Understanding Winter Windstorm Predictability over Europe

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Abstract. Winter windstorms belong to the most damaging meteorological events in the extra-tropics. Their impact on society makes it essential to understand and improve seasonal forecasts of these extreme events. Skilful predictions on a seasonal time scale have been shown in previous studies by investigating hindcasts from various forecast centres. This study aims to explain storm forecast skill based on relevant dynamical factors. Therefore, a number of factors are investigated which are known to influence either windstorms directly or their synoptic relevant systems, mid-latitude cyclones. These factors are analysed for their relation to windstorm forecast performance based on a reanalysis (ERA5) and the seasonal hindcast of the UK Met Office (GloSea5).

Within GloSea5, relevant dynamical factors are (1) validated with respect to their physical connections to windstorms, (2) investigated with respect to the seasonal forecast skill of the factors themselves, and (3) assessed on the relevance and influence of their forecast performance to windstorm forecast skill. Although not all investigated factors reveal a clear and consistent influence on windstorm forecast skill over Europe, core factors like mean-sea-level pressure gradient, sea surface temperature, equivalent potential temperature and Eady Growth Rate show consistent results within these three steps: Their physical connection is well represented in the model; these factors are skilfully predicted in storm-relevant regions, and consequently, this skill leads to increased forecast skill of winter windstorms over Europe. This study thus explains existing forecast skill in winter windstorms, but also indicates potential for further model developments to improve seasonal winter windstorm predictions.

1 Introduction

Severe winter windstorms are one of the most damaging and loss-bringing events in the extra-tropics, especially for the European region (MunichRE, 2010). Hence, it is of great scientific interest for stakeholders and the general public to understand these extreme events. This study aims to understand the near-surface windstorm, which is produced by the strongest of extra-tropical cyclones. Windstorms in this study are thus more related to the direct impacts of a cyclonic system rather than just the low-pressure systems. Leckebusch et al. (2008) developed an objective tracking algorithm for these strongest wind events. They used a threshold that intentionally relates to observed losses (Klawa and Ulbrich, 2003) and detects ca. the top 2% strongest, coherent extreme events in the extra-tropics. This objective windstorm tracking has been used for multiple different studies in the past, spanning different regions and hazards (Ng and Leckebusch, 2021; Nissen et al., 2013), individual event analysis (Donat et al., 2011b) plus climate (Donat et al., 2011a; Schuster et al., 2019) and seasonal studies (Befort et al., 2019; Renggli et al., 2011; Walz et al., 2018; Degenhardt et al., 2022).

Seasonal hindcasts have been investigated in multiple studies for different storm-relevant aspects, like the forecast skill of the North Atlantic Oscillation (NAO; Parker et al., 2019; Athanasiadis et al., 2017; Scaife et al., 2019, 2014), stratospheric conditions (Nie et al., 2019) or connections between tropical cyclones and extra-tropical storms (Angus and Leckebusch, 2020). In addition, different regions and events were investigated concerning their seasonal forecast skill (Dunstone et al., 2018; Scaife et al., 2017a). For extreme European winter windstorms, one of the first studies was published in Renggli et al. (2011) based on the DEMETER (Palmer et al., 2004) and ENSEMBLES (Weisheimer et al., 2009) pilot seasonal hindcasts. More recent studies investigated later operational systems, like the ECMWF systems (SEAS 3 and 4) and the UK Met Office's GloSea5 (Global Seasonal forecasting system version 5) (Befort et al., 2019). They found forecast skill in windstorm frequencies and a link to the large-scale pattern of the NAO. Following this, Degenhardt et al. (2022) found a strong positive and significant forecast skill for windstorm frequency and (for the first time) intensity. A connection to the three dominant large-scale patterns over Europe showed the NAO, Scandinavian Pattern and East-Atlantic Pattern together explain between 60% and 80% of interannual variability of windstorms over Europe in these seasonal hindcasts, corroborating results from Walz et al. (2018) based on century-long reanalysis data. These skilful storm forecasts found in seasonal hindcasts lead to the motivation for this study. This study aims to understand which dynamical factors drive the seasonal winter windstorm prediction skill.

Multiple studies have investigated dynamical factors influencing cyclone, storm generation and intensification in the past. The Eady Growth Rate (EGR) parameter (Eady, 1949) is used as a standard measure for baroclinic instability of the atmospheric flow which is known as a source and intensifying factor for extra-tropical cyclones (Hoskins and Valdes, 1990). Pinto et al. (2008) investigated important dynamical factors and their connection to strong cyclones over Europe for future climate change scenarios, based on previously identified contributors like EGR in the upper troposphere (Hoskins and Hodges, 2002), upper-tropospheric divergence (Ulbrich et al., 2001), the jet stream speed (Kurz, 1990; Hoskins et al., 1983; Shaw et al., 2016) and the equivalent-potential temperature (Θ_e), as another stability measure (Chang et al., 1984).

For the EGR, this study uses the same diagnostic level of 400hPa as in Pinto et al. (2008) for the upper troposphere and 700hPa (resulting from 2 available model levels) to diagnose lower troposphere baroclinicity. The location and strength of the jet stream are important for whether the end of the North Atlantic storm track reaches Europe (Parker et al., 2019). Θ_e is a parameter that describes the temperature of a fully dried air parcel dry-adiabatically lowered onto a reference level, usually 1000hPa (Bolton, 1980). It is not only a measure of the moisture content in the atmosphere and its static stability but links to the concept of the isentropic Potential Vorticity (PV; e.g. Hoskins, 2015; Hoskins et al., 1985). Thus, Raymond (1992) demonstrated that latent heat release leads to a redistribution of PV, with positive PV tendencies below the maximum heating level and negative tendencies above. It is known that the downwards propagation of an upper-tropospheric positive PV anomaly favours the strengthening of cyclones (Hoskins et al., 1985; Büeler and Pfahl, 2017). Hence, PV is connected to cyclonic systems and can indicate their strength and location over the North Atlantic. Hoskins et al. (1985) compared different isentropic levels for the PV, including 350K, which is used in this study as it is a good average representative for the synoptic scales in the troposphere. They have also connected this concept with Rossby Wave transition. Upper-tropospheric divergence is also part of the equation for the Rossby Wave Source (RWS), a measure of developing Rossby waves which potentially transmit predictability from the tropics to the extra-tropics (Beverley et al., 2019; Dunstone et al., 2018; Scaife et al., 2017b).

Other factors influencing the generation and intensification of cyclones are the general environmental conditions which are thus indirectly connected to windstorms like the sea surface temperature (SST) distribution, SST gradient and mean sea level pressure (MSLP) gradient (Shaw et al., 2016). Recently, the SST and the jet stream have been identified as drivers for storm track biases in CMIP6 data (Priestley et al., 2023). Beyond those generally well-established factors, other studies identify the important role of tropical precipitation as an indicator for European climate predictability (e.g. Scaife et al., 2017b): tropical convective precipitation triggers enhanced divergence, which again leads to the establishment of Rossby Waves trains that impact Europe. Wild et al. (2015) found a connection between European windstorm and a surface temperature anomaly difference. They used the difference of the surface temperature anomalies over North America and the SST over the western North Atlantic.

The current study investigates dynamical factors connected to windstorms in seasonal forecasts from the UK Met Office, GloSea5 (MacLachlan et al., 2015), and the respective seasonal windstorm forecast skill. This study aims for a better understanding of the origin of the seasonal forecast skill and hence confidence in real-time forecasts.

This study uses a 3-step approach to understand the role of different dynamical factors for the winter windstorm predictability over Europe.

Step 1: Validation of dynamical factors: Is the observed physical link between factors and storms well represented in the model?
Step 2: Skill of Factors: Is the dynamical factor skilfully predicted on a seasonal timescale?
Step 3: Relevance of Factors for Storm forecast skill: Is the forecast skill of windstorms related to the factor's forecast skill?

The study will first introduce the data sets used in section 2, followed by a description of applied methods in section 3. In section 4, the results are presented and structured in the above-mentioned 3-step approach. The study finishes with a discussion and conclusion presented in section 5.

2 Data

This study investigates the seasonal forecast from the UK Met Office's Global Seasonal Forecasting System version 5 (GloSea5; MacLachlan et al., 2015), in comparison to ECMWF reanalysis, ERA5 (Hersbach et al., 2019). Both data sets are used for 1993 to 2016. GloSea5 is a multi-member ensemble model with 4 initialisations per month (on the 1^{st}, 9^{th}, 17^{th} & 25^{th} of each month) and 7 members per initialisation. Currently, 3 different model versions are available, which differ in small system updates. This study investigates the northern hemisphere winter (December to February, DJF) and therefore uses initial dates

Table 1. Dynamical Factors (focused on in this paper) concerning storminess, cyclones or windstorms over Europe.

Factor	Version	Level	Parameter (ERA5/GloSea5)	Analysis Regions
Sea-Surface Temperature	Original	Surface	sea surface temperature (6h/6h)	Boxes of 10°x10° over North Atlantic
Mean Sea-Level Pressure	absolute value of gradient		mean sea level pressure (6h/6h)	
Equivalent potential Temperature Θ_e		850hPa	temperature T, specific humidity (6h/12h)	
Eady Growth Rate	original	400hPa	u-wind component, T, Geopotential (6h/12h)	

around the 1st of November (25^{th} Oct., 1^{st} and 9^{th} Nov.). This leads to 63 ensemble members for GloSea5 (3 system updates x 7 members x 3 initial dates). The seasonal model output has a spatial resolution of 0.83° longitude x 0.56° latitude. ERA5 is a commonly used reanalysis and provides observation-near data, which are used as a reference in this study. The reference data have a resolution of 0.25x0.25°. Further details of ERA5 can be found in Hersbach et al. (2019). All factors are calculated as described in the method section (including the appendix), and are summarised in Table 1 (for the focused factors and Tab. A1 in the appendix for all factors). The windstorm tracking is based on 10m wind speeds. In the case of a grid-cell by grid-cell comparison of both data sets, a re-gridding from ERA5 to the spatial resolution of GloSea5 has been done by a bilinear interpolation using Climate Data Operators (Schulzweida, 2019).

3 Method

3.1 Storm Tracking

The windstorm analysis is done via an impact-based algorithm developed by Leckebusch et al. (2008). This objective identification and tracking uses a clustered exceedance of the 98^{th} percentile of surface wind speeds. These synoptic-scale wind clusters are tracked following a nearest-neighbour approach. Only events above a minimum size and duration will be considered: a coherent wind cluster must persist for at least 48 hours and reach at least a size of 130000 km^2 (cf. details e.g., in Leckebusch et al., 2008). Consequently, an individual storm track and a grid cell-based footprint of each storm is created. This footprint is used to count the number of storms over a defined region. The target area in this study is the extended area of the British Isles (-15° to 10° E & 48° to 60° N). Recently, the authors showed significantly skilful seasonal windstorm predictions for this area (Degenhardt et al., 2022). The individual windstorm tracks are also used to calculate the track density (used in section 4.3; Kruschke, 2015).

3.2 Factors

The dynamical factors included here are selected based on their known connections to windstorms or cyclones. Factors like EGR or PV, are dynamical factors which act on a smaller and shorter scale than other tested factors but can influence the cyclone or windstorm directly. Other factors act on a larger and longer scale. These are, for example, MSLP gradient or SST, and they have a more indirect link to windstorms as they reflect the general state of atmospheric conditions. A summary of all factors and the way they are used can be found in Table A1. Individual factors are used as seasonal (3-month) averages in the following analysis.

Standard calculations have been used, e.g., the gradient of MSLP and SST, the jet characteristics (Parker et al., 2019), or the divergence at 200hPa. Other factors have been calculated following the original studies, like EGR (Eady, 1949), or PV (Hoskins et al., 1985). Rossby Wave Source (RWS) has been calculated as described in Beverley et al. (2019) and the Temperature Dipole is used from Wild et al. (2015).

Fig. A1 in the appendix is a schematic of an idealised storm-cyclone system, which highlights where the respective factors would be expected to be of relevance. The EGR (green), as one of the most important factors to strengthen cyclones, is located northeast of the storm centre (at the lowest level) and slopes towards the northwest with decreasing pressure levels. The upper tropospheric baroclinicity (EGR 400hPa) triggers respective upper-level divergence (peach) and hence, influences the jet stream (orange). The counterpart to this is the SST (coloured sea areas) which influences the low-level baroclinicity (EGR 700hPa), the MSLP gradient (light blue) and hence, the wind speed (yellow). Another process related to the potential predictability of windstorms is caused by convective tropical precipitation (dark blue) via ascent and divergence, triggering a Rossby wave train (purple) propagating into the North Atlantic region in higher altitudes.

3.3 Composite Analysis

To understand how and when these factors and the windstorm forecast quality influence each other, a composite analysis has been done by separating data sets into two different anomaly categories depending on storm frequency and factor prediction skill, respectively.

Firstly, separation is done by the number of storms, thus the seasons' overall activity (used in Fig. 1). The storm counts over the extended area of the British Isles (-15° to 10° E & 48° to 60° N) in ERA5, and each GloSea5 ensemble member is used and separated into 3 categories, the 10 strongest seasons, the 10 weakest seasons and the 3 neutral seasons (10-3-10). A separation into 10-3-10-splitting has the aim of still using data sets with at least 10 years of data to achieve representative results but also to ignore the 3 neutral seasons to reduce the noise. The separation is done individually per model ensemble member to ensure that each composite compares strong versus weak storm seasons internally. This might lead to different seasons within the sub-samples. The strong-weak-composites are presented as (member-individual) standardised composite anomalies to allow for a clear comparison between the ERA5 and GloSea5 data sets. An example categorisation for individual years can be seen in the appendix (Fig. A2) for ERA5 and GloSea5 ensemble mean windstorm counts in the UK region.

The second categorisation (used in Fig. 4) uses the forecast skill of the respective factor: well or poorly forecast years are identified using the absolute difference of the respective seasonally averaged factor over an individually defined region in the GloSea5 ensemble mean and ERA5. These categories are built for consistency according to the 10-3-10 approach again, i.e., the 10 seasons with the lowest (greatest) absolute difference between the respective ERA5- and GloSea5-factor are used as well (poorly) predicted seasons.

Both composite methods are presented as composite anomaly differences, tested for significance via a student's t-test.

3.4 Statistical metric of prediction skill

All steps include correlations using ranked τ_b-Kendall correlations (Kendall, 1945). Kendall correlation is a similar measure to the commonly used Person's correlation but investigates ranked time series and is less reliant on normally distributed data. In more detail, correlation is used in step 1: verification of individual members (section 4.1), in step 2: the skill analysis (section 4.2) for the factor individual forecast skill and in step 3: the relevance study (section 4.3) for the storm forecast skill for different data samples. Correlations are a straightforward statistic to use for either relationship between two time series or even forecast skill (e.g., Befort et al., 2019; Athanasiadis et al., 2014; Scaife et al., 2014). Kendall correlation is used because it cannot be assumed that the data are normally distributed. The same correlation method is used as in Degenhardt et al. (2022) for a better comparison, and this study builds upon their results.

4 Results

In this section, the focus will be on 4 factors, MSLP gradient, SST, Θ_e (850hPa), EGR (400hPa). The authors have selected these 4 factors (see full Tab A1) because they show coherent results throughout all investigation steps and a postulated link to windstorms forecast skill. More factors (see Table A1) have been tested within the 3-step approach, but not all the required links could be clearly identified as discussed in section 5. Additional results for five moderately performing factors can be found in the supplementary material (appendix Fig. A3-A6), EGR (700hPa), MSLP meridional gradient, precipitation, divergence (200hPa) & PV (350K).

4.1 Validation of dynamical factors in GloSea5 via anomaly composite analysis - Does the model represent the same physical connections between causal factors as the reanalysis?

Composite anomalies of the dynamical factors separated into strong and weak storm seasons in the observational and model data are compared in Fig. 1. Standardised composite anomalies for ERA5 and GloSea5 (mean over each ensemble member composite) are used to validate the connection between individual factors and windstorms in both data sets (Fig. 1). The composite anomalies between strong and weak storm seasons give a useful indication of how the factors are connected to windstorms.

It is clear that a stronger storm season is characterised by a stronger MSLP-gradient over the northern part of the North Atlantic, as expected. This pattern is coherent in observations and the model. The SST-pattern (Fig. 1c & d) shows a clear tripole

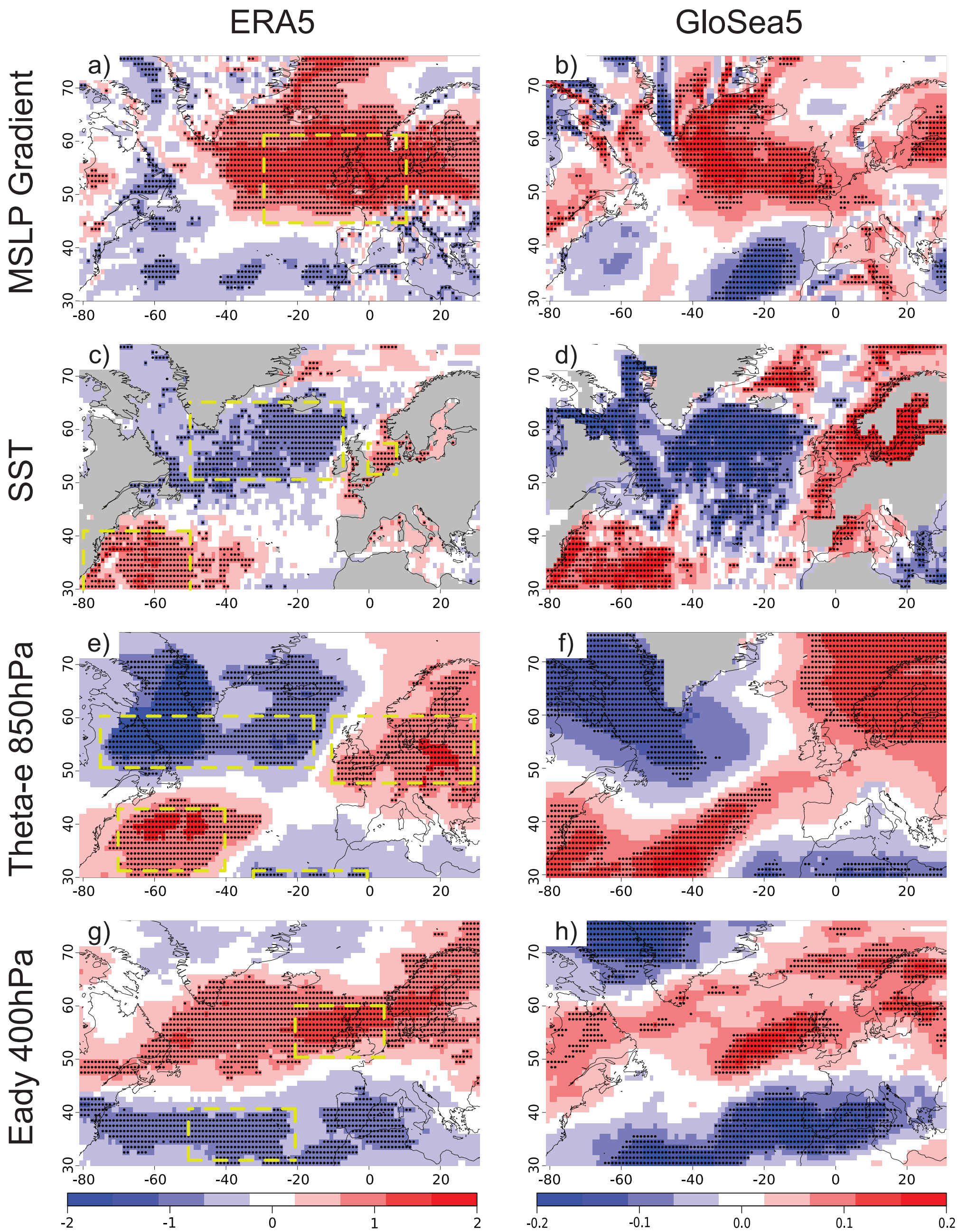

Figure 1. Composite Anomalies, standardised with respect to the climatology, of the respective factor for strong storm seasons minus weak storm seasons in ERA5 (left column) and over the mean of all GloSea5 ensemble members (right column): a) & b) MSLP gradient, c) & d) SST, e) & f) Θ_e, g) & h) EGR; dots are shown for differences significant at the 90% level (p=0.9). Yellow boxes are selected regions for investigation step 3, Fig. 4, process-based-view (right column).

(positive-negative-positive anomaly) structure over the North Atlantic in both ERA5 and GloSea5 (Fig. 1d). The GloSea5 mean signal (mean overall ensemble mean composites) is weaker but still reveals a similar pattern. The three centres of action in the SST composite of ERA5 are also reflected in the composite pattern of Θ_e. The model means of composites result in a quadrupole pattern for Θ_e but with a stronger influence of potential latent heat release over the centre of the North Atlantic than in ERA5. Also, the EGR (400hPa) shows a clear and significant pattern over the North Atlantic, with higher baroclinicity in a latitudinal band around 50° N during strong storm seasons over the UK. These factors are known to have a link with cyclones and windstorms, but the former also gets influenced by the latter. Nonetheless, the investigated windstorm systems (max. 2% of days per grid cell) influence the seasonal average factors only marginally.

The appendix includes the composites for more factors (Fig. A3) like EGR (700hPa), MSLP meridional gradient or PV (350K), which show similar results to the previous factors, with a strong and coherent increase in the factor during stronger storm seasons over the UK in ERA5 and a good representation of the pattern in GloSea5. Nevertheless, precipitation shows a north-south dipole in ERA5 upstream of the British Isles and Iberian Peninsula, which is less dominant in GloSea5, but also less relevant for windstorm forecasts. As Scaife et al. (2017b) suggest, tropical precipitation is also important for European storm forecast skill. The model has a strong signal and clear dipole around the equator, revealing shifted precipitation in the tropics in strong UK storm seasons.

Composites are categorical separations of data sets, which are useful for identifying the difference between two data subsamples. A coherent link between storms and factors is also of great interest. Hence, a correlation analysis between the factors' time series and windstorm frequency is used for additional validation (see Fig. 2). Maps are created to show the correlation link between the windstorm target region (the extended area of the British Isles) and systematic (10°x10° boxes) regions over the North Atlantic. Fig. 2 presents the four focused factors as examples, with the remainder in the appendix (Fig. A4). These results show the regions where a factor is relevant for windstorms over the extended area of the British Isles (red dotted box in each panel) and how this connection is represented in the different ensemble members (histograms). The results can be separated into two parts. First, the ERA5 connection (1^{st} row of each box) compared to the GloSea5 member mean connection (2^{nd} row of each box). All factors show that in each factor box the correlation results in the same sign in ERA5 and GloSea5 member mean. Factor regions which are further outside the storm-related area have some discrepancies, such as the MSLP gradient (Fig. 2a) or PV (Fig. A4e) region over Newfoundland or the eastern Mediterranean Sea. In these regions, GloSea5 members do not agree with the observed relation. This can be seen in the second part of this figure's interpretation, the percentile of ERA5 within the GloSea5-member distribution. For example, the region around Newfoundland of the EGR (400hPa, Fig. 2d) in ERA5-correlation is at the 100% percentile of the GloSea5-member-distribution, which means the correlation in ERA5 is outside the GloSea5 member correlation distribution and hence statistically different, as the percentile is greater 95%. Another example, the SST box over the North Sea (Fig. 2b), has an ERA5-percentile of 56%, so the GloSea5-member distribution covers the ERA5 correlation.

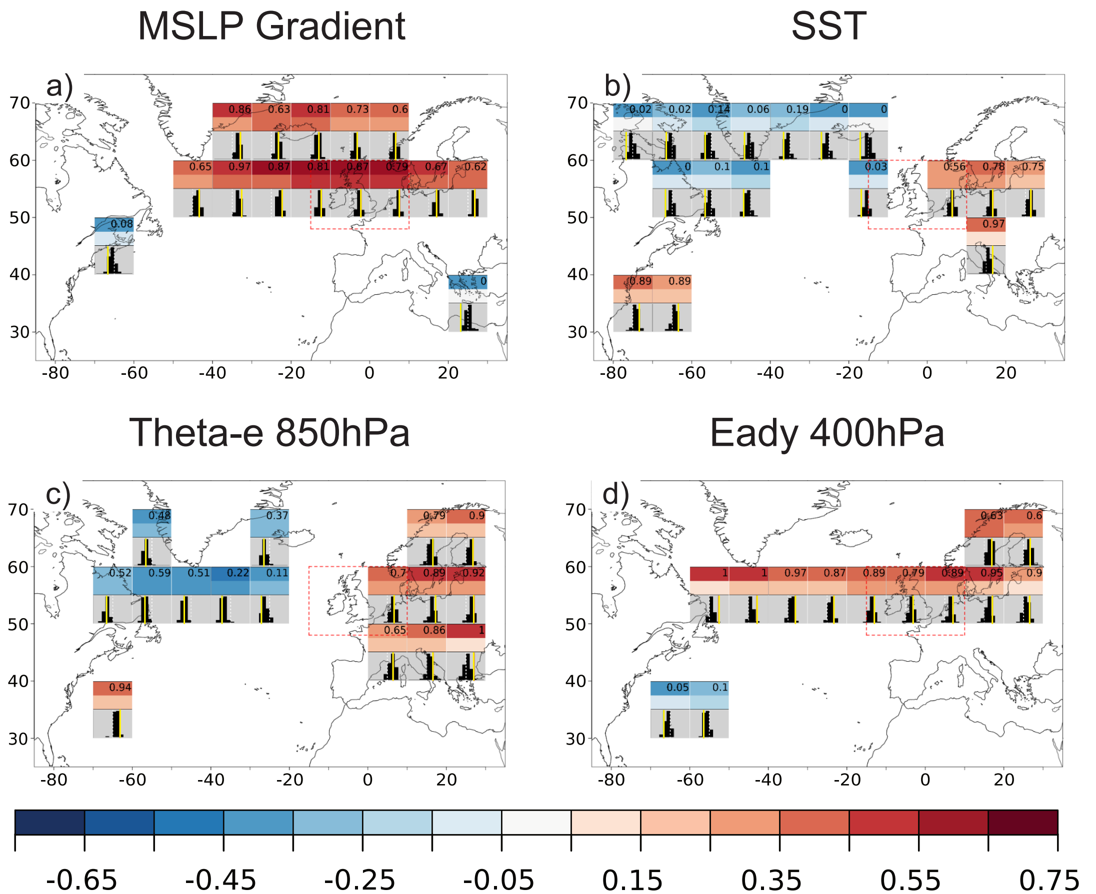

Figure 2. Correlation Maps between seasonal storm counts over the UK and dynamical factors (averaged in 10x10° regions). Only factors with a 95% significant correlation in ERA5 are shown. ERA5 connections (1^{st} row - colour), GloSea5 member connection mean (2^{nd} row - colour), GloSea5 individual member correlation distribution (histograms below). The distributions are scaled from -1 to 1 with 0 in the centre. The yellow line is the ERA5 correlation value within the GloSea5 member distribution, and the number in the 1^{st} row represents the percentile of ERA5 in that distribution.

4.2 Skill of Factors - Are the dynamical factors skilfully predicted?

The previous results suggest that relevant factors are well represented in their physical connection to windstorms. This was shown from an ensemble mean perspective (with composites, Fig. 1) but also within individual ensemble members (correlations per member, Fig. 2). Thus, the GloSea5 model represents a consistent physical development between respective factors and windstorms with a similar spatial pattern, but weaker signals. The next step tests if these factors themselves are well predicted. Thus, this step evaluates how well the model suite can forecast the necessary ingredients for storm development. The storm-relevant regions (section 4.1) should be well predicted to have a positive influence on the windstorm forecast performance. The Kendall correlation is used to assess the skill of the ensemble mean compared to ERA5. Fig. 3 shows this correlation skill

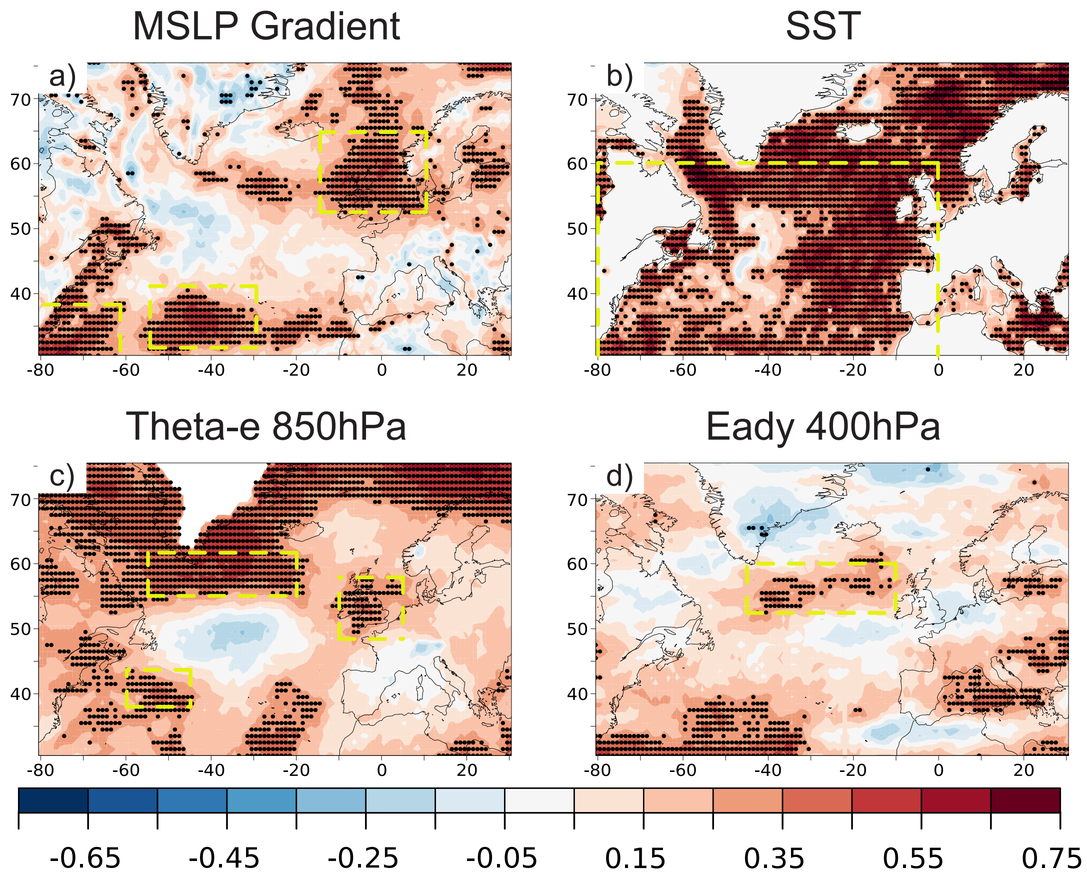

Figure 3. Kendall Correlation maps for selected dynamical factors between ERA5 and GloSea5 per grid cell, significance on 95% level marked by a dot. Yellow boxes are selected regions for investigation step 3, Fig. 4, (left column) factor-skill-view.

for the main four dynamical factors. The MSLP gradient has a skilful and coherent region of predictability over the North Atlantic and the British Isles. The SST is well predicted overall, with a small gap downstream of Newfoundland. The same gap but larger and with a stronger negative correlation is also identified for Θ_e. The EGR (400hPa) correlates significantly in the region upstream of the British Isles, northeast of the Atlantic storm track. Beyond the four main factors discussed thus far, the EGR (700hPa) reveals the same area of skill as in 400hPa (cf. appendix Fig. A5). The MSLP meridional gradient shows an extended region of skill over the North Atlantic compared to the total gradient but no coherent skill over the British Isles. Precipitation, divergence and PV at 350K show very little to no skilful prediction close to the target region, the British Isles and Europe. However, precipitation is skilfully predicted in the tropics (cf. appendix Fig. A5), which is the region Scaife et al. (2017b) suggested could be important for European predictability, as this convective precipitation would trigger Rossby Waves which propagate towards Europe.

4.3 Relevance of Factors for Storm forecast skill - Is the storm forecast skill (found by Degenhardt et al., 2022) related to the forecast skill of the factor or the regions that show a strong connection to windstorms?

The final step aims to find factors and individual regions influencing the seasonal forecast skill of windstorms. Therefore, the storm seasons have been split into two sub-samples to generate two storm forecast skills. These different storm season sub-samples are separated by two approaches, one by the factor individual forecast skill (Factor-skill-view, results from section 4.2) and one by the centre-of-action from the composite analysis (Process-based-view, results from section 4.1).

In more detail:

a) The Factor-skill-view answers the question: "Does the existing factor's forecast skill improve the windstorm forecast?" This first view focuses on the regions with already existing and significant factor skills, resulting from the approach-step-2: forecast skill (section 4.2, Fig. 3). Therefore, regions are selected that show coherent areas of skilful forecasts for the individual factors. These regions are used to define the sub-samples for calculating the storm forecast skill. This would show whether the existing factor forecast skill is a source of the existing model's windstorm forecast and might be a source of potential improvement. If this is the case, it would mean that the correct factor prediction leads to higher storm forecast skill. Thus, the storm seasons are split between well and poorly predicted factor seasons.

b) The Process-based-view focuses on the question: "Does an improved factor forecast in areas of a strong connection (centre of action) improve the windstorm forecast?" This second view uses the same method as the factor-skill-view, but with other selected regions to create the sub-samples. The regions used for this view are the ones that appeared most relevant in the connection between factor and windstorms (centre of action – section 4.1, Fig. 1). This view aims to assess whether a better prediction of the factors in these storm-relevant regions (Both views, factor-skill) would improve the seasonal windstorm forecast skill. These regions have not necessarily been selected because they are skilfully predicted in GloSea5 but because they show a physical link between storms and factors.

The differences in the respective forecast skill of the storm frequency for these two approaches are shown in Fig.4. The left column provides the differences in skill for the factor-based view, the right column the difference in forecast skill for the process-based view. The region used for separation is marked individually in each panel (see also Tab. A2 & A3). For both views, the selected regions (which can be multiple) are spatially averaged, and well- and poorly-predicted seasons are detected by the absolute difference between the resulting ERA5- and GloSea5-factor in the used regions. The regions selected are those in which the respective factor is skillfully predicted for the factor-skill-view. For the process-based view, this is not a criterion. In both approaches a red (blue) colour in the results (see Fig. 4) means, that a well-predicted factor in the marked regions leads to an increase (decrease) in seasonal windstorm forecast skill at the respective area.

Three boxes with high skill were identified from the MSLP gradient forecast skill analysis (cf. Fig. 3a). The correlation difference in Fig. 4a shows the storm forecast skill for years which are overall well predicted minus storm forecast skill for poorly predicted years within these boxes. It can be concluded that for years in which the MSLP gradient in these three regions is well predicted, these years show an increase in storm prediction skill over parts of the North Atlantic, British Isles and Scandinavia. The second view, separated by centres of action in the composite anomalies (Fig. 1a), shows a less strong increase in storm forecast skill for the selected region of MSLP gradient but still a slight increase in skill over Scandinavia. As SST was overall well predicted (Fig. 3b), the whole North Atlantic region was used to identify well and badly predicted SST-seasons for the factor-skill view (Fig. 4c). When SSTs over the North Atlantic are well predicted, the total storm prediction skill over Europe increases. The Northern European part shows that well-predicted years have a significant value on these grid cells, but the badly predicted ones do not. The process-based-view for SST uses the four centres of action defined from the composite analysis (Fig. 1c) in the North Atlantic. A good forecast in these four centres of action implies an increase in windstorm forecast skill over Europe as well, but with a weaker change and mostly only with skill over Scandinavia. The Θ_e relevance for windstorms is tested by using three regions of skilful Θ_e-forecasts (Fig. 3c). When all these three regions are well predicted, the windstorm forecast skill over Europe, especially Scandinavia and East Europe, increased (Fig. 4e). SST and Θ_e show very similar centres of action and the Θ_e process-based-view (Fig. 4f) has four similar boxes selected to SST (Fig. 4d). A possible explanation might be that higher SSTs can result in more convection, hence, more moisture in 850hPa and a higher Θ_e. A good forecast of Θ_e in these four boxes implies an overall increase in seasonal windstorm forecast over Europe. This increase in Fig. 4f is higher and covers a bigger area than the increase by well-predicted SST regions (Fig. 4d), which might be because Θ_e influences cyclonic systems directly, and SST is more a global state surrounding the cyclonic systems. The relevant signal from the factor-skill-view is not as strong for the EGR in 400hPa (Fig. 4g,h) as for the previous three factors in the respective views, but still is a well-predicted region related to an increase of storm forecast skill downstream the box and over the British Isles. As well as the factor-skill-view, the process-based-view shows less increase in windstorm forecast skill for the EGR compared to the previous three factors. The remaining factors can be found in Fig. A6, appendix. The EGR in the lower troposphere (700hPa) has two very similar boxes in both views and hence, almost the same increase in windstorm forecast skill over Europe. Factors like MSLP meridional gradient, precipitation and divergence show the skill-dependent selected regions increasing the windstorm forecast skill over Europe. The process-based-view shows increasing signals for factors like precipitation and PV 350K.

The last approach step can be summaries that both views, factor-skill view and process-based view, show an increase in windstorm forecast skill when the respective dynamical factor is well predicted. But the factor-skill view, based on regions that already have skilful factor forecasts, shows higher increases in most dynamical factors than the process-based view, which is based on the physical connection of the factors to windstorms. This means that the model gains most windstorm forecast skill from the good representation of the dynamical factors independent of their physical connection to windstorms. The latter has a weaker effect and potential for improvements.

5 Discussion and Conclusion

This study investigates the connection between atmospheric dynamical factors and the forecast performance of seasonal winter windstorm predictions. As skilful seasonal prediction for tracked windstorms was recently shown (Befort et al., 2019; Degenhardt et al., 2022; Lockwood et al., 2023), this study aimed to explain the forecast skill further. A dependency of windstorms and their forecast skill on large-scale patterns, like NAO, SCA or EA, has also previously been established (Degenhardt et al., 2022). Here, a more in-depth analysis of the mechanics of forecast skill generation is presented, and consequently, 10 dynamically important factors were selected and tested in multiple settings concerning their impact on the seasonal forecast skill of windstorm frequency (see Tab. A1). To reflect on the main contribution of those individual processes to the complex development of extra-tropical cyclones and storms, it has been differentiated between small-/short-scale or large-/long-scale factors. These factors are investigated in a 3-step approach: first, validation of the relevance of the factor to winter windstorms. Second, the forecast skill of the individual factor itself on a seasonal scale. And third, the relevance of the factor's forecast for the overall winter windstorm frequency forecast skill.

The ERA5 composite anomalies of the four focus factors, MSLP gradient, SST, Θ_e and EGR (400hPa), show a strong link between windstorms and factors. This agrees with literature, as these four factors are known to be the strongest factors for storms and cyclones (e.g., Pinto et al., 2008). The relation to windstorms for all these important factors is well simulated in the seasonal forecast suite, GloSea5. The SST shows the known horseshoe anomaly pattern (Czaja and Frankignoul, 1999) and a clear connection is identified with a positive SST and Θ_e signal over Europe (Northern Sea and Baltic Sea) leading to stronger storm seasons as stronger SSTs may enhance Θ_e, leading to more baroclinic instability in the lower troposphere. The lower tropospheric EGR (700hPa) agrees with this concept in ERA5, as the stronger EGR (700hPa) reaches over the North Atlantic to central Europe although it is more limited in GloSea5. Similarly, the SST composites in GloSea5 show three centres of action (positive - east of America, negative – south of Iceland and positive – North Sea), but a more extended negative SST composite anomaly in GloSea5 further south over the North Atlantic is in line with the recently found SST bias south of Greenland in CMIP6 models causing a bias in cyclone tracks (Priestley et al., 2023). The Θ_e composite anomalies of GloSea5 show a slightly different pattern over the North Atlantic, with a more extended positive signal than in ERA5, reaching from southwest to northeast. This is in line with the results from the factor precipitation, where in GloSea5, the North Atlantic precipitation is simulated further west. Studies like Fink et al. (2009) and Pinto et al. (2008) investigated storms from a Lagrangian perspective, but some of their characteristics can also be seen in the here presented Eulerian view. The dry pole in the northwest Atlantic is in line with Fink et al. (2009), and shows the general atmospheric state around an extreme cyclone with dry air behind. The composites of EGR (400hPa) in ERA5 and GloSea5 show a strong link to EGR just upstream of the target area (extended region of British Isles). The pattern in GloSea5 is in line with the knowledge that the EGR affects strong cyclones in a west-east band through their centre (Pinto et al., 2008) and the cyclone centre is located north of the windstorm field (cf. Leckebusch et al., 2008), which explains the strong EGR influence north of the North Atlantic storm track.

The physical connections between windstorms and individual factors within the model data mostly agree with the observed connections. These connections may enhance model forecast performances when the individual factors are well forecast in storm-relevant regions. The individual forecast skills of these factors show high and significant skill in windstorm-relevant regions over the North Atlantic but also have gaps. The forecast skill of the upper tropospheric EGR is significant at the northeastern end of the Atlantic storm track, an important area for intensifying strong cyclones before landfall in Europe. Even the forecast skill of the MSLP gradient, SST and Θ_e show significant skill around the British Isles, but the area around 50° N and 40° to 50° W is a gap for these factors. This reduction in forecast skill may link to previous studies, e.g. Scaife et al. (2011); Athanasiadis et al. (2022), which identify large SST biases in model data.

After the factors have been verified as having the same physical link in observations and models and the model shows forecast skill for important regions of the factor, the third step is connecting the factor performance to windstorm forecast skill. It has been found that all major factors increase the forecast skill of winter windstorms over the British Isles and the North Sea by increasing the forecast skill of relevant factors in storm-relevant regions. SST and Θ_e additionally improve the windstorm forecast skill over Central Europe and Southern Scandinavia. The process-based-view, sub-sampling based on the centre of action from the composite analysis (step 1), is less conclusive. But the factors SST and Θ_e present four centres of action, helping to increase the windstorm prediction over Europe when these regions are well predicted.

The overall conclusion from this three-step approach leads to a well-represented connection between the four focused dynamical factors and winter windstorm forecast skill. All four factors (MSLP gradient, SST, Θ_e & EGR 400hPa) show an agreement in the physical link, via composite analysis and in the stricter correlation maps, suggesting the model does include the overall physical link correctly. The model provides positive forecast skill within relevant regions for all four factors, which means the model performance for the individual factor is positive. The final investigation step shows that well-predicted seasons of the factors in the relevant regions support skilful windstorm forecasts.

In addition, the further investigated factors (cf. appendix) show similar results. Well-predicted regions of precipitation and divergence over the tropics and sub-tropics have a positive influence on storm predictability over Europe. For precipitation, this is in line with Scaife et al. (2017b), who found that tropical Atlantic precipitation is an influencing factor for European predictability of atmospheric patterns. Further crucial factors (not shown) in this study were, e.g., the Rossby Wave Source (RWS), SST gradient (total and meridional component) or the North-America/North-Atlantic temperature gradient identified by Wild et al. (2015). The RWS factor did not show a clear pattern or relation. The ERA5 composite is very scattered, but the GloSea5 mean shows at least a pattern agreeing with the conceptional idea of the tropical North Atlantic precipitation triggering convective rising, which triggers the RWS further North (Scaife et al., 2017b). A similar scattered result is seen from all analysis steps for the SST gradients. The temperature dipole from Wild et al. (2015) has been tested, as a connection between North American surface temperature and North Atlantic sea surface temperature anomalies are linked to windstorms over Europe. But the results in this study were not conclusive, probably because the storm target region differs in both studies.

This study concludes that the existing windstorm forecast skill in GloSea5 can be explained by different dynamical atmospheric factors connected to cyclones and windstorms. Thus, the model predicts the winter storm season well for what appear to be the correct reasons, increasing forecast confidence. Large-scale factors like the MSLP gradient or SST strongly relate to windstorms in both the observational and model data sets. Their seasonal forecast skill is high in storm relevant regions, and seasons which are well predicted have a positive influence on windstorm forecasts. The same is found for factors like Θ_e in 850hPa and EGR in the upper troposphere. This approach results in a new understanding of dynamical factors and covers multiple perspectives, which implies new knowledge about where the windstorm forecast skill might originate. This also reveals areas for additional effort needed to potentially improve windstorm forecast skill over the downstream end of the North-Atlantic storm track, and to tackle the signal-to-noise paradox, which is shown to affect storminess in Degenhardt et al. (2022). The signal-to-noise paradox is a known limitation for seasonal predictions skill which may also limit windstorm forecast skill and its influencing factors.

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Appendix A

This part of the appendix includes additional information about the method and calculation for the dynamical factors, hence for section 3.2.

MSLP and SST represent more general information about environmental conditions. Their respective gradients are calculated using the NCL (NCAR Command Language) implemented function (grad_latlon_cfd) and computed the absolute value of the gradient vectors. The Climate Data Operator (CDO; Schulzweida, 2019) has an implemented function (uv2dv) to calculate the respective wind divergence from both wind components (u & v). For calculating the Rossby Wave Source (RWS), the python package windspharm (Dawson, 2016) was used as an example script from GitHub. This script is based on the RWS equation used, e.g., by Beverley et al. (2019); Dunstone et al. (2018). Studies like Parker et al. (2019) investigated the jet stream on its seasonal predictability and connection to the NAO. This study follows their calculation of jet location and speed but for 200hPa rather than 850hPa. The jet is defined over a 9-day running mean of the zonal average of the wind; both only the u-component and the total wind were tested. The jet location is defined here as the latitude at which the maximum wind (respectively u or total wind) is found, and as jet speed, the respective wind is used. An investigation from Wild et al. (2015) analysed how temperature anomalies over North America and the North Atlantic can influence the winter windstorm season over Europe. They created a Temperature-Dipole index which uses surface temperature at two regions, one over North America (105° - 80° W, 38° - 55° N) and one over the western North Atlantic (85° - 50° W, 15° - 35° N). The difference in the respective anomalies creates the so-called temperature index. The PV (Hoskins, 2015; Hoskins et al., 1985) is calculated using two implemented NCL-functions (pot_vort_isobaric & int2p_n_Wrap). Therefore first, the pressure level data are used to calculate PV on pressure levels, and second, these values are interpolated onto $Theta$ levels. The 350K level is later used in this study. The PV Advection is calculated from the pressure-level data and then advected by both (u & v) wind components. Θ_e as an individual factor on 850hPa (Chang et al., 1984), is calculated with the NCL-function, pot_temp_equiv. The Eady Growth Rate (EGR) is calculated with an implemented NCL function (eady_growth_rate) which uses the 2-layer approach. This means whenever it is referred to the EGR at 400hPa, it is calculated using data from 300hPa and 500hPa, and for the EGR at $\sim$700hPa, it is 500 & 850hPa. PV and EGR are additionally analysed in this study after post-processing with a bandpass filter. This bandpass filter was run with an R-implemented function using the Butterworth filter (Butterworth, 1930), with filter characteristics of 2 to 8 days for PV and 2 to 4 days for EGR. The filter was performed for each GloSea5 member individually. Because of data storage and

Table A1. Dynamical Factors (all tested for this study) concerning storminess, cyclones or windstorms over Europe.

Factor	Version	Level	Parameter (ERA5/GloSea5)	Analysis Regions
Temperature Dipole index		Surface	sea surface temperature (6h/6h)	North America (105°-80° W, 38°-55° N) North Atlantic (85°-50° W, 15°-35° N)
Sea-Surface Temperature	Original			Boxes of 10°x10° over North Atlantic
	Gradient			
	meridional Gradient			
Mean Sea-Level Pressure	Gradient		mean sea level pressure (6h/6h)	
	Meridional Gradient			
Total precipitation	mean		total precipitation (1h/daily)	
	Only December mean			
Jet	Location	200hPa	u- & v-wind component (6h/12h)	60°-0° W, 30°-75° N
	Speed			
Potential Vorticity	original	350K	u- & v-wind component, temperature T (6h/12h)	Boxes of 10°x10° over North Atlantic
	Bandpass 2-8d			
	Advection	400hPa		
Equivalent potential Temperature Θ_e		850hPa		
Eady Growth Rate	original	400hPa	u, T, Geopotential (6h/12h)	
	3d variability			
	Bandpass 2-4d			
	original	700hPa		
Divergence		200hPa	u- & v-wind component (6h/12h)	
Rossby Wave Source				

computational times, the filtering was only executed for a region -100° to 40° E and 30° to 75° N. The total precipitation is used as in Scaife et al. (2017b) to investigate the link between tropical precipitation and the predictability of European climate conditions, like geopotential height. To be not restricted to the four used tropical regions used in Scaife et al. (2017b) and for a better comparison to the other used factors, the seasonal precipitation mean is investigated on the grid-cell level.

This part of the appendix includes the results for the remaining tested dynamical factors. Therefore, it belongs to the Result section 4.

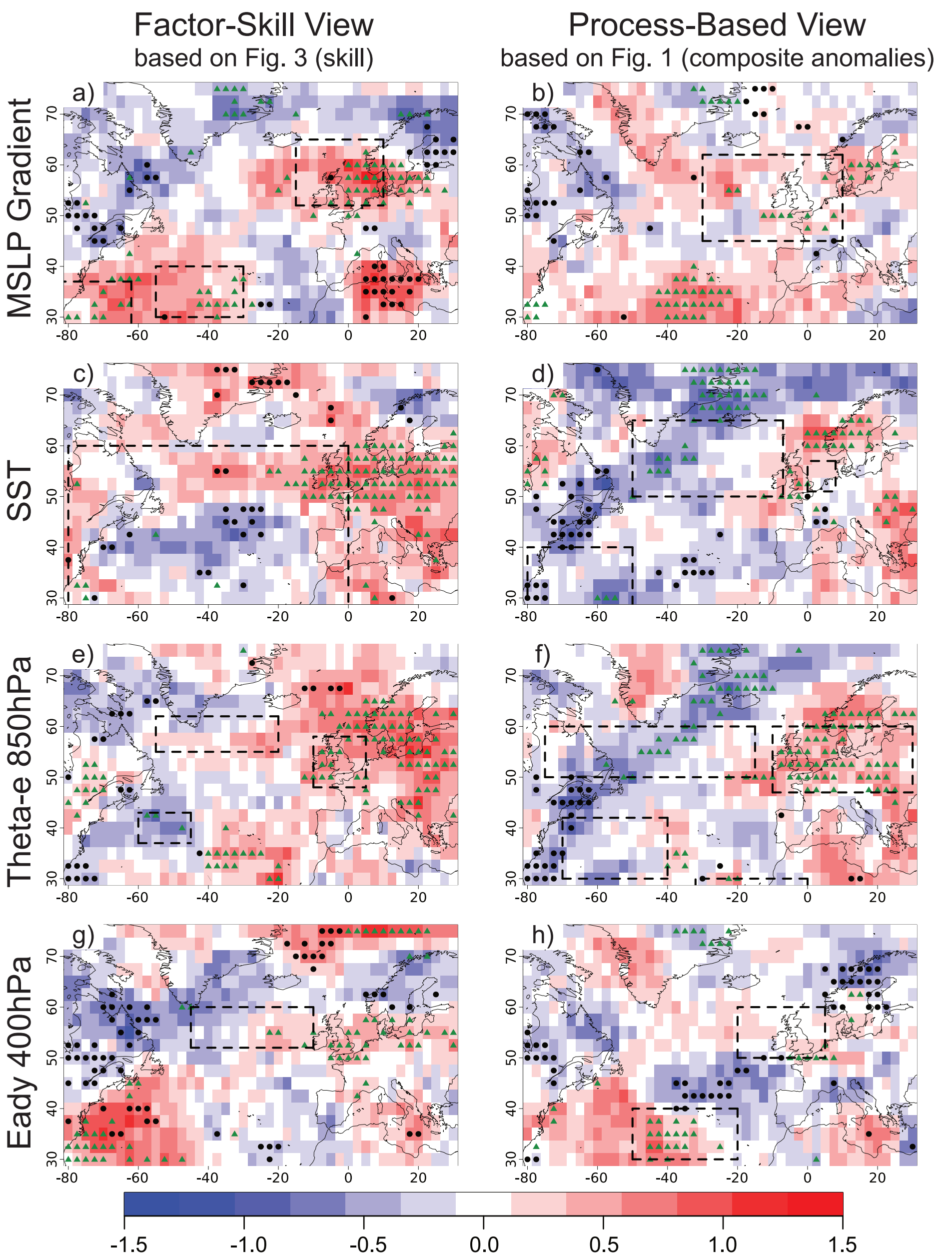

Figure 4. Difference of windstorm forecast skill (as Kendall correlation between ERA5 and GloSea5 windstorm frequency) with seasonal separation by the Factor-skill-view (left column, based on Fig. 3) and the Process-based-view (right column, based on Fig. 1). The data set is individually per factor separated into well and badly predicted seasons, depending on the individually selected boxes. The Kendall correlation is calculated for each sub-samples and shown here is the difference between them (well predicted minus badly predicted). Black dots indicate grid cells with significant storm forecast skill in the factor-badly predicted seasons, while green triangles indicate significant forecast skill in the factor-well predicted seasons.

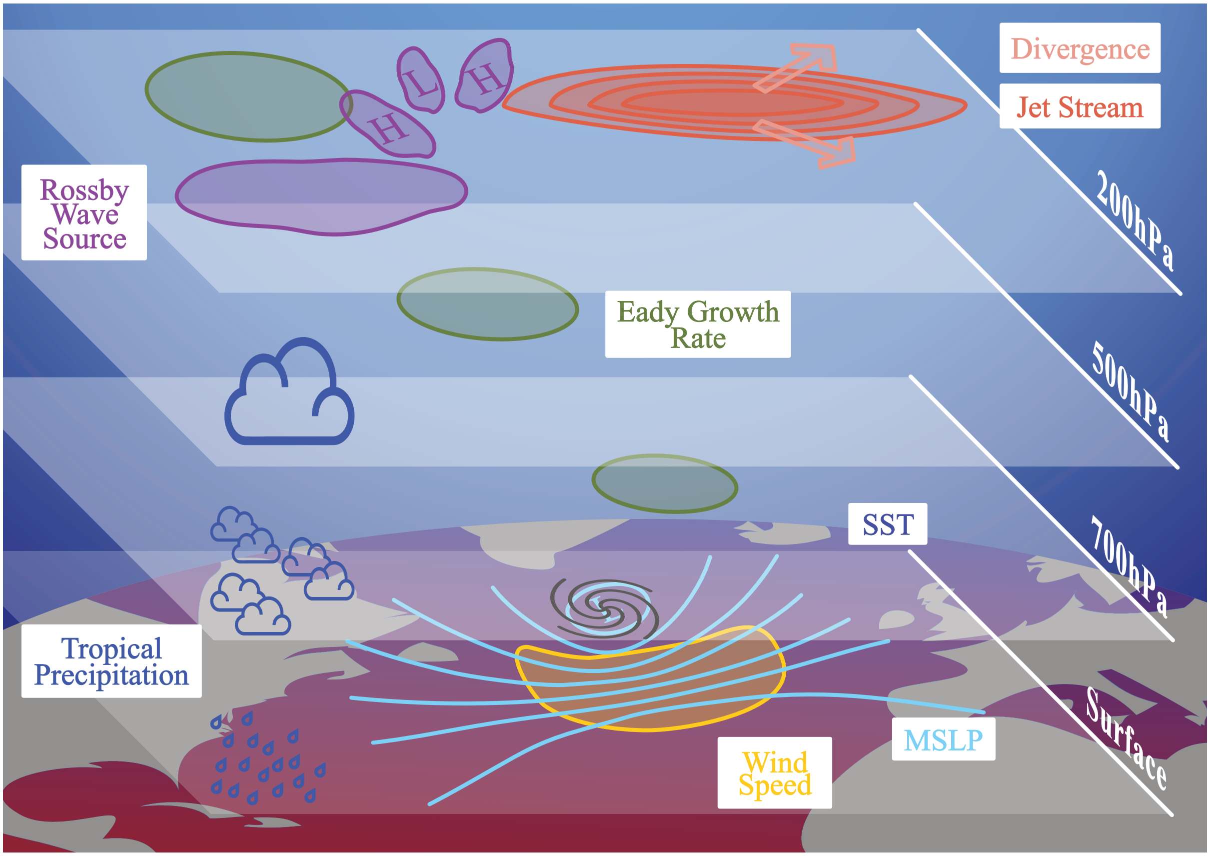

Figure A1. Schematic map of the spatial location of factors compared to an idealised storm system.

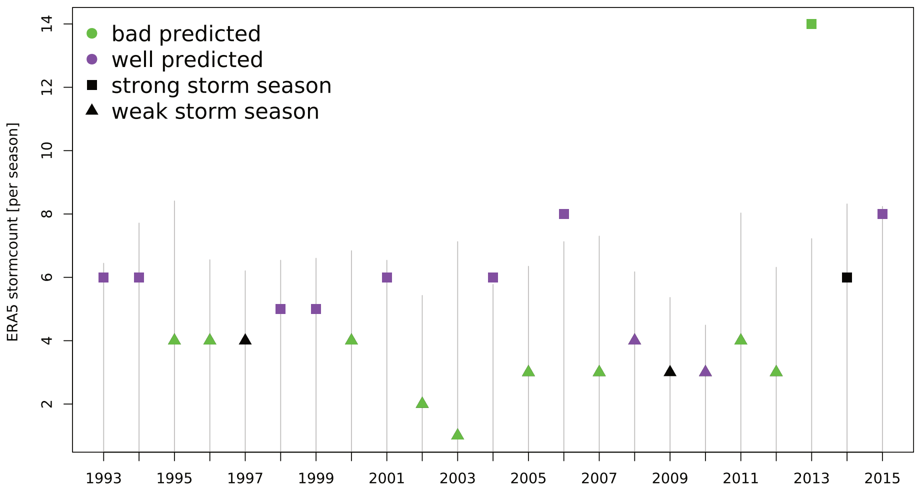

Figure A2. ERA5 UK storm counts as dots, and GloSea5 ensemble mean counts as bars. Badly predicted seasons (green), well predicted seasons (purple), weak ERA5 seasons (triangles) and strong ERA5 seasons (squares).

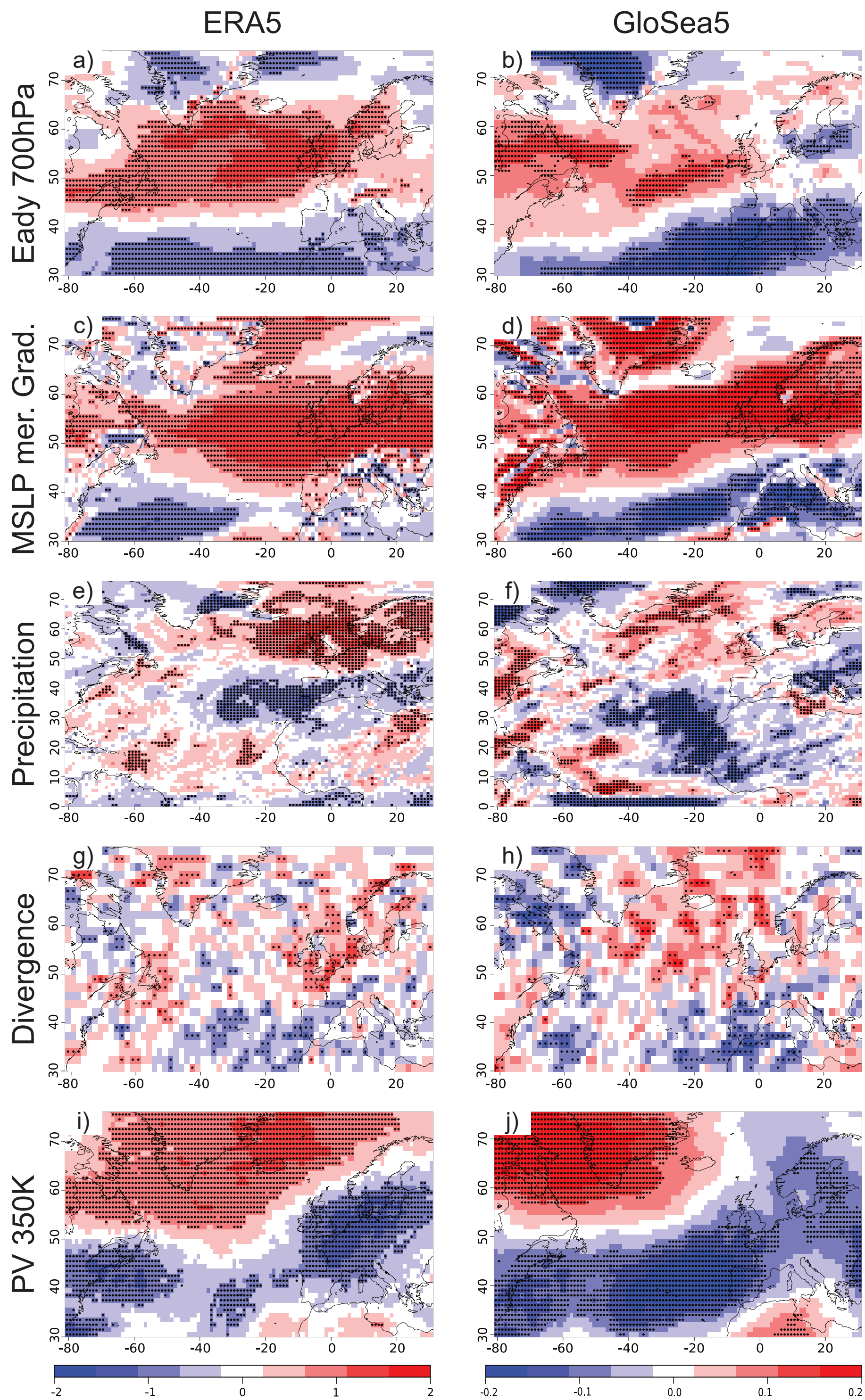

Figure A3. As Fig. 1 for remaining factors.

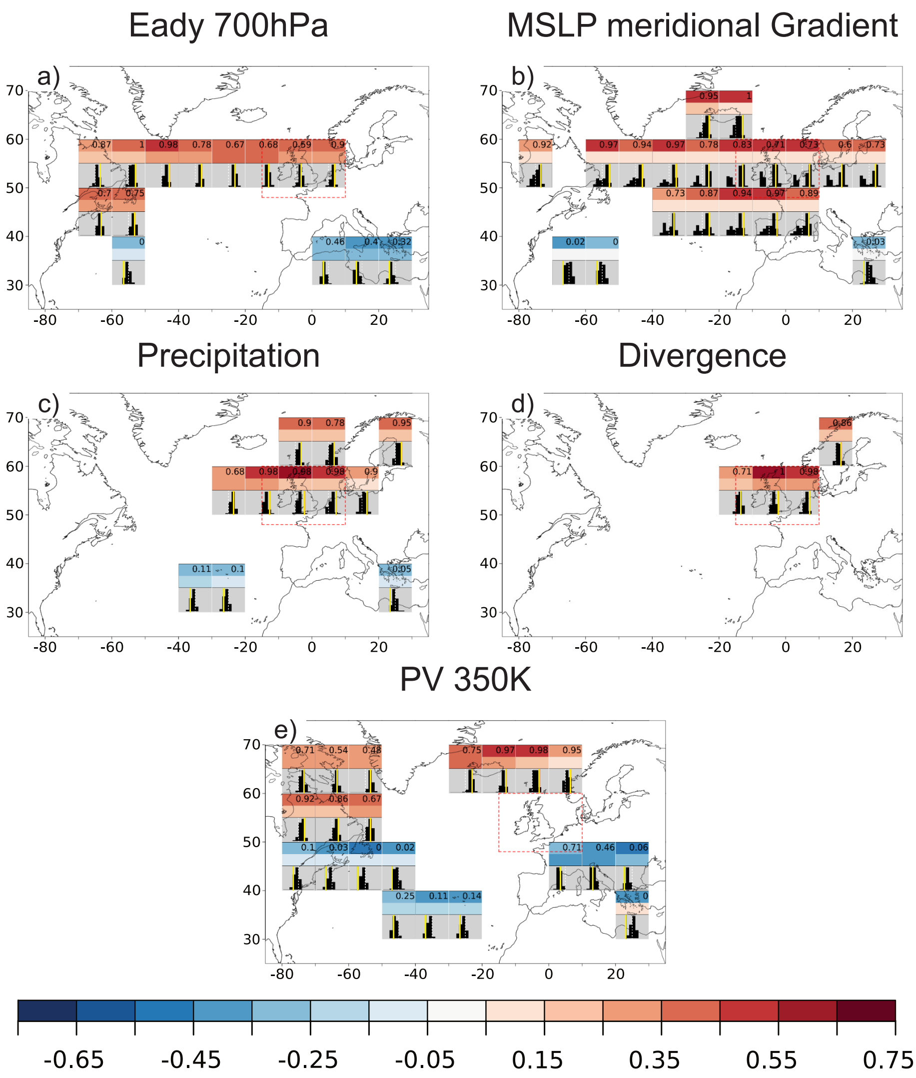

Figure A4. As Fig. 2 for remaining factors.

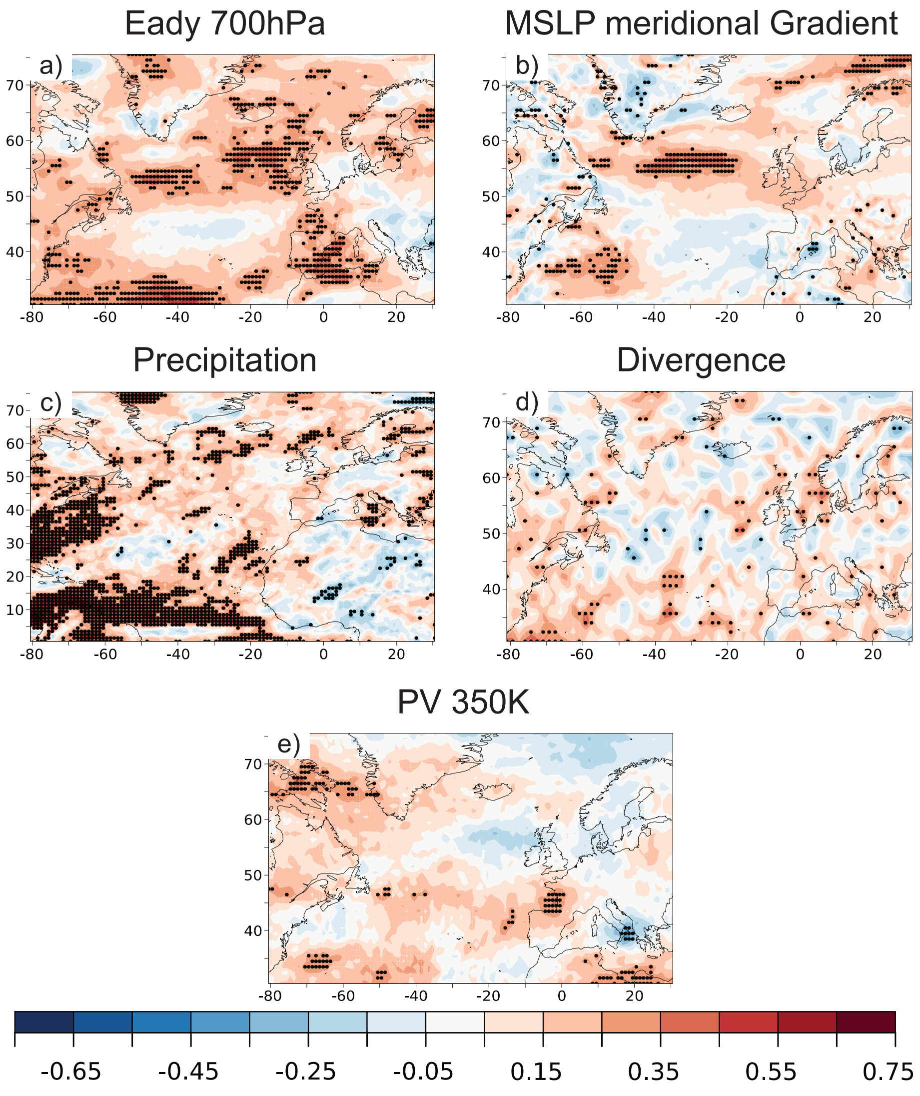

Figure A5. As Fig. 3 for remaining factors.

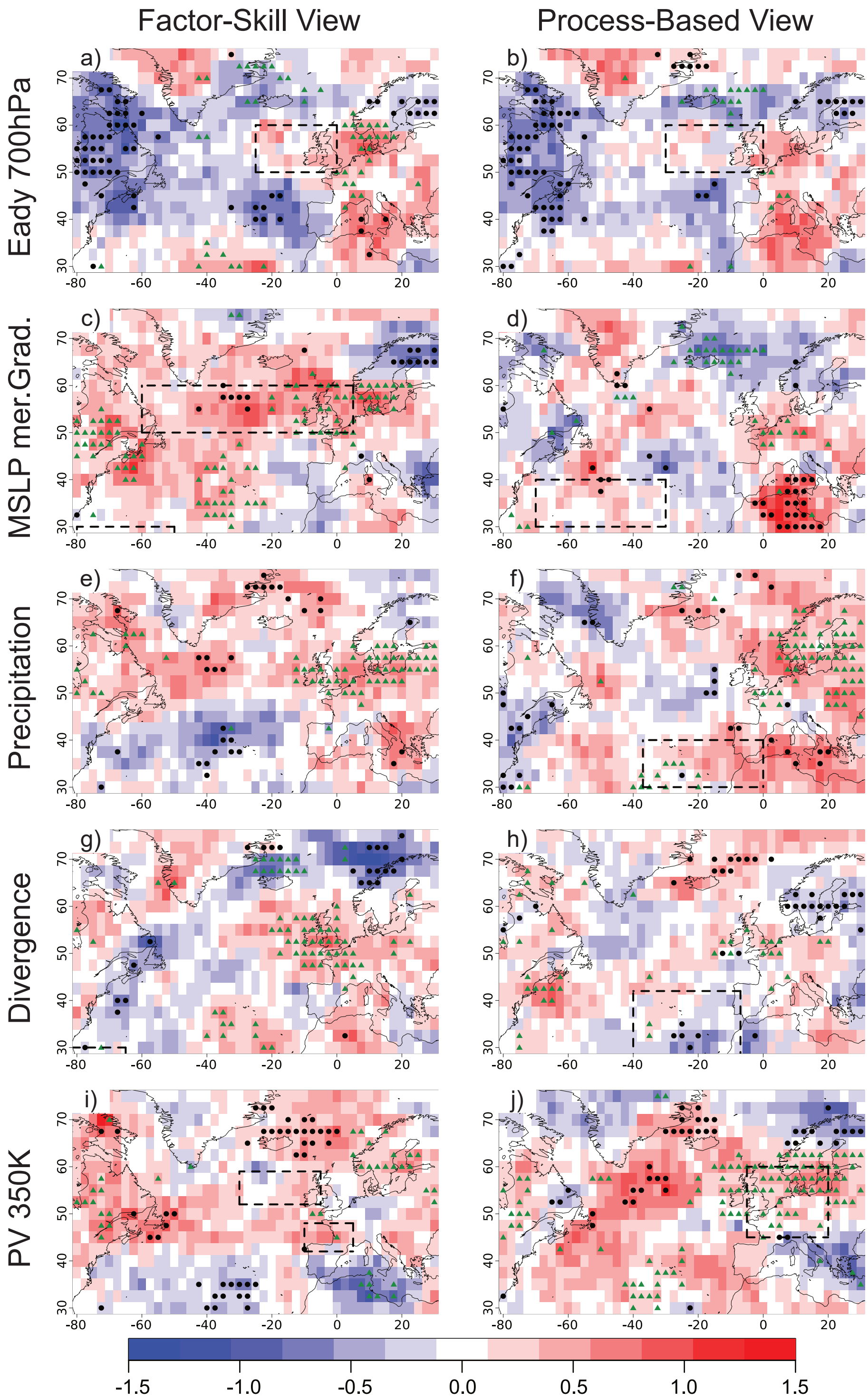

Figure A6. As Fig. 4 for remaining factors.

Table A2. Skilful regions of factor forecast skill used for factor-skill view in Fig. 4.

Factor	Box 1	Box 2	Box 3	Boxmean
Mean Sea-Level Pressure Gradient	-15° - 10° E 52° - 65° N	-55° - -30° E 30° - 40° N	-85° - -62° E 27° - 37° N	Box 1-3
Sea-Surface Temperature	-35° - -5° E 40° - 64° N	-80° - -45° E 20° - 35° N	-80° - 0° E 10° - 60° N	Box 1&2
Equivalent Potential Temperature Θ_e	-10° - 5° E 48° - 58° N	-60° - -45° E 37° - 43° N	-55° - -20° E 55° - 62° N	Box 1-3
Eady Growth Rate 400hPa	-45° - -10° E 52° - 60° N			
Eady Growth Rate 700hPa	-25° - 0° E 50° - 60° N			
Mean Sea-Level Pressure Meridional Gradient	-60° - 5° E 50° - 60° N	-80° - -50° E 10° - 30° N		Box 1&2
Total Precipitation	-85° - -15° E 5° - 20° N	-90° - -55° E 20° - 45° N		Box 1&2
Divergence	-90° - -65° E 20° - 30° N			
Potential Vorticity 350K	-30° - -5° E 52° - 59° N	-10° - 5° E 42° - 48° N	-30° - -10° E 12° - 24° N	Box 1-3

Table A3. Relevant regions of ERA5 & GloSea5 for the process-based view in Fig. 4.

Factor	Box 1	Box 2	Box 3	Box 4	Boxmean
Mean Sea-Level Pressure Gradient	-40° - 0° E 30° - 40° N	-30° - 10° E 45° - 62° N	-40° - 0° E 15° - 30° N		Box 1-3
Sea-Surface Temperature	-80° - -50° E 27° - 40° N	-50° - -7° E 50° - 65° N	0° - 8° E 51° - 57° N	-20° - -10° E 21° - 27° N	Box 1-4
Equivalent Potential Temperature Θ_e	-70° - -40° E 30° - 42° N	-32° - 0° E 25° - 30° N	-10° - 30° E 47° - 60° N	-75° - -15° E 50° - 60° N	Box 1-4
Eady Growth Rate 400hPa	-50° - -20° E 30° - 40° N	-20° - 5° E 50° - 60° N			Box 1&2
Eady Growth Rate 700hPa	-70° - 10° E 25° - 35° N	-30° - 0° E 50° - 60° N			Box 1&2
Mean Sea-Level Pressure Meridional Gradient	-70° - -30° E 30° - 40° N	-30° - 10° E 45° - 57° N	-40° - 0° E 15° - 30° N		Box 1-3
Total Precipitation	-37° - 0° E 30° - 40° N	-25° - 10° E 50° - 62° N			Box 1&2
Divergence	-40° - -7° E 42° - 27° N	-15° - 7° E 45° - 63° N			Box 1&2
Potential Vorticity 350K	-5° - 20° E 45° - 60° N	-80° - -52° E 15° - 23° N			Box 1&2