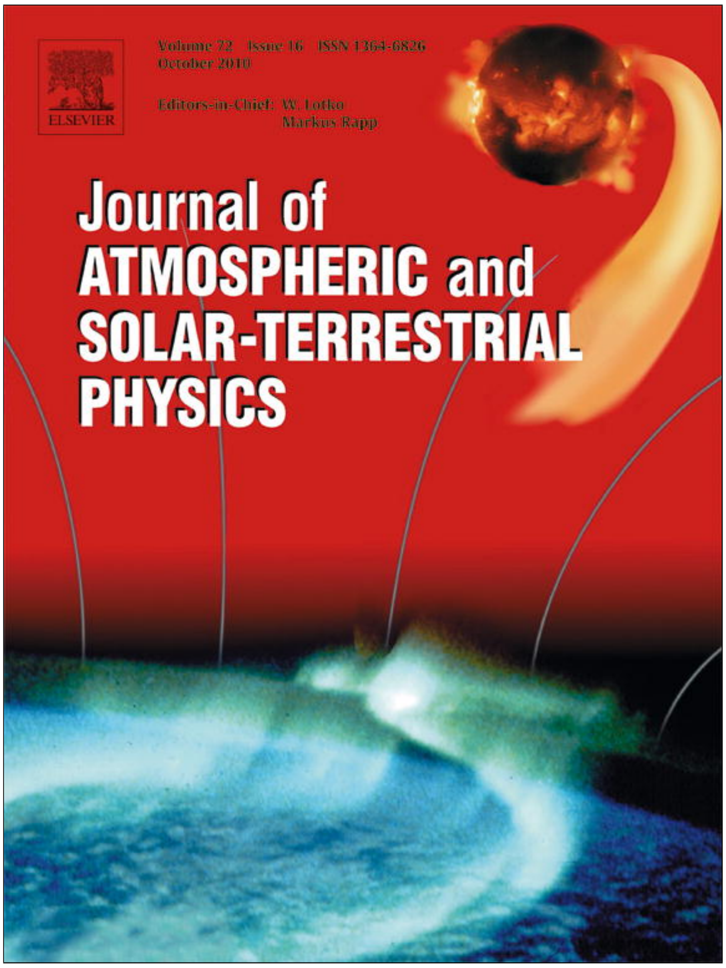
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Stratospheric wave activity and the Pacific Decadal Oscillation

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ABSTRACT

Using the monthly mean NCEP/NCAR reanalysis and NOAA Extended Reconstructed sea surface temperature (SST) datasets, strong correlations between the SST anomalies in the North Pacific and calculated three-dimensional Eliassen–Palm vertical fluxes are indicated in December 1958–1976 and 1992–2006. These correlations between the interannual variations of the SST anomalies and the penetration of planetary waves into the stratosphere are much less during the decadal sub-period 1976–1992 in the positive phase of the Pacific Decadal Oscillation (PDO) and the decadal cold SST anomalies in the North Pacific. Interannual variations of the polar jet in the lower stratosphere in January are strongly associated with SST anomalies in the Aleutian Low region in December for the years with positive PDO index. This sub-period corresponds well with that of the violation of the Holton–Tan relationship between the equatorial Quasi-Beinnial Oscillation (QBO) and the stratospheric circulation in the extra-tropics. It is shown that interannual and interdecadal variations of stratospheric dynamics, including stratospheric warming occurrences in January, depend strongly on changes of the upward propagation of planetary waves from the troposphere to the stratosphere over North Eurasia in preceding December. These findings give evidences of a large impact of the decadal SST variations in the North Pacific on wave activity in early winter due to changes of thermal excitation of planetary waves during distinct decadal periods. Possible causes of the decadal violation of the Holton–Tan relationship, its relation to the PDO and an influence of the 11-year solar cycle on the stratosphere are discussed.

1. Introduction

It is well known that interannual variations of the extra-tropical circulation in the stratosphere are linked to the Quasi-Biennial Oscillation (QBO) in the equatorial lower stratosphere. Holton and Tan (1980) have indicated the significant correlations of the polar stratospheric vortex with QBO during wintertime. Strong (weak) stratospheric vortex in the Arctic is mainly observed for the west (east) QBO zonal wind 50 hPa at Singapore (hereafter H–T relations). Major stratospheric warmings occurred more often for the east QBO (eQBO) years than for the west QBO (wQBO) years (Labitke, 1982). This QBO modulation of the stratospheric circulation in the high latitudes may be explained by a reflection of planetary waves from the critical line (zero zonal wind line) in the tropics for the eQBO years, which may result in an increase of planetary wave activity in the high latitudes and its forcing on the polar vortex. For the wQBO years, the critical line is in the Southern Hemisphere and a dissipation of planetary waves close to the equator can lead to a decrease of wave activity in the high latitudes and strong polar vortex in the Arctic. Numerical experiments in the mechanistic planetary wave model of the response of stratospheric wave activity changes to the movement of the critical line in the northern tropics showed that many signatures of the stratospheric warmings (focusing to the polar regions, sharp amplification of planetary waves) were simulated (Jadin and Kiryushov, 1988). It is difficult to confirm these model results by diagnostics of the observational data because of a strong variability of the critical line and a poor understanding of the reflection or absorption of planetary waves (McIntyre, 1982).

Besides the QBO modulation of the extra-tropical circulation, there exist decadal variations in the winter stratospheric dynamics of the Northern Hemisphere. Labitzke and van Loon (1988) separated the years on the wQBO and eQBO phases and indicated the clear decadal ($\sim$10–12 years) cycle in temperature variability of the lower stratosphere at the North Pole. They attributed these decadal oscillations to the influence of the 11-year cycle of solar activity on the stratosphere. The warm and weak stratospheric vortex in the Arctic is observed for the eQBO years during the low solar activity while the cold and strong vortex takes place for the eQBO during high solar activity. Opposite situation was indicated in the relationship of the polar vortex with the QBO/solar cycle for the wQBO years. Although the existence of 10–12 year variability in stratospheric parameters

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under the grouping in the wQBO and eQBO years is stable during a few decades (Labitzke, 2005), there are doubts that the 11-year solar cycle can be the cause of this decadal variability because of its small changes (less than 1% in the ultraviolet radiation responsible for most of ozone heating; Rottman, 1999) from the minimum to maximum solar cycle (Baldwin et al., 2001).

It was also indicated that there is the decadal violation of the H–T relations (Naito and Hirota, 1997). Recently, Lu et al. (2008) showed that H–T relations are weakened for the average (November–March) winter months and even reversed for the late winter months (February–March) during the 1977–1997 decadal period. Correlations of the zonal mean zonal wind with the QBO index (January–February) are significant ($\sim$0.6) in the high latitudes of the lower stratosphere only for the years with low solar activity during 1958–2006. For high solar activity, these correlations are small. However, for the 1977–1997 decadal period the H–T relations are weaker for both high and low solar activities. Thus, the cause of this decadal violation is unlikely to be connected with the 11-year solar modulation of the H–T relations (Lu et al., 2008).

The alternative point of view on causes of the decadal variations in atmosphere can be associated with an influence of the SST anomalies on thermal planetary wave excitation, which can lead to a constructive or destructive interference with the topographic planetary wave source especially in the stratosphere. In the troposphere, this signal is masked by high-frequency variability. Jadin (1990) has shown in the model simulations that eddy ozone transport and circulation in the stratosphere depend strongly on shifts of the induced SST anomalies. Analysis of the observational data indicated significant correlations among stratospheric angular momentum, defined as the atmospheric angular momentum above 100 hPa, total ozone and combined SST anomalies in the North Atlantic and North Pacific in 1979–1992 (Jadin, 2001). There are the well-known decadal variations of the SST anomalies in the North Pacific (Nitta and Yamada, 1989), sea level pressure of the Aleutian Low (Trenberth, 1990) after the late 1970s, which were named as the Pacific Decadal Oscillation (PDO; Mantua and Hare, 2002). It is interesting that the decadal period of positive phase of the PDO index defined as the principal component (PC) of the first empirical orthogonal function (EOF) of the SST anomalies in the North Pacific is well consistent with that of the violation of the H–T relations from the late 1970s to mid-1990s.

The aim of this work is to investigate possible linkages among PDO, decadal variations of planetary wave activity and the circulation in the lower stratosphere in early winter. We consider the three-dimensional structure of the lower stratospheric wave activity and circulation in early winter (December) in contrast with many studies, which used the two-dimensional Eliassen–Palm fluxes and zonal-mean circulation (Dunkerton and Baldwin, 1991; Lu et al., 2008, 2009; Wei et al., 2007).

2. Data and method of analysis

The monthly mean data from NCEP/NCAR reanalysis (Kalnay et al., 1996) and the NOAA Extended Reconstructed SST (Smith and Reynolds, 2003) datasets were used in this study covering the years from 1958 to 2007. The atmospheric dataset has a $2.5^\circ \times 2.5^\circ$ horizontal resolution and extends from 1000 to 10 hPa with 17 vertical pressure levels. Three-dimensional (3D) Eliassen–Palm (EP) fluxes in the stratosphere were calculated as a diagnostic tool to measure wave activity propagation (Plumb, 1985). The 3D structures of zonal wind and EP fluxes were considered because modulation of wave activity in the high latitudes by the QBO can have a large longitudinal asymmetry. The EOF and singular value decomposition (SVD) methods (Bretherton et al., 1992) were applied for the analysis.

3. Results

The interaction of planetary waves with zonal mean flow has significant intra-seasonal differences between the early (November–December) and the late (February–March) winter. These differences have been revealed in the decadal variations (Lu et al., 2008) and the trends (Hu et al., 2005) of atmospheric parameters; therefore we analyzed the relations among zonal wind, vertical component of EP flux and SST anomalies for each winter month. As is well known (Labitke, 1982; McIntyre, 1982), wave activity amplification and focusing of planetary waves to the polar region can create "preconditions" for the appearances of stratospheric sudden warmings. Recently, Zyulyaeva and Jadin (2009) indicated that similar "preconditions" (on the monthly mean timescales) are most prominent in December along with the propagation of planetary waves from the troposphere to the stratosphere, which results in polar vortex variations in subsequent January. Fig. 1 shows the spatial pattern of the first EOF (43% of total variance) of the vertical component (EPz) of the 3D EP flux in December, its PC 1 and the correlations of zonal wind anomalies in January at 30 hPa with PC 1 of the EPz flux in previous December. It should be noted that results of the analysis for 100 hPa level are similar to those at 30 hPa, but with smaller contributions of the leading modes to total variance; therefore we represented the results for the 30 hPa level.

It is seen that the increase (decrease) of planetary wave penetration from the troposphere to the stratosphere in December is consistent very well with weak (strong) polar jet in subsequent January. The occurrences of major stratospheric warmings in January 1970, 1977, 1985, 1998 and 2003 (Labitke and Naujokat, 2000; Labitke et al., 2005) correspond to the strong penetration of planetary waves in previous December. Basic features of the correlations shown in Fig. 1b are quite similar to the spatial pattern of the first zonal wind EOF (46.2% of total variance) in January. The correlation coefficient between their first PCs is -0.58, exceeding the 95% confidence level, while that for the simultaneous PCs in December is only -0.29. From mid- to late winter, zonal wind changes depend not only on the upward penetration of planetary waves from the troposphere over northern Eurasia, but also on their downward propagation from the stratosphere to the troposphere over North Atlantic, forming the "stratospheric bridge" in the lower and middle stratosphere in January–February (Zyulyaeva and Jadin, 2009). A possible cause of the downward wave signal can be associated with a planetary wave reflection in the high latitude mid-stratosphere (Perlwitz and Harnik, 2003). It should be noted that the "stratospheric bridge" is beginning to form in early winter, when the upward propagation of eddy energy from the troposphere influences strongly on subsequent development of stratospheric dynamics in late winter.

Intra-seasonal variations of the wave-zonal flow interaction can be important for the understanding of differences in QBO and solar cycle (SC) signal modulations of the stratosphere in early and late winter. We separated the data according to the QBO phases of the zonal wind (30 hPa) at Singapore and calculated the correlations of EPz PC1 with SC index in December using the ERA-40 dataset (Uppala et al., 2005). Here, the 10.7 cm solar flux (F10.7) was used as the proxy of the 11-year SC index. There are no significant correlations of stratospheric wave activity with SC index either for the wQBO/eQBO years or for all years in December (not shown). This is consistent with the absence of SC

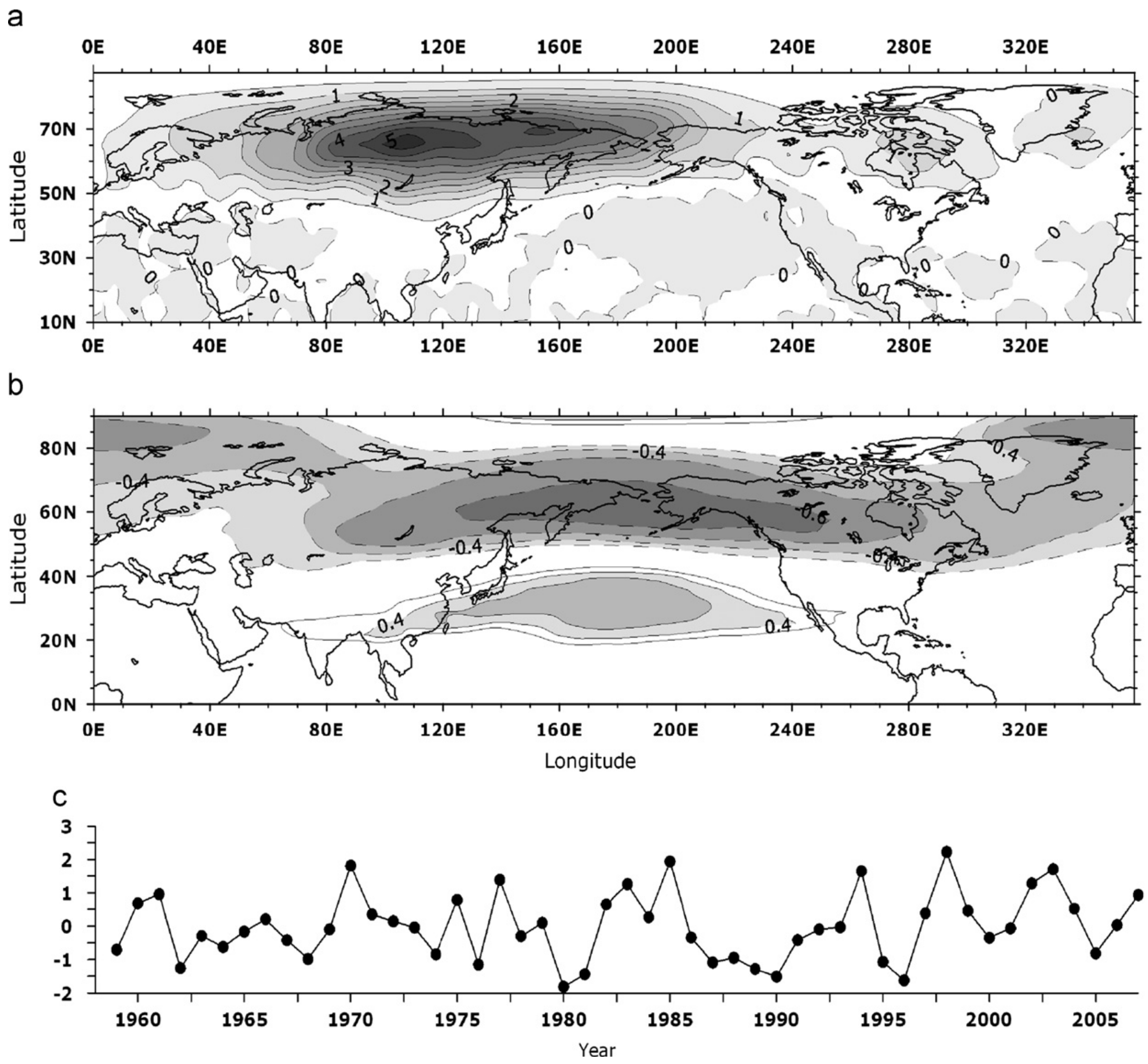

Fig. 1. First EOF of the vertical component of the 3D EP flux anomalies expressed as the regression coefficient (10^{-5} m^2 s^{-2}) of their anomalies with its PC 1 (c) (units are arbitrary) for December 1959–2006 (a) and correlations of the zonal wind anomalies at 30 hPa with the same PC 1 for the subsequent January 1958–2007. The years correspond to January.

signal in the stratospheric circulation in early winter (Baldwin et al., 2001). The 11-year solar cycle cannot modulate the upward penetration of planetary waves from the troposphere in December, the sources of which are the topographic source and thermal excitation associated with the SST anomalies. However, decadal SST anomalies can result in changes of thermal excitation of the stationary planetary waves, and hence atmospheric wave activity and circulation. Multiple interactions in the coupled ocean–atmosphere system can result in an ocean forcing on the atmosphere, which appears to be most remarkable in the winter stratosphere.

We conducted the SVD analysis of relations between the SST anomalies in the North Pacific and North Atlantic (north of 20°N), EPz and zonal wind at 30 hPa for each month (December–February) in 1958–2007. Fig. 2 shows the first SVD modes and their coefficients of the relations between the SST anomalies in the North Pacific and EPz anomalies in December 1958–2006. The SVD spatial patterns are very similar to those of their first EOFs as well as their time series both for SST (Jadin and Zyulyaeva, 2010) and EPz anomalies (Zyulyaeva and Jadin, 2009) except the shift of the EPz maximum to western Siberia (Fig. 1). The correlation coefficients of the PCs of the first SVD and EOF modes for SST and EPz anomalies are 0.83 and 0.91, respectively. Thus, these are the leading modes of the SST and EPz anomaly relations. Square covariance function (SCF) (Bretherton et al., 1992) is equal to 61%, showing the strong relations between these modes. It should be noted that PC of the first EOF of the SST anomalies is similar to the PDO index determined by Mantua et al. (1997) for the other period.

The striking feature of time behavior of the SVD coefficients is that the relative extreme SST coolings (warmings) in the center of action 37°N, 160°W correspond well with the extreme increase (decrease) of wave penetration to the stratosphere at 30 hPa (100°E, 65°N) and hence to the appearance of major stratospheric warmings (coolings) in January. The occurrences of the major stratospheric warmings in January 1960, 1970, 1977, 1994, 1998 and 2003 are associated with both strong increases of wave penetration from the troposphere to stratosphere over European Russia and western Siberia and strong SST decreases in the central Pacific in the previous December except the major stratospheric warming in January 1985. The opposite relations are observed for the cold stratospheric vortex. Notice that this link between

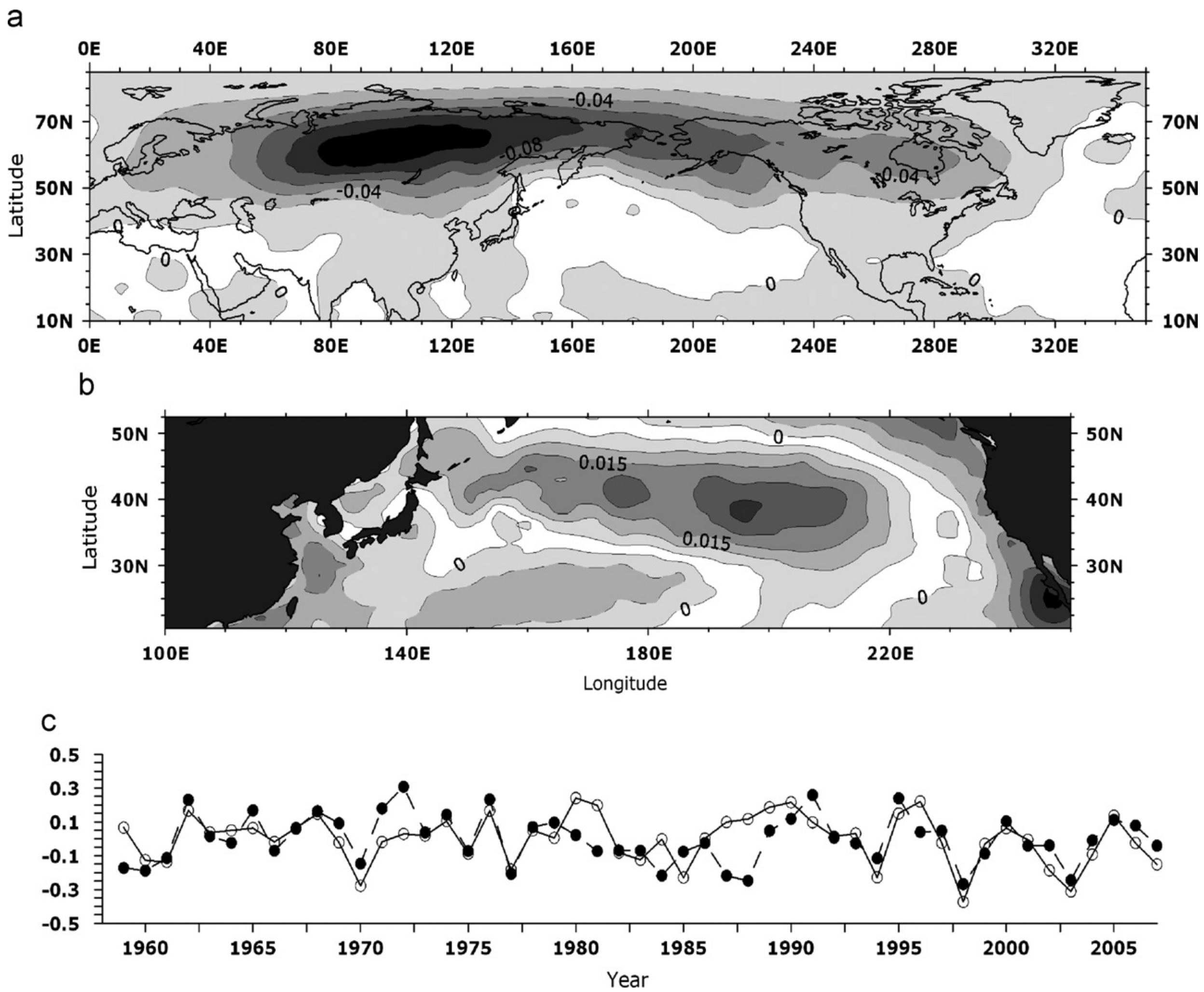

Fig. 2. First SVD modes of the SST anomalies in the North Pacific expressed as the regression coefficient (10^{-7} m^2 s^{-2}) of their anomalies with its coefficient (c) (units are arbitrary) for December ($\times$ 0.01 °C) (b), regressions of the vertical 3D EP flux anomalies on the same coefficient (a) and their coefficients (c) for the SVD SSTs (dashed line with black circles) and for the SVD 3D EP (solid line with light circles) modes in December 1959–2007. The years correspond to January.

the SST anomalies and EP fluxes is weakened for the period 1977–1991, when the positive phase of PDO is observed. The calculations of similar SVD modes for the North Atlantic in December indicated very weak correlations between SSTs and penetration of planetary waves into the stratosphere. For January, also there are no significant relations between the SSTs both in the North Pacific and North Atlantic and zonal wind and EP flux anomalies (not shown). This is in accordance with results of Zyulyaeva and Jadin (2009), who indicated very weak simultaneous correlations of the leading PCs of zonal wind and EP flux in January, when the intra-seasonal variations in the lower stratosphere are controlled by the vacillation cycle (Holton and Mass, 1976) and the downward EP flux from the stratosphere to the troposphere.

Because stratospheric circulation in the high latitudes in January is strongly controlled by intensity of the upward propagation from the troposphere in previous December (Fig. 1), significant correlations between interannual and decadal variations of the leading mode of the SST anomalies in the North Pacific in December and the zonal wind in the lower stratosphere in January must be observed, excluding the middle (from late 1970s to late 1990) decadal sub-period. Fig. 3 shows the correlations of the zonal wind at 30 hPa in January with the PDO index determined as PC1 of the North Pacific SST anomalies in December for all years (1958–2007), the early (1958–1978) sub-period and middle (1979–1998) sub-period. Spatial pattern of the correlations for all years resembles that of its leading mode (Fig. 1b) with the westerly (easterly) polar jet anomalies and the easterly (westerly) subtropical jet ones for the negative (positive) values of the PDO index. Correlations are not high (less than 0.4), which implies a modulation of the stratospheric circulation by the PDO together with other factors. They are strengthening up to 0.7 during the early sub-period, indicating a large linkage of the PDO with wave activity of the stratosphere in December 1958–1978. In contrast, there is no linkage of the polar jet with the PDO during 1979–1998, when the decadal positive phase of the PDO is observed. Strong relations are restored during the recent decadal period (not shown). Thus, there are decadal variations in a possible modulation of stratospheric wave activity and circulation by the PDO.

In order to identify possible causes of the decadal violation in the modulation of stratospheric wave activity and circulation by the PDO, we calculated the correlations of the SST anomalies both in the North Pacific and North Atlantic (December) with the zonal wind at 30 hPa in January (62.5°N, 160°E; Fig. 3a) for 1959–1978 and 1979–1998 (Fig. 4).

In the early decadal sub-period, significant correlations of the SSTs in the North Pacific in December with the stratospheric polar

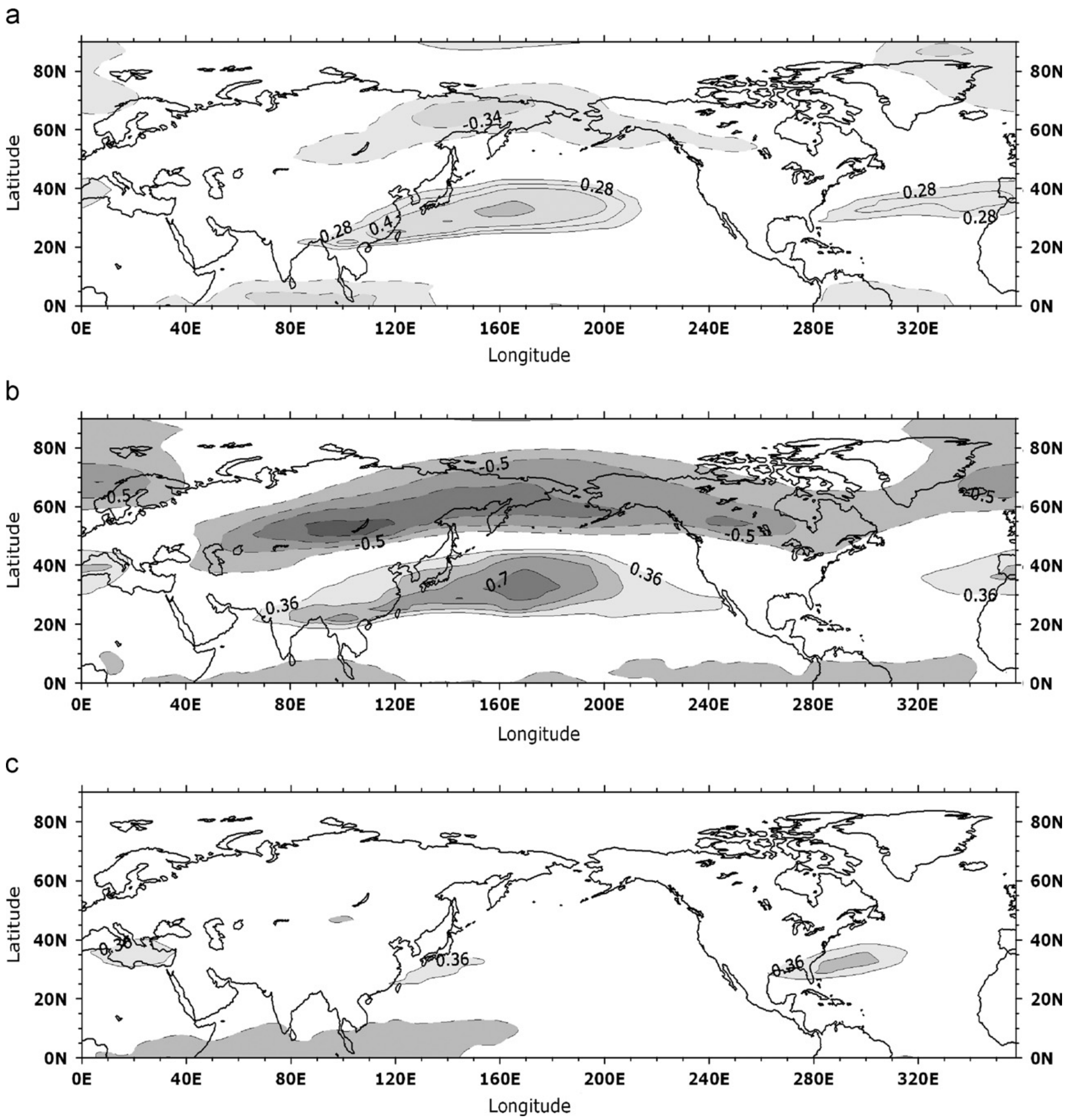

Fig. 3. Correlations of the zonal wind at 30 hPa in January with PDO index in December (d) for the periods: (a) 1959–2007; (b) 1959–1978 and (c) 1979–1998. Correlations significant on the 95% confidence level are shaded.

jet in January are observed. Their features are similar to the PDO spatial pattern (Fig. 2) as the leading mode of the SST anomalies in the North Pacific. In contrast with the North Pacific, features of correlations in the North Atlantic (Fig. 4c) are not related to the leading modes of the SST anomalies in the North Atlantic in 1958–1978 except for significant correlations in the subtropical Atlantic (Jadin et al., 2008). It should be noted that SSTs in the North Atlantic experience larger intra-seasonal variations during the wintertime than those in the North Pacific (Peng and Fyfe, 1996; Jadin et al., 2008).

The correlations of SSTs with polar stratospheric jet are strongly distinguished in the middle (1979–1998) sub-period both in the North Pacific and North Atlantic (Fig. 4b, d). The interannual polar jet variations in January during this decadal period are mainly associated with the SST anomalies in the Aleutian Low region in December, not with SSTs in the central North Pacific (Fig. 2). Namely similar structure of the linkage between the interannual variations of the stratospheric dynamics, total ozone and the SST anomalies in the North Pacific has been indicated for January 1979–1992 by Jadin (2001). There are no significant correlations between the SST anomalies in the North Atlantic in December and the polar jet in January. Thus, the strong (weak) polar jet in the stratosphere in January is associated with the warm (cold) SST anomalies in the central North Pacific in December during the early decadal sub-period (1958–1978), while during the middle sub-period (1979–1998) similar relations are observed for the SST anomalies in the high latitudes of the North Pacific in the Aleutian Low region.

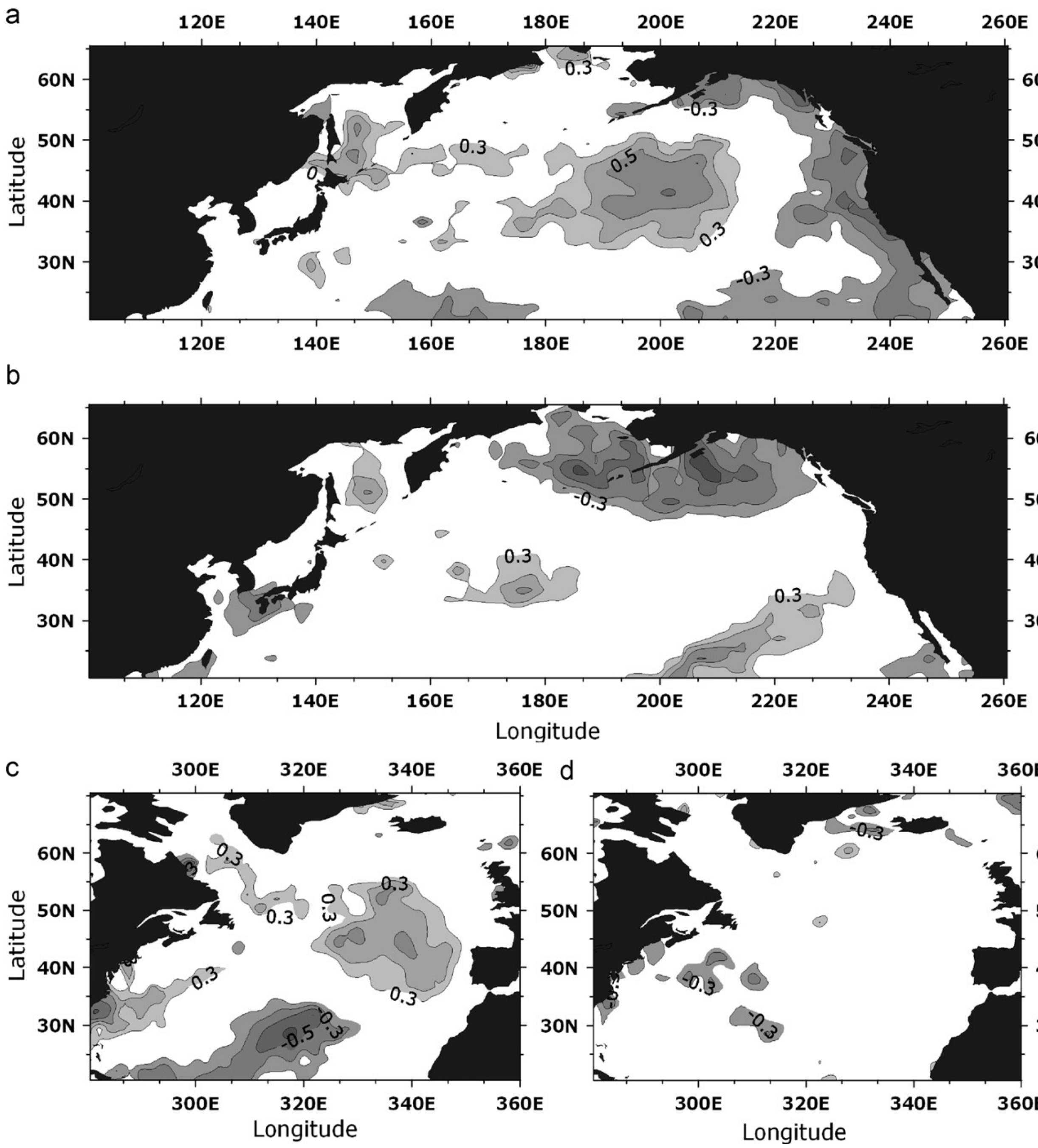

Fig. 4. Correlations of the SSTs in the North Pacific (December) with the zonal wind at 30 hPa in January for the periods: (a) 1959–1978 and (b) 1979–1998. The same for the SSTs in the North Atlantic (c) and (d). Correlations significant on the 95% confidence level are shaded.

4. Discussion and concluding remarks

Results presented here give evidences that the penetration of planetary waves from the troposphere is associated with the interannual and decadal variations of the SST anomalies in the North Pacific in early winter. This linkage is not stable during the record considered. Interannual variations of the planetary wave penetration from the troposphere to the stratosphere are strongly linked to the PDO index in December during 1958–1977 and 1997–2006 (Fig. 2), while there are significant correlations with the SSTs in the Aleutian Low region during 1978–1996. Similar relations with the SST anomalies in the North Atlantic appear to be much smaller in early winter of 1958–2007.

Taking into account the strong linkage between the interannual variations of the stratospheric circulation in January and the intensity of the upward propagation of planetary waves from the troposphere in previous December (Zyulyaeva and Jadin, 2009), these findings can be interpreted as an influence of the North Pacific on the atmosphere, whose signal is most prominent in the stratosphere in December–January. It is difficult to suggest that a downward stratosphere forcing in January results in the SST anomalies in the preceding December namely in North Pacific; rather these results correspond well to the interference mechanism of the topographic source (Rockies) and thermal excitation (depending on SST anomalies) of the stationary planetary wave generation (Jadin, 1990, 2001). The decadal shift of the SST's correlations with stratospheric wave activity and circulation (Fig. 4) hints on this simple mechanism. This mechanism can have a relation to the interaction between the Aleutian and Icelandic Lows, which starts with intensification of the Aleutian Low in early winter and then forms the interannual seesaw across Rockies (Honda et al., 2001; Honda and Nakamura, 2001). It is interesting that larger correlations of this interaction are observed in 1973–1994, i.e. in the decadal period of positive PDO index, than for other decadal periods.

The decadal period 1976–1991 of weak correlations between the SSTs in the North Pacific and EPz (Fig. 2) in December corresponds to that of the violation of the Holton–Tan relationship (Lu et al., 2008). It is well known that SST variability in the North Pacific has the quasi-biennial (QB) mode (Tanimoto et al., 1993, among others), which can be different from the stratospheric QBO (Barnett, 1991). Notice, that there are slight but statistically significant correlations of the zonal wind at 30 hPa with PDO index for all decadal periods (Fig. 3). A close correspondence in the decadal sub-periods of positive PDO index and that of the Holton–Tan relationship violation is intriguing and may have a relation with differences in the stratospheric QBO and the QB of the ocean on decadal timescales. The mechanism of such decadal change is still not clear, and it may be related to the modulation of PDO on the background climatic conditions (e.g., Power et al., 1999; Wang et al., 2007, 2008). In addition, our results are in good agreement with the results of Wei et al. (2007), who showed that correlations of the zonally mean zonal wind and EP fluxes relating to the H–T oscillation with the ENSO are smaller for warm ENSO than for cold ENSO events. More often warm ENSO events and cold SST anomalies in the central North Pacific were observed during 1976–1989 (Lau and Nath, 1996).

A cause of the absence of modulation of the extra-tropical lower stratospheric circulation by the 11-year solar cycle appears to become clear, at least in early winter. In this seasonal period, the variability of the lower stratosphere is partly controlled by the penetration of eddy energy from the troposphere to the stratosphere, which, in turn, is associated with the SST anomalies in the North Pacific with long-term changes different from those of the solar cycle. From mid- to late winter (January–March), an influence of the 11-year cycle on the stratosphere is possible due to a modulation of the "stratospheric bridge" (Zyulyaeva and Jadin, 2009; Jadin and Zyulyaeva, 2010) in the upper stratosphere. It is also interesting that the SST anomalies in the North Atlantic have 8–12 year periodicity similar to the 11-year solar cycle (Deser and Blackmon, 1993). It is possible that decadal variations of the ocean–atmosphere interaction in late winter can be associated with the "atmospheric and stratospheric bridge" (Lau and Nath, 1996; Zyulyaeva and Jadin, 2009). The analysis of relations between the interannual and decadal variations of the stratospheric circulation, wave activity and SST anomalies in late winter will be conducted in a future study.

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