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Key Points:

- First evidence is found for skillful seasonal predictions of Summer Northern European rainfall
- Model convective rainfall variability is the primary source of skill, while dynamical circulation is still poorly predicted
- Large ensembles are required to achieve skillful rainfall forecasts

Supporting Information:

- Data Set S1

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Skilful Seasonal Predictions of Summer European Rainfall

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Abstract Year-to-year variability in Northern European summer rainfall has profound societal and economic impacts; however, current seasonal forecast systems show no significant forecast skill. Here we show that skillful predictions are possible (r ~0.5, $p < 0.001$) using the latest high-resolution Met Office near-term prediction system over 1960–2017. The model predictions capture both low-frequency changes (e.g., wet summers 2007–2012) and some of the large individual events (e.g., dry summer 1976). Skill is linked to predictable North Atlantic sea surface temperature variability changing the supply of water vapor into Northern Europe and so modulating convective rainfall. However, dynamical circulation variability is not well predicted in general—although some interannual skill is found. Due to the weak amplitude of the forced model signal (likely caused by missing or weak model responses), very large ensembles (>80 members) are required for skillful predictions. This work is promising for the development of European summer rainfall climate services.

1. Introduction

European summer rainfall anomalies are often persistent for weeks to months and spatially coherent over large areas, for example, the dry summers of 1976 and 2003 spanned June–August leading to increased water shortages (Rodda & Marsh, 2011), fire hazards (Fink et al., 2004), and crop failure (Ciais et al., 2003) both in the UK and across much of Northern Europe. Equally, the succession of wet summers over 2007–2012 (Blackburn et al., 2008; Marsh & Hannaford, 2007; Parry et al., 2013) caused widespread flooding.

There are a number of potential drivers of European summer rainfall variability, including variability in the behavior of the North Atlantic jet (i.e., storm track; Folland et al., 2009; O'Reilly et al., 2017), preconditioning of soil moisture anomalies (Schär et al., 1999; Seneviratne et al., 2006), or changes in moisture availability due to varying sea surface temperatures (SSTs; Årthun et al., 2017; Knight et al., 2006). However, the relative contribution of each process to European summer rainfall variability, their inherent predictability, and the skill of current seasonal prediction systems to represent and predict them are still poorly understood.

The Summer North Atlantic Oscillation (SNAO; Folland et al., 2009) is the mode of circulation variability associated with latitudinal shifts in summer North Atlantic jet position. A positive/negative phase of the SNAO gives a north/south shifted jet position resulting in drier/wetter conditions for Northern Europe. Previous studies, however, estimate that the SNAO explains only a relatively small proportion (22%) of the total regional summer mean sea level pressure variance (for comparison, in winter the NAO explains 37%) and only ~25% of Northern European summer rainfall variability (Folland et al., 2009). To date, no skill has been reported for predicting the SNAO in seasonal forecast systems.

Soil moisture can be an important source of persistence (Koster et al., 2003) which can then amplify or dampen summer European rainfall anomalies (Ferranti & Viterbo, 2006). Initialization of soil moisture has been shown to give modest improvement in seasonal forecasts for some extreme European summers (such as 2003) but not in general (Prodhomme et al., 2016).

On longer, multidecadal timescales, variations in European summer rainfall have been linked to changes in North Atlantic SSTs, with wet periods linked to warm phases of the Atlantic multidecadal variability (AMV) such as in the 1950–1960s and 1990–2000s and dry periods linked to cool AMV phases such as in the 1970–1980s (Knight et al., 2006; Sutton & Dong, 2012; Sutton & Hodson, 2005). Decadal predictions show skillful hindcasts (retrospective forecasts) for predicting AMV (Hermanson et al., 2014; Smith et al., 2010), likely linked to persistence, ocean dynamics (Robson et al., 2012), and changes in aerosol forcings over the past

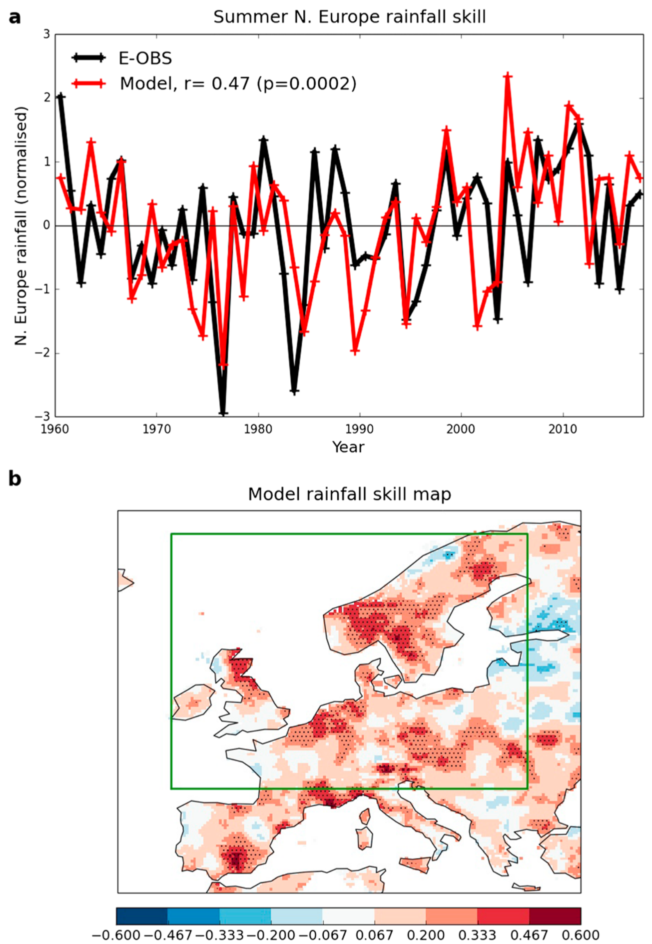

Figure 1. Skilful predictions of European summer rainfall. (a) Observed (E-OBS) and model ensemble mean predicted time series of summer (JJA) northern European rainfall. (b) Correlation skill map for European rainfall with 95% significant regions stippled (assessed using a 1-sided Student's *t* test); the green box shows the northern European region.

century (Booth et al., 2012). Climate models can simulate a robust increase in summer European rainfall in response to North Atlantic warming, but only when very long model simulations are run (Knight et al., 2006), or for decadal prediction case studies when very large lagged ensembles (~100 members) are used (Robson et al., 2013). For the standard operational hindcast ensemble sizes (~10–20 members), typically used in current seasonal forecast systems, there is no statistically significant skill for predicting Northern European summer rainfall variability (for example, European Centre for Medium-Range Weather Forecasts S4 and Met Office GloSea5 models both show no significant skill: $r < 0.3$, $p > 0.1$). We return to the need for large ensembles later. Finally, empirical statistical forecast models of European summer rainfall have also been constructed using lagged predictors of North Atlantic SSTs (Colman & Davey, 1999, Ossó et al., 2018). While good skill was found in hindcasts, a decade of real-time seasonal forecasts in the former study showed relatively poor skill (A. Colman, personal communication, 2017).

2. New Large Ensembles of High-Resolution Initialized Seasonal Predictions

We reexamine seasonal European summer rainfall skill using the latest high-resolution version of the initialized Met Office Decadal Climate Prediction System (DePreSys3, Dunstone et al., 2016). This system uses the HadGEM3-GC2 coupled climate model (Williams et al., 2015) with N216 (~60 km) atmospheric and 0.25° ocean resolution (see Supplementary Information S1). DePreSys3 has already shown very promising hindcast skill for seasonal to interannual predictions of the winter NAO when large ensembles are used (Dunstone et al., 2016). Here we use an 80 member ensemble, over a 58 year hindcast period (1960–2017) and find highly significant skill (Figure 1a, $r = 0.47$, $p < 0.001$ using a two-sided Student's *t* test) for predicting Northern European summer rainfall variability when assessed against the European land surface rainfall data set (E-OBS v16e, Haylock et al., 2008). For Northern Europe we use a previously defined box (Figure 1b, Sutton & Dong, 2012) but combine this with a mask based on the first empirical orthogonal function of E-OBS observed summer rainfall (Figure S1 in the supporting information). This provides a more physically based definition for Northern Europe rainfall variability as this mask removes the far north Norwegian coast which primarily varies in antiphase (Figure S1). However, we note that similar significant skill is achieved ($r = 0.45$, $p < 0.001$) if this mask is not used and that the skill is also robust if the lower resolution Global Precipitation Climatology Centre observational product is used instead ($r = 0.45$, $p < 0.001$).

The model predictions capture much of the observed variability including the transition from wetter summers in the early 1960s to drier conditions in the 1970s and 980s, the particularly wet summers in the late 2000s, and the following drier summers (Figure 1a). In addition to this low-frequency variability the model hindcasts simulate some of the extreme summers such as 1976—the driest summer in both the observed and model time series. Overall, the sign of the rainfall anomaly is correctly forecast in two thirds of summers.

Analysis on a grid point basis (E-OBS 0.25° grid) reveals significant local rainfall skill in parts of the UK, Scandinavia, and Central Europe (Figure 1b). In addition to the skill of the box average, the model captures some aspects of the large-scale patterns associated with extreme dry and wet years (Figure 2), along with weaker but significant rainfall skill for Southern Europe ($r = 0.34$, $p = 0.008$, Figure S2). The 80-member DePreSys3 hindcast ensemble is the combination of two 40-member ensembles initialized in November (8–10 month lead) and May (2–4 month lead). Intriguingly, despite the difference in lead time, both show similar levels of skill when considered individually (r ~0.37, $p < 0.01$, Figure S3). This is consistent with a

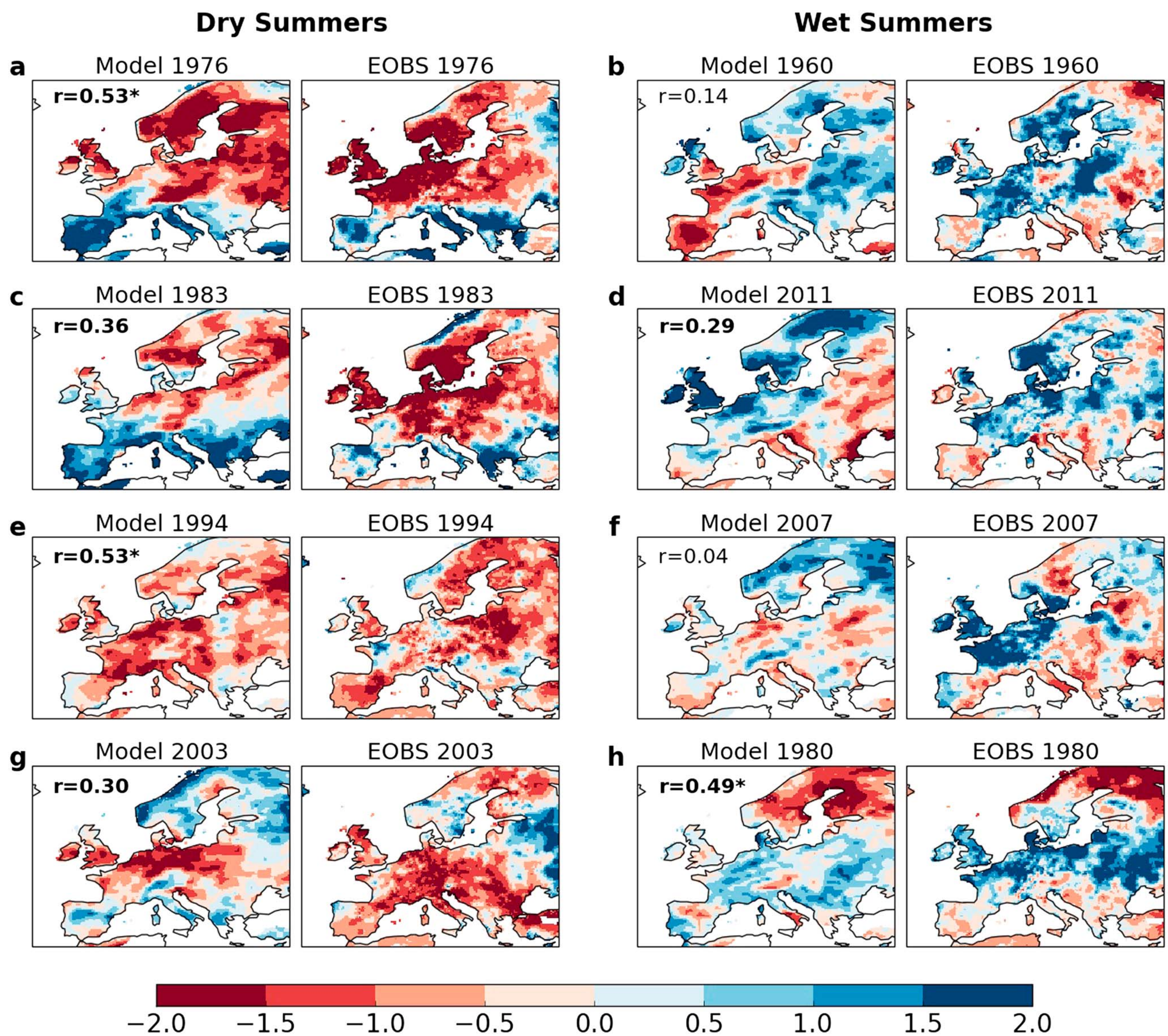

Figure 2. Individual extreme summers. (a–h) The four (left) driest and (right) wettest observed northern European summers are plotted alongside the model predictions as normalized anomaly rainfall maps. They are shown in order of the (top to bottom) driest/wettest summers. Pattern correlations (using an uncentered Pearson's correlation coefficient) are calculated over the displayed region to help illustrate the model performance. Correlations in bold are significant ≥90% level, and an asterisk marks significance ≥95%, using bootstrapping with replacement to assess the probability of achieving such correlations by chance.

slowly varying predictable driver of summer rainfall skill and also that skill is strongly dependent on ensemble size; we explore these possibilities in sections 4 and 5, respectively.

3. Skilful Predictions of Convective Rainfall

We first probe the model skill using the Japanese 55-year Reanalysis (JRA-55, Kobayashi et al., 2015). This covers the entire 58 year period of our hindcasts and has a largely faithful reproduction of observed Northern European rainfall variability when compared to the gridded E-OBS station-based observational data set (Figure S4a, r = 0.92). However, using the reanalysis, rainfall can be split into two components: "large-scale" (frontal rain) and "convective" (from the convective parameterization scheme). While this is an imperfect split, as in reality much of the convective rainfall is embedded within large-scale frontal systems, it does provide the opportunity to probe the drivers of model rainfall skill on a process level. We also note that the exact partitioning is likely to depend on the model used in the reanalysis. Large-scale JRA-55 rainfall shows

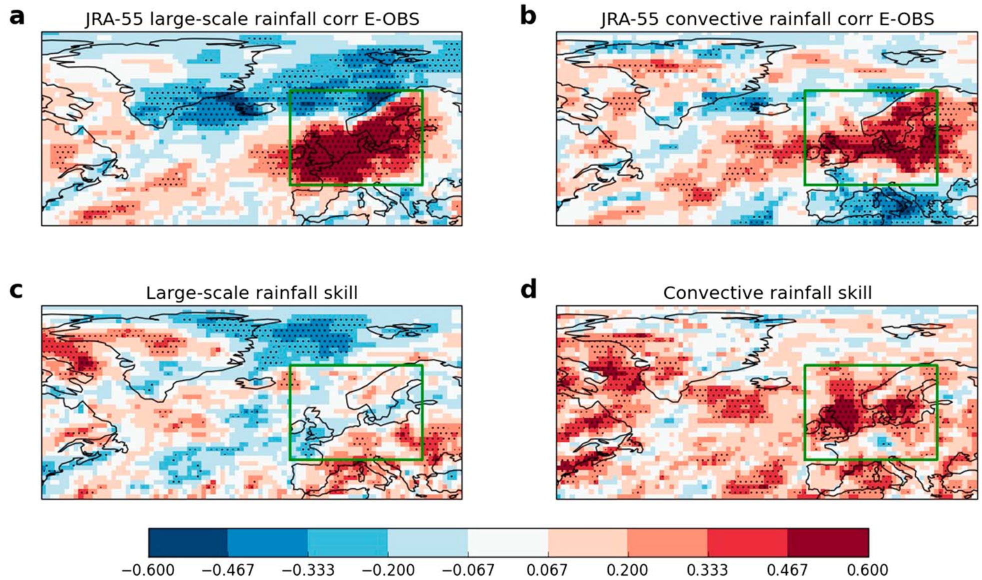

Figure 3. Using Japanese 55-year Reanalysis (JRA-55) to explore convective versus large-scale rainfall. (a and b) The JRA-55 fields of large-scale and convective rainfall correlated with the E-OBS northern European time series. (c and d) The skill at each grid point of the equivalent model fields in predicting the JRA-55 large-scale and convective rainfall. In all panels stippling shows significance at the 95% level according to a 1-sided Student's *t* test.

strong correlations with the total observed Northern European rainfall (Figure 3a, $r = 0.87$, $p < 0.001$) and clearly exhibits a north-south dipole related to the position of the North Atlantic jet (and hence SNAO phase). However, the convective rainfall also correlates strongly with total Northern European rainfall (Figure 3b, $r = 0.56$, $p < 0.001$). It has less of a dipole structure, and the cross-correlation with large-scale rainfall is quite low ($r = 0.26$, $p = 0.05$). This suggests that observed summer European rainfall is not solely influenced by the dynamical behavior of the summer North Atlantic jet but also likely from thermodynamic processes that contribute to convective rainfall variability.

The model hindcast rainfall data can also be split into convective and large-scale components with a similar partitioning to that in JRA-55 (Figures S4b–S4g). To assess how well the model captures the JRA-55 variability, we calculate the model skill at each grid point, for each component (Figures 3c and 3d). This reveals that the model skillfully predicts much of the JRA-55 convective rainfall variability, especially over the UK and Scandinavia (regions identified as skillful in Figure 1b). However, the model has little large-scale rainfall skill, except weakly over parts of Central Europe.

4. Exploring the Driving Mechanisms on Low and High Frequencies

We now partition the data into low and high-frequency components, corresponding to 5 year and interannual timescales (see Supplementary Information S1), in order to understand the driving mechanisms of rainfall variability (Figure 4) and whether these are skillfully predicted (Figure 5). On the low frequency the model is able to capture much of the observed variability (Figure 4a) with significant skill ($r = 0.71$, $p = 0.014$, assuming 11 independent data points in a Student's *t* test). The high frequency also shows significant skill with a similar level of significance (Figure 4b, $r = 0.35$, $p = 0.008$). Correlating the low- and high-frequency model time series with the original, we find that the two timescales contribute almost equally to explaining the total model variance.

To probe the sources of low-frequency skill we correlate model fields with the observed Northern European rainfall time series (left column, Figure 4). In agreement with previous studies (Knight et al., 2006; Sutton & Dong, 2012; Sutton & Hodson, 2005), we find a strong positive correlation between Northern European rainfall and North Atlantic SSTs (Figure 4c). The characteristic "horseshoe" pattern is that associated with AMV but here has strongest correlations in the North Atlantic subpolar gyre region. Similarly, we calculate the correlation with the zonal and meridional components of the model moisture flux (at 850 hPa) and overplot as vectors (Figure 4c). These show a strong anticyclonic moisture circulation over the North Atlantic that feeds

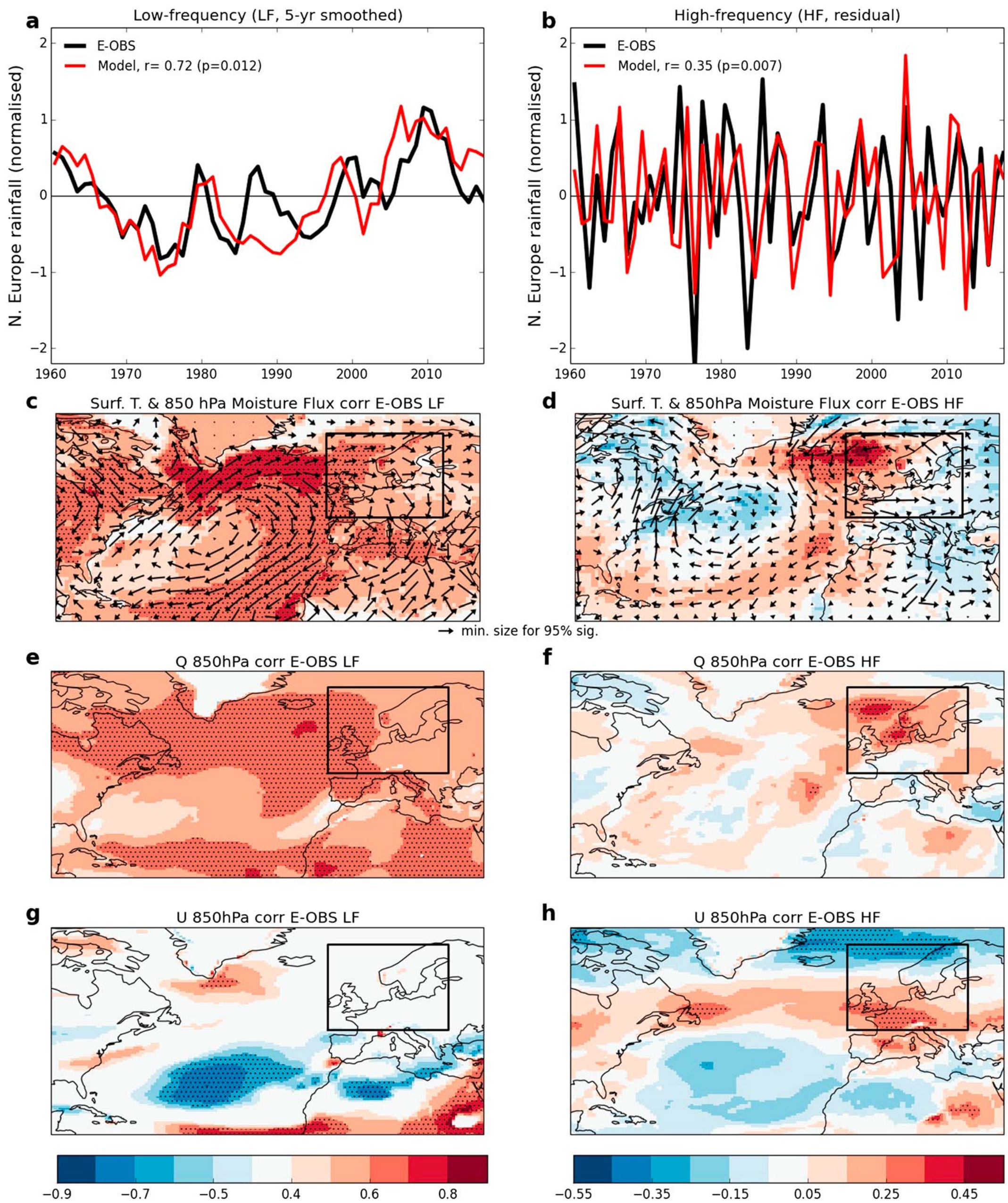

Figure 4. Mechanisms driving skillful northern European predictions. (left column) Low-frequency (5 year smoothed) and (right column) higher frequency (residual) are considered. (a and b) Time series of observed and model predictions for the two timescales with significant skill shown (low-frequency p value has been adjusted to account for reduced number of degrees of freedom). (c and d) Correlation of observed time series with model predicted fields of sea surface temperature and with 850 hPa moisture flux vectors overplotted (arrows). Moisture flux is split into contributions from (e and f) specific humidity and (g and h) zonal wind. In all panels stippling shows regions of significant correlation at the 95% level, according to a 1-sided Student's *t* test.

higher moisture air into Northern Europe during wet summer periods. As the moisture flux is a product of wind (mainly u-wind in this case, *U* 850 hPa) and specific humidity (*Q* 850 hPa) the wetter years could either be due to an increase in the strength of the prevailing westerlies, an increase in specific humidity, or a combination of both. To determine the prime driver in the model we consider each separately in Figures 4e and 4g. We find a strong relationship with specific humidity in the North Atlantic (Figure 4e) but no significant correlation with zonal wind (Figure 4g).

In order for these factors to explain forecast skill, they also must be skillfully predicted by the model. Low-frequency North Atlantic SSTs are well predicted by the model (Figure 5a), as is specific humidity (Figure 5c)

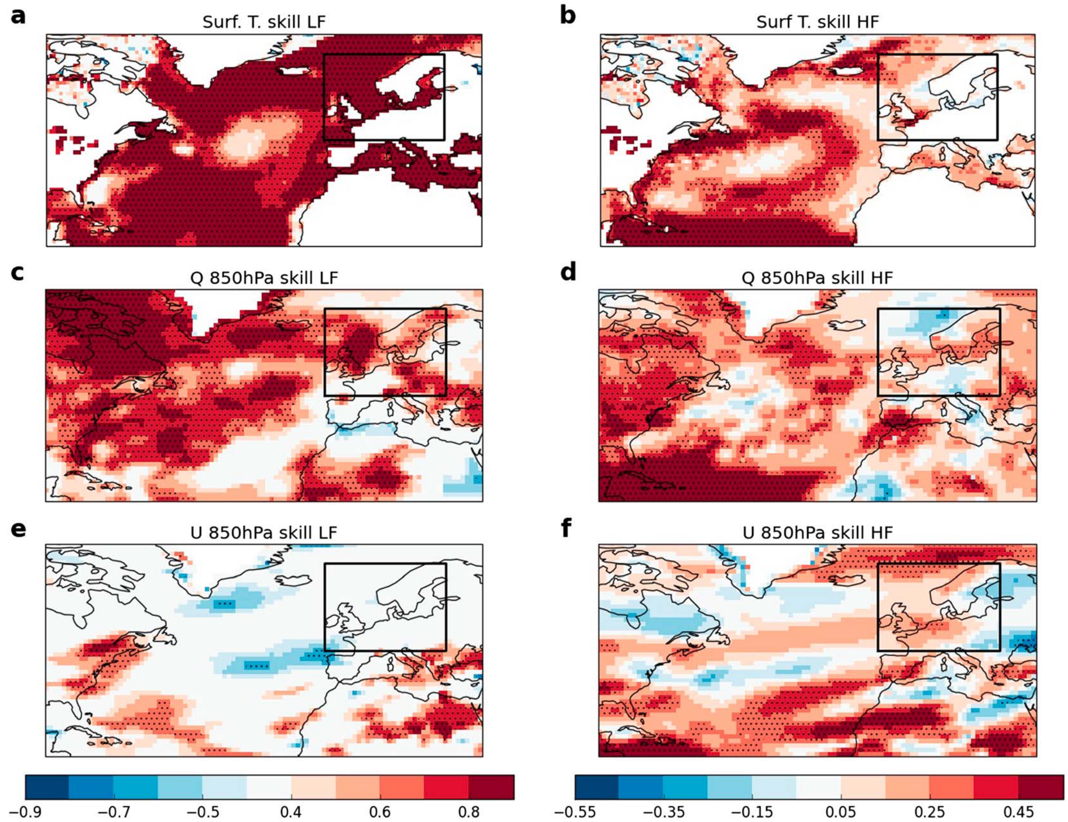

Figure 5. Are the drivers well predicted by the model? As Figure 4, split into (left) low-frequency and (right) high-frequency variabilities. (a–f) The skill in predicting the drivers identified in Figures 4c–4g. Skill is plotted for predicting SST (a and b) assessed against the Hadley Centre Sea Ice and Sea Surface Temperature data set (Rayner et al., 2003) observational data set. (c and d) Specific humidity and (e and f) zonal wind are assessed against the Japanese 55-year Reanalysis. In all panels stippling shows regions of significant correlation at the 95% level, according to a 1-sided Student's *t* test.

in the regions identified above. However, in agreement with our findings, the low-frequency zonal wind is not skillfully predicted by the model (Figure 5e) and hence does not drive the skillful part of the low-frequency model rainfall. Consistent with this, the model has no significant skill in forecasting the SNAO (hence North Atlantic jet) on this timescale (not shown). Hence, on the low-frequency timescale, the model rainfall skill appears to originate primarily from a thermodynamic response via skillful predictions of North Atlantic SSTs. Warmer SSTs promote more evaporation, leading to increased low-level moisture, which is then advected over Northern Europe by the climatological prevailing westerly winds. The atmospheric moisture content just above the boundary layer is an important determinant of convective efficiency (Derbyshire et al., 2004), as the progression of convecting updraughts into the troposphere is retarded by the evaporative cooling of entrained environmental air. The moister the environment, the less evaporative cooling, and so the stronger the upward transport of water and subsequent conversion to precipitation in convecting clouds. Thus, a moister low-level environment leads to increased convective rainfall. In support of this hypothesis, we find in addition that this increased moisture is indeed the dominant contribution to the greater convective instability found in the wettest summers (as shown in Figure S5).

The interannual timescale appears to be associated with more local SSTs, with Figure 4d showing a tripole with positive centers to the north of the UK and west of Portugal, with a negative center to the east of Newfoundland (regions skillfully predicted in Figure 5b). This SST pattern is similar to previous studies (Gastineau & Frankignoul, 2015, Ossó et al., 2018) where it is linked to European summer climate variability but further experiments would be needed to establish causality in the model. Positioned near these centers are a cyclonic moisture flux circulation over Northern Europe and an anticyclonic circulation over the Northeast Atlantic. Together these feed moist air into Northern Europe during wet summers. Again splitting this moisture flux into changes in humidity and winds, we find some very local correlations with humidity over the North Sea (Figure 4f) which show modest skill (Figure 5d). However, unlike on the low-frequency timescale, we now see significant correlations in the zonal winds (Figure 4h) with a skillfully predicted dipole pattern in the North Atlantic jet over Northern Europe (Figure 5f). We note that this correlation analysis to identify possible drivers does not establish causality and further model experiments are needed to test these conclusions.

5. Weak Model Dynamical Signals

The model Northern European summer rainfall skill appears driven partly by dynamical shifts in the position of the Atlantic jet on interannual timescales and partly by low-frequency changes in North Atlantic SSTs that drive changes in European moisture convergence and hence convective precipitation. The relatively weak model dynamical signal, particularly on the low-frequency timescale, raises the question as to the relative role of dynamics and thermodynamics in driving summer European rainfall. Common experience is that a large proportion of the variability is driven by dynamics (O'Reilly et al., 2017; Sutton & Dong, 2012), much of which is caused by shifts in the North Atlantic jet (associated with the SNAO). However, there is also emerging evidence that thermodynamic processes, such as the advection of ocean temperature anomalies in the high latitude North Atlantic and Nordic Seas, can play a significant role in driving northwest Europe temperature and rainfall on multiyear timescales (e.g., Årthun et al., 2017). In Supplementary Information S2 and Figure S6 we use three different methods (all using observed mean sea level pressure) in an attempt to partition the role of dynamical and nondynamical drivers of observed Northern European summer rainfall. The result is a range of correlations between the residual (nondynamic) and the total observed rainfall: r = 0.36–0.74. Hence, there does appear to be significant scope for a nondynamic component (encompassing the r = 0.47 skill), although the relative roles of dynamics and nondynamical drivers are uncertain.

The amplitude of ensemble mean rainfall variability is much smaller than that observed (by a factor of ~7, Figure S7a), and this is explored further in Supplementary Information S3. Hence, to extract the forced signal, and enable skillful predictions, a very large ensemble (80 members, Figure S7b) is required and higher skill is projected for even larger ensembles (Murphy, 1990). A surprising consequence of this is that the model ensemble has higher skill for predicting the observed summer rainfall (r = 0.47, $p < 0.0013$) than it does for predicting itself (Figure S7b, model-model skill is r ~0.1 and not significant). This large discrepancy clearly illustrates that model members are not interchangeable with the real world and this can be quantified in the ratio of the predictable components (RPC, Eade et al., 2014). We find an RPC ~5 (0.47/0.1), which implies that while the system is not "over dispersive" (as the model total variance across all ensemble members closely matches that observed, Figure S7a), the model predictions are "under confident." This is opposite to the "over confident" predictions often associated with tropical seasonal forecasts and so this unusual situation extends the "signal-to-noise paradox" found recently for winter NAO (RPC $>$ 2, Dunstone et al., 2016; Eade et al., 2014; Scaife et al., 2014). Further work is needed to establish the source of these signal-to-noise problems, but they may stem from a common model deficiency in the strength of the North Atlantic jet response in both winter and summer. Alternatively, given that model skill appears to originate primarily from convective rainfall, this might point to a deficiency in the model convective rainfall parametrization scheme, whereby the sensitivity to large-scale environmental changes is too low. However, this work clearly points to the current need for large ensembles to generate skillful summer European seasonal rainfall forecasts.

6. Conclusions

We have shown the first skillful seasonal predictions of European summer rainfall using a general circulation model. The model successfully captures multiannual periods of wet Northern European summers (e.g., 2007–2012) and also some extreme dry summers (e.g., 1976 and 2003). Using the JRA-55 reanalysis we find a significant role for convective rainfall in European summer (distinct from large-scale rainfall variability) and that this is the primary source of model skill. The skill originates from skillful predictions of low-frequency variations in North Atlantic SSTs which control moisture availability and hence convective rainfall efficiency over Northern Europe, together with a modest ability to predict high-frequency circulation changes. We stress that the model only explains part of the observed variability and in particular is unable to capture much of the dynamical variability in the position of the North Atlantic jet associated with the SNAO. However, the level of skill appears to be consistent with observed variability that is not associated with dynamical changes. An important issue, also found in winter forecasts, is that the current forecast system exhibits only a very weak rainfall signal and hence very large ensembles (80 members) are required to make skillful forecasts. Nevertheless, our results are very encouraging for the development of climate services to aid preparation for future summer flood and drought events.

Acknowledgments
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