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CAFE
Climate Advanced Forecasting of sub-seasonal Extremes

D2.2: Identification of large-scale weather patterns that lead to severe temperature condition and their predictability

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1. Introduction

Heatwaves have important impacts on society and our environment. We only need to remind ourselves of the summer of 2003 which caused upwards of 40000 fatalities (Garcia-Herrerra, R et al. 2010). Additionally, they also impact the crop production, ecosystems and infrastructures (Horton et al, 2016). This impact could be further intensified by our warming climate, by potentially increasing the frequency of heatwaves (Collins et al, 2013).

Forecasting heatwaves is therefore of very high importance to prevent some of the impact. Some resource management issues require predictions beyond 10 days. The sub-seasonal forecast targets the range between 15 and up to 60 days, and helps cover the gap between short range and seasonal forecast.

This project aims at evaluating the link between large-scale weather patterns and severe warm events over Europe on sub-seasonal time scale and measure current level of predictive skill. In this report we will show the first results showing the link between circulation patterns and heatwaves.

2. Heatwave determination

The first step in this work is to define heatwaves. We use a similar method to Stefanon et al., 2012. The idea being that a heatwave has to exceed a certain temperature threshold, over a large enough area for a minimum amount of days. This allows to identify events that are extreme enough, eliminates isolated 'hot' grid points and isolated days.

The whole analysis based on the ERA-5 reanalysis dataset (Hersbach *et al.*, 2020) from the European Center for Medium-range Weather Forecasts (ECMWF) from 1979 to 2020. For the heatwave definition we use the 2 meter temperature (2mT), to describe the atmospheric circulation the geopotential height at 500hPa (Z500). Other parameters such as the sea surface temperature (SST) and the soil moisture content are used to represent the surface conditions. The spatial resolution is

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31km*31km. The analysis is performed for the warm period May to September and over the domain 30-80°N, 25-60°E.

We use the 90th percentile of the climatological distribution based on 42 years as temperature threshold. At least 90% of the grid points inside a circle of 500km radius have to exceed the temperature threshold for at least 4 days. We also account for some intermittency and for the propagation by accepting circles that overlap by 60% as being part of the same event.

This methodology identifies 120 events with a total of 798 heatwave days.

3. Identification of associated large-scale circulation patterns

This section deals with the characterization of atmospheric circulation patterns associated with the 120 heatwave events identified above. We will be using the geopotential height at 500hPa anomaly (Z500) as this allows us to identify the large-scale circulation associated with the different heatwave types.

The clustering algorithm is performed in an empirical orthogonal functions space (EOF) using the first 9 principal components explaining 81% of the variance.

This procedure helps reduce the degrees of freedom which will facilitate the clustering procedure.

We compute the average of each event and apply a k-means clustering to the 120 events to identify the main categories of heatwaves based on their large-scale circulation. Due to the large-scale features size and the domain size we limit the cluster number to a maximum of 6. We use different metrics to obtain an objective criterium on the appropriate number of clusters.

The sum of squared error (SSE) and the Davies-Bouldin Score indicate that 5 and 6 clusters are the optimal partitions. When comparing the clustering with 5 and 6 clusters (not shown), we determine that the cluster number six represents a variation from the 'Scandinavian' cluster (Figure 1: top middle).

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We therefore use 5 clusters for our study. After performing robustness testing, we determine a robustness of 81%.

The resulting clusters are shown in Figure 1.

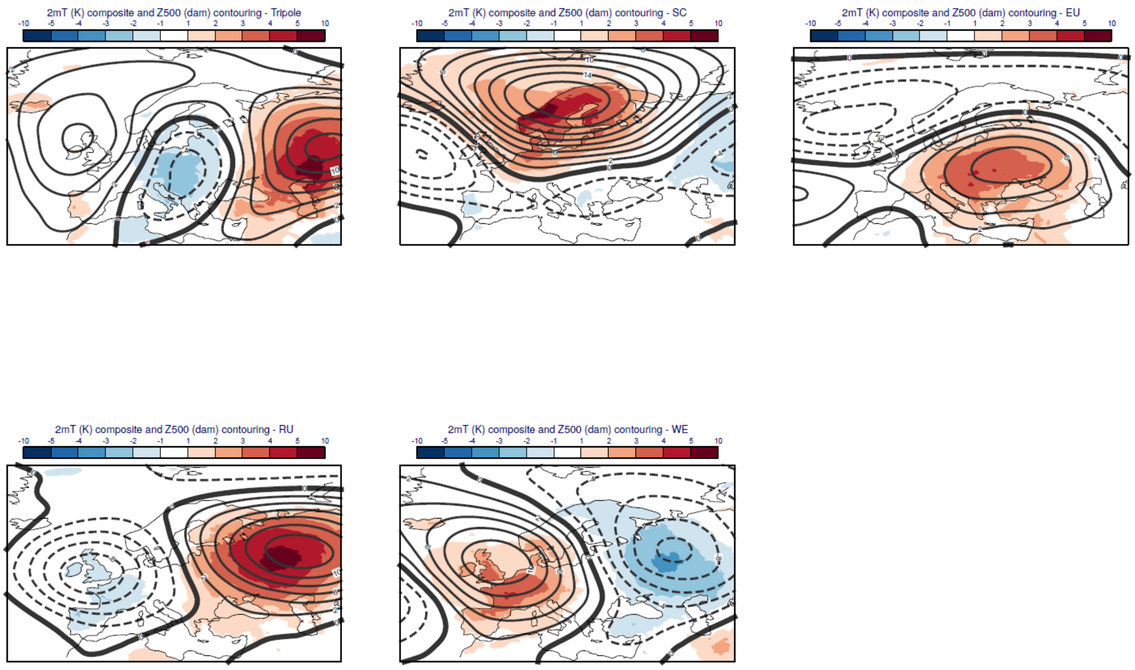

Figure 1: These maps represent the most recurrent heatwave types over Europe. Each individual map is a composite (average) of all events within the same cluster. The colour shading is the 2mT anomaly and the black contouring the Z500 anomaly (continuous lines show positive anomalies and dashed lines the negative anomalies).

The tripole structure (top left), shows severe warm events over Russia co-occurring with warm conditions over the Iberian Peninsula and the Atlantic. This cluster has 22 events for a total of 128 days and is one of the least populated. The Scandinavian (SC: top middle) shows strong positive 2mT anomaly located over Scandinavia. This is the second most populated cluster with 27 events and 186 days. The European cluster (EU: top right) is characterized by a 2mT temperature anomaly spread across a large area between eastern Germany and western Russia but with less amplitude. This is one of the lower populated clusters with 23 Events and 135 days. The Russian cluster (RU: bottom left) has a large amplitude and is the largest populated with 28 events and 225 days. The western European (WE: bottom right) shows a lower amplitude across

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France, the Benelux and the British Isles. This is the least populated cluster with 20 Events and 124 days.

All of the 5 cluster maps in Figure 1, show anti-cyclonic structures (positive anomaly in Z500: black continuous lines) centred over positive anomalies of 2mT. The anti-cyclonic anomalies are occurring together with cyclonic structures (negative anomaly in Z500), which hints towards blocking anti-cyclones This is in accordance with the current literature, showing that persistent anti-cyclones and/or blocking anti-cyclones are a key ingredient for heatwaves (Pfahl and Wernli, 2012; Stefanon et al, 2012; Pfahl et al, 2014; Zschenderlein et al, 2019). Section two and three are a summary of the work for milestones M2.1 and M2.4.

4. Temporal evolution and daily attribution of large-scale circulation patterns

We assess the time evolution of the reference patterns (shown in Figure 1) by constructing an index for each circulation pattern. The index measures the distance between the reference pattern and the daily circulation anomaly. The index is standardized using the standard deviation of this distance as in Michel and Rivière, 2011. This allows us to better understand the process leading to heatwaves and determine if the circulation features are the only necessary drivers for heatwaves. The higher the value, the closer the daily field is to the circulation pattern.

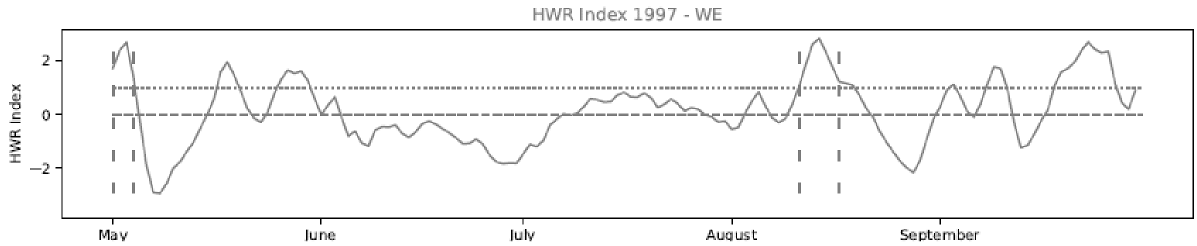

Figure 2: This figure represents the evolution of the Z500 index (grey line) of the WE cluster for the summer 1997. The grey vertical dashed lines represent the start and end of the heatwaves. The dotted line shows the standard deviation.

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Figure 1 shows for example, the time evolution of the circulation pattern associated with the WE heatwaves. We observe that each heatwave is characterised by continuous increase of the index at the start and a decrease at the end. The figure also shows that the WE circulation does not always lead to a heatwave event.

The analysis of the heatwaves time cycle is still in progress. The main questions we would like to address are

- What is the minimum persistence in the circulation for heatwave occurrence?
- What is the role of the amplitude of the high pressure system and the physical processes that trigger its onset and maintenance?
- Can the occurrence of a specific heatwave or circulation type condition the occurrence of other heatwaves?

5. Predictability

We determined that anti-cyclones are a key ingredient for heatwave occurrence. In this section we search for other potential drivers such as surface parameters. They fluctuate on a much slower time scale than the atmospheric variables and therefore they potentially can condition the weather. To this end we are analysing the effect of the sea surface temperature (SST) and soil moisture on the occurrence of heatwaves.

The tropical variability is dominated by the El Nino Southern Oscillation (ENSO), a quasi-biennial phenomenon that takes place over the equatorial Pacific, and the Madden and Julian Oscillation (MJO). The MJO is the most relevant mode of tropical convection travelling eastward across the globe with a time scale of 30 to 60 days. Rossby wave activity can be triggered in association to ENSO and MJO (Lee et al 2019). Those Rossby Waves create teleconnections between the tropics and European weather. Rossby Waves have been shown to enhance the risk of extreme temperatures (Fragkoulidis et al. 2018) and have an impact on blocking occurrence (Masato et al. 2012).

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This chain of effects motivated us to analyse whether the SST anomaly had particular patterns for the different heatwave types. Figure 2, we shows SST anomaly composites for each heatwave type, two weeks prior to the events.

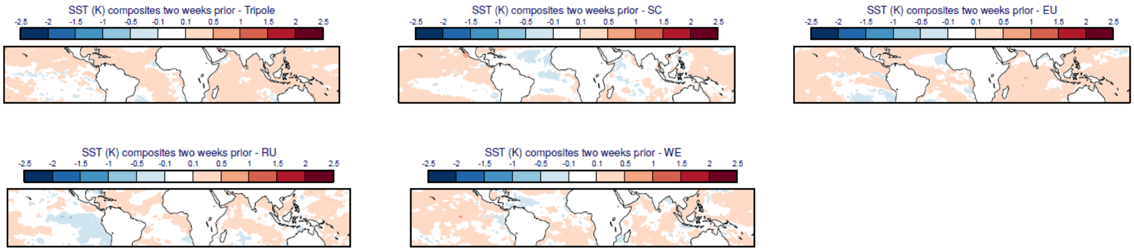

Figure 3: SST anomaly two weeks prior to the events as colour shading for each heatwave type.

The results show quite different patterns with mostly colder tropics for SC, warmer for the tripole (besides over the equatorial Pacific), warm SST with local cold anomalies near western Africa for EU and spotty anomalies for WE with colder tropical Atlantic. The RU cluster has the most striking features with a large cold anomaly over the equatorial Pacific that could be the signal for La Nina events. Further investigation is needed to establish the link between La Nina and the RU heatwaves, and will be based on the analysis of the individual events.

The soil moisture can play a role in the occurrence or intensity of heatwaves. A negative soil moisture anomaly can trigger a positive feedback, where insufficient water content reduces the effect of surface cooling by evapo-transpiration. This means that dry conditions exacerbate the local temperature anomalies (Miralles et al. 2019) and could be an important factor in the initial conditions of heatwave events.

The soil wetness index (SWI) represents the saturation level of the soils. In Figure 3 we represented initial results showing the anomaly of the SWI two weeks prior to the start of the heatwaves.

The SWI associated with the tripole heatwave type shows a strong dry anomaly centred over eastern Europe and extending to Russia that could enhance the local temperature anomaly. Similarly, the SWI for the EU cluster has a dry anomaly over most of Europe. The RU and WE have dry anomalies with less amplitude, spread across most of Europe and part of South RU, and over western Europe respectively. The SC

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however shows very little signal of drier conditions, limiting the soil moisture's role in the development of extreme warm temperatures.

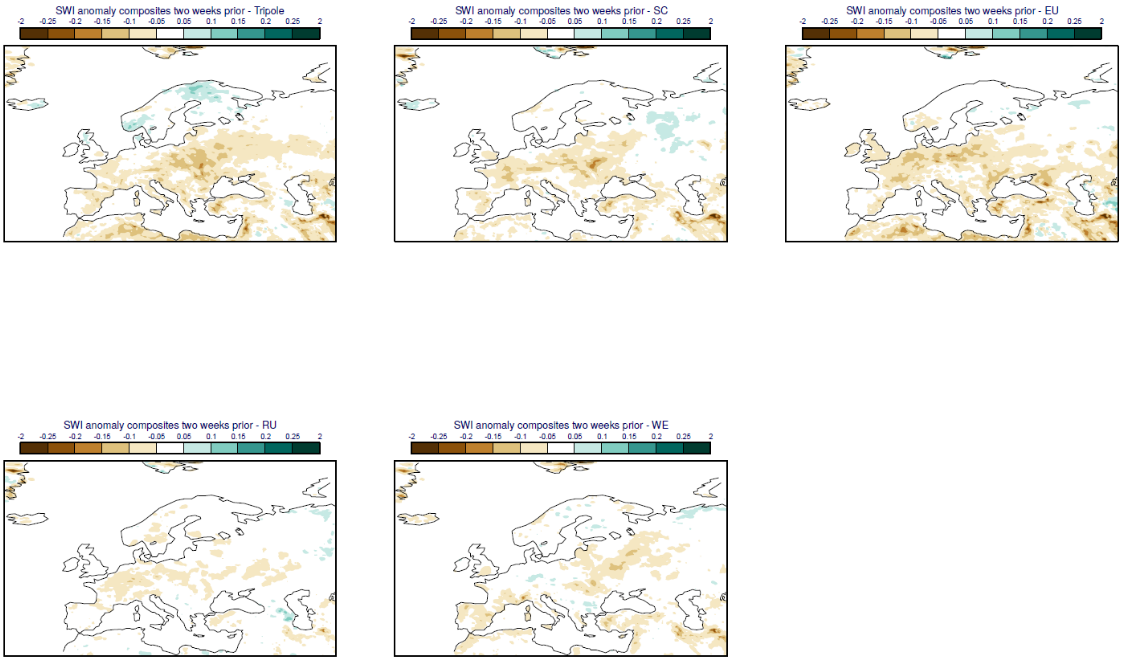

Figure 4: SWI anomaly composites two weeks before the events as colour shading for each heatwave type.

Initial results show that SST has little signal besides for the RU cluster. This would need further investigation, and we might focus on individual events. The soil moisture anomaly shows some more promising results with clear patterns that are characteristic to each individual cluster. However, we based this on the assumption that the composites (averages) are representative of the individual events. We will therefore further investigate to determine the relevance to individual heatwaves and the impact on predictability.

6. Conclusion

In the first part of the research, we identified 120 heatwave events over Europe during the period from 1979 to 202. Using a cluster analysis, we have classified objectively five different types of heatwaves and we characterized their corresponding large-scale circulation structures. We started to study the potential role of surface

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parameters such as the SST and the soil moisture content in conditioning the heatwave occurrence.

Further research will focus on assessing the forecast skill of numerical weather prediction models for heatwaves and their drivers.

7. Training and Secondments

- Secondment at MPI-PKS with Prof. Holger Kantz (and co-supervisor):

  The secondment was scheduled in March 2020 and was postponed to June for 3 months online and 3 months off-line starting in September. Unfortunately, it had to be cut short at the end of October due to the second lockdown of Germany and the United Kingdom. The collaboration had started before hand, as Prof. Kantz is my co-supervisor, so the collaboration was only improved during this period, in particular off-line.

The following schedule is part of the contingency plan. Originally, two secondments in Barcelona (one at CRM with Dr. Corral and with the Catalonian meteorological office) were planned during the summer 2021.

- Secondment at CRM with Dr. Corral:

  The secondment is scheduled to October 2021 for 2 months.

- Last secondment:

  The last secondment is scheduled for March 2022 with company that cooperates with ECMWF

I have followed a workshop on Compound Weather and Climate Extremes from the University of Bern from 12 to 15 January. The workshops I expect to follow are an ECMWF training course on predictability and ensemble forecast systems, the CAFE workshops and the NCAR colloquium ‘The Science of Subseasonal to Seasonal (S2S) Predictions’.

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8. Research outputs and Outreach

We intended to have a first draft of an article ready for submission by end of last year, unfortunately this has been delayed due to both the lack of efficiency during home office and unexpected workload. In fact all of my work took a high amount of time since the heatwave identification and the clustering in particular, had a lot of parameters (temperature percentiles, heatwave minimal duration, cluster numbers, number of EOFs) that had to be tested and tuned for our purpose. This also required a lot of computing time, making this process very time consuming. The draft is expected to be ready for submission by summer and will report on the first part of the thesis work.

A blog post was published on the ECMWF website in collaboration with Nikolaos Mastrantonas. This blog post summarised our topics and the CAFE project in general.

9. Covid-19

I have started working from home since mid-March 2020 and have only been in an office during the 2 months stay at MPI-PKS. The home office situation has been quite difficult and efficiency has dropped, especially at the start. As the secondment had to be rescheduled continuously, it was part of the meeting discussions and in my mind for most of the first half of the year, which took time out of my work. Currently the situation has improved as I adapted to the long-term situation (return to office will probably not happen before the second half of 2021). My supervisors Dr. Ferranti and Prof. Kantz have always been available for video meetings and been ready to help. My efficiency is now closer to normal, but I still miss the possibility to easily interact with other colleagues and discuss. The reduced efficiency combined with work that was more time consuming than expected, means that the current work is delayed by around 3 months.

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