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Key Points:
- Dominant time scales of European temperature variability during the cold season are identified
- Atmospheric and oceanic sources of SAT variability are identified
- A mechanism through which ocean temperature provides predictability of land surface temperature is identified

Supporting Information:
- Supporting Information S1

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Time Scales and Sources of European Temperature Variability

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Abstract Skillful predictions of continental climate would be of great practical benefit for society and stakeholders. It nevertheless remains fundamentally unresolved to what extent climate is predictable, for what features, at what time scales, and by which mechanisms. Here we identify the dominant time scales and sources of European surface air temperature (SAT) variability during the cold season using a coupled climate reanalysis, and a statistical method that estimates SAT variability due to atmospheric circulation anomalies. We find that eastern Europe is dominated by subdecadal SAT variability associated with the North Atlantic Oscillation, whereas interdecadal and multidecadal SAT variability over northern and southern Europe are thermodynamically driven by ocean temperature anomalies. Our results provide evidence that temperature anomalies in the North Atlantic Ocean are advected over land by the mean westerly winds and, hence, provide a mechanism through which ocean temperature controls the variability and provides predictability of European SAT.

Plain Language Summary Surface air temperature (SAT) over Europe displays pronounced variability on interannual to multidecadal time scales. A better understanding of the underlying source of SAT variability in different regions, to what extent this source is predictable, and at which time scale, is key in order to achieve skillful predictions of European climate. Here we provide the first assessment of SAT variability in Europe as a function of region and time scale. For each region and time scale, we also quantify the relative contribution from atmospheric circulation and ocean temperature on SAT variability. As ocean temperatures are considered more predictable than atmospheric circulation changes, identifying regions where ocean temperature is a main source of SAT variability is important for identifying regions with high potential for predictability.

1. Introduction

Surface air temperature (SAT) over Europe displays pronounced variability on interannual to multidecadal time scales (Arguez et al., 2009; Årthun et al., 2017; Gámiz-Fortis et al., 2011; Hurrell & Van Loon, 1997; Kushnir, 1994; Moron et al., 1998). The existence of such slowly evolving signals in climate implies higher predictability, and it is therefore important to understand the underlying sources of variability as different sources have different levels of predictability (Bellucci et al., 2015; Latif & Keenlyside, 2011; Meehl et al., 2014; Yeager & Robson, 2017). A major source of multiannual SAT variability and, hence, predictability is understood to reside in the ocean (Årthun et al., 2017; Latif & Keenlyside, 2011; Matei et al., 2012; Meehl et al., 2014; O'Reilly et al., 2017; Sutton & Dong, 2012; Yeager & Robson, 2017; Zhang et al., 2007). However, the relationship and causality between North Atlantic sea surface temperature (SST) variability and the atmosphere, and the underlying mechanisms, are still unclear and vary for different regions and time scales (Gastineau & Frankignoul, 2015; Ghosh et al., 2017; Schlichtholz, 2016; Yamamoto et al., 2015; Zhou et al., 2015).

Here we investigate the dominant time scales and sources of SAT variability over Europe, using a coupled climate reanalysis covering the time period 1901–2010 (Laloyaux et al., 2017). Specifically, we assess to what extent observed multiannual SAT variability in the cold season is driven by atmospheric circulation anomalies, associated with, for example, the North Atlantic Oscillation (NAO; Hurrell & Van Loon, 1997), or whether SAT anomalies are caused by anomalous North Atlantic SST. To assess the physical mechanisms underlying SAT variability, we use a statistical method that disentangles the roles of dynamics (atmospheric circulation anomalies) and thermodynamics (e.g., SST anomalies; Deser et al., 2016; O'Reilly et al., 2017).

This study provides the first assessment of SAT variability in Europe as a function of region and time scale. The quantification of the relative contribution from atmospheric circulation and ocean temperature on SAT variability on different time scales, and the regional manifestation of these time scales and sources, provides new and improved understanding of multiannual SAT variability over Europe. Most notably, we find that northern European SAT is dominated by a distinct interdecadal time scale of variability whose source has previously not been determined. A better understanding of the underlying source of SAT variability in different regions, to what extent this source is predictable, and at which time scale, is key in order to achieve skillful predictions of European climate.

2. Data and Methods

2.1. Data Set

This study uses data from the CERA-20C, a coupled climate reanalysis covering 1901–2010 produced by the European Centre for Medium-Range Weather Forecasts (Laloyaux et al., 2017). We use monthly data on a 1° grid. The variables considered are SST, SAT, sea level pressure (SLP), surface winds (925 hPa), and turbulent (the sum of latent and sensible) heat fluxes. The CERA-20C reanalysis contains 10 ensemble members. The analysis performed here is based on the ensemble mean. We find that the analysis presented herein is not sensitive to the number of ensemble members considered. All time series were linearly detrended before analysis. Quadratic detrending was also tested but did not have a qualitative influence on the results.

We focus in this study on the cold season (November to April). European SAT variability during the warm season is dominated by multidecadal variability, which has previously been shown to be associated with the Atlantic Multidecadal Oscillation (AMO; O'Reilly et al., 2017; Sutton & Dong, 2012; Zhang et al., 2007). We furthermore focus on SAT variability and not precipitation as cold season precipitation anomalies over Europe are mostly dynamically driven (e.g., Hanssen-Bauer & Førland, 2000) and show less distinct time scales of variability (Årthun et al., 2017; O'Reilly et al., 2017).

2.2. Statistical Methods

Cross-spectral analysis is performed using the multitaper method (Ghil et al., 2002). The number of tapers is set to 3, as a compromise between the need to resolve decadal scales and the benefit of multiple spectral degrees of freedom. The significance of spectral peaks is assessed by a theoretical red noise spectrum computed by fitting a first-order autoregressive process with a 95% confidence interval around the red noise. Empirical orthogonal functions are calculated for area-weighted SLP over the study region to identify the leading modes of atmospheric circulation. The statistical significance of correlations presented in the paper is assessed according to a random phase test (Ebisuzaki, 1997). Low-pass filtering is performed using a third-order Butterworth filter. When calculating correlations from 5-year low-pass filtered time series the first and last two (five for 11-year filter) points of the time series are ignored.

2.3. Constructed Circulation Analogs

To disentangle the role of mean versus variable atmospheric circulation in driving regional SAT anomalies, we employ the constructed circulation analog method. This method has previously been used in statistical weather predictions (Lorenz, 1969; van den Dool, 1994; van den Dool et al., 2003) and to infer the dynamical contribution to SAT trends (Cattiaux et al., 2010; Deser et al., 2016) and multidecadal variability (O'Reilly et al., 2017).

Circulation analogs allow us to infer the contribution of dynamics to SAT variability, using SLP anomalies to represent dynamical circulation anomalies. Monthly SLP anomalies in the North Atlantic-Nordic Seas region (30–80°N, 60W–50°E) are first calculated by removing the monthly climatology and linear trend from each grid point. For each month (January–December; 1901–2010), the Euclidean distance is then calculated between the target SLP field and the SLP anomaly fields in the same calendar month. The 80 months that are closest to the target month are then selected, excluding those that occur within $\pm$2 years of the target month to avoid sampling the nearest years. We then randomly select a subsample of 50 months and calculate the optimal linear fit (using multiple linear regression) to the target SLP for each grid point. The resulting regression coefficients are thereafter used to construct the analog SLP anomalies.

To obtain the SAT analog field associated with an atmospheric circulation anomaly, the SLP regression coefficients are multiplied by the SAT anomaly for the respective month. The procedure of random subsampling and subsequent regression is repeated 100 times and the resulting constructed SLP and SAT analogs

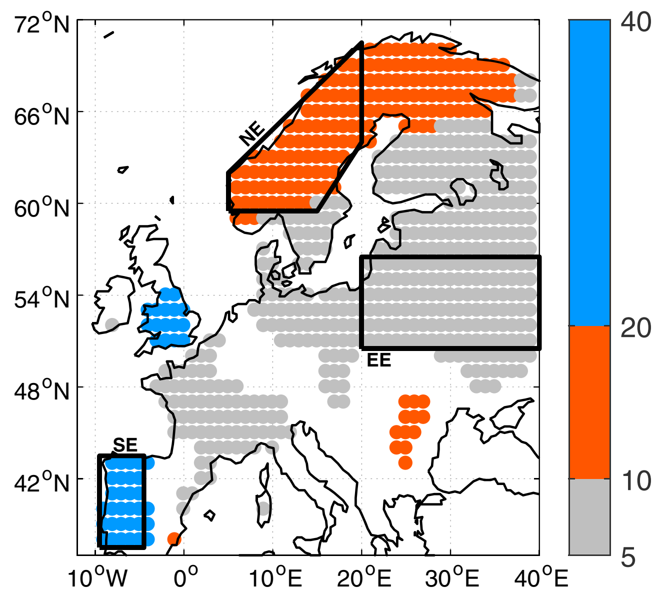

Figure 1. Dominant time scale (in years) of surface air temperature variability during the cold season (November–April). The time scale is identified from a multitaper spectral analysis at each grid point. Only significant peaks for time scales longer than 5 years are shown. In case of multiple spectral peaks the dominant one is defined with respect to the theoretical red noise spectrum. The regions used to produce surface air temperature time series for northern Europe (NE; 6–20°E, 57–70°N), eastern Europe (EE; 20–40°E, 51–56°N), and southern Europe (SE; 9–5°W, 38–43°N) are shown.

are then averaged to obtain the final dynamical analog fields associated with an atmospheric circulation anomaly. Lastly, the decomposed monthly anomalies are combined into seasonal anomalies.

Following O'Reilly et al. (2017), we estimate the uncertainty in the dynamical decomposition by randomly picking one of the 100 subsamples used to produce the constructed analog for each month, and which are then used to calculate seasonal averages. This is repeated 1,000 times yielding 1,000 random analogs for each season, from which the uncertainty is calculated from.

The constructed circulation analog approach quantifies the dynamical, that is, atmospheric circulation related, contribution to SAT variability, and the contribution of thermodynamical processes is obtained as a residual. The thermodynamical SAT anomaly includes the influence of changes in SST, but also includes the effect of land surface properties and sea ice. However, based on the findings presented herein it will be argued that the thermodynamic component relates to SST and thus can be interpreted as the advection of ocean-driven anomalous SAT by the mean atmospheric circulation.

3. Dominant Time Scales of European SAT Variability

The dominant time scales of European SAT variability for the cold season (November–April) are first identified (Figure 1). Over most of eastern and central Europe subdecadal (<10 years) variability dominates. Significant multidecadal (>20 years) variability is found over southern Great Britain and the Iberian Peninsula, whereas interdecadal (10–20 years) variability is most prominent over northern Europe (Scandinavia) and also in a small region in southeastern Europe. The specific time scales differ geographically; multidecadal variability over Great Britain is characterized by a narrow spectral peak at approximately 30 years, while Iberian SAT has a broader peak (25–40 years). Interdecadal SAT variability is characterized by a 14-year time scale in northern Europe and a shorter 11-year time scale in southeastern Europe. The 11-year time scale is often associated with the solar cycle, which has been found to influence European winter climate (Ineson et al., 2011) and eastern Europe in particular (Chen et al., 2015). Because of its small spatial extent, this time scale is not pursued further herein. Bimodality with several significant spectral peaks is only found for a small region along the French Mediterranean coast where there is also significant multidecadal variability and for parts of southern Scandinavia where subdecadal variability is also significant (not shown).

4. Sources of SAT Variability

We now assess the source of the geographically distinct SAT variability identified in Figure 1. Specifically, we ask if the SAT variability is a direct response to variations in the large-scale atmospheric circulation (dynamics), or whether the source of variability is mean advection of anomalous heat arising from ocean temperatures in the North Atlantic (thermodynamics). The decomposition of SAT anomalies into dynamical and thermodynamic components is achieved by a constructed circulation analog approach (section 2; Deser et al., 2016; O'Reilly et al., 2017).

The fraction of SAT variance explained by dynamics over Europe during the cold season in the period 1901–2010 is shown in supporting information Figure 1a. Dynamically induced anomalies are most important over central and eastern Europe, explaining approximately 60% of the variance. Over northern Europe, 20–50% of the SAT variability is a result of dynamical anomalies. The importance of dynamics is reduced if only decadal SAT variability is considered (>10 years; supporting information Figure 1b), suggesting different sources of variability at longer time scales. The dynamical SAT component explains a somewhat larger fraction of the SAT variance in winter (December–February; not shown). However, the results from the analog analysis are qualitatively similar if we consider shorter time periods within the cold season.

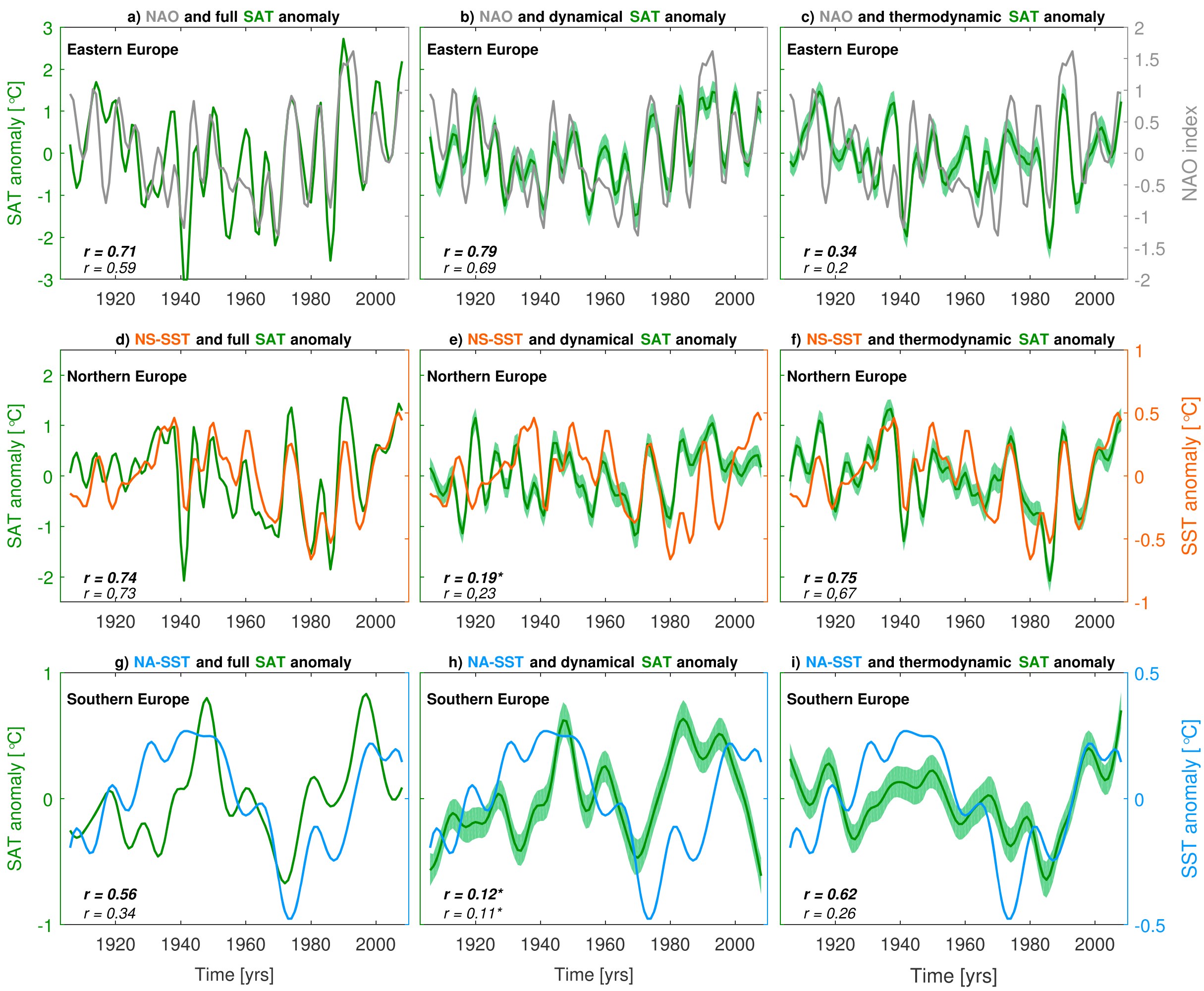

Figure 2. Time series of decomposed surface air temperature (SAT) anomalies in eastern Europe (upper row), northern Europe (middle), and southern Europe (lower), compared with, respectively, the North Atlantic Oscillation (NAO) index and sea surface temperature (SST) anomalies from the Norwegian Sea (NS-SST; 0–20°E, 57–70°N) and North Atlantic (NA-SST; 35–5°W, 30–45°N). The time series in (a-f) have been 5-year low-pass filtered to highlight multiannual variability, whereas an 11-year low-pass filter has been applied in (g-i) to highlight multidecadal variability (Sutton & Dong, 2012). The shading shows the interquartile range from the random subsampling used to construct the dynamical analogs. Correlations between detrended filtered (bold) and unfiltered time series are given. Asterisk indicates a correlation not significant at the 95% confidence level according to a random phase test (Ebisuzaki, 1997).

4.1. Subdecadal

On interannual time scales, atmospheric circulation anomalies over the North Atlantic drive much of the climate variability over Europe in winter (Wallace & Gutzler, 1981). The dominant atmospheric modes of variability, as identified from an empirical orthogonal function analysis of SLP, are the NAO (Hurrell & Van Loon, 1997) and the East Atlantic Pattern (Barnston & Livezey, 1987). This is also true for the CERA-20C data (not shown). The NAO reflects the variable strength and latitude of the dominant westerly winds (Woollings et al., 2010) and therefore exerts a strong influence on European SAT (supporting information Figure S2; Hurrell & Van Loon, 1997). Consistent with a large portion of central and eastern Europe exhibiting predominantly subdecadal SAT variability, the power spectrum of the NAO index has a statistically significant subdecadal peak (Hurrell & Van Loon, 1997; Moron et al., 1998; Reintges et al., 2017). The significant subdecadal variability in eastern and central Europe (Figure 1) furthermore disappears if the SAT variability associated with the NAO is removed by regressing the SAT time series onto the NAO index (not shown), indicating that the subdecadal SAT peak in central and eastern Europe is linked to atmospheric variability.

The interannual correlation between eastern European SAT (Figure 1) and the NAO index is 0.59 (Figure 2a). The correlation between the dynamical SAT component and the NAO index (whose variability reflects atmospheric circulation changes) is 0.69 (0.79 for low-pass filtered data; Figure 2b), whereas the correlation is weak

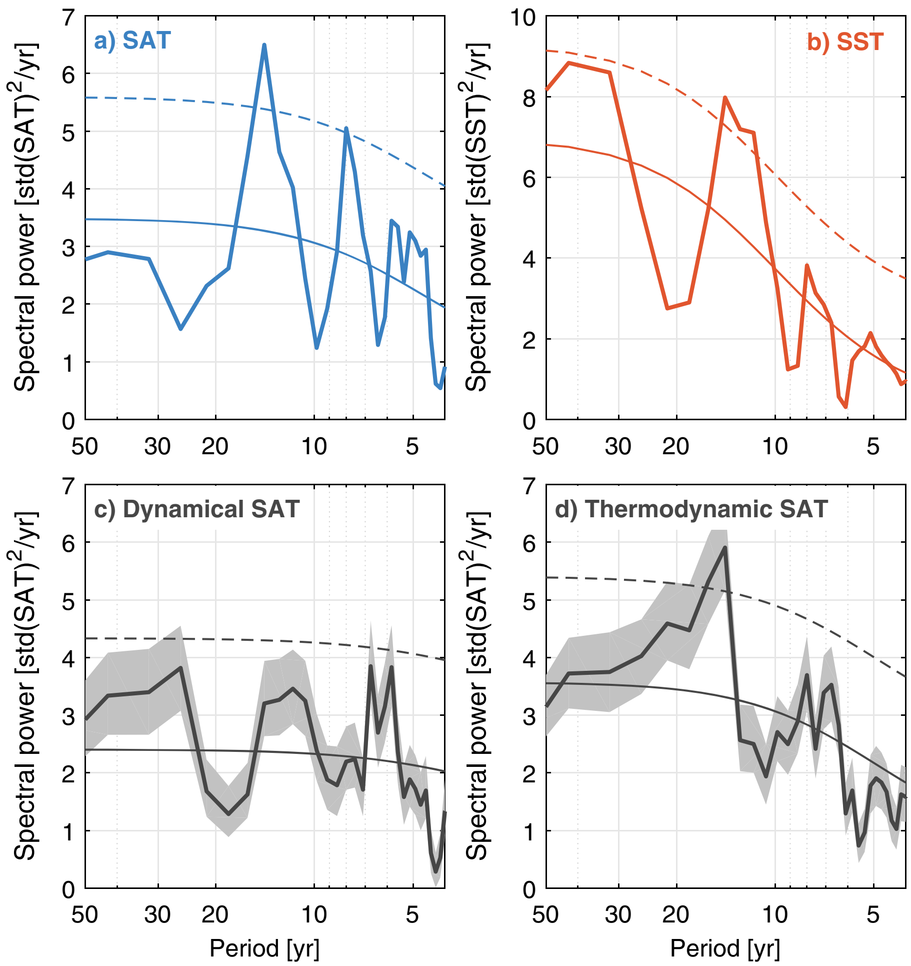

Figure 3. Power spectra of cold season northern European SAT, and its dynamical and thermodynamic components, as well as Norwegian Sea SST. The time series have been standardized prior to analysis. Thin lines are the theoretical red noise spectra and corresponding 95% significance levels (dashed lines). The gray shading in (c and d) shows the interquartile range from the random subsampling used to construct the dynamical analogs.

for the thermodynamic component. Regressing the dynamical SAT time series for eastern Europe onto North Atlantic SLP also yields a NAO-like pattern (not shown). These results are all consistent with dynamically forced subdecadal SAT variability in eastern Europe.

4.2. Interdecadal

The interdecadal SAT variability over northern Europe is rooted in the thermodynamic component, as witnessed by a common dominant time scale of 14 years (Figures 3a and 3d). The dynamical SAT component does not have a dominant time scale, consistent with atmospheric variability being principally stochastic. The interdecadal time scale of thermodynamic SAT variability is also found for Norwegian Sea SST (Figure 3b; Årthun & Eldevik, 2016; Årthun et al., 2017). We therefore further explore the relationship between SAT and SST anomalies by analyzing the time series of Norwegian Sea SST and the decomposed SAT anomalies over northern Europe (Figure 1). For the full SAT time series, the correlation between Norwegian Sea SST and SAT is 0.73 for the interannual time series and 0.74 for 5-year low-pass filtered time series (Figure 2d). The strong covariability between SST and SAT is dominated by the thermodynamic component, the correlations being of similar magnitudes on both interannual and multiannual time scales (Figure 2f). For the dynamical SAT component, the correlation with SST is 0.23 on the interannual time scale and not statistically significant for 5-year low-pass filtered data (Figure 2e).

The decomposition of SAT variability into its dynamical and thermodynamic components demonstrates that interdecadal SAT variability in northern Europe is mainly of a thermodynamic origin, and related to SST

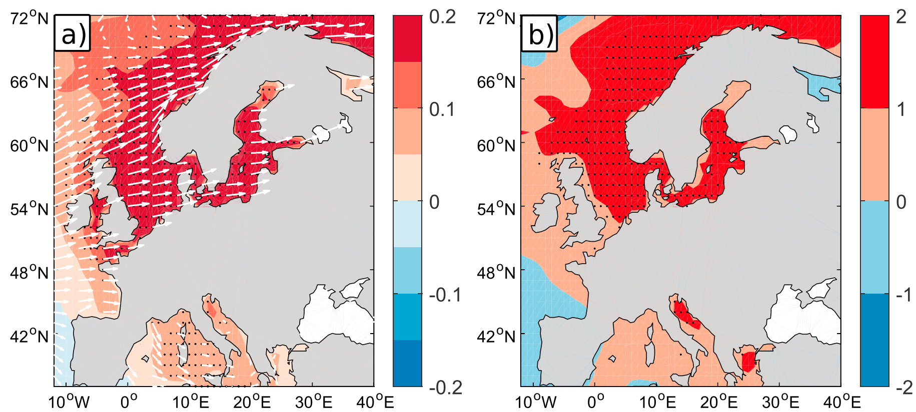

Figure 4. (a) Sea surface temperature (SST) variability associated with thermodynamic surface air temperature (SAT) in northern Europe, calculated by linear regression (unit: °C/°C). The white arrows show the mean surface winds over the ocean (925 hPa). (b) Surface turbulent heat fluxes regressed onto the annual rate of change of thermodynamic SAT in northern Europe (unit: W m^{-2}/Δ°C). Heat fluxes out of the ocean are defined as positive. Dots indicate correlations significant at the 95% confidence level according to a random phase test (Ebisuzaki, 1997).

variability in the Norwegian Sea. In support of the latter, the SST pattern associated with variations in thermodynamic SAT in northern Europe shows the largest signal in the Norwegian Sea (Figure 4a). In this area the surface winds are predominantly westerly, acting to transport the SST anomalies over land. Increasing thermodynamic SAT is furthermore associated with turbulent heat flux anomalies from the ocean to the atmosphere in the Norwegian Sea (Figure 4b), consistent with anomalous ocean heat being communicated to the atmosphere. The SST pattern associated with dynamical SAT anomalies shows positive SST anomalies mostly confined to the North Sea and Baltic Sea (supporting information Figure S3a), and negative anomalies in the central Norwegian Sea. This SST pattern is similar to that associated with the NAO (supporting information Figure 3b; Arguez et al., 2009). Combined, these findings suggest that SAT variability on interdecadal time scales over northern Europe are driven by mean advection of anomalous SAT arising from ocean temperatures in the Norwegian Sea.

4.3. Multidecadal

The multidecadal time scale that dominates SAT variability over the Iberian Peninsula and Great Britain is commonly associated with large-scale changes in North Atlantic SST, often referred to as the AMO (O'Reilly et al., 2017; Sutton & Dong, 2012; Zhang et al., 2007). The AMO is sometimes associated with time scales longer than that identified for SAT herein, but we note that the length of the SAT record (110 years) makes multidecadal variability somewhat more elusive to detail confidently. To assess the relationship between southern European SAT (region defined in Figure 1) and North Atlantic SSTs on multidecadal time scales, we analyze 11-year low-pass filtered time series (Sutton & Dong, 2012). Considering the basin-wide AMO index (75–0°W, 0–60°N), the correlation between southern European SAT and the AMO index is not significant for the full time series ($r = 0.28$) and for the dynamical component ($r = -0.16$). The AMO is, on the other hand, significantly correlated to the thermodynamic component ($r = 0.59$). The opposing dynamic and thermodynamic SAT response to the AMO is in agreement with Yamamoto and Palter (2016), who found that the imprint of AMO on wintertime SAT is weak because of a dynamic anomaly that masks the thermodynamic response to SST. The correlations, however, increase if SSTs are averaged over the region immediately west and upwind of the Iberian Peninsula; there is now a clear and significant relationship between SAT and SST (Figure 2g). The covariability is rooted in the thermodynamic component (Figure 2i), consistent with ocean-driven anomalous SAT advected over land by the mean winds (see, e.g., Kållberg et al. (2005) for a global wind climatology).

5. Conclusions and Implications for Climate Predictability

In this study, we have documented distinct time scales of temperature variability across Europe (Figure 1) and identified the underlying sources of variability (Figure 2). We have furthermore identified a mechanism through which ocean temperature variability provides predictability of land surface temperature and identified distinct regions within Europe where this mechanism dominates SAT variability. The ocean-induced variance over land concerns both an interdecadal (14 years; northern Europe) and a multidecadal time scale

(Great Britain; Iberian Peninsula), with the latter similar to the large-scale AMO. The former is furthermore distinctly associated with temperature anomalies circulating the ocean (Årthun et al., 2017) and thus of lagged covariance and oceanic predictability that carries over to land. We note that we have focused on the impact of anomalous ocean temperatures, rather than on the debated mechanisms for low-frequency ocean variability (Buckley & Marshall, 2016; Frankcombe et al., 2010; Latif & Keenlyside, 2011; Moron et al., 1998; Muir & Fedorov, 2017).

Model studies have demonstrated some multiyear skill in predicting continental SAT anomalies over northwestern Europe (Doblas-Reyes et al., 2013; Lienert & Doblas-Reyes, 2017; Matei et al., 2012; Robson et al., 2013; Scaife et al., 2014). However, the skill and prediction horizon are limited by the models' inability to predict atmospheric circulation anomalies beyond seasonal to interannual time scales (Meehl et al., 2014; Smith et al., 2014). As the thermodynamic SAT variability identified here is closely related to SST, it is possible that this component can be more skillfully predicted by dynamical prediction models as North Atlantic SSTs are themselves predictable up to a decade ahead (Langehaug et al., 2017; Matei et al., 2012; Yeager & Robson, 2017). Identifying regions that have a significant thermodynamic SAT variability that is complimentary to that of large-scale atmospheric circulation anomalies, such as northern Europe, is therefore important for identifying regions with high potential for predictability.

Acknowledgments
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