Troposphere-Stratosphere Dynamical Coupling in Regard to the North Atlantic Eddy-Driven Jet Variability

Waheed IQBAL

Department of Meteorology (MISU) and Bolin Centre for Climate Research, Stockholm University, Sweden

Finnish Meteorological Institute, Finland

Abdel HANNACHI

Department of Meteorology (MISU) and Bolin Centre for Climate Research, Stockholm University, Sweden

Toshihiko HIROOKA

Department of Earth & Planetary Sciences, Kyushu University, Fukuoka, Japan

Léon CHAFIK

Department of Meteorology (MISU) and Bolin Centre for Climate Research, Stockholm University, Sweden

and

Yayoi HARADA

Climate Research Department, Meteorological Research Institute, Tsukuba, Japan

(Manuscript received 29 August 2018, in final form 5 February 2019)

Abstract

For several decades, the interaction between the troposphere and the stratosphere has attracted the attention of climate scientists, not least for the benefit it has on understanding dynamical processes and predictability. This interaction has been revived recently in regard to downward disturbance propagation effects on tropospheric circulations. In the current study, we investigate such interactions over the North Atlantic region in relation to the eddy-driven jet stream. The atmospheric low-frequency variability in the winter over the North Atlantic sector is mainly associated with variations in the latitudinal positions of the North Atlantic eddy-driven jet stream. The Japanese Reanalysis JRA-55 data has been used to analyze the jet latitude statistics. The results reveal robust trimodality of the North Atlantic jet reflecting the latitudinal (i.e., northern, central and southern) positions in agreement with other reanalysis products. 30 major Sudden Stratospheric Warming (SSW) events are analyzed in relation to the three modes or regimes of the eddy-driven jet. The frequency of occurrence of the eddy-driven jet to be in a specific latitudinal position is largely related to the wave amplitude. The stratospheric polar vortex experiences significant changes via upward wave propagation associated with the jet positions. It is found that when the jet is close to its central mode the wave propagation of zonal wave number 2 (WN2) from the troposphere to the stratosphere is significantly high. Eliassen-Palm (EP) fluxes from all waves and zonal wave number 1 (WN1)
1. Introduction

Sudden Stratospheric Warnings (SSWs) are an extraordinary manifestation of the troposphere-stratosphere coupling. These stratospheric warming events impact extra-tropical weather systems (e.g., Baldwin and Dunkerton 1999). Besides minor and major types, the warmings are also classified as Canadian and final warmings. Early winter warmings associated with the eastward shift of the Aleutian high are called Canadian warmings, whereas in the final warmings, the cyclonic stratospheric polar vortex does not recover (Butler et al. 2015). Major SSW events are defined by a rapid temperature increase (30 to 50K) and reversal of zonal wind (poleward of 60°) in the mid-to-high latitude stratosphere; if the zonal wind does not reverse then the warming will be a minor SSW. Major SSWs mainly occur in the Northern Hemisphere. Only one event has been reported in the Southern Hemisphere (for details see Manney et al. 2005; Krüger et al. 2005). The average rate of major SSWs in the Northern Hemisphere is six per decade (Charlton and Polvani 2007).

Major SSWs lead to strong planetary wave reflection or downward propagation (e.g., Kodera et al. 2016). As a result, cold advection from high latitudes brings surface weather much colder than usual. Over Europe, Siberian winds result in deadly weather conditions. Stratospheric warming events are known to be forced by upward propagating Rossby and gravity waves from the upper troposphere. In a number of recent studies (e.g., Martius et al. 2009; Nath et al. 2016; Harada and Hirooka 2017), the two-way coupling between the troposphere and the stratosphere has been demonstrated. The effects of stratospheric dynamics on tropospheric weather were not much acknowledged until late 1990s (see Kidston et al. 2015 for a recent review). Baldwin and Dunkerton (1999, 2001) demonstrated that the stratospheric variability can impact the surface weather at large and may lead to a longer predictability time scale. For a detailed discussion on the coupling between the troposphere and the stratosphere, the reader is directed to Haynes (2005) and Kidston et al. (2015).

Other critical factors that can influence the Northern Hemisphere mid-latitude weather are the jet streams and the planetary wave activity (e.g., Cohen et al. 2007). The dynamic interaction of the troposphere with eddy-driven jet streams and Rossby waves impacts the stratospheric polar vortex through vertical wave propagation (Matsuno 1971). Subsequently, downward wave propagation affects the surface temperature gradient, which influences tropospheric jet streams (e.g., Kodera et al. 2016, 2017; Mukougawa et al. 2017). In the North Atlantic sector, the atmospheric low-frequency variability in the winter is related to shifts in the preferred latitudinal positions of the North Atlantic eddy-driven jet (e.g., Woollings et al. 2010a). The North Atlantic eddy-driven jet has three preferred latitudinal positions situated, respectively, south, close to, and north of its climatological mean position. They represent, respectively, the Greenland blocking, a low-pressure system over the Atlantic, and a high-pressure system over the Atlantic region (Woollings et al. 2010b).

The major variability in the stratosphere is associated with the dynamics of the polar vortex. SSWs occur during the Northern Hemisphere winter when planetary scale waves are excited by either the topography, or the non-linear interactions of eddies in the troposphere (Haynes 2005). A strong stratospheric polar vortex does not allow the planetary waves to propagate upward (e.g., Scaife et al. 2000). However, a weaker stratospheric polar vortex cannot resist the upward wave propagation from the troposphere (e.g., Hartmann et al. 2000), resulting either in displace-
ment or in splitting of the stratospheric polar vortex. These types of events, are respectively, called vortex displacement and vortex split warmings. The vortex displacement type of events is caused by zonal wave number 1 (WN1) activity, whereas the main contributions for the vortex split events are from zonal wave number 2 (WN2) (e.g., Kidston et al. 2015; Harada and Hirooka 2017). It has been observed that vortex displacement events are preceded by blocking over the Atlantic only (e.g., Mitchell et al. 2013).

Woollings et al. (2010a) analyzed the relationship between the stratospheric variability and tropospheric blocking events. They reported the existence of a significant relationship between the stratospheric variability and blocking over the North Atlantic region. Using National Centers for Environmental Prediction (NCEP) reanalysis, Colucci and Kelleher (2015) revisited the same issue for the period from 1980 to 2012 and found that SSW events coincide with tropospheric blocking, but blocking is not a necessary condition for SSWs. In an idealized modeling study, Garfinkel et al. (2013) found that a jet stream in the troposphere close to 30° and 50° latitude results in a stronger stratospheric polar vortex whereas a jet stream close to 40° latitude results in a weaker stratospheric polar vortex. Until now, there have been no systematic studies on the position of the North Atlantic eddy-driven jet and the relation between SSWs using reanalysis data-sets.

The objective of the current study is two-fold; (1) analyzing the variability of the North Atlantic eddy-driven jet in the Japanese Reanalysis (JRA-55; Kobayashi et al. 2015) in comparison with the European Reanalysis (ERA-40; Uppala et al. 2005) and (2) investigating the relationship between major warmings and preferred latitudinal positions of the North Atlantic eddy-driven jet. The interactions between the eddy-driven jet stream and the wave activity are complex and not fully understood; and in the present study, we attempt to explore one key aspect of this complex puzzle.

The data and methods are described in Section 2, the variability of the North Atlantic jet using JRA-55 is presented in Section 3, and troposphere-stratosphere interactions are presented in Section 4. A summary and conclusions are presented in the last section.

2. Data and methods

2.1 Reanalysis data

The analysis is based on daily reanalysis data for winter (December-February; DJF). The daily data of zonal wind, temperature, geopotential height, and meridional wind have been taken from the JRA-55 (Kobayashi et al. 2015) for the period from 1958 to 2014. In addition, the daily zonal wind data from the ERA-40 (Uppala et al. 2005) available for the period from 1958 to 2001, have also been used to compare the characteristics of the North Atlantic jet with that from JRA-55. Both reanalysis data-sets are at a horizontal resolution of 1.125° × 1.125°. It is worth mentioning here that the ERA-40 data are used only in Section 3 for comparison with JRA-55. Information about the warming event types (vortex displacement or vortex split) and the onset dates is inferred from the SSW compendium data (Butler et al. 2017). In this compendium the major warming onset date is the day when the daily zonal mean zonal wind at 10 hPa and 60°N changes from westerly to easterly (similar to the criterion of Charlton and Polvani 2007). The classification of these SSWs to vortex split and vortex displacement is performed by analyzing temperature anomalies at 10 hPa and the potential vorticity at 550 K (e.g., Butler et al. 2017).

2.2 Analysis methods

The study of the jet variability is based on the computations of the jet latitude index (JLI; Woollings et al. 2010b). Briefly, this method uses daily zonal wind at low levels (925–700 hPa) averaged over the North Atlantic sector (0–60°W). This mean wind is then filtered using a low-pass filter to avoid small-scale disturbances. The latitude at which the maximum of this filtered zonal wind occurs is called the jet latitude, and the wind speed is called the jet speed. For further details about the JLI, the reader is directed to Woollings et al. (2010b). The estimation of the probability density functions (PDFs) is performed by using the kernel method of Silverman (1981). The standard smoothing parameter, $h = 1.06\sigma n^{-\frac{1}{5}}$, was used, where $\sigma$ is the standard deviation and $n$ is the sample size.

In order to study the impact of the stratosphere on the troposphere and vice versa, we have used the Eliassen-Palm (EP) fluxes. The calculation of the fluxes is performed using the Transformed Eulerian Mean equations (Andrews et al. 1987). These equations provide a suitable tool for diagnosing the eddy forcing in the zonal mean circulation system. EP flux vectors are an important diagnostic tool in the meridional plane to study the effect of the troposphere on the stratosphere. When the EP flux is pointing upward, this implies that the eddy-heat fluxes are dominant, and a meridional direction of EP fluxes implies momentum fluxes or forcing dominance. The divergence (convergence) of the EP flux is related to the accel-
ation (deceleration) of the associated zonal flow. For further details about the relationship between EP flux divergence and the mean flow, the reader is directed to Andrews and McIntyre (1976) and Andrews et al. (1987).

There are a few variants of the EP fluxes. In this study we make use of the two most used fluxes; (1) EP flux (Edmon et al. 1980; Figs. 9, 10) and (2) Plumb flux (Plumb 1985). The first type of flux is a latitude-height cross-section whereas the Plumb flux provides a latitude, longitude, and height view to study the wave activity. We used the vertical component of EP flux at 100 hPa (EPFZ100) averaged over 30–90°N to study the vertical wave propagation. It has been shown that EPFZ100 is a good representative of the upward wave activity from the troposphere to the stratosphere (e.g., Newman and Nash 2000). Data for EPFZ100 is obtained from Harada and Hirooka (2017) which is computed following the definition of Andrews et al. (1987). The vertical component of the EP flux represents the eddy-heat forcing from the troposphere to the stratosphere (e.g., Newman and Nash 2000). Data on the sphere in log-pressure coordinates are given by:

\[
F_p = \frac{1}{2a^2 \cos^2 \phi} \left( \frac{\partial \psi'}{\partial \lambda} - \psi' \frac{\partial^2 \psi'}{\partial \lambda^2} \right),
\]

where \( p \) is the pressure, and \( \phi \) and \( \lambda \) are the latitude and longitude, respectively. A prime denotes a small perturbation to the zonal mean. The stream-function, Earth’s rotation rate, radius of Earth, and buoyancy frequency are respectively, given by \( \psi, \Omega, a, \) and \( N. \) The pressure \( p \) (hPa) is divided by 1000 hPa.

For 2D latitude-height cross-sections, we employed the EP flux methodology of Edmon et al. (1980), which is given by:

\[
\{F_u, F_v\} = \left\{ -a \cos \phi \overline{u'v'}, f a \cos \phi \overline{v'} \right\}.
\]

The terms \( F_u \) and \( F_v \) refer, respectively, to the meridional and vertical components of the EP flux. The wind components are denoted by \( u \) and \( v, \) the primes denote the deviations from the zonal mean and the overbar shows the zonal mean. The variable \( \theta \) represents potential temperature and \( \theta_p \) is the partial derivative of \( \theta \) with respect to \( p. \)

The lead/lag relationship between the jet states and the major SSWs is analyzed by performing a Supposed Epoch Analysis (SEA; e.g., Adams et al. 2003). SEA is a statistical technique used to find the correlation of a time series with a lead/lag to key events. The key events here refer to the onset dates of the major SSWs (see Table 3).

The downward wave propagation from the stratosphere to the troposphere can be analyzed using a reflective index (RI; Perlwitz and Harnik 2004). The RI is the difference of the zonal mean zonal wind averaged over 58–74°N, between 2 hPa and 10 hPa pressure surfaces.

\[
RI = \overline{\mathbf{u}}_{2\,\text{hPa}} - \overline{\mathbf{u}}_{10\,\text{hPa}}.
\]

Positive values of RI correspond to a non-reflective stratospheric basic state whereas negative values of RI imply a reflective stratosphere. We computed the daily values of RI from JRA-55 to report the variability of the wave reflection for three preferred latitudinal positions of the North Atlantic eddy-driven jet.

### 3. Variability of the North Atlantic jet in JRA-55

In this section, we analyze the North Atlantic eddy-driven jet variability from the JRA-55 data and compare the results with that of ERA-40 for the winters of 1958–2001. The use of the JLI is to explore the statistical characteristics of the North Atlantic jet. Previously, this has been done using ERA-40 reanalysis (e.g., Woollings et al. 2010b; Hannachi et al. 2012). An Analysis based on the Coupled Model Inter-comparison Project (CMIP) has been carried out by Hannachi et al. (2013) for CMIP3 and by Iqbal et al. (2018) for CMIP5. To the best of our knowledge, the JRA-55 data are explored here for the first time. The comparison of the two reanalyses is shown in Fig. 1. The first 500 winter days of JLI from the two reanalyses (Fig. 1a) depict similar variability of the North Atlantic jet. Certainly the two reanalyses have a good match for variability of the North Atlantic jet. The kernel estimation of PDFs of the daily JLI time series shows three maxima that are well separated. These maxima are located respectively close to 37°N, 46°N, and 57°N. The location and relative frequencies of these modes are very similar in the two reanalyses, demonstrating the robustness of the trimodal structure of the jet PDF to the choice of analysis dataset.

In order to develop a physical representation of...
these three modes, composites were computed of 500 hPa geopotential height anomalies for 700 days closest to each mode of the North Atlantic eddy-driven jet. The obtained spatial patterns associated with each of these modes are shown in Fig. 2. The southern mode represents atmospheric conditions similar to the negative phase of the North Atlantic Oscillation (NAO) and depicts Greenland blocking. The central and the northern modes represent respectively a positive and a negative East Atlantic pattern. These flow patterns obtained from the JRA-55 are similar to those from the ERA-40 (Woollings et al. 2010b). These spatial patterns are quite robust for changes in the sample size used for the composites. Composites of 20 hPa geopotential height anomalies for 700 days closest to each state of the North Atlantic eddy-driven jet are presented in the Supplementary Material. The spatial patterns for both the northern and the central modes of the jet are similar to a WN1 pattern, whereas the southern mode of the jet resembles a WN2 pattern (Fig. S1).

4. Wave activity and the North Atlantic jet during winter

Stratospheric variability corresponds to different strengths of the stratospheric polar vortex. An Empirical Orthogonal Function (EOF) analysis of geopotential height anomalies in the stratosphere at the 20 hPa level (Fig. 3), shows that planetary scale waves are the main contributors to the stratospheric variability. The leading mode with 34 % of explained variance reflects the zero wave pattern, representing mainly the Arctic Oscillation (AO). The next two EOFs represent the WN1 pattern, synonymous with a displaced vortex with centers of actions situated over northern Canada and Scandinavia/northern Siberia for EOF2, and Iceland and north-eastern Russia for EOF3. These two patterns explain altogether 37 % of the total winter stratospheric variability. The fourth pattern with 8 % variance is a WN2 pattern for split events. Note that these four leading patterns explain altogether 79 % of the variability, and 45 % is explained by displaced and split events (Fig. 3). A similar spatial structure of variability for EOF analysis of 100 hPa geopotential

Fig. 1. Comparison of the two reanalysis data-sets: ERA-40 and JRA-55 for the JLI (in °N) computed for winter during the period from 1958 to 2001. JLI for the first 500 winter days (a); the probability distribution function of daily JLI time series along with a kernel estimation to PDF (solid black line) and a Gaussian (blue dotted line) for ERA-40 (b); same as in (b) but for JRA-55 (c). The two kernels estimated for ERA-40 and JRA-55 JLI PDFs are presented in panel (d).
Fig. 2. Spatial patterns of geopotential height anomalies (gpm) at 500 hPa for the composite of 700 days closest to each mode in Fig. 1. The anomalies are computed by removing a smooth seasonal cycle. Panels (a) to (c), respectively, represent the spatial pattern associated with the northern, central, and southern mode of the North Atlantic jet. Stippling indicates the regions where the composites are different from the winter climatology at a 5% significance level from the Student’s t-test.

EOF1 (34%)  EOF2 (23%)  EOF3 (14%)  EOF4 (8%)

Fig. 3. Spatial patterns of variability in the stratosphere. The first four EOFs of winter geopotential height anomalies at 20 hPa for the period from 1958 to 2014. The amount of explained variance is also shown above each panel.
heights is observed (not shown), but with less percentage of explained variance. The EOF analysis for 700 days closest to each state of the jet also represents similar spatial structures, and the sum of explained variance by the first four EOFs is more than 80 % (see. Figs. S2–4).

The use of EPFZ100 has been reported to be a good indicator of upward wave activity from the troposphere to the stratosphere (Newman and Nash 2000). Positive EPFZ100 values imply upward propagation that can affect the stratospheric polar vortex. Since only the longest-scale waves can affect the stratospheric dynamics (Charney and Drazin 1961), we consider the contributions of all waves, WN1, and WN2 to EP fluxes. The inter-annual variability of EPFZ100 shows the dominance of WN1 in general; however, a higher wave activity associated with WN2 is also occasionally observed (Fig. 4).

The upward wave propagation for each preferred latitudinal position of the North Atlantic eddy-driven jet is analyzed via a composite analysis similar to Fig. 2, but for EPFZ100. The composites of the EPFZ100 for 700 days closest to each state of the jet are presented in Fig. 5. All three states of the North Atlantic jet have some differences for the upward wave activity. The averaged values of EPFZ100 for three modes – southern, central, and northern – are shown in Table 1. Contributions to upward wave propagation from the troposphere to the stratosphere from all waves are higher for the northern latitudinal position of the North Atlantic eddy-driven jet. The contributions of WN1 are relatively stronger for the case when the jet is either in the southern state or in the northern state.

Fig. 4. (Harada and Hirooka 2017). Inter-annual variability of EP fluxes at the high troposphere. The distribution of EPFZ100 (× 10^4 kg s^-2) during the winters of 1958–2014. The contributions of EPFZ100 associated with all waves (gray bars), WN1 (red curve) and WN2 (blue curve) are plotted for each winter year. Note that there are two y-axes; Left: for all waves, right: for the decomposed components (WN1, WN2).

Fig. 5. Histogram and kernel PDF of the DJF daily EPFZ100 (× 10^4 kg s^-2) for all waves (a), WN1 (b) and WN2 (c). The kernel estimations of the PDF of the 700 days closest to each mode of the North Atlantic jet are also shown in each panel.
However, WN2 upward fluxes are stronger for the central position of the North Atlantic eddy-driven jet. RI values for the same 700 days closest to each state of the North Atlantic eddy-driven jet are 11.3, 7.7, and 5.5 m s$^{-1}$, respectively, for southern, central, and northern position of the jet. In all these three composites, the basic state in the stratosphere is non-reflective.

Kernel estimation of PDF of EPFZ100 for 700 days closest to each mode of the North Atlantic jet is also shown in Fig. 5. EPFZ100 contributions from all waves in all three cases are almost similar, whereas there are significant differences between the EP fluxes associated with WN1 and WN2 for the days when the North Atlantic eddy-driven jet is close to either southern or northern latitudinal positions. The total wave activity is nearly symmetrical with a near-Gaussian shape. However, WN1 and WN2 histograms are quite asymmetric or skewed with a long tail toward large fluxes, reflecting the high impact of planetary-scale (WN1, WN2) waves in the stratosphere. The results of the two sample Kolmogorov–Smirnov (K–S) test performed to assess the interdependence of these samples are shown in Table 2. The time series of EPFZ100 from all waves are not significantly different from each other. However, the EPFZ100 flux for the central position of the North Atlantic jet is significantly different from that of the northern and the southern positions of the jet for both WN1 and WN2.

The occurrence of positive EPFZ100 from all waves and decomposed components is almost the same for three preferred positions of the North Atlantic eddy-driven jet (Fig. 5a). The frequency of weak WN1 upward propagation associated with the central mode of the jet is higher than that from the southern position of the jet. The relative frequency of WN1 EPFZ100 is higher for the northern position of the North Atlantic eddy-driven jet as compared to the other two modes. EPFZ100 associated with WN2 is stronger for the central mode as compared to both the southern and the northern modes of the jet (Fig. 5c).

An alternative way to look at the wave activity effects on the jet can be obtained by analyzing the PDF structure of the jet for various strengths of the vertical component of the EP flux. This is presented in Fig. 6, where the kernel estimations of the PDFs of low, medium, and high fluxes when considering all waves, WN1, and WN2 are compared. The stronger EPFZ100 from WN2 impacts the central mode of the jet (with higher frequencies), making the other two modes extremely less frequent. The trimodal feature of the North Atlantic eddy-driven jet might undergo significant changes associated with the extreme amplitudes of the EP flux. This implies that given the higher frequencies of stronger or weaker EP flux will result in less or more frequent jet for southern, central, and northern positions of the North Atlantic eddy-driven jet.

### 4.1 Major SSWs in relation to the North Atlantic eddy-driven jet

A list of major SSWs, their onset dates, and the stratospheric polar vortex types for these events is shown in Table 3. There were 16 events with a vortex displacement type and 14 events with a vortex split type in the analysis period. In this section, we use different statistical approaches to study the possible relationship between the jet states and the wave activity.

Figure 7 shows the average position of the jet conditioned on the types of SSWs with vortex split and vortex displacement types with a time lead/lag of one week. Here ‘All’ refers to the total number of SSW events (i.e., 30). The climatological value of JLI during the DJF season is around 47.5°N. It can be observed that the jet is closest to its climatological position before and after any displacement event, whereas...
the jet is well below in the south for the vortex split events. In all these three categories in Fig. 7, the jet is always southward of its climatological position. It has been reported that the split events impact the European climate, whereas the displacement events are more likely to have an impact over the North American region (e.g., Kidston et al. 2015; Bancalá et al. 2012; Martius et al. 2009). It is worth mentioning that owing

Fig. 6. Kernel estimation to the PDF of the daily JLI (°N) time series for low, medium, and high values of EPFZ100 computed for all Waves (a), WN1 (b), and WN2 (c). The black curve in each panel represents the kernel estimation to full time series (i.e., DJF). The classification of low, medium, and high EPFZ100 is based on percentiles (i.e., Low: EPFZ100 ≤ P_{25}, Medium: P_{25} < EPFZ100 ≤ P_{75} and High: EPFZ100 > P_{75}).

Table 3. List of SSWs in JRA-55 from 1958–2014 and their type. S and D respectively, represent the vortex splitting and the vortex displacement type events.

| Sr No. | Date       | Type | Sr No. | Date       | Type |
|--------|------------|------|--------|------------|------|
| 1      | 17-Jan-1960| D    | 16     | 23-Jan-1987| D    |
| 2      | 30-Jan-1963| S    | 17     | 08-Dec-1987| S    |
| 3      | 18-Dec-1965| D    | 18     | 21-Feb-1989| S    |
| 4      | 23-Feb-1966| S    | 19     | 15-Dec-1998| D    |
| 5      | 07-Jan-1968| S    | 20     | 26-Feb-1999| S    |
| 6      | 02-Jan-1970| D    | 21     | 11-Feb-2001| D    |
| 7      | 18-Jan-1971| S    | 22     | 31-Dec-2001| D    |
| 8      | 31-Jan-1973| S    | 23     | 18-Jan-2003| S    |
| 9      | 09-Jan-1977| S    | 24     | 05-Jan-2004| D    |
| 10     | 22-Feb-1979| S    | 25     | 21-Jan-2006| S    |
| 11     | 29-Feb-1980| D    | 26     | 24-Feb-2007| D    |
| 12     | 06-Feb-1981| D    | 27     | 22-Feb-2008| D    |
| 13     | 04-Dec-1981| D    | 28     | 24-Jan-2009| S    |
| 14     | 24-Feb-1984| D    | 29     | 09-Feb-2010| S    |
| 15     | 01-Jan-1985| S    | 30     | 07-Jan-2013| S    |
to the small sample size of the two types of events, we avoided the segregation of events into displacement or vortex split for further analysis.

SEA is performed over the DJF daily JLI time series and EPFZ100 for the WN1 and WN2 components (Fig. 8). The North Atlantic eddy-driven jet is significantly poleward of its climatological position two days before the onset of an SSW event. There is a lead-time of about 20 days for the North Atlantic jet to be significantly on the equator side for any SSW event. The wave activity from both WN1 and WN2 is significantly above normal for two to five days before an event and then gradually decreases until it reaches the negative anomalies around three to five days after the on-set date of the SSW event.

4.2 Meridional cross sections of the EP flux
As pointed out by Birner and Albers (2017), the fluxes at 100 hPa are not enough to study the upward propagation. Therefore, here, we use 2D EP fluxes for latitude-height cross-sections. The winter climatology of EP fluxes (Fig. 9) from all waves, WN1, and WN2 shows weaker upward wave propagation over the polar region as compared to mid-latitudes in the stratosphere. The strong stratospheric polar vortex during winter implies less vertical wave propagation over the polar region from large-scale planetary waves. The differences of the EP fluxes for composites of jet states from the winter climatology show significant changes in the associated stratospheric zonal circulation (i.e., divergence in Fig. 10). Significant deceleration of the associated zonal flow over the

Fig. 7. Composites of SSW events and the mean position of the North Atlantic jet (in °N). The composites are analyzed for the onset, one week before (Pre), and one week after (Post) of an event. The winter mean for the JLI over the analysis period is represented by a black dashed line.

Fig. 8. SEA performed for all 30 selected events (including split and displacement types) shown in Table 3. The values on the y-axis show the deviation from the mean values and the x-axis values are the lead/lag days from an event. The black color represents zero lag, whereas the red and blue colors respectively, denote the Post and Pre composites. The 95 % confidence limits are shown by the continuous and dashed curves. The jet latitude deviation is in °N (a), whereas the EPFZ100 anomalies (b, c) are expressed in \( \times 10^4 \) kg s\(^{-2}\).
Fig. 9. Latitude-height cross-sections of the winter EP flux climatology for all waves (a), WN1 (b), and WN2 (c). The arrows represent the EP flux and the divergence (m s$^{-1}$ day$^{-1}$) is shaded.

Fig. 10. Latitude-height cross-sections of EP flux difference between winter climatology and the three states of the North Atlantic eddy-driven jet. The columns from left to right respectively, represent the northern, central, and southern jet, whereas the rows from top to bottom respectively, represent all waves, WN1, and WN2. EP flux vectors are displayed only where the EP flux divergence is different from the climatology at a 5% significance level. The divergence (in m s$^{-1}$ day$^{-1}$) is shaded.
stratospheric polar region is observed for the southern mode of the jet associated with both all waves and WN1 EP fluxes implying stronger upward wave propagation. Similar stronger wave activity associated with WN2 can be seen for the central mode of the jet (Fig. 10h). For the central mode of the jet, both all waves and the WN1 EP flux are lower than the winter mean upward propagation. It is important to mention here that these results are in good agreement with the EP flux analysis for only one level (Table 1).

4.3 Plumb wave activity

Here, we examine the 3D Plumb wave activity. To simplify the interpretation, we focus on analyzing the latitudinal averages of the fluxes over the latitudinal band: 45°–65°N. The longitude-height cross-sections of the horizontal and vertical components of the Plumb wave activity are shown in Fig. 11. The upward wave activity from the troposphere to the stratosphere is stronger over the Pacific as compared to the Atlantic sector. Departures of the wave activity composites for each jet state from the mean wave activity during the Northern Hemisphere winter are shown in Fig. 12. In all three states the wave activity differences from the winter climatology are mainly in the Atlantic sector and eastern Pacific. A stronger anomalous upward wave activity over the North Atlantic sector is observed for the northern position of the jet. The anomalous upward wave propagation over the North Atlantic sector is reduced when the jet is either in the central or in the southern positions.

5. Summary and conclusions

In this study, we analyzed the characteristics of the North Atlantic eddy-driven jet from the JRA-55 during the winter time (DJF) for the period from 1958 to 2014. These characteristics of the North Atlantic eddy-driven jet were compared to those in previous
The second part of the paper was devoted to exploring the associations between the stratospheric variability and the North Atlantic jet variability (tropospheric variability) through eddy-mean flow interactions using WAFs. A total of 30 major sudden stratospheric warming events have been examined for a possible relation with the preferred latitudinal positions of the North Atlantic eddy-driven jet. We used 2D EP fluxes as well as 3D Plumb fluxes.

Considering the fact that only the planetary and large-scale waves can propagate from the troposphere to the stratosphere, we used the EP flux contributions from the leading two waves (WN1, WN2), in addition to considering the all waves contributions. The vertical component of EP fluxes at 100 hPa (EPFZ100) averaged over 30–90°N was used as an indicator of upward wave propagation. The contributions to upward wave propagation at 100 hPa from all waves were higher for the northern latitudinal position of the North Atlantic eddy-driven jet. We have shown that the WN1 upward propagation is significantly stronger when the North Atlantic eddy-driven jet is either in the northern or in the southern positions compared to the central jet positions.

The EPFZ100 composite of 700 days closest to each latitudinal position of the North Atlantic eddy-driven jet revealed stronger wave activity: (1) for the north position associated with all waves fluxes, (2) for the south and north positions associated with the WN1 fluxes and (3) for the central position associated with the WN2 fluxes. By extending this 1D analysis to latitude-height vertical cross-sections, we confirmed the strong wave activity from WN2 for central position of the North Atlantic eddy-driven jet. The stronger wave activity and EP flux divergence are manifestations of a weakening stratospheric polar vortex. The composites of all waves and WN1 EP flux depicted significant deceleration for the northern position of the jet.

A 3D view from the Plumb wave activity composites for three latitudinal positions of the North Atlantic eddy-driven jet shows stronger upward wave propagation for the northern mode only over the North Atlantic sector. In all three states of the North Atlantic eddy-driven jet, the wave activity differences from the winter climatology are mainly in the Atlantic sector. We also showed that the jet latitude PDF trimodality feature of the North Atlantic eddy-driven jet reduces to a unimodal shape for higher WN2 EP fluxes. The position of the North Atlantic jet is reported to be south of its climatological position about 20 days both before and after the onset of a major warming event.

The aim of the analysis performed was to improve our understanding of the interaction between the North Atlantic eddy-driven jet and the wave activity. The results indicated strong relationships for different latitudinal positions of the North Atlantic jet and the associated wave activity. The strong upward wave activity associated with the central mode of the jet and weak upward propagation from the other two modes of the North Atlantic eddy-driven jet were found to be interesting features. The significant changes in the stratospheric dynamics for the eddy-driven jet latitudinal positions may be a useful source of predictability for both the stratosphere and the troposphere.

Acknowledgments

The authors would like to thank Tim Woollings for useful discussions. W. Iqbal is supplied by International Exchange Scholarship 2017 from Kyushu University, Japan. T. Hirooka was funded by International Meteorological Institute of Stockholm University, Stockholm Sweden. The computations were performed on resources provided by the Swedish National Infrastructure for Computing at the National Supercomputing Centre. This work was partly supported by Grants-in-Aid for Scientific Research (16H04052, 17H01159 and 18H01280) from Japan Society of Promotion of Science. L. Chafik acknowledges support from the Swedish National Space Board (SNSB; Dnr 133/17). We thank two anonymous reviewers for their useful suggestions.

References

Adams, J. B., M. E. Mann, and C. M. Ammann, 2003: Proxy evidence for an El Niño-like response to volcanic forcing. Nature, 426, 274–278.
Andrews, D. G., and M. E. McIntyre, 1976: Planetary waves in horizontal and vertical shear: The generalized Eliassen-Palm relation and the mean zonal acceleration. J. Atmos. Sci., 33, 2031–2048.
Andrews, D. G., J. R. Holton, and C. B. Leovy, 1987: Middle Atmosphere Dynamics. International Geophysics Series Vol. 40, Academic Press, New York, 489 pp.
Baldwin, M. P., and T. J. Dunkerton, 1999: Propagation of the Arctic Oscillation from the stratosphere to the troposphere. J. Geophys. Res., 104, 30937–30946.
Baldwin, M. P., and T. J. Dunkerton, 2001: Stratospheric harbingers of anomalous weather regimes. Science, 294, 581–584.
Bincalá, S., K. Krüger, and M. Giorgetta, 2012: The pre-conditioning of major sudden stratospheric warmings. J. Geophys. Res., 117, D04101, doi:10.1029/2011JD016769.

Birner, T., and J. R. Albers, 2017: Sudden stratospheric warmings and anomalous upward wave activity flux. SOLA, 13A, 8–12.

Butler, A. H., D. J. Seidel, S. C. Hardiman, N. Butchart, T. Birner, and A. Match, 2015: Denning sudden stratospheric warmings. Bull. Amer. Meteor. Soc., 96, 1913–1928.

Butler, A. H., J. P. Sjoberg, D. J. Seidel, and K. H. Rosenlof, 2007: A new look at stratospheric sudden warmings and anomalous upward wave activity flux. SOLA, 3, 8–12.

Charlton, A. J., and L. M. Polvani, 2007: A sudden stratospheric warming compendium. Earth Syst. Sci. Data, 9, 63–76.

Charlton, A. J., and L. M. Polvani, 2007: A new look at stratospheric sudden warmings. Part I: Climatology and modeling benchmarks. J. Climate, 20, 449–469.

Charney, J. G., and P. G. Drazin, 1961: Propagation of planetary-scale disturbances from the lower into the upper atmosphere. J. Geophys. Res., 66, 83–109.

Cohen, J., M. Barlow, P. J. Kushner, and K. Saito, 2007: Stratosphere–troposphere coupling and links with Eurasian land surface variability. J. Climate, 20, 5335–5343.

Colucci, S. J., and M. E. Kelleher, 2015: Diagnostic comparison of tropospheric blocking events with and without sudden stratospheric warming. J. Atmos. Sci., 72, 2227–2240.

Edmon, H. J., Jr., B. J. Hoskins, and M. E. McIntyre, 1980: Eliassen-Palm cross sections for the troposphere. J. Atmos. Sci., 37, 2600–2616.

Garfinkel, C. I., D. W. Waugh, and E. P. Gerber, 2013: The effect of tropospheric jet latitude on coupling between the stratospheric polar vortex and the troposphere. J. Climate, 26, 2077–2095.

Hannachi, A., T. Woollings, and K. Fraedrich, 2012: The North Atlantic jet stream: A look at preferred positions, paths and transitions. Quart. J. Roy. Meteor. Soc., 138, 862–877.

Hannachi, A., E. A. Barnes, and T. Woollings, 2013: Behaviour of the winter North Atlantic eddy-driven jet stream in CMIP3 integrations. Climate Dyn., 41, 995–1007.

Harada, Y., and T. Hirooka, 2017: Extraordinary features of the planetary wave propagation during the boreal winter 2013/2014 and the zonal wave number two predominance. J. Geophys. Res., 122, 11374–11387.

Hartmann, D. L., J. M. Wallace, V. Limpasuvan, D. W. Thompson, and J. R. Holton, 2000: Can ozone depletion and global warming interact to produce rapid climate change? Proc. Natl. Acad. Sci. USA, 97, 1412–1417.

Haynes, P., 2005: Stratospheric Dynamics. Annu. Rev. Fluid Mech., 37, 263–293.

Iqbal, W., W.-N. Leung, and A. Hannachi, 2018: Analysis of the variability of the North Atlantic eddy-driven jet stream in CMIP5. Climate Dyn., 51, 235–247.
Plumb, R. A., 1985: On the three-dimensional propagation of stationary waves. *J. Atmos. Sci.*, **42**, 217–229.
Scaife, A. A., J. Austin, N. Butchart, S. Pawson, M. Keil, J. Nash, and I. N. James, 2000: Seasonal and interannual variability of the stratosphere diagnosed from UKMO TOVS analyses. *Quart. J. Roy. Meteor. Soc.*, **126**, 2585–2604.
Silverman, B. W., 1981: Using kernel density estimates to investigate multimodality. *J. R. Stat. Soc.*, **43**, 97–99.
Uppala, S. M., P. W. Källberg, A. J. Simmons, U. Andrae, V. Da C. Bechtold, M. Fiorino, J. K. Gibson, J. Haseler, A. Hernandez, G. A. Kelly, X. Li, K. Onogi, S. Saarinen, N. Sokka, R. P. Allan, E. Andersson, K. Arpe, M. A. Balmaseda, A. C. M. Beljaars, L. Van De Berg, J. Bidlot, N. Bormann, S. Caires, F. Chevallier, A. Dethof, M. Dragosavac, M. Fisher, M. Fuentes, S. Hagemann, E. Hólm, B. J. Hoskins, L. Isaksen, P. A. E. M. Janssen, R. Jenne, A. P. Mcnally, J.-F. Mahfouf, J.-J. Morcrette, N. A. Rayner, R. W. Saunders, P. Simon, A. Sterl, K. E. Trenberth, A. Untch, D. Vasiljevic, P. Viterbo, and J. Woollens, 2005: The ERA-40 re-analysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961–3012.
Woollings, T., A. Charlton-Perez, S. Ineson, A. G. Marshall, and G. Masato, 2010a: Associations between stratospheric variability and tropospheric blocking. *J. Geophys. Res.*, **115**, D06108, doi:10.1029/2009JD012742.
Woollings, T., A. Hannachi, and B. Hoskins, 2010b: Variability of the North Atlantic eddy-driven jet stream. *Quart. J. Roy. Meteor. Soc.*, **136**, 856–868.