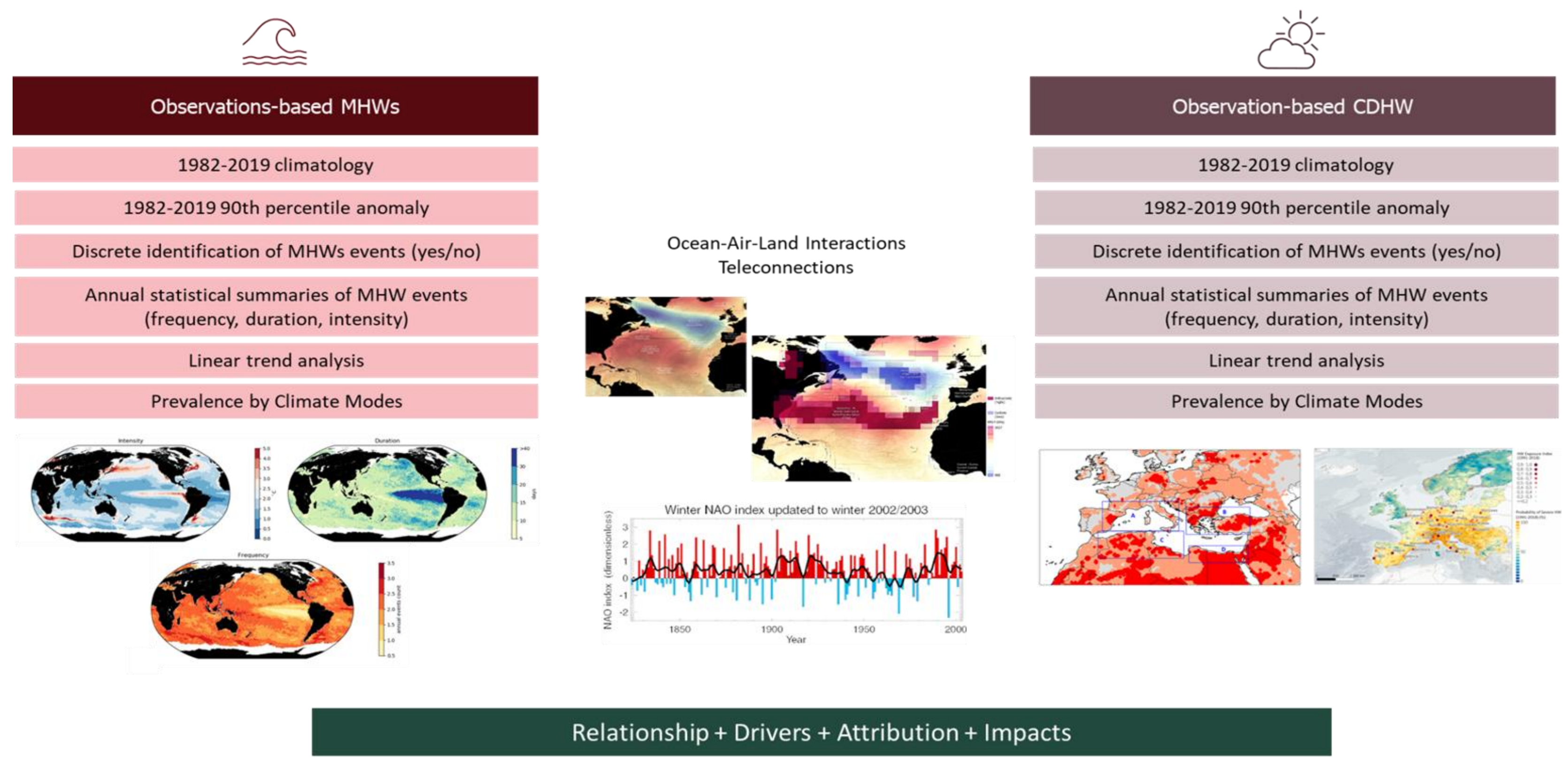
ATMOSPHERIC DRIVERS AND TELECONNECTIONS OF MARINE HEATWAVES: TOWARDS A FRAMEWORK FOR PREDICTING COMPOUND EXTREMES

Fabíola Silva[1], on behalf of the +ATLANTIC Team, in collaboration with the ESA XHEAT and Horizon Europe ObsSea4Clim projects.

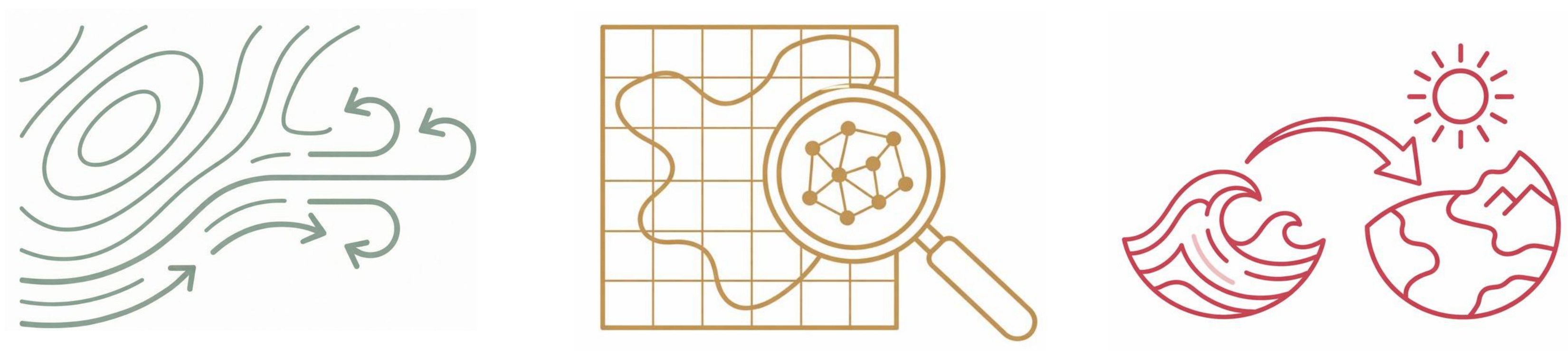
[1] CoLAB +ATLANTIC, Lisbon, Portugal [fabiola.silva@colabatlantic.com]





ABSTRACT

Marine Heatwaves (MHWs) are prolonged periods of anomalously warm sea surface temperatures (SST) with significant impacts on marine ecosystems and potential to influence weather patterns over land. While their relevance is well established, the scientific community faces open questions in three key areas that hlimit our predictive capabilities:



1. The drivers:
What are the precise atmospheric mechanisms that contributes to initiate, sustain, and cause the decline of MHWs?

2. The detection:
How can we move beyond simple temperature thresholds to more meaningful detection methods that capture the coherent, large-scale nature of these events?

3. The impacts:
How do we quantify the teleconnections between ocean heat and land-based extremes to better anticipate cascading, compound events?

DATA & METHODS

Despite significant progress in understanding, measuring and predicting extreme weather and climate events, several questions remain, especially regarding the feedback mechanisms between the ocean and the atmosphere. The multi-project framework focuses on disclosing teleconnections between ocean extremes and land-based climate impacts, as well as the atmosphere's impact on the ocean. It directly addresses the dynamics of persistent atmospheric patterns that can lead to spatially compounded extremes across regions. In this regard, the +ATLANTIC team has been investigating these topics through a multi-project framework:

- In the Horizon Europe ObsSea4Clim project, we are investigating the relationship between MHWs in the North Atlantic and large-scale climate modes. Investigating the role of atmospheric blocking and persistent high-pressure systems in driving air–sea heat flux anomalies.

- Within the ESA XHEAT project, we are analysing teleconnections to identify the role of MHWs in compound extreme events in Europe. We also explore the usage of Machine Learning in post-processing the traditional MHW methods to establish a novel mechanistic detection method that accounts for the spatio-temporal connectivity of the anomalies.

Addressing these challenges requires a comprehensive analysis of the ESA-CCI and Copernicus datasets, as well as NOAA/NCAR-Hurrel Climate Modes. This requires a systematic work plan designed to investigate relationships, dependencies and predictive capacities.

Advanced statistical and machine learning (ML) methods have been applied to model temporal and spatial dependencies, while teleconnection patterns have been explored to understand their role in event prediction. This structured approach aims to provide actionable insights into the mechanisms behind compound and cascading extreme events. In terms of extreme event indicators, the WMO's standard 1991–2020 climatology has been used from a univariate perspective to ensure comparability with the literature. Furthermore, the following method has been employed:

- **MHWs:** Hobday's method (Hobday et al., 2016) with the 90th percentile threshold for detection;

- **Large-scale and climate modes**: Atmospheric parameter anomalies (geopotential, wind speed and net heat flux) and the North Atlantic Oscillation (NAO) index;

- **Droughts:** Standardised Precipitation Index – SPI (Keyantash, 2021), Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) and Soil Moisture Anomaly (SMA) indices;

- **Heatwaves:** Excess Heat Factor (EHF) (Nairn and Fawcett, 2009), using the 90th percentile threshold for detection.

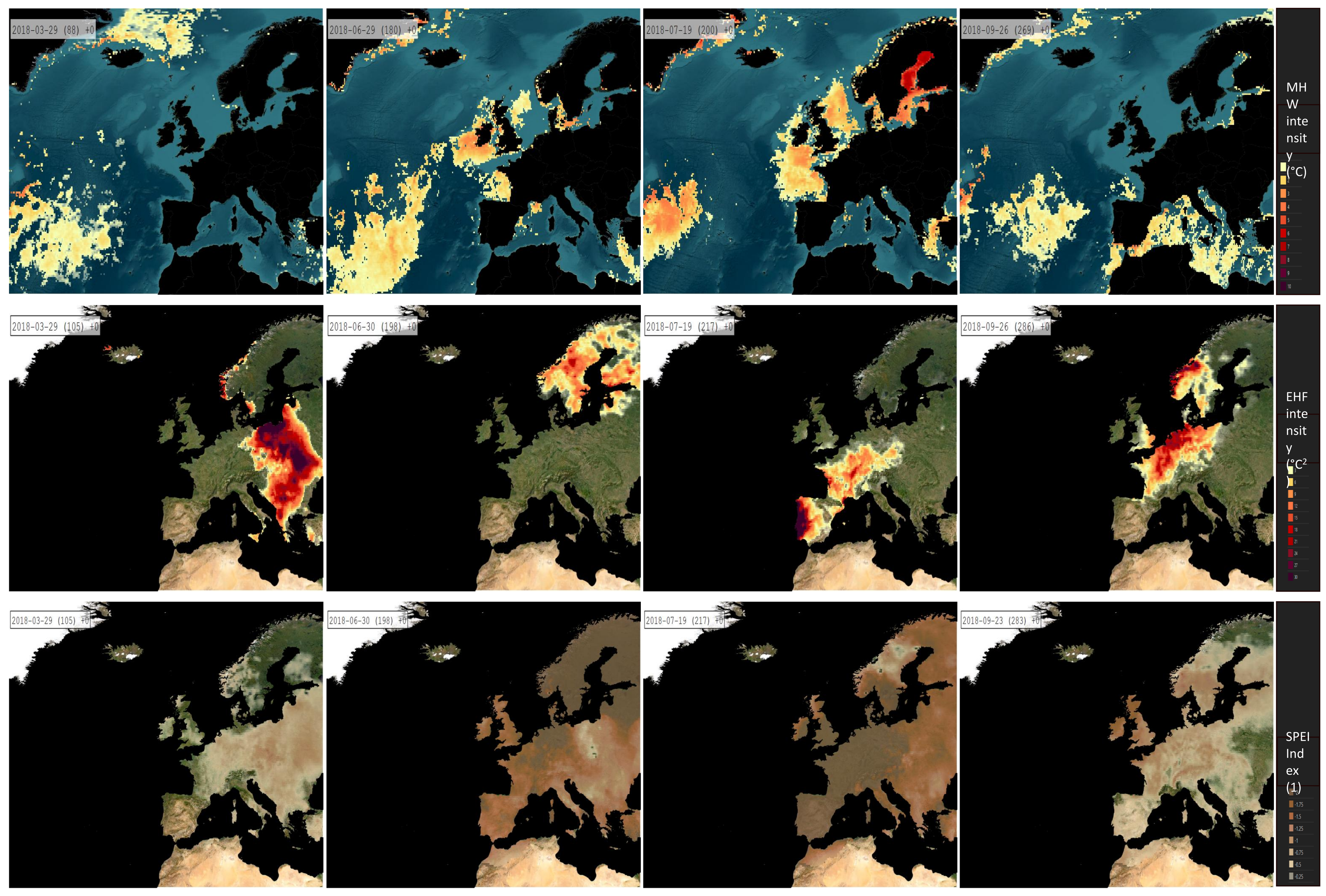


Figure 1. Sample sequence of the MHWs, EHF and SPEI indices, corresponding to the Spring and Summer seasons of 2018, when strong MHWs and HW occurred over the North Atlantic and the European domain..

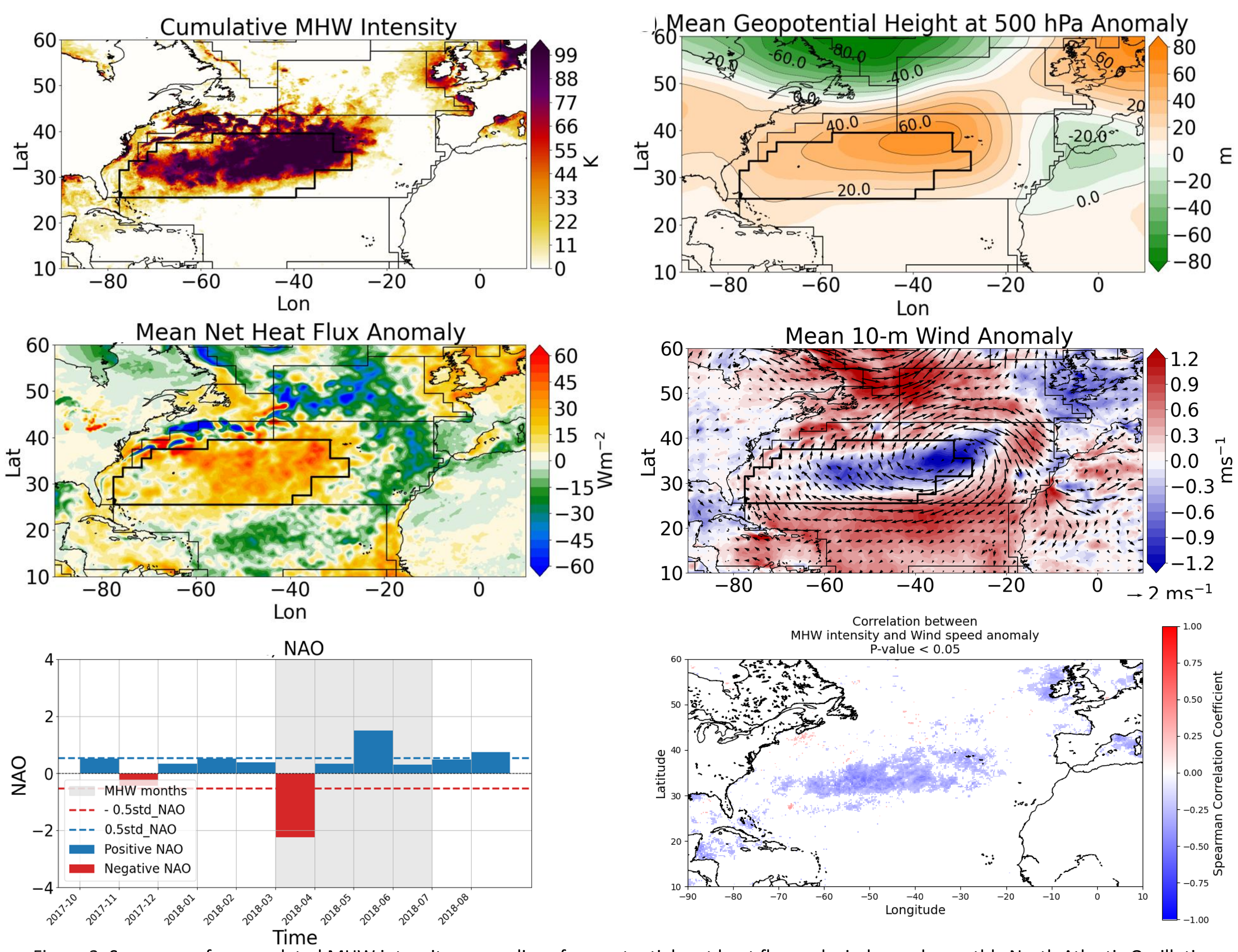


Figure 2. Sequence of accumulated MHW intensity, anomalies of geopotential, net heat flux and wind speed, monthly North Atlantic Oscillation (NAO) index, and lagged in 5 days Spearman Rank correlation between the MHW and wind speed for the MHW event occurred between 21/03/2018 and 07/07/2018, showcasing the agreement between the atmospheric pattern and the Sea Surface Temperature (SST) anomaly from the 90th percentile (the 30-years climatological threshold used in MHWs detection).

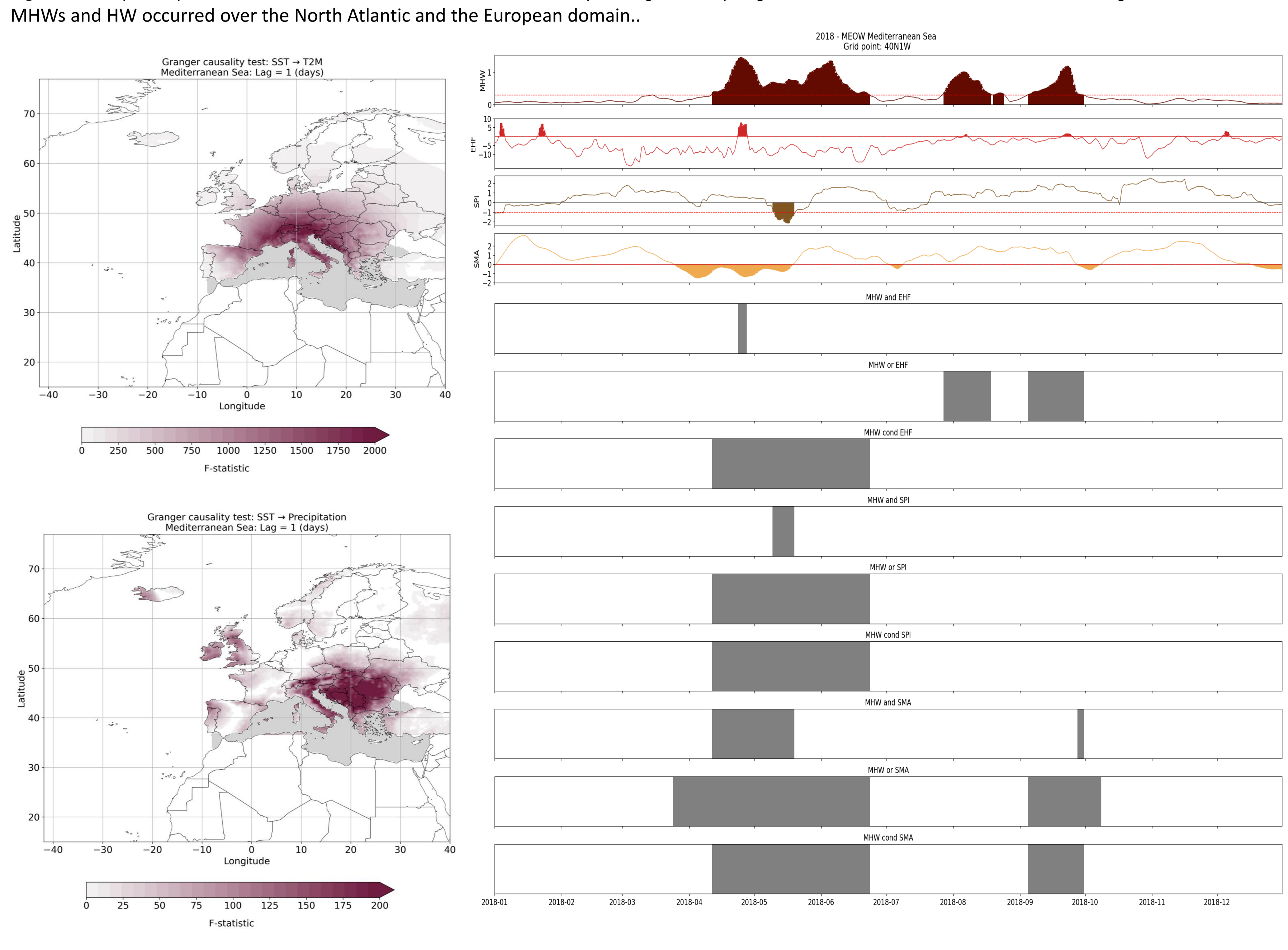


Figure 3: Granger causality sequence between the spatial average Sea Surface Temperature (SST) anomaly over the Mediterranean Sea and 2-metre temperature (top left) and rainfall (bottom left) anomalies, and the extreme compound algorithm (right) using generalised extreme value (GEV) distribution. This algorithm is based on Shan et al. (2024).

NEXT STEPS & REFERENCES

The next steps of the XHEAT project will involve researching whether climate modes and prolonged extreme sea surface temperature (SST) events in the North Atlantic-Mediterranean basin are leading to more frequent warm and dry conditions. The aim is to illustrate how persistent heatwaves (MHWs) in these basins modify atmospheric stability and lead to compound events across Europe. Additionally, the compound algorithm will be improved and validated. The next stages will also include developing the ML algorithm to demonstrate whether a data-driven algorithm can show the impact of MHWs.

Within ObsSea4Clim, work will continue with an investigation into the impact of atmospheric conditions on MHW events in the North Atlantic. This will include applying ML techniques to detect and label individual MHWs, focusing on the area occupied by the event. By computing the event severity metrics, it will be possible to study individual MHWs and their characteristics, as well as enabling intercomparison between them. This work emphasises the critical need to integrate marine and atmospheric datasets in climate studies, offering new insights into the cascading impacts of oceanic changes on societal risks.

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