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Key Points:
- The stratosphere plays a key role for severe winter storm frequency prediction
- The benefit of correctly predicting the stratosphere is highest between Greenland and Europe
- The tropics are important for both stratosphere and winter storm prediction

Supporting Information:
- Supporting Information S1

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Factors Influencing the Seasonal Predictability of Northern Hemisphere Severe Winter Storms

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Abstract We investigate the role of the tropics, the stratosphere, and atmosphere-ocean coupling for seasonal forecasts of strong, potentially damaging, Northern Hemisphere extratropical winter wind storm frequencies. This is done by means of relaxation experiments with the European Centre for Medium-Range Weather Forecasts model, which allow us to prescribe perfect forecasts for specific parts of the coupled atmosphere-ocean system. We find that perfect predictions of the Northern Hemisphere stratosphere significantly enhance winter storm predictive skill between eastern Greenland and Northern Europe. Correct seasonal predictions of the occurrence of stratospheric sudden warmings play a decisive role. The importance of correctly predicting the tropics and of two-way atmosphere-ocean coupling, both for forecasting stratospheric sudden warming risk and, correspondingly, severe winter storm frequency, is noted.

Plain Language Summary Wind storms rank among the most expensive types of natural hazards in the Northern Hemisphere (NH) during winter and can yield severe damage and heavy loss in both Europe and North America. Therefore, predictions of these events well in advance are of large interest to a number of societal, economic, and scientific sectors. We investigate the factors that potentially influence winter storm frequency, namely, sea surface temperature anomalies in the tropics, and conditions in the NH stratosphere. We find that correct seasonal predictions of the NH stratosphere significantly improve winter storm seasonal predictions between eastern Greenland and Northern Europe. Correct seasonal predictions of the occurrence of extreme events in the stratosphere, so-called stratospheric sudden warmings, play a decisive role. We further note the importance of correctly predicting the tropics and of two-way atmosphere-ocean coupling, both for forecasting stratospheric sudden warming risk and, correspondingly, severe winter storm frequency.

1. Introduction

Wind storms associated with intense synoptic-scale extratropical cyclones rank among the most expensive types of natural hazards in the Northern Hemisphere (NH) during the winter season. In particular, the strong winds these extreme events are associated with, and the accompanying heavy precipitation, can yield severe damage and heavy loss in both the North Atlantic/Europe (NAE) region (Munich Re Group, 2008) and North America (Munich Re Group, 2013). Surprisingly, the topic of predictability of winter wind storms has been addressed in only a limited number of studies, even though it is of large interest to a number of societal, economic, and scientific sectors. In this study we assess the sources of predictability of NH winter wind storm frequency on a seasonal time scale. We specifically focus on the potentially damaging events by means of an objective tracking algorithm explicitly designed for this purpose.

Some of the interannual variability of winter wind storm frequency over the NAE region is associated with the North Atlantic Oscillation (NAO) whereby the positive NAO phase, associated with below normal sea level pressure (SLP) anomalies centered near Iceland and above normal SLP anomalies centered over the Azores, favors a stronger westerly jet stream in the northern North Atlantic (NA) and an associated higher number of wind storms over Northern Europe (e.g., Deser et al., 2000; Donat et al., 2010; Hurrell & Deser, 2010; Pinto et al., 2009). However, Donat et al. (2010) showed that the relation between the NAO and the wind storm climate over the NA is not linear and that 30–40% of gale days in Europe occur during the negative or neutral phase of the NAO. This suggests already that the seasonal prediction of winter wind storm frequency in the NAE

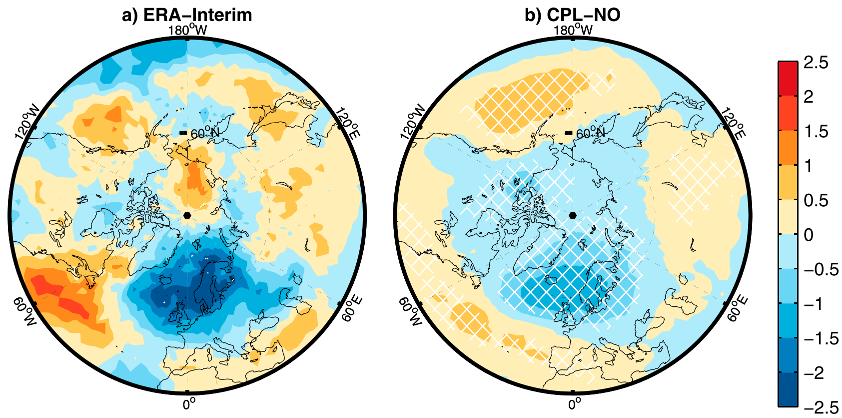

Figure 1. Average severe winter (December–February) storm frequency anomaly of (a) winters with stratospheric sudden warming occurrence in ERA-Interim and (b) CPL-NO ensemble members which capture an observed major stratospheric sudden warming correctly. Contour interval is 0.5 storms per winter; hatching indicates 95% statistical significance (note that the ERA-Interim anomalies in (a) show almost no significance).

region is more demanding than simply the seasonal prediction of the NAO, as recently shown by Befort et al. (2018). Likewise, Renggli et al. (2011) find comparatively high skill for winter storm frequency over Europe in a multimodel seasonal hindcast ensemble of the DEMETER (Palmer et al., 2004) project, while Johansson (2007) and Müller et al. (2005) show only small (although significant) NAO skill in the same ensemble forecast. On the other hand, the UK Met Office GloSea5 hindcasts analyzed in Scaife et al. (2014) give a slightly better prediction of winter storminess over Europe based on the predicted NAO than the direct prediction of winter storminess using the model.

A successful forecast of NH winter storm frequency, and confidence in such a prediction, depends on knowledge of the factors that influence its variability. Mentioned in this context are, for example, sea surface temperature (SST) anomalies in the NA (Renggli et al., 2011) and the tropical Pacific, in particular, in association with the El Niño–Southern Oscillation (e.g., Ineson & Scaife, 2009). Another source of predictability could be the NH stratosphere, notably the state of the stratospheric polar vortex and the occurrence of extreme events, so-called major stratospheric sudden warmings (SSWs). The signatures of SSWs can descend down to the troposphere with the resulting surface pattern projecting onto the negative phase of the NAO and hence affecting surface weather and climate (Kidston et al., 2015). The winter storm frequency anomalies that occur together with major SSWs in ERA-Interim reanalyses (Dee et al., 2011; composite in Figure 1a) and one ensemble experiment analyzed in this study, which is comparable to an operational seasonal forecast (Figure 1b; see section 2 for the details) reveal a pronounced region between Greenland and Scandinavia that is significantly affected in such a way that a lower number of severe winter storms can be expected in winters that contain an SSW. Likewise, more potentially damaging storms are predicted for the same region when no SSW occurs in the stratosphere (not shown).

In this article, we investigate the role of the tropics and the NH stratosphere for seasonal predictions of NH winter wind storms. To do this, we analyze seasonal forecast experiments performed with the European Centre for Medium-Range Weather Forecasts (ECMWF) seasonal forecast model where a relaxation technique has been applied in such a way that different parts of the atmosphere, namely, the tropics or the NH stratosphere, are relaxed toward reanalysis data. This technique allows us to obtain "perfect forecasts" for the relaxed regions and investigate their respective effects on the predictability of winter storms. By comparing atmosphere-only with coupled atmosphere-ocean model experiments, we further explore the importance of atmosphere-ocean coupling.

2. Data and Methods

2.1. Model and Relaxation Experiments

Nine different experiments are analyzed in this study, which have all been performed with the ECMWF seasonal forecast model and of which seven have been used and described in detail in Hansen et al. (2017). The atmospheric ECMWF Integrated Forecast System is run in its cycle CY40R1 at spectral truncation T255 with 60 levels in the vertical, extending up to 0.01 hPa, meaning that the same horizontal and vertical resolution are

Table 1
Overview of Relaxation Experiments

	SST/SI		
Relaxation	NEMO	Observed	Climatological
None	CPL-NO 1981–2012 51 members	OBS-NO	CLIM-NO
Tropical	CPL-TROPICS 1981–2013 28 members	OBS-TROPICS	CLIM-TROPICS
Stratospheric	CPL-STRAT CY41R1	OBS-STRAT	CLIM-STRAT

Note. If not otherwise stated in the table, the experiments are performed with model cycle CY40R1 for the period 1979–2013 with nine ensemble members each.

used here as for ERA-Interim. In three experiments, the Integrated Forecast System is coupled to the NEMO ocean model run at 1° horizontal resolution with higher resolution near the equator. All experiments were designed as seasonal forecasts initialized around the beginning of November during the ERA-Interim period (1979–2013) and run until the end of February. For each experiment an ensemble of at least nine members was created as described in Greatbatch et al. (2012) and Hansen et al. (2017) for the atmosphere-only experiments and in Watson et al. (2016) for the coupled experiments.

The set of nine experiments uses different combinations of lower boundary conditions and relaxation regions; an overview is provided in Table 1. Three experiments are forced globally with daily observed SST and sea ice (SST/SI; indicated by "OBS" being the first part of the experiment name; see Table 1), three experiments use daily climatological (1979–2014) SST/SI ("CLIM") and another three the fully coupled model version ("CPL"). Three experiments do not use any relaxation in the atmospheric model component (indicated by "–NO" being the last part of the experiment name), in another three the whole depth of the atmosphere in the Tropics between 20°S and 20°N is relaxed toward ERA-Interim ("–TROPICS"), and a third type of relaxation is applied in the NH stratosphere north of 20°N and roughly above 100 hPa ("-STRAT"). The latitudes indicate the centers of 20° wide transition zones, where the relaxation coefficient is changing from zero to full relaxation. More details, discussion and application of the relaxation technique are given, for example, in Hansen et al. (2017), Hoskins et al. (2012), Jung et al. (2010, 2011), Greatbatch et al. (2012, 2015).

The performance of probabilistic predictions like the ensemble winter storm frequency forecasts analyzed in this study can be quantified by the ranked probability score (RPS), which compares the cumulative density function of the probabilistic forecast with the cumulative density function of the corresponding observation (here: ERA-Interim) over a given number of discrete probability categories (Murphy, 1969). The categories chosen here are three classes of winter storm frequency ("below normal," "normal," and "above normal") delimited by the lower and upper tercile of storm frequencies. To account for varying ensemble sizes between the different experiments, we make use of Ferro's (2007) version of the RPS as adapted by Kruschke et al. (2014) (see the supporting information for more details). A low RPS value indicates a good prediction. In this study, we analyze the ranked probability skill score (RPSS), which quantifies the benefit of a forecast fc compared to a reference forecast ref:

$$\mathrm{RPSS} = 1 - \frac{\mathrm{RPS}_{\mathrm{fc}}}{\mathrm{RPS}_{\mathrm{ref}}} \tag{1}$$

The reference forecasts chosen in this study are a simple climatological forecast derived from ERA-Interim, the forecast of the CPL-NO experiment, or a forecast conditioned with the occurrence of SSWs (see section 4.2). A positive RPSS indicates a forecast benefit with respect to the reference forecast, and a RPSS of one characterizes a perfect forecast (Wilks, 2006). The significance (95%) of the skill is tested via bootstrapping by computing a distribution of the RPSS from 1,000 randomly selected $\mathrm{RPS}_{\mathrm{fc}}$ and $\mathrm{RPS}_{\mathrm{ref}}$ pairs (see the supporting information for the details).

2.2. Tracking Algorithm

To identify and track individual winter wind storm events in ERA-Interim and model data, the objective tracking algorithm introduced by Leckebusch et al. (2008) is applied in the NH (north of 20°N). A comprehensive description of the current state of this scheme as applied in our study is given by Kruschke (2015). The algorithm is based on instantaneous 6-hourly 10-m wind speed and searches for contiguous exceedances of the local 98th percentile of the same, as the strongest 2% of surface winds are associated with potentially damaging storms (Klawa & Ulbrich, 2003; Leckebusch et al., 2007; Schwierz et al., 2010). To compute the local November to February 98th percentile for the model experiments, all ensemble members of the respective experiment are considered together. The clusters, which have to have a minimum size of 150,000 km^2, are tracked over time and must exist for at least four time increments, that is, 18 hr, to be counted as an event. From the single events, wind storm frequencies for every single winter (December–February, DJF) are defined on a 2.5° × 2.5° grid as the number of tracks within a radius of 700 km.

3. Climatological Wind Storm Frequencies in DJF

Before we examine potential sources of NH winter wind storm frequency seasonal predictability, we look at the climatology of these frequencies to see if they are already influenced by any of the factors considered, that is, the tropics, the stratosphere, SST variability, or atmosphere-ocean coupling. Two main severe storm zones are observed in the NH (Figure 2a), which coincide with the well-known NH storm tracks. Though not obtained using band-pass-filtered mean SLP or geopotential height (e.g., Blackmon et al., 1977), we also use the term "storm track" for these regions of high storm frequencies in the following. Figure 2a reveals the North Pacific (NP) storm track with an average of eight (potentially damaging) wind storms per DJF season, and the NA storm track with 7.5 storms per winter. The observed interannual variability (Figure 2b) is highest in the exit regions of the NP and NA storm tracks.

Some systematic differences appear between the model and ERA-Interim, as can be seen in Figure 2c showing the bias for the CPL-NO experiment, which in its setup is comparable to an operational seasonal forecast. The number of storms is underestimated in the western United States suggesting that the storms do not enter far enough over the North American continent. Another significant underestimation can also be seen over northern Russia. These biases are strongly reduced in the CPL-STRAT experiment (Figure 2i), leading to the highest pattern correlation (0.97) of all experiments with ERA-Interim in the NH northward of 30°N, although the reason that this particular experiment is improved compared to the others is not clear to us at this time. Relaxation of the tropical atmosphere has a systematic effect on the NP storm track, which is significantly reduced by around 1.5 storms per winter (Figures 2f–2h). However, this region is close to the edge of the relaxation zone (30°N including the transition zone); hence, aspects of the nonlinear life cycle of the storms might not evolve realistically. Apart from that, the winter storm climatologies are very similar in all simulations, especially over the NA, and the general pattern of the winter storm climatology is reproduced well in the experiments.

4. What Are the Sources of Prediction Skill?

4.1. General Skill

Our CPL-NO experiment uses a coupled ocean-atmosphere version of the ECMWF seasonal forecast model and no relaxation which makes it comparable to the operationally used systems like the ECMWF System S4 (Molteni et al., 2011). It shows some significant skill (compared to a climatological forecast derived from ERA-Interim) in predicting the DJF severe winter storm frequency over the British Isles and southern Scandinavia (Figure 3a), comparable to System S4 during a recent 20-year period (Befort et al., 2018). In Figure 3, we reference the performance of the other experiments to the CPL-NO simulation, highlighting where an operational forecast could be improved by a perfect forecast of specific regions. Within the experiments using tropical relaxation, that is, a perfect forecast of this region, CPL-TROPICS stands out, showing significantly improved skill over large parts of both the NP and NA. The skill improvement in this experiment compared to CPL-NO is also larger than that in OBS-TROPICS in which observed SST/SI is specified globally. It should be noted that this improvement in skill between CPL-TROPICS and OBS-TROPICS, that is, the difference between Figure 3d and 3e, is significant at the 95% level (not shown), pointing to the importance of atmosphere-ocean coupling as a factor for enhancing forecast skill. CPL-TROPICS also shows the highest skill of all tropical relaxation experiments in predicting SSWs and the highest NAO prediction skill (Hansen et al., 2017), where the latter is suggested by Hansen et al. (2017) to be a consequence of the former.

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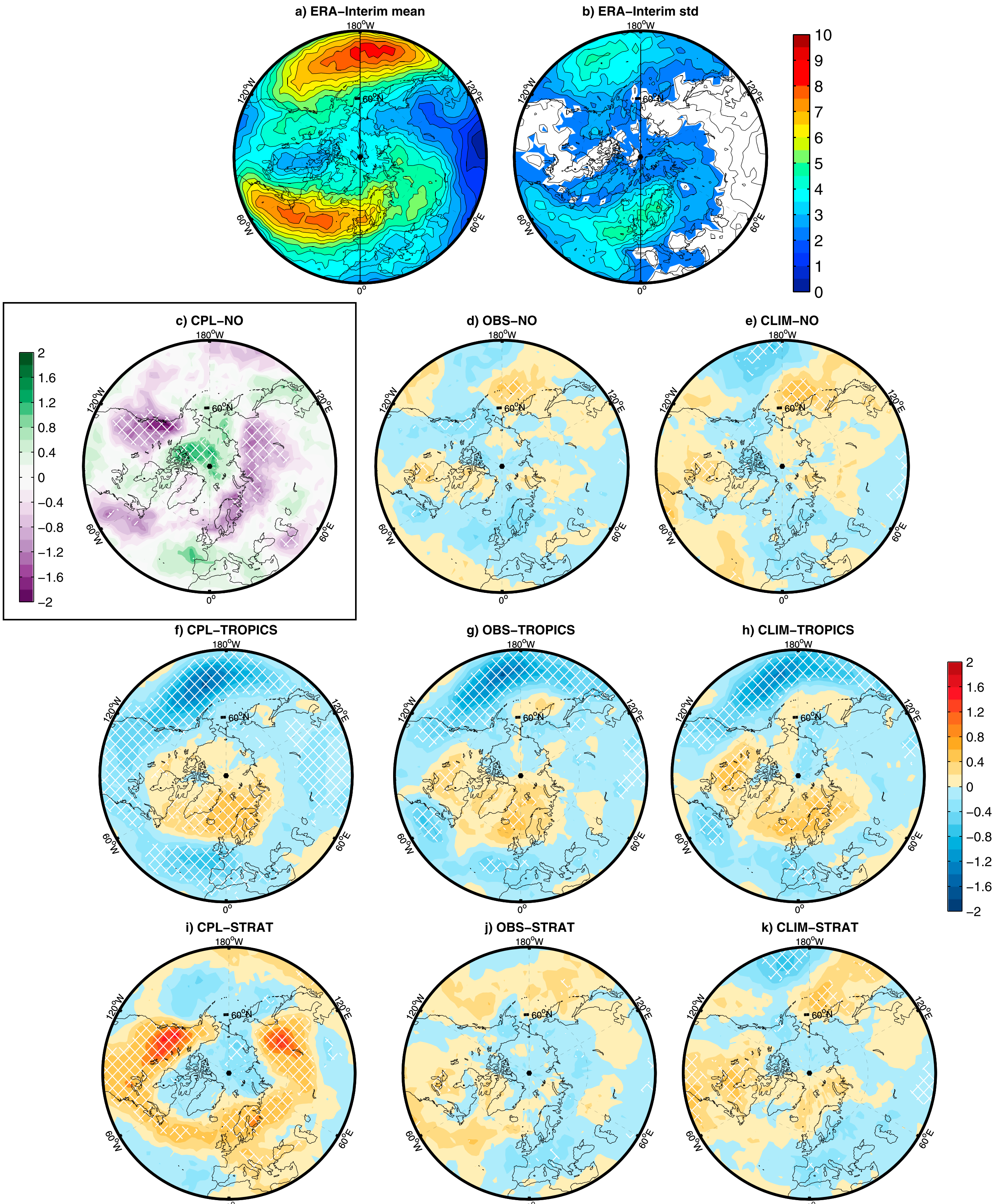

Figure 2. Climatological severe winter storm frequencies in December–February northward of 30°N. (a) ERA-Interim mean, (b) ERA-Interim standard deviation (only values >2 are colored to increase visibility), (c) CPL-NO ensemble mean difference to ERA-Interim (model minus ERA-Interim), and (d–k) relaxation experiments ensemble mean difference to CPL-NO (model minus CPL-NO). Hatching indicates 95% statistical significance as tested with a two-sided *t* test.

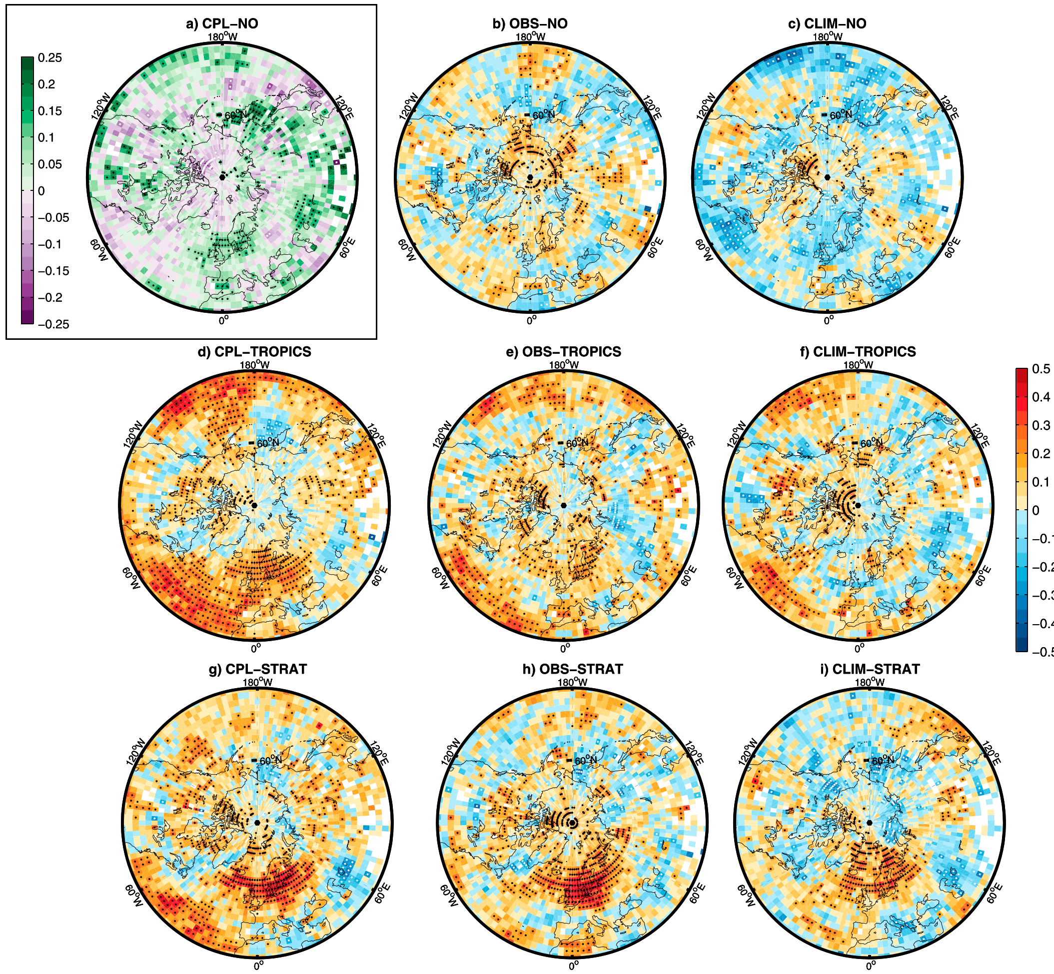

Figure 3. Ranked probability skill score for severe winter storm frequency in December–February northward of 30°N. The reference forecast is a climatological forecast for CPL-NO and CPL-NO for all other experiments. Black and white dots indicate statistical significance at the 95% level.

Quite strikingly, all stratospheric relaxation experiments indicate that a perfect forecast of the stratosphere can significantly improve the severe winter storm frequency seasonal prediction over a pronounced region extending from the NA east of Greenland over the British Isles and Northern Europe (Figures 3g–3i). This region corresponds well with the surface area often mentioned as being affected by major SSWs (e.g., Baldwin et al., 2001; Charlton & Polvani, 2007; Domeisen et al., 2015; Marshall & Scaife, 2010; Sigmond et al., 2013). Stratospheric extreme events can propagate down to the troposphere during the weeks after their occurrence in the stratosphere. The same region of increased skill can also be seen in CPL-TROPICS and to a significantly (not shown) lesser extent in OBS-TROPICS. We hypothesize that the skill in these experiments involves an atmospheric bridge via the stratosphere, which could develop from El Niño–Southern Oscillation (Ineson & Scaife, 2009), the quasi-biennial oscillation in the equatorial stratosphere (Garfinkel, Shaw, et al., 2012; Holton & Tan, 1980, 1982), or the Madden-Julian oscillation (Garfinkel, Feldstein, et al., 2012; Liu et al., 2014). This hypothesis will be tested in the following section.

4.2. Skill Dependence on SSWs

We now examine how the skill depends on the occurrence of SSWs in the ensemble members comprising the different model experiments. Scaife et al. (2016) found a strong dependence of the NAO prediction skill in the MetOffice seasonal prediction system on the simple occurrence of major SSWs in the seasonal forecast ensemble members, apparently independent of the quality of the SSW forecast. Testing this for winter storm frequency predictions in the ECMWF model by referencing ensemble members that include SSWs to those that do not, we cannot find a similar relation (see supporting information Figure S1). The experiments using

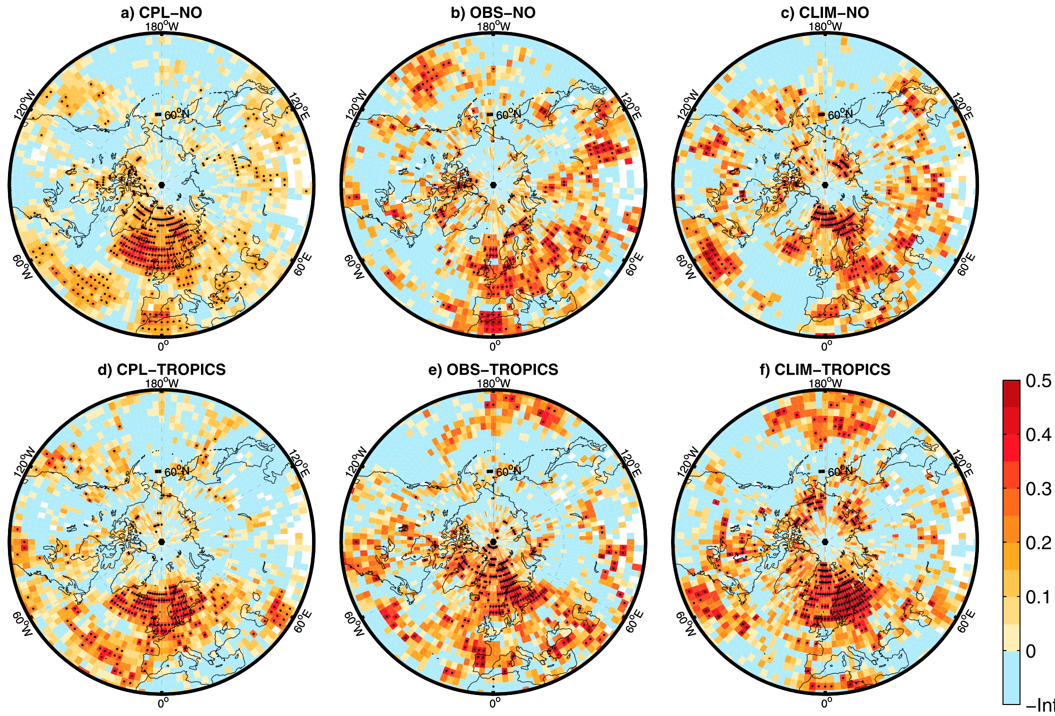

Figure 4. Skill improvement, indicated by the ranked probability skill score, for severe winter storm frequency in December–February of those ensemble members which capture stratospheric sudden warming occurrence correctly (hits and correct rejections) compared to those which do not. Black dots indicate statistical significance at 95% level.

stratospheric relaxation form a special case here, as all SSWs in these experiments are "correctly predicted" due to the experimental setup.

We now test, in the experiments that do not include stratospheric relaxation, whether those ensemble members which contain correct SSW predictions, meaning that an SSW sometime during DJF was both (not) predicted by the ensemble member and (not) observed ("hits" and "correct rejections"), are better in terms of their winter storm frequency prediction than those ensemble members, which include wrong SSW predictions (SSW was predicted by the ensemble member but not observed and vice versa). Figure 4 shows that this is true for all experiments in that same area where the stratospheric relaxation experiments suggested a role for the stratosphere. (Note that in Figure 4 negative RPSS values are not discretized as we focus here on the forecast improvements only.) This clearly indicates that over the British Isles and Northern Europe, a seasonal prediction of DJF severe winter storm frequency highly benefits from a correct representation of the NH stratosphere. This benefit is mainly stemming from the "hit" SSW ensemble members, which cover the winters where there is a potential influence from the stratosphere following major SSWs (compare Figure S2). The ensemble members where SSWs are correctly rejected contribute less to the increased wind storm frequency skill; however, an influence from atmosphere-ocean coupling can be seen in the correct rejections ensemble members in such a way that CPL-NO and CPL-TROPICS show significant DJF storm frequency skill improvement along the eastern part of the NA storm track toward the British Isles and Northern Europe (CPL-TROPICS; compare Figure S3).

5. Summary and Conclusions

Given their large damage and loss potential, multiple sectors of society are interested in skillful predictions of severe NH winter wind storms. In this study we have investigated the role of the tropics and the stratosphere as well as specified SST/SI and atmosphere-ocean coupling for seasonal forecasts of winter storm frequencies, focusing on the strongest and hence potentially most damaging storm events. This has been done by means of relaxation experiments to obtain perfect forecasts for specific parts of the coupled atmosphere-ocean system (see Table 1). The experiments were then analyzed regarding their benefit in comparison to other experiments unconstrained in the respective regions and in particular to an experiment comparable with operational seasonal forecasts. Results from the latter show that the ECMWF seasonal forecast model is (weakly, but significantly) skillful compared to a climatological forecast in predicting NH severe winter storms over the British Isles and Northern Europe.

By analyzing a subset of the experiments used in this study, Hansen et al. (2017) highlighted the importance of the NH stratosphere for seasonal predictions of the NAO, confirming, for example, the results of Douville (2009). The relation between the NAO and winter storms is known to be nonlinear (e.g., Donat et al., 2010), and it is not always the case that winter storm frequency is better predicted based on a prediction of the NAO than when it is predicted directly (Befort et al., 2018). Nonetheless, we find that the stratosphere also plays a key role for winter storm frequency prediction. The region that benefits most from correct stratospheric predictions in individual ensemble members extends from the east of Greenland over the British Isles toward Northern Europe. This area coincides with that often mentioned as being affected by major SSWs whose influence can extend down from the stratosphere to the troposphere and the surface. A significantly lower (higher) number of potentially damaging winter wind storms can be expected in this area in winters with (without) SSW occurrence. It follows that when the risk of an SSW in the NH stratosphere is correctly predicted, the prediction skill for potentially damaging winter wind storms can be expected to increase significantly in a region that is vulnerable to such events. Correct prediction of the occurrence of major SSWs seems to be more important for a skillful winter storm frequency prediction over this region than correct prediction of the absence of the same.

As found by Hansen et al. (2017), our experiment using two-way atmosphere-ocean coupling together with relaxation in the tropical atmosphere shows the highest skill of all experiments at hindcasting SSW risk, including the quasi-operational forecast analyzed in this study (not shown). This highlights the importance of correct predictions in the tropics for predictions of the extratropical stratosphere, and, by implication, for seasonal predictions of severe winter storm frequency over the NAE, as implied by the strong performance of CPL-TROPICS in Figure 3 and also Figure S4 in the supporting information.

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