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Large discrepancies in the representation of compound long-duration dry and hot spells over Europe in CMIP5

Colin Manning[1], Emanuele Bevacqua[2], Martin Widmann[3], Douglas Maraun[4], Anne F. Van Loon[5]

[1]School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, United Kingdom
[2]Department of Computational Hydrosystems, Helmholtz Centre for Environmental Research—UFZ, Leipzig, Germany
[3]University of Birmingham, Edgbaston, Birmingham, B152TT, United Kingdom
[4]Wegener Center for Climate and Global Change, University of Graz, Graz, Austria
[5]Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, the Netherlands

Correspondence to: Colin Manning (colin.manning@newcastle.ac.uk)

Abstract. Long-duration dry spells in combination with temperature extremes during summer have led to extreme impacts on society and ecosystems in the past. Such events are expected to become more frequent due to increasing temperatures as a result of anthropogenic climate change. However, there is little information on how long-duration dry and hot spells are represented in global climate models (GCMs). In this study, we evaluate 33 CMIP5 GCMs in their representation of long-duration dry spells and temperatures during dry spells. We define a dry spell as a consecutive number of days with daily precipitation less than 1mm. CMIP5 models tend to underestimate the persistence of dry spells in Northern Europe while a large variability exists between model estimates in Central and Southern Europe where models have contrasting biases. Our results indicate that this variability in model estimates is due to inherent model differences and not internal variability. In Northern Europe, differences in the representation of persistent dry spells are related to the representation of persistent anticyclonic conditions. We also find a large spread in the representation of temperature extremes during dry spells. In Central and Southern Europe this spread in temperature extremes between models is related to the representation of dry spells, where models that produce longer dry spells also produce higher temperatures, and vice versa. Overall, there are large discrepancies in the representation of long-duration dry and hot events in the CMIP5 ensemble where the simulated climates vary from models with shorter-cooler dry spells to models with longer-hotter dry spells. This information is important to consider when interpreting the plausibility of future projections from climate models.

1 Introduction

The combination of long-duration dry spells with extremely high temperatures in Europe has resulted in severe impacts across the continent. For example, the events of 2012 and 2018 led to extremely low crop yields (Kovačević et al., 2013; Beillouin et al., 2020) which resulted in agricultural insured losses of US$2 billion in Serbia in 2012 (Zurocev et al., 2015), while in 2018, financial support was required by farmers from governments in Sweden (€116 million), Germany (€340 million) and Poland (€116 million) (D'Agostino,2018). Such events, characterised by the combination of multiple drivers causing extreme impacts, are known as compound events (Zscheischler et al., 2018; Zscheischler et al., 2020; Bevacqua et al., 2021). Anthropogenic climate change is expected to influence compound events (Seneviratne et al., 2012; Zscheischler et al., 2018; Seneviratne et al., 2021), and given the importance of climate models for assessing climate risk, it is important to understand how climate models represent the joint behaviour of the underlying drivers to assess future risk from compound events (Villalobos-Herrera

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et al., 2021). However, studies evaluating climate model representation of compound events are still rare (Bevacqua et al., 2019; Zscheischler et al., 2020/2021, Villalobos-Herrera et al., 2021, Ridder et al, 2021). Here, we assess how well general circulation models (GCMs) represent long-duration dry and hot events on the synoptic timescales that underlie the seasonal extremes over Europe during June, July and August (JJA). We also study differences between models and potential reasons for these differences.

In summer, persistent dry spells and temperature extremes arise from the presence of blocking or anticyclonic conditions (Quesada et al., 2012; Pfahl and Wernli, 2012; Sousa et al., 2018). Such conditions reduce rainfall (Sousa et al., 2017) and therefore increase the likelihood of long dry spells (Rothlisberger and Martius, 2019), while also allowing for more incoming solar radiation that causes temperatures to rise throughout an event (Miralles et al., 2014; Folwell et al., 2016). The dry and hot conditions can deplete soil moisture levels (Manning et al., 2018) which, in turn, amplifies temperature extremes through land-atmosphere feedbacks (Seneviratne et al., 2010). Altogether, the above leads to an increased probability of extremely high temperatures during a dry spell (Manning et al., 2019). Understanding the representation of such long duration dry and hot events within climate models requires the assessment of different components of the compound events such as the representation of the duration of dry spells, temperatures during dry spells, and the relationship between dry spells and extreme temperatures. Furthermore, it is important to understand the representation of the persistence of anticyclonic conditions that are an important driver behind long-duration dry and hot events (Rothlisberger and Martius, 2019).

Climate models have been separately evaluated in terms of their representation of the duration of dry spells and extreme temperatures, but the combination of dry spells and extreme temperatures has not been assessed. Studies have evaluated compound dry and hot conditions at seasonal timescales (Zscheischler et al., 2020/2021) as well as hot conditions during seasonal drought (Ridder et al., 2021), though no explicit focus has been given to hot-dry spells. In terms of dry spells, the multi-model mean of CMIP5 models has been found to underestimate both the annual number of dry days with precipitation below 1 mm (Polade et al. 2014) as well as the mean annual maximum duration over much of Europe (Sillman et al., 2013; Lehtonen et al., 2014), though the variability within the ensemble or potential reasons for this underestimation have not been assessed. Likely reasons include the known underestimation of the frequency of blocking events in Europe lasting longer than 5 days (Antsey et al., 2013; Masato et al., 2013; Dunn-Sigouin and Son, 2013). For instance, Maraun et al. (2021), who found an underestimation of dry spell lengths over Austria in an ensemble of high-resolution models, show that it is partly explained by an underestimation in the persistence of the relevant synoptic weather types.

CMIP5 models also underestimate high temperatures over much of Europe except for Eastern Europe where an overestimation is found (Sillmann et al., 2013; Cattiaux et al., 2013; Di Luca et al., 2020). Di Luca et al. (2020) showed that this bias in CMIP5 largely arises from biases in the synoptic variability of temperature extremes rather than seasonal or annual mean biases. An

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analysis of a smaller climate model ensemble further showed that models that simulate more persistent anticyclonic conditions tend to have longer heat waves (Plavcova and Kyselý, 2016).

In this study, we evaluate the ability of 33 GCMs from the CMIP5 ensemble to represent long-duration dry and hot events. We firstly assess the representation of dry spells and quantify the link between dry spells and persistent anticyclonic conditions. We then analyse temperature extremes during dry spells and the relationship between dry spells and temperature extremes. Throughout the analysis, we study the spread between models in their performance and assess potential reasons for it by studying the link between biases in dry spells, temperatures and the persistence of anticyclonic conditions. For example, do models with more persistent dry spells have higher temperatures and more persistent anticyclonic conditions?

2 Data

We employ daily maximum temperature and daily accumulated precipitation from the EOBS dataset (Haylock et al., 2008) version 16.0 between 1979 and 2008. To indicate the presence of anticyclonic conditions, we also use mean sea level pressure (MSLP) from the ERA5 reanalysis dataset (Hersbach et al., 2020), also between 1979 and 2008. Daily maximum temperatures, daily precipitation accumulations and the daily mean MSLP were obtained for 33 climate models within the coupled model intercomparison project 5 (CMIP5) for simulation years from 1976 to 2005. All data was regridded to a 2.5° by 2.5° lat-lon grid using the remapcon operator from the Climate Data Operators code (Schulzweida et al., 2006). Each model has a varying number of initial condition ensemble members (between 1 and 10) used to investigate internal variability. See Supplementary Table 1 for model details.

3 Methods

3.1 Dry Spells and Extreme Temperatures

The duration of a dry spell (D_{DS}) is defined as the number of consecutive days with precipitation below 1 mm. Only dry spells longer than 5 days are considered. The dry day threshold is consistent with previous studies and allows for comparison between observations and climate models which systematically overestimate the number of drizzle days (Orlowsky et al., 2012; Donat et al., 2013; Lehtonen et al., 2014; Pfleiderer et al., 2018). To compare temperatures during dry spells between models and with observations, we calculate the mean of the maximum daily-maximum-temperature during a dry spell (Tx_{DS}).

To quantify the relationship between temperatures and dry spells, we assess whether the odds (i.e. the probability of an event divided by the probability of a non-event) of a hot day is enhanced during a dry spell. Specifically, we calculate an odds ratio ($OR_{HD,n}$) as:

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$$OR_{HD,n} = \frac{P_{HD,n}/(1-P_{HD,n})}{0.05/(1-0.05)}, \quad (1)$$

where $P_{HD,n}$ is the probability of exceeding a hot day threshold during a dry spell lasting longer than n days (we consider dry spell durations ranging within n = 5-20 days). The hot day threshold is defined as the 95th percentile of the distribution of all daily temperatures during JJA for a given model and location, and 0.05 is the climatological probability. Values above 1 indicate that the odds of a hot day are increased during a dry spell that exceeds a specified duration. We also assess if the $OR_{HD,n}$ value at a given location can be achieved by random chance. To do so, we shuffle annual blocks of the precipitation series 1,000 times to provide 1,000 synthetic series of precipitation. By shuffling annual blocks, and not the daily values, we conserve the serial correlation of daily precipitation and the seasonality of dry spells. For each synthetic series, we calculate $OR_{HD,n}$ and estimate the upper bound of the 95% confidence interval, which is the 95th percentile of the 1,000 synthetic $OR_{HD,n}$ values. $OR_{HD,n}$ is deemed significant if it is greater than this upper bound.

3.2 Anticyclonic Spells and Their Influence on Dry Spells

Mean sea level pressure (MSLP) is used to indicate the presence of an anticyclone. At a given location, we define an anticyclonic day when MSLP is greater than a specific threshold. The duration of an anticyclonic spell is then defined as the number of consecutive anticyclonic days. The results are tested for a range of MSLP thresholds between 1008 hPa and 1022 hPa.

We quantify the relationship between the persistence of anticyclonic spells (AS) and of dry spells (DS) following the approach of Rothlisberger and Martius (2019), who studied the influence of blocking on dry spells. The climatological persistence of k-type spells (i.e., AS spell or DS spell) at grid point g can be quantified by calculating the climatological (daily) survival probability ($Ps_{g,k}$) as:

$$Ps_{g,k} = P\big(Spell_{g,k}(t+1) = 1 \,\big|\, Spell_{g,k}(t) = 1\big), \quad (2)$$

where t refers to a daily timestep, k indicates either AS or DS, and $Spell_{g,k}$ is a binary variable where 1 indicates a dry day for dry spells and an anticyclonic day for anticyclonic spells. To assess the effect of anticyclonic spells on dry spell persistence, the survival probability of dry spells during anticyclonic spells is calculated as:

$$Psa_{g,DS} = P\big(Spell_{g,DS}(t+1) = 1 \,\big|\, Spell_{g,AS}(t) = 1 \,\cap\, D_{AS}(t) \geq 5\big), \quad (3)$$

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where $D_{AS}(t)$ indicates the total duration of the anticyclonic spell that overlaps with this day. $Psa_{g,DS}$ therefore represents the survival probability of a dry spell when it co-occurs with an anticyclonic spell whose total duration is at least 5 days. In a next step, the odds of a dry spell surviving during an anticyclonic spell, $Psa_{g,DS}/(1 - Psa_{g,DS})$, are compared with the climatological survival odds of dry spells, $Ps_{g,DS}$/(1-$Psa_{g,DS}$) by calculating an odds ratio (OR):

$$OR_{DS} = \frac{Psa_{g,DS}/(1-Psa_{g,DS})}{Ps_{g,DS}/(1-Psa_{g,DS})}, \quad (4)$$

The value of OR_{DS} indicates how the odds of dry spell survival change when an anticyclonic spell is present at the same time. For example, a value greater than one indicates that the anticyclonic spell enhances the dry spell survival probability. This approach demonstrates the relationship between anticyclonic conditions and the day to day persistence of dry spells but does not give an idea of what controls the overall duration of a dry spell. Attempts were made to compare the durations of dry spells with the duration of anticyclonic spells that overlap. However, this proved difficult without building in a result by design as the duration of anticyclonic spells depends on the MSLP threshold used. The total lengths of either spell type are therefore not always comparable. In order to quantify the influence of anticyclonic conditions on dry spell durations, it is likely that one would need to build a statistical model that would predict dry days.

3.2 Estimation of Duration Return Levels

We estimate return levels (RLs) for the duration of dry spells that have an estimated return period (RP) of 5 years. We choose to look at RLs with a RP of 5 years so that we focus on dry spells that may be impactful but also frequent enough to draw robust conclusions.

RLs are estimated using a parametric approach in which we fit an exponential distribution to the duration of all dry spells and anticyclones that exceed 5 days. The use of the exponential distribution is common for modelling the probability of dry spells (Serinaldi et al., 2009; Manning et al., 2019). The RL (d) for a RP (T) of n years is estimated as:

$$d = F^{-1}\left(1 - \frac{\mu}{T} \right), \quad (5)$$

where F^{-1} is the inverse of the fitted cumulative distribution function (CDF) and μ is the exceedance rate, calculated as $\mu = \frac{N_E}{N_Y}$, where N_E is the number of dry spells exceeding a duration of 5 days and N_Y is the number of years.

3.3 Calculation of Metrics and Regional Analysis

For a given metric, prior to computing multi-model means, we calculate the ensemble mean for each model individually. This ensures that each model has equal weighting in the calculation of multi-model mean metrics. We also present regional results

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in order to summarise results across the CMIP5 ensemble. For each model, metrics are averaged across three IPCC European regions (Northern Europe, Central Europe, and Southern Europe) as defined by Seneviratne et al., (2012). The separation between the regions is shown by black dashed lines in Figure 1c.

4 Results

4.1 Representation of Long-Duration Dry Spells in CMIP5 Models

The return level (RL) for the duration of a dry spell with an expected return period of 5 years across Europe is presented for EOBS (Figure 1a) and the multi-model mean of the 33 CMIP5 models (Figure 1b). The spatial distribution of RLs based on EOBS (Figure 1a) is in line with documented differences in synoptic variability across Europe. That is, persistent anticyclonic conditions in the south favour longer dry spells than over northern Europe, where shorter durations are in line with a higher synoptic variability between cyclonic and anticyclonic conditions (Ulbrich et al., 2012).

The spatial variability of RLs in southern and northern Europe is well captured by the CMIP5 multi-model mean (Figure 1b). However, the mean relative difference between EOBS and CMIP5 (Figure 1c) indicates that CMIP5-based 5-year RLs can be shorter than those from EOBS (blue grid cells) by 30-50% across a large area of Europe including Scandinavia, Western Central Europe and the Iberian Peninsula. It is particularly the case in Scandinavia, where more than 90% of models show shorter 5-year RLs than EOBS, as indicated by the stippling. In contrast, CMIP5 based 5-year RLs in the south-eastern part of the domain are higher than those from EOBS. Boxplots in Figure 1d show the variability of the 5-year RLs which are averaged across each of the IPPC regions. The boxplots reflect the results in Figure 1c, particularly in Northern Europe where CMIP5 models tend to produce shorter 5-year RLs. The results in Central and Southern Europe vary more across the models as they tend to simulate both lower and higher RLs. The spread across the CMIP5 ensemble is also quite high with differences between models and EOBS ranging from 20% shorter to 60% longer. The interquartile range is higher in Central and Southern Europe than in Northern Europe while the overall variability is highest in Southern Europe.

The differences between EOBS- and CMIP5-based RLs can arise from internal variability within climate realisations and from systematic model biases. To understand the sources of these differences, we compare the regional means of the 5-year RLs for all ensemble members of each model. Figure 2 shows that the differences between members within each model ensemble is smaller than the differences across all CMIP5 models (top row). This indicates that the spread across the CMIP5 ensemble (Figure 1d) is very likely due to model biases and not internal variability. This result and the spread between models (Figure 1d) points to inadequacies of the CMIP5 ensemble in capturing the climatology of long-duration dry spells. It can therefore be expected that, for many models, future projections of dry spells and associated variables such as temperature and soil moisture are also not fully realistic. In the next section, we investigate whether such biases are related to the representation of persistent anticyclonic conditions in models.

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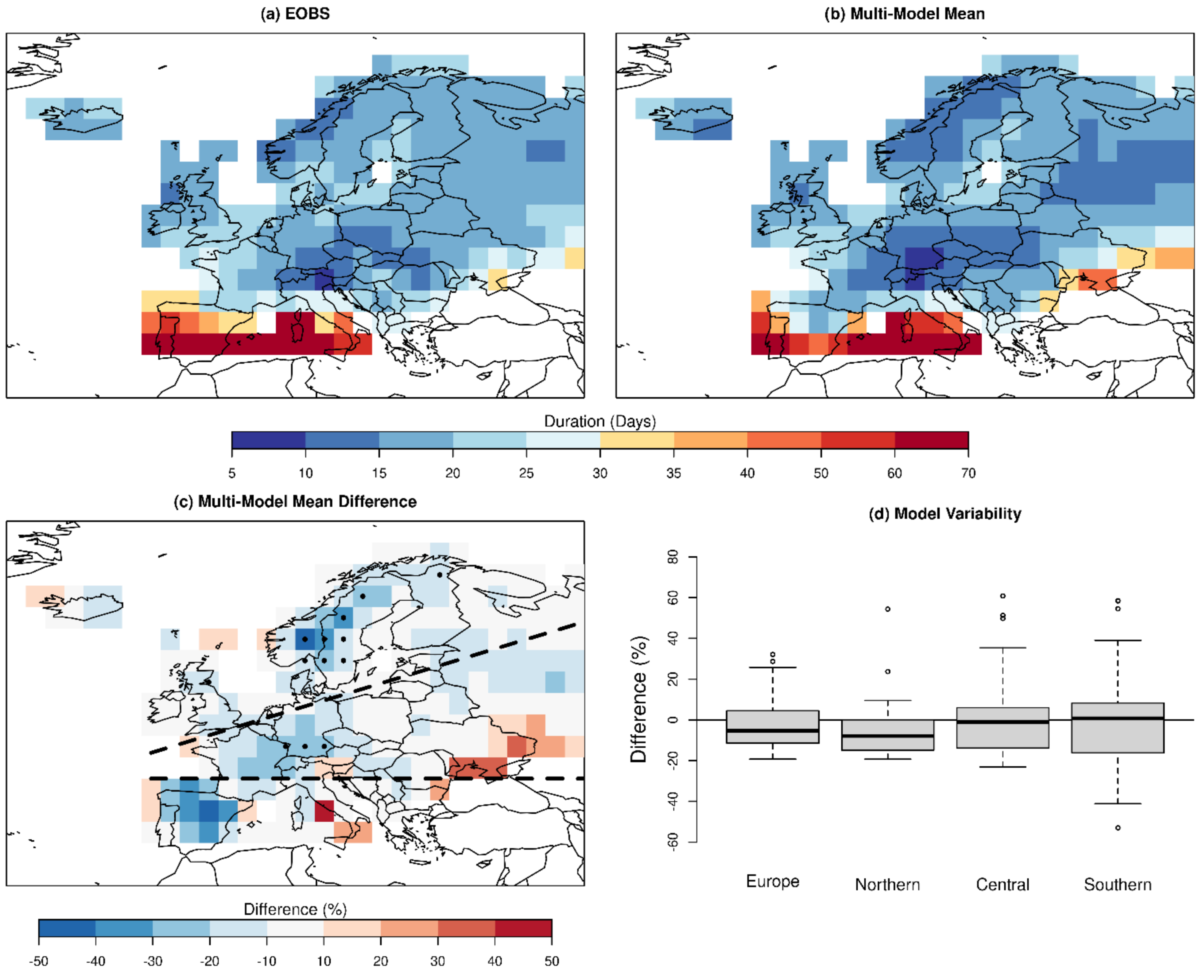

Figure 1: Duration Return Levels (RLs) of dry spells for a 5-year return period for (a) EOBS, and (b) the mean of the CMIP5 multi-model ensemble. (c) Multi-model mean percentage difference between CMIP5 models and EOBS (stippling indicates
200 where 90% of CMIP5 models are below or above EOBS). (d) Model spread in the relative difference averaged across all grid cells in Europe, Northern Europe, Central Europe and Southern Europe (dashed lines in (c) indicate the three European IPCC regions).

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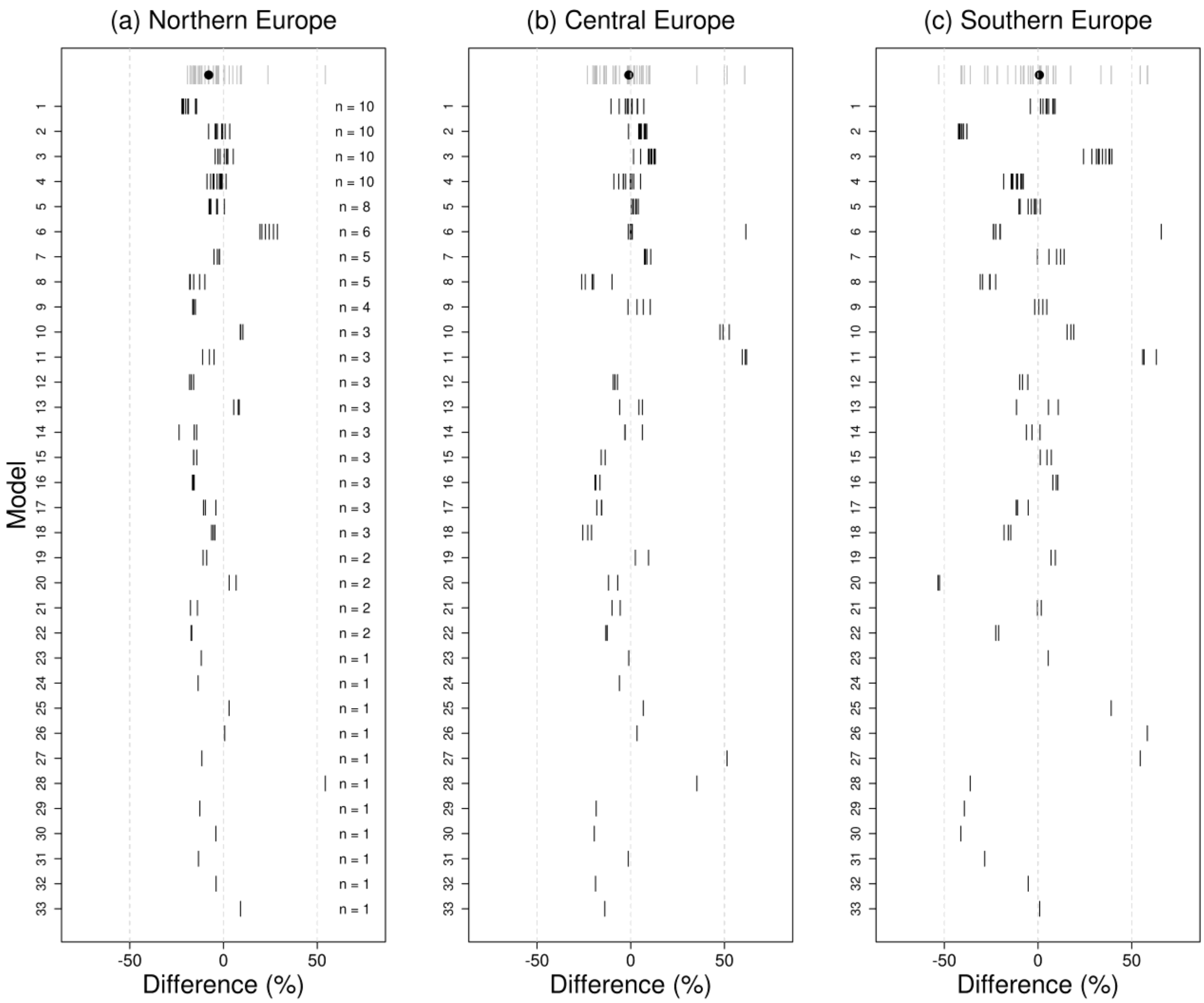

Figure 2: Relative difference in Duration RLs (model - EOBS) calculated for all members of each model ensemble in four regions: (a) Northern Europe; (b) Central Europe; and (c) Southern Europe. First row provides the ensemble mean of each model (grey lines) and the multi-model ensemble mean (black dot), while each subsequent row provides the relative difference for each ensemble member of models 1-33 and the number of members (n) in each model ensemble.

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4.2 Link Between Dry Spells and Anticyclonic Conditions

The presence of anticyclonic conditions increases the likelihood of a dry spell persisting. In this section we quantify this relationship using survival probabilities following the approach of Röthlisberger and Martius (2019). The odds ratio (OR_{DS}) presented in Fig. 3 shows whether a dry spell is more likely to persist for another day when it co-occurs with an anticyclonic spell. For Fig. 3a,b, an anticyclonic spell is defined when MSLP exceeds 1012 hPa for at least 5 days. The survival probability of dry spells in EOBS is increased at all locations across the domain when co-occurring with an anticyclonic spell ($OR_{DS} > 1$ everywhere), though there are spatial variations in this ratio with lowest values over parts of Central and Southern Europe. This spatial variability indicates that dry spell persistence in Northern Europe is more reliant on synoptic conditions than in Central and Southern Europe where other factors such as moisture availability, convective systems, and topography may play a role.

The spatial variation in the CMIP5 Multi-Model Mean (Fig. 3b) is similar to that in EOBS though the magnitude of the relationship is underestimated over most of Europe, particularly in parts of Northern and Central Europe. The sensitivity of the results to the MSLP threshold used to define an anticyclonic spell is demonstrated in Fig. 3c-e. For each MSLP threshold tested, OR_{DS} is calculated locally at each grid cell and then averaged over each of the three regions. For EOBS, in each region, OR_{DS} increases with increasing MSLP threshold. Hence, the more intense the anticyclonic spell (higher MSLP), the more likely a dry spell is to persist. The same relationship is seen in the CMIP5 multi-model mean (solid blue line), although the ratio is underestimated compared to EOBS in Northern and Central Europe for lower MSLP thresholds. There is also a large spread in the CMIP5 ensemble (shaded blue area) showing that there are discrepancies between models in how they capture this relationship.

Given the link between MSLP and dry spells seen in observations and in the models, we now ask whether differences in the persistence of dry spells between models are linked to differences in the persistence of anticyclonic conditions. To understand this, we calculate the inter-model Pearson correlation coefficient between dry spell survival probabilities and survival probabilities of MSLP above 1012 hPa (Fig. 4a), although the sensitivity of results to this threshold is discussed. A positive correlation is seen across much of Northern Europe meaning that models with more persistent anticyclonic conditions also have more persistent dry spells. These areas generally coincide with the areas that have high probability ratios shown in Figure 3b. Strongest correlations are generally in the northwest and at coastal grid cells, indicating that land has an influence in modulating this relationship. Little association is seen between the two elsewhere, except for negative correlations in mountainous areas surrounding the northern Mediterranean coast where the representation of orographic effects may play a role. The correlations and their spatial variability are largely insensitive for MSLP thresholds between 1008 hPa and 1022 hPa. Above 1022 hPa, the relationship is no longer visible, possibly due to the difference in number of dry days and days with MSLP > 1022hPa.

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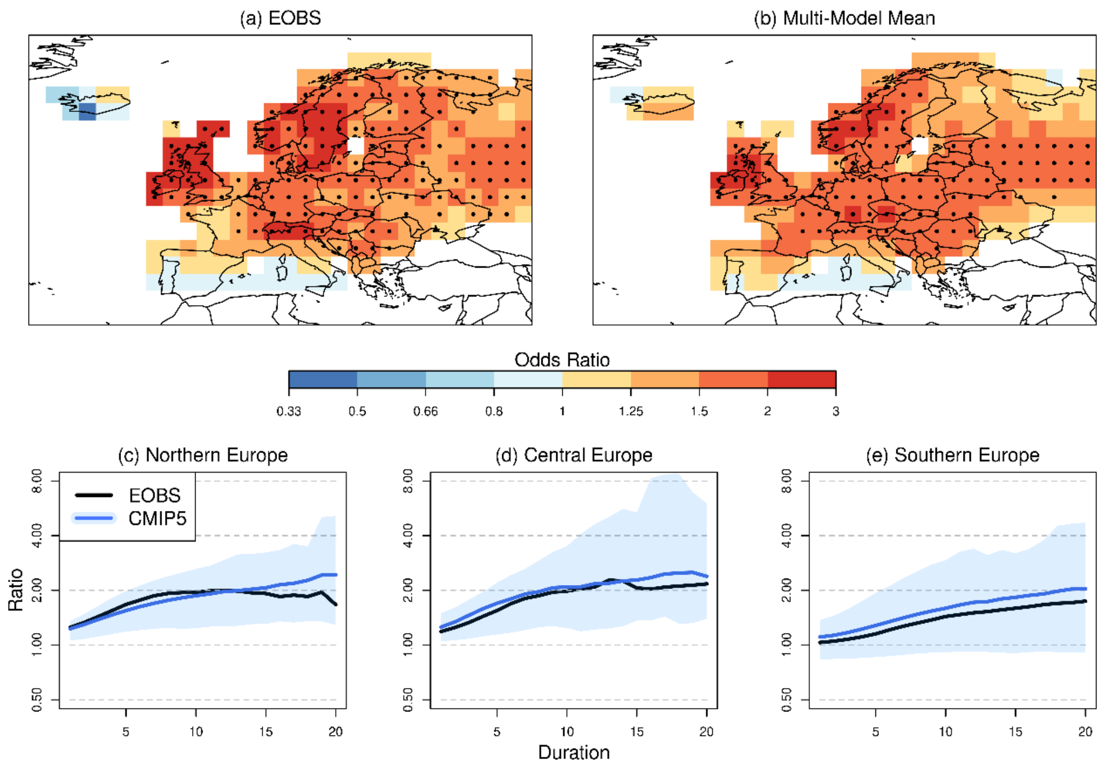

Figure 3: Odds Ratios (OR_{DS}) for dry spells when co-occurring with an anticyclonic spell in (a) EOBS and (b) CMIP5. An anticyclonic spell is defined when MSLP exceeds 1012 hPa for at least 5 consecutive days. Sensitivity of the probability ratio to MSLP threshold in (c) Northern Europe, (d) Central Europe and (e) Southern Europe for EOBS (black line) and the CMIP5 multi-model mean (blue solid line – blue area show the centered 90% spread of the models).

The points in the scatter plots shown in Fig. 4b-d provide the areal mean survival probabilities for dry spells and anticyclonic spells over the three European regions, which reflect the correlations shown in Fig. 4a (the grey dot in each panel represents the EOBS values to illustrate model differences from EOBS and ERA5). In Northern Europe, the models where MSLP tends to persist more also tend to have dry spells that persist for longer, and vice versa. In addition, we also note that our identified anticyclonic conditions, i.e. the MSLP spells, tend to persist longer in CMIP5 models than in ERA5 (this result is confirmed by an analysis of the 5-year return levels of anticyclonic spell durations; see Supplementary Figure 1). The higher persistence of MSLP above 1012 hPa in CMIP5 models is also seen above thresholds between 1008 and 1022 hPa (not shown), hence the result is insensitive to the specified MSLP threshold within this range. Notably, this result is in contrast with previous studies indicating that atmospheric blocking does not persist enough in most climate models (Antsey et al., 2013; Masato et al., 2013; Dunn-Sigouin and Son, 2013; Davini et al., 2021). However, results of studies focussing on blocking may not be directly

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comparable with our results focussing on MSLP spells because blocking algorithms identify a specific synoptic pattern which results in far less 'blocking days' than days with MSLP above 1012 hPa.

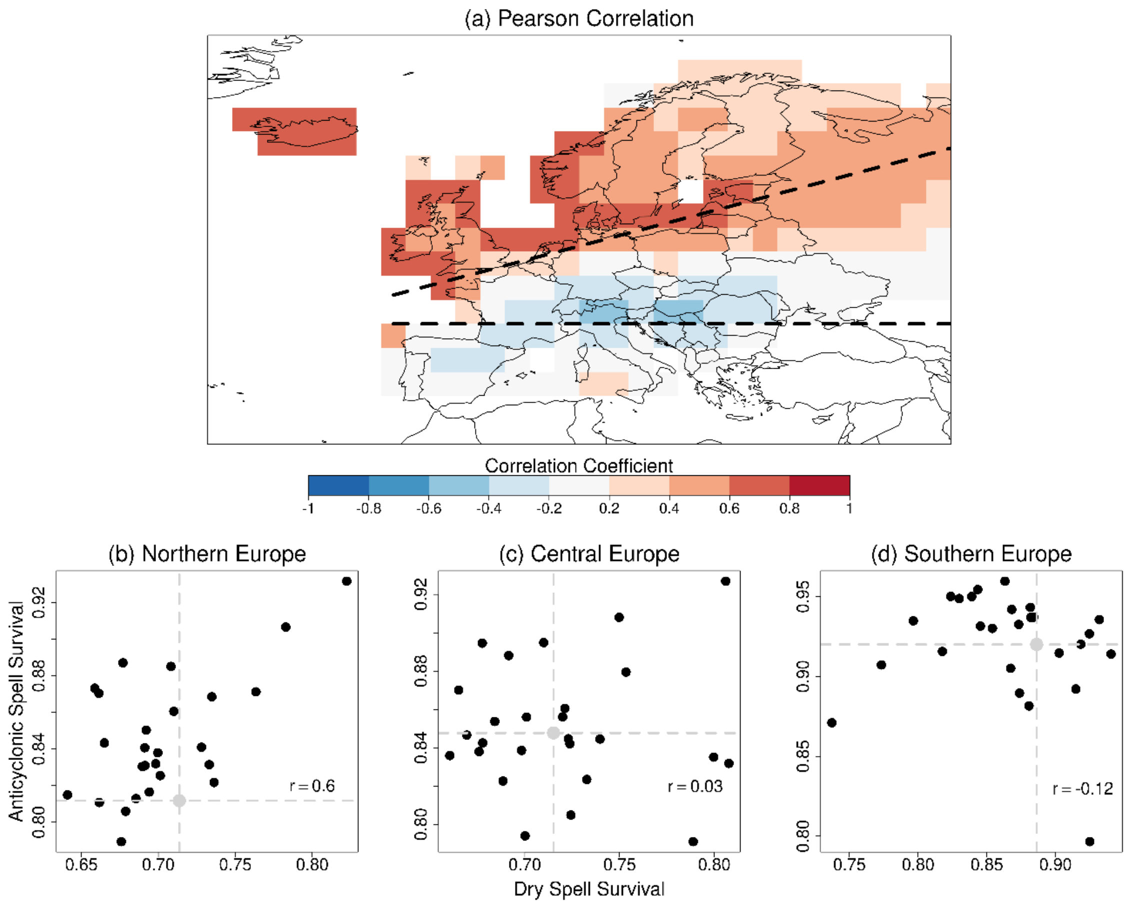

Figure 4: Relationship between dry spell survival probabilities and MSLP (> 1012hPa) survival probabilities. (a) Inter-model Pearson correlation coefficient. (b-d) Inter-model relationship between dry spell and MSLP survival probabilities when averaged across the three IPCC regions, i.e. (b) Northern Europe, (c) Central Europe, and (d) Southern Europe for each CMIP5 model. The Pearson correlation coefficient calculated from the 33 models is provided in the bottom left corner of each panel. The three IPCC regions (Seneviratne et al., 2012) are indicated by the grey dashed lines in panel (a).

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4.3 Representation of Temperature During Dry Spells

The mean of the maximum temperatures during dry spells exceeding 5 days (Tx_{DS}) for EOBS and the CMIP5 multi-model mean is presented in Fig. 5. The spatial pattern of temperature seen in EOBS is generally reproduced by CMIP5 though, as also shown in Cattiaux et al. (2013), underestimations of Tx_{DS} are seen across most of Europe (Fig. 5c,d). The majority of models show an underestimation in Tx_{DS} in both Northern and Southern Europe though the models in Central Europe have contrasting biases in this region (Fig. 5d). Central Europe also has the largest model spread in Tx_{DS}.

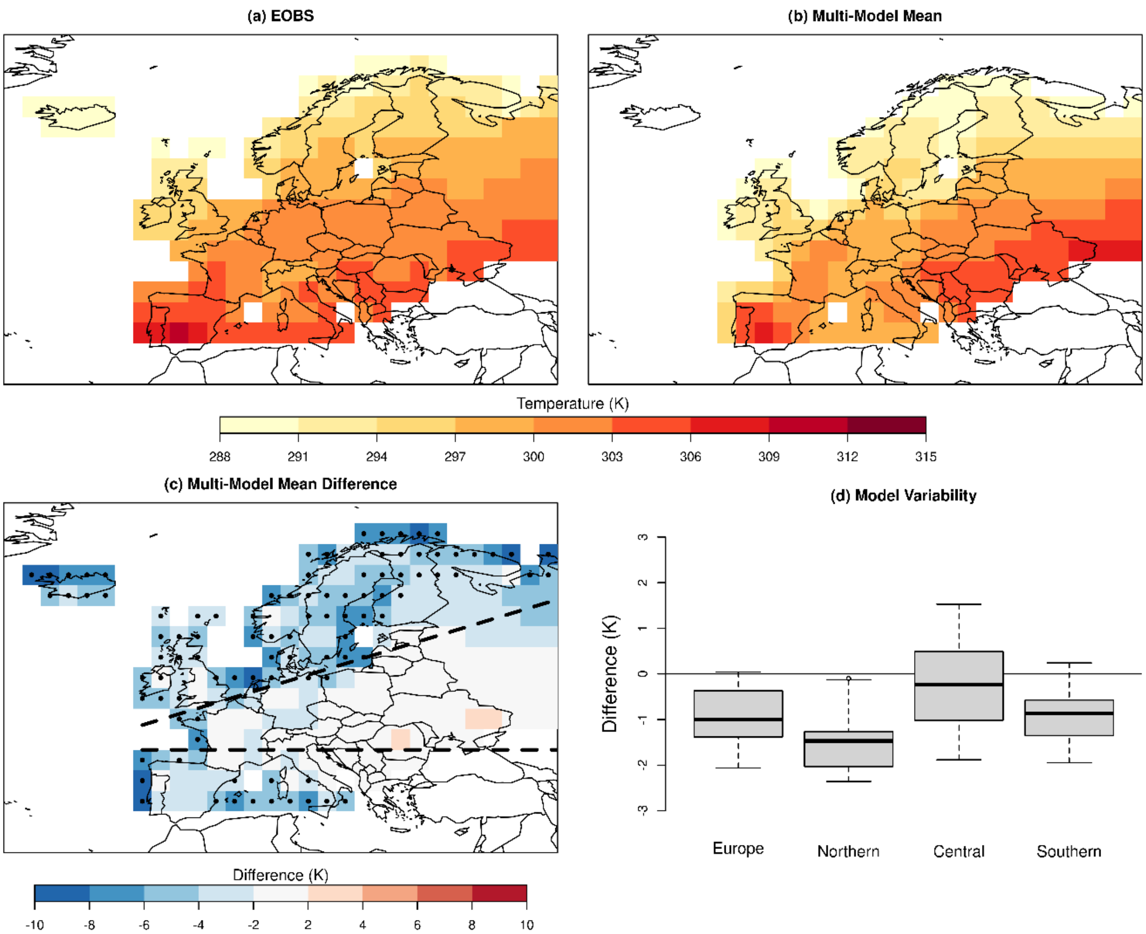

Figure 5: Mean maximum temperatures during dry spells longer than 5 days in (a) EOBS and (b) the CMIP5 multi-model mean. (c) Multi-model mean difference between CMIP5 models and EOBS (stippling indicates where 90% of CMIP5 models are below or above EOBS). The variability in the percentage difference across all models averaged across all grid cells in Europe, Northern Europe, Central Europe and Southern Europe is given in (d). The separation between the three European regions is shown by the dashed lines in (c).

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We also assess whether the differences between models are more likely due to internal variability or from systematic differences between models. In Fig. 6, we compare the regional means of Tx_{DS} for all ensemble members of each model. Similarly to dry spell durations, we also see that the spread in the differences between members within each model ensemble is quite low and much less than the spread across the CMIP5 ensemble (top row). This indicates that the spread across the CMIP5 ensemble is largely due to inherent model differences and not internal variability.

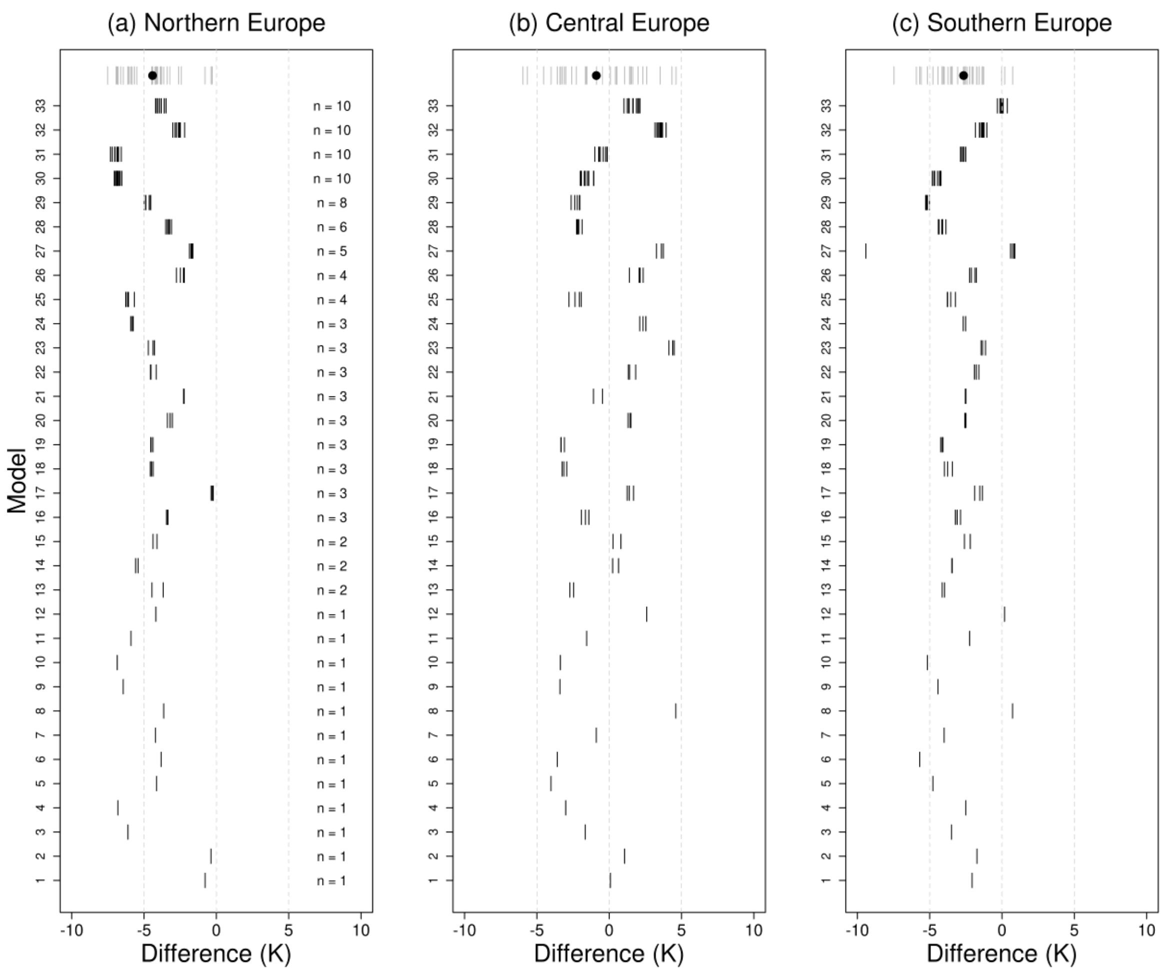

Figure 6: Difference in Tx_{DS} (model - EOBS) calculated for all members of each model ensemble in four regions: (a) Northern Europe; (b) Central Europe; and (c) Southern Europe. First row provides the ensemble mean of each model (grey lines) and the multi-model ensemble mean (black dot), while each subsequent row provides the differences for each ensemble member of models 1-33 and the number of members (n) in each model ensemble. Models are sorted by number of members in descending order.

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4.4 Relationship between Temperature Extremes and Dry Spells

In the EOBS dataset, there is an increased probability of temperature exceeding its 95th percentile during dry spells that last longer than 5 days (Fig. 7a). Stippling, which is present across a large area of Europe, indicates that we are 95% confident that the results cannot be achieved via random chance at those locations. The highest ratios in EOBS are seen in northwestern Europe, where ratios > 2 indicate that the odds of temperature exceeding the 95th percentile is more than doubled during a dry spell that is longer than 5 days. Across the rest of Northern, Central, and Southeastern Europe, ratios generally vary between between 1.25 and 2. In parts of Southern Europe, the ratios vary around 1 and there is a lack of stippling. This is a consequence of the high number of dry days there during summer. That is, the closer the total number of dry days is to the total number of summer days, the closer the odds ratio will be to 1. The spatial variability in the odds ratio reflects differences in the degree of coupling between dry spells and temperature which is likely due to differences in drivers of dry spells and temperature extremes across Europe. In more Northern parts with higher synoptic variability, dry spells and temperature extremes are both driven by, and linked to, the synoptic variability of anticyclonic systems (Röthlisberger and Martius, 2019). In Southern Europe, dry conditions are the norm throughout summer such that dry spells and temperature extremes vary independently there. Hence, the odds ratio results should be interpreted with caution, requiring careful consideration of the number of dry days at a given location.

The spatial variability of the odds ratio is well captured by the CMIP5 multi-model mean (Fig. 7b) though over- and under-estimations are evident in parts of France and Northern Europe. Figure 7c-e shows the spread between models and the sensitivity of the estimated ratio to the duration of dry spell. The ratio is calculated for dry spells exceeding 1 to 20 days and then averaged across the three regions. For EOBS in Central and Northern Europe, the ratio increases with increasing duration up to 10 days and levels off at around 2, although there is likely to be some spatial variation in the ratio as shown in Figure 7a. In Southern Europe, the ratio remains close to 1 and increases slightly after 10 days. The CMIP5 multi-model mean ratio shows a similar pattern to EOBS in that it increases with increasing dry spell duration and is generally quite comparable in magnitude. However, the CMIP5 ensemble shows considerable spread in the estimated odds ratio, particularly in Central and Southern Europe. The spread is largest for the longest durations which is likely a sampling issue as the number of dry spells decreases with the increasing duration threshold.

The relevance of differences in the odds ratio between models is challenging to interpret. An under- or over-estimation can indicate that temperature extremes coincide with long dry spells less or more often than in observations respectively. Both of which may have different implications for impacts. However, this interpretation is complicated by the fact that the odds ratio is influenced by the number of dry days at a given location. Hence, models with a higher number of dry days are more likely to have a smaller ratio, and vice versa. Overall, the results give an indication that the models generally capture the observed

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relationship between dry spells and temperature, as they compare well spatially (Fig. 7a,b) and capture the increased probability of extreme temperatures during longer dry spells (Fig. 7c-e).

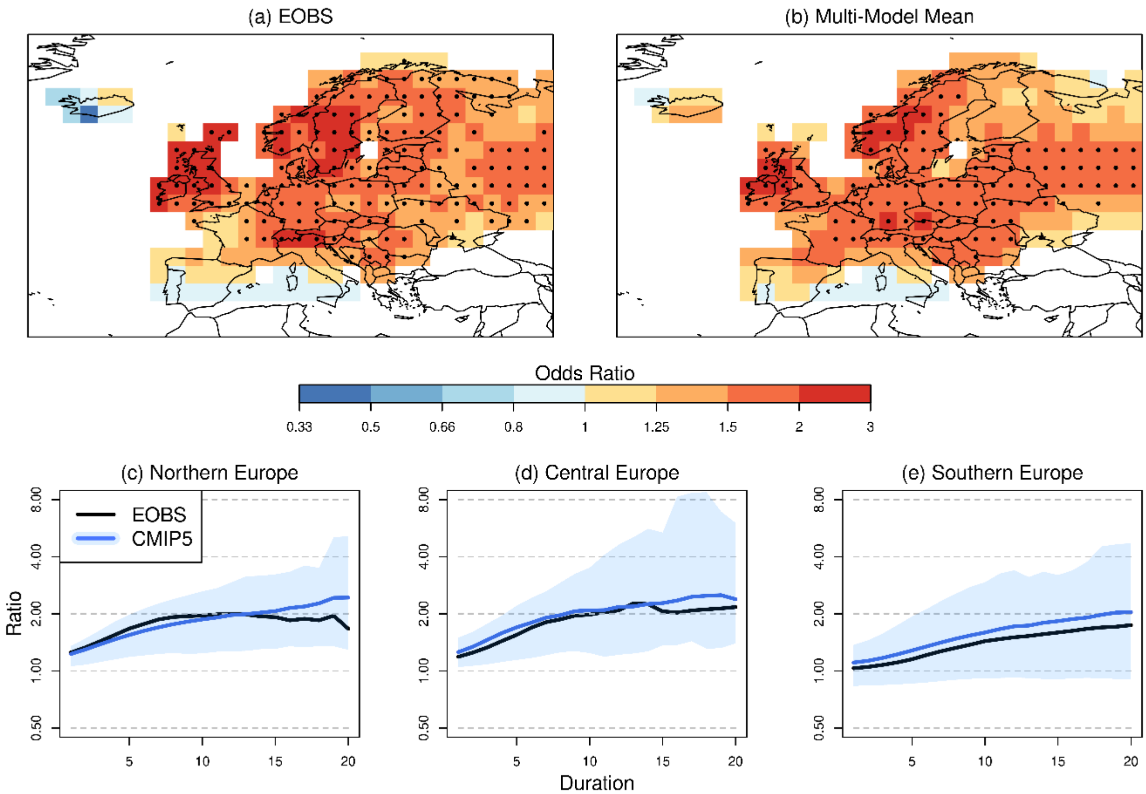

Figure 7: Comparison of the relationship between dry spells and temperature quantified as the odds ratio ($OR_{HD,n}$) (see section 3.1) in (a) EOBS and (b) the CMIP5 multi-model mean. Stippling indicates that we are 95% certain that the odds ratio cannot be achieved via random chance. Only dry spells longer than 5 days are included. Sensitivity of the odds ratio to the duration of dry spell averaged across (a) Northern Europe, (b) Central Europe and (c) Southern Europe for EOBS (black line) and the CMIP5 multi-model mean (solid blue line). The blue area represents the model spread in the ratio.

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4.5 Relationship between Temperature and Dry Spell Duration Biases

In this section we assess the relationship between dry spell duration and temperature biases and compare models in terms of their joint ranking in their representation of these two components. To do so, we calculate the inter-model Pearson correlation coefficient between RL_{DS} and Tx_{DS} (Fig. 8). A positive inter-model correlation is found between RL_{DS} and Tx_{DS} over a large area of Central and Southern Europe (Fig. 8a) while there is generally little correlation between them in Northern Europe. Positive correlations indicate that models which simulate longer dry spells tend to produce higher extreme temperatures. This is particularly the case over Central European countries such as France and Germany where correlations vary between 0.6 and 1.

The points in the scatter plots shown in Fig. 8b-d provide the areal mean RL_{DS} and Tx_{DS} values over the three European regions (the grey dot in each panel represents the EOBS values to illustrate how models differ from EOBS). The figure gives an overview of the relationship between the biases and the differences in the representation of long-duration dry and hot events. A large spread exists between the models, particularly in Central and Southern Europe where the positive relationship is seen between RL_{DS} and Tx_{DS}. The climatology of events in CMIP5 models ranges from shorter-cooler events to longer-hotter events, particularly in Southern Europe where the variability in RL_{DS} is much higher than that seen in the rest of Europe. From an impact perspective, models with longer-hotter dry spells indicate a higher compound event risk, or at least the expected impacts from a simulated climate with shorter-cooler events may be much different to those in a simulated climate with longer-hotter events.

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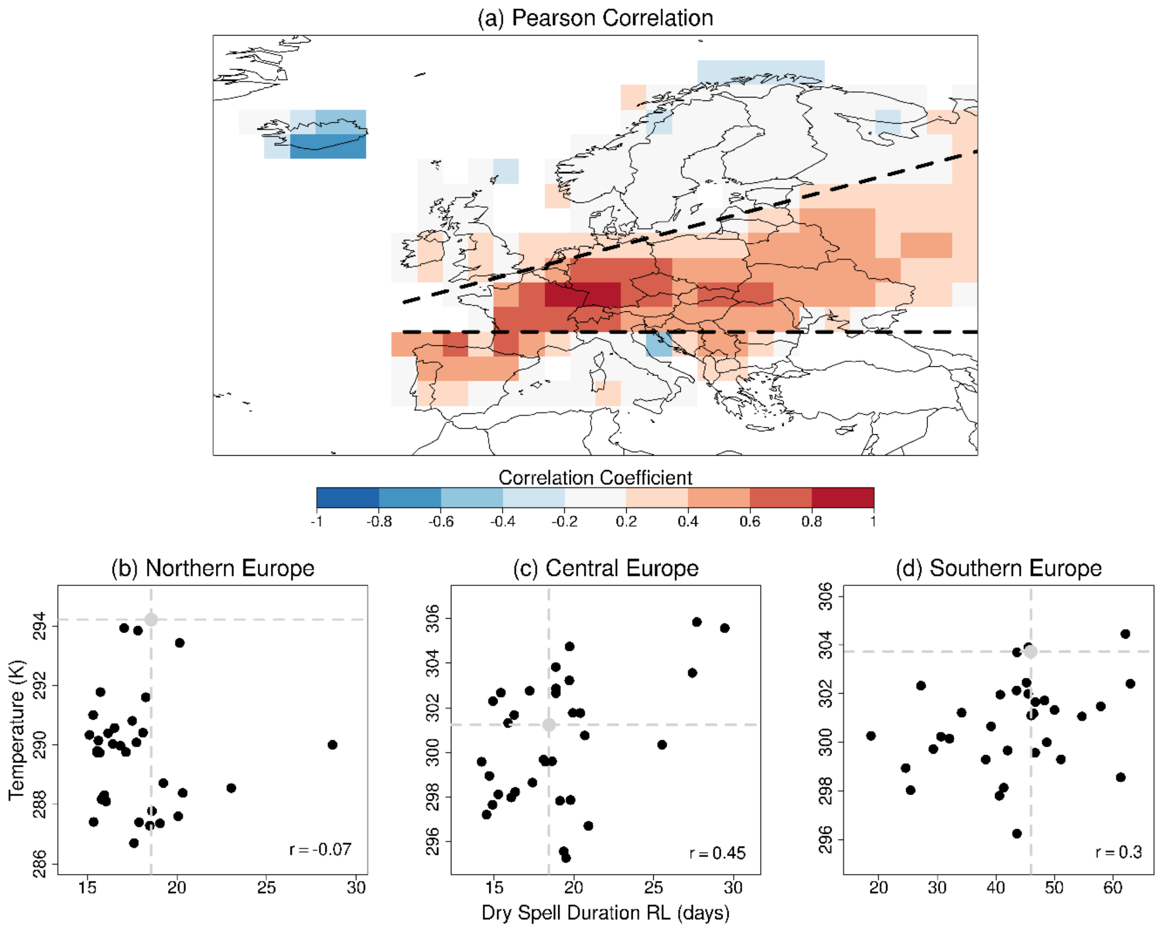

Figure 8: Relationship between the 5-year RLs for the duration of dry spells and the mean of the annual JJA daily maximum temperature (Txn). (a) Inter-model Pearson correlation coefficient. Panels (b), (c) and (d) show the inter-model relationship between dry-spell RL vs. Txn averaged across (b) Northern Europe, (c) Central Europe, and (d) Southern Europe for each CMIP5 model. The Pearson correlation coefficient calculated from the 33 models is provided in the bottom left corner of each panel. The three IPCC regions (Seneviratne et al., 2012) are indicated by the grey dashed lines in panel (a).

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5 Discussion & Conclusion

Large uncertainties are present in the CMIP5 ensemble in terms of the representation of long-duration, dry and hot events. A large spread exists between models in their representation of the duration of dry spells as well as the magnitude of temperatures that occur within dry spells. Furthermore, within Central and Southern Europe, models that simulate longer dry spells also tend to simulate hotter temperatures during dry spells, and vice versa. Hence, the CMIP5 ensemble simulates a large range of climatologies from those with shorter-cooler dry spells to those with longer-hotter dry spells in these regions.

The duration of dry spells is calculated as the consecutive number of days with precipitation less than 1 mm. Our findings are consistent with previous analyses of CMIP5 (e.g. Polade et al. 2014; Sillman et al., 2013; Lehtonen et al., 2014). In Northern Europe, CMIP5 models tend to underestimate the 5-year return level for the duration of a dry spell while there are contrasting differences between models in Central and Southern Europe where some models underestimate and others overestimate the 5-year return level. These model differences are found to be due to inherent differences in model formulations and not internal variability. For example, in Northern Europe, we find that the representation of dry spell persistence is related to a model's representation of persistent anticyclonic conditions, i.e. models that simulate more persistent anticyclonic spells have longer dry spells. Hence, the representation of large-scale circulation features are important for the representation of dry spells in Northern Europe. This is also likely to be the case in Central and Southern Europe (e.g. Sousa et al., 2017; Maraun et al., 2021), though with reduced importance as we do not see an inter-model relationship between the metrics studied here.

There is an increased probability of temperature extremes occurring during dry spells, as seen in EOBS. This increased probability is also captured in CMIP5 models though the models tend to underestimate the strength of the relationship and there is some spread between the models. It is difficult to interpret these differences between models in their representation of this relationship, as the relationship itself likely strongly influenced by the representation dry spells, as discussed in section 4.4. To understand how models differ in their representation of temperature extremes during dry spells, we calculated the mean of the maximum temperature from all dry spells longer than 5 days. Temperature extremes are underestimated in Northern and Southern Europe while contrasting differences are seen in Central Europe. There is also a large spread between models throughout Europe and results indicate that this spread arises from differences in model formulations rather than by internal variability.

Lastly, to understand how models differ in their representation of compound long-duration dry and hot events, we assessed the relationship between the 5-year return level in dry spell duration and the mean of the maximum temperatures from dry spells longer than 5 days. We see a positive association between the two in Central and Southern Europe meaning that models which simulate longer dry spells also simulate higher temperatures, and vice versa. The reasoning for this relationship is likely related to land-atmosphere interactions which have an important influence on both temperature and precipitation in this region

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(Seneviratne et al., 2010). Climate models have difficulty in accurately simulating soil moisture as well as the partitioning between latent and sensible heat fluxes at the land surface which can contribute to precipitation and temperature biases (Dong et al., 2022). However, the direction of causality of biases is not straightforward and biases arising from atmospheric drivers may amplify those driven by soil moisture. For instance, long dry spells could deplete soil moisture which may in turn increase temperatures (Mueller and Seneviratne, 2014; Berg et al., 2015; Lin et al., 2017). Similarly, warmer models may deplete soil moisture more leading to reduced moisture recycling, less precipitation, and longer dry spells (Vogel et al., 2018). Alternatively, the representation of persistent anticyclonic conditions may modulate both the representation of duration and temperature of dry spells, although we do not see a relationship between anticyclonic spell persistence and the other quantities in these regions.

Overall, the results reveal a large spread in the representation of long-duration dry and hot events within the CMIP5 ensemble in that there are models which simulate shorter-cooler dry spells as well as models which simulate longer-hotter dry spells. Such a spread poses difficulties for impact modelling as the expected simulated impacts from a simulated climate with shorter-cooler events may be much different to those in a simulated climate with longer-hotter events. Bias adjustment procedures can create more usable data for impact studies though these methods have their limitations (Doblas-Reyes et al., 2021) and can have unintended consequences such as increasing biases in the modelled impact (Zscheischler et al., 2019) or breaking the relationship between drivers, such as the large-scale circulation, and the hazard of interest (Addor et al., 2016; Maraun et al., 2021). Given that model differences in dry spell durations and extreme temperatures are related to the representation of external drivers such as blocking systems, soil moisture and land-atmosphere interactions, their biases are unlikely to be reduced in a meaningful way through bias adjustment, and so a performance-based constraint on model selection (e.g. Vogel et al., 2018) or a process based analysis of plausible future extremes is likely required (Fischer et al., 2021). Finally, the current analysis has focussed on an older generation of climate models in CMIP5 and so it would be interesting to apply this analysis to the latest generation of models in the CMIP6 ensemble to understand their added value compared to CMIP5 models in the representation of long-duration dry and hot events.

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Appendix A: Additional Tables and Figures

Table A1: CMIP5 models used in the analysis. The model IDs correspond to those in Figures 2 and 6. Models are arranged in descending order of ensemble size (N)

ID	Institute	Model	N	ID	Institute	Model	N
1	CCCma	CanCM4	10	18	NCC	NorESM1-M	3
2	CNRM-CERFACS	CNRM-CM5	10	19	CSIRO-BOM	ACCESS1-0	2
3	CSIRO-QCCCE	CSIRO-Mk3-6-0	10	20	LASG-CESS	FGOALS-g2	2
4	MOHC	HadCM3	10	21	MPI-M	MPI-ESM-P	2
5	ICHEC	EC-EARTH	8	22	BNU	BNU-ESM	1
6	IPSL	IPSL-CM5A-LR	6	23	CMCC	CMCC-CESM	1
7	CCCma	CanESM2	5	24	CMCC	CMCC-CM	1
8	MOHC	HadGEM2-ES	4	25	CMCC	CMCC-CMS	1
9	NOAA-GFDL	GFDL-CM3	4	26	INM	inmcm4	1
10	BCC	bcc-csm1-1	3	27	IPSL	IPSL-CM5B-LR	1
11	BCC	bcc-csm1-1-m	3	28	NASA-GISS	GISS-E2-H	1
12	CSIRO-BOM	ACCESS1-3	3	29	NASA-GISS	GISS-E2-R	1
13	IPSL	IPSL-CM5A-MR	3	30	NOAA-GFDL	GFDL-ESM2G	1
14	MOHC	HadGEM2-CC	3	31	NOAA-GFDL	GFDL-ESM2M	1
15	MPI-M	MPI-ESM-LR	3	32	NSF-DOE-NCAR	CESM1-BGC	1
16	MPI-M	MPI-ESM-MR	3	33	NSF-DOE-NCAR	CESM1-CAM5	1
17	NCAR	CCSM4	3				

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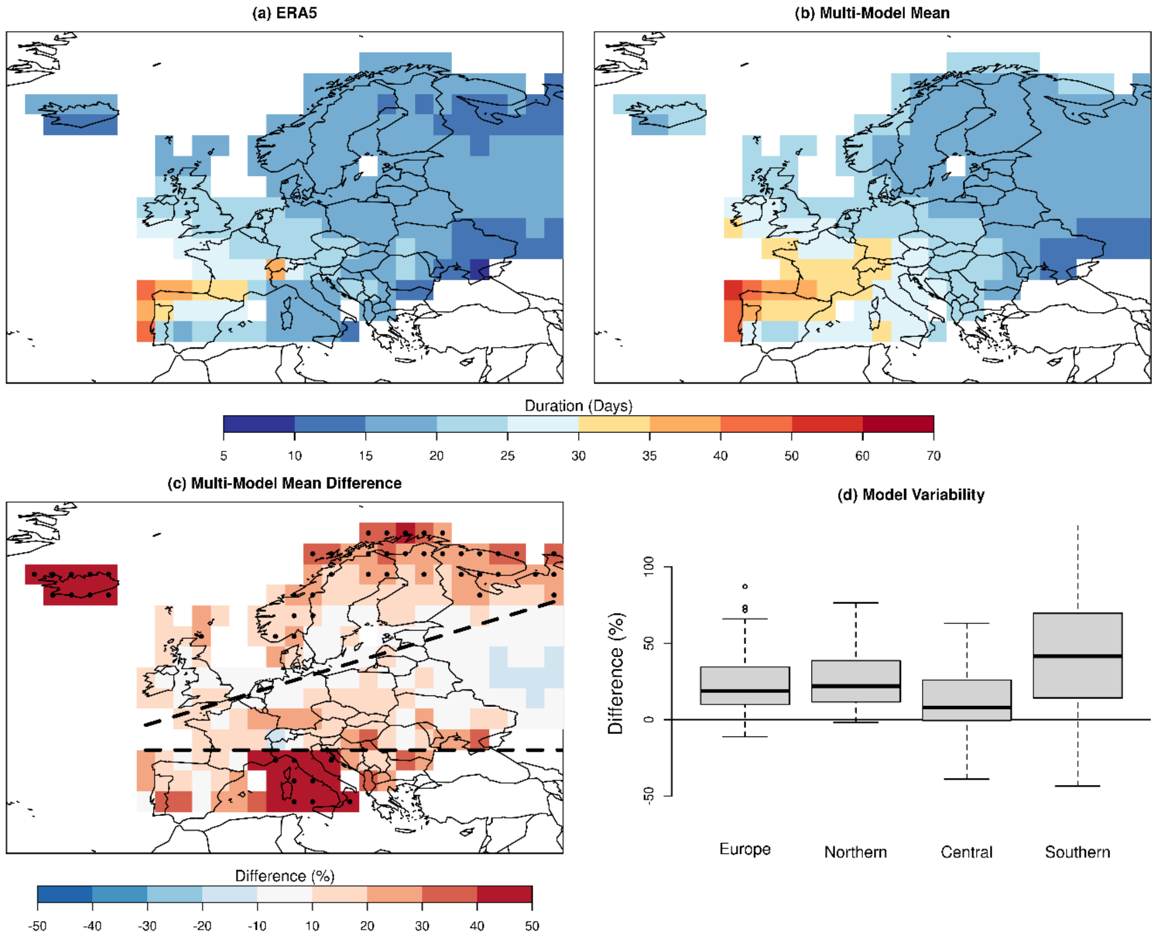

Figure A1: Duration Return Levels (RLs) of anticyclonic spells (consecutive days with MSLP > 1012 hPa) for a 5-year return period for (a) ERA5, and (b) the mean of the CMIP5 multi-model ensemble. The multi-model mean percentage difference between CMIP5 models and EOBS is provided in (c); stippling indicates where 90% of CMIP5 models are below or above EOBS. (d) model variability in the relative difference averaged across all grid cells in Europe, Northern Europe, Central Europe and Southern Europe (dashed lines in (c) indicate the three regions).

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