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Pacific Modulation of the North Atlantic Storm Track Response to Sudden Stratospheric Warming Events

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Key Points:
- On average over all events, SSW events are followed by a reduction in North Atlantic storm track activity
- One third of the SSWs does not exhibit the canonical downward response but shows an increase in storm track activity in the North Atlantic
- The Pacific is found to contribute to the sign of the North Atlantic response in both cases

Supporting Information:
- Supporting Information S1

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Abstract Sudden stratospheric warming (SSW) events have been suggested to be followed by a surface impact, though this response varies between events. Using reanalysis data, we identify two types of tropospheric responses to SSWs: Two thirds of the SSW events are dominated by a zonally symmetric tropospheric response with an equatorward shift of the jet in the Atlantic, consistent with the canonical SSW response in the form of a negative signature of the North Atlantic Oscillation. For the remaining third of SSW events, a zonally asymmetric response is found, associated with a poleward shift of the jet in the Atlantic. The Pacific is found to contribute to the sign of the North Atlantic response, as synoptic wave propagation from the Eastern Pacific links the Pacific and Atlantic storm tracks for both equatorward and poleward jet responses.

Plain Language Summary The stratosphere, the layer of the atmosphere starting at about 10 km above the Earth's surface, can have a major impact on surface weather in winter, in particular during stratospheric extreme events, known as sudden stratospheric warmings. The tropospheric response is strongest in the North Atlantic and Europe; however, not all events exhibit the same surface response, which remains a major open research question. Here, we analyze the changes in surface weather after 26 sudden stratospheric warming events. We identify two types of responses: For two thirds of the events, the effect of the stratosphere leads to a southward shift of the westerly jet in the Atlantic and an eastward extension in the Pacific. For the remaining one third of events, sudden stratospheric warmings are associated with a northward shift of the jet in both basins. We find that the anomalous weather patterns in the Pacific may contribute to the sign of the Atlantic response by propagation of synoptic storms from the East Pacific toward the Atlantic. The results of this study can potentially improve the understanding of the coupling between the stratosphere and surface weather and help to extend weather prediction timescales.

1. Introduction

One of the most significant remote influences on winter weather in the Northern Hemisphere comes from the stratosphere, where changes in the stratospheric circulation can exhibit a downward impact through coupling between the stratospheric polar vortex and the tropospheric jet stream (Baldwin & Dunkerton, 1999; Charlton et al., 2003; Domeisen et al., 2019; Scaife et al., 2005). In particular, a reversal of the westerly winds in the polar stratosphere, known as a sudden stratospheric warming (SSW), is often associated with a negative phase of the North Atlantic Oscillation (NAO) (e.g., Baldwin & Dunkerton, 2001; Limpasuvan et al., 2004), causing substantial changes of tropospheric weather with a persistence of several weeks to months (Baldwin et al., 2003; Sigmond et al., 2013). Overall, about two thirds of SSW events are followed by a persistent negative NAO response (e.g., Charlton-Perez et al., 2018; Domeisen, 2019; Karpechko et al., 2017). Surface impacts of these events include cold spells over northern Eurasia (e.g., Kolstad et al., 2010; Lehtonen & Karpechko, 2016; Thompson & Wallace, 2001) and increased precipitation over the Mediterranean (Ayarzagüena et al., 2018; Butler et al., 2017). However, not all events exhibit the same surface response.

In the search for the origin of the different tropospheric response in the North Atlantic, a range of factors has been proposed for the downward influence. In the stratosphere, these factors include the spatial geometry of the stratospheric polar vortex breakdown (i.e., displacement vs. split events; Mitchell et al., 2013; Seviour et al., 2013), the type of enhanced upward wave flux (i.e., zonal wave number 1 or 2; Nakagawa & Yamazaki, 2006), and the reflection of planetary waves (Kodera et al., 2016). In particular, SSW events that exhibit a tropospheric response were found to be followed by a more persistent anomaly in the lower stratosphere (Hitchcock & Simpson, 2014; Jucker, 2016; Karpechko et al., 2017; Maycock & Hitchcock, 2015; Runde et al., 2016). Other studies have focused on whether the observed variability of the downward response is related to tropospheric internal variability: A given SSW event may influence the troposphere depending on the strength of stratosphere-troposphere coupling (e.g., Hitchcock et al., 2013) and the background state of the tropospheric circulation (e.g., Chan & Plumb, 2009; Garfinkel et al., 2013; Maycock et al., 2011; Song & Robinson, 2004). For an overview of the proposed mechanisms for the tropospheric response to stratospheric variability, see Kidston et al. (2015) and Tripathi et al. (2015).

It has recently been shown that SSW events with a downward impact are preceded by a stronger tropospheric wave activity compared to non-downward propagating events in a coupled chemistry-climate model (White et al., 2019). However, while there is evidence for both lower-stratospheric and tropospheric factors, the extent of the tropospheric influence, and particularly the role of Pacific variability, on the downward impact in the North Atlantic remains unclear and will be investigated here from a tropospheric perspective.

In the troposphere, synoptic-scale eddy feedback was found to play a significant role in the downward influence of the stratosphere and the persistence of the tropospheric response (e.g., Domeisen et al., 2013; Polvani & Kushner, 2002; Simpson et al., 2009; Kunz & Greatbatch, 2013; Hitchcock & Simpson, 2014). Particularly, by eddy momentum flux convergence the eddies act to maintain the jet in its shifted position, which contributes to the enhanced persistence of the NAO (Eichelberger & Hartmann, 2007; Lorenz & Hartmann, 2001). Eichelberger and Hartmann (2007) have pointed out the importance of eddy-mean flow feedback in affecting the spatial structure of the Northern Annular Mode (NAM; Thompson & Wallace, 2001) and the differences between the Pacific and the Atlantic sectors. The tropospheric response to a stratospheric forcing is found to be sensitive to the climatological state of the troposphere, in particular the latitudinal position of the jet (Chan & Plumb, 2009; Garfinkel et al., 2013). Garfinkel et al. (2013) have shown that the amplitude of the tropospheric response to changes in the stratospheric polar vortex depends strongly on eddy feedbacks and demonstrated that the response of the jet to stratospheric perturbation depends nonmonotonically on jet latitude. More generally, the tropospheric characteristics of the North Pacific and North Atlantic jets, and particularly the jet latitude, have been shown to affect storm track intensity throughout the seasonal cycle (Afargan & Kaspi, 2017; Yuval et al., 2018). A more poleward, eddy-driven jet, as observed over the Atlantic in winter, is found to be related to a more intense storm track, while a more equatorward, Pacific-like jet is associated with a weaker storm track in winter.

In this study, we investigate the difference among SSW events in the tropospheric characteristics of the downward response to stratospheric forcing. Rather than focusing on the structure of the stratospheric polar vortex breakdown, we here focus on identifying the signature of the tropospheric jet and storm track response to SSWs. A better understanding of the dynamics of the storm track response to SSW events is expected to increase the subseasonal to seasonal prediction of persistent winter weather patterns following stratospheric extreme events. The data and methods are described in section 2. In section 3, we demonstrate the tropospheric circulation response to SSW events, focusing on the Atlantic jet and storm track and their evolution around the time of occurrence of a SSW event. Section 4 examines the variability of the storm track response to SSW events in the Eastern Pacific and Atlantic sectors. A summary and discussion of our results are given in section 5.

2. Data and Methods

We use daily reanalysis data from the European Centre for Medium-Range Weather Forecasts (ERA-Interim) dataset (Dee et al., 2011) for the years 1979 to 2019. The midlatitude storm track is diagnosed from the vertically integrated transient eddy kinetic energy (EKE)

$$\mathrm{EKE} = \frac{1}{2g}\int(\overline{u'^2} + \overline{v'^2})\mathrm{dp} \tag{1}$$

computed by bandpass filtering daily horizontal winds (u, v) using a Butterworth filter with a cutoff period of 3–10 days, integrated between 1,000 and 200 hPa. The $(')$ denotes transient eddies (i.e., bandpass time-filtered), and the overbar indicates the time mean. The cutoff period is chosen to match the typical

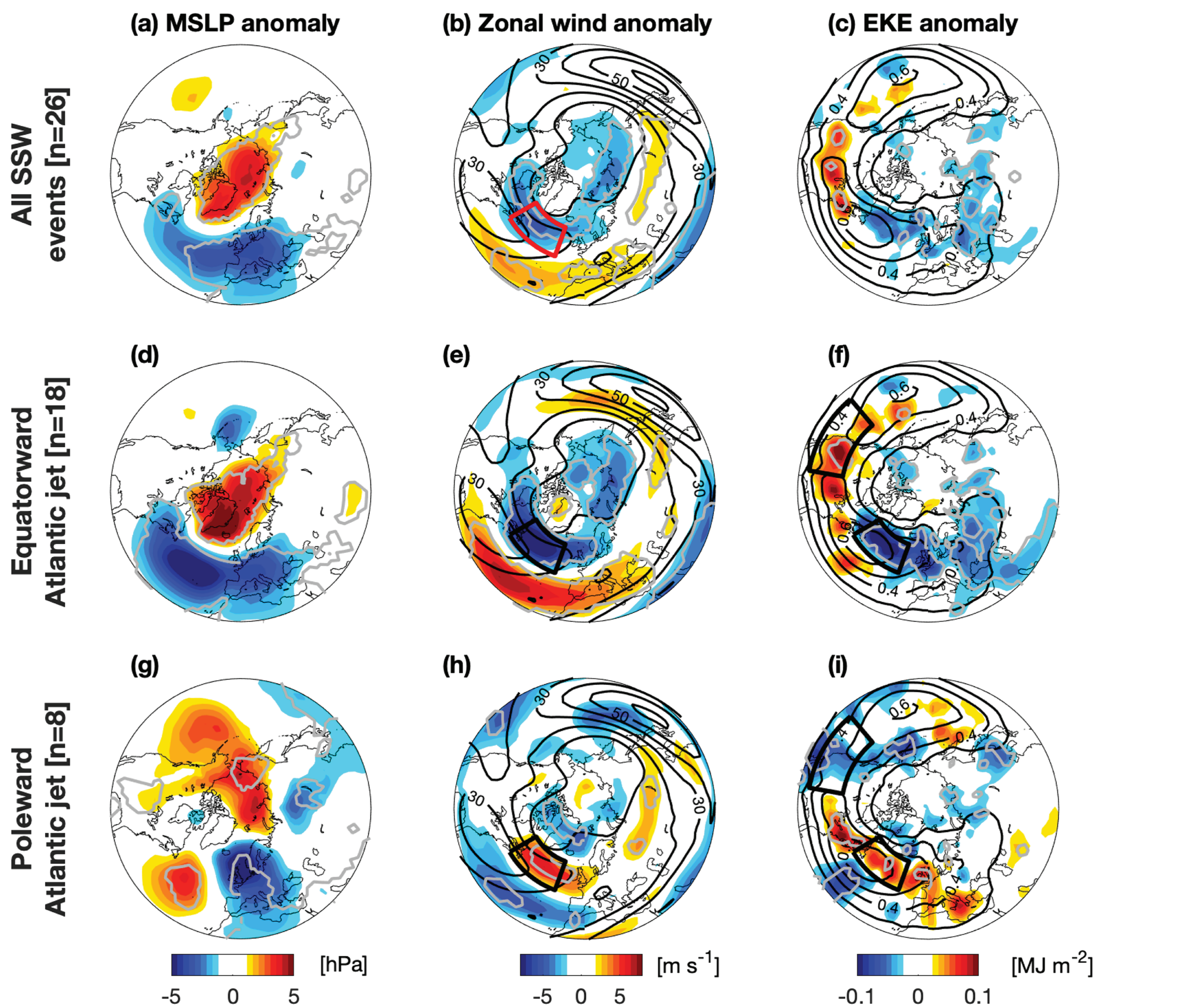

Figure 1. Composites of the tropospheric circulation averaged over the 30 days following (top row) all 26 historical SSW events, and SSW events associated with (middle) equatorward and (bottom) poleward Atlantic jet shifts (18 and 8 events, respectively) in the ERA-Interim reanalysis (1979–2019). Color shading represents the anomalies of (a, d, and g) MSLP (hPa), (b, e, and h) zonal wind (m/s) at 300 hPa, and (c, f, and i) vertically integrated EKE (MJ/m^2). Anomalies are computed with respect to the daily climatology. Black contours represent the DJF climatology of (b, e, and h) 300-hPa zonal wind (contour interval 10 m/s, starting from 10 m/s), and (c, f, and i) EKE (contour interval 0.1 MJ/m^2, starting from 0.3 MJ/m^2). Anomalies significant at the 95% level (using a Student's *t* test) are enclosed by gray contours. The red box in (b) indicates the area with the strongest SSW influence on zonal wind in the midlatitude North Atlantic. The brackets in the title of each panel indicate the number of SSWs in each composite.

timescale of synoptic cyclones in midlatitudes. All eddy quantities in this study are computed using the same bandpass time filtering of atmospheric fields.

Major SSW events for the period 1979–2014 are chosen according to Table 2 in Butler et al. (2017) for ERA-Interim. Two additional SSW events, on 12 February 2018 and 2 January 2019, are detected according to a wind reversal at 10 hPa and 60° N. Between 1979 and 2019, 26 SSW events are selected. We use the zonal wind at 300 hPa to define the type of the SSW downward impact on the troposphere. SSWs followed by an equatorward shift of the North Atlantic jet (i.e., the canonical negative NAO response) are defined if zonal wind anomalies, computed with respect to daily climatology, averaged over a period of 30 days after the SSW central date (CD) and over the midlatitude Atlantic region (45° N to 60° N, 300° E to 340° E, red box in Figure 1b) are negative. If a SSW is followed by mean positive zonal wind anomalies in this region, it is defined as a poleward Atlantic jet shift response. This yields a criterion for two composites, representing

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Table 1
List of Historical SSW Events in ERA-Interim Reanalysis and Their Tropospheric Downward Response in Terms of the Atlantic Jet Shift

SSW event date	Atlantic jet shift (EQ/PL)
22-Feb-79	PL
29-Feb-80	EQ
4-Mar-81	EQ
4-Dec-81	EQ
24-Feb-84	EQ
1-Jan-85	EQ
23-Jan-87	EQ
8-Dec-87	EQ
14-Mar-88	EQ
21-Feb-89	PL
15-Dec-98	PL
26-Feb-99	PL
20-Mar-00	EQ
11-Feb-01	EQ
30-Dec-01	EQ
18-Jan-03	PL
5-Jan-04	EQ
21-Jan-06	EQ
24-Feb-07	EQ
22-Feb-08	PL
24-Jan-09	PL
9-Feb-10	EQ
24-Mar-10	EQ
6-Jan-13	EQ
12-Feb-18	EQ
2-Jan-19	PL

Note. EQ/PL = equatorward/poleward.

the variability of the tropospheric response: either an equatorward Atlantic jet shift or a poleward shift (see Table 1). We identify 18 out of 26 SSWs (~69%) as equatorward Atlantic jet shift (EQ) and 8 (~31%) as poleward Atlantic jet shift (PL) events (listed in Table 1).

3. Tropospheric Circulation Response to SSW Events

The composite response of daily mean sea level pressure (MSLP) and zonal wind anomalies at 300 hPa, averaged over a period of 30 days after 26 SSW events between 1979 and 2019, is characterized by a dipole pattern of MSLP over the North Atlantic (Figure 1a) and an equatorward shift of the Atlantic jet stream (Figure 1b). In contrast, the Pacific response following these events is much weaker, with a rather small increase in MSLP in the eastern North Pacific (Figure 1a) and a poleward shift of the jet (Figure 1b). Storm track intensity, diagnosed by the vertically integrated EKE, exhibits the opposite response in the Pacific as compared to the Atlantic (Figure 1c). While over the North Atlantic and Europe (hereafter NAE), storm track intensity is reduced after SSW events, with a decrease of approximately 0.1 MJ/m^2 (equivalent to a reduction of ~15% of the climatological Atlantic storm track intensity), in the central and eastern Pacific EKE is increased after SSWs (~10% of the climatological Pacific intensity). This response is statistically significant (using a Student's t test) over most of the NAE sector, as well as over North America (Figure 1c). One key feature emerging from Figure 1c is the eastward extension of increased storm track activity from the eastern Pacific and across North America (positive EKE anomalies in Figure 1c), while a decrease is observed over the midlatitude North Atlantic (negative EKE anomalies). This result highlights the potential role of synoptic eddies in connecting the Pacific and the Atlantic storm tracks (Drouard et al., 2015; Jiménez-Esteve & Domeisen, 2018; Li & Lau, 2012a; Seager et al., 2010).

We separate the SSW events based on the characteristics of their tropospheric jet shift in the North Atlantic as defined in section 2 above. The first composite is characterized by a zonally symmetric MSLP anomaly, which consists of a dipole pattern in both the Atlantic and the Pacific sectors (Figure 1d) and corresponds to an equatorward Atlantic jet shift (Figure 1e). In contrast, in the second composite a zonally asymmetric response of MSLP emerges for a poleward Atlantic jet shift, with a negative MSLP anomaly in the eastern Atlantic and Eurasia and a positive anomaly in the eastern Pacific (Figure 1g). In the Pacific sector, zonal wind anomalies in the zonally symmetric case correspond to a poleward and eastward extension of the jet (Figure 1e), while in the asymmetric case, however, zonal wind anomalies indicate a weakening of the subtropical jet in the central and eastern Pacific (Figure 1h). Particularly, over the Atlantic sector, the response in the asymmetric case is comparable in magnitude but opposite in sign to the equatorward jet composite shown in Figure 1e.

Changes in the vertically integrated EKE for an equatorward and a poleward Atlantic jet shift composites are shown in Figures 1f and 1i, respectively. In the Atlantic, EKE is strongly reduced in midlatitudes for SSW events with an equatorward jet shift, while increasing in the subtropics (Figure 1f). In the east Pacific and North America, storm track activity is enhanced up to 0.15 MJ/m^2, which is 25% above the climatological value over the Pacific in DJF. During SSW events with a poleward shift of the Atlantic jet, the opposite response is observed. and EKE is decreased south of 40° N throughout the Pacific and the Atlantic basins (Figure 1i). The response is statistically significant (using a Student's t test) over most of the North Atlantic sector and over the eastern Pacific. An additional significance test, performed for the difference between the two composites rather than evaluating the significance of their difference with respect to climatology, shows a qualitatively similar significance (Figure S1 in the supporting information).

These results indicate two types of tropospheric response to SSW events. The first is a zonally symmetric response with an equatorward shift of the Atlantic jet, associated with an increase in storm track intensity between 30° N to 45° N over the eastern Pacific, North America, and the Atlantic, and a strong reduction

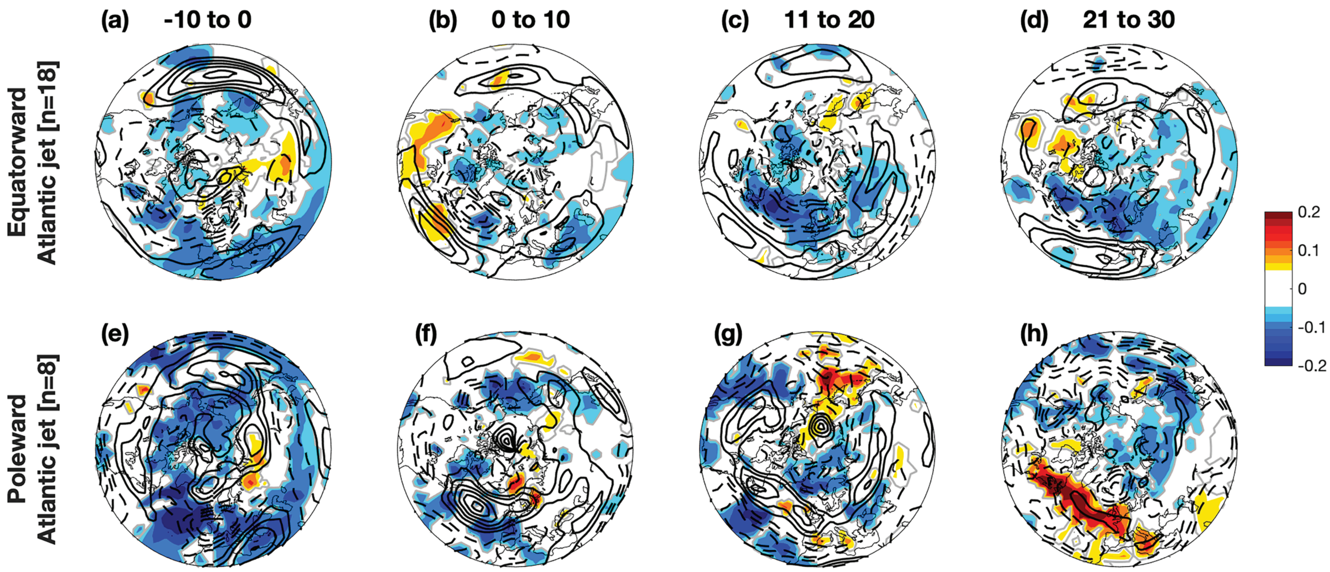

Figure 2. Composites of vertically integrated EKE anomalies (color shading, K m/s) averaged over the specified time intervals for SSW events with (top) an equatorward Atlantic jet shift (18 events) and (bottom) poleward Atlantic jet shift (8 events). Black contours show the 300-hPa zonal wind anomalies (m/s, contour interval 2 m/s starting from −2 and 2 m/s. Positive and negative values are shown by solid and dashed contours, respectively) for each composite. Time intervals are defined in days with respect to the central date (Day 0) of the SSW events. The brackets in the title of each row indicate the number of SSWs in each composite. Only anomalies significant at the 90% level (using a Student's *t* test) are shown.

of storm track intensity between latitudes 45° N to 60° N over the Atlantic. The second type of response is a zonally asymmetric MSLP anomaly, associated with a poleward shift of the jet and the storm track in the Atlantic and an increase in storm track intensity over the NAE. In both cases, convergence of transient eddy momentum fluxes in the North Atlantic are consistent with the jet shift (Figure S3), confirming the role of eddy-mean flow processes in maintaining the jet in its shifted position.

In the eastern Pacific, SSW events with a poleward Atlantic jet shift are associated with a large-scale ridge anomaly, as indicated by MSLP anomalies (Figure 1g), as well as the corresponding geopotential height anomalies at 500 hPa (Figure S3). These anomalies extend along the western coast of North America. SSW events with an equatorward Atlantic jet shift, however, do not exhibit robust geopotential height anomalies in the eastern Pacific (Figures 1d and S3d). These large-scale flow patterns are in agreement with the influence of Pacific trough and ridge anomalies shown in Drouard et al. (2015) and Rivière and Drouard (2015), which are associated with differences in the synoptic wave propagation further downstream, and may result in either an equatorward or a poleward Atlantic jet anomaly, respectively.

3.1. Time Evolution of the Tropospheric Signature

To estimate the impact of stratosphere-troposphere coupling on the tropospheric storm tracks, we examine their temporal evolution within specified time intervals with respect to the SSW CD for the above defined equatorward (Figures 2a–2d) and poleward Atlantic jet shifts (Figures 2e–2h). EKE is vertically integrated while zonal wind is evaluated at a pressure level of 300 hPa for comparison with Figure 1. Prior to the occurrence of a SSW, negative EKE and zonal wind anomalies are found in the Atlantic for both composites, while anomalies centered over the Pacific tend to be positive (Figures 2a and 2e). Over North America, zonal wind anomalies tend to be negative prior to SSW events that are followed by an equatorward jet shift and positive for SSW events with a poleward jet shift.

In the first 10-day period after the SSW CD, a clear negative NAO pattern appears in the North Atlantic after events with an equatorward jet shift (as expected by the choice of criterion), while the opposite pattern appears in the composite of events with a poleward jet shift (Figures 2b and 2f, respectively). During this period, EKE is enhanced in the North Atlantic, as well as over a small region in the central Pacific and across North America.

The equatorward shift of the jet persists in the North Atlantic in the second and third intervals (Days 11 to 20 and Days 21 to 30 after the SSW CD), and negative EKE anomalies dominate the midlatitude region in the

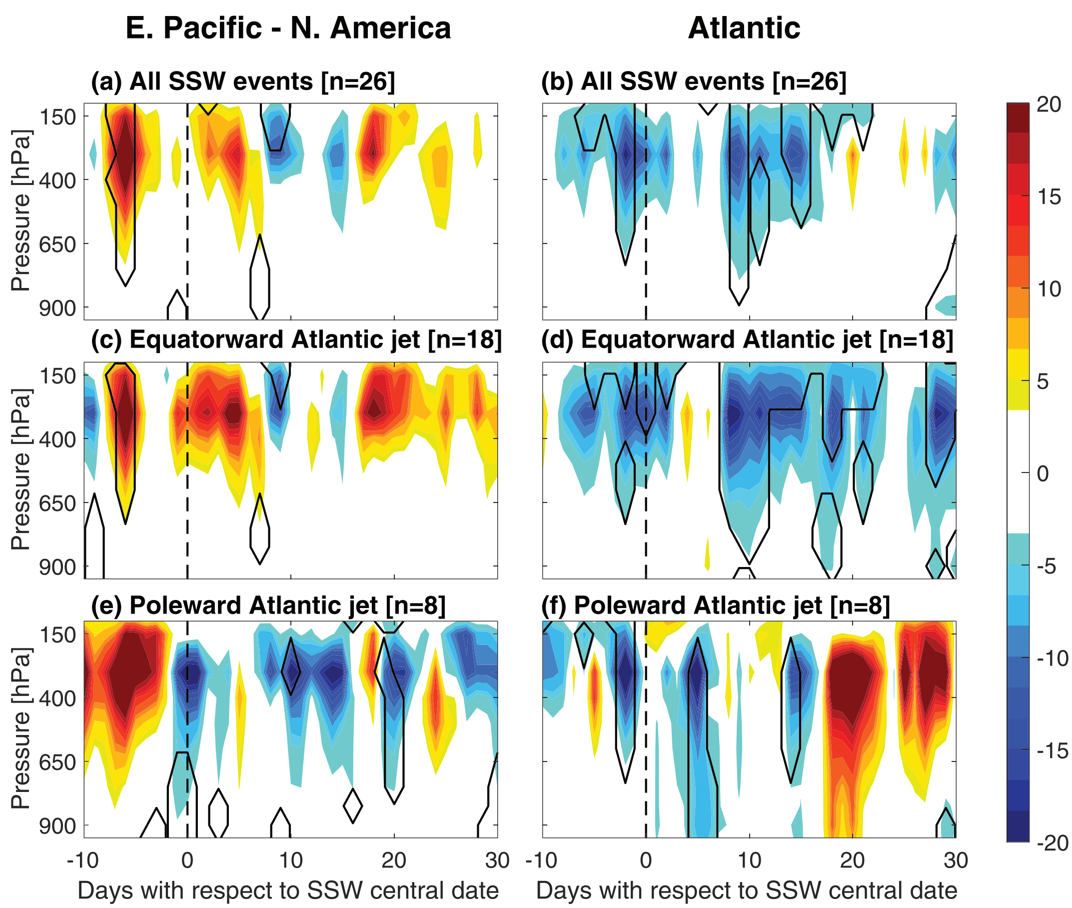

Figure 3. Temporal evolution of EKE anomalies (color shading, m^2/s^2) with respect to the SSW central date of SSW events, area averaged over the East Pacific - North America (left column) and the Atlantic (right column) sectors for (a and b) all 26 historical SSW events, (c and d) SSW events with equatorward Atlantic jet shift, and (e and f) SSW events with poleward Atlantic jet shift. Box dimensions for each region are described in the text and shown in Figure 1f. Anomalies with 95% significance (using Student's t test) are enclosed by black contours.

North Atlantic for the entire period (Figures 2c and 2d). For SSW events with a poleward jet shift, however, EKE anomalies reach their peak in the North Atlantic in the third interval (Days 21 to 30 after the SSW CD) (Figure 2h). All EKE anomalies shown in Figure 2 are statistically significant (using Student's t test) at 90% significance level. For comparison, the significance of EKE anomalies has also been evaluated based on the difference between the two composites rather than the difference from climatology (Figure S2). Results are found to be qualitatively the same.

We further examine the persistence of tropospheric storm track response to SSW events with respect to the SSW CD (Figure 3). EKE anomalies are computed by averaging two regions: the East Pacific - North America sector (30–45° N, 220–260° E) and the Atlantic (45–60° N, 300–340° E) sector (see black boxes in Figures 1f and 1i). When averaged over all SSW events, the composite response of EKE in the North Atlantic is negative for 69% of the time (i.e., in the 30 days following the CD of all SSWs), whereas in the East Pacific - North America, positive EKE anomalies are found for 59% of the time (Figures 3b and 3a, respectively).

For SSW events with an equatorward Atlantic jet shift, composites of EKE anomalies show a persistent reduction of EKE lasting up to 30 days (and longer up to 50 days, not shown) after the SSW CD (Figure 3d). This response persists for a longer period relative to the composite of all events (Figure 3b), and its magnitude is stronger. In the East Pacific - North America sector, a persistent decrease is found after SSW events with a poleward shift of the Atlantic jet (60% of the time, Figure 3e), in contrast to the more positive anomalies found after SSW events with an equatorward Atlantic jet shift (Figure 3c).

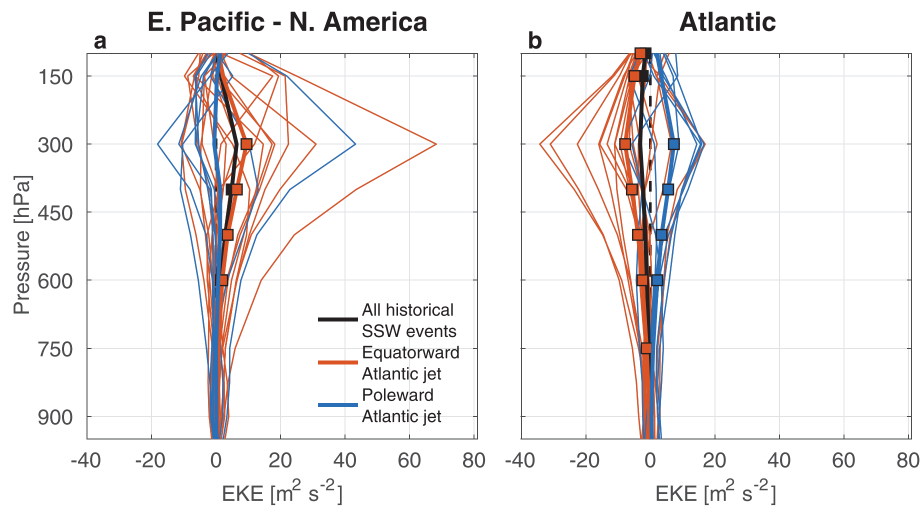

Figure 4. Time-mean anomalies (averaged over 30 days following the SSW central date) of EKE (m^{-2} s^{-2}) for all historical SSW events between 1979 and 2019, area averaged over (a) East Pacific-North America (30–45° N, 220–260° E) and (b) Atlantic (45–60° N, 300–340° E) sectors. SSW events associated with an equatorward or poleward jet shift in the Atlantic are highlighted in red and blue, respectively. Bold curves represent the average of each composite (black, red, and blue, for all, equatorward-shifted and poleward-shifted events, respectively). For each vertical level, anomalies with 95% significance (using Student's *t* test) are denoted by squares.

4. Variability in the Storm Track Response to SSW Events

The results shown in the previous section demonstrate a robust difference between two types of tropospheric responses to SSWs, particularly in the North Atlantic, and support the well-known view that not all SSWs are followed by a negative NAM phase. Here, the variability in the downward impact is demonstrated by the time-mean anomalies of transient EKE, averaged over 30 days after the SSW CD (Figure 4). Each curve represents a single SSW event out of 26 historical events. EKE anomalies are computed by averaging over the East Pacific-North America sector and the Atlantic sector (see black boxes in Figures 1f and 1i).

Over both sectors, transient EKE can exhibit either a positive or a negative response to SSW events (Figure 4). In the Atlantic sector, however, negative EKE anomalies occur in the majority (58%) of the events, based on their value at 300 hPa (Figure 4b). These anomalies are primarily associated with an equatorward shift of the Atlantic jet (highlighted in red), while positive anomalies tend to be related to a poleward shift of the jet (in blue). On the other hand, in the East Pacific - North America sector, positive EKE anomalies tend to be associated with an equatorward Atlantic jet shift, while negative anomalies are often found for a poleward Atlantic jet shift (Figure 4a).

Averaging over each composite clearly demonstrates the robustness of the tropospheric storm track response, with a statistically significant decrease (increase) of EKE for an equatorward (poleward) jet shift in the Atlantic (bold red and blue lines in Figure 4b, respectively). An opposite response is found in the East Pacific-North America region, although the response is less robust, particularly for SSWs with a poleward Atlantic jet response (Figure 4a).

5. Summary and Discussion

In this study we have examined the variability of the storm track response to SSW events. In agreement with previous studies, we show that tropospheric transient eddy activity exhibits a significant change in response to a weakening of the stratospheric polar vortex, persisting for 30 days after the onset of a SSW event or longer.

For two thirds of SSW events, the North Atlantic jet shifts equatorward, corresponding to the canonical negative NAO response. During these events, both the Atlantic and the Pacific exhibit a dipole pattern anomaly of mean sea level pressure, associated in the Pacific with a poleward and eastward extension of the Pacific jet relative to the climatological jet position. Transient eddies in the North Atlantic are enhanced after the onset of these SSW events, equatorward of their climatological position. These eddies coincide with the zonally symmetric structure of the jet in the Atlantic, as evident from the associated eddy momentum flux convergence for this type of response (Figure S3a). A second type of response found for one third of the SSW events is a poleward shift of the Atlantic jet (i.e., corresponding to a positive phase of the NAO). Such a downward impact of SSWs is associated with a weakening of the zonal wind in the central and eastern Pacific and a reduction of EKE downstream of the Pacific storm track. Eddy momentum flux convergence in the North Atlantic coincides with the poleward jet position (Figure S3b), consistent with a positive eddy feedback (i.e., Barnes & Hartmann, 2010).

These two states resemble the two dominant patterns of weak polar vortex found in Kretschmer et al. (2018), which are associated with either a negative phase of the NAO or a negative phase of the Western Pacific Oscillation, respectively. These two patterns may also be possible to link to different mechanisms, corresponding either to absorption or reflection of upward-propagating planetary wave activity (Kodera et al., 2016). For both types of tropospheric responses, we show that anomalies in transient eddies in the subtropical East Pacific - North America region tend to be opposite in sign to the midlatitude North Atlantic (Figures 3, 4). The Pacific is suggested to play a role in modulating the North Atlantic response to SSWs, thus increasing the persistence of the tropospheric response in the Atlantic. This connection from the Pacific to the Atlantic is in agreement with previous work showing that an anomalous storm track activity in the East Pacific - North America region may modify the propagation of the synoptic wave trains from the North Pacific to the North Atlantic and affect the eddy feedback onto the mean flow in the North Atlantic and thus the position of the North Atlantic jet (Drouard et al., 2015; Rivière & Drouard, 2015).

While SSW events frequently have a strong impact on the tropospheric circulation, there is a high variability among the events. This variability often leads to the impression that only roughly two thirds of the observed SSW events have a downward influence (e.g., Charlton-Perez et al., 2018; Domeisen, 2019; Karpechko et al., 2017; Sigmond et al., 2013). These downward responses have been associated with anomalies in the stratosphere, particularly negative NAM anomalies, which have been found to play a role in determining the variability of the downward tropospheric impact (Jucker, 2016; Karpechko et al., 2017; Runde et al., 2016). However, others have shown that there is no significant difference in the stratosphere between SSW events with a downward impact and those without (e.g., Maycock & Hitchcock, 2015). We find that the type of downward response tends to be linked to anomalies in the eastern North Pacific. In particular, different states of transient eddy activity can be observed in the North Pacific between SSW composites followed by an equatorward or poleward jet shift in the Atlantic, hinting at a North Pacific forcing.

While in most winters the occurrence of SSWs may dominate over any ENSO-induced anomalies in the North Atlantic and Eurasia (Polvani et al., 2017), the North Pacific can also impact the downstream North Atlantic through tropospheric energy and momentum transfer (e.g., Li & Lau, 2012b; Schemm et al., 2018). For La Niña conditions, increased quasi-stationary wave activity flux from the Pacific to the Atlantic can contribute to a positive phase of the NAO (and vice versa for El Niño conditions) (Jiménez-Esteve & Domeisen, 2018). In our analysis, five out of eight events that are identified as SSWs without a negative NAO response occurred during La Niña winters (1988/1989, 1998/1999, 2007/2008, and 2008/2009, where two SSW events occurred during winter 1998/1999; see Table 1 in Domeisen et al., 2019), compared to only 5 out of 18 events for SSWs with an equatorward Atlantic jet shift, confirming that a combination of a poleward jet shift in the Atlantic and La Niña is more likely to reverse the downward impact of the stratosphere, particularly in the Atlantic. As ENSO events also tend to influence the frequency of SSW events (for example, Domeisen et al., 2019), this would have to be explored in more detail.

Two recent SSW events occurred in mid-February 2018 (e.g., Karpechko et al., 2018; Kautz et al., 2019) and in early January 2019 (Lee & Butler, 2019). The 2018 event was followed by a strong and persistent negative NAO (Lee & Butler, 2019). Such a downward response is consistent with the canonical downward response often observed after SSW events (e.g., Butler et al., 2017). The 2019 SSW event, however, was followed by a weakly positive NAO. These two SSW events thus correspond to different Atlantic jet classifications as defined in this study, with the 2018 event identified as an equatorward Atlantic jet shift response and the 2019 SSW event as a poleward jet shift (Table 1).

In summary, the consistency between the Pacific and Atlantic storm track anomalies with respect to SSW events suggests a modulating influence of the Pacific on the Atlantic response to SSW events. A better understanding of these processes may help to improve subseasonal to seasonal prediction.

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