Influence of Enhanced Variability with Zonal Wavenumber 1 on Arctic Oscillation in Late Winter to Early Spring in El Niño Conditions

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Abstract

We investigated the relationship between the atmospheric variability in El Niño conditions and Arctic Oscillation (AO) during the period from late autumn to early spring, focusing on the vertical linkage between the troposphere and the stratosphere, based on a composite analysis. The results of the composite analysis indicate that the vertical linkage is the clearest in late winter to early spring, particularly in the three-month of February – April (FMA). In FMA, the upper tropospheric patterns and upward propagation of planetary waves with zonal wavenumber 1 are enhanced and contribute to a negative phase of the stratospheric Northern Annular Mode (NAM) in El Niño conditions.

The results also indicate that the stratospheric negative potential vorticity (PV) anomalies associated with the negative phase of NAM induce a lowered tropopause, vertical compression of the tropospheric column, positive surface pressure anomalies in the polar region and hence the negative phase of the AO. This vertical linkage and the impact of sea level pressure near the pole are consistent with a quantitative estimation based on geostrophic and hydrostatic adjustment associated with the stratospheric PV anomalies.

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1. Introduction

The El Niño-Southern Oscillation (ENSO) is one of the most dominant modes of climate variability. Several previous studies have indicated that the ENSO has a major impact on atmospheric circulation, including tropical convective activities and global teleconnection patterns, and influences weather conditions in many parts of the world. The stratospheric response to the ENSO has been suggested by many previous studies (e.g., van Loon and Labitzke 1987; Manzini et al. 2006; Camp and Ting 2007; Randel et al. 2009). Taguchi and Hartmann (2006) suggested that stratospheric sudden warming (SSW) events or a weaker-than-normal stratospheric polar vortex are observed more frequently in El Niño events than in La Niña events. They performed impact experiments using climate model simulations with the lower boundary condition of sea surface temperature (SST) likely associated with both events and indicated that El Niño conditions could result in enhanced and suppressed upward propagation of planetary waves with zonal wavenumbers 1 and 2, respectively. On the other hand, Calvo et al. (2010) indicated that the ENSO response in the stratosphere is related to the Brewer-Dobson (B-D) circulation change induced by the ENSO-related wave drag effects, and it is suggested that the variability of B-D circulation is associated with the modulation of equatorial Rossby waves in response to the ENSO-related convective heating anomalies (Taguchi 2010). Simpson et al. (2011) suggested with the Canadian Middle Atmosphere Model (CMAM) simulation that the B-D circulation fraction is induced by the synoptic-scale wave drag. Butler and Polvani (2011) indicated that the SSWs occur with equal probability during El Niño and La Niña winters. Overall, there is no agreement on the ENSO influences on the stratospheric circulation as well as their mechanisms.

In relation to the downward interaction, Baldwin and Dunkerton (1999, 2001) indicated a tendency for the downward propagation of the stratospheric zonally-symmetric signal (i.e. Northern Annular Mode; NAM) and a persistent impact on the tropospheric circulation with a timescale of months. Ineson and Scaife (2009) indicated that a relationship exists between the atmospheric characteristics during El Niño events and the climate conditions in Europe based on their numerical model simulations. They suggested that enhanced upward propagation of planetary waves with zonal wavenumber 1 contribute to decelerating the stratospheric polar-night jet stream, and indicated that this stratospheric disturbance propagates downward and influences the surface climate in Europe. Their results are based on the statistical analyses or the numerical simulation, and there is a lack in their discussion for the dynamical mechanism of downward propagation of the stratospheric signal directly related to the ENSO.

Although the principal mechanism of the downward propagation remains unclear, several related mechanisms are proposed in the previous studies. Kodera et al. (2008) indicated the reflection of the planetary waves in the stratosphere due to the structure of the zonal mean wind field and its impact on the tropospheric circulation as a feature of zonally-asymmetric variability. Perlwitz and Harnik (2004) decomposed the downward interaction to two processes of zonal mean and wave components, and indicated with a time-lagged singular value decomposition analysis that the timescales of the downward interaction of the zonally-symmetric variability are much longer than those of the zonally-asymmetric variability (up to 12 days). In relation to the zonally-symmetric variability, Ambaum and Hoskins (2002) (hereafter, AH02) proposed the simple mechanism of the impact of the stratospheric circulation on the surface near the pole with a comprehensive and quantitative approach based on a diagnostic model of geostrophic and hydrostatic adjustment. Their simple diagnostics makes it possible to quantify and assess the contribution of the stratosphere to the surface with longer timescales and to compare the contribution to the ENSO-related characteristics.

The main purpose of this study is to provide a clear vision for the mechanism of the dynamical process from the modulation of tropical circulation in El Niño conditions to the appearance of above-normal sea level pressure anomalies near the pole, that is the negative phase of Arctic Oscillation (AO) (Thompson and Wallace 1998) during the period from late autumn to early spring, and to show the coherent statistical relationship among the meteorological variables quantitatively relevant to the AH02’s diagnostics.

2. The data and method of statistical analysis

In this study, we use the three-month means during the period from the central month of November (OND) to that of April (MAM) from the Japanese 55-year reanalysis dataset (JRA-55; Kobayashi et al. 2015) and COBE-SST (JMA 2006) to diagnose the atmospheric circulation and the oceanographic condition. Unless noted otherwise, normal is defined as the 55-year averages during the period from 1958 to 2012, and the anomalies are defined as deviations from the normal. We conducted a composite
analysis to diagnose the statistical characteristics during El Niño years with 13 years in winter during the 55-year period. In the Japan Meteorological Agency (JMA)’s definition of the El Niño years, the five-month running mean SST deviation for NINO.3 satisfies above +0.5°C for at least six consecutive months. The SST deviation is defined as the deviation from the latest sliding 30-year mean. It has been suggested that atmospheric responses to tropical circulation during El Niño events do not always correspond to those observed during La Niña events (Hoerling et al. 2001, Wu and Hsieh 2004). A composite analysis therefore has an advantage when deriving nonlinear responses to ENSO phases and is suitable to examine the characteristic patterns in El Niño conditions. To assess the sources, sinks, and propagation of planetary wave packets, we employed the Eliassen-Palm (E-P) flux (e.g., Edmon et al. 1980).

3. Results

First we show the seasonal dependence of the vertical linkage from the stratosphere to the surface near the pole in El Niño conditions. Figure 1 shows time-height cross-section and time-series of the 70°N–90°N averaged zonal mean circulation for the three-month mean composite during the period from OND to MAM. In Fig. 1a, the height shows positive anomalies in the stratosphere through the period with large and significant amplitudes, in particular, in JFM and FMA. The stratospheric characteristics are consistent with the results shown in the previous studies (e.g., Camp and Tung 2007; Taguchi and Hartmann 2006). In association with the stratospheric positive height anomalies, the vertical velocity shows downward circulation anomalies from the lower stratosphere to the troposphere and has its maximum amplitudes in FMA (Fig. 1b), corresponding to significant positive sea level pressure anomalies (Fig. 1c). We hence indicate the statistical characteristics in FMA and focus on the mechanism of the vertical linkage below.

Figure 2 shows the three-month mean composite anomalies of the total precipitation and the 300-hPa heights in FMA during El Niño years. In the central and eastern equatorial Pacific,
above-normal precipitation is seen (Fig. 2b) to be associated with higher-than-normal SST (Fig. 2a). The 300-hPa height anomalies show a distinct wave structure along a great circle from the central tropical Pacific to North America with positive anomalies over the central tropical Pacific and eastern Canada and negative ones over the northeastern part of the North Pacific and the southern USA (Fig. 2c), corresponding to the positive phase of the Pacific North American (PNA) pattern (Wallace and Gutzler 1981). It is well known that the positive phase of the PNA pattern is related to the El Niño phase (e.g., Renwick and Wallace 1996). These anomaly patterns have zonal wavenumber 1 component and exhibit a dominant variability in mid- and high-latitudes of the Northern Hemisphere. Figure 3 shows the FMA mean composite map for the eddy component of the 300-hPa heights (i.e., the height is subtracted from the zonal averages) and the latitudinal power spectrum based on a fast Fourier transform (FFT) algorithm for the same periods as in Fig. 2. The height eddies in the mid-latitudes exhibit a distinct wave pattern with a ridge over western North America, from the North Atlantic to western Eurasia, and a zonally elongated trough from eastern Eurasia to the North Pacific, corresponding to the dominance of waves with zonal wavenumber 1 (Fig. 3a). The greater-than-normal amplitude of waves with zonal wavenumber 1 is seen in the mid-latitudes, in particular, over the latitude band from 50°N to 60°N (Fig. 3b).

Figure 4 shows the E-P flux and its divergence with zonal wavenumbers 1 and 2 and all zonal wavenumbers in FMA. The E-P flux exhibits enhanced upward propagation of planetary waves with zonal wavenumber 1 in the tropospheric mid-latitudes, in particular, over the latitude bands from 40°N to 60°N. Planetary wave packets with zonal wavenumber 1 propagate northward compared to normal in the lower stratosphere and converge at high-latitudes. The enhanced upward propagation of a planetary wave are clearly characterized by the zonal wavenumber 1 component in comparison with that of all wavenumbers (Figs. 4a and 4c), and those with zonal wavenumber 2 are suppressed compared to normal (Fig. 4b). These characteristics indicate that the enhanced variability with zonal wavenumber 1 has a major impact on the stratospheric circulation and supports the results of previous studies, such as Taguchi and Hartmann (2006), Garfinkel and Hartmann (2008). Figure 5 shows the FMA mean composite anomalies of zonal mean zonal wind, height, and sea level pressure. The zonal wind anomalies shown in Fig. 5a indicate that the stratospheric polar-night jet stream is weaker than normal, which is associated with the convergence of the planetary wave packets. This indicates that the enhanced propagation and the breaking of the planetary wave with zonal wavenumber 1 contribute to the negative phase of the stratospheric NAM during El Niño years (Fig. 5b).
The impact of the stratospheric PV anomalies on the polar tropospheric circulation can be evaluated based on a simple quasi-geostrophic diagnostic model given by AH02. Their model is based on the PV equation and the diagnostic omega equation with zonal symmetry around the pole assumed and the effect neglected, and provides linear solutions that decay with height below the stratospheric PV anomalies, as seen in Fig. 6g. The theoretical approach in AH02 indicates that the stratospheric negative PV anomalies contribute to lower the tropopause height. They also indicate with the diagnostic solution of the omega equation with boundary conditions at the surface and the tropopause that the lowered tropopause contributes to increase the surface pressure through a vertical compression or squashing of the tropospheric column near the pole. Associated with the negative stratospheric PV anomalies (Fig. 6g), above-normal potential temperatures are seen above near the 400-hPa level (Figs. 6d and 6e), corresponding to the lowered tropopause. The anomalous downward circulation associated with the lowered tropopause reaches its maximum in the mid-troposphere and decreases toward the surface. In the transformed Eulerian-mean (TEM) framework, the residual mean meridional circulation near the poles also exhibits enhanced downward motion during El Niño years (not shown). Associated with these vertical circulation anomaly profiles, vertical convergence anomalies are seen below the 850-hPa level (Fig. 6c). The influence of the lowered tropopause on the tropospheric circulation near the pole are consistent with the AH02’s theory. The zonal mean height and sea level pressure show positive anomalies in the polar regions of the lower troposphere, which indicates a negative phase of the NAM or the AO. These anomaly patterns from the stratosphere to the surface near the pole are generally consistent with the vertical linkage in terms of the geostrophic and hydrostatic adjustments proposed by AH02.

Using the hydrostatic balance, AH02 estimated the change in the tropopause pressure to be approximately 30 hPa per 1/6 fractional change in 500-K PV with a Burger number of 1 and a normal tropopause pressure of approximately 400 hPa using their Eq. (1). A composite of 500-K PV in the polar region shows a normal of approximately 50 PVU and anomalies of approximately -4 PVU (Figs. 6f and 6g), indicating a fractional change of approximately -1/10. In line with AH02’s estimation, this fraction of PV induces a change in the tropopause pressure of approximately 16 hPa, corresponding approximately to the composite pressure anomalies in the tropopause (not shown). They also estimated with their Eq. (10) that a change in the tropopause height of 500 m results in a surface pressure of 9 hPa via the stretching effect of the tropospheric column, with a horizontal scale of atmospheric disturbances L ~ 1000 km and appropriate constants in the troposphere. According to their estimation and the same horizontal scale L, tropopause pressure anomalies of approximately +16 hPa increase the surface pressure by approximately 5 hPa. The composite anomalies of the sea level pressure have the same order as the estimation of the change (Fig. 5c). The difference in the pressure between the composite anomalies and the estimated fractions (approximately 3 hPa) may be primarily due to the selection of the horizontal scale L or other effects that are ignored in AH02’s identical models, such as meridional temperature advection and surface friction. The composite anomalies in Fig. 6 include the variability such as the equatorial Quasi-Biennial Oscillation (QBO) (Kuroda 2007) or the solar 11-year cycle (Kuroda and Kodera 2002), which also may contribute to the difference mentioned above.

These results indicate that the enhanced variability of zonal wavenumber 1 associated with El Niño conditions has an influence on the negative phase of the AO via a wave and mean-flow interaction and the stratospheric-tropospheric coupling, and these characteristics are clearest in FMA.

4. Discussion and conclusions

We investigated the relationship between atmospheric characteristics in El Niño conditions and the negative phase of the AO
pattern performing a composite analysis during the period from late autumn to early spring and the mechanism of the stratospheric–tropospheric vertical linkage based on the AH02's theory. In El Niño conditions, the PNA pattern contributes to the enhancement of height eddies and stronger-than-normal planetary wave packets with zonal wavenumber 1. The enhanced planetary wave packets propagate upward and northward from the tropospheric mid-latitudes to the lower stratosphere and contribute to the negative phase of the stratospheric NAM, corresponding to the results of previous studies. The stratospheric negative PV anomalies associated with the decelerated polar-night jet stream and a lowered tropopause are seen in the composite, corresponding to the influence of the stratospheric PV anomalies on the tropopause height suggested by AH02. The solutions with tropospheric boundary conditions under the lowered tropopause support the vertical profiles of the anomalous downward circulation and the positive height and surface pressure anomalies seen in the zonal mean composite analysis. The quantitative estimations for the impact on the surface pressure near the pole based on the AH02's diagnostic model have the same order of magnitude as the composite surface pressure anomalies. The geostrophic and hydrostatic adjustment proposed by AH02 therefore may contribute the linkage from the stratosphere to the surface near the pole. These results are most clearly and significantly seen in FMA, indicating a stronger relationship between the enhanced variability with zonal wavenumber 1 seen in El Niño conditions and the negative phase of the AO via the stratospheric–tropospheric interaction in the period.

The above-mentioned process is one of the candidate factors for El Niño conditions to affect the negative phase of the NAM or the AO. The dynamical coupling between the stratosphere and the troposphere is complicated by wave and mean-flow interactions, such as reflections of planetary waves (Perlwitz and Harnik 2004; Kodera et al. 2008, 2013), the downward propagation of zonally symmetric modes referred to as the AO or the NAM (Baldwin and Dunkerton 2001), and the redistribution of the stratospheric potential vorticity (Hartley et al. 1998). The synoptic eddies also may contribute to the formation or maintenance of the tropospheric zonally symmetric pattern through the eddy-feedback mechanism (e.g., Nakamura et al. 1997). The strength of the stratospheric polar-night jet stream is known to be related to the QBO (Holton and Tan 1980), and to exhibit the nonlinear behavior to the relationship between ENSO and QBO (e.g., Calvo et al. 2009; Taguchi 2015) and that between ENSO and the 11-year solar cycle (Calvo and Marsh 2011). The composite of the zonal mean zonal wind in Fig. 5a shows insignificant but clear negative (easterly wind) anomalies in the equatorial stratosphere, indicating the possibility that a phase of the QBO also contributes to the processes shown in this study.

Recent studies have revealed that the forecast skill of the NAM in the extended-range predictions is closely related to the wave and mean-flow interaction at the tropopause level and the behavior of the wave propagation is related to the structure of the zonal mean zonal wind (Mukougawa and Hirooka 2007). Saito and Maeda (personal communication) indicates that JMA's seasonal forecast model exhibits high predictability at the stratospheric high-latitudes and near the surface in late wintertime, and they suggest that the seasonal dependence of the predictability is related to the seasonal variability of the upward propagating planetary waves. Clarifying the relationship between the ENSO and the AO in terms of the vertical linkage between the stratosphere and the troposphere is therefore important to assess the predictability and the progression of seasonal forecasting.

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