Interactive comment: Anonymous Referee #1

Summary:

Using JRA-55 reanalysis data, the authors describe an approximately 15-day hiatus (which they term a "short break") in the seasonal strengthening of the Arctic stratospheric polar vortex during late November. They go on to attribute this hiatus to an increase of the planetary wave flux into the stratosphere at this time, itself resulting from cooling over Siberia and an increase in land-sea temperature contrast. The paper is well written, logically structured, and the figures are clear. I think that such an analysis of the seasonal evolution of the stratospheric polar vortex could be of interest for the community, and if this "short break" is a robust feature it could be a useful test of the seasonal evolution of the polar vortex in climate models. However, I have two major concerns, the first being whether this feature is indeed robust, and the second regarding the calculation of anomalies of the seasonal evolution within the paper. I hope that the authors find my comments below to be constructive.

Reply:

Thank you very much for your comments, which were extremely useful for our revision. We have considered your comments carefully, and have been making changes accordingly.

Major comments:

1. The authors state that this "short break" feature is statistically significant at the 99% level using a two-tailed t test (L10-11, P3). I think more information is needed as to exactly how this statistical test was carried out for this to be convincing. Is it testing whether the late November trend is statistically consistent with zero? Or distinct from the trends before or after this period? (It might be a good idea to include both of these tests). Overall it is important to have an idea of whether this feature would persist if we were to have many more years of data? From Fig. 1b it is clear that there is large variability in the strength of the polar vortex in November, and that the short break does not occur every year, hence a reader may be sceptical as to whether this is indeed a robust feature.

I suggest trying a bootstrap test as follows: resample with replacement from the 38 available years (giving say 1000 different 38-year composites). Within these composites then how often is there a zero (or near-zero) trend in late November? Is it more than 95% of the time?

Reply:

Following to your second comment, we have been comparing the observed wind in late November with an expected wind assumed by a sinusoidal seasonal evolution of the same period along with *t*-test. In the revised version, we included these additional results with *t*-test. We used *t*-test for the differences of two means. The difference of early and late November is not statistically significant (t=0.28), however, that of late November and early December is significant at 95% level (t=2.11). The significant at 99% level in submitted version was mistaken. We are sorry for our mistake.

Thank you for your suggestion about a bootstrap test. However, we consider that think *t*-test for the difference of two means is suitable for our study.

2. The authors define a deviation from 'expected' seasonal evolution as that from a linear trend. However, I would expect that the zeroth order expectation of a seasonal evolution would be sinusoidal (since the seasonal evolution of solar forcing is sinusoidal). Because of this, there is potential that the use of a linear trend is somewhat over-estimating anomalies. I encourage the authors to either calculate anomalies from a sinusoidal evolution (or at least demonstrate that this is not significantly different from a linear evolution).

Reply:

We additionally calculated the sinusoidal regression analysis. The deviation defined as actual climatological meteorological fields in late November from those of an expected sinusoidal seasonal evolution during the same period.

The results were almost the same as their linear seasonal evolutions. The difference of late November and the expected by sinusoidal seasonal evolution is statically significant at the 90% confidence level. We changed figures in the revised version.

Minor comments:

1. Fig 1a shows the maximum in zonal-mean zonal wind at 50hPa to occur at about 60N, but throughout the paper the "PNJ index" is taken to be at 65N (and the PNJ is described as being at 65N in the abstract). I think some motivation behind this choice should be included in the paper, or the PNJ index taken to be at 60N.

Reply:

Fig. A1 shows that the short break is relatively weak at 60°N. Referring to your suggestion, we redefined that the PNJ index is taken to be the meridional average in 60-80N, not in a single latitude at 65N. We have confirmed that the short break can be seen even by this definition. These results were added in the revised version.

2. L22-23, P1 "The signal further propagates into the troposphere to produce the Arctic Oscillation. . .". This makes it sound as though the AO is entirely produced by stratospheric variability. In fact, the AO would exist in the absence of a stratosphere. I suggest replacing with something like "PNJ variability can influence the AO".

Reply:

We changed "produce" to "influence" in the revised version.

3. Section 2 is very short. I think appendix A could be included with this section since it is often referred to in the following analysis.

Reply:

We moved appendix A into Section 2 in the revised version.

4. L12, P3 "We note the signal throughout the whole stratosphere". What exactly is meant by 'the signal'? Is there a decrease in the rate of strengthening of the vortex over the whole stratosphere?

Reply:

The signal means the short break of the PNJ. We added this sentence in the revised version.

5. The authors state that the momentum budget approximately closes ("A=B+C" L3, P4). This could easily be shown by adding a "B+C" line in Fig. 2.

Reply:

We added the line of the sum of Term B and Term C in Fig. 2 (black line) in the revised version.

6. L3-5 This speculation about changes in the frequency of SSW events and the relation to sea ice changes seems quite disconnected with the rest of the paper (i.e. it doesn't relate to the results of this study). I suggest removing this sentence.

Reply:

We removed this sentence in the revised version.

Interactive comment: Anonymous Referee #2

The authors present a concise discussion of an apparent feature in the climatological early-winter development of the Arctic stratospheric polar vortex during which the seasonal acceleration of the zonal mean zonal wind is slowed for several weeks in mid-November. This slow down is associated with enhanced upward wave fluxes at 100 hPa that are in turn argued to be connected to a climatological enhancement of a tropospheric trough over Siberia. The paper is generally well written and the arguments are for the most part clearly made.

Reply:

Thank you very much for your comments, which were extremely helpful for our revision. We have considered your comments carefully, and have been making changes accordingly.

I have several more general comments:

It is not immediately clear to me that this feature is in fact 'climatological' in the sense of being common in some sense to all years, or whether it is a result of early warmings (not necessarily major ones) that have happened to cluster in late November such that consideration of a longer record would reveal a smoother evolution. There is some text arguing that the feature is statistically significant but not enough details are given to evaluate this claim (e.g what precisely is the random variable being tested, and what is the null hypothesis).

This would seem to be a pretty central issue for this paper to clarify given that the text mostly argues that this is a climatological feature. If it really is a feature of the climatology, models should recover it and this could (and should) be explored. However, appendix C seems to walk back on this claim suggesting that the feature could be a result of early warmings which is a bit confusing.

Reply:

Many papers studying on the extreme weathers or extreme events usually show anomaly fields from climatological mean. This paper does not show anomaly fields from the climatology, but those of the long-year mean seasonal march as climate. Readers may consider that this paper is anomaly fields from climatological mean. To avoid misleading, we repeatedly use the term of 'climatology' without explicitly showing our definition of the climatology. We defined climatological values as this 38-year average values. We explicitly wrote the definition in the revised version.

The warmings do not always occur in late November in each year. In some years the short break occurs in the middle of November, and in some years the short break occurs in early December, or no slow down from November to early December. But on average – this is the climatology in our definition -- the short break is largest in late November. In the revised version, we carefully used the term of climatology.

A second issue is that I would like to see much more discussion of the literature. Both of the phenomenology of early winter warmings, sometimes called 'Canadian' warmings. See papers by Gloria Manney and Karen Labitzke, for instance, which are in fact referenced but only at the end of Appendix C – these should be part of the introduction! But also of some work with mechanistic models – see the fourth point below; Taguchi and Yoden 2002 Fig. 7 also seems quite relevant.

Reply:

We cited these papers in the revised version, and we will move Appendix C to the main text.

This brings me to a third point which is that the figures and discussion in the appendix should be largely incorporated into the main text as they are central to the main argument.

Reply:

We moved appendix A into Section 2 in the revised version.

A fourth and final point is that it's not so obvious to me that the explanation for this 'short break' is in fact due to some feature of the tropospheric circulation. I'm not super convinced by the analysis connecting the 100 hPa wave activity flux to the Siberian trough (see specific comments given below)–in fact this kind of early-winter feature is not uncommon to see in mechanistic models (for instance see Fig. 1 of Gray et al. 2003) that have highly simplified tropospheric evolutions. Even in the figures presented in the present manuscript, the tropospheric flow features in late November are pretty subtle features – why should the heating associated with land-sea contrasts exhibit a climatological feature with a timescale of a few weeks? On the other hand the seasonal transition from easterly to westerly winds in the stratosphere is a highly non-linear transformation in terms of the ability for waves to propagate into the stratosphere (see Plumb 1989 for a very relevant discussion of this point). It seems to me that an alternative reason for this climatological feature is that the onset of winter-time westerlies permits wave activity that is always present in the troposphere to propagation upwards - this propagation time (along with the timescale for the response) could be an explanation for the 2 week timescale of the feature.

The first three of the points given above need to be substantially addressed in order for this work to be publishable. I would further encourage the authors to consider and discuss the possible relevance of the final point.

Reply:

That is a good point. The stratospheric circulation is affected not only by the troposphere but also from the stratospheric conditions. One of the well-known internal effects is the effect of the QBO. Generally, in the easterly phase of the QBO, the stratospheric vortex is week in mid-winter. We compared the difference between the zonal-mean zonal wind, EP flux, and the flux divergence with the year of easterly phase of the QBO (QBO-E) and westerly phase of that (QBO-W). The short break during QBO-E is clearer than during QBO-W. However, the difference is not statistically significant. We added this result and figures in the revised version.

Specific Comments:

It would help to provide a clear definition of what 'climatological' means – physically it might be clearer to define the reference evolution as 'radiative' (see discussion in chapter 7 of Andrews Holton and Leovy 1987). I would think a sinusoidal reference state would be more appropriate than a linear one.

Reply:

Following to your suggestion, we executed regression analyses with sinusoidal reference state. The deviation is therefore defined as actual meteorological fields in late November from those of the expected sinusoidal seasonal evolution during the same period. The results were almost the same as its linear seasonal evolution. We changed corresponding figures in the revised version.

p 1. l 10: This is a pretty sweeping statement - please justify with multiple specific citations or delete. (The comment applies also to p2 l 5)

Reply:

We added multiple citations in the revised version.

p 3. l 10. This statement needs to be much more clearly justified. need to justify statistical significance of this 'blip' - include pre-satellite period; radiosondes alone do a pretty good job of constraining the zonal mean state. How many winters is this break apparent in? interannual variability still looks pretty broad on the basis of Fig. 1b.

Reply:

We used *t*-test for the differences of two means. The difference of early and late November is not statistically significant (t=0.28), however, that of late November and early December is significant at 95% level (t=2.11). We further investigated an additional analysis, that is the difference of late November and the expected sinusoidal seasonal evolution of the same period.

We investigated how many winters the short break occurred. The definition of the short break of the PNJ in each year was negative deviation from the PNJ that is expected by sinusoidal seasonal evolution. The number of the negative years were 23 years (Relative frequency is 0.61).

We added this additional results in the revised version.

p. 3 l 15: These bumps are associated with stratospheric sudden warmings - while I appreciate the context, but calling them 'extreme short breaks' comes across as a bit unaware of the existing literature.

Reply:

We changed "extreme short breaks" to "short breaks (SSWs)" in the revised version.

Fig. 4, p 17 l15: The problem with the use of 100 hPa wave activity flux measures as indications of the wave source regions is that the wave activity at 100 hPa is only very weakly correlated with anomalies within the troposphere (see de la Camara et al. 2017, Fig. 15), especially on sub-monthly timescales. A big reason for this is that the long waves that propagate into the stratosphere are dwarfed by wave activity variability associated with waves that are trapped with the troposphere. This seems pretty consistent with Figs. A1d and A3d which show downward anomalies almost uniformly over the highlighted Siberian region in the troposphere below the upward wave flux anomaly at 100 hPa.

It could be helpful to show the wave 1 and 2 wave activity fluxes down to the surface.

Reply:

We investigated the vertical component of the wave activity fluxes (figure 4) with wave numbers 1 and 2. We added these figures in the revised version.

References:

R. A. Plumb, (1989) On the seasonal cycle of stratospheric planetary waves, PAGEOPH, 130, pp. 233-242.

L. J. Gray et al. (2003) Flow regimes in the winter stratosphere of the northern hemisphere, Q. J. R. Meteorol. Soc. 129, pp. 925–945.

M. Taguchi and S. Yoden (2002) Internal Interannual Variability of the Troposphere–Stratosphere Coupled System in a Simple Global Circulation Model. Part II: Millennium Integrations. J. Atmos. Sci., 59, pp. 3037-3050.

A. de la Camara et al. (2017) Sensitivity of Sudden Stratospheric Warmings to Previous Stratospheric Conditions J. Atmos. Sci., 74, pp. 2857-2877.

Reply:

Above papers were cited in the revised manuscript.

Interactive comment: G. Manney

This seems to be an interesting and useful paper overall, and may be the first long-term climatology to focus on the evolution of the zonal mean winds in Arctic fall/early winter. However, I do feel that the abstract and introduction misrepresent the state of knowledge and the literature on early winter in the stratosphere. The interannual variability in November and December in the NH, while less than that later in winter, is substantial and has been widely reported, at least since the work of Labitzke et al (1977, 1982). Numerous studies have described early winter minor warmings (see Manney et al, 2002, and numerous references therein) and shown them to be very common (occur-ring in nearly every Arctic fall/winter season). It follows from the ubiquity of early winter minor warmings that the strengthening of the PNJ in fall/early winter is not monotonic (see, e.g., Figure 10 of Manney et al, 2002), and nowhere in the literature have I seen it suggested that it might be. The statement (in the abstract and introduction) that “It is generally acknowledged that the climatological PNJ speed increases monotonically from October to December” is thus contradicted by the literature. I believe this paper would benefit greatly from a more complete and balanced summary of the literature on the early winter circulation in the NH, and from some brief discussion of how the results shown here relate to those in previous work that showed early winter zonal mean wind evolution for individual winters and/or climatologies for shorter periods of years than the current work.

Reply:

Thank you very much for your comments, which were extremely useful for our revision. We have considered your comments carefully, and have been making changes accordingly.

Thanks to you, we knew numerous studies have described early winter minor warmings. However, these studies are based on a case study or focused on a statistical analysis only within the occurrence of minor warmings in early winter. Our view of the PNJ is from the climatological seasonal march from October through April. No previous studies explicitly showed this short break viewing from extra-seasonal evolution. This is advantage to the previous studies. Following to your suggestion, we cited your paper along with other papers showing minor warmings in the introduction section in the revised version.

References:

(The Labitzke et al papers are already cited in this manuscript.)

Manney, G.L.,W.A. Lahoz, J.L. Sabutis, A. O’Neill, and L. Steenman-Clark, Simulations of fall and early winter in the stratosphere, Q. J. Roy. Meteorol. Soc., 128, 2205–2237, 2002.

Ando_etal_2017_ACP_manuscript_revised1_ver20180307_diff.docx

Main document changes and comments

Page 1: Deleted	**Author**

monotonically

Page 1: Inserted	**Author**

the climatological seasonal march. We

Page 1: Inserted	**Author**

Brasefield, 1950; Palmer, 1959;

Page 1: Inserted	**Author**

Schoeberl and Newman 2015;

Page 1: Inserted	**Author**

occasionally

Page 1: Deleted	**Author**

produce

Page 1: Inserted	**Author**

influence

Page 1: Deleted	**Author**

).

Page 1: Inserted	**Author**

; Hitchcock and Simpson, 2014; Kidston et al. 2015).

Page 2: Inserted	**Author**

Thompson and Wallace, 2001; Angell, 2006;

Page 2: Deleted	**Author**

Thompson and Wallace, 2001

Page 2: Inserted	**Author**

Cohen et al., 2013

Page 2: Deleted	**Author**

).

Page 2: Inserted	**Author**

; Hamilton, 1999; Labizke and van Loon, 1999).

Page 2: Inserted **Author**

Limpasuvan et al., 2004;

Page 2: Inserted **Author**

; Hu et al., 2014

Page 2: Inserted **Author**

Ambaum et al., 2002; Thompson et al., 2002;

Page 2: Inserted **Author**

Reichler et al., 2012; Butler et al., 2014; Kim et al., 2014; Nakamura et al., 2015;

Page 2: Deleted **Author**

2015

Page 2: Inserted **Author**

2015; Hoshi et al, 2017; Polvani et al., 2017; Kretschmer et al., 2018

Page 2: Deleted **Author**

of the PNJ

Page 2: Deleted **Author**

of the PNJ

Page 2: Deleted **Author**

monotonically

Page 2: Deleted **Author**

climatological

Page 2: Inserted **Author**

the

Page 2: Deleted **Author**

monotonically

Page 2: Deleted **Author**

.

Page 2: Inserted **Author**

(e.g., Kodera and Kuroda, 2002; Waugh and Polvani, 2010; Karpechko and Manzini, 2012; Yamashita et al., 2015; Maury et al., 2016).

Page 2: Deleted **Author**

found

Page 2: Inserted **Author**

detected

Page 2: Deleted **Author**

of the climatological PNJ

Page 2: Inserted **Author**

The early winter warming has been known as Canadian Warmings (CWs; Labitzke, 1977, 1982). Numerous studies have described CWs (e.g., Labitzke et al. 1977, 1982; Manney et al. 2001, 2002; Fig. 7 in Taguchi and Yoden, 2002). However, no previous studies explicitly showed this short break viewing from climatological extra-seasonal evolution. Manney et al. (2001) indicated that CWs that occurred in November 2000 may have had a profound impact on the development of a vortex and a low-temperature region in the lower stratosphere. Waugh and Randel (1999) presented an overview of climatological PNJ. They found that the PNJ becomes more distorted and its position shifts away from the pole from October through December. They also recognized a climatological southward shift of the center of the polar vortex in late November (Fig.

Page 2: Moved from page 24 (Move #1) **Author**

4d in Waugh and Randel, 1999).

Page 2: Inserted **Author**

Page 2: Moved from page 24 (Move #2) **Author**

The shift recognized by Waugh and Randel (1999) may be related to the occurrence of wavenumber 1-type minor SSW events (CWs) in late November (Labitzke and Naujokat, 2000; Manney et al.,

Page 2: Inserted **Author**

2001). These studies implicitly remind us that the CWs may affect the short break of climatological PNJ. Moreover, small-amplitude warmings occur during late November (

Page 3: Moved from page 24 (Move #3) **Author**

Maury et al., 2016).

Page 3: Deleted **Author**

The climatological short break in late November might possibly have been known, but it has not yet been addressed in terms of dynamic meteorology. We

Page 3: Inserted **Author**

Therefore, the late November climatological short break is related to early winter SSW events.
However, these studies are based on a case study or focused on a statistical analysis only within the occurrence of minor warmings. Our view of the PNJ is from the climatological seasonal march from October through April.

No previous studies explicitly showed this climatological short break, nor have yet been addressed in terms of dynamic meteorology. We thus

Page 3: Deleted Author

.

Page 3: Inserted Author

and analysis methods.

Page 3: Deleted Author

climatological

Page 3: Inserted Author

2.1 Data

Page 3: Inserted Author

2.2 Transformed Eulerian Mean (TEM) Diagnostics

Page 3: Deleted Author

A3 in Appendix A

Page 3: Inserted Author

3

Page 3: Deleted Author

in Appendix A.

Page 3: Inserted Author

as follows:

Page 3: Moved from page 21 (Move #4) Author

Eliassen-Palm (EP) flux analysis is widely used in dynamic meteorology to diagnose wave and zonal-mean flow interactions. The EP flux shows the propagation of Rossby (planetary) waves (Andrews and McIntyre, 1976). The meridional (F^{ϕ}) and vertical (F^{z}) components of the EP flux ($\mathbf{F}$) are defined as follows:

$F^{\phi} \equiv \rho_0 a\cos\phi\left[(\partial\bar{u}/\partial z)\,\overline{v'\theta'}/\bar{\theta}_z - \overline{u'v'}\right]$ (

Page 3: Inserted Author

1)

Page 3: Moved from page 21 (Move #5) Author

$F^{z} \equiv \rho_0 a\cos\phi\{[f - (a\cos\phi)^{-1}\,\partial(\bar{u}\cos\phi)/\partial\phi]\,\overline{v'\theta'}/\bar{\theta}_z - \overline{w'u'}\},$ (

Page 3: Inserted **Author**

2)

Page 3: Moved from page 21 (Move #6) **Author**

where a is the radius of the Earth, f is the Coriolis parameter, ϕ is latitude, θ is potential temperature, u is zonal wind, and v is meridional wind. Overbars denote zonal means, primes denote anomaly from the zonal mean, z is a log-pressure coordinate, and ρ_0 is air density. $\bar{\theta}_z = \partial\bar{\theta}/\partial z$ is computed from the zonal mean of the potential temperature in log-pressure coordinates. The eddy-flux terms $u'v'$ and $v'\theta'$ are computed from the zonal anomalies in the 6-hourly data, and the product is zonally averaged and then time averaged to obtain 15-day means.

We used the primitive form of the Transformed Eulerian Mean (TEM) momentum equation to examine the diagnostics of the zonal-mean momentum (e.g., Andrews et al., 1987; Holton and Hakim, 2012; Vallis, 2017):

Page 4: Moved from page 21 (Move #7) **Author**

$\partial\bar{u}/\partial t = \bar{v}^*\{f - (a\cos\phi)^{-1}\partial(\bar{u}\cos\phi)/\partial\phi\} - \bar{w}^*\partial\bar{u}/\partial z + (\rho_0 a\cos\phi)^{-1}\mathbf{\nabla}\cdot\mathbf{F} + \bar{X}$, (

Page 4: Inserted **Author**

3)

Page 4: Moved from page 21 (Move #8) **Author**

(A) (B) (C)

where $\bar{v}^*$ and $\bar{w}^*$ are the meridional and vertical components of the residual mean meridional circulation, $\bar{X}$ is a residual Term that includes internal diffusion and surface friction as well as sub-grid scale forcing such as gravity wave drag.

Page 4: Inserted **Author**

Term A in equation (3

Page 4: Moved from page 21 (Move #9) **Author**

) is the temporal tendency of the zonal-mean zonal wind, Term B is the Coriolis force acting on the residual mean meridional circulation and the meridional advection of zonal momentum, and Term C is the divergence of the EP flux vector, i.e., wave forcing.

Page 4: Inserted **Author**

The vertical component of the 3-dimentional wave activity flux (WAF; Plumb, 1985) at 100 hPa provides a useful diagnostic for identifying the source region of vertically propagating stationary planetary waves. The zonal average of the WAF is the EP flux, so the vertical component of the WAF shows from where the wave propagates to the stratosphere. The eddy terms are computed from the zonal deviations relative to each 15-day mean (i.e., stationary wave component).

Page 4: Deleted	**Author**

climatological

Page 4: Deleted	**Author**

99% level, and the short break in late February is statistically significant at the 95% level (the two-tailed

Page 4: Inserted	**Author**

95% confidence level (*t* test for the differences of two means; late November and early December, that of early and late November is not statistically significant (t=0.28)), and that of late February is not statistically significant (t=0.43; late February and early March, that of early and late February is not statistically significant (t=0.19)) (the two-sided

Page 5: Inserted	**Author**

(the short break of the PNJ)

Page 5: Deleted	**Author**

65

Page 5: Inserted	**Author**

60-80

Page 5: Deleted	**Author**

, following Kodera and Koide (1997).

Page 5: Inserted	**Author**

because the short break can be clearly seen in these latitudes (Fig. 1a).

Page 5: Deleted	**Author**

the climatological 15-day running mean of

Page 5: Deleted	**Author**

of the PNJ

Page 5: Deleted	**Author**

extreme

Page 5: Inserted	**Author**

(SSWs)

Page 5: Deleted	**Author**

.

Page 5: Inserted **Author**

, that is, the short breaks do not always occur in late November and early February in each year.

Page 5: Inserted **Author**

(38-year average – this is the climatology in our definition)

Page 5: Deleted **Author**

of the PNJ

Page 5: Deleted **Author**

and early February

Page 5: Deleted **Author**

these two periods

Page 5: Inserted **Author**

late November

Page 5: Deleted **Author**

it is common that the cause of the February short break corresponds to the occurrence of SSWs, and because

Page 5: Deleted **Author**

more

Page 5: Inserted **Author**

is the only one that is

Page 5: Deleted **Author**

than that of February, this paper does not target the February short break.

Page 5: Inserted **Author**

.

Page 5: Inserted **Author**

in late November. The numbers of occurrence of the short break

Page 5: Inserted **Author**

is described in Appendix C

Page 5: Deleted **Author**

of PNJ

Page 5: Deleted **Author**

Appendix A,

Page 5: Deleted	Author

A3

Page 5: Inserted	Author

3

Page 5: Deleted	Author

Appendix A).

Page 5: Inserted	Author

Section 2.2; light blue and black lines in Fig. 2b).

Page 5: Deleted	Author

of the PNJ

Page 5: Deleted	Author

A3

Page 5: Inserted	Author

3

Page 5: Deleted	Author

in the seasonal evolution of PNJ

Page 5: Deleted	Author

linear

Page 5: Inserted	Author

sinusoidal

Page 5: Deleted	Author

linear

Page 5: Inserted	Author

sinusoidal

Page 5: Inserted	Author

(since that of solar forcing is sinusoidal (e.g., Andrews et al. 1987))

Page 6: Deleted	Author

$-(\mathcal{A}_{1-15Nov} + \mathcal{A}_{1-15Dec})/2.,$ (1

Page 6: Inserted	Author

$-(\text{sinusoidal regression expression of } \mathcal{A}_{16-30Nov}),$ (4

Page 6: Deleted	Author

$\{(\mathcal{A}_{1-15Nov} + \mathcal{A}_{1-15Dec})/2.\}$

Page 6: Inserted	Author

$(\text{sinusoidal regression expression of } \mathcal{A}_{16-30Nov})$

Page 6: Deleted	Author

linear

Page 6: Inserted	Author

sinusoidal

Page 6: Deleted	Author

,

Page 6: Inserted	Author

(calculated by regression analyses with sinusoidal reference state),

Page 6: Deleted	Author

climatological meteorological

Page 6: Deleted	Author

and A6d

Page 6: Inserted	Author

A6d, A7, and B2). Many studies usually define anomaly fields as the ones from climatological mean, but this paper does not define anomaly fields from the climatology. The definition of the anomaly field that those of the long-year mean seasonal march (we called "deviation"). The dark blue dotted line in Fig. 3a shows the sinusoidal regression expression of the PNJ index. The short break is statistically significant at the 90% confidence level (*t* test for the differences; late November and the expected by sinusoidal seasonal evolution

Page 6: Deleted	Author

climatological

Page 6: Deleted	Author

linear

Page 6: Inserted	Author

sinusoidal

Page 6: Deleted	Author

in late November

Page 6: Deleted **Author**

) during late November.

Page 6: Inserted **Author**

).

Page 6: Deleted **Author**

in the seasonal evolution

Page 6: Deleted **Author**

climatological

Page 6: Deleted **Author**

B1

Page 6: Inserted **Author**

A1

Page 6: Deleted **Author**

B2, B3, B4

Page 6: Inserted **Author**

A2, A3, A4

Page 6: Deleted **Author**

B5

Page 6: Inserted **Author**

A5

Page 6: Deleted **Author**

1

Page 6: Inserted **Author**

4

Page 6: Deleted **Author**

1

Page 6: Inserted **Author**

4

Page 6: Deleted **Author**

wave activity flux

Page 6: Deleted	Author

; Plumb, 1985

Page 6: Deleted	Author

climatological

Page 7: Deleted	Author

of the WAF

Page 7: Deleted	Author

1

Page 7: Inserted	Author

4

Page 7: Deleted	Author

in late November

Page 7: Deleted	Author

of PNJ in late November.

Page 7: Inserted	Author

.

Page 7: Deleted	Author

climatological

Page 7: Inserted	Author

The vertical component of the WAF with wave planetary-scale components is described in Appendix A6.

Page 7: Deleted	Author

of the climatological 15-day running means

Page 8: Deleted	Author

climatological

Page 8: Deleted	Author

climatological

Page 8: Deleted	Author

of the PNJ

Page 8: Deleted	Author

The short break of the PNJ is possibly due to the occurrence of SSW events. SSW can occur even in November, although its amplitude is smaller in November than in late winter (Charlton and Polvani, 2007; Maury et al., 2016). The relationship between the short break of the PNJ and SSW in early winter is discussed in detail in Appendix C.

Page 8: Inserted **Author**

Some studies have described the PNJ variations are related to the quasi-biennial oscillation (OBO; Baldwin et al. 2001) (e.g., Holton and Tan, 1980, 1982; Gray et al. 2003; Anstey and Shepherd 2014). This might also affect to the short break, and is discussed in detail in Appendix B. The seasonal evolution from easterly to westerly winds in the stratosphere is a highly non-linear transformation in terms of the ability for waves to propagate into the stratosphere (Plumb 1989). A hidden alternative mechanism may control the short break, but it is out of the scope of present study.

Page 8: Deleted **Author**

found

Page 8: Inserted **Author**

detected

Page 8: Deleted **Author**

climatological

Page 8: Deleted **Author**

climatological

Page 8: Deleted **Author**

climatological

Page 8: Deleted **Author**

late November

Page 8: Deleted **Author**

climatological

Page 8: Deleted **Author**

The short break in the climatological PNJ during late February and its long-term trend are interesting topics for future research. SSW events have occurred almost every year since 2000 (Reichler et al., 2012), and this recent frequent occurrence of SSW events might be associated with Arctic sea ice losses (e.g., Kim et al., 2014; Nakamura et al., 2015; Hoshi et al., 2017). In the future, the typical short break of the PNJ should be examined in a composite analysis as well.

Page 9: Deleted **Author**

was

Page 9: Inserted **Author**

and the Generic Mapping Tools (GMT) were

Page 9: Inserted **Author**

Ambaum, M. H. P. and Hoskins, B. J.: The NAO troposphere-stratosphere connection, J. Clim., 15(14), 1969–1978, doi:10.1175/1520-0442(2002)015<1969:TNTSC>2.0.CO;2, 2002.

Page 9: Inserted **Author**

Angell, J. K.: Changes in the 300-mb north circumpolar vortex, 1963–2001. J. Clim., 19, 2984–2995, doi:10.1175/JCLI3778.1, 2006.

Anstey, J. A. and Shepherd, T. G.: High-latitude influence of the quasi-biennial oscillation, Q. J.

Page 9: Moved from page 11 (Move #10) **Author**

R.

Page 9: Inserted **Author**

Meteorol. Soc., 140(678), 1–21, doi:10.1002/qj.2132, 2014.

Page 9: Inserted **Author**

Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K., Haynes, P. H., Randel, W. J., Holton, J. R., Alexander, M. J., Hirota, I., Horinouchi, T., Jones, D. B. A., Kinnersley, J. S., Marquardt, C., Sato, K. and Takahashi, M.: The quasi-biennial oscillation, Rev. Geophys., 39(2), 179–229, doi:10.1029/1999RG000073, 2001.

Page 10: Inserted **Author**

Brasefield, C. J.: Winds and temperatures in the lower stratosphere. J. Meteor., 7, 66–69, doi:10.1175/1520-0469(1950)007<0066:WATITL>2.0.CO;2, 1959.

Butler, A. H., Polvani, L. M. and Deser, C.: Separating the stratospheric and tropospheric pathways of El Niño–Southern Oscillation teleconnections, Environ

Page 10: Moved from page 11 (Move #11) **Author**

. Res. Lett.,

Page 10: Inserted **Author**

9(2), 24014, doi:10.1088/1748-9326/9/2/024014, 2014.

Page 10: Inserted **Author**

Cohen, J.; Jones, J.; Furtado, J. C.; and Tziperman, E.: Warm Arctic, cold continents: A common pattern related to Arctic sea ice melt, snow advance, and extreme winter weather, Oceanography, 26(4), 150–160, doi:10.5670/oceanog.2013.70, 2013.

Page 10: Inserted **Author**

de la Cámara, A., Albers, J. R., Birner, T., Garcia, R. R., Hitchcock, P., Kinnison, D. E. and Smith, A. K.: Sensitivity of Sudden Stratospheric Warmings to Previous Stratospheric Conditions, J. Atmos. Sci., 74(9), 2857–2877, doi:10.1175/JAS-D-17-0136.1, 2017.

Page 10: Inserted **Author**

Gray, L. J., Sparrow, S., Juckes, M., O'Neill, A. and Andrews, D. G.: Flow regimes in the winter stratosphere of the northern hemisphere, Q. J. R. Meteorol. Soc., 129, 925–945, doi:10.1256/qj.02.82, 2003.

Hamilton, K.: Dynamical coupling of the lower and middle atmosphere: Historical background to current research, J. Atmos. Solar-Terrestrial Phys., 61(1–2), 73–84, doi:10.1016/S1364-6826(98)00118-7, 1999.

Page 11: Inserted **Author**

Hitchcock, P. and Simpson, I. R.: The Downward Influence of Stratospheric Sudden Warmings, J. Atmos. Sci., 71(10), 3856–3876, doi:10.1175/JAS-D-14-0012.1, 2014.

Page 11: Deleted **Author**

Hoshi, K., Ukita, J., Honda, M., Iwamoto, K., Nakamura, T., Yamazaki, K., Dethloff, K., Jaiser,

Page 11: Inserted **Author**

Holton, J. R. and Tan, H.-C.: The Influence of the Equatorial Quasi-Biennial Oscillation on the Global Circulation at 50 mb, J. Atmos. Sci., 37(10), 2200–2208, doi:10.1175/1520-0469(1980)037<2200:TIOTEQ>2.0.CO;2, 1980.

Holton, J. R. and Tan, H.-C.: The Quasi-Biennial Oscillation in the Northern Hemisphere Lower Stratosphere, J. Meteorol. Soc. Japan. Ser. II, 60(1), 140–148, doi:10.2151/jmsj1965.60.1_140, 1982.

Hu, J., Ren, R., and Xu, H.: Occurrence of Winter Stratospheric Sudden Warming Events and the Seasonal Timing of Spring Stratospheric Final Warming. J. Atmos. Sci., 71, 2319–2334, doi:10.1175/JAS-D-13-0349.1, 2014.

Page 11: Moved to page 9 (Move #10) **Author**

R.

Page 11: Deleted **Author**

and Handorf, D.: Poleward eddy heat flux anomalies associated with recent Arctic sea ice loss, Geophys

Page 11: Moved to page 10 (Move #11) **Author**

. Res. Lett.,

Page 11: Deleted **Author**

44(1), 446–454, doi:10.1002/2016GL071893, 2017.

Page 11: Inserted **Author**

Karpechko, A. Y. and Manzini, E.: Stratospheric influence on tropospheric climate change in the Northern Hemisphere, J. Geophys. Res. Atmos., 117(5), 1–14, doi:10.1029/2011JD017036, 2012.

Kidston, J., Scaife, A. a., Hardiman, S. C., Mitchell, D. M., Butchart, N., Baldwin, M. P. and Gray, L. J.: Stratospheric influence on tropospheric jet streams, storm tracks and surface weather, Nat. Geosci., 8(6), 433–440, doi:10.1038/ngeo2424, 2015.

Page 11: Deleted **Author**

Koide, H.: Spatial and seasonal characteristics of recent decadal trends in

Page 11: Inserted **Author**

Kuroda, Y.: Dynamical response to

Page 11: Deleted **Author**

northern hemispheric troposphere and stratosphere

Page 11: Inserted **Author**

solar cycle

Page 11: Deleted **Author**

. Atmos., 102(D16), 19433–19447

Page 11: Inserted **Author**

., 107(D24), 4749

Page 11: Deleted **Author**

97JD01270, 1997.

Page 11: Inserted **Author**

2002JD002224, 2002.

Page 12: Inserted **Author**

Kretschmer, M., Coumou, D., Agel, L., Barlow, M., Tziperman, E. and Cohen, J.: More-Persistent Weak Stratospheric Polar Vortex States Linked to Cold Extremes, Bull. Am. Meteorol. Soc., 99(1), 49–60, doi:10.1175/BAMS-D-16-0259.1, 2018.

Page 12: Inserted **Author**

Labiztke, K., and van Loon, H.: The Stratosphere: Phenomena, History, and Relevance, 179 pp., Springer, New York, 1999.

Page 12: Inserted **Author**

Limpasuvan, V., Thompson, D. W. J. and Hartmann, D. L.: The life cycle of the Northern Hemisphere sudden stratospheric warmings, J. Clim., 17(13), 2584–2596, doi:10.1175/1520-0442(2004)017<2584:TLCOTN>2.0.CO;2, 2004.

Page 12: Inserted **Author**

Manney, G. L., Lahoz, W. A., Sabutis, J. L., O'neill, A. and Steenman-Clark, L.: Simulations of fall and early winter in the stratosphere, Q. J. R. Meteorol. Soc., 128, 2205–2237, doi:10.1256/qj.01.88, 2002.

Page 13: Inserted	**Author**

Schoeberl, M. R. and Newman, P. A.: Middle atmosphere: Polar vortex, Encyclopedia of Atmospheric Sciences, 2nd edition, 12–17, Elsevier, Amsterdam, doi:10.1016/B978-0-12-382225-3.00228-0, 2015.

Palmer, C. E.: The stratospheric polar vortex in winter. J. Geophys. Res., 64, 749–764, doi:10.1029/JZ064i007p00749, 1959.

Page 13: Inserted	**Author**

Plumb, R. A.: On the seasonal cycle of stratospheric planetary waves, Pure Appl. Geophys. PAGEOPH, 130(2–3), 233–242, doi:10.1007/BF00874457, 1989.

Polvani, L. M., Sun, L., Butler, A. H., Richter, J. H. and Deser, C.: Distinguishing stratospheric sudden warmings from ENSO as key drivers of wintertime climate variability over the North Atlantic and Eurasia, J. Clim., 30(6), 1959–1969, doi:10.1175/JCLI-D-16-0277.1, 2017.

Page 13: Inserted	**Author**

Taguchi, M. and Yoden, S.: Internal Interannual Variability of the Troposphere–Stratosphere Coupled System in a Simple Global Circulation Model. Part II: Millennium Integrations, J. Atmos. Sci., 59(21), 3037–3050, doi:10.1175/1520-0469(2002)059<3037:IIVOTT>2.0.CO;2, 2002.

Page 13: Inserted	**Author**

Thompson, D. W. J., Baldwin, M. P. and Wallace, J. M.: Stratospheric connection to Northern Hemisphere wintertime weather: Implications for prediction, J. Clim., 15(12), 1421–1428, doi:10.1175/1520-0442(2002)015<1421:SCTNHW>2.0.CO;2, 2002.

Page 14: Inserted	**Author**

and Polvani, L. M.: Stratospheric polar vortices. The Stratosphere: Dynamics, Transport, and Chemistry, Geophys. Monogr., 190, Amer. Geophys. Union, 43–57, doi:10.1029/2009GM000887, 2010.

Waugh, D. W.

Page 14: Inserted	**Author**

Yamashita, Y., Akiyoshi, H., Shepherd, T. G. and Takahashi, M.: The Combined Influences of Westerly Phase of the Quasi-Biennial Oscillation and 11-year Solar Maximum Conditions on the Northern Hemisphere Extratropical Winter Circulation, J. Meteorol. Soc. Japan. Ser. II, 93(6), 629–644, doi:10.2151/jmsj.2015-054, 2015.

Page 15: Deleted	**Author**

Page 15: Inserted	Author

60-80

Page 15: Deleted	Author

1b

Page 15: Inserted	Author

1b); the sinusoidal regression expression of the PNJ index ($\hat{f}(t) = 10.36\sin(2\pi t/365 + 1.54) + 7.52$ (t=1: 01JAN), dark blue dotted line); the standard error of the PNJ index (gray shading

Page 15: Deleted	Author

A3

Page 15: Inserted	Author

3

Page 15: Deleted	Author

A3

Page 15: Inserted	Author

3

Page 15: Deleted	Author

A3

Page 15: Inserted	Author

3

Page 15: Inserted	Author

the sum of Term B and Term C (black line);

Page 15: Deleted	Author

Red stars indicate

Page 15: Inserted	Author

Blue cross mark indicates

Page 15: Deleted	Author

early

Page 15: Inserted	Author

late

Page 15: Inserted	Author

expected by sinusoidal seasonal evolution,

Page 15: Deleted	Author

early December,

Page 15: Deleted **Author**

, and the blue cross mark indicates the mean of the early November and early December values.

Page 15: Inserted **Author**

.

Page 15: Deleted **Author**

1

Page 15: Inserted **Author**

4

Page 15: Deleted **Author**

linear

Page 15: Inserted **Author**

sinusoidal

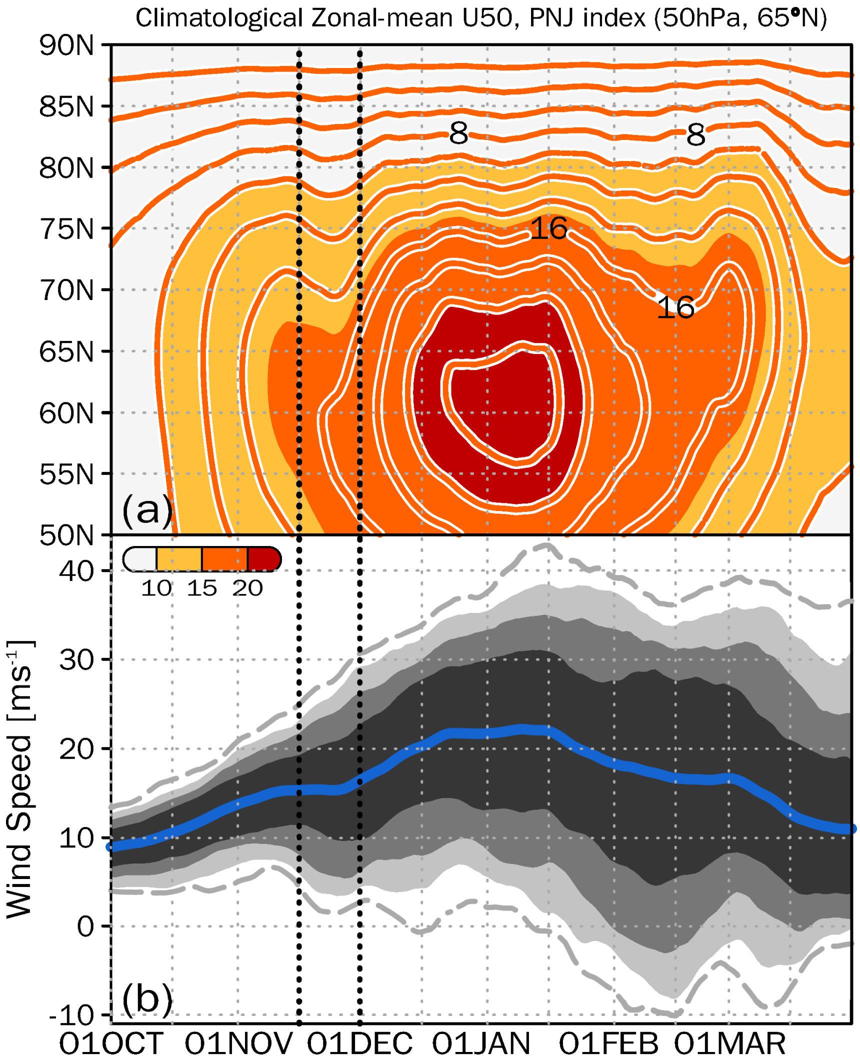
Page 15: Deleted **Author**

1

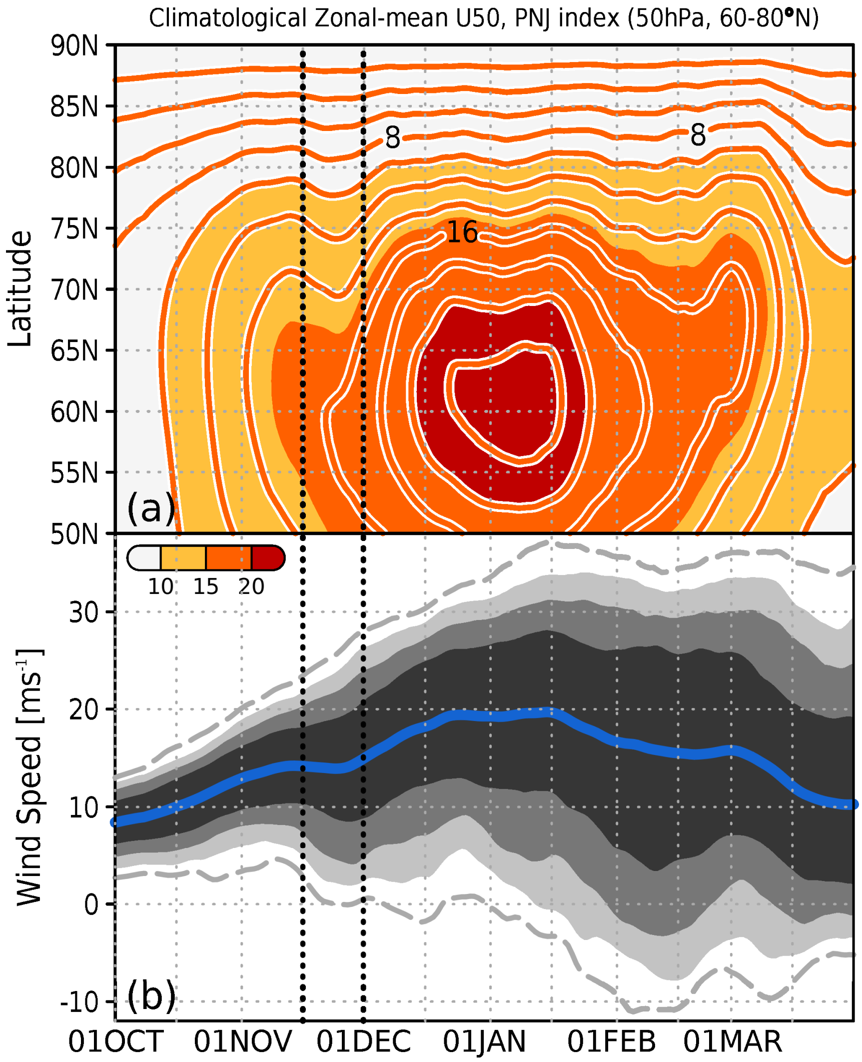
Page 15: Inserted **Author**

4

Page 16: Deleted **Author**



Page 16: Inserted	Author



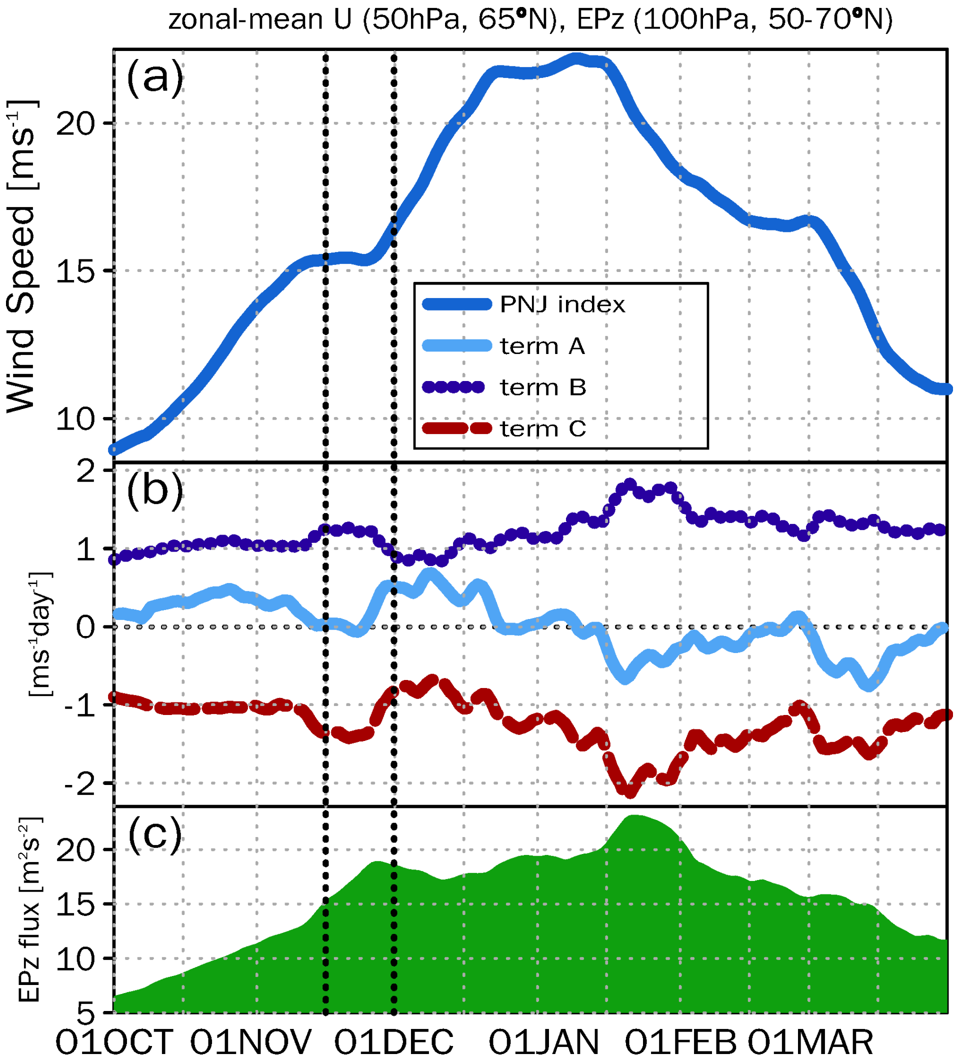
Page 16: Deleted	Author

65

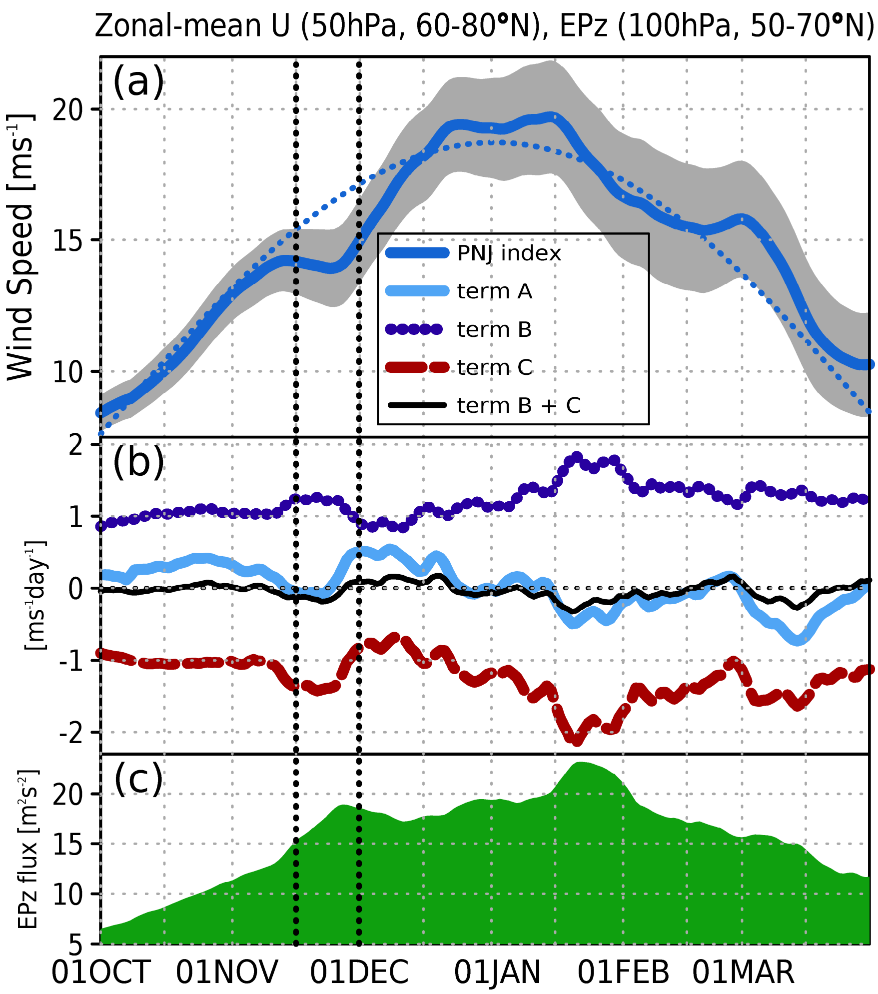
Page 16: Inserted	Author

60-80

Page 17: Deleted	Author



Page 17: Inserted **Author**



Page 17: Deleted	Author

1b

Page 17: Inserted	Author

1b); the sinusoidal regression expression of the PNJ index ($\hat{f}(t) = 10.36\sin(2\pi t/365 + 1.54) + 7.52$ (t=1: 01JAN), dark blue dotted line); the standard error of the PNJ index (gray shading

Page 17: Deleted	Author

A3

Page 17: Inserted	Author

3

Page 17: Deleted	Author

A3

Page 17: Inserted	Author

3

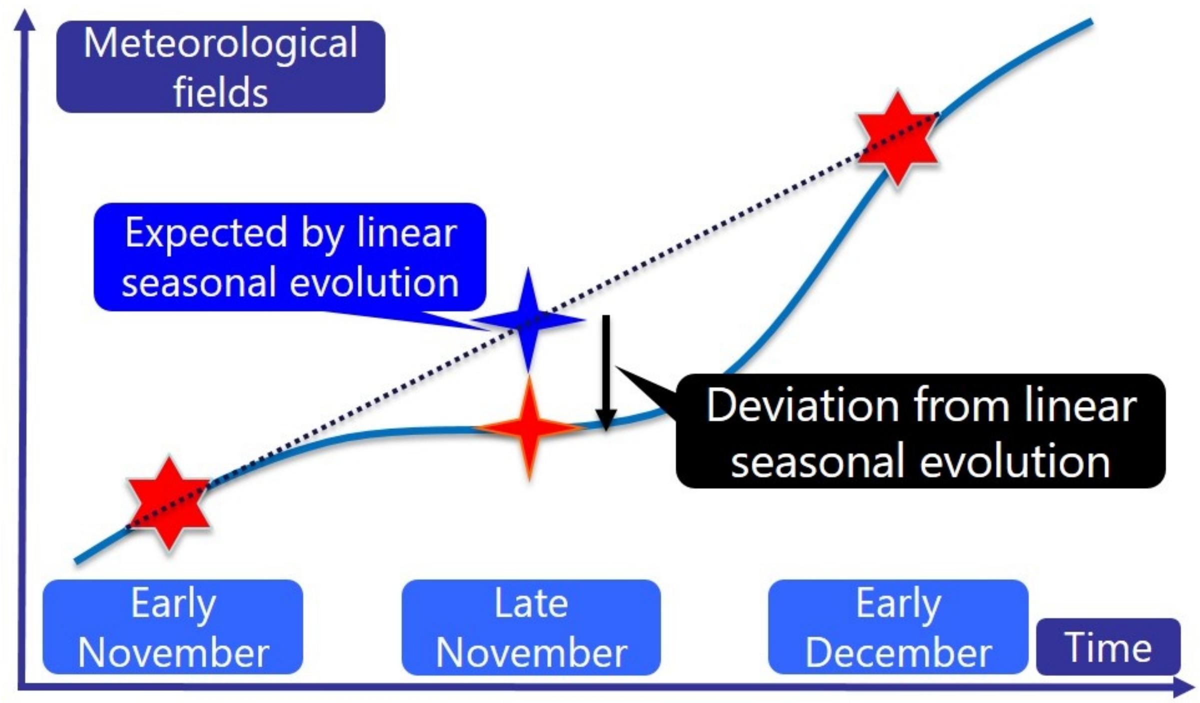
Page 17: Deleted	Author

70°N;

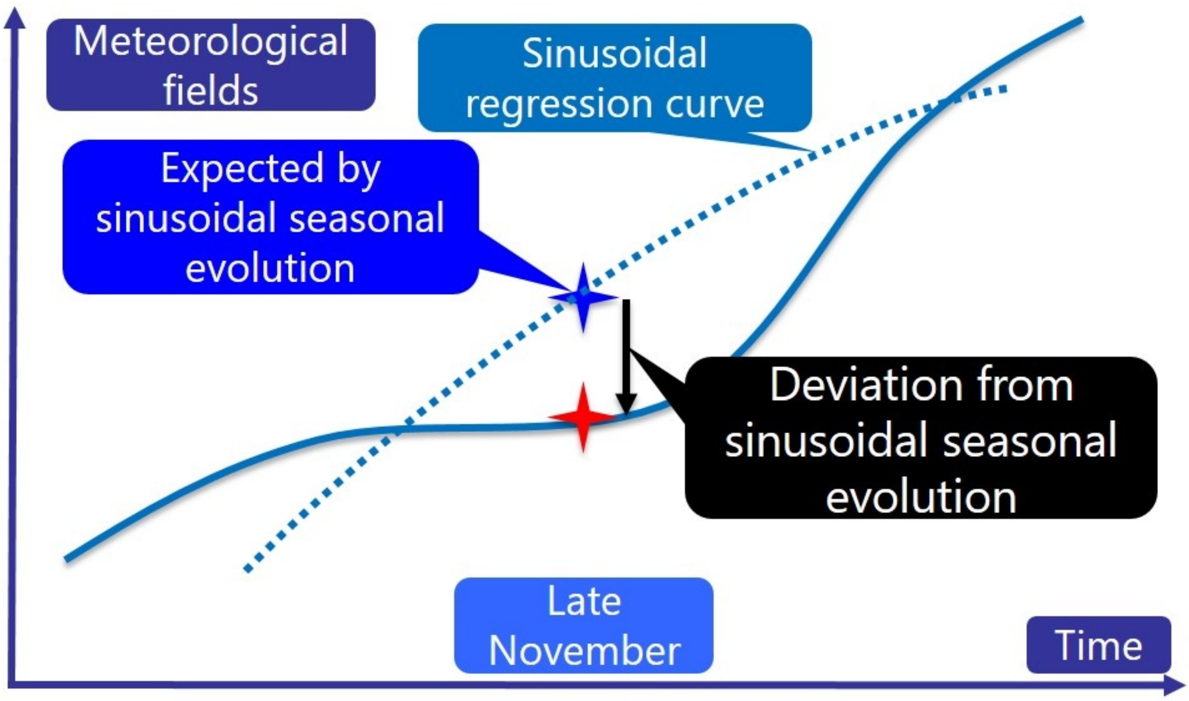
Page 17: Inserted	Author

80°N; the sum of Term B and Term C (black line);

Page 17: Deleted	Author



Page 18: Inserted	Author



Page 18: Deleted	**Author**

Red stars indicate

Page 18: Inserted	**Author**

Blue cross mark indicates

Page 18: Deleted	**Author**

early

Page 18: Inserted	**Author**

late

Page 18: Deleted	**Author**

and early December

Page 18: Inserted	**Author**

expected by sinusoidal seasonal evolution

Page 18: Deleted	**Author**

, and the blue cross mark indicates the mean of the early November and early December values.

Page 18: Inserted	**Author**

.

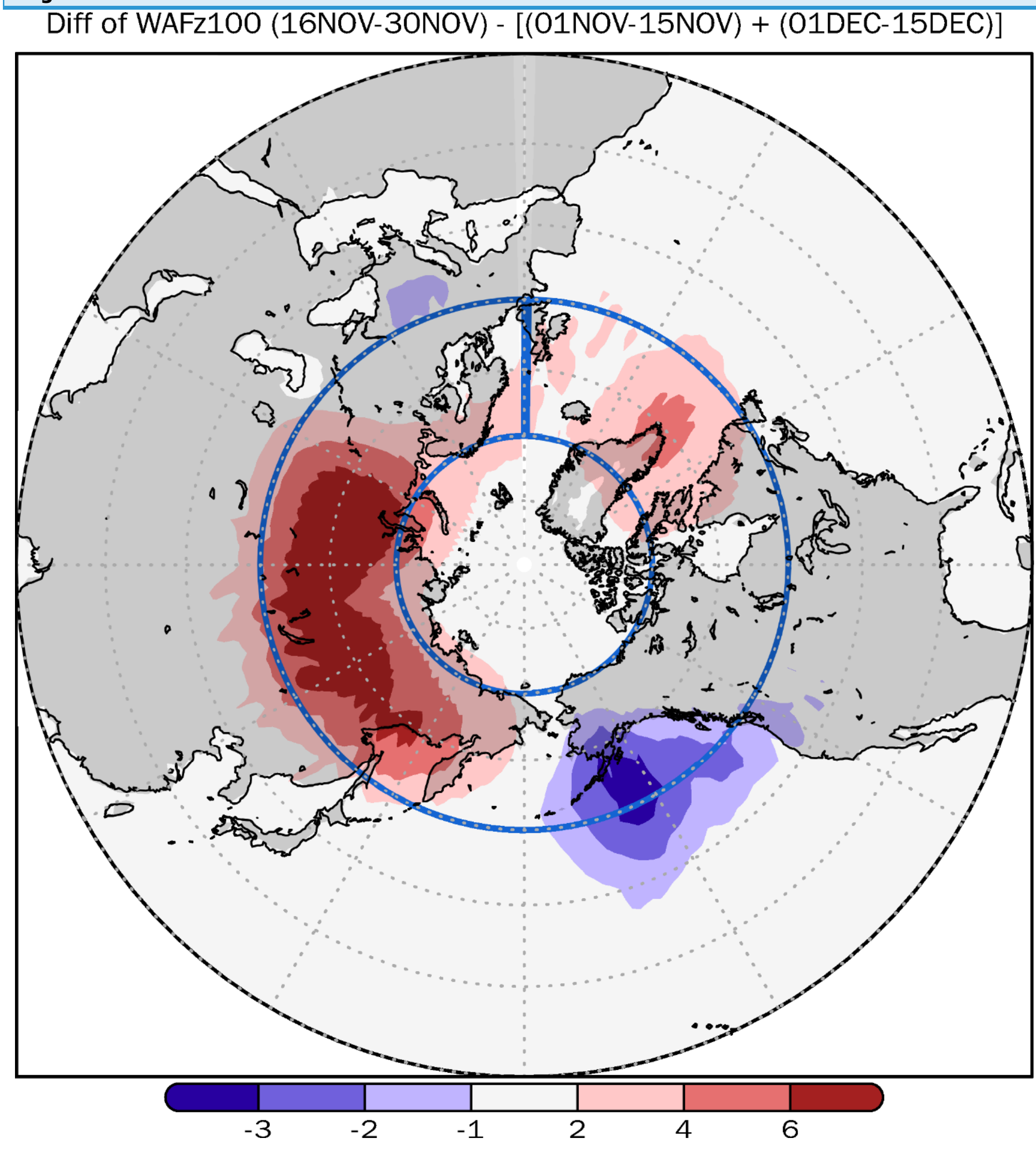
Page 18: Deleted	**Author**

1

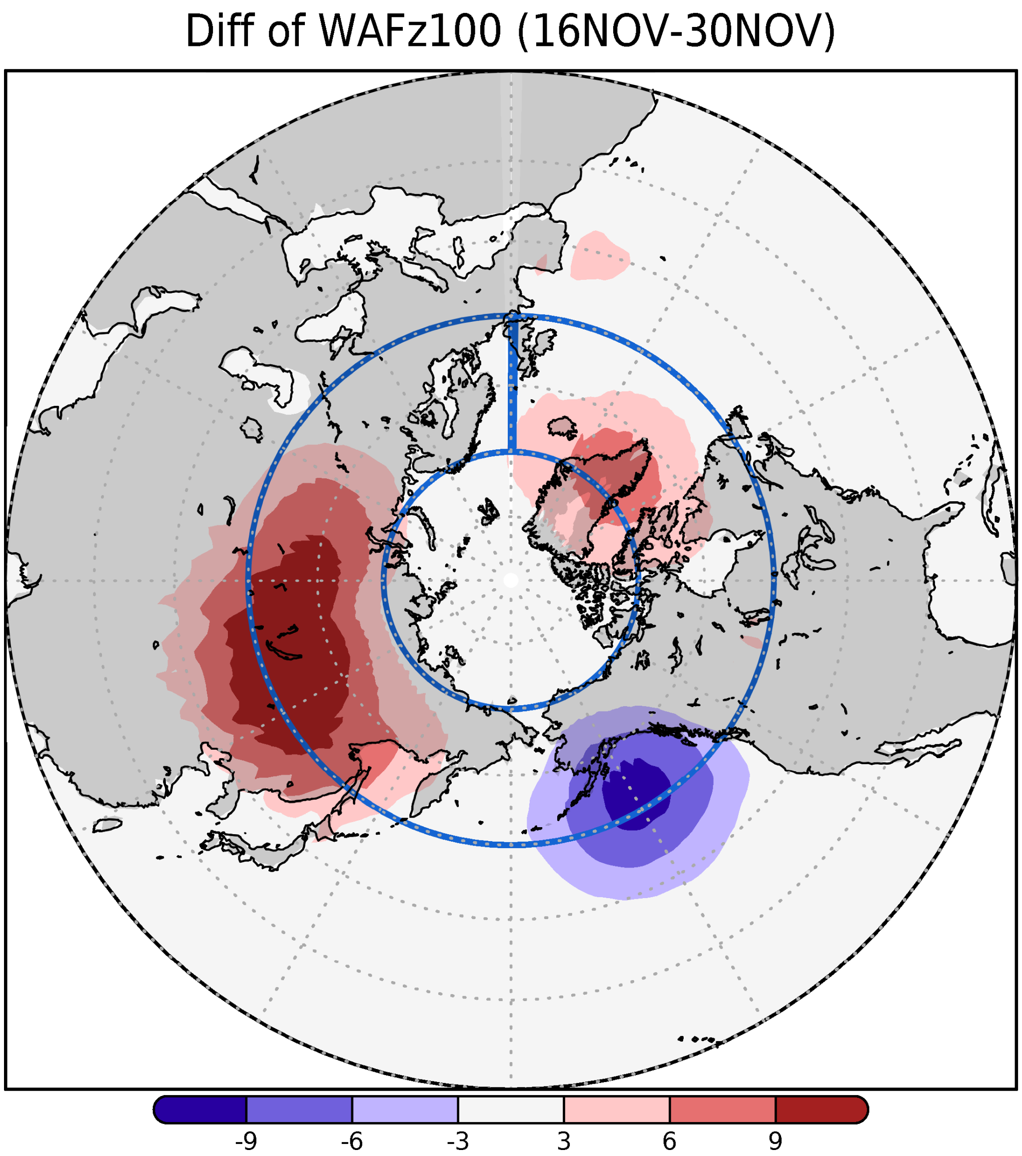
Page 18: Inserted **Author**

4

Page 19: Deleted **Author**



Page 19: Inserted **Author**



Page 19: Deleted **Author**

linear

Page 19: Inserted **Author**

sinusoidal

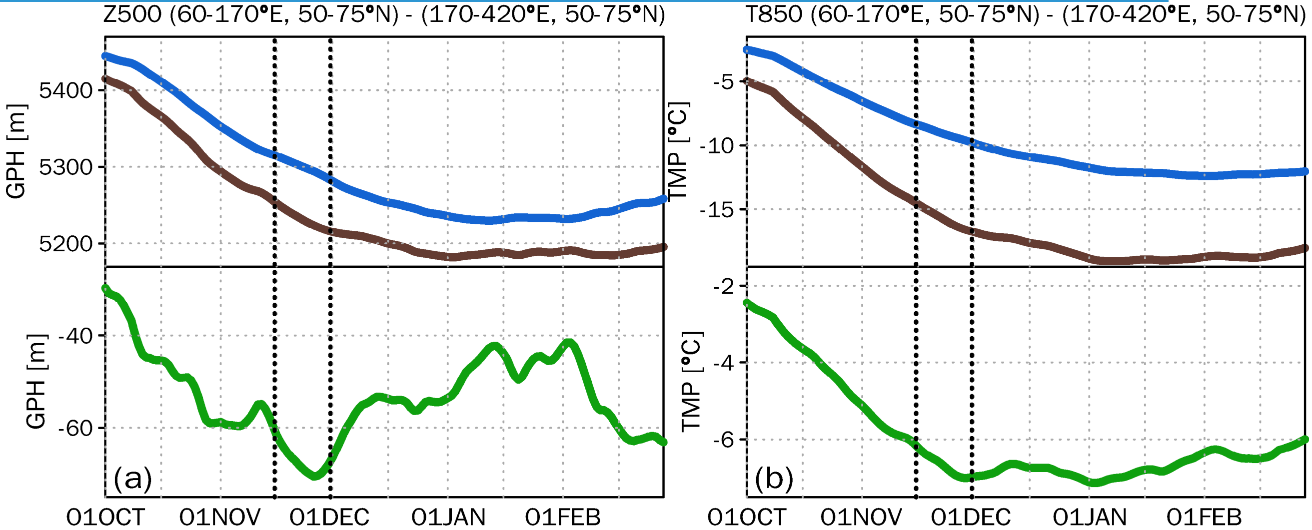
Page 19: Deleted **Author**

1

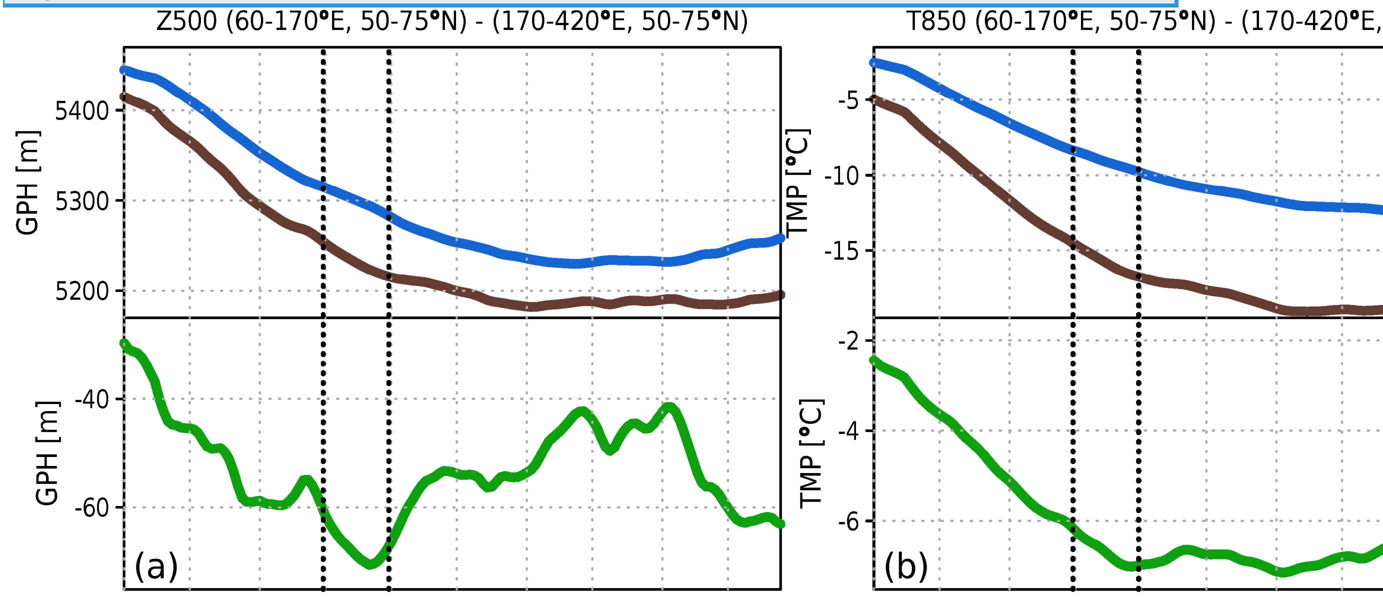
Page 19: Inserted **Author**

4

Page 20: Deleted Author



Page 20: Inserted Author



Page 21: Deleted Author

Transformed Eulerian Mean (TEM) Diagnostics

Page 21: Moved to page 3 (Move #4) Author

Eliassen-Palm (EP) flux analysis is widely used in dynamic meteorology to diagnose wave and zonal-mean flow interactions. The EP flux shows the propagation of Rossby (planetary) waves (Andrews and McIntyre, 1976). The meridional (F^{ϕ}) and vertical (F^{z}) components of the EP flux ($\mathbf{F}$) are defined as follows:

$F^{\phi} \equiv \rho_0 a\cos\phi\left[(\partial\bar{u}/\partial z)\,\overline{v'\theta'}/\bar{\theta}_z - \overline{u'v'}\right]$ (

Page 21: Deleted **Author**

A1)

Page 21: Moved to page 3 (Move #5) **Author**

$F^{z} \equiv \rho_0 a\cos\phi\{[f - (a\cos\phi)^{-1}\,\partial(\bar{u}\cos\phi)/\partial\phi]\,\overline{v'\theta'}/\bar{\theta}_z - \overline{w'u'}\},$ (

Page 21: Deleted **Author**

A2)

Page 21: Moved to page 3 (Move #6) **Author**

where a is the radius of the Earth, f is the Coriolis parameter, ϕ is latitude, θ is potential temperature, u is zonal wind, and v is meridional wind. Overbars denote zonal means, primes denote anomaly from the zonal mean, z is a log-pressure coordinate, and ρ_0 is air density. $\bar{\theta}_z = \partial\bar{\theta}/\partial z$ is computed from the zonal mean of the potential temperature in log-pressure coordinates. The eddy-flux terms $u'v'$ and $v'\theta'$ are computed from the zonal anomalies in the 6-hourly data, and the product is zonally averaged and then time averaged to obtain 15-day means.

We used the primitive form of the Transformed Eulerian Mean (TEM) momentum equation to examine the diagnostics of the zonal-mean momentum (e.g., Andrews et al., 1987; Holton and Hakim, 2012; Vallis, 2017):

Page 21: Deleted **Author**

Page 21: Moved to page 4 (Move #7) **Author**

$\partial\bar{u}/\partial t = \bar{v}^{*}\{f - (a\cos\phi)^{-1}\,\partial(\bar{u}\cos\phi)/\partial\phi\} - \bar{w}^{*}\,\partial\bar{u}/\partial z + (\rho_0 a\cos\phi)^{-1}\mathbf{\nabla}\cdot\mathbf{F} + \bar{X},$ (

Page 21: Deleted **Author**

A3)

Page 21: Moved to page 4 (Move #8) **Author**

(A) (B) (C)

where $\bar{v}^*$ and $\bar{w}^*$ are the meridional and vertical components of the residual mean meridional circulation, $\bar{X}$ is a residual Term that includes internal diffusion and surface friction as well as sub-grid scale forcing such as gravity wave drag.

Page 21: Deleted	**Author**

Term A in equation (A3

Page 21: Moved to page 4 (Move #9)	**Author**

) is the temporal tendency of the zonal-mean zonal wind, Term B is the Coriolis force acting on the residual mean meridional circulation and the meridional advection of zonal momentum, and Term C is the divergence of the EP flux vector, i.e., wave forcing.

Page 21: Deleted	**Author**

The vertical component of the wave activity flux (WAF; Plumb, 1985) at 100 hPa provides a useful diagnostic for identifying the source region of vertically propagating stationary planetary waves. The vertical component of the WAF is proportional to the vertical component of the EP flux. The eddy terms are computed from the zonal deviations relative to each 15-day mean.

Wavenumber decomposition was carried out by applying Fourier analysis to the geopotential height and air temperature fields.

Appendix B

Page 21: Deleted	**Author**

B1

Page 21: Inserted	**Author**

A1

Page 21: Deleted	**Author**

average

Page 21: Inserted	**Author**

sinusoidal evolution

Page 21: Deleted	**Author**

1

Page 21: Inserted	**Author**

4

Page 21: Deleted **Author**

linear

Page 21: Inserted **Author**

sinusoidal

Page 21: Deleted **Author**

B2

Page 21: Inserted **Author**

A2

Page 21: Deleted **Author**

B3

Page 21: Inserted **Author**

A3

Page 21: Deleted **Author**

anomalies

Page 21: Inserted **Author**

deviations

Page 21: Deleted **Author**

1

Page 21: Inserted **Author**

4

Page 22: Deleted **Author**

B4

Page 22: Inserted **Author**

A4

Page 22: Deleted **Author**

B5

Page 22: Inserted	Author

A5

Page 22: Deleted	Author

Appendix C.

Page 22: Inserted	Author

Appendix A6. The anomalous upward propagation of the WAF with wavenumber decomposition

The WAF at 100 hPa is only very weakly correlated with anomalies within the troposphere, especially on sub-monthly timescales (Fig. 15 in de la Cámara et al. 2017). A big reason is that the planetary-scale waves that propagate into the stratosphere are dwarfed by the WAF variability associated with waves that are trapped with the troposphere. We therefore consider the planetary-scale wave components (wavenumbers 1 to 2) of the WAF. Figure A7 show the same as Fig. 4, but with wavenumber decomposition, (a) wavenumber 1 and (b) that of 2. The large positive deviation of the WAF with wavenumber 1 is centered over high-latitude Eurasia (Fig. A7a). However, the negative deviation of the WAF with wavenumber 2 is also centered over Eurasia (Fig. A7b). Thus, the WAF with wavenumber 1 contributed to the positive deviation.

Appendix B.

Page 22: Deleted	Author

SSW events

Page 22: Inserted	Author

QBO

Page 22: Inserted	Author

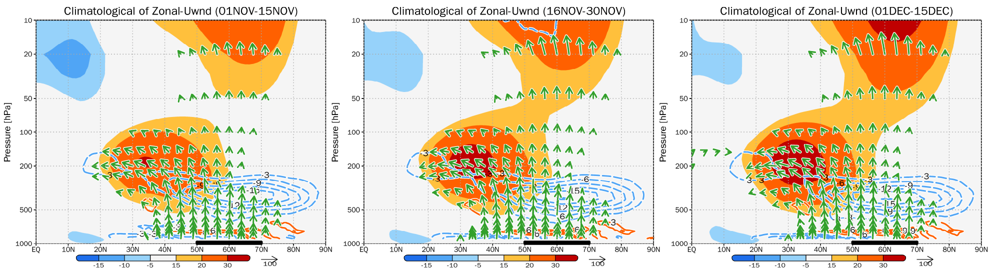
Some studies have described the PNJ variations are related to the quasi-biennial oscillation (QBO; Baldwin et al. 2001) (e.g., Holton and Tan, 1980, 1982; Gray et al. 2003; Anstey and Shepherd 2014). The PNJ is anomalously weak during the easterly phase of the QBO (QBO-E), whereas the PNJ is anomalously strong in the westerly phase of the QBO (QBO-W). We compared the difference between the composite average in the years of QBO-E and that of QBO-W. QBO-E and QBO-W are defined as the direction of the zonal-mean zonal wind at 50 hPa averaged over 10°S-10°N in November. The short break occur during late November in both years. The PNJ in QBO-E has clearer short break than in QBO-W (Figs. A7 and A8). However, the difference is not statistically significant.

Appendix C. Histogram of the short break of the PNJ in late November

We investigated how many winters the short break appear. The definition of the occurrence of the short break was the year when the deviation of the PNJ in late November from the one expected by sinusoidal seasonal evolution was negative. The number of the negative years were 23 years (Relative frequency is 0.61) (Figure C1).

Page 23: Moved from page 24 (Move #12)	Author

(c) (b) (a)

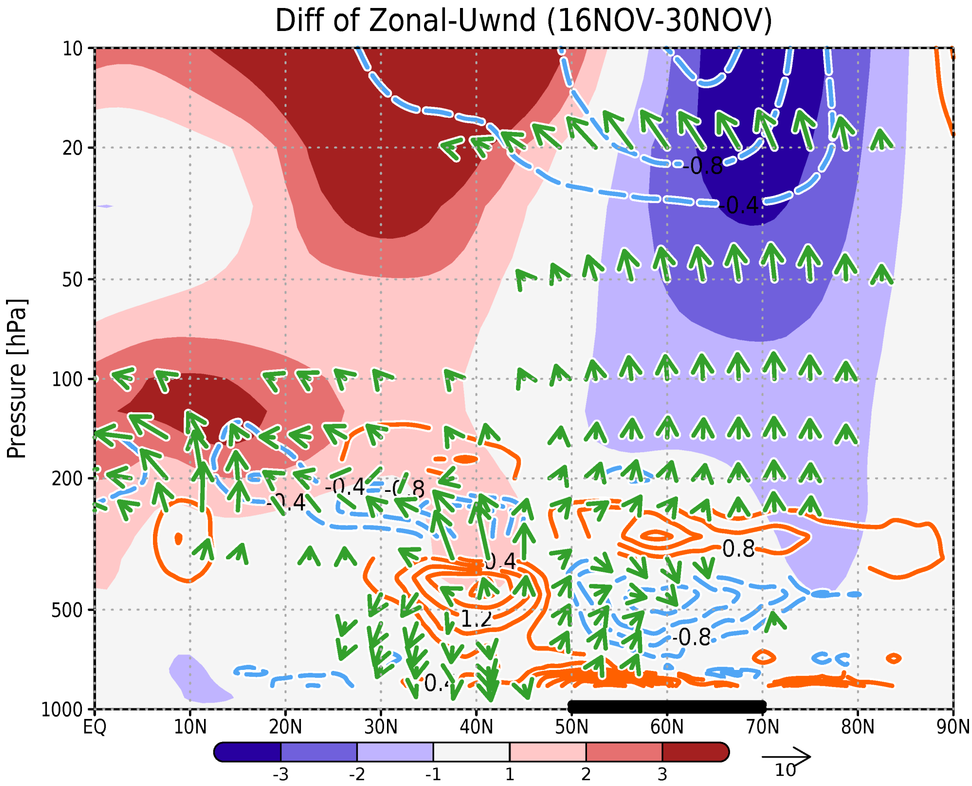


(d)

Page 24: Deleted **Author**

As illustrated in Fig. 1b, the interannual spread of the PNJ is larger during January and February than from October to November. The larger spread in winter can be attributed to the fact that most SSW events occur during January and February, and SSW event magnitudes are also large during this period (Charlton and Polvani, 2007;

Page 24: Inserted **Author**



Page 24: Moved to page 3 (Move #3) **Author**

Maury et al., 2016).

Page 24: Deleted **Author**

The upper percentile wind speed values do not show a short break of the PNJ during November, whereas they do show the late February short break. This result is consistent with the fact that SSW events are rare and their amplitudes are smaller in November than in late winter.

Manney et al. (2001) indicated that minor early winter SSWs that occurred in November 2000, which they called Canadian Warmings (CWs; Labitzke, 1977, 1982), may have had a profound impact on the development of a vortex and a low-temperature region in the lower stratosphere. Waugh and Randel (1999) presented an overview of climatological stratospheric polar vortices, including during the early winter period, and examined them by an elliptical diagnostics analysis. Elliptical diagnostics define the area, center, elongation, and orientation of each vortex and are used to quantify their structure and evolution. They found that the PNJ in the NH becomes more distorted and its position shifts away from the pole from October through December. They also recognized a climatological southward shift of the center of the polar vortex in the NH in late November (Fig.

Page 24: Moved to page 2 (Move #1) **Author**

4d in Waugh and Randel, 1999).

Page 24: Deleted **Author**

This finding is consistent with our study results.

Page 24: Moved to page 2 (Move #2) **Author**

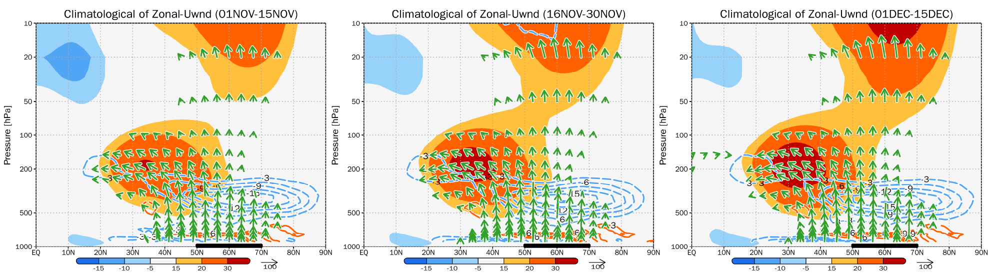
The shift recognized by Waugh and Randel (1999) may be related to the occurrence of wavenumber 1-type minor SSW events (CWs) in late November (Labitzke and Naujokat, 2000; Manney et al.,

Page 24: Deleted **Author**

2001), and these CWs might affect the short break in the seasonal evolution of climatological PNJ during late November. Moreover, Maury et al. (2016) defined an SSW event in terms of a comprehensive description of stratospheric warming events without a priori distinctions between major and minor events. Small-amplitude warmings occur during late November but not in early November or in December. Therefore, the late November climatological short break of the PNJ may be related to early winter SSW events. Our study results are consistent with these previous studies.

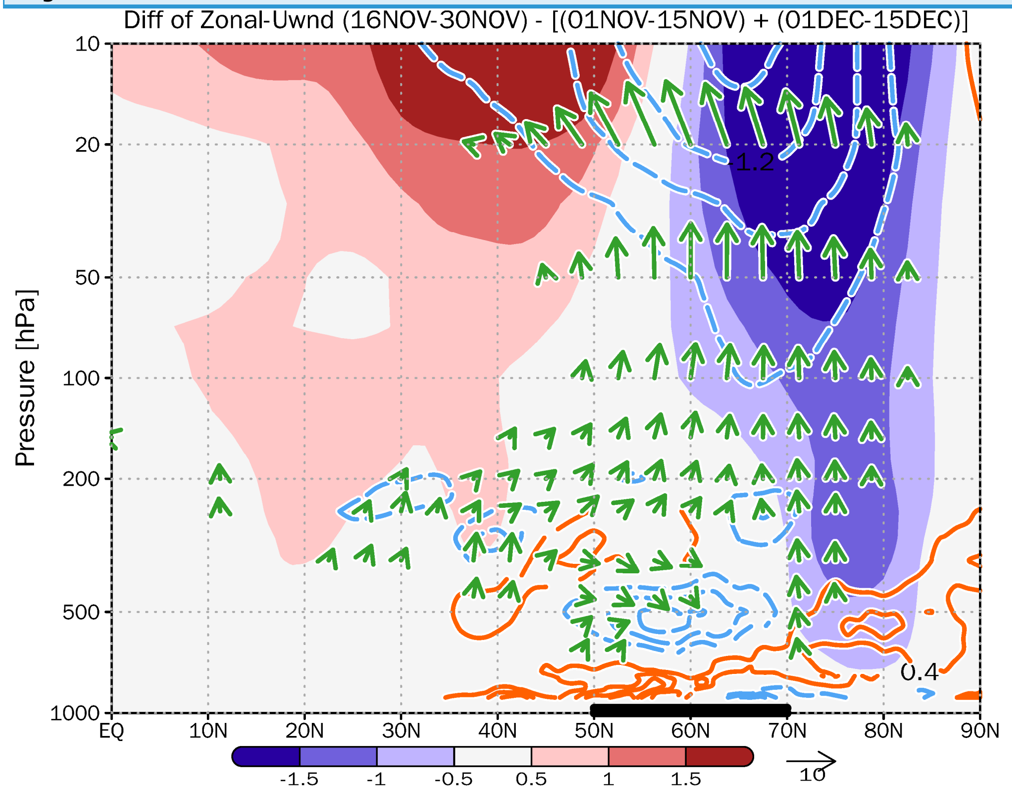
Page 24: Moved to page 23 (Move #12) **Author**

(c) (b) (a)



(d)

Page 24: Deleted **Author**



Page 24: Deleted **Author**

mean of the early November and early December values

Page 24: Inserted	Author

expected sinusoidal regression expression

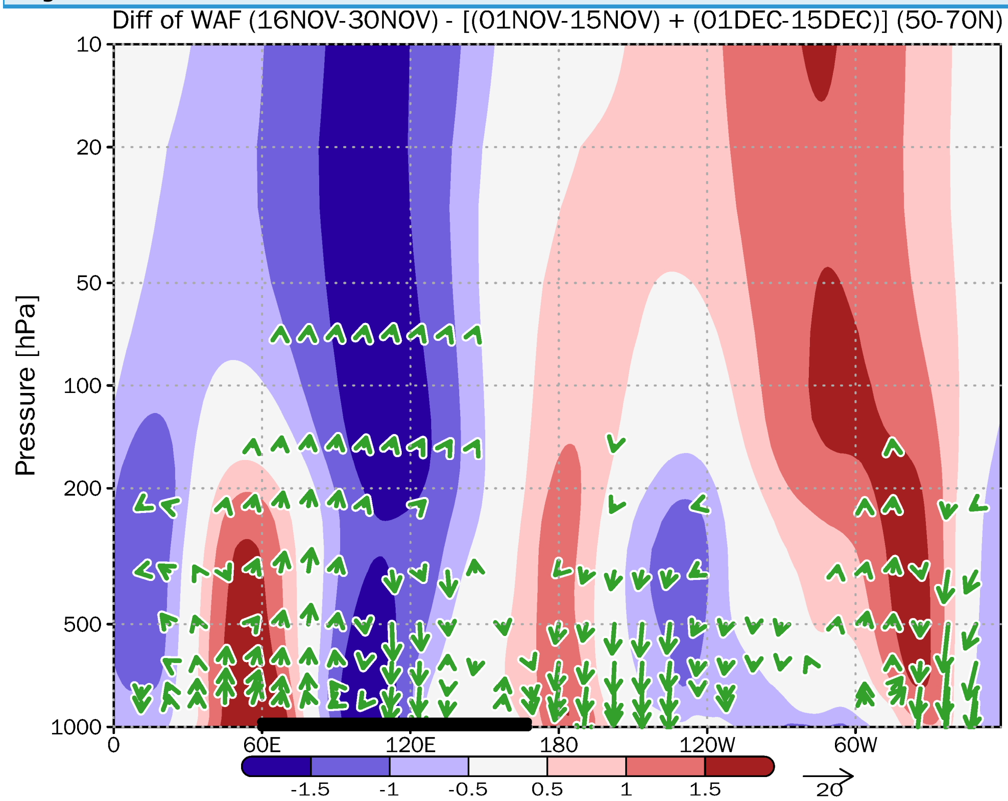
Page 24: Deleted	Author

1

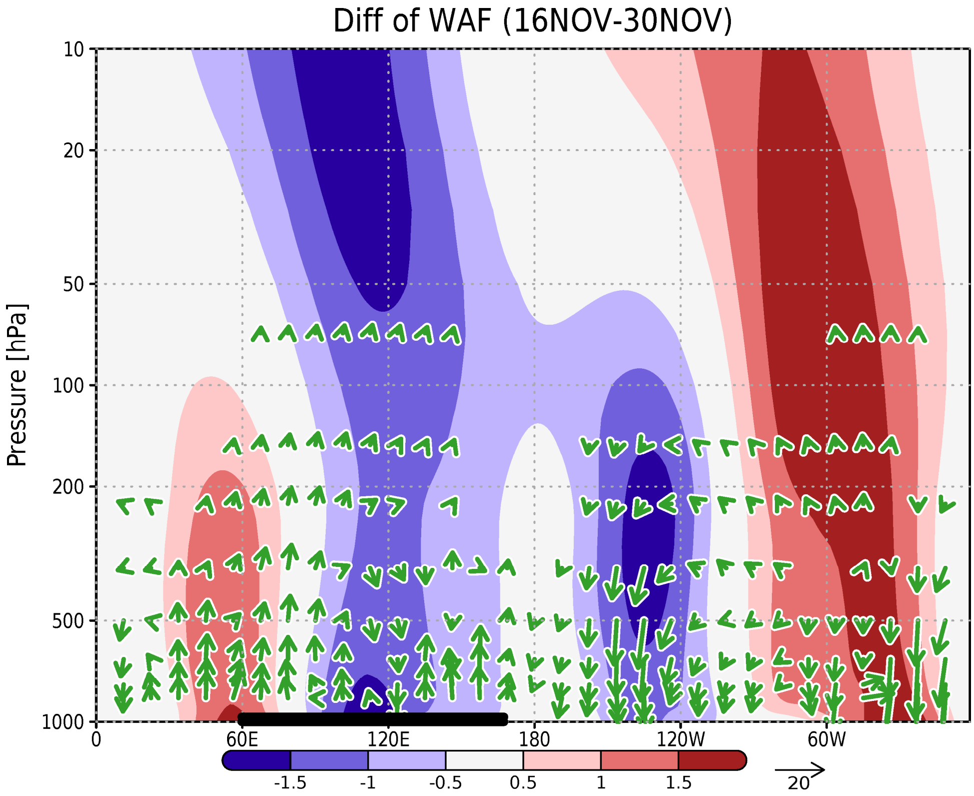
Page 24: Inserted	Author

4

Page 26: Deleted	Author



Page 26: Inserted	Author



Page 26: Deleted	**Author**

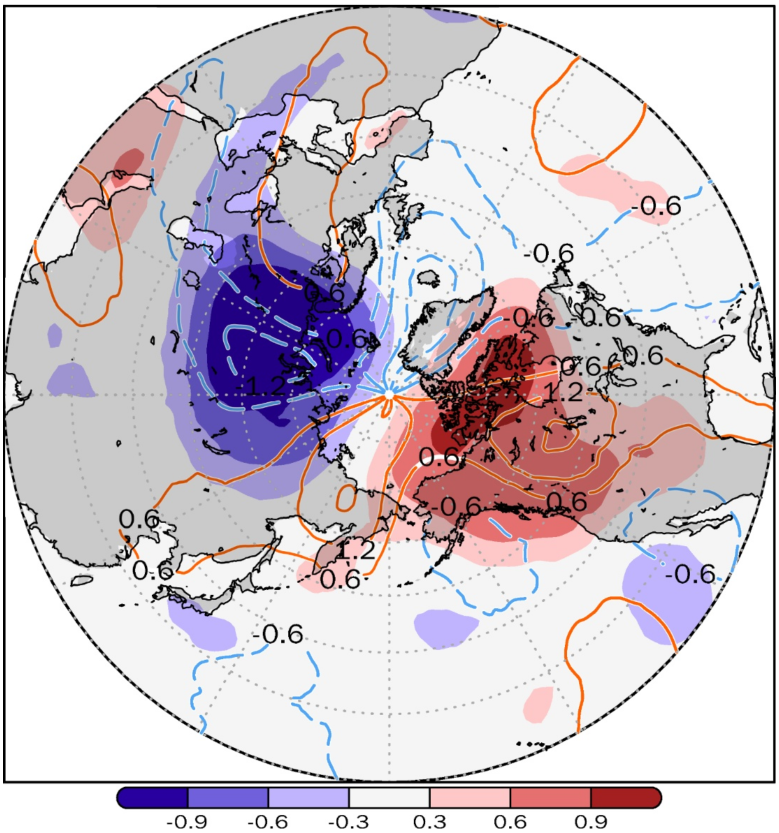
1

Page 26: Inserted	**Author**

4

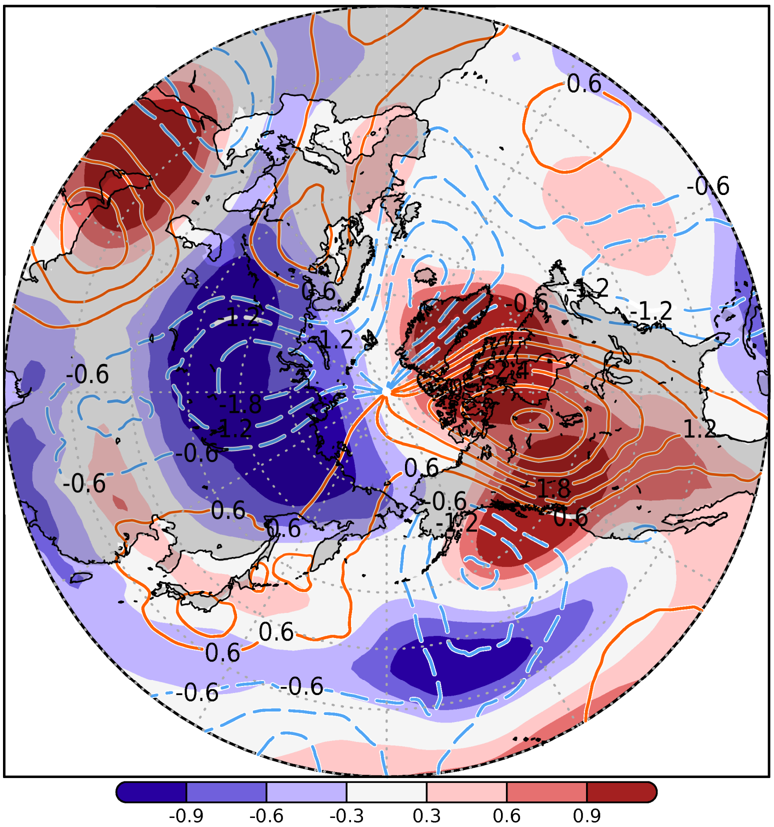
Page 27: Deleted	**Author**

Diff of V',T'100 (16NOV-30NOV) - [(01NOV-15NOV) + (01DEC-15DEC)]



Page 27: Inserted **Author**

Diff of V',T'100 (16NOV-30NOV)



Page 27: Deleted **Author**

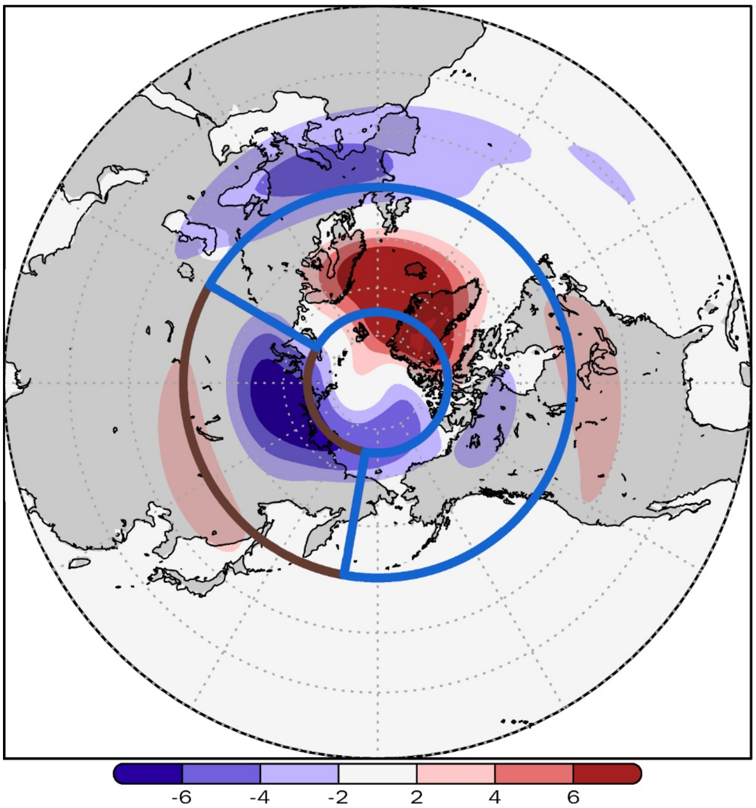
1

Page 27: Inserted **Author**

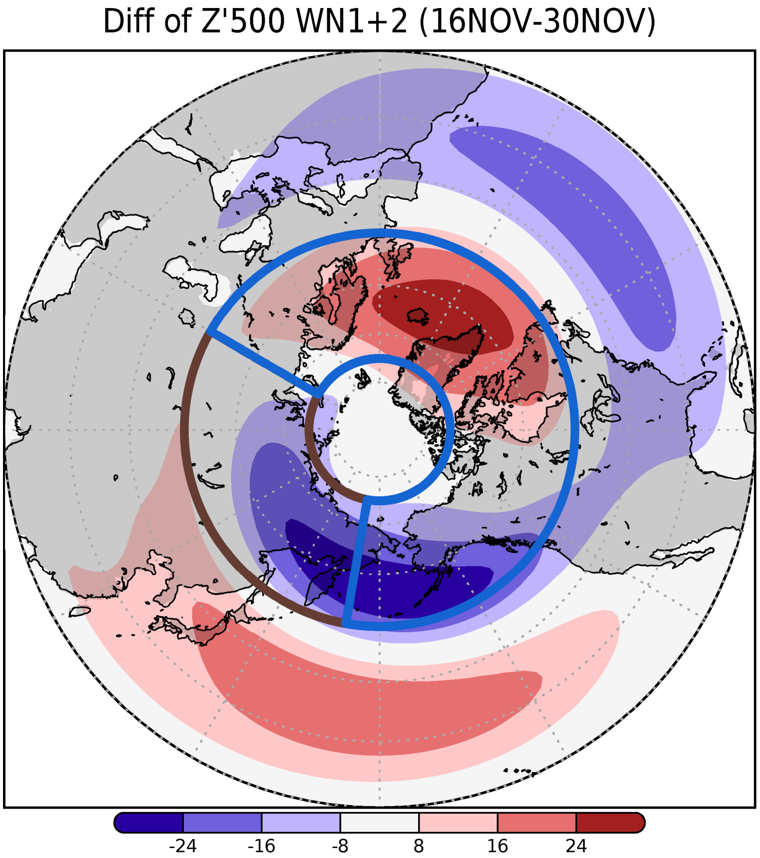
4

Page 28: Deleted **Author**

Diff of Z'500 WN1+2 (16NOV-30NOV) - [(01NOV-15NOV) + (01DEC-15DEC)]



Page 28: Inserted	Author



Page 28: Deleted	Author

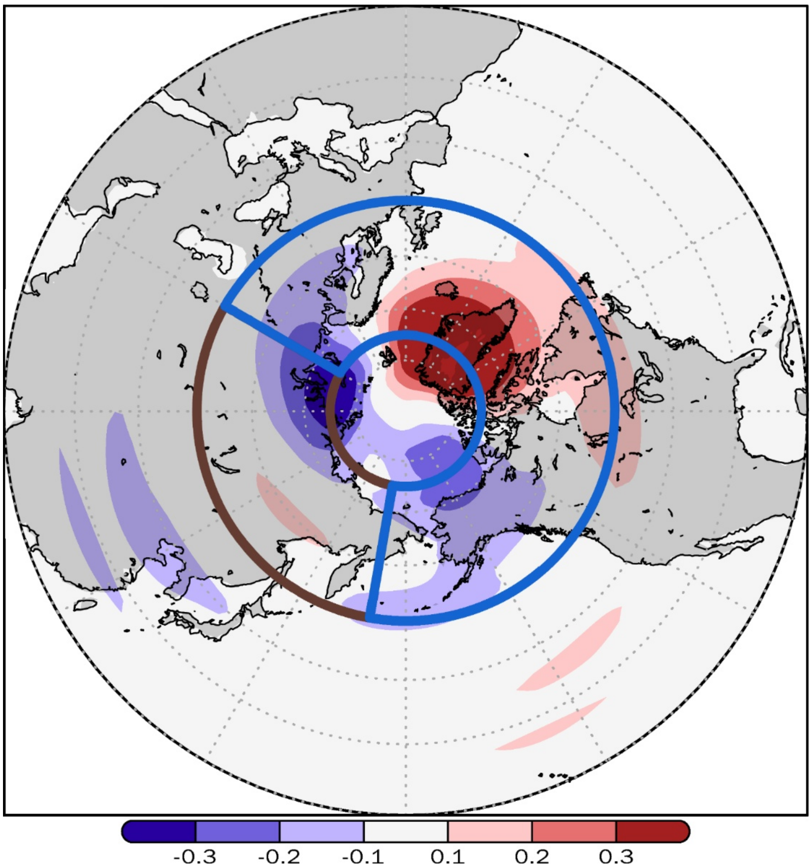
1

Page 28: Inserted	Author

4

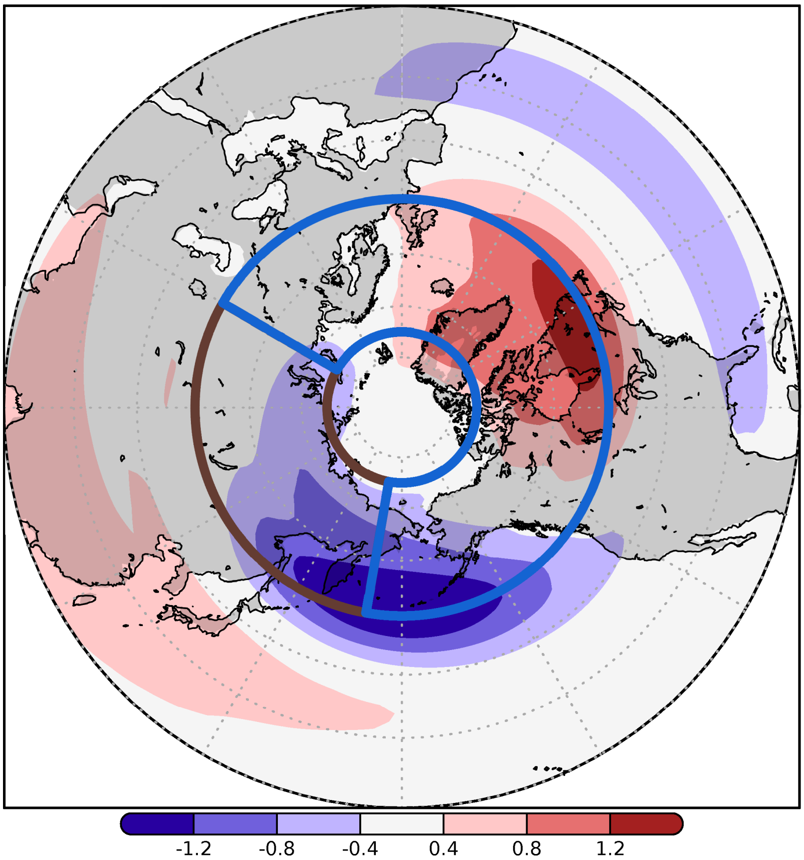
Page 29: Deleted	Author

Diff of T'850 WN1+2 (16NOV-30NOV) - [(01NOV-15NOV) + (01DEC-15DEC)]



Page 29: Inserted **Author**

Diff of T'850 WN1+2 (16NOV-30NOV)



Page 29: Inserted	Author

(b) (a)

Page Break

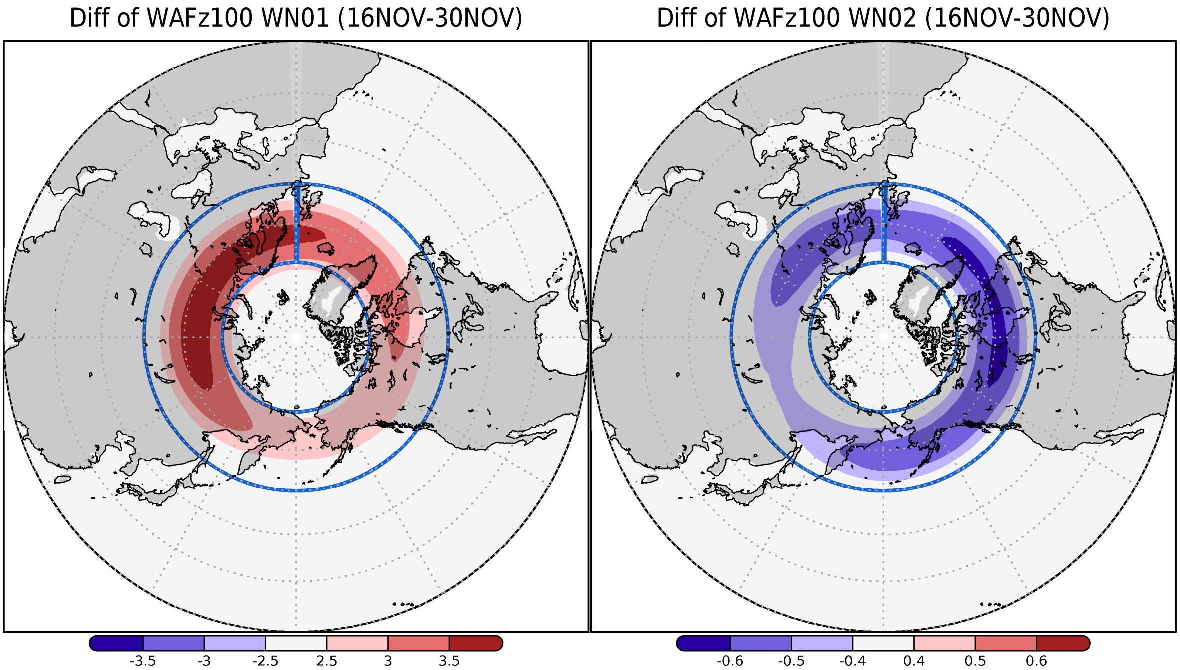


Figure A7. Same as Fig. 4, but with wavenumber decomposition; **(a)** wavenumber 1 and **(b)** wavenumber 2.

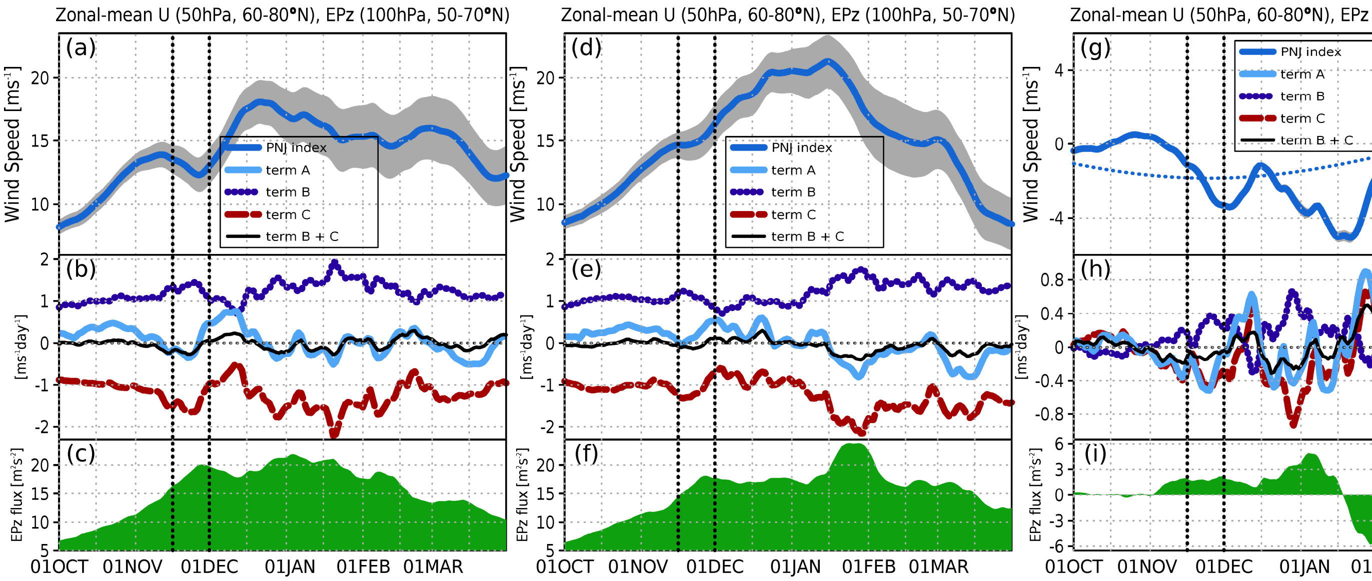


Figure B1. Same as Fig. 2, but **(a), (b), (c)** for QBO-E, **(d), (e), (f)** for QBO-W, and **(g), (h), (i)** difference of (QBO-E) – (QBO-W).

(c) (b) (a)

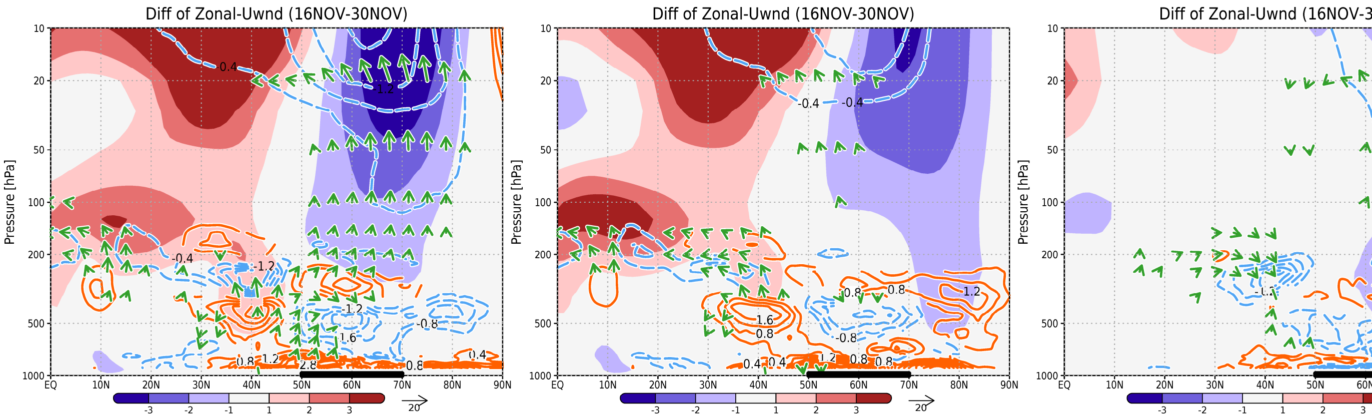


Figure B2. Same as Fig. A1d, but **(a)** for QBO-E, **(b)** for QBO-W, and **(c)** difference of (QBO-E) – (QBO-W).

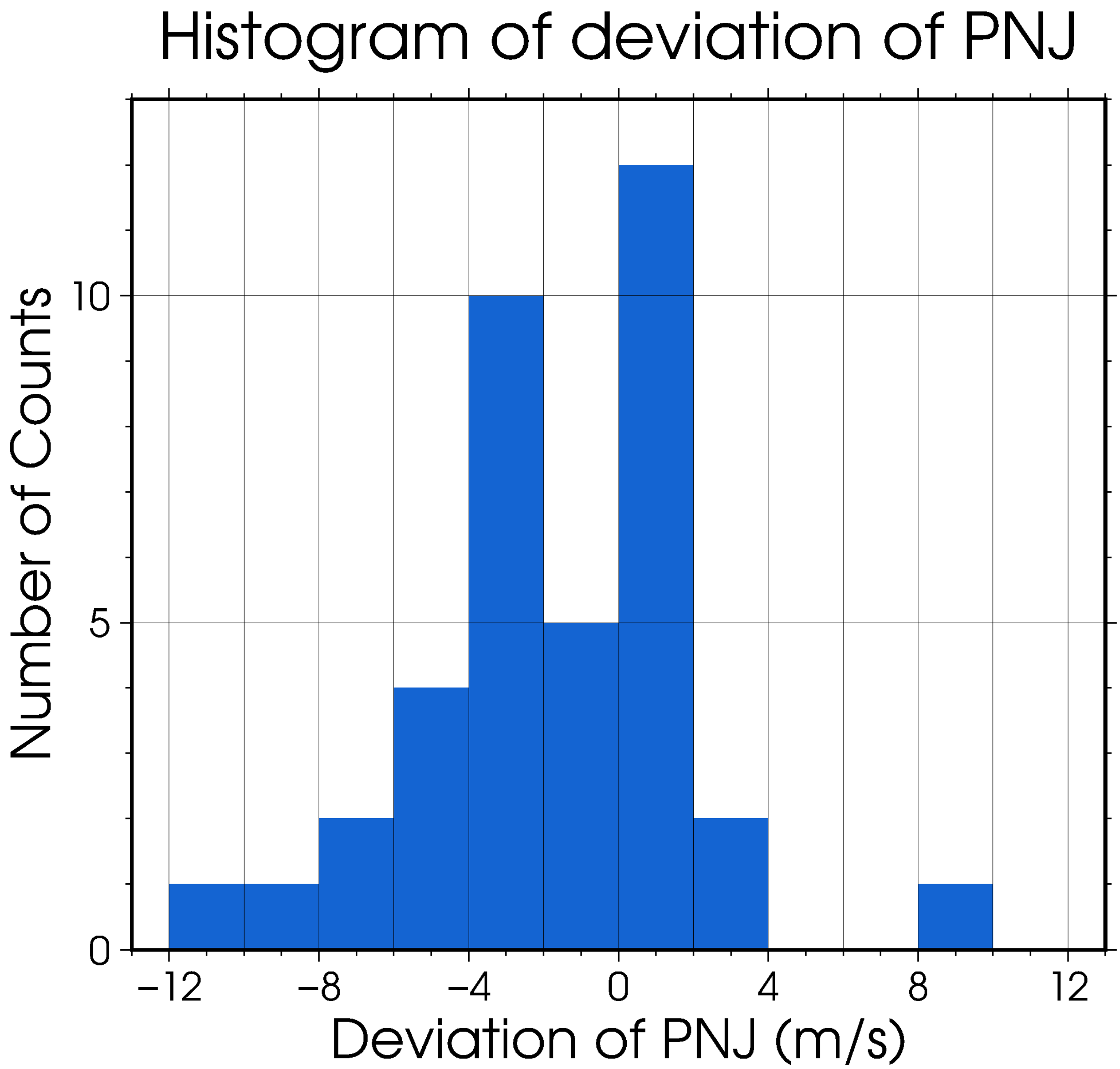


Figure C1. Histogram of the deviation of the PNJ in late November from the expected by sinusoidal seasonal evolution in each year (2.0m/s bins). The horizontal axis shows the deviation for the center of each bin. The vertical axis indicates the number of counts for each bin. The negative sign indicates the occurrence of the short break.

Header and footer changes

Text Box changes

Page 24: Inserted **Author**

(c)

Page 24: Inserted **Author**

(b)

Page 24: Inserted **Author**

(a)

Page 24: Inserted **Author**

(d)

Page 24: Deleted **Author**

(c)

Page 24: Deleted **Author**

(b)

Page 24: Deleted **Author**

(a)

Page 24: Deleted **Author**

(d)

Page 30: Inserted **Author**

(b)

Page 30: Inserted **Author**

(a)

Page 32: Inserted **Author**

(c)

Page 32: Inserted	Author

(b)

Page 32: Inserted	Author

(a)

Header and footer text box changes

Footnote changes

Endnote changes

Detection of a climatological short break in the Polar Night Jet in early winter and its relation to cooling over Siberia

Yuta Ando[1], Koji Yamazaki[1, 2], Yoshihiro Tachibana[1], Masayo Ogi[3], Jinro Ukita[4]

[1]Weather and Climate Dynamics Division, Mie University, 1577 Kurimamachiya-cho, Tsu, Mie 514-8507, Japan
[2]Hokkaido University, Kita 10, Nishi 5, Kita-ku, Sapporo, Hokkaido 060-0810, Japan
[3]Centre for Earth Observation Science, University of Manitoba, 530 Wallace Building, Winnipeg MB R3T 2N2, Canada
[4]Graduate School of Science and Technology, Niigata University, 8050 Ikarashi 2-no-cho, Nishi-ku, Niigata, Niigata 950-2181, Japan

Correspondence to: Yoshihiro Tachibana (tachi@bio.mie-u.ac.jp)

Abstract. The Polar Night Jet (PNJ) is a strong stratospheric westerly circumpolar wind at around 65°N in winter, and the strength of the climatological PNJ is widely recognized to increase ~~monotonically~~ from October through late December. Remarkably, the climatological PNJ temporarily stops increasing during late November. We examined this short break in terms of the atmospheric dynamical balance and the climatological seasonal march. We found that it results from an increase in the upward propagation of climatological planetary waves from the troposphere to the stratosphere in late November, which coincides with a maximum of the climatological Eliassen-Palm flux convergence in the lower stratosphere. The upward propagation of planetary waves at 100 hPa, which is strongest over Siberia, is related to the climatological strengthening of the tropospheric trough over Siberia. We suggest that longitudinally asymmetric forcing by land–sea heating contrasts caused by their different heat capacities can account for the strengthening of the trough.

1 Introduction

In the Northern Hemisphere (NH) winter, the high-latitude stratosphere is characterized by strong westerly winds around the polar vortex, the so-called Polar Night Jet (PNJ) (e.g., Brasefield, 1950; Palmer, 1959; AMS, 2015; Schoeberl and Newman 2015; Waugh et al., 2017). The PNJ exhibits large interannual and intraseasonal variations dynamically forced by the upward propagation of planetary-scale Rossby waves from the troposphere. On an intraseasonal timescale, the PNJ strength signal propagates downward and poleward from the upper stratosphere to the high-latitude lower stratosphere during winter (e.g., Kuroda and Kodera, 2004; Li et al., 2007). This variation is called the PNJ oscillation. The signal further propagates into the troposphere occasionally to ~~produce~~influence the Arctic Oscillation (AO; Thompson and Wallace, 1998, 2000) signal at the surface (e.g., Baldwin and Dunkerton, 2001; Deng et al., 2008~~).~~; Hitchcock and Simpson, 2014; Kidston et al. 2015). The AO, which is the dominant hemispheric seesaw variability in sea level pressure between the polar area and the surrounding mid-latitudes, strongly influences NH weather patterns and its associated extreme weather events (e.g., Thompson and Wallace, 2001; Angell, 2006; Black and McDaniel, 2009; ~~Thompson and Wallace, 2001~~Cohen et al., 2013; Ando et al., 2015; Drouard et al., 2015; Xu et al., 2016; He et al., 2017).

Propagating large-amplitude planetary waves sometimes cause a sudden decrease in the strength of the PNJ accompanied by a sudden increase in polar temperature, a phenomenon known as a sudden stratospheric warming (SSW) event (Matsuno, 1970; Labitzke, 1977~~).~~; Hamilton, 1999; Labizke and van Loon, 1999). Extreme SSW events occur mostly in mid or late winter; in early winter or early spring, SSWs are weaker and less frequently occur (e.g., Limpasuvan et al., 2004; Charlton and Polvani, 2007; Hu et al., 2014; Maury et al., 2016).

Although the interannual variability of the PNJ has been well studied (e.g., Ambaum et al., 2002; Thompson et al., 2002; Frauenfeld and Davis, 2003; Kolstad et al., 2010; Reichler et al., 2012; Butler et al., 2014; Kim et al., 2014; Nakamura et al., 2015; Woo et al., ~~2015~~2015; Hoshi et al, 2017; Polvani et al., 2017; Kretschmer et al., 2018), the climatological seasonal evolution~~ of the PNJ~~ has been overlooked. Considering the downward propagation of the PNJ strength signal from the lower stratosphere and its effect on tropospheric weather and climate, a detailed understanding of the climatological seasonal evolution ~~of the PNJ~~ is important for weather patterns and extreme weather events. It is generally acknowledged that the climatological PNJ speed increases ~~monotonically~~ from October to December and reaches a maximum in early January. Subsequently, the speed of ~~climatological~~the PNJ decreases ~~monotonically~~ until spring~~.~~ (e.g., Kodera and Kuroda, 2002; Waugh and Polvani, 2010; Karpechko and Manzini, 2012; Yamashita et al., 2015; Maury et al., 2016).

We ~~found~~detected that in the lower stratosphere the climatological PNJ temporarily stops increasing in late November, and it temporarily stops decreasing in late February (Fig. 1; see Section 3.1 for a detailed explanation). These "short breaks" in the seasonal evolution~~ of the climatological PNJ~~ cannot be detected in monthly averaged data; their detection requires data with a finer temporal resolution. The climatological short break in February is likely due to the fact that SSWs occur less frequently in late February compared with January and early February. The vertical structure and timescale of the short break in late November is different from that of February (see Section 3.1 for a detailed explanation). A detailed understanding of the short break in late November is important in terms of dynamic meteorology of intraseasonal variations in stratosphere. The early winter warming has been known as Canadian Warmings (CWs; Labitzke, 1977, 1982). Numerous studies have described CWs (e.g., Labitzke et al. 1977, 1982; Manney et al. 2001, 2002; Fig. 7 in Taguchi and Yoden, 2002). However, no previous studies explicitly showed this short break viewing from climatological extra-seasonal evolution. Manney et al. (2001) indicated that CWs that occurred in November 2000 may have had a profound impact on the development of a vortex and a low-temperature region in the lower stratosphere. Waugh and Randel (1999) presented an overview of climatological PNJ. They found that the PNJ becomes more distorted and its position shifts away from the pole from October through December. They also recognized a climatological southward shift of the center of the polar vortex in late November (Fig. 4d in Waugh and Randel, 1999).

The shift recognized by Waugh and Randel (1999) may be related to the occurrence of wavenumber 1-type minor SSW events (CWs) in late November (Labitzke and Naujokat, 2000; Manney et al., 2001). These studies implicitly remind us that the CWs may affect the short break of climatological PNJ. Moreover, small-amplitude warmings occur during late November (Maury et al., 2016). ~~The climatological short break in late November might possibly have been known, but it has not yet been addressed in terms of dynamic meteorology. We~~Therefore, the late November climatological short break is related to early winter SSW events.

However, these studies are based on a case study or focused on a statistical analysis only within the occurrence of minor warmings. Our view of the PNJ is from the climatological seasonal march from October through April. No previous studies explicitly showed this climatological short break, nor have yet been addressed in terms of dynamic meteorology. We thus examine this climatological short break of the PNJ in late November through a dynamical analysis to infer a possible origin. In Section 2, we briefly describe the data used~~.~~ and analysis methods. Section 3 provides a detailed description of the late November ~~climatological~~ short break. Section 4 discusses a possible cause of the short break, and Section 5 presents our conclusions.

2 Data and methods

2.1 Data

We used the 6-hourly Japanese 55-year Reanalysis (JRA-55) dataset with the 1.25° horizontal resolution (Kobayashi et al., 2015; Harada et al., 2016). Because the quality of the stratospheric analysis was improved after the inclusion of satellite data in JRA-55 in 1979, the analysis period was restricted to the period from 1979 through 2016. We therefore defined climatological values as their 38-year average values during 1979–2016.

2.2 Transformed Eulerian Mean (TEM) Diagnostics

As our main analysis method, we performed an Eliassen-Palm (EP) flux analysis based on the transformed Eulerian mean (TEM) momentum equation (Equation ~~A3 in Appendix A~~3). This method, which is widely used in dynamic meteorology to diagnose wave and zonal-mean flow interaction, is described in detail ~~in Appendix A.~~as follows:

Eliassen-Palm (EP) flux analysis is widely used in dynamic meteorology to diagnose wave and zonal-mean flow interactions. The EP flux shows the propagation of Rossby (planetary) waves (Andrews and McIntyre, 1976). The meridional (F^{ϕ}) and vertical (F^{z}) components of the EP flux ($\mathbf{F}$) are defined as follows:

$$F^{\phi} \equiv \rho_0 a \cos\phi \left[(\partial \bar{u}/\partial z)\, \overline{v'\theta'}/\bar{\theta}_z - \overline{u'v'} \right] \qquad (1)$$

$$F^z \equiv \rho_0 a\cos\phi\{[f - (a\cos\phi)^{-1}\,\partial(\bar{u}\cos\phi)/\partial\phi]\,\overline{v'\theta'}/\bar{\theta}_z - \overline{w'u'}\}, \quad (2)$$

where a is the radius of the Earth, f is the Coriolis parameter, ϕ is latitude, θ is potential temperature, u is zonal wind, and v is meridional wind. Overbars denote zonal means, primes denote anomaly from the zonal mean, z is a log-pressure coordinate, and ρ_0 is air density. $\bar{\theta}_z = \partial\bar{\theta}/\partial z$ is computed from the zonal mean of the potential temperature in log-pressure coordinates. The eddy-flux terms $u'v'$ and $v'\theta'$ are computed from the zonal anomalies in the 6-hourly data, and the product is zonally averaged and then time averaged to obtain 15-day means.

We used the primitive form of the Transformed Eulerian Mean (TEM) momentum equation to examine the diagnostics of the zonal-mean momentum (e.g., Andrews et al., 1987; Holton and Hakim, 2012; Vallis, 2017):

$$\underbrace{\partial\bar{u}/\partial t}_{(A)} = \underbrace{\bar{v}^*\{f - (a\cos\phi)^{-1}\,\partial(\bar{u}\cos\phi)/\partial\phi\}}_{(B)} - \bar{w}^*\,\partial\bar{u}/\partial z + \underbrace{(\rho_0 a\cos\phi)^{-1}\nabla\cdot\mathbf{F}}_{(C)} + \bar{X}, \quad (3)$$

where $\bar{v}^*$ and $\bar{w}^*$ are the meridional and vertical components of the residual mean meridional circulation, $\bar{X}$ is a residual Term that includes internal diffusion and surface friction as well as sub-grid scale forcing such as gravity wave drag. Term A in equation (3) is the temporal tendency of the zonal-mean zonal wind, Term B is the Coriolis force acting on the residual mean meridional circulation and the meridional advection of zonal momentum, and Term C is the divergence of the EP flux vector, i.e., wave forcing.

The vertical component of the 3-dimentional wave activity flux (WAF; Plumb, 1985) at 100 hPa provides a useful diagnostic for identifying the source region of vertically propagating stationary planetary waves. The zonal average of the WAF is the EP flux, so the vertical component of the WAF shows from where the wave propagates to the stratosphere. The eddy terms are computed from the zonal deviations relative to each 15-day mean (i.e., stationary wave component).

3 Results

3.1 Climatological short break of the Polar Night Jet

First, we outline the seasonal evolution of the PNJ. A latitude–time cross section of the ~~climatological~~ zonal-mean zonal wind at 50 hPa over 50–90°N shows that the strength of the zonal-mean westerlies at 50 hPa ($\overline{\mathrm{U}}50$) increases with time from approximately October to late December. Subsequently, $\overline{\mathrm{U}}50$ decreases with time from late December through March (Fig. 1a). An examination of the intraseasonal variation of $\overline{\mathrm{U}}50$ reveals two short breaks. Between 60° and 80°N, there is a pause in the increasing trend in late November, and there is another pause in the decreasing trend in late February. The short break in late November is statistically significant at the 99% level, and the short break in late February is statistically significant at the 95% level (the two-tailed95% confidence level (t test for the differences of two means; late November and early December, that of early and late November is not statistically significant (t=0.28)), and that of late February is not statistically significant (t=0.43; late February and early March, that of early and late February is not statistically significant (t=0.19)) (the two-sided Student's t test; e.g., Wilks, 2011). The climatological short break in February is likely associated with the less frequent occurrence of SSWs in late February than in January and early February. We note the signal (the short break of the PNJ) throughout the whole stratosphere. In contrast, the climatological short break in November is restricted to the lower and mid stratosphere (figure not shown).

Here, we defined the zonal-mean zonal wind speed at 6560-80°N and 50 hPa as a PNJ index, following Kodera and Koide (1997). because the short break can be clearly seen in these latitudes (Fig. 1a). The time series of the climatological 15-day running mean of this PNJ index clearly shows a short break of the PNJ during late November (blue line in Fig. 1b). There are various bumps in the time series of a lower dashed-dotted line in Fig. 1b. This signifies that extreme short breaks (SSWs) occur regardless of the time of the season., that is, the short breaks do not always occur in late November and early February in each year. The climatological (38-year average – this is the climatology in our definition) short break of the PNJ, however, occurs only during late November and early February (blue line in Fig. 1b). This suggests that the short breaks in each year more often occur during these two periodslate November than during the other periods. Because it is common that the cause of the February short break corresponds to the occurrence of SSWs, and because the short break in late November moreis the only one that is statistically significant than that of February, this paper does not target the February short break.. We thus focus on the climatological short break in late November. The numbers of occurrence of the short break of the PNJ in late November is described in Appendix C.

3.2 Anomalous upward propagation of the EP flux during late November

In this section, we show that the late November climatological short break of PNJ is caused by anomalous upward propagation of planetary waves. To investigate the dynamical cause of the short break in late November, we compared the time series of the PNJ index (Fig. 2a) with the intraseasonal variation of each term of the TEM equation (Appendix A, Equation (A33)) (Fig. 2b). Here, Term A is the temporal tendency of the PNJ (i.e., its zonal acceleration); Term B is the Coriolis force acting on the residual mean meridional circulation and the meridional advection of zonal momentum; and Term C is the EP flux divergence at 50 hPa averaged over 60–70°N. The temporal tendency of the zonal wind accords well with the sum of the forcing terms of the TEM momentum diagnostic (A = B + C; Appendix A).Section 2.2; light blue and black lines in Fig. 2b). The EP flux divergence (wave forcing) generally governs the zonal wind tendency, and the short break of the PNJ in November is also caused by wave forcing (Term C in equation (A33)).

The vertical component of the EP flux (F^z) at 100 hPa, averaged over latitudes 50–70°N (Fig. 2c), is used as a measure of planetary-scale Rossby wave propagation into the stratosphere (e.g., Coy et al., 1997; Pawson and Naujokat, 1999; Newman et al., 2001). In late November, the upward EP flux at 100 hPa rapidly increases to its maximum, and this enhanced EP flux is linked to the EP flux convergence at 50 hPa, which brings about the short break~~ in the seasonal evolution of PNJ~~.

3.3 Calculation of anomalous fields with respect to a ~~linear~~sinusoidal seasonal evolution in late November

We identified a period between 16 and 30 November for the late-November short break (see Fig. 1). We further defined a climatological meteorological field deviation, $\mathcal{A}_{dev}$, during the period of the short break as a deviation from the expected ~~linear~~sinusoidal seasonal evolution (since that of solar forcing is sinusoidal (e.g., Andrews et al. 1987)) of that field (Fig. 3):

$$\mathcal{A}_{dev} = \mathcal{A}_{16-30Nov} \; \sim\!\!\sim\!\! -(\mathcal{A}_{1-15Nov} + \mathcal{A}_{1-15Dec})/2.,\; (1 \sim\!\!\sim - (\text{sinusoidal regression expression of } \mathcal{A}_{16-30Nov}), \quad (4)$$

where $\mathcal{A}$ is a climatological meteorological field (e.g., geopotential height) and subscripts indicate the averaging period. ~~{$(\mathcal{A}_{1-15Nov} + \mathcal{A}_{1-15Dec})/2.$}~~(sinusoidal regression expression of $\mathcal{A}_{16-30Nov}$) is the expected climatological meteorological field during late November given a ~~linear~~sinusoidal seasonal evolution~~,~~ (calculated by regression analyses with sinusoidal reference state), and $\mathcal{A}_{dev}$ is the deviation of the actual climatological meteorological field in late November from the expected ~~climatological meteorological~~ field. All anomalous fields during the short break were calculated in this manner (see Figs. 4, A1d, A3d, A4d, A5d, ~~and A6d~~A6d, A7, and B2). Many studies usually define anomaly fields as the ones from climatological mean, but this paper does not define anomaly fields from the climatology. The definition of the anomaly field that those of the long-year mean seasonal march (we called "deviation"). The dark blue dotted line in Fig. 3a shows the sinusoidal regression expression of the PNJ index. The short break is statistically significant at the 90% confidence level (t test for the differences; late November and the expected by sinusoidal seasonal evolution).

The~~ climatological~~ meridional structures of the EP flux and zonal wind from November to early December are shown in Figs. A1a–c. Deviations of meteorological fields, that is, those that deviate from the expectation of a ~~linear~~sinusoidal seasonal evolution (see Fig. 3),~~ in late November~~ are also shown in Fig. A1d. An upward EP flux propagation deviation (vectors in Fig. A1d) is seen at 50–80°N from the upper troposphere (300 hPa) through the stratosphere (above 100 hPa~~) during late November.~~). This flux deviation causes an EP flux convergence deviation in the high-latitude stratosphere (contours in Fig. A1d), which corresponds to the short break ~~in the seasonal evolution~~ of the PNJ. This anomalous upward EP flux originates at mid (40–60°N) and high latitudes (65–80°N). The detailed evolution of the ~~climatological~~ EP flux and zonal wind from November to early December is described in Appendix ~~B1~~A1. For reference, other climatological atmospheric fields from November to early December are described in Appendices ~~B2, B3, B4~~A2, A3, A4, and ~~B5~~A5.

3.4 Links between the anomalous upward propagation of the EP flux and a tropospheric trough over eastern Siberia

This section shows that the anomalous (Term $\mathcal{A}_{dev}$ in Eq. ~~1~~4) upward propagation of planetary waves coincides with a deepening of the eastern Siberia trough (negative deviation of the geopotential height) in late November. To identify the specific area of the anomalous (Term $\mathcal{A}_{dev}$ in Eq. ~~1~~4) upward propagation of the EP flux during the period of the short break, we investigated the horizontal distribution of the ~~wave activity flux~~ (WAF~~; Plumb, 1985~~). The largest positive deviation of the vertical component of the~~ climatological~~ WAF of the stationary wave component at 100 hPa in late November is centered over Siberia and extends over most of the Eurasian continent (Fig. 4). This distribution implies that the Eurasian area is particularly important for stratosphere–troposphere coupling during late November.

During late November, the Rossby wave deviation propagates upward over central Siberia (60–100°E) in the lower troposphere and around East Siberia in the upper troposphere (Fig. A3d). The WAF divergence deviation is negative (figure not shown), indicating convergence in the stratosphere. We further examined the horizontal structure responsible for the upward WAF at 100 hPa. The vertical component~~ of the WAF~~ is proportional to the meridional eddy heat flux ($v'T'$, where prime denotes the anomaly from the zonal mean). Over Siberia, the area of northerly wind and negative air temperature deviations (Fig. A4d) corresponds to the area of positive WAF deviations (Fig. 4). During late November, the trough over Siberia strengthens with time (see Fig. A3d). These results show that the anomalous (Term $\mathcal{A}_{dev}$ in Eq. ~~1~~4) upward propagation of planetary waves occurs simultaneously with the deepening of the eastern Siberia trough~~ in late November~~.

3.5 Geopotential height and air temperature in the middle troposphere

In section 3.4, we showed that the deepening of the trough over Siberia is associated with the strengthening the anomalous (Term $\mathcal{A}_{dev}$ in Eq. 1) vertical propagation of planetary waves and the occurrence of the short break~~ of PNJ in late November.~~. In this section, we show that the deepening of the eastern Siberia trough is associated with geopotential height and air temperature deviations. It is generally known that Rossby waves that propagate into the stratosphere in the high latitudes are planetary-scale waves with wavenumbers 1 to 2 (e.g., Baldwin and Dunkerton, 1999). Here, to identify the source of the deviations, we consider the planetary-scale wave components (i.e., wavenumbers 1 to 2) of geopotential height and air temperature in the troposphere. During late November, deviations of eddy geopotential height at 500 hPa (Z500) are strongly negative over Siberia, whereas they are strongly positive over the Atlantic Ocean (Fig. A5d). This positive–negative contrast means that the~~ climatological~~ trough over Siberia is strengthened and the planetary-scale eddy at Z500 is amplified at high latitudes. Cold deviations of eddy air temperature at 850 hPa (T850) are also seen over Siberia along the Arctic Ocean coast (Fig. A6d), west of the negative geopotential deviation (Fig. A5d). The area of these cold deviation is included in the northerly wind deviation area. Where these areas coincide, the eddy meridional heat flux ($v'T'$) is enhanced. A similar but small enhancement of $v'T'$ is also seen over Greenland, where a positive T deviation is observed (Fig. A6d), and over the North Atlantic Ocean, where a positive geopotential deviation is observed (Fig. A5d). The vertical component of the WAF with wave planetary-scale components is described in Appendix A6.

4 Discussion

Why does the atmospheric trough strengthen over Siberia at this time of the year? We hypothesize that a high-latitude land–sea thermal contrast strengthens the trough. Figure 5 shows the time series ~~of the climatological 15-day running means~~ of Z500 and T850 over Siberia (60–170°E, 50–75°N; inside the brown box in Figs. A5 and A6) and outside of Siberia (170°E–60°W, 50–70°N; inside the blue box in Figs. A5 and A6). The time series of the differences between inside and outside of Siberia (green lines) are also shown. During late November, the rate of increase in the zonal contrast (wave amplitude) of Z500 reaches a maximum (green line in Fig. 5a). Similarly, the rate of increase in the zonal T850 contrast, which roughly corresponds to a high-latitude land–sea thermal contrast, approaches a maximum during late November (green line in Fig. 5b). Siberia is of course a land region whereas the area outside of Siberia is occupied mainly by oceans, in particular, the North Atlantic Ocean. Therefore, we hypothesize that thermal forcing due to the land–sea contrast results in the amplification of the trough over Siberia. It is generally known that there are three main sources of the stationary waves that are responsible for zonally asymmetric circulation in the NH: a land–sea thermal contrast, large-scale orography, and tropical diabatic heating (e.g., Smagorinsky, 1953; Inatsu et al., 2002). Large-scale orography (in the NH, the Himalayas, and Rockies in particular) has been found by many studies to be an important source of planetary waves (e.g., Held et al., 2002; Chang, 2009; Saulière et al., 2012). We demonstrated here that the source of the ~~climatological~~ planetary wave in the troposphere during late November is at higher latitude than the Himalayas (see Figs. 4, A5d, and A6d). Strengthening of the high-latitude land–sea thermal contrast may mainly account for the short break in the ~~climatological~~ PNJ during late November. We did not find any short breaks ~~of the PNJ~~ in the Southern Hemisphere (figure not shown). The absence of a short break in the Southern Hemisphere is logically consistent with our hypothesis, because there are no high-latitude zonal land–sea thermal contrasts there.

~~The short break of the PNJ is possibly due to the occurrence of SSW events. SSW can occur even in November, although its amplitude is smaller in November than in late winter (Charlton and Polvani, 2007; Maury et al., 2016). The relationship between the short break of the PNJ and SSW in early winter is discussed in detail in Appendix C.~~

Some studies have described the PNJ variations are related to the quasi-biennial oscillation (QBO; Baldwin et al. 2001) (e.g., Holton and Tan, 1980, 1982; Gray et al. 2003; Anstey and Shepherd 2014). This might also affect to the short break, and is discussed in detail in Appendix B. The seasonal evolution from easterly to westerly winds in the stratosphere is a highly non-linear transformation in terms of the ability for waves to propagate into the stratosphere (Plumb 1989). A hidden alternative mechanism may control the short break, but it is out of the scope of present study.

5 Conclusions

We ~~found~~detected a short break in the seasonal evolution of climatological PNJ during late November (see Fig. 1). Examination of the atmospheric dynamical balance showed that an increase in upward propagation of ~~climatological~~ planetary waves from the troposphere to the stratosphere in late November is accompanied by convergence of the ~~climatological~~ EP flux in the stratosphere, which brings about this short break in the ~~climatological~~ PNJ (see Fig. 2). The upward propagation of Rossby (planetary) waves over Siberia from the troposphere to the stratosphere is a dominant cause of the ~~late November~~ short break (see Fig. 4). This upward propagation of planetary-scale Rossby waves at high latitudes is associated with amplification of ~~climatological~~ eddy geopotential height and air temperature, that is, with a strengthening of the trough over Siberia. Further, we inferred that this strengthening of the trough is forced by the high-latitude land–sea thermal contrast around Siberia (see Fig. 5). Influence of the November short break upon tropospheric extreme weather and climate remains to be examined. ~~The short break in the climatological PNJ during late February and its long-term trend are interesting topics for future research. SSW events have occurred almost every year since 2000 (Reichler et al., 2012), and this recent frequent occurrence of SSW events might be associated with Arctic sea ice losses (e.g., Kim et al., 2014; Nakamura et al., 2015; Hoshi et al., 2017). In the future, the typical short break of the PNJ should be examined in a composite analysis as well.~~

Acknowledgments

We deeply thank Dr. Kunihiko Kodera for very insightful discussions. Students in the Weather and Climate Dynamics Division offered us fruitful advice. This study was supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) through a Grant-in-Aid for Scientific Research on Innovative Areas (Grant Number 22106003), the Green Network of Excellence (GRENE) Program Arctic Climate Change Research Project, the Arctic Challenge for Sustainability (ArCS) Project, and Belmont Forum InterDec Project. The work of M. Ogi was supported by the Canada Excellence Research Chairs (CERC) Program. The Grid Analysis and Display System (GrADS) ~~was~~and the Generic Mapping Tools (GMT) were used to draw the figures.

References

Ambaum, M. H. P. and Hoskins, B. J.: The NAO troposphere-stratosphere connection, J. Clim., 15(14), 1969–1978, doi:10.1175/1520-0442(2002)015<1969:TNTSC>2.0.CO;2, 2002.

AMS: Polar vortex, Glossary of Meteorology, 2015. [Available online at http://glossary.ametsoc.org/wiki/polar_vortex]

Ando, Y., Ogi, M. and Tachibana, Y.: Abnormal Winter Weather in Japan during 2012 Controlled by Large-Scale Atmospheric and Small-Scale Oceanic Phenomena, Mon. Weather Rev., 143(1), 54–63, doi:10.1175/MWR-D-14-00032.1, 2015.

Andrews, D. G. and McIntyre, M. E.: Planetary Waves in Horizontal and Vertical Shear: The Generalized Eliassen-Palm Relation and the Mean Zonal Acceleration, J. Atmos. Sci., 33(11), 2031–2048, doi:10.1175/1520-0469(1976)033<2031:PWIHAV>2.0.CO;2, 1976.

Andrews, D. G., Holton, J. R., and Leovy, C. B.: Middle Atmosphere Dynamics, Academic Press, San Diego, 1987.

Angell, J. K.: Changes in the 300-mb north circumpolar vortex, 1963–2001. J. Clim., 19, 2984–2995, doi:10.1175/JCLI3778.1, 2006.

Anstey, J. A. and Shepherd, T. G.: High-latitude influence of the quasi-biennial oscillation, Q. J. R. Meteorol. Soc., 140(678), 1–21, doi:10.1002/qj.2132, 2014.

Baldwin, M. P. and Dunkerton, T. J.: Propagation of the Arctic Oscillation from the stratosphere to the troposphere, J. Geophys. Res. Atmos., 104(D24), 30937–30946, doi:10.1029/1999JD900445, 1999.

Baldwin, M. P. and Dunkerton, T. J.: Stratospheric harbingers of anomalous weather regimes, Science, 294(5542), 581–584, doi:10.1126/science.1063315, 2001.

Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K., Haynes, P. H., Randel, W. J., Holton, J. R., Alexander, M. J., Hirota, I., Horinouchi, T., Jones, D. B. A., Kinnersley, J. S., Marquardt, C., Sato, K. and Takahashi, M.: The quasi-biennial oscillation, Rev. Geophys., 39(2), 179–229, doi:10.1029/1999RG000073, 2001.

Black, R. X. and McDaniel, B. A.: Submonthly Polar Vortex Variability and Stratosphere–Troposphere Coupling in the Arctic, J. Clim., 22(22), 5886–5901, doi:10.1175/2009JCLI2730.1, 2009.

Brasefield, C. J.: Winds and temperatures in the lower stratosphere. J. Meteor., 7, 66–69, doi:10.1175/1520-0469(1950)007<0066:WATITL>2.0.CO;2, 1959.

Butler, A. H., Polvani, L. M. and Deser, C.: Separating the stratospheric and tropospheric pathways of El Niño–Southern Oscillation teleconnections, Environ. Res. Lett., 9(2), 24014, doi:10.1088/1748-9326/9/2/024014, 2014.

Chang, E. K. M.: Diabatic and Orographic Forcing of Northern Winter Stationary Waves and Storm Tracks, J. Clim., 22(3), 670–688, doi:10.1175/2008JCLI2403.1, 2009.

Charlton, A. J. and Polvani, L. M.: A New Look at Stratospheric Sudden Warmings. Part I: Climatology and Modeling Benchmarks, J. Clim., 20(3), 449–469, doi:10.1175/JCLI3996.1, 2007.

Cohen, J.; Jones, J.; Furtado, J. C.; and Tziperman, E.: Warm Arctic, cold continents: A common pattern related to Arctic sea ice melt, snow advance, and extreme winter weather, Oceanography, 26(4), 150–160, doi:10.5670/oceanog.2013.70, 2013.

Coy, L., Nash, E. R. and Newman, P. A.: Meteorology of the polar vortex: Spring 1997, Geophys. Res. Lett., 24(22), 2693–2696, doi:10.1029/97GL52832, 1997.

de la Cámara, A., Albers, J. R., Birner, T., Garcia, R. R., Hitchcock, P., Kinnison, D. E. and Smith, A. K.: Sensitivity of Sudden Stratospheric Warmings to Previous Stratospheric Conditions, J. Atmos. Sci., 74(9), 2857–2877, doi:10.1175/JAS-D-17-0136.1, 2017.

Deng, S., Chen, Y., Luo, T., Bi, Y. and Zhou, H.: The possible influence of stratospheric sudden warming on East Asian weather, Adv. Atmos. Sci., 25(5), 841–846, doi:10.1007/s00376-008-0841-7, 2008.

Drouard, M., Rivière, G. and Arbogast, P.: The Link between the North Pacific Climate Variability and the North Atlantic Oscillation via Downstream Propagation of Synoptic Waves, J. Clim., 28(10), 3957–3976, doi:10.1175/JCLI-D-14-00552.1, 2015.

Frauenfeld, O. W. and Davis, R. E.: Northern Hemisphere circumpolar vortex trends and climate change implications, J. Geophys. Res., 108(D14), 4423, doi:10.1029/2002JD002958, 2003.

Gray, L. J., Sparrow, S., Juckes, M., O'Neill, A. and Andrews, D. G.: Flow regimes in the winter stratosphere of the northern hemisphere, Q. J. R. Meteorol. Soc., 129, 925–945, doi:10.1256/qj.02.82, 2003.

Hamilton, K.: Dynamical coupling of the lower and middle atmosphere: Historical background to current research, J. Atmos. Solar-Terrestrial Phys., 61(1–2), 73–84, doi:10.1016/S1364-6826(98)00118-7, 1999.

Harada, Y., Kamahori, H., Kobayashi, C., Endo, H., Kobayashi, S., Ota, Y., Onoda, H., Onogi, K., Miyaoka, K. and Takahashi, K.: The JRA-55 Reanalysis: Representation of Atmospheric Circulation and Climate Variability, J. Meteorol. Soc. Japan. Ser. II, 94(3), 269–302, doi:10.2151/jmsj.2016-015, 2016.

He, S., Gao, Y., Li, F., Wang, H. and He, Y.: Impact of Arctic Oscillation on the East Asian climate: A review, Earth-Science Rev., 164, 48–62, doi:10.1016/j.earscirev.2016.10.014, 2017.

Held, I. M., Ting, M. and Wang, H.: Northern Winter Stationary Waves: Theory and Modeling, J. Clim., 15(16), 2125–2144, doi:10.1175/1520-0442(2002)015<2125:NWSWTA>2.0.CO;2, 2002.

Hitchcock, P. and Simpson, I. R.: The Downward Influence of Stratospheric Sudden Warmings, J. Atmos. Sci., 71(10), 3856–3876, doi:10.1175/JAS-D-14-0012.1, 2014.

Holton, J., and Hakim, G. J.: An Introduction to Dynamic Meteorology, 5th Edition, Academic Press, San Diego, 552 pp, 2012.

Hoshi, K., Ukita, J., Honda, M., Iwamoto, K., Nakamura, T., Yamazaki, K., Dethloff, K., Jaiser,Holton, J. R. and Tan, H.-C.: The Influence of the Equatorial Quasi-Biennial Oscillation on the Global Circulation at 50 mb, J. Atmos. Sci., 37(10), 2200–2208, doi:10.1175/1520-0469(1980)037<2200:TIOTEQ>2.0.CO;2, 1980.

Holton, J. R. and Tan, H.-C.: The Quasi-Biennial Oscillation in the Northern Hemisphere Lower Stratosphere, J. Meteorol. Soc. Japan. Ser. II, 60(1), 140–148, doi:10.2151/jmsj1965.60.1_140, 1982.

Hu, J., Ren, R., and Xu, H.: Occurrence of Winter Stratospheric Sudden Warming Events and the Seasonal Timing of Spring Stratospheric Final Warming. J. Atmos. Sci., 71, 2319–2334, doi:10.1175/JAS-D-13-0349.1, 2014.

R. and Handorf, D.: Poleward eddy heat flux anomalies associated with recent Arctic sea ice loss, Geophys. Res. Lett., 44(1), 446–454, doi:10.1002/2016GL071893, 2017.

Inatsu, M., Mukougawa, H. and Xie, S.-P.: Tropical and Extratropical SST Effects on the Midlatitude Storm Track., J. Meteorol. Soc. Japan, 80(4B), 1069–1076, doi:10.2151/jmsj.80.1069, 2002.

Karpechko, A. Y. and Manzini, E.: Stratospheric influence on tropospheric climate change in the Northern Hemisphere, J. Geophys. Res. Atmos., 117(5), 1–14, doi:10.1029/2011JD017036, 2012.

Kidston, J., Scaife, A. a., Hardiman, S. C., Mitchell, D. M., Butchart, N., Baldwin, M. P. and Gray, L. J.: Stratospheric influence on tropospheric jet streams, storm tracks and surface weather, Nat. Geosci., 8(6), 433–440, doi:10.1038/ngeo2424, 2015.

Kim, B.-M., Son, S.-W., Min, S.-K., Jeong, J.-H., Kim, S.-J., Zhang, X., Shim, T. and Yoon, J.-H.: Weakening of the stratospheric polar vortex by Arctic sea-ice loss, Nat. Commun., 5, 4646, doi:10.1038/ncomms5646, 2014.

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., Miyaoka, K. and Takahashi, K.: The JRA-55 reanalysis: General specifications and basic characteristics, J. Meteorol. Soc. Japan, 93(1), 5–48, doi:10.2151/jmsj.2015-001, 2015.

Kodera, K. and Koide, H.: Spatial and seasonal characteristics of recent decadal trends inKuroda, Y.: Dynamical response to the northern hemispheric troposphere and stratospheresolar cycle, J. Geophys. Res. Atmos., 102(D16), 19433–19447., 107(D24), 4749, doi:10.1029/97JD01270, 1997.2002JD002224, 2002.

Kolstad, E. W., Breiteig, T. and Scaife, A. A.: The association between stratospheric weak polar vortex events and cold air outbreaks in the Northern Hemisphere, Q. J. R. Meteorol. Soc., 136(649), 886–893, doi:10.1002/qj.620, 2010.

Kretschmer, M., Coumou, D., Agel, L., Barlow, M., Tziperman, E. and Cohen, J.: More-Persistent Weak Stratospheric Polar Vortex States Linked to Cold Extremes, Bull. Am. Meteorol. Soc., 99(1), 49–60, doi:10.1175/BAMS-D-16-0259.1, 2018.

Kuroda, Y. and Kodera, K.: Role of the Polar-night Jet Oscillation on the formation of the Arctic Oscillation in the Northern Hemisphere winter, J. Geophys. Res., 109(D11), D11112, doi:10.1029/2003JD004123, 2004.

Labitzke, K.: Interannual Variability of the Winter Stratosphere in the Northern Hemisphere, Mon. Weather Rev., 105(6), 762–770, doi:10.1175/1520-0493(1977)105<0762:IVOTWS>2.0.CO;2, 1977.

Labitzke, K.: On the Interannual Variability of the Middle Stratosphere during the Northern Winters, J. Meteorol. Soc. Japan. Ser. II, 60(1), 124–139, doi:10.2151/jmsj1965.60.1_124, 1982.

Labitzke, K., and B. Naujokat: The lower Arctic stratosphere in winter since 1952, SPARC Newsletter, 15, 11-14, 2000.

Labiztke, K., and van Loon, H.: The Stratosphere: Phenomena, History, and Relevance, 179 pp., Springer, New York, 1999.

Li, Q., Graf, H.-F., and Giorgetta, M. A.: Stationary planetary wave propagation in Northern Hemisphere winter – climatological analysis of the refractive index, Atmos. Chem. Phys., 7, 183-200, https://doi.org/10.5194/acp-7-183-2007, 2007.

Limpasuvan, V., Thompson, D. W. J. and Hartmann, D. L.: The life cycle of the Northern Hemisphere sudden stratospheric warmings, J. Clim., 17(13), 2584–2596, doi:10.1175/1520-0442(2004)017<2584:TLCOTN>2.0.CO;2, 2004.

Manney, G. L., Sabutis, J. L. and Swinbank, R.: A unique stratospheric warming event in November 2000, Geophys. Res. Lett., 28(13), 2629–2632, doi:10.1029/2001GL012973, 2001.

Manney, G. L., Lahoz, W. A., Sabutis, J. L., O'neill, A. and Steenman-Clark, L.: Simulations of fall and early winter in the stratosphere, Q. J. R. Meteorol. Soc., 128, 2205–2237, doi:10.1256/qj.01.88, 2002.

Matsuno, T.: Vertical Propagation of Stationary Planetary Waves in the Winter Northern Hemisphere, J. Atmos. Sci., 27(6), 871–883, doi:10.1175/1520-0469(1970)027<0871:VPOSPW>2.0.CO;2, 1970.

Maury, P., Claud, C., Manzini, E., Hauchecorne, A. and Keckhut, P.: Characteristics of stratospheric warming events during Northern winter, J. Geophys. Res. Atmos., 121(10), 5368–5380, doi:10.1002/2015JD024226, 2016.

Nakamura, T., Yamazaki, K., Iwamoto, K., Honda, M., Miyoshi, Y., Ogawa, Y. and Ukita, J.: A negative phase shift of the winter AO/NAO due to the recent Arctic sea-ice reduction in late autumn, J. Geophys. Res. Atmos., 120(8), 3209–3227, doi:10.1002/2014JD022848, 2015.

Newman, P. A., Nash, E. R. and Rosenfield, J. E.: What controls the temperature of the Arctic stratosphere during the spring?, J. Geophys. Res. Atmos., 106(D17), 19999–20010, doi:10.1029/2000JD000061, 2001.

Schoeberl, M. R. and Newman, P. A.: Middle atmosphere: Polar vortex, Encyclopedia of Atmospheric Sciences, 2nd edition, 12–17, Elsevier, Amsterdam, doi:10.1016/B978-0-12-382225-3.00228-0, 2015.

Palmer, C. E.: The stratospheric polar vortex in winter. J. Geophys. Res., 64, 749–764, doi:10.1029/JZ064i007p00749, 1959.

Pawson, S. and Naujokat, B.: The cold winters of the middle 1990s in the northern lower stratosphere, J. Geophys. Res. Atmos., 104(D12), 14209–14222, doi:10.1029/1999JD900211, 1999.

Plumb, R. A.: On the Three-Dimensional Propagation of Stationary Waves, J. Atmos. Sci., 42(3), 217–229, doi:10.1175/1520-0469(1985)042<0217:OTTDPO>2.0.CO;2, 1985.

Plumb, R. A.: On the seasonal cycle of stratospheric planetary waves, Pure Appl. Geophys. PAGEOPH, 130(2–3), 233–242, doi:10.1007/BF00874457, 1989.

Polvani, L. M., Sun, L., Butler, A. H., Richter, J. H. and Deser, C.: Distinguishing stratospheric sudden warmings from ENSO as key drivers of wintertime climate variability over the North Atlantic and Eurasia, J. Clim., 30(6), 1959–1969, doi:10.1175/JCLI-D-16-0277.1, 2017.

Reichler, T., Kim, J., Manzini, E. and Kröger, J.: A stratospheric connection to Atlantic climate variability, Nat. Geosci., 5(11), 783–787, doi:10.1038/ngeo1586, 2012.

Saulière, J., Brayshaw, D. J., Hoskins, B. and Blackburn, M.: Further Investigation of the Impact of Idealized Continents and SST Distributions on the Northern Hemisphere Storm Tracks, J. Atmos. Sci., 69(3), 840–856, doi:10.1175/JAS-D-11-0113.1, 2012.

Smagorinsky, J.: The dynamical influence of large-scale heat sources and sinks on the quasi-stationary mean motions of the atmosphere, Q. J. R. Meteorol. Soc., 79(341), 342–366, doi:10.1002/qj.49707934103, 1953.

Taguchi, M. and Yoden, S.: Internal Interannual Variability of the Troposphere–Stratosphere Coupled System in a Simple Global Circulation Model. Part II: Millennium Integrations, J. Atmos. Sci., 59(21), 3037–3050, doi:10.1175/1520-0469(2002)059<3037:IIVOTT>2.0.CO;2, 2002.

Thompson, D. W. J. and Wallace, J. M.: The Arctic oscillation signature in the wintertime geopotential height and temperature fields, Geophys. Res. Lett., 25(9), 1297–1300, doi:10.1029/98GL00950, 1998.

Thompson, D. W. J. and Wallace, J. M.: Annular Modes in the Extratropical Circulation. Part I: Month-to-Month Variability*, J. Clim., 13(5), 1000–1016, doi:10.1175/1520-0442(2000)013<1000:AMITEC>2.0.CO;2, 2000.

Thompson, D. W. J. and Wallace, J. M.: Regional Climate Impacts of the Northern Hemisphere Annular Mode, Science, 293(5527), 85–89, doi:10.1126/science.1058958, 2001.

Thompson, D. W. J., Baldwin, M. P. and Wallace, J. M.: Stratospheric connection to Northern Hemisphere wintertime weather: Implications for prediction, J. Clim., 15(12), 1421–1428, doi:10.1175/1520-0442(2002)015<1421:SCTNHW>2.0.CO;2, 2002.

Vallis, G. K., Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-scale Circulation, 2nd Edition, Cambridge University Press, 946 pp, 2017.

Waugh, D. W., Sobel, A. H. and Polvani, L. M.: What Is the Polar Vortex and How Does It Influence Weather?, Bull. Am. Meteorol. Soc., 98(1), 37–44, doi:10.1175/BAMS-D-15-00212.1, 2017.

Waugh, D. W. and Polvani, L. M.: Stratospheric polar vortices. The Stratosphere: Dynamics, Transport, and Chemistry, Geophys. Monogr., 190, Amer. Geophys. Union, 43–57, doi:10.1029/2009GM000887, 2010.

Waugh, D. W. and Randel, W. J.: Climatology of Arctic and Antarctic Polar Vortices Using Elliptical Diagnostics, J. Atmos. Sci., 56(11), 1594–1613, doi:10.1175/1520-0469(1999)056<1594:COAAAP>2.0.CO;2, 1999.

Wilks, D. S.: Statistical Methods in the Atmospheric Science, 3rd Edition, Academic Press, San Diego, 704 pp, 2011.

Woo, S.-H., Kim, B.-M. and Kug, J.-S.: Temperature Variation over East Asia during the Lifecycle of Weak Stratospheric Polar Vortex, J. Clim., 28(14), 5857–5872, doi:10.1175/JCLI-D-14-00790.1, 2015.

Xu, T., Shi, Z., Wang, H. and An, Z.: Nonstationary impact of the winter North Atlantic Oscillation and the response of mid-latitude Eurasian climate, Theor. Appl. Climatol., 124(1–2), doi:10.1007/s00704-015-1396-z, 2016.

Yamashita, Y., Akiyoshi, H., Shepherd, T. G. and Takahashi, M.: The Combined Influences of Westerly Phase of the Quasi-Biennial Oscillation and 11-year Solar Maximum Conditions on the Northern Hemisphere Extratropical Winter Circulation, J. Meteorol. Soc. Japan. Ser. II, 93(6), 629–644, doi:10.2151/jmsj.2015-054, 2015.

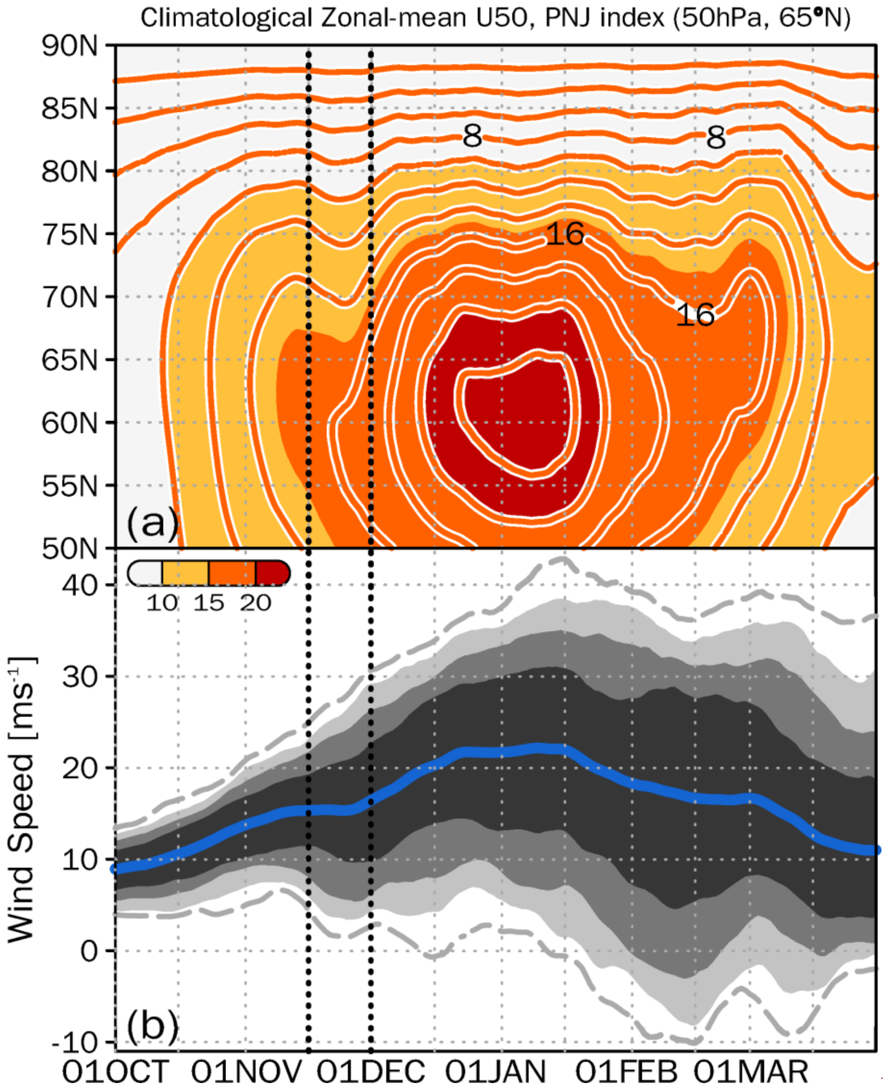
Figure 1. **(a)** Latitude–time cross section of the 15-day running mean of the climatological zonal-mean zonal wind at 50 hPa ($\overline{\mathrm{U}}50$; lines and color shading) from 1 October through 31 March. The contour interval is 2.0 m s[–1]. **(b)** Time series of the climatological 15-day running mean of the PNJ index (m s[–1], blue), defined as zonal-mean zonal wind speed at 6560-80°N and 50 hPa. Dark gray shading indicates the 20th to 80th percentiles, medium gray shading indicates the 10th to 90th percentiles, and light gray shading indicates the 5th to 95th percentiles. The two dashed lines indicated the daily minimum and maximum of the PNJ. The vertical black dotted lines indicate the period of the short break in late November.

Figure 2. Time series of climatological 15-day running means of the **(a)** PNJ index (m s[–1], dark blue) (same as Fig. 1b1b); the sinusoidal regression expression of the PNJ index ($\hat{f}(t) = 10.36\sin(2\pi t/365 + 1.54) + 7.52$ (t=1: 01JAN), dark blue dotted line); the standard error of the PNJ index (gray shading); **(b)** the temporal tendency of the PNJ (i.e., zonal acceleration [m s[–1] day[–1]]; Term A in equation (A33), light blue line), the Coriolis force acting on the residual mean meridional circulation and the meridional advection of zonal momentum (m s[–1] day[–1], Term B in equation (A33), purple line) at 50 hPa, and the EP flux divergence (m s[–1] day[–1]), Term C in equation (A33), red line) at 50 hPa averaged over latitudes 60–70°N; the sum of Term B and Term C (black line); and **(c)** the vertical component of EP flux (F^z) at 100 hPa (m^2 s^{-2}) averaged over latitudes 50–70°N from 1 October through 31 March. The vertical black dotted lines indicate the period of the late November short break.

Figure 3. Schematic diagram of a late November deviation in the seasonal evolution of a climatological meteorological field. Red stars indicate Blue cross mark indicates the values of the meteorological field in earlylate November expected by sinusoidal seasonal evolution, and early December, the red cross mark indicates its actual value in late November, and the blue cross mark indicates the mean of the early November and early December values.. The vertical difference between the actual value (red cross mark) and the expected value (blue cross mark) during late November, which is calculated by equation (14), is the field deviation.

Figure 4. Vertical component of the late November deviation of the climatological WAF (Plumb, 1985) at 100 hPa (10^{-3} m^2 s^{-2}) with respect to its linearsinusoidal seasonal evolution, calculated by equation (14) (see Section 3.3). The blue box (0–360°E, 50–70°N) indicates the averaging area used to calculate the fields shown in Fig. 2c.

Figure 5. Time series of the climatological 15-day running mean **(a)** Z500 (m) and **(b)** T850 (°C) over Siberia (60–170°E, 50–75°N; brown lines), outside Siberia (170°E–60°W, 50–75°N; blue lines), and their anomalies within Siberia from their values outside of Siberia (green lines) from 1 October through 31 March. The vertical black dotted lines indicate the period of the late November short break.



Climatological Zonal-mean U50, PNJ index (50hPa, 65°N)
90N
85N
80N
75N
70N
65N
60N
55N
50N
8
8
16
16
(a)
10 15 20
40
30
20
10
0
-10
Wind Speed [ms-1]
(b)
01OCT 01NOV 01DEC 01JAN 01FEB 01MAR

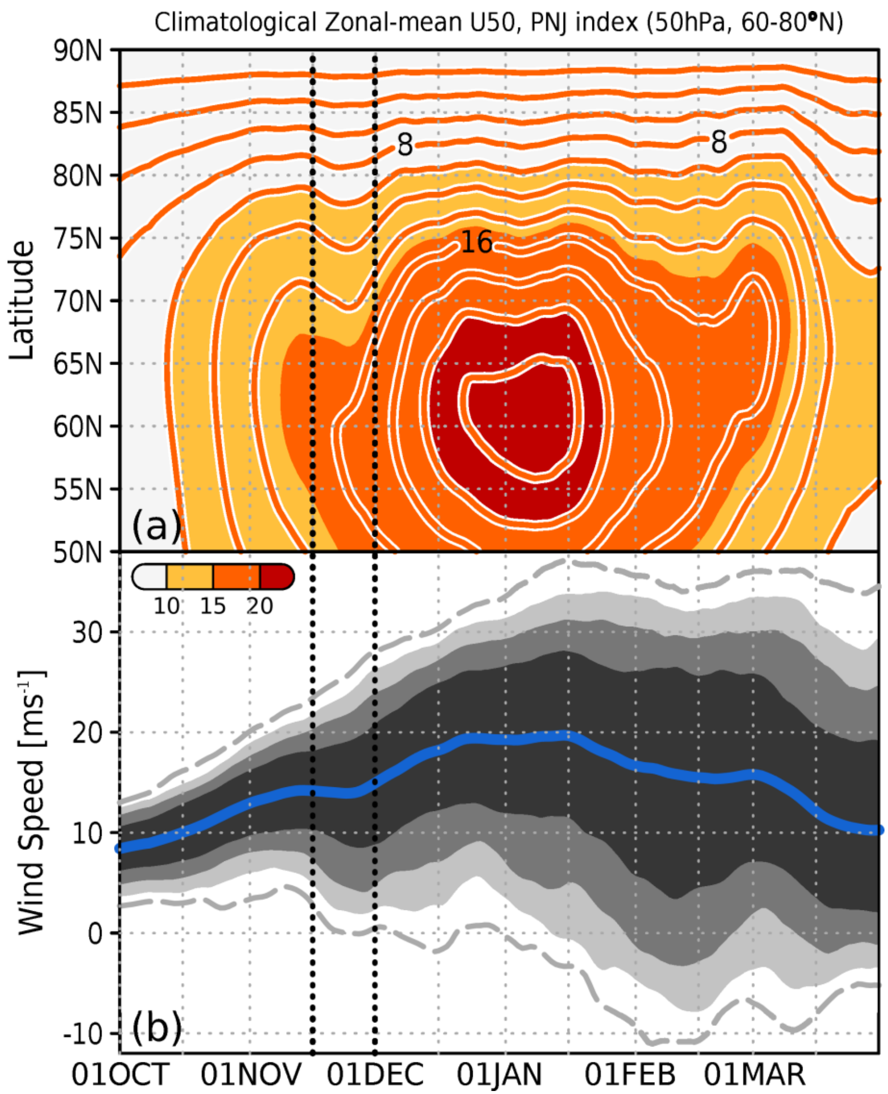
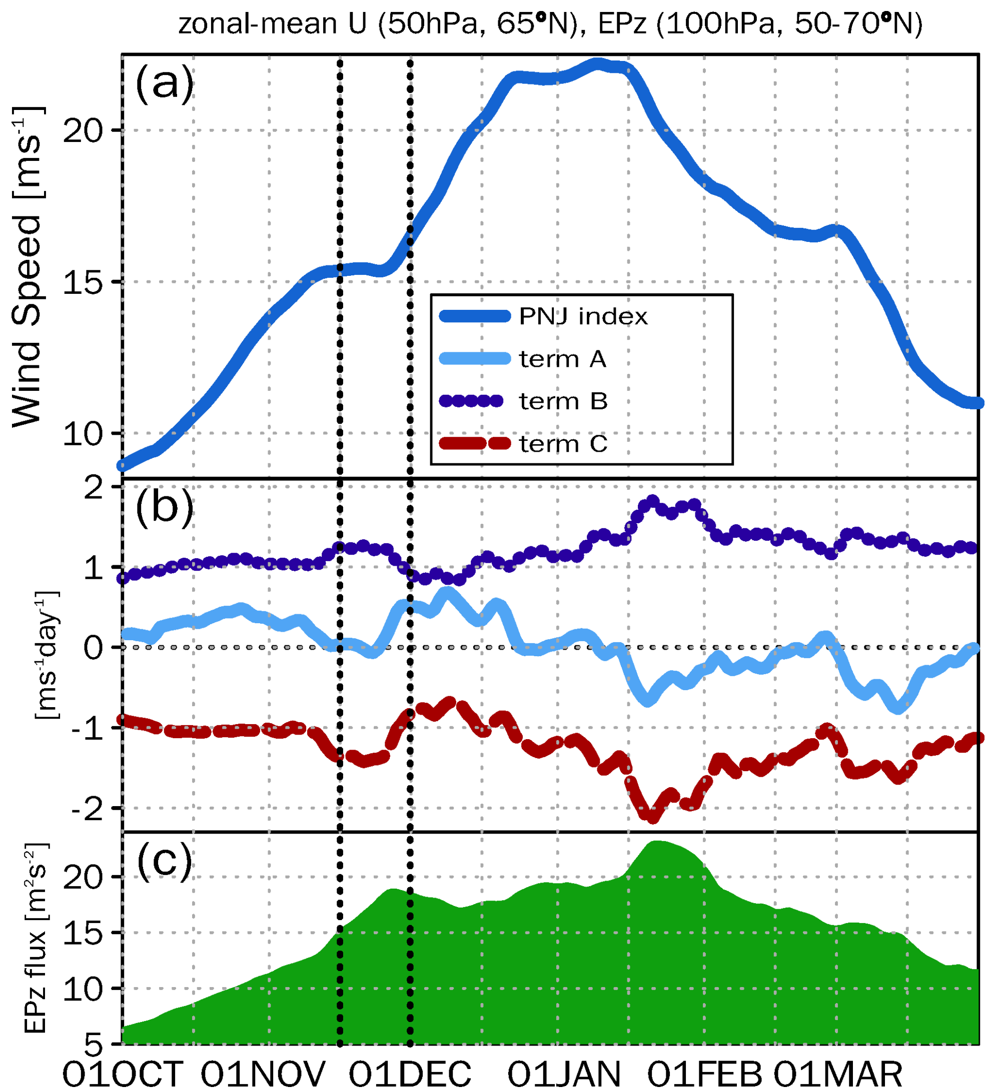


Figure 1. (a) Latitude–time cross section of the 15-day running mean of the climatological zonal-mean zonal wind at 50 hPa ($\overline{U}50$; lines and color shading) from 1 October through 31 March. The contour interval is 2.0 m s^{-1}. **(b)** Time series of the climatological 15-day running mean of the PNJ index (m s^{-1}, blue), defined as zonal-mean zonal wind speed at ~~65~~60-80°N and 50 hPa. Dark gray shading indicates the 20th to 80th percentiles, medium gray shading indicates the 10th to 90th percentiles, and light gray shading indicates the 5th to 95th percentiles. The two dashed lines indicated the daily minimum and maximum of the PNJ. The vertical black dotted lines indicate the period of the short break in late November.


zonal-mean U (50hPa, 65°N), EPz (100hPa, 50-70°N)
(a)
(b)
(c)
Wind Speed [ms-1]
[ms-1day-1]
EPz flux [m2s-2]
PNJ index
term A
term B
term C
20
15
10
2
1
0
-1
-2
20
15
10
5
01OCT
01NOV
01DEC
01JAN
01FEB
01MAR

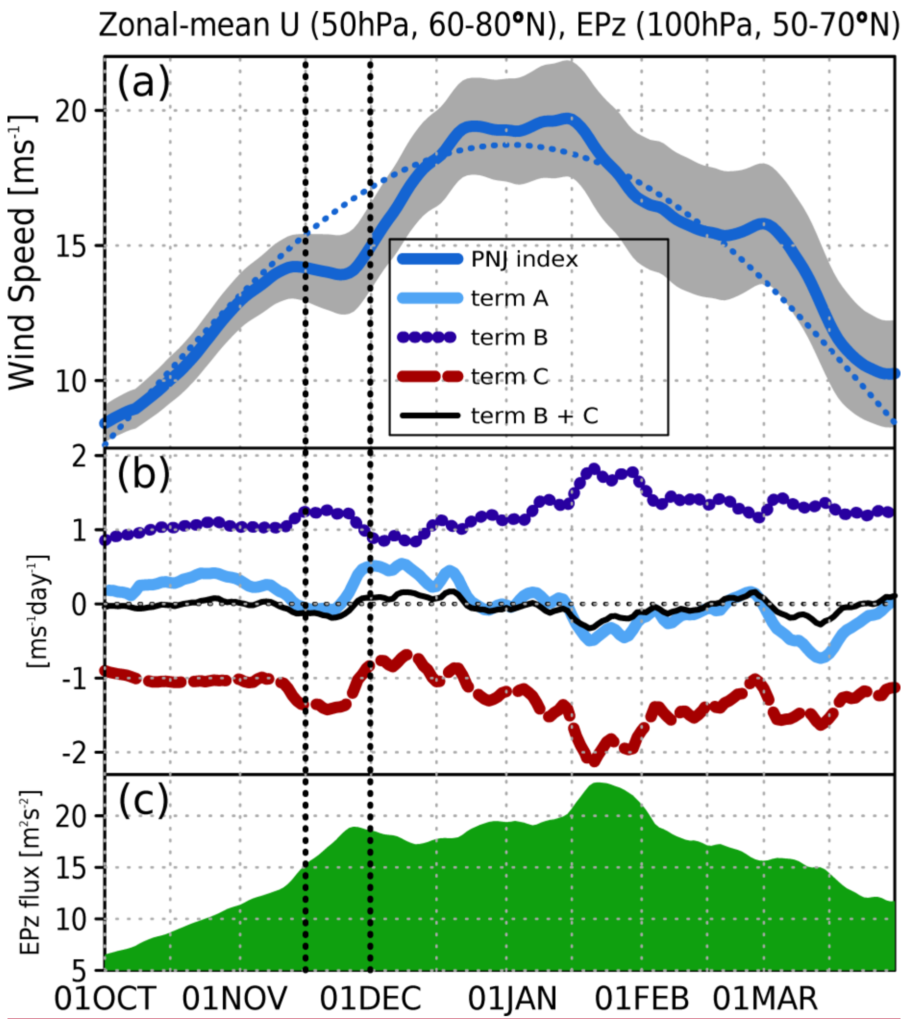
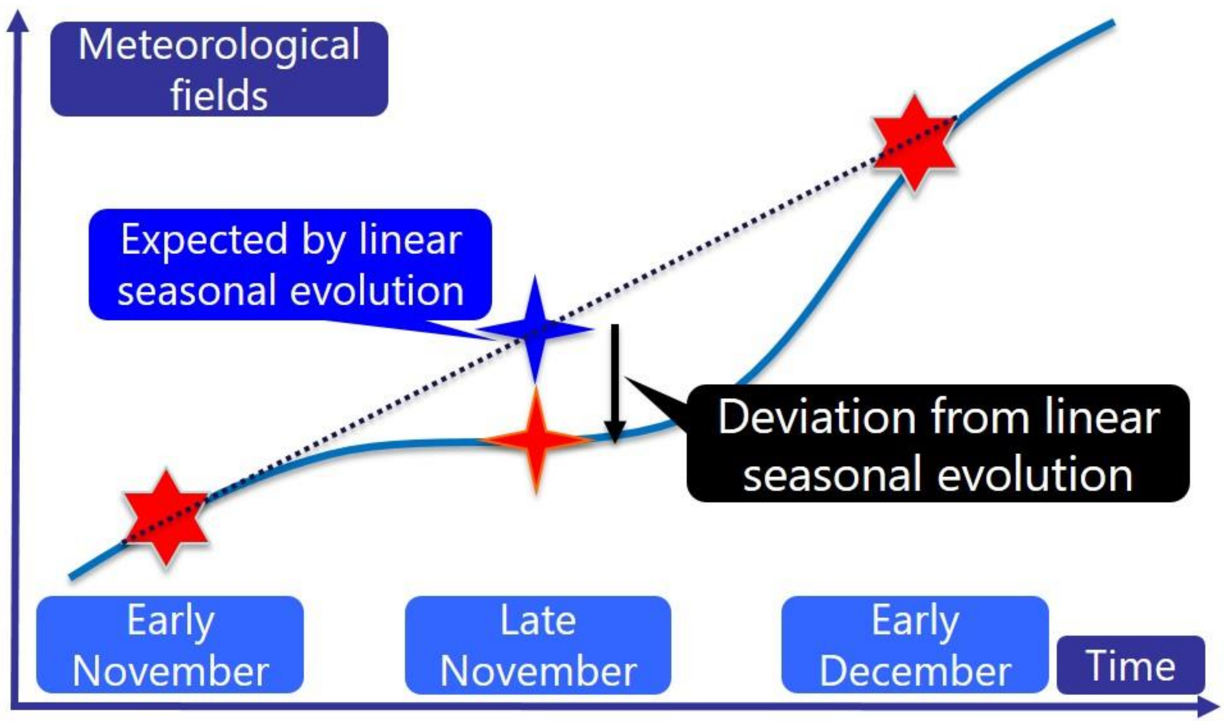


Figure 2. Time series of climatological 15-day running means of the **(a)** PNJ index (m s^{-1}, dark blue) (same as Fig. ~~1b~~1b); the sinusoidal regression expression of the PNJ index ($\hat{f}(t) = 10.36\sin(2\pi t/365 + 1.54) + 7.52$ (t=1: 01JAN), dark blue dotted line); the standard error of the PNJ index (gray shading); **(b)** the temporal tendency of the PNJ (i.e., zonal acceleration [m s^{-1} day^{-1}]; Term A in equation (A3), light blue line), the Coriolis force acting on the residual mean meridional circulation and the meridional advection of zonal momentum (m s^{-1} day^{-1}, Term B in equation (~~A3~~3), purple line) at 50 hPa, and the EP flux divergence (m s^{-1} day^{-1}), Term C in equation (~~A3~~3), red line) at 50 hPa averaged over latitudes 60~~–70°N;~~80°N; the sum of Term B and Term C (black line); and **(c)** the vertical component

of EP flux (F^z) at 100 hPa (m^2 s^{-2}) averaged over latitudes 50–70°N from 1 October through 31 March. The vertical black dotted lines indicate the period of the late November short break.


Meteorological fields
Expected by linear seasonal evolution
Deviation from linear seasonal evolution
Early November
Late November
Early December
Time

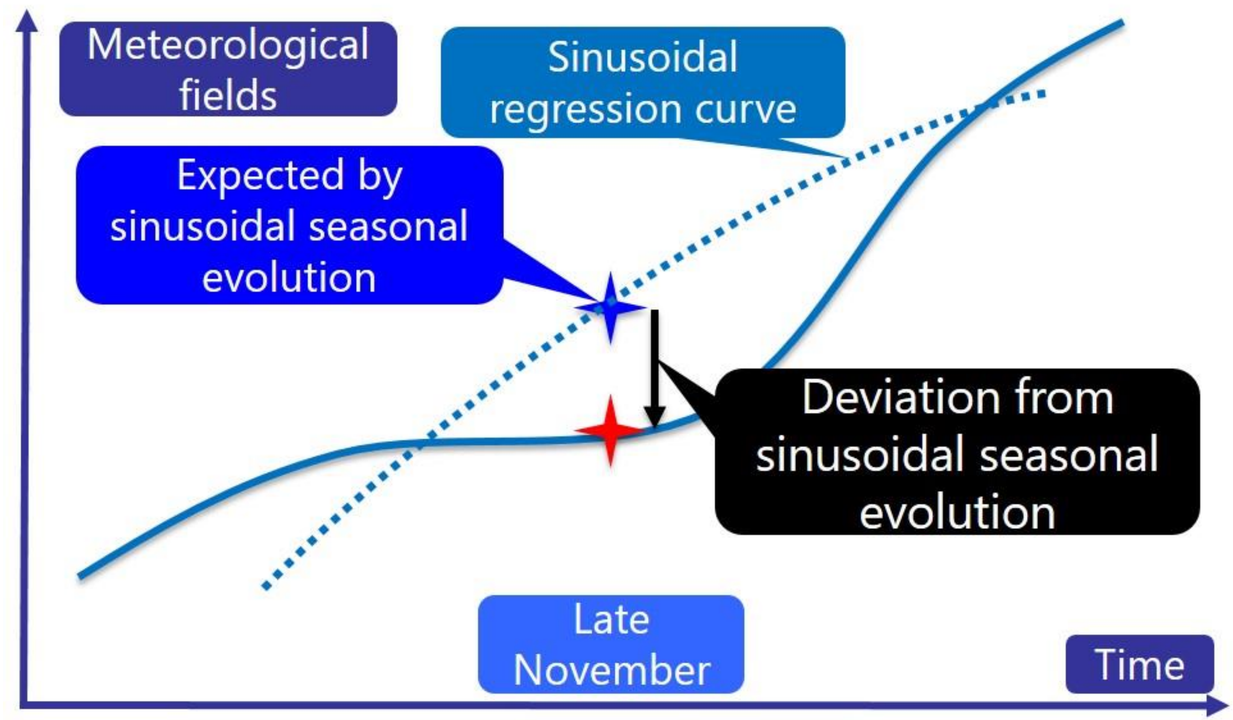
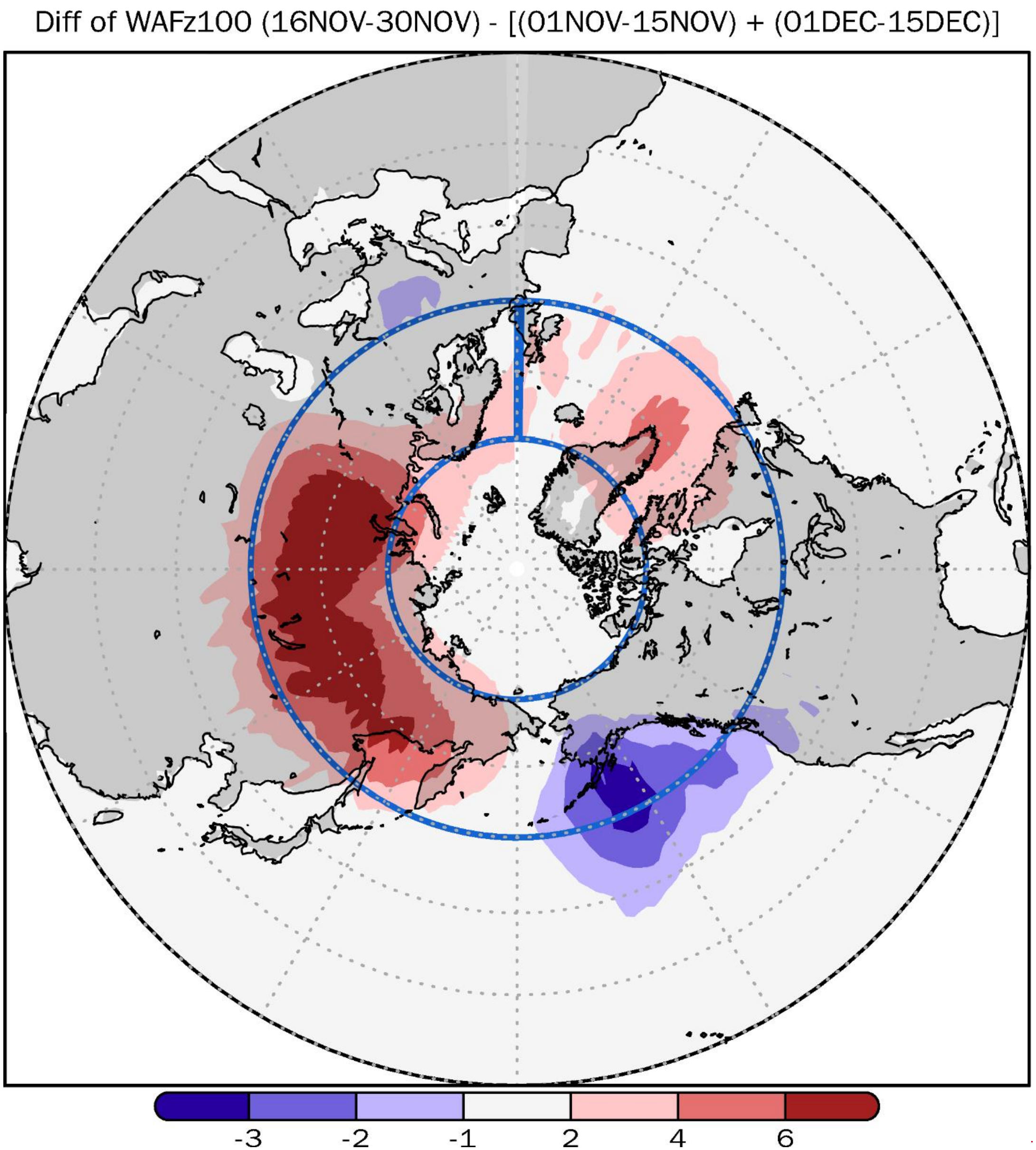


Figure 3. Schematic diagram of a late November deviation in the seasonal evolution of a climatological meteorological field. ~~Red stars indicate~~ Blue cross mark indicates the values of the meteorological field in ~~early~~late November ~~and early December~~expected by sinusoidal seasonal evolution, the red cross mark indicates its actual value in late November~~, and the blue cross mark indicates the mean of the early November and early December values.~~. The vertical difference between the actual value (red cross mark) and the expected value (blue cross mark) during late November, which is calculated by equation (~~1~~4), is the field deviation.


Diff of WAFz100 (16NOV-30NOV) - [(01NOV-15NOV) + (01DEC-15DEC)]
-3
-2
-1
2
4
6

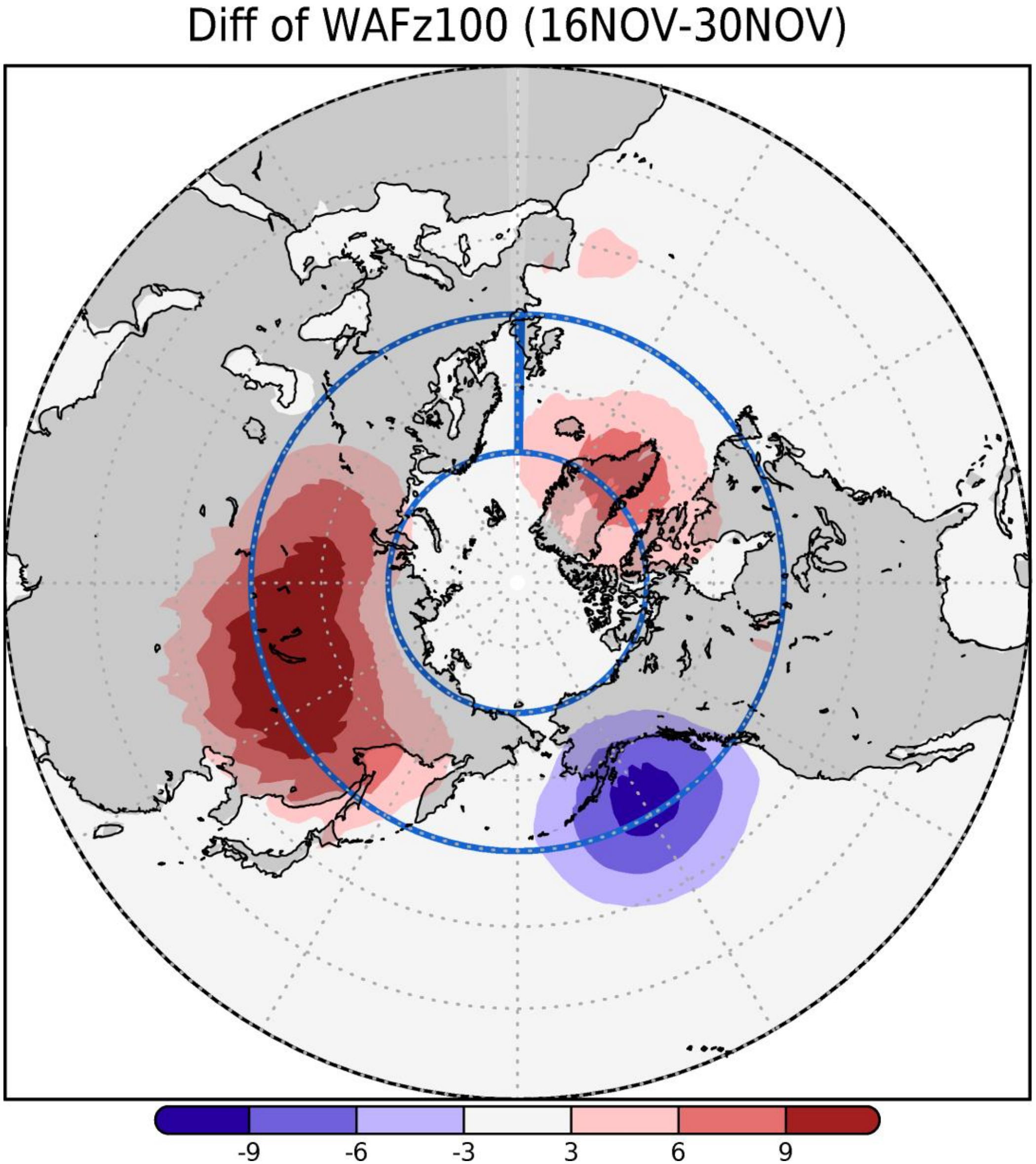
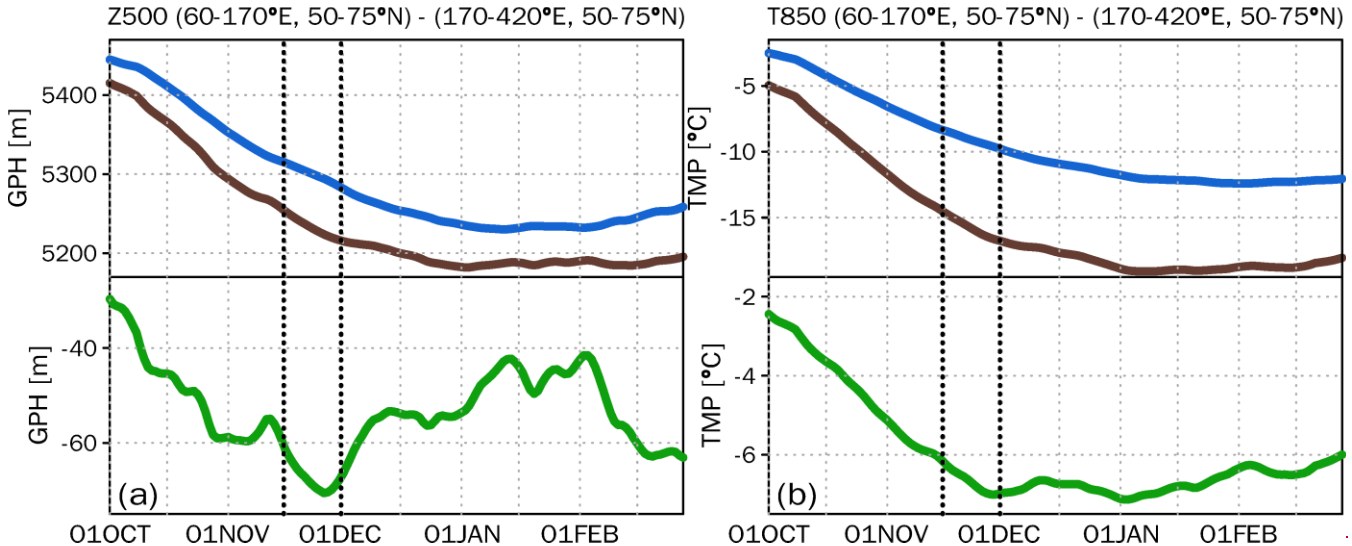


Figure 4. Vertical component of the late November deviation of the climatological WAF (Plumb, 1985) at 100 hPa (10^{-3} m^2 s^{-2}) with respect to its ~~linear~~sinusoidal seasonal evolution, calculated by equation (~~1~~4) (see Section 3.3). The blue box (0–360°E, 50–70°N) indicates the averaging area used to calculate the fields shown in Fig. 2c.


Z500 (60-170°E, 50-75°N) - (170-420°E, 50-75°N)
T850 (60-170°E, 50-75°N) - (170-420°E, 50-75°N)
GPH [m]
TMP [°C]
(a)
(b)
01OCT
01NOV
01DEC
01JAN
01FEB

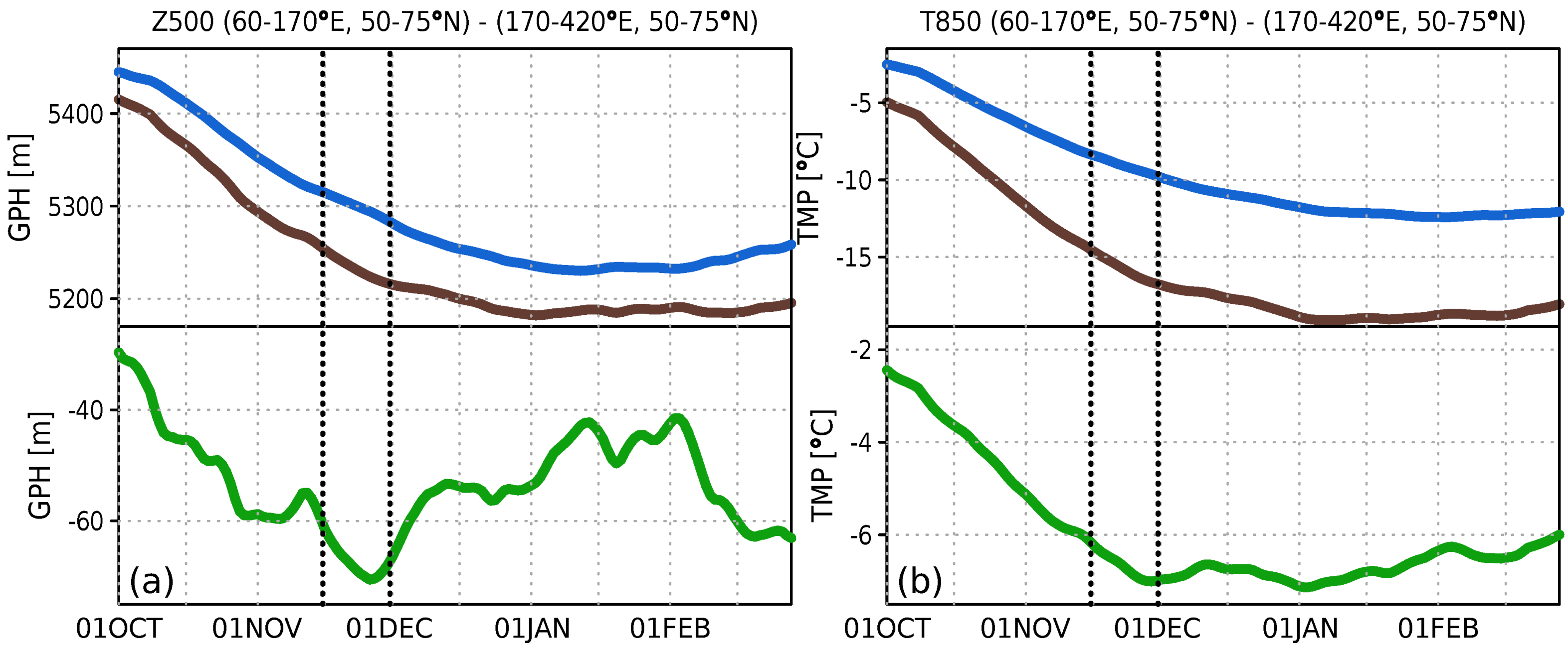

Z500 (60-170°E, 50-75°N) - (170-420°E, 50-75°N)
T850 (60-170°E, 50-75°N) - (170-420°E, 50-75°N)
GPH [m]
TMP [°C]
(a)
(b)
01OCT
01NOV
01DEC
01JAN
01FEB

Figure 5. Time series of the climatological 15-day running mean **(a)** Z500 (m) and **(b)** T850 (°C) over Siberia (60–170°E, 50–75°N; brown lines), outside Siberia (170°E–60°W, 50–75°N; blue lines), and their anomalies within Siberia from their values outside of Siberia (green lines) from 1 October through 31 March. The vertical black dotted lines indicate the period of the late November short break.

Appendices

Appendix A Transformed Eulerian Mean (TEM) Diagnostics

Eliassen-Palm (EP) flux analysis is widely used in dynamic meteorology to diagnose wave and zonal-mean flow interactions. The EP flux shows the propagation of Rossby (planetary) waves (Andrews and McIntyre, 1976). The meridional (F^{ϕ}) and vertical (F^{z}) components of the EP flux ($\mathbf{F}$) are defined as follows:

$$F^{\phi} \equiv \rho_0 a \cos\phi \left[(\partial \bar{u}/\partial z)\, \overline{v'\theta'}/\bar{\theta}_z - \overline{u'v'} \right] \quad \text{(A1)}$$

$$F^{z} \equiv \rho_0 a \cos\phi \left\{ [f - (a\cos\phi)^{-1}\, \partial(\bar{u}\cos\phi)/\partial\phi]\, \overline{v'\theta'}/\bar{\theta}_z - \overline{w'u'} \right\}, \quad \text{(A2)}$$

where a is the radius of the Earth, f is the Coriolis parameter, ϕ is latitude, θ is potential temperature, u is zonal wind, and v is meridional wind. Overbars denote zonal means, primes denote anomaly from the zonal mean, z is a log-pressure coordinate, and ρ_0 is air density. $\bar{\theta}_z = \partial\bar{\theta}/\partial z$ is computed from the zonal mean of the potential temperature in log-pressure coordinates. The eddy-flux terms $u'v'$ and $v'\theta'$ are computed from the zonal anomalies in the 6-hourly data, and the product is zonally averaged and then time averaged to obtain 15-day means.

We used the primitive form of the Transformed Eulerian Mean (TEM) momentum equation to examine the diagnostics of the zonal-mean momentum (e.g., Andrews et al., 1987; Holton and Hakim, 2012; Vallis, 2017):

$$\underbrace{\partial\bar{u}/\partial t}_{(A)} = \underbrace{\bar{v}^{*}\{f - (a\cos\phi)^{-1}\, \partial(\bar{u}\cos\phi)/\partial\phi\}}_{(B)} - \bar{w}^{*}\, \partial\bar{u}/\partial z + \underbrace{(\rho_0 a\cos\phi)^{-1}\nabla\cdot\mathbf{F}}_{(C)} + \bar{X}, \quad \text{(A3)}$$

where $\bar{v}^{*}$ and $\bar{w}^{*}$ are the meridional and vertical components of the residual mean meridional circulation, $\bar{X}$ is a residual Term that includes internal diffusion and surface friction as well as sub-grid scale forcing such as gravity wave drag. Term A in equation (A3) is the temporal tendency of the zonal-mean zonal wind, Term B is the Coriolis force acting on the residual mean meridional circulation and the meridional advection of zonal momentum, and Term C is the divergence of the EP flux vector, i.e., wave forcing.

The vertical component of the wave activity flux (WAF; Plumb, 1985) at 100 hPa provides a useful diagnostic for identifying the source region of vertically propagating stationary planetary waves. The vertical component of the WAF is proportional to the vertical component of the EP flux. The eddy terms are computed from the zonal deviations relative to each 15-day mean.

~~Wavenumber decomposition was carried out by applying Fourier analysis to the geopotential height and air temperature fields.~~

~~Appendix B~~ Climatological fields from early November to early December and their late November deviations

Appendix ~~B1~~A1 Zonal mean zonal wind, EP flux, and EP flux divergence

Figures A1a–c show the climatological zonal mean zonal wind, EP flux, and EP flux divergence in the NH during (a) early November, (b) late November, and (c) early December. The subtropical jet is commonly centered in the upper troposphere at 35°N, 200 hPa, and the PNJ is centered in the stratosphere at 65°N. These two westerly maxima gradually strengthen with time. The EP flux propagates upward from the lower troposphere to the mid- and upper troposphere in the low latitudes, and it propagates into the stratosphere in the high latitudes. The EP flux also gradually propagates upward with time. Figure A1d shows the departures of the fields shown in Fig. A1b from the ~~average~~sinusoidal evolution of the fields shown Figs. A1a and A1c (calculated by equation (~~1~~4)). Thus, Fig. A1d shows the late November field deviations from a ~~linear~~sinusoidal seasonal evolution.

Appendix ~~B2~~A2 Vertical component of the wave activity flux of the stationary wave component at 100 hPa

Figures A2a–c show the vertical component of the climatological wave activity flux (WAF) of the stationary wave component at 100 hPa during early November, late November, and early December, respectively. During all three periods, a strong positive signature is centered in the Russian far east and extends from eastern Europe to the east coast of Asia.

Appendix ~~B3~~A3 Eddy component of geopotential height and zonal and vertical components of the WAF averaged over 50–70°N

Figures A3a–c show the eddies (anomalies from the zonal mean) of climatological geopotential height and the zonal and vertical components of the climatological WAF distribution, averaged over 50–70°N (inside the blue box in Fig. A2) during early November, late November, and early December, respectively. Over East Siberia (100–120°E), an area of strong negative eddies (i.e., a geopotential height trough) extends from the middle troposphere to the stratosphere with a westward-upward tilt, and an area of positive eddies (i.e., a ridge) occurs near the surface over East Siberia (i.e., the area of Siberian High). Over 180°E–120°W, there is an area of strong positive anomalies in the stratosphere (i.e., the Aleutian High). Rossby waves propagate upward over East Siberia from the lower troposphere to the upper troposphere. Figure A3d shows the late November ~~anomalies~~deviations. Note that the WAF was calculated with equation (~~1~~4), not from the zonal anomalies of climatological geopotential height shown in Fig. A3d.

Appendix ~~B4~~A4 Zonal anomalies of meridional wind and air temperature at 100 hPa

Figures A4a–c show the zonal anomalies of climatological meridional wind and air temperature at 100 hPa during early November, late November, and early December, respectively. During all three periods, northerly winds and negative air temperatures occur over Siberia and southerly winds and positive air temperatures occur over the northwest Pacific Ocean. This collocation corresponds to the area of positive anomalies of the WAF over Siberia (see Figs. A2a–c).

Appendix ~~B5~~A5 Geopotential height and air temperature in middle troposphere

Figures A5a–c show the climatological eddy geopotential height at 500 hPa (Z500) during early November, late November, and early December, respectively. Negative anomalies (trough) are seen from East Siberia to East Asia, whereas positive anomalies (ridge) are over the North Atlantic Ocean to Europe. Figure A5d shows the planetary-scale eddy geopotential height deviation at 500 hPa. Figure A6 is the same as Fig. A5, but for air temperature at 850 hPa (T850). Negative anomalies (cold air) are seen over East Siberia to East Asia, and positive anomalies (warm air) are apparent over the North Atlantic Ocean to Europe (Figs. A6a–c).

~~Appendix C.~~

Appendix A6. The anomalous upward propagation of the WAF with wavenumber decomposition

The WAF at 100 hPa is only very weakly correlated with anomalies within the troposphere, especially on sub-monthly timescales (Fig. 15 in de la Cámara et al. 2017). A big reason is that the planetary-scale waves that propagate into the stratosphere are dwarfed by the WAF variability associated with waves that are trapped with the troposphere. We therefore consider the planetary-scale wave components (wavenumbers 1 to 2) of the WAF. Figure A7 show the same as Fig. 4, but with wavenumber decomposition, (a) wavenumber 1 and (b) that of 2. The large positive deviation of the WAF with wavenumber 1 is centered over high-latitude Eurasia (Fig. A7a). However, the negative deviation of the WAF with wavenumber 2 is also centered over Eurasia (Fig. A7b). Thus, the WAF with wavenumber 1 contributed to the positive deviation.

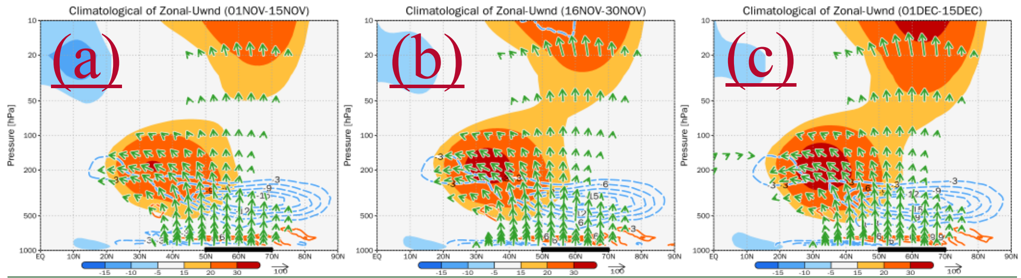
Appendix B. Relationship between the early winter (November) short break of the PNJ and ~~SSW events~~ QBO

Some studies have described the PNJ variations are related to the quasi-biennial oscillation (QBO; Baldwin et al. 2001) (e.g., Holton and Tan, 1980, 1982; Gray et al. 2003; Anstey and Shepherd 2014). The PNJ is anomalously weak during the easterly phase of the QBO (QBO-E), whereas the PNJ is anomalously strong in the westerly phase of the QBO (QBO-W). We compared the difference between the composite average in the years of QBO-E and that of QBO-W. QBO-E and QBO-W are defined as the direction of the zonal-mean zonal wind at 50 hPa averaged over 10°S-

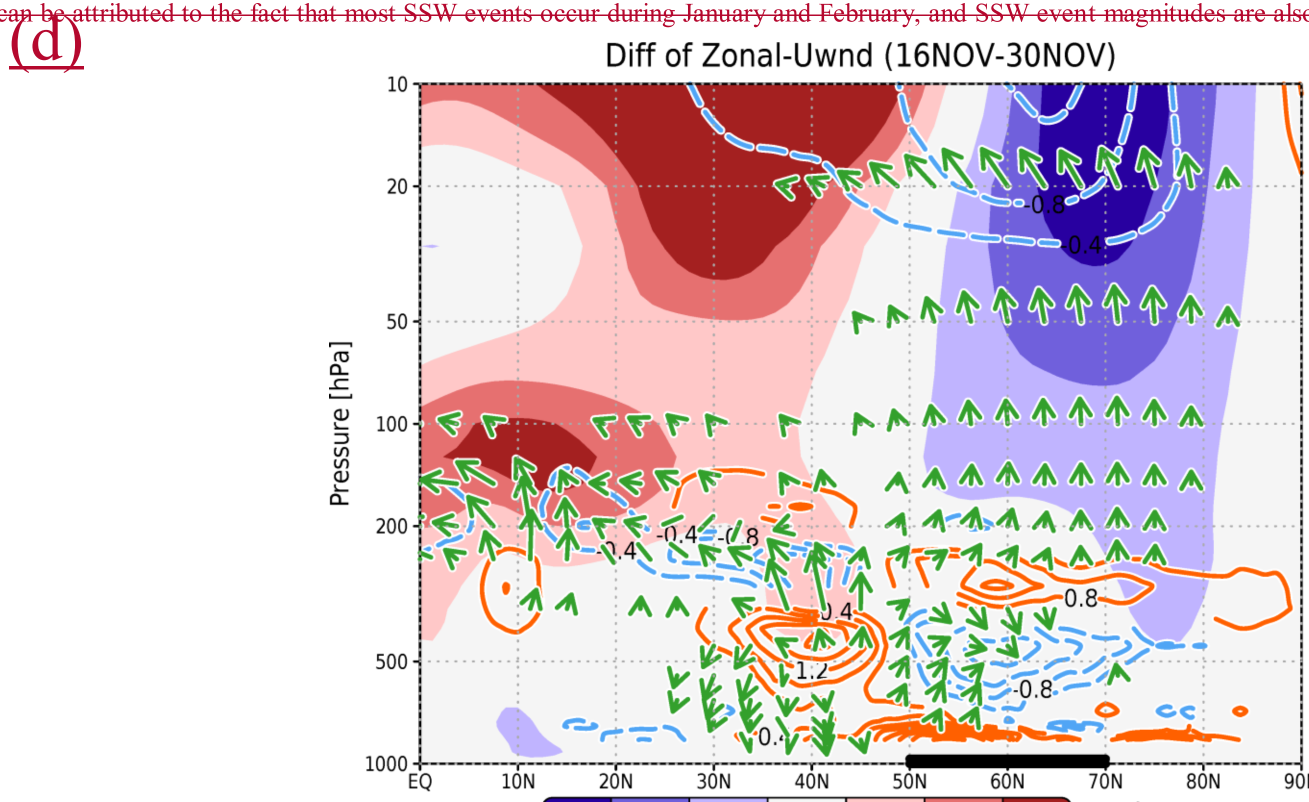
10°N in November. The short break occur during late November in both years. The PNJ in QBO-E has clearer short break than in QBO-W (Figs. A7 and A8). However, the difference is not statistically significant.

Appendix C. Histogram of the short break of the PNJ in late November

We investigated how many winters the short break appear. The definition of the occurrence of the short break was the year when the deviation of the PNJ in late November from the one expected by sinusoidal seasonal evolution was negative. The number of the negative years were 23 years (Relative frequency is 0.61) (Figure C1).



~~As illustrated in Fig. 1b, the interannual spread of the PNJ is larger during January and February than from October to November. The larger spread in winter can be attributed to the fact that most SSW events occur during January and February, and SSW event magnitudes are also large during~~



~~this period (Charlton and Polvani, 2007;~~

Maury et al., 2016). The upper percentile wind speed values do not show a short break of the PNJ during November, whereas they do show the late February short break. This result is consistent with the fact that SSW events are rare and their amplitudes are smaller in November than in late winter.

Manney et al. (2001) indicated that minor early winter SSWs that occurred in November 2000, which they called Canadian Warmings (CWs; Labitzke, 1977, 1982), may have had a profound impact on the development of a vortex and a low-temperature region in the lower stratosphere. Waugh and Randel (1999) presented an overview of climatological stratospheric polar vortices, including during the early winter period, and examined them by an elliptical diagnostics analysis. Elliptical diagnostics define the area, center, elongation, and orientation of each vortex and are used to quantify their structure and evolution. They found that the PNJ in the NH becomes more distorted and its position shifts away from the pole from October through December. They also recognized a climatological southward shift of the center of the polar vortex in the NH in late November (Fig. 4d in Waugh and Randel, 1999). This finding is consistent with our study results.

The shift recognized by Waugh and Randel (1999) may be related to the occurrence of wavenumber 1-type minor SSW events (CWs) in late November (Labitzke and Naujokat, 2000; Manney et al., 2001), and these CWs might affect the short break in the seasonal evolution of climatological PNJ during late November. Moreover, Maury et al. (2016) defined an SSW event in terms of a comprehensive description of stratospheric warming events without a priori distinctions between major and minor events. Small-amplitude warmings occur during late November but not in early November or in December. Therefore, the late November climatological short break of the PNJ may be related to early winter SSW events. Our study results are consistent with these previous studies.

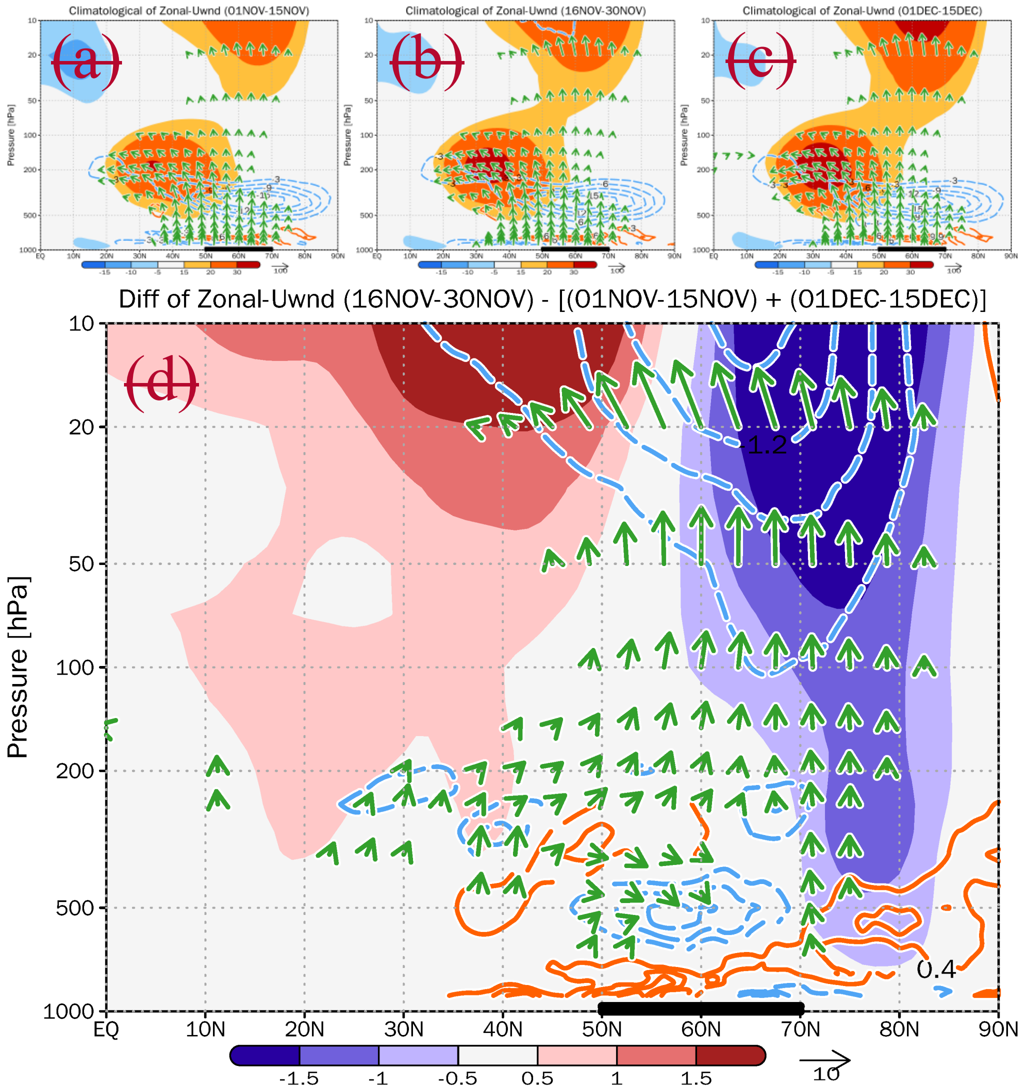


Figure A1. Climatological zonal-mean zonal wind speed (m s^{-1}, color shading), EP flux (m^2 s^{-2}, vectors), and the flux divergence (m s^{-1} day^{-1}, contours) during **(a)** early November (1–15 November), **(b)** late November (16–30 November), and **(c)** early December (1–15 December). **(d)** Late November deviations (late November deviations from the mean of the early November and early December valuesexpected sinusoidal regression expression calculated with equation (14); see Section 3.3). The EP flux is standardized by density (1.225 kg m^{-3}) and the radius of the Earth (6.37 × 10^6 m). The vertical component of the vectors is multiplied by a factor of 250. The bold black line indicates the longitudinal range for Siberia (50–70°N).

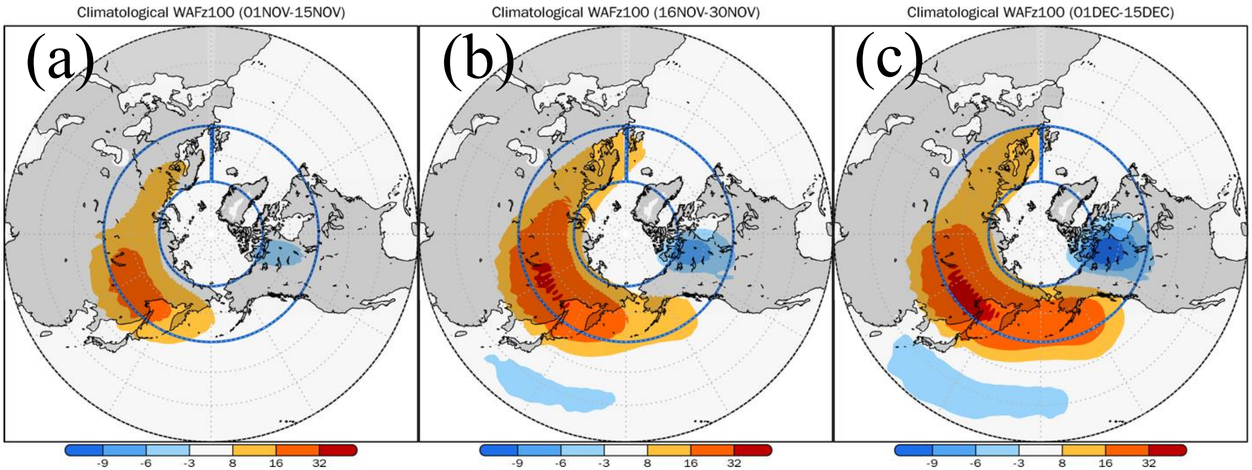
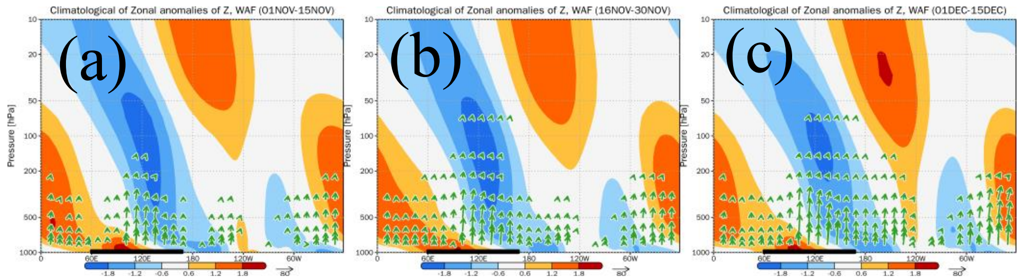
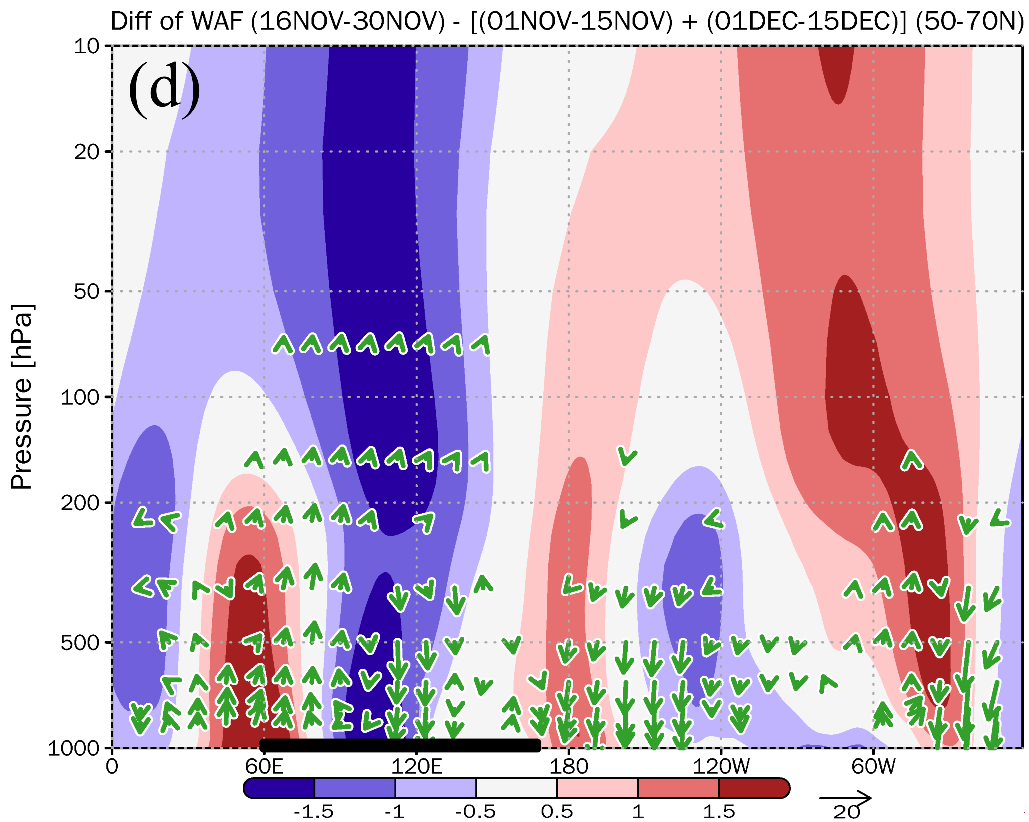


Figure A2. Vertical component of the climatological wave activity flux (Plumb, 1985) at 100 hPa (10^{-3} m^2 s^{-2}) during **(a)** early November, **(b)** late November, and **(c)** early December. The box outlined in blue (0–360°E, 50–70°N) indicates the averaging area used for calculating the fields shown in Fig. A3.


Climatological of Zonal anomalies of Z, WAF (01NOV-15NOV)
Climatological of Zonal anomalies of Z, WAF (16NOV-30NOV)
Climatological of Zonal anomalies of Z, WAF (01DEC-15DEC)
(a)
(b)
(c)
Pressure [hPa]
60E
120E
180
120W
60W
-1.8
-1.2
-0.6
0.6
1.2
1.8
80



Diff of WAF (16NOV-30NOV) - [(01NOV-15NOV) + (01DEC-15DEC)] (50-70N)
(d)
Pressure [hPa]
10
20
50
100
200
500
1000
0
60E
120E
180
120W
60W
-1.5
-1
-0.5
0.5
1
1.5
20

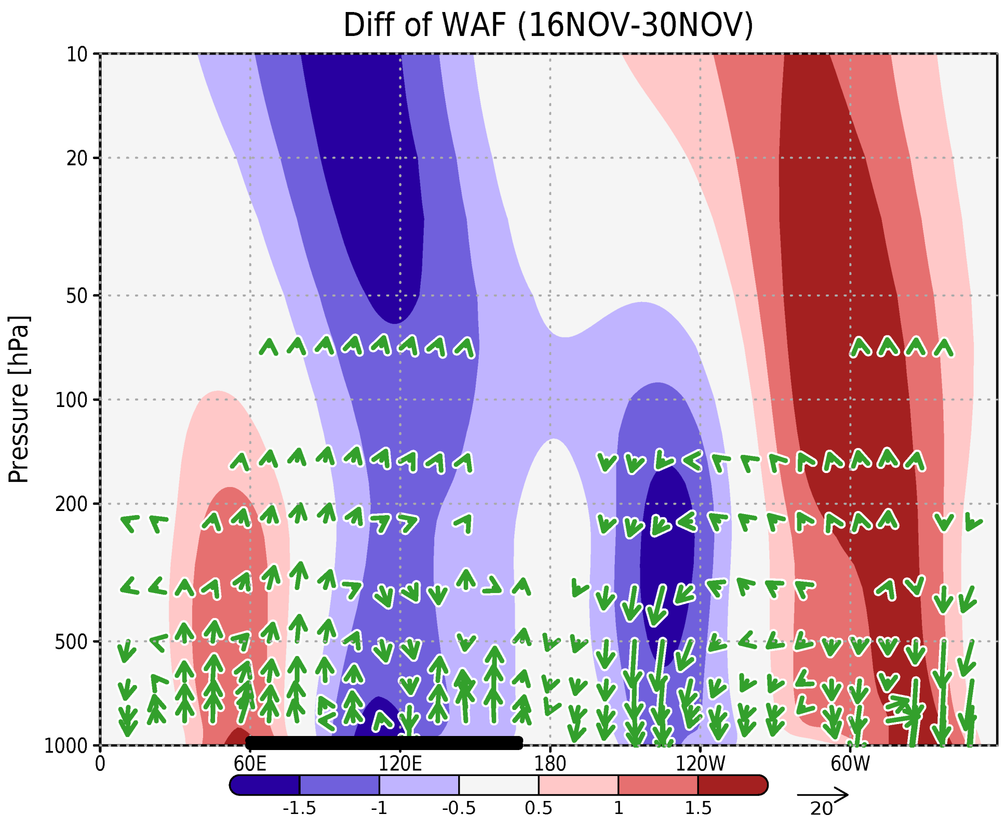
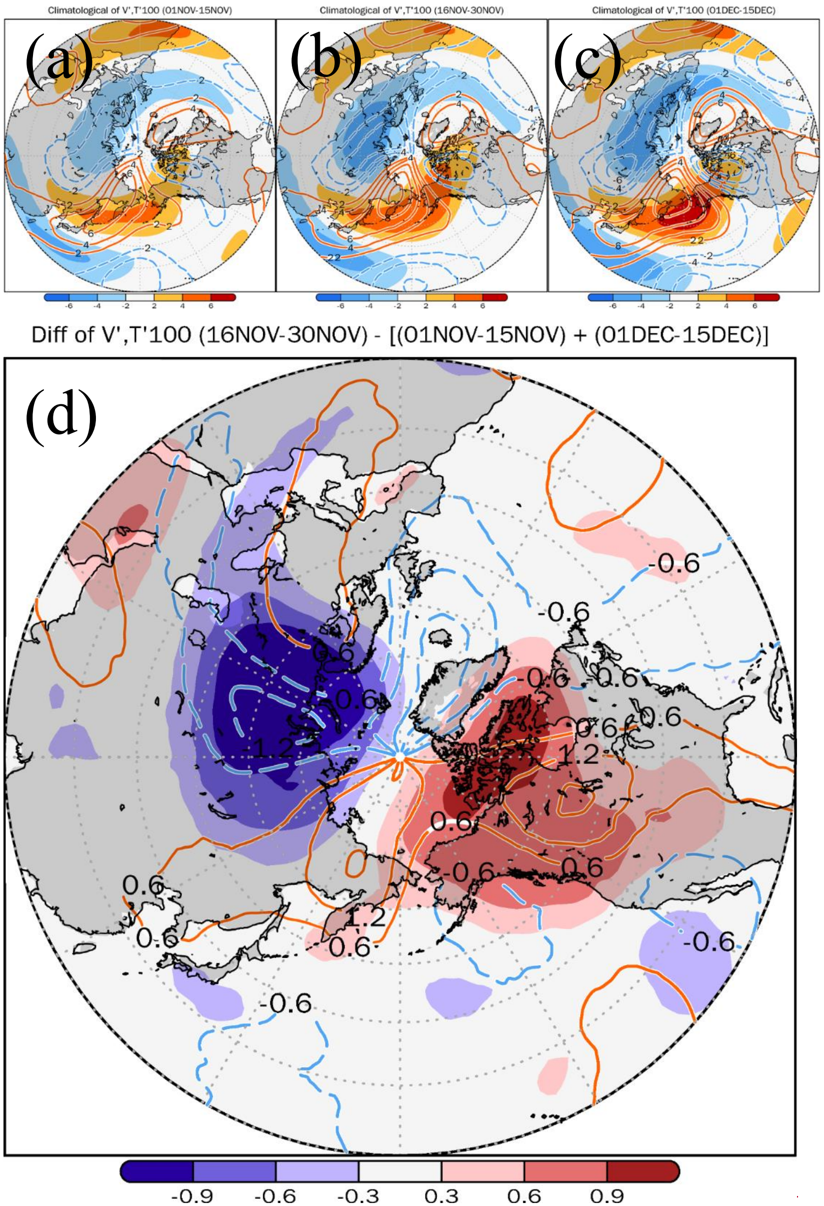


Figure A3. Zonal anomalies of climatological geopotential height (m, color shading) and zonal and vertical components of WAF (10^{-3} m^2 s^{-2}, vectors), averaged over latitude 50–70°N (inside the blue box in Fig. A2) during **(a)** early November, **(b)** late November, and **(c)** early December. **(d)** Late November field deviations calculated by equation (~~1~~4) (see Section 3.3). The geopotential height is normalized by the standard deviation at each height. The WAF magnitude is standardized by pressure (p p_s^{-1}, p_s is a standard sea-level pressure) and the square of the radius of the Earth (6.37×10^6 m). The vertical components of the vectors are multiplied by a factor of 500. The black line indicates the latitudinal range for Siberia (60–170°E).


Climatological of V',T'100 (01NOV-15NOV)
Climatological of V',T'100 (16NOV-30NOV)
Climatological of V',T'100 (01DEC-15DEC)
(a)
(b)
(c)
Diff of V',T'100 (16NOV-30NOV) - [(01NOV-15NOV) + (01DEC-15DEC)]
(d)
-0.9
-0.6
-0.3
0.3
0.6
0.9

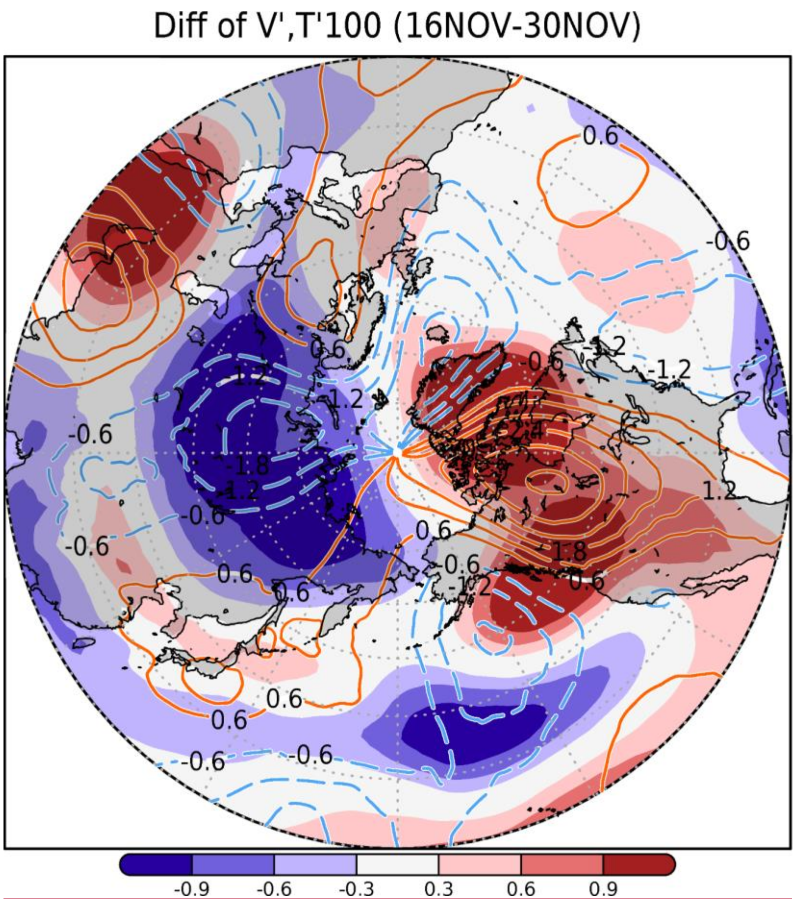


Figure A4. Zonal anomalies of climatological meridional wind (m s^{-1}, contours) and air temperature (°C, color shading) at 100 hPa during **(a)** early November, **(b)** late November, and **(c)** early December. **(d)** Late November deviations calculated by equation (~~1~~4) (see Section 3.3).

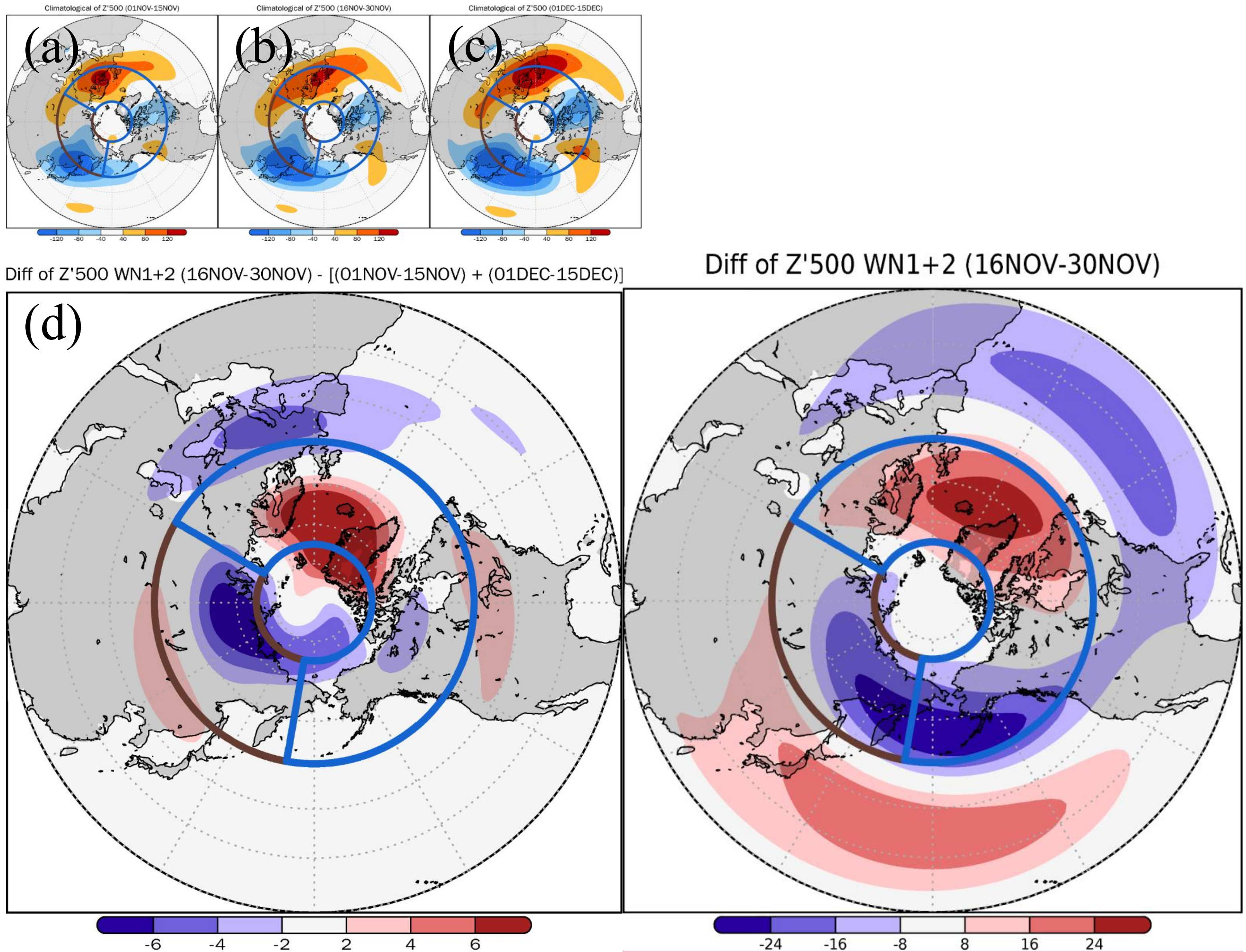
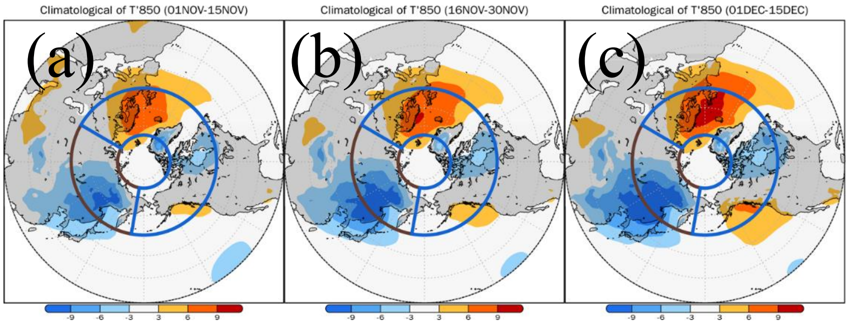
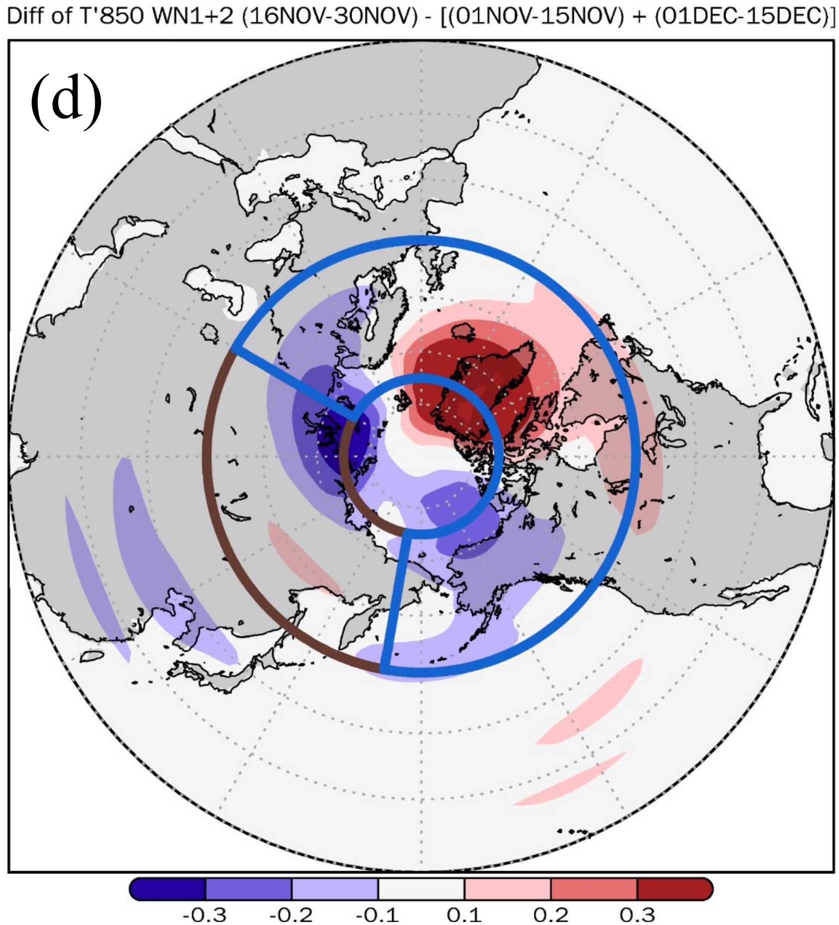

Climatological of Z'500 (01NOV-15NOV)
Climatological of Z'500 (16NOV-30NOV)
Climatological of Z'500 (01DEC-15DEC)
(a)
(b)
(c)
-120 -80 -40 40 80 120
Diff of Z'500 WN1+2 (16NOV-30NOV) - [(01NOV-15NOV) + (01DEC-15DEC)]
(d)
-6 -4 -2 2 4 6
Diff of Z'500 WN1+2 (16NOV-30NOV)
-24 -16 -8 8 16 24

Figure A5. Zonal anomalies of climatological geopotential height at 500 hPa (m) during **(a)** early November, **(b)** late November, and **(c)** early December. **(d)** Late November deviations calculated by equation (~~1~~4) (see Section 3.3) with wavenumber decomposition; only planetary-scale components, wavenumbers 1 to 2, were used. The brown (60–170°E, 50–75°N) and blue (170°E–60°W, 50–75°N) boxes indicate the averaging areas used for calculating the fields shown in Fig. 5.



Climatological of T'850 (01NOV-15NOV)
Climatological of T'850 (16NOV-30NOV)
Climatological of T'850 (01DEC-15DEC)
(a)
(b)
(c)
-9
-6
-3
3
6
9


Diff of T'850 WN1+2 (16NOV-30NOV) - [(01NOV-15NOV) + (01DEC-15DEC)]
(d)
-0.3
-0.2
-0.1
0.1
0.2
0.3

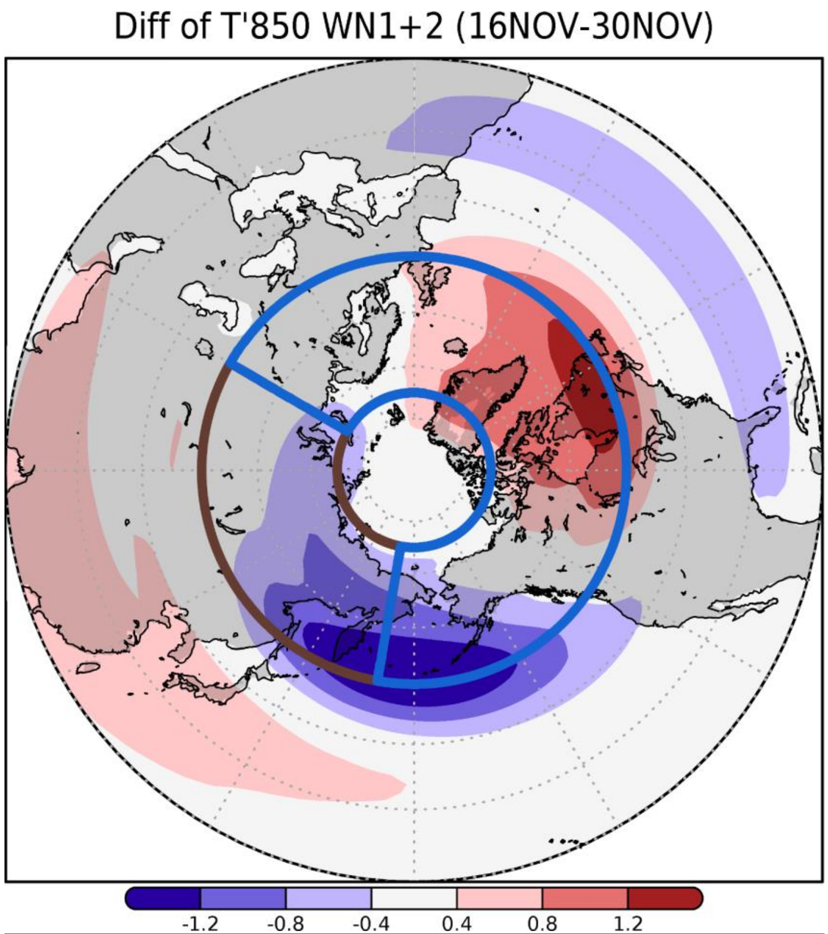


Figure A6. Same as Fig. A5, but for air temperature at 850 hPa (°C).

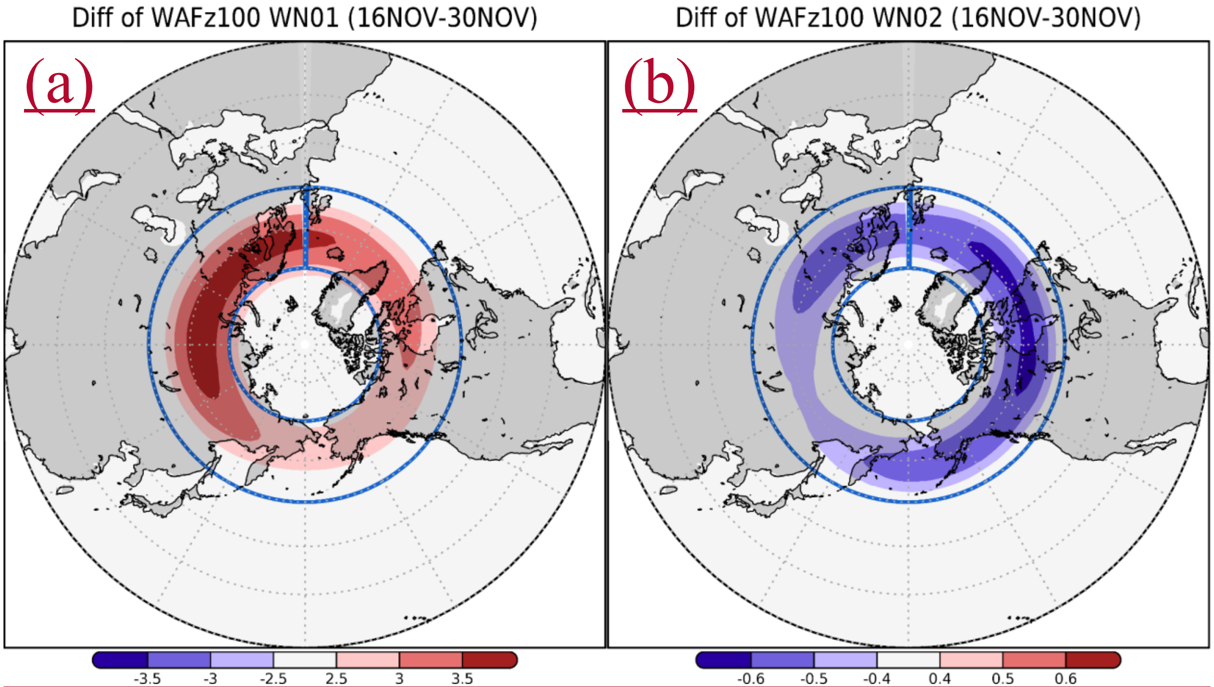


Figure A7. Same as Fig. 4, but with wavenumber decomposition; **(a)** wavenumber 1 and **(b)** wavenumber 2.

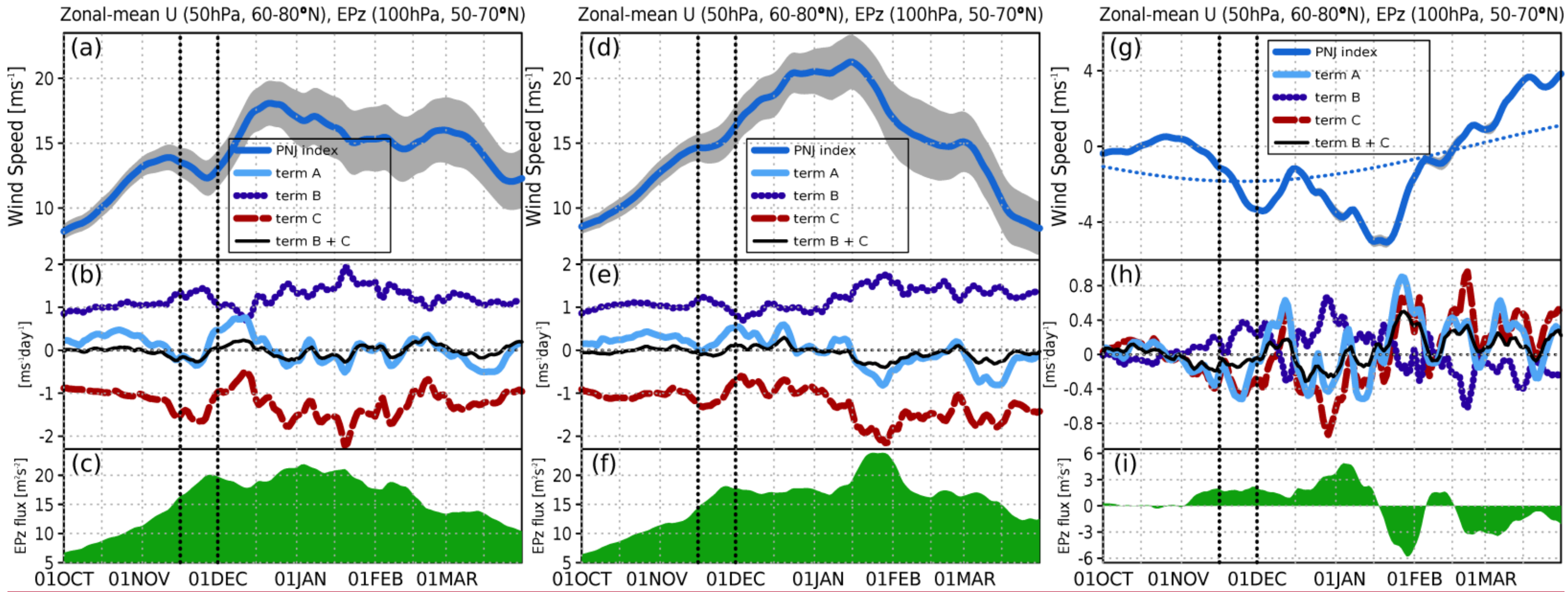


Figure B1. Same as Fig. 2, but **(a), (b), (c)** for QBO-E, **(d), (e), (f)** for QBO-W, and **(g), (h), (i)** difference of (QBO-E) – (QBO-W).

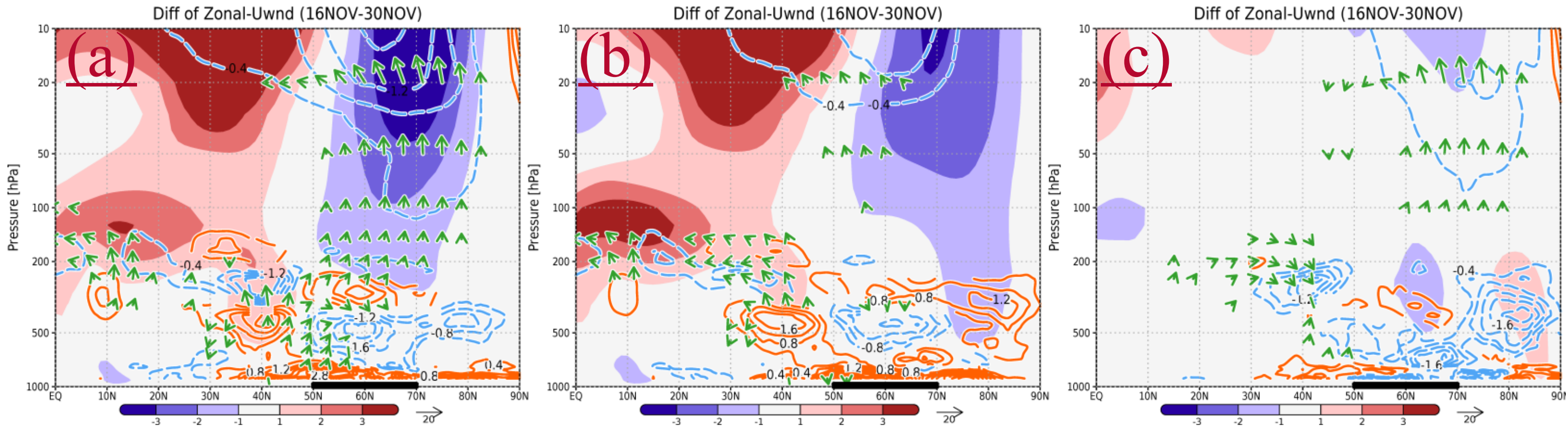


Figure B2. Same as Fig. A1d, but **(a)** for QBO-E, **(b)** for QBO-W, and **(c)** difference of (QBO-E) – (QBO-W).

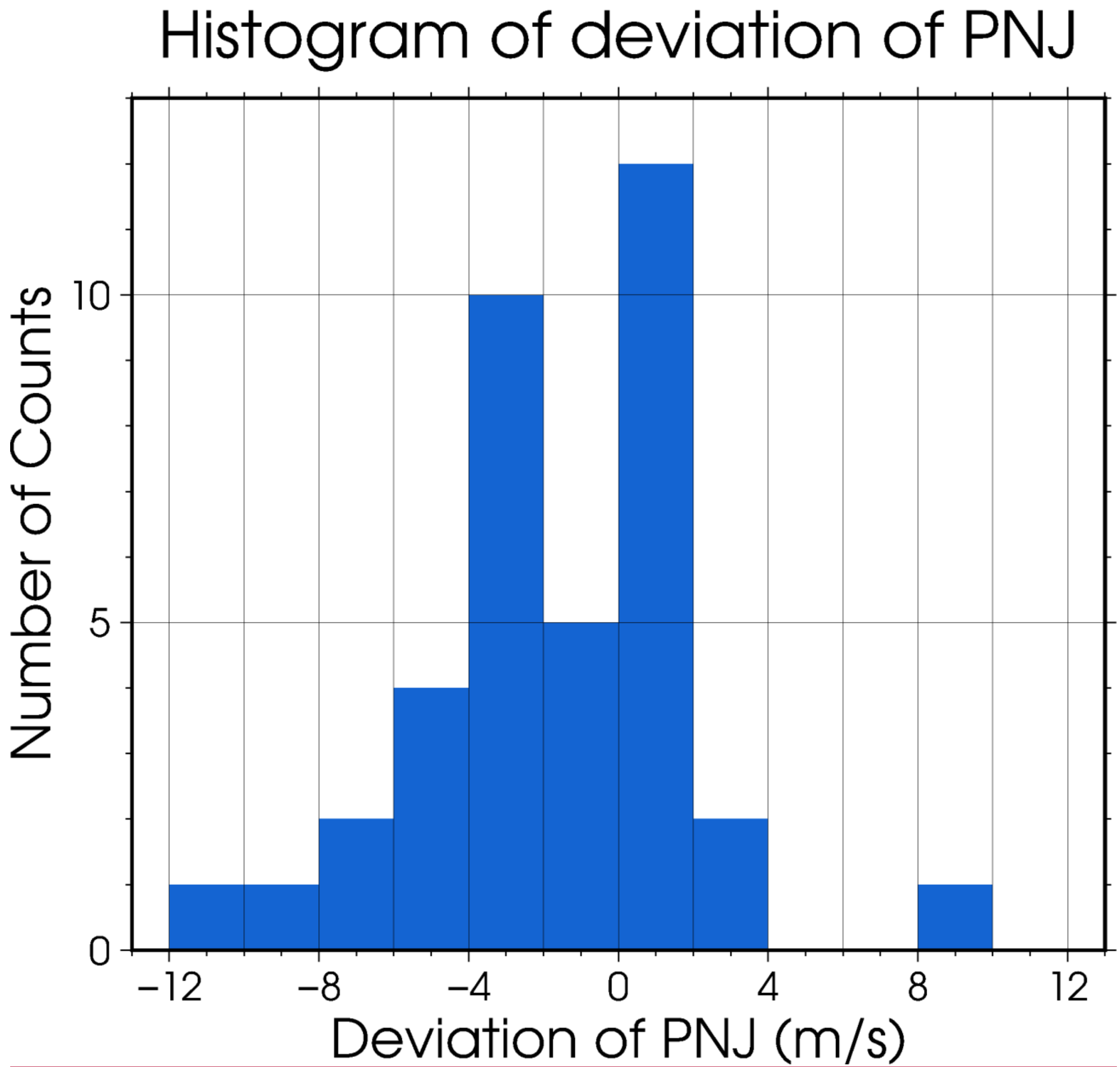

Histogram of deviation of PNJ
Number of Counts
10
5
0
−12
−8
−4
0
4
8
12
Deviation of PNJ (m/s)

Figure C1. Histogram of the deviation of the PNJ in late November from the expected by sinusoidal seasonal evolution in each year (2.0m/s bins). The horizontal axis shows the deviation for the center of each bin. The vertical axis indicates the number of counts for each bin. The negative sign indicates the occurrence of the short break.