

RESEARCH LETTER

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Key Points:

- Multidecadal variations in European winter precipitation are linked to North Atlantic atmospheric circulation changes
- A new pattern of winter precipitation emerged over the British Isles in recent decades
- Recent precipitation changes over the British Isles coincide with shifts in storm tracks and atmospheric rivers

Supporting Information:

- Supporting Information S1

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Emerging European winter precipitation pattern linked to atmospheric circulation changes over the North Atlantic region in recent decades

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Abstract Dominant European winter precipitation patterns over the past century, along with their associated extratropical North Atlantic circulation changes, are evaluated using cluster analysis. Contrary to the four regimes traditionally identified based on daily wintertime atmospheric circulation patterns, five distinct seasonal precipitation regimes are detected here. Recurrent precipitation patterns in each regime are linked to changes in atmospheric blocking, storm track, and sea surface temperatures across the North Atlantic region. Multidecadal variability in the frequency of the precipitation patterns reveals more (fewer) winters with wet conditions in northern (southern) Europe in recent decades and an emerging distinct pattern of enhanced wintertime precipitation over the northern British Isles. This pattern has become unusually common since the 1980s and is associated with changes in moisture transport and more frequent atmospheric river events. The observed precipitation changes post-1950 coincide with changes in storm track activity over the central/eastern North Atlantic toward the northern British Isles.

1. Introduction

Recent unusual wintertime climatic conditions in Europe and other midlatitude regions have received increasing attention [e.g., Francis and Vavrus, 2012; Cohen *et al.*, 2014; Screen and Simmonds, 2014]. Wintertime variability in the North Atlantic region is dominated by distinct weather regimes, such as the two phases of the North Atlantic Oscillation (NAO), the Atlantic Ridge, and European Blocking, which exert pronounced impacts on regional climate [Vautard, 1990; Hurrell, 1995; Cassou *et al.*, 2004; Hurrell and Deser, 2009]. Such recurrent regimes are often determined based on cluster analysis of wintertime sea level pressure (SLP), which can reveal nonlinear or asymmetric features in dominant wintertime circulation regimes. Alternatively, leading modes of SLP can be identified using Empirical Orthogonal Function (EOF) analysis, though caution is warranted when interpreting EOF patterns [e.g., Dommenget and Latif, 2002], given that they do not necessarily represent physical/dynamical modes of the climate system. Both approaches robustly reveal the NAO as the leading mode of variability across the North Atlantic region. In contrast, the spatial expression and temporal characteristics of additional wintertime circulation patterns are sensitive to the analysis domain and period due to low-frequency modulations in the North Atlantic ocean-atmosphere system. Hurrell and Deser [2009] further highlight the considerable within-season variance in the atmospheric circulation of the North Atlantic as a limitation of regime-based approaches making it difficult to characterize winters as falling into one single circulation pattern or NAO phase.

Here to understand variability and change in European wintertime precipitation and the accompanying circulation and oceanic changes across the broader North Atlantic region, we focus on characteristic European precipitation patterns and assess multidecadal variations in their frequency over time. By combining a rigorous statistical analysis and dynamical interpretations, the study aims at providing new insights into links between North Atlantic extratropical variability and observed low-frequency changes in winter precipitation over Europe. It is noted that by design this study focuses on recurring wintertime *precipitation*—not *circulation*—patterns and changes in their frequency over time. Thus, while links to dominant climate modes

(e.g., NAO) are likely, one would not necessarily expect precipitation patterns to be explained solely by one specific circulation mode or weather regime [e.g., *Hurrell and Deser, 2009; Gastineau et al., 2013*, and references therein].

According to *Scaife et al. [2008]* heavy winter precipitation events in northern Europe are 50% more likely during sustained positive NAO periods than during its negative phase, with implications for UK flooding events [*Huntingford et al., 2014*]. *Maidens et al. [2013]* found the winter of 2010/2011 with record-breaking low temperatures across northern Europe to coincide with an anomalously negative NAO phase and intense atmospheric blocking. They attributed the success in predicting the exceptional 2010/2011 wintertime conditions by October 2010 to anomalous ocean heat content and associated North Atlantic sea surface temperature (SST). Similarly, *Keenlyside and Omrani [2014]* suggested that warm North Atlantic SST associated with the Atlantic Multidecadal Oscillation (AMO) contributed to recent cold European winters, as positive AMO phases are associated with more negative NAO episodes [*Peings and Magnusdottir, 2014; Gastineau and Frankignoul, 2015*]. *Huntingford et al. [2014]* also implicated wetter conditions in northern Europe with changes in the AMO, as its warm phase is associated with higher precipitation across the Eastern Atlantic [*Alexander et al., 2014*]. This suggests that extratropical ocean conditions may influence atmospheric conditions, especially on multidecadal time scales, while the converse occurs at shorter time scales [*Gulev et al., 2013*].

Leading modes of variability, such as the NAO and AMO, often exert their impact on European winter climate through modulation of atmospheric blocking activity over the North Atlantic-European sector [e.g., *Scherrer et al., 2006; Croci-Maspoli et al., 2007; Häkkinen et al., 2011; Davini et al., 2015; Luo et al., 2015*]. Atmospheric blocking represents a prominent weather phenomenon in the extratropics: During a blocking situation, the large-scale midlatitude zonal flow is impeded and meridional anomalies occur in the upper level jet; the anomalous circulation pattern remains largely stationary, generally persists for several days at a time, and is often associated with extreme events [e.g., *Coumou and Rahmstorf, 2012*]. For example, a strong anticyclone over Scandinavia and eastward extension of the North Atlantic storm track were implicated in the severe flooding in England and Wales in autumn 2000 [*Pall et al., 2011*]. European extreme wintertime hydroclimatic events have also been linked to atmospheric rivers (AR) [e.g., *Zhu and Newell, 1994; Gimeno et al., 2014*]. These phenomena are channels of intense horizontal water vapor transport in the lower troposphere that are mainly fed by local moisture convergence along the cold front of an extratropical cyclone [*Dacre et al., 2015*]. If seen in satellite imagery or reanalysis data, these elongated structures are often reminiscent of the meanders formed by a river and can be thousands of kilometers long [e.g., *Brands et al., 2017*]. While AR-associated precipitation totals—often enhanced through orographic uplift [*Gimeno et al., 2014*—are lower further inland, they account for the majority of flooding events in the UK [e.g., *Lavers et al., 2011, 2012*] and more broadly for heavy precipitation at the upper tail of the distribution over western Europe [*Lavers and Villarini, 2013*]. The unusually stormy and wet winter of 2013/2014 over the UK coincided with an intensified and eastward extended North Atlantic storm track, whose persistence in that position was linked to warm tropical Atlantic conditions [*Huntingford et al., 2014; Kendon and McCarthy, 2015*].

2. Data and Methods

Monthly gridded observational/reanalysis products were used to assess regional hydroclimate and circulation conditions. At 2° horizontal resolution, these included SLP, air temperature, winds, and geopotential height from the twentieth century reanalysis v2c (20CR; 1871–2012) [*Compo et al., 2011*]; SST at 1° resolution from the UK Hadley Centre HadISST v1.1 (1870–present) [*Rayner et al., 2003*]; and precipitation at 0.5° resolution from the Global Precipitation Climatology Centre v6 (GPCC; 1901–2010) [*Schneider et al., 2014*]. The common analysis period was 1901–2010. However, results are consistent for the more recent period post-1979 with improved data coverage using the European Centre for Medium range Weather Forecasting reanalysis product (ERA-Interim; 1979–present) [*Uppala et al., 2005*], precipitation from the Climate Prediction Center (CPC) Merged Analysis product (CMAP; 1979–present) [*Xie and Arkin, 1996*] and the ENSEMBLES daily gridded observational product (E-OBS v15.0; 1950–present) [*Haylock et al., 2008*], and NOAA Optimum Interpolation SST v2 (1982–present) [*Reynolds et al., 2002*], as seen in supporting information Figure S6. Given the robustness of the results, we also only show the longer period 1901–2010 based on the 20CR ensemble mean, as the ensemble spread in the reanalysis among its 56 ensemble members is small for key metrics, such as wintertime blocking days or position of the eddy-driven jet.

The limited availability and spatial coverage of long-term high-quality daily European precipitation station data prior to the 1950s makes it difficult to assess long-term trends in precipitation extremes [e.g., *KleinTank and Können, 2003; Zolina et al., 2005, 2014*], compared to mean precipitation changes [*Zolina et al., 2009*]. Our study therefore focuses on seasonal precipitation totals using the GPCC gridded product, rather than daily extremes, and on year-to-year variations for seasonal precipitation averages, rather than long-term trends. For details see supporting information S1 [*Uppala et al., 2005; Haylock et al., 2008; Huffman et al., 2009; Dee et al., 2011*]. Analyses are based on the January–March (JFM) season, as European wintertime precipitation exhibits similar spatiotemporal features in the long-term mean and variability, whether focusing on JFM or December–February (not shown).

Hierarchical cluster analysis was used to identify recurrent states (or regimes) of European precipitation by grouping them according to an objective similarity criterion, without an a priori determination of the number of clusters. We performed Ward's cluster method [*Ward, 1963*] as described by *Cheng and Wallace [1993]* on detrended area-weighted anomaly maps of JFM precipitation. Five dominant patterns of precipitation were identified by the clustering algorithm. The years for each cluster are listed in Table S1 and their temporal evolution in Figures 3 and S8.

Blocking days over the region 30° – 70° N were calculated for 20CR following the method by *Scherrer et al. [2006]* and *Häkkinen et al. [2011]* and refer to the number of days per season that exhibit blocking conditions at each gridpoint based on the meridional gradient of the daily geopotential height at 500 hPa. Variations in the number of blocking days could result from a change in the duration of blocking events or their number. For details, see supporting information S2 [*Rex, 1950; Woollings et al., 2008; Davini et al., 2012*]. Storm track activity is measured by the covariance of band-pass filtered daily v and T at 850h Pa, (i.e., $\langle v'T' \rangle$) using a sixth-order Butterworth filter.

Wintertime AR events are detected with the algorithm described in *Brands et al. [2017]*. This algorithm operates on the intensity (IVT) and direction (D) of the vertically integrated water vapor transport (IVT) obtained from 20CR and is applied for the eight target regions displayed in supporting information Figure S2. For a given target region and instant of time, the algorithm first queries whether the IVT is anomalously strong and then “crawls” up the flow until IVT falls below a certain threshold. If the detected structure is longer than 3000 km, the region is affected by an AR at that instant in time. Thereby, six-hourly AR occurrence-absence time series are obtained which are then accumulated for each JFM season to yield year-to-year AR count series describing the AR-activity in that region. A more detailed description of the algorithm is provided in supporting information S2.

3. Wintertime European Precipitation Patterns and Links to Regional Circulation

A cluster analysis performed on JFM precipitation reveals recurrent anomaly patterns across Europe (Figure 1a). Pattern A is characterized by anomalously dry conditions for the British Isles, southern Norway and Sweden, and northern central Europe. In pattern B, anomalous wet conditions in excess of +20 mm/month are observed over the British Isles, western, central, and parts of eastern Europe, as well as southern Norway and Sweden. Pattern C is characterized by very wet conditions for southern and western Europe, including the British Isles with the exception of Scotland, which exhibits anomalous dry conditions, as does Norway. Pattern D is the opposite to pattern C with a severe reduction in precipitation (< -40 mm/month) for southern and western Europe, while Norway records wet anomalies in excess of +50 mm/month. Pattern E is strikingly similar overall to cluster D, except for the British Isles: in pattern D, the British Isles, with the exception of Scotland, are characterized by significant reductions in precipitation. In pattern E, on the other hand, Ireland and Scotland experience anomalously wet conditions in excess of +50 mm/month, while southeastern England is anomalously dry.

Pattern A is characterized by a weakened meridional pressure gradient with anomalous high SLP extending from Iceland toward Scandinavia and reduced SLP south of 50° N (Figure 1b). Pattern B broadly exhibits anomalies of the opposite sign to A. Comparing the SLP anomalies in Figure 1b with the traditional daily weather regimes or EOF-based circulation patterns [*Vautard, 1990; Cassou et al., 2004; Hurrell and Deser, 2009*] reveals that while certain features of the positive/negative NAO or ridge pattern are present—a one-to-one correspondence is challenging. This is not surprising given that one would not expect JFM precipitation to be purely dominated by one circulation type given the considerable within-season variance and limitations with the EOF- or regime-based approaches identified earlier [e.g., *Hurrell and Deser, 2009*].

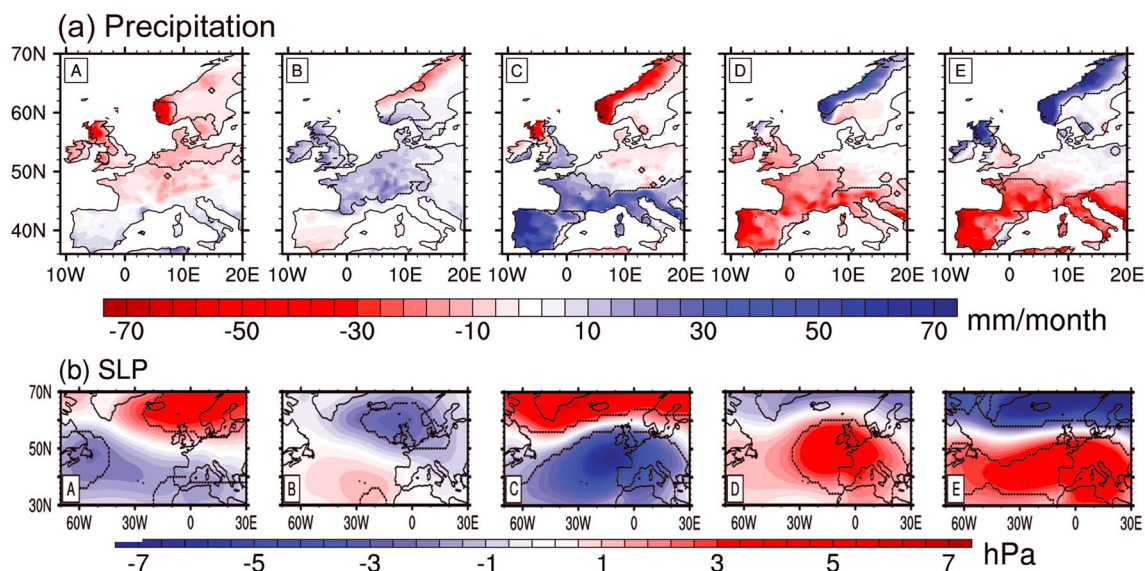


Figure 1. (a) Composite anomalies of precipitation (mm/month) clustered for the European region, along with (b) the associated SLP (hPa) anomalies, both for JFM for the period 1901–2010. The area enclosed by the black contours denotes anomalies that are significant at the 2% significance level as estimated by Student's t test.

The results indicate that subtle differences in the SLP patterns can yield relatively large differences in the precipitation distribution (e.g., British Isles). To understand these differences in the circulation anomalies characterizing precipitation clusters D and E, we composite the detrended JFM anomalies for the same years for related fields, such as surface winds, atmospheric blocking, storm track activity, and SST (Figure 2).

4. Emergence of Distinct Wintertime Precipitation Pattern Over the British Isles in Recent Decades

Pattern D is characterized by a strengthening and northward shift in the westerly flow and storm track activity over Europe north of 50°N (Figures 2a–2c). This coincides with enhanced blocking activity over the eastern Atlantic and centered over the British Isles and western central Europe. In pattern E, an albeit not significant reduction in blocking extends from Greenland across the northern tier into Europe. Over the British Isles, pattern E is associated with a significant southward displacement of the enhanced storm track activity compared to D, where the significant strengthening of $\langle v'T' \rangle$ is located north of the British Isles (Figures 2b and 2c). The latter accounts for the distinct wintertime precipitation signal over the northern British Isles, with dry conditions across the entire British Isles when the storm track is shifted to the north of the country (D), while northern Ireland, northern England, and Scotland experience wet conditions during enhanced storm track activity further south (E). A significant enhancement in the North Atlantic storm track, including over the British Isles, (Figure 2c) thus results in significant regional precipitation changes over the northern British Isles. Interestingly, the anomaly patterns of SST across the North Atlantic region are very distinct: pattern D exhibits anomalously warm SST for much of the North Atlantic. In contrast, pattern E is characterized by warm SST anomalies over the eastern Atlantic and European shelf areas, while anomalous cold SST dominate the sub-polar northwest Atlantic. Turbulent heat flux anomalies (Figure S4) indicate negative correlations with the SST anomalies; i.e., reduced heat flux out of the ocean corresponds to warmer SST, indicative of the atmosphere forcing the ocean, consistent with the findings of Gulev *et al.* [2013] for interannual time scales.

AR events play an important role in heavy precipitation events in the midlatitudes along the Atlantic eastern seaboard [Gimeno *et al.*, 2014]. Given the distinct precipitation patterns in clusters D and E over the British Isles, Figure 2e further explores the role of IVT and the frequency of occurrence of AR events along the eastern Atlantic seaboard for the two clusters. Both clusters are characterized by significant reductions in IVT across the subtropical North Atlantic and extending onto Europe, mirrored by reduced occurrence of AR events for the Iberian Peninsula and France (Figure 2e). Consistent with the precipitation in pattern D, extensive and significant increases in IVT anomalies occur only at the very northern edge of the British Isles toward Iceland. In contrast, pattern E exhibits very strong enhanced IVT anomalies over the British Isles, also reflected

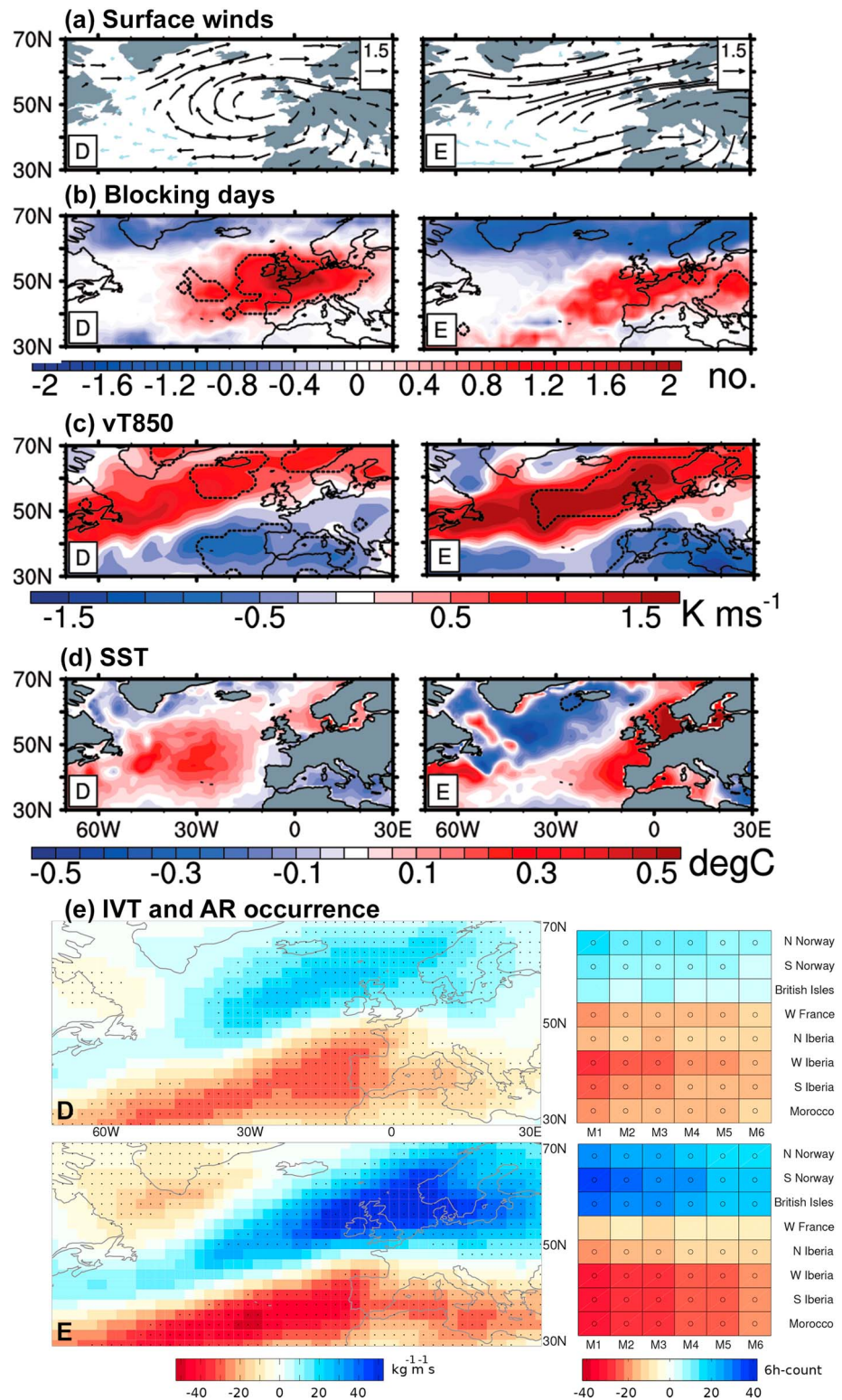


Figure 2. Composite anomalies of (a) surface winds (m/s), (b) number of blocking days per season, (c) 2–6 day band-pass filtered $\langle v'T' \rangle$ at 850 hPa (K m/s), (d) SST (°C), and (e, f) integrated water vapor transport (IVT; kg/m/s) and atmospheric river (AR) occurrence, all for JFM for the period 1901–2010 for years in clusters D and E. Count of occurrence of AR events for eight target regions along the eastern Atlantic seaboard. Dashed contours and black vectors in Figures 2a–2d and stippling/circles in Figures 2e and 2f denote anomalies significant at the 2% significance level as estimated by Student’s *t* test. M1 to M6 represent the six method modifications of *Brands et al.* [2017] using different percentile thresholds to define an AR.

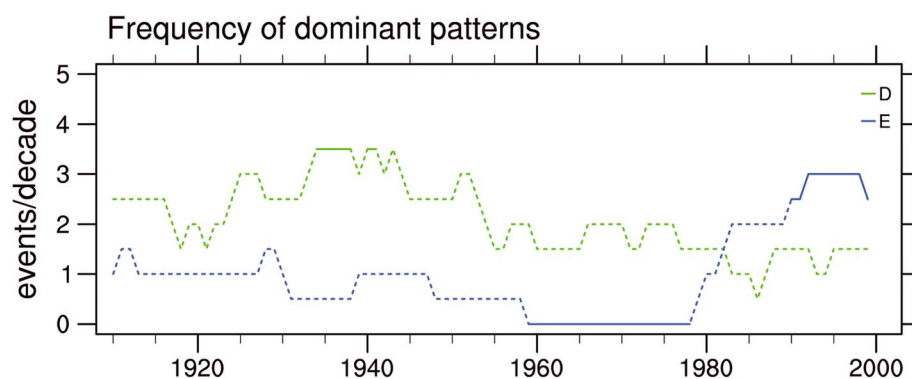


Figure 3. Running average of the number of events in the JFM precipitation clusters D and E per decade for the period 1901–2010. (NB: the value for each decade is plotted with the year at the center of the decade.) Solid lines indicate periods when the number of events/decade is significantly different from average occurrence rates at the 5% significance level (as estimated by Monte Carlo testing).

in significantly more frequent AR events for the British Isles (Figure 2e). AR events occur significantly more frequently over Norway in both patterns D and E. These results are in agreement with the changes in atmospheric circulation and the storm track (Figures 2a–2c).

The frequency of the dominant JFM precipitation patterns described here varied over time. The number of events, i.e., how often a winter was classified as exhibiting a particular pattern D or E in each decade, is shown in Figure 3 for the period 1901–2010. Multidecadal variations in the frequency of occurrence of these two different regimes are apparent: Pattern D occurred unusually often (in excess of three times per decade) in the 1930s and 1940s. In contrast, it was observed only rarely (less than once per decade) in the 1980s (Figure 3). Pattern E occurred very rarely during the period 1960–1980, while it has become much more common with 2–3 winters per decade since 1990 (Figure 3).

5. Circulation Changes Across the North Atlantic Region

Given the striking changes in the frequency of JFM precipitation patterns D–E over the second half of the twentieth century, with large implications for wintertime hydroclimatic conditions across Europe, difference fields for the period 1981–2010 relative to 1951–1980 are shown in Figure 4. The period 1981–2010 was characterized by significant reductions in JFM precipitation across the Iberian Peninsula, southern France, and northern Italy, while northern Germany, the Benelux States, Denmark, western Norway, Sweden, as well as the northern British Isles experienced significantly wetter conditions (Figure 4). Over the British Isles, the increasing frequency of pattern E in the more recent 30 year period (Figure 3) can account for the increasingly wetter conditions over the British Isles.

The large-scale SLP change and associated surface winds across the broader North Atlantic region are consistent with a low-frequency shift in the NAO toward a more positive phase post-1980 (Figure 4b) and the associated regional precipitation changes [Hurrell, 1995]. Significant changes in blocking activity over the North Atlantic sector occurred as well, with Greenland blocking reduced by 1–1.5 days/season averaged over the JFM season, while blocking over the Azores increased by 1.5 days/season (Figure 4c). On the other hand, the blocking activity over the British Isles, albeit reduced, did not change significantly, consistent with Barnes *et al.* [2014]. Barnes and Polvani [2013] related these changes to the eddy-mean flow feedback, which implies that the position of the jet and frequency of poleward and equatorward wave breaking are strongly coupled. The storm track activity indicates an eastward extension relative to its mean track position toward the northern British Isles (Figure 4d), consistent with increased winter precipitation and enhanced AR incidence there in recent decades [Huntingford *et al.*, 2014, and references therein]. The eastward extension in the storm track might be associated with a shift in the NAO toward its positive phase during the period 1980–2000 and strengthened eastward (weakened westward) component of the North Atlantic storm track [Luo *et al.*, 2015]. These changes are in line with a northward shift in the jet stream, in agreement with the stronger zonal flow over the North Atlantic in a warmer climate with an intensified and less wobbly jet stream predicted by many climate models [e.g., Barnes and Polvani, 2013]. The North Atlantic SST in the more recent 30 year period were

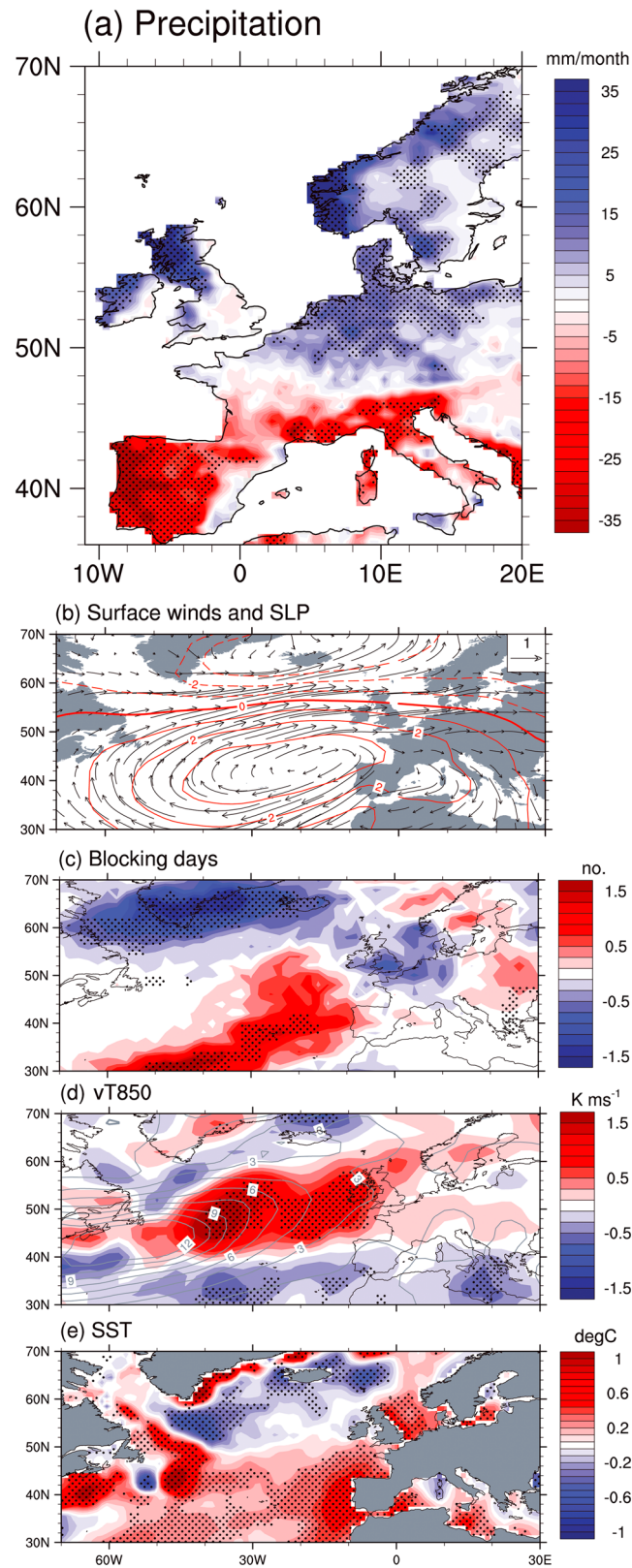


Figure 4. Difference in JFM fields for the period 1981–2010, relative to 1951–1980, for (a) precipitation (mm/month), (b) SLP (hPa; colored) and surface winds (m/s; vectors), (c) number of blocking days per season, (d) 2–6 day band-pass filtered $\langle v'T' \rangle$ at 850 hPa (K m/s; colored difference; contours long-term mean), and (e) SST (°C). Stippling denotes differences significant at the 2% significance level according to Monte Carlo testing.

characterized by warm anomalies south of 50°N, the European Seas, Labrador Sea, and along the eastern Greenland coast, while the subpolar North Atlantic 50°–70°N, 0–45°W was anomalously cold (Figure 4e). As such, the change in SST over the past 60 years reflects changes in the incidence of pattern E.

6. Summary and Conclusions

Dominant European winter precipitation patterns over the past century, along with their associated extratropical North Atlantic circulation changes, were evaluated using cluster analysis. Contrary to the four regimes traditionally identified based on wintertime daily atmospheric circulation patterns [e.g., Cassou *et al.*, 2004], five distinct precipitation regimes were detected here, because we focused on recurring wintertime seasonal mean precipitation—not daily circulation—patterns and changes in their frequency over time. Thus, some resemblance to circulation-based regimes or climate modes is likely. However, one would not necessarily expect seasonal mean precipitation patterns to be explained solely by the four dominant daily circulation regimes described by Vautard [1990] or Cassou *et al.* [2004].

Using various reanalysis products for the period 1901–2010, we assessed interannual to multidecadal variations in the frequency of these characteristic European wintertime precipitation patterns and links to accompanying changes in atmospheric blocking, moisture transport, storm track activity, and oceanic conditions. Five recurrent precipitation patterns were found, including an emergent precipitation pattern over the British Isles in recent decades. The related precipitation pattern D exhibited dry conditions for much of southern and central Europe and the British Isles. It was characterized by a strengthened meridional pressure gradient and northward displacement of the storm track, including northward displacement of ARs toward the Norwegian coast. In contrast, pattern E was associated with wet conditions over the northern British Isles driven by enhanced moisture transport and more frequent AR incidence along the west coasts of the British Isles and Norway.

Leading modes of North Atlantic climate variability, such as the NAO, Eastern Atlantic Pattern (EAP), and AMO, exert considerable impact on European winter hydroclimate across a range of time scales [e.g., Hurrell, 1995; Hurrell and Deser, 2009; Alexander *et al.*, 2014], often mediated through atmospheric circulation anomalies associated with blocking activity, storm track variability, and AR events over the North Atlantic-European sector.

As such, multidecadal variations in the frequency of occurrence of the respective precipitation regimes exhibit some consistency with low-frequency variations in leading modes of circulation variability in the North Atlantic region: Pattern D occurred unusually often (in excess of three times per decade) in the 1930s and 1940s, coinciding with a positive phase in the AMO. In contrast, it was observed only rarely (less than once per decade) in the 1980s during the negative phase of the AMO. The SST anomaly pattern associated with this cluster D is consistent with a positive phase of the AMO, indicating a warmer North Atlantic (Figure 2d). The 1960s–1980s were characterized by unusually few winters with pattern E. This coincides with anomalous low or neutral phases in the NAO index around 1960s–1970s, consistent with the spatial patterns in Figure 2. Pattern E has become more common with two to three events per decade since 1990, coinciding with a shift toward a more positive NAO post-1980 [Hurrell, 1995]. Changes in the frequency of patterns D and E thus likely reflect a combination of large-scale wintertime changes in the eddy-driven jet stream associated with the NAO and EAP [Woollings *et al.*, 2010; Woollings and Blackburn, 2012]. The results also show that subtle differences in the atmospheric circulation patterns yield relatively large differences in the precipitation distribution over the UK [Kendon and McCarthy, 2015] and in subpolar North Atlantic SST.

Considering Europe as a whole, the changes in the frequency of large-scale circulation patterns and resulting precipitation regimes are reflected in fewer winters with wet conditions in southern Europe but more in northern Europe; this is associated with a stronger storm track over the central and eastern North Atlantic toward the northern British Isles, weaker storm track activity south of 40°N, and corresponding changes in blocking activity over recent decades.

Similarly, Fleig *et al.* [2014] found changes in the frequency of dominant circulation patterns, rather than hydrothermal changes within circulation types, to contribute to wetting (drying) trends in northern (southern) Europe. These contributions were most pronounced for the JFM season and northwestern Europe. Multidecadal variations in dominant precipitation regimes, and their low-frequency modulation by North Atlantic modes of variability, such as NAO, EAP, and AMO, through effects on the large-scale circulation,

likely contributed to observed changes in wintertime hydroclimate across Europe: Wintertime precipitation across Europe has sustained considerable trends over the past century [e.g., Moberg *et al.*, 2006; Christensen *et al.*, 2013; Zolina *et al.*, 2013; Macdonald, 2014; Spinoni *et al.*, 2015], with central, western, and northern Europe having become significantly wetter, while southern Europe sustained significant drying [IPCC, 2013]. However, as subtle differences in precipitation patterns D and E shown here demonstrate, it is not sufficient to look at changes in leading circulation patterns and/or associated climate modes to spot this emergent pattern of precipitation and SST that potentially greatly affects UK wintertime precipitation [Huntingford *et al.*, 2014], especially also in light of projected increases in AR frequency by the end of the 21st century for the latitude range 45°–55°N over western Europe [Gao *et al.*, 2016].

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