JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D20120, doi:10.1029/2007JD008611, 2007

Modulation of northern hemisphere wintertime stationary planetary wave activity: East Asian climate relationships by the Quasi-Biennial Oscillation

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Received 5 March 2007; revised 23 May 2007; accepted 27 June 2007; published 30 October 2007.

[1] The modulation of the relationship between the tropospheric stationary planetary wave activity and the East Asian winter climate by the tropical quasi-biennial oscillation (QBO) wind in the stratosphere is investigated. In the QBO easterly phase, a significant warming appears in northeastern Asia in the presence of high wave activities. This corresponds to a weakened East Asian trough at 500-hPa, which determines the extent to which cold waves penetrate into East Asia. However, in the QBO westerly phase, both the surface warming and the weakening of the East Asian trough become insignificant in response to high wave activities. The possible mechanism for this QBO modulation on the tropospheric wave activities may be attributed to the indirect influence of the QBO induced polar and extratropical stratospheric circulation changes. Under the QBO easterly phase conditions, the tropospheric wave activity flux divergence in the higher-latitude region is enhanced due to enhanced upward Eliassen-Palm (EP) flux into the stratosphere, while the wave flux convergence in the subtropical troposphere is increased due to the decrease in the equatorward flux. This leads to an enhanced wave activity difference and thus the associated East Asian climate anomalies become larger and robust. An opposite effect (i.e., reduced wave activity difference) appears in the QBO westerly phase. Further analyses reveal that the QBO significantly modulates both the zonal wave number 1 and 2 in the sea level pressure field but not for wave number 3. The combination of wave number 1 and 2 patterns leads to the strongest surface temperature anomalies in northern Asia.

Citation: Chen, W., and T. Li (2007), Modulation of northern hemisphere wintertime stationary planetary wave activity: East Asian climate relationships by the Quasi-Biennial Oscillation, *J. Geophys. Res.*, *112*, D20120, doi:10.1029/2007JD008611.

1. Introduction

[2] The interannual variability of the northern hemisphere atmosphere is characterized by the Arctic Oscillation (AO) [e.g., *Thompson and Wallace*, 1998; *Baldwin and Dunkerton*, 1999]. The AO is an intrinsic mode accounting for one third of the Northern Hemisphere (NH) winter surface temperature variability [*Hurrell et al.*, 2003]. The surface air temperature anomalies associated with a positive phase of the AO present a planetary wave signature with positive anomalies throughout high latitudes of Eurasia and much of North America, and negative anomalies over extreme eastern Canada, North Africa, and the Middle East [*Thompson and Wallace*, 2000]. The AO also corresponds to a north-south seesaw of zonal-mean zonal wind between 35°N and 55°N [*Thompson and Wallace*, 2000] and the fluctuations of the northern hemisphere atmospheric circulation are usually characterized by large-amplitude stationary waves [*Branstator*, 1984; *Ting et al.*, 1996]. As shown by *DeWeaver and Nigam* [2000], there exists a strong relationship between the zonal-mean and eddy flow anomalies. The eddy fluxes of stationary waves have been considered as an important factor of the variability of AO [*Limpasuvan and Hartmann*, 1999, 2000]. The results described above suggest that the regional impacts of AO may be associated with the wave activity.

[3] East Asian climate is dominated by the East Asian summer and winter monsoon [*Chang*, 2004]. The East Asian winter monsoon is an important climate system and exerts a large social and economic impact on many East Asian countries. There have been many efforts to understand the winter climate, and to predict the variation of the winter monsoon circulation in East Asia [*Chan and Li*, 2004; *Chang et al.*, 1979; *Chang and Lau*, 1982; *Ding and Krishnamurti*, 1987; *Zhang et al.*, 1997]. The land-ocean thermal contrast is the primary driver for the monsoon [*Webster*, 1987; *Young*, 1987]. Considering that the stationary planetary waves in the troposphere are forced by the topographic and diabatic heating features arising from the distribution of land and oceans [*Andrews et al.*, 1987], *Chen et al.* [2005] demonstrated a direct relationship between the

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0148-0227/07/2007JD008611$09.00

stationary planetary wave activity and the East Asian winter monsoon on interannual timescales. When the planetary wave activity is higher, the East Asian winter monsoon tends to be weaker.

[4] During the northern winter season the stratospheric and tropospheric circulations are dynamically linked through the interaction of mean flow with upward propagating planetary-scale waves [*Charney and Drazin*, 1961; *Matsuno*, 1970; *Perlwitz and Graf*, 1995]. There is strong evidence that much of the planetary wave activity observed in the winter stratosphere is excited in the troposphere [e.g., *Randel*, 1987 and references therein]. The strength of the stratospheric polar vortex determines the transmission-refraction properties of these vertically propagating waves, and, thus, modifies the structure of ultra-long tropospheric waves [*Li et al.*, 2006]. *Chen and Robinson* [1992], using a three-dimensional linear time-dependent primitive equation model, found that the vertical propagation of wave activity into the stratosphere is very sensitive to the vertical shear of the zonal winds and the vertical gradient of buoyancy frequency near the tropopause. On interannual timescales, the wintertime stratospheric circulation is influenced in several ways. One of the strongest influences is the quasi-biennial oscillation (QBO) in the equatorial lower stratosphere, with variable period averaging about 28 months [*Holton and Tan*, 1980, 1982; *Baldwin and Dunkerton*, 1991; *Dunkerton and Baldwin*, 1991]. When the equatorial winds are easterly, the northern polar vortex is more disturbed and disruption of the vortex by sudden stratospheric warmings is more likely. The mechanism involves a modulation of the waveguide for upward propagating planetary waves. This QBO influence has been confirmed in modeling studies [e.g., *O'Sullivan and Young*, 1992; *Niwano and Takahashi*, 1998; *Chen and Huang*, 1999].

[5] Previous studies have shown that the QBO has an influence on the extratropical stratosphere, but its influence on the troposphere has not been convincingly established. *Coughlin and Tung* [2001] found that the equatorial QBO signal is transmitted to extratropical latitudes not only in the upper atmosphere but also to the surface. The process of transmission is suggested to be related with the QBO modulation of the waveguide for vertically propagating planetary waves. This influences the intensity of the polar vortex in the winter extratropical stratosphere which in turn affects the tropospheric planetary waves, latter of which are sensitive to the upper boundary condition. Hence it is important to investigate the possible impact of the QBO on the relationship between the planetary wave activity and the East Asian winter monsoon.

[6] Following a brief description of the data and analysis methods in section 2, the overall stationary planetary wave activity-East Asian climate relationship in the NH winter is presented in section 3. In section 4 the modulation of the relationship by the QBO easterly and westerly phases is examined. A possible mechanism responsible for this modulation is discussed in section 5. Finally, the major findings are summarized in section 6.

2. Data and Methods

[7] This study is based on 47 years (1958–2004) of the monthly mean pressure level data from the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) reanalysis [*Kalnay et al.*, 1996; obtained from the NOAA Climate Diagnostics Center]. The reanalysis data set is known to be probably unreliable at stratospheric levels before 1958 due to the lack of sufficient observational data in the upper atmosphere [*Kistler et al.*, 2001]. The data set has a $2.5° \times 2.5°$ horizontal resolution and extends from 1000 to 10-hPa with 17 vertical pressure levels. In addition, we employ the monthly temperature data from 160 China stations (obtained from China Meteorological Administration). Seasonal means are constructed from the monthly means by averaging the data of December, January, and February (DJF), which results in data fields for 46 winters (1959–2004).

[8] We expand the seasonal mean geopotential height into zonal Fourier harmonics and use the sum of zonal wave numbers 1 to 3 to represent the stationary planetary wave activity for each individual winter. The Eliassen-Palm flux (EP flux) is used as a diagnostic tool, which is a measure of the wave activity propagation. The EP flux divergence indicates the eddy forcing of the zonal mean flow [*Andrews et al.*, 1987]. The detailed information for the EP flux and its divergence can be found in *Chen et al.* [2003]. To measure the tropospheric planetary wave activity, we adopt the index from *Chen et al.* [2002, 2003], which is based on the teleconnectivity in the divergence of the EP flux. Positive values of this index represent a divergent EP flux in the north and a convergent flux in the south over the middle latitudes of the troposphere, whereas negative values measure the signals of opposite signs. The interannual variability of planetary wave activity measured by the normalized index is shown in Figure 1, and it has been shown to have a significant positive correlation with the AO [*Chen et al.*, 2003, 2005]. In our composite analysis, we select the high and low index cases in which absolute values of the normalized wave activity index are larger than 0.5. Based on this criterion, the selected 15 high index winters are 1967, 1972, 1973, 1974, 1976, 1983, 1984, 1989, 1990, 1993, 1994, 1997, 1999, 2000, and 2002; and the 14 low index winters are 1960, 1962, 1963, 1965, 1966, 1970, 1977, 1978, 1980, 1981, 1985, 1996, 2001, and 2003. Here, the winter of 1960 refers to December of 1959 and January and February of 1960. The composite cross-sections of EP flux vectors for high indices, low indices, and their difference are consistent with the results in *Chen et al.* [2005] (see their Figure 3). When the planetary wave activity is higher, the equatorward propagation of planetary waves at the middle and upper troposphere is stronger, with a weaker upward propagation into the stratosphere.

[9] The zonal-mean zonal wind at 50-hPa over the equator has been chosen to classify the winters into easterly or westerly phases of the QBO, since the winds at 50-hPa have been shown to be well correlated with the rawinsonde observations and can potentially be used to examine the effect of the QBO away from the tropical stratosphere [*Pawson and Fiorino*, 1998]. Winters of the easterly (westerly) QBO phase are defined when the monthly mean 50-hPa zonal winds at the equator are easterlies (westerlies) in all three months from December to February. Winters during which the 50-hPa zonal winds change sign are unclassified. All those selected high and low index winters are further classified into the westerly and easterly phases of QBO,

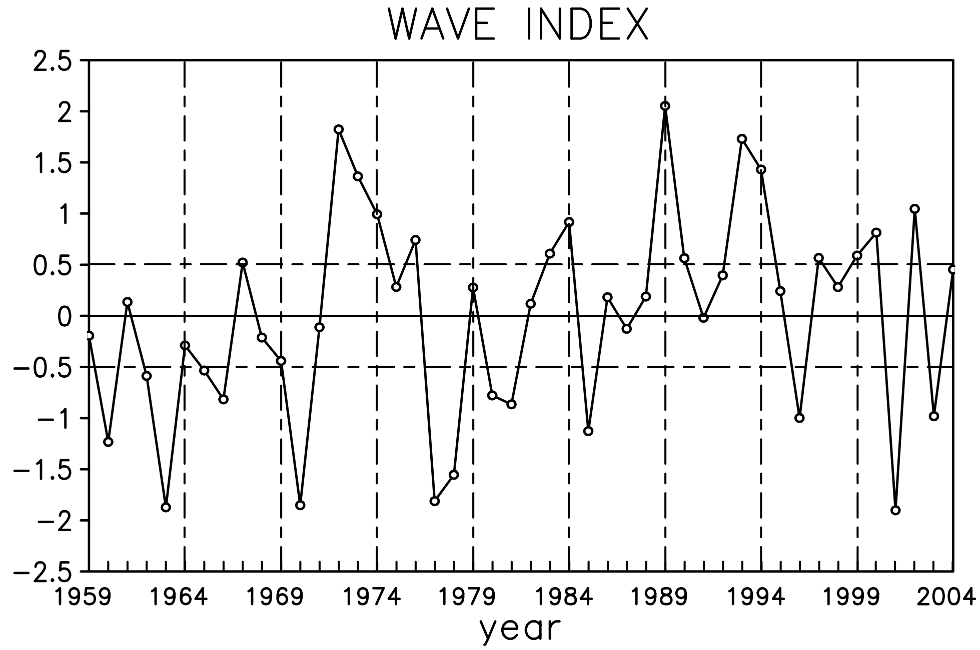

Figure 1. Normalized time series of the tropospheric planetary wave activity index averaged for December–January–February (DJF).

respectively (Table 1). We noted that some studies had explored the relation between solar cycle, QBO and the strength of polar vortex [e.g., *Balachandran et al.*, 1999; *Labitzke and van Loon*, 1988; *Kodera and Kuroda*, 2002; *Naito and Hirota*, 1997]. Hence we carefully checked the possible influence of the solar cycle on this classification. The solar radio flux data are obtained from the National Geophysical Data Center, NOAA (http://www.ngdc.noaa.gov/stp/SOLAR/ftpsolarradio.html). The solar maximum and minimum phases are defined with equal periods of four years as did in *Kodera and Kuroda* [2002]. As shown in Table 1, the classification of the westerly and easterly phases of QBO doesn't have strong bias against solar flux.

3. Relationship Between Stationary Planetary Wave Activity and East Asian Winter Climate

[10] The field of correlation between the planetary wave activity index and China surface temperature is shown in Figure 2a. This correlation pattern is similar to that found in earlier studies [e.g., *Chen et al.*, 2005], which depicts a significant effect of the planetary wave activity on the temperature in northeastern China. These features are confirmed by the composite pattern of temperature difference between the high and low wave activity winters (Figure 2b). As shaded in the figure, these temperature differences exceed significantly the 95% confidence level determined by the two-sided Student's t-test. During the high wave activity winters, the surface temperature in northeastern China tends to be abnormally warm. Reverse situation emerges in the winters of the low wave indices.

[11] The lower tropospheric temperature anomalies in the reanalysis data show consistent variations with China surface temperature associated with the planetary wave activity. Figure 3 presents the composite patterns of 850-hPa temperature for high indices (Figure 3a), low indices (Figure 3b), and the difference between the two composites (Figure 3c). In both high and low index winters, there exists a cold tongue extending from eastern Siberia down to the South China Sea, which depicts the prevailing East Asian winter monsoon. In the difference field, a significant warming of 2°C and higher appears over northeastern Asia (45°N–60°N), which extends northwestward to high latitudes and eastward to North Pacific. In addition, a cooling exists over Alaska area.

[12] Many studies have shown that the East Asian winter monsoon is associated closely with the East Asian trough [e.g., *Staff members of Academia Sinica*, 1957; *Lau and Chang*, 1987]. Hence the composite patterns of 500-hPa geopotential height are presented in Figure 4. The atmospheric circulation over extratropical East Asia is dominated by a trough along the East Asian coast (Figures 4a–4b). Corresponding to the high wave activity cases, the polar vortex is deepened [*Chen et al.*, 2005]. The cooling over Alaska shown in Figure 3c might be linked to the stronger polar vortex. More importantly, significant high values appear over the North Pacific to Northeast China (Figure 4c), which indicate a weaker East Asian trough. A weak trough implies that the cold waves affecting East Asia become relatively inactive. These cold waves are characterized by cold continental air-flowing off the continent to the east and also being tunneled equatorward [*Boyle and Chen*, 1987]. Therefore the warming

Table 1. Distribution of the Winters in the High or Low Wave Indices for the Westerly and Easterly Phases of the QBO

	West QBO	East QBO
High wave index	1967[a], 1972, 1974[b], 1976[b], 1983, 1989[a], 2000[a]	1973, 1990[a], 1994[b], 1997[b], 1999[a], 2002[a]
Low wave index	1960, 1962[b], 1965[b], 1970[a], 1981[a], 1996[b], 2003	1963[b], 1966, 1977[b], 1978, 1980[a], 1985[b], 2001[a]

[a]Indicates the year with the solar maximum phase.
[b]Indicates the year with the solar minimum phase.

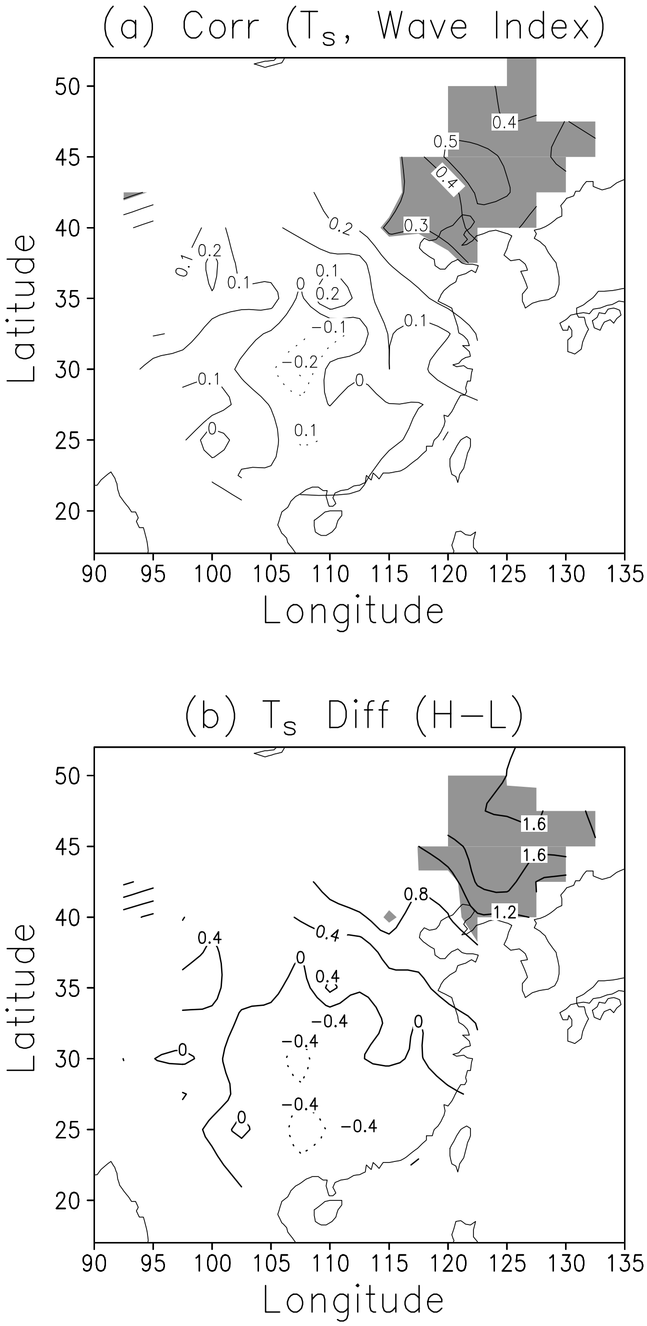

Figure 2. DJF correlation between the surface temperature of 160 China stations and the planetary wave activity index for 46 winters from 1958 to 2004 (a), and composite differences in DJF station surface temperature between high and low wave activity winters (b). Shadings indicate significant values at the 95% confidence levels. Contour interval in (b) is 0.4°C.

in Figure 3c is likely to be caused by the weaker East Asian trough in association with the high planetary wave activity.

4. Modulation of the Wave Activity — East Asian Climate Relationship by QBO

[13] The correlation map between the zonal-mean zonal wind at 50-hPa over the equator and China surface temperature (Figure 5a) shows no significant signals, suggesting that the QBO may have no direct impacts on the winter surface temperature in China. Meanwhile, the correlation between the two time series of the QBO index and the

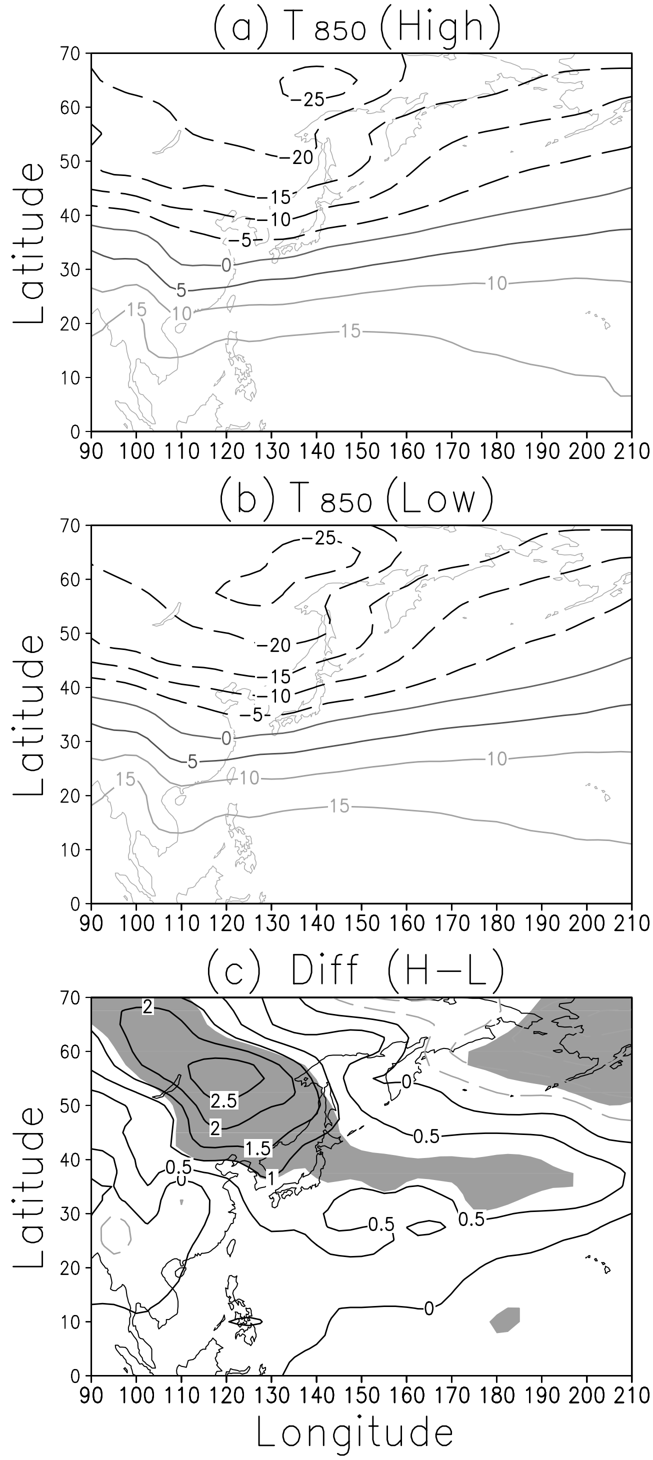

Figure 3. Composite patterns of DJF 850-hPa temperature for (a) high and (b) low planetary wave activity winters and (c) the difference between high and low indices (high minus low). Contour intervals are 5°C in (a) and (b) and 0.5°C in (c), with negative values shown by dashed contours. Shadings in (c) indicate significant values at the 95% confidence levels.

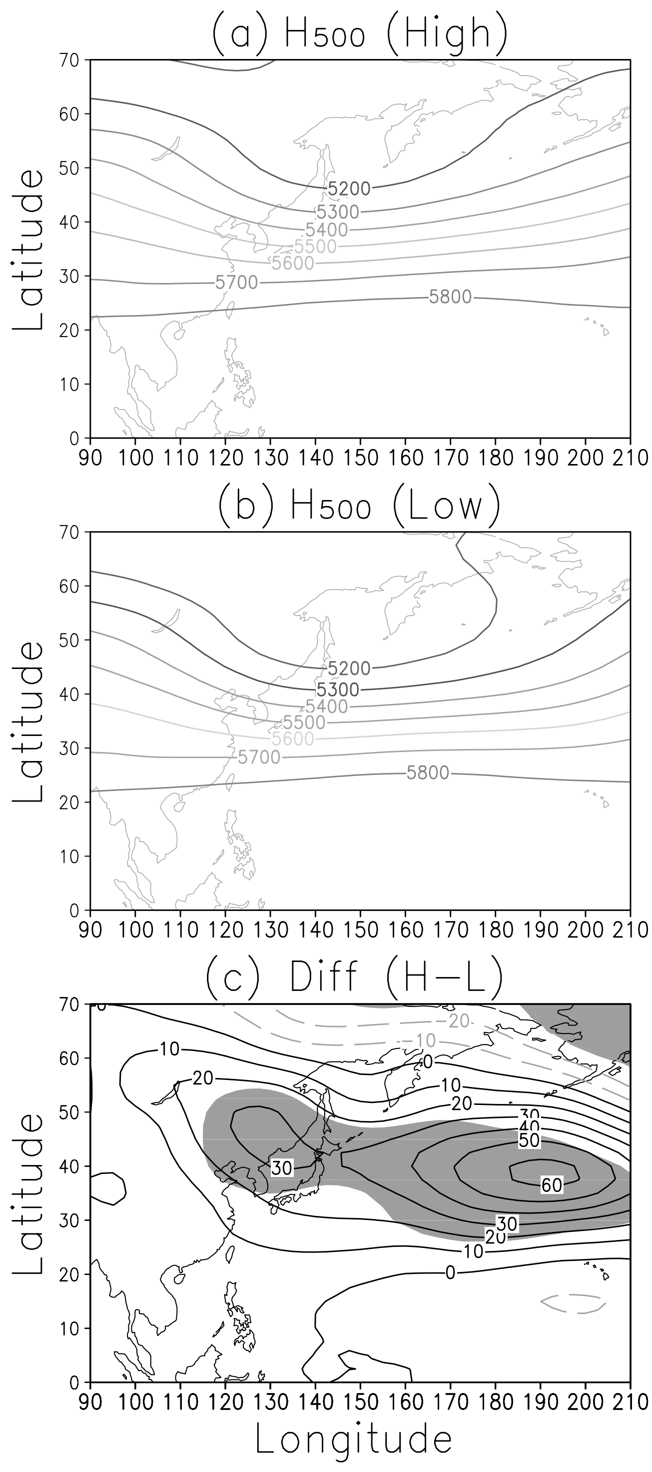

Figure 4. As in Figure 3, but for 500-hPa geopotential height. Contour intervals are 100 gpm in (a) and (b) and 10 gpm in (c).

planetary wave activity index is only 0.15, implying that the tropospheric planetary wave activity is generally independent of the stratospheric QBO on the interannual timescale. However, when the composite differences in China station temperature between the high and low wave activity winters are separated into the QBO easterly and westerly phases (see Table 1), the results depict important distinctions. Recall that for all wave activity composite case, temperature differences show a robust warming in northeast China and a weak, insignificant cooling in central and southern China (Figure 2b). In the westerly QBO phase winters (Figure 5b), the cooling in the central and southern China becomes stronger and significant, while the warming in northern

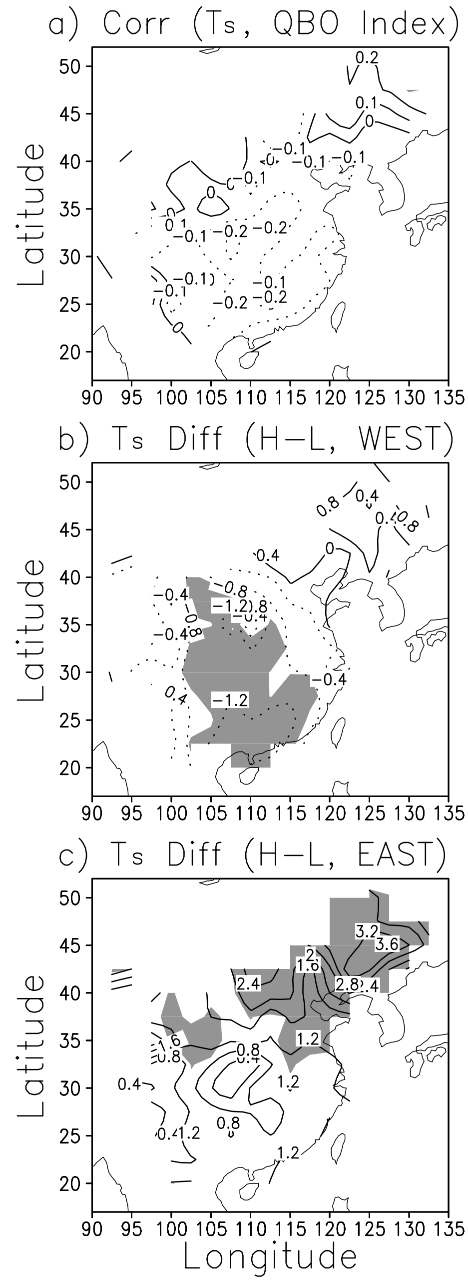

Figure 5. DJF correlation between the station surface temperature and the zonal-mean zonal wind at 50 hPa over the equator for 46 winters from 1958 to 2004 (a), and composite differences in DJF station surface temperature between high and low wave activity winters for the westerly QBO phase (b) and the easterly QBO phase (c), respectively. Contour interval in (b) and (c) is 0.4°C. Shadings indicate significant values at the 95% confidence levels.

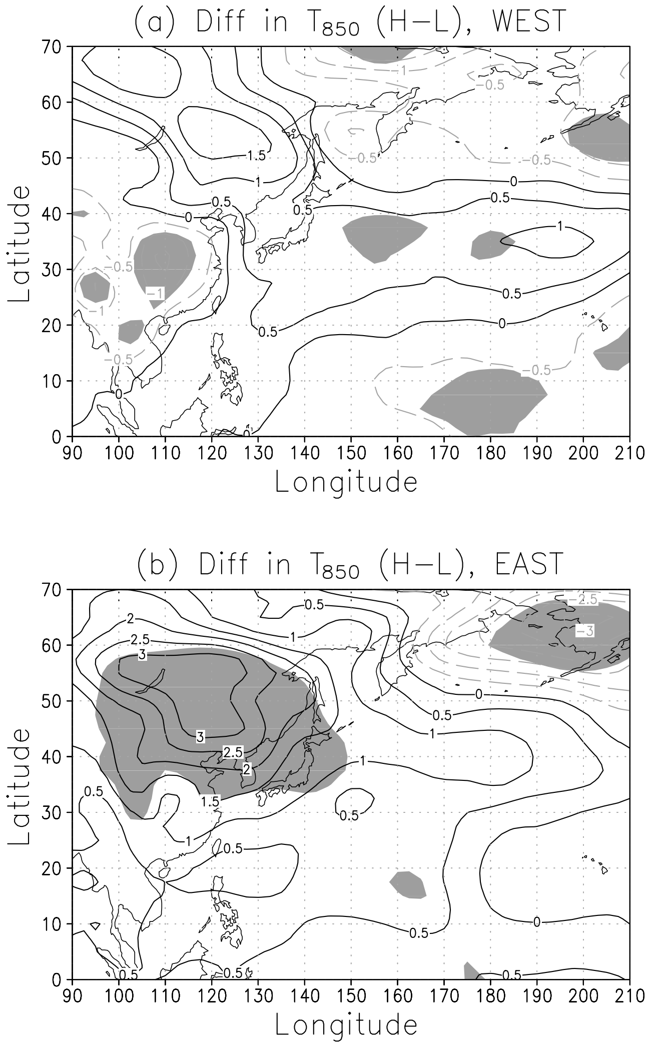

Figure 6. Differences in DJF 850-hPa temperature between high and low wave activity winters for (a) the westerly QBO phase and (b) the easterly QBO phase, respectively. Contour interval is 0.5°C. Shadings indicate significant values at the 95% confidence levels.

China becomes weaker and insignificant. In the easterly phase winters (Figure 5c), positive anomalies appear in the whole China with a maximum anomaly of 3°C and higher in northeastern China. The significant warming covers Northeast and North China and extends to the western China. Therefore the tropical QBO winds tend to modulate strongly the relationship between the tropospheric planetary wave activity and East Asian winter climate. The significant warming in Northeast China associated with the planetary wave activity primarily appears in the QBO easterly phase winters. In the QBO westerly winters, it is the cooling in central and southern China that is closely linked to the planetary wave activity.

[14] Again, the effect of the QBO modulation on the surface temperature variations associated with the planetary wave activity (as shown in Figures 5b–5c) can be confirmed by the composite patterns of 850-hPa temperature fields (Figure 6). The pattern in the QBO easterly phase (Figure 6b) is quite similar to that in Figure 3c, but with more expended and enhanced warming in northeastern Asia and cooling in Alaska. However, in the QBO westerly phase, there is only a weak significant cooling in central China (Figure 6a), while the warming in northeastern Asia is not significant.

[15] The QBO modulation on the relationship between the wave activity and East Asian winter climate may be further revealed from the difference of the East Asian trough (Figure 7). Significant positive anomalies of 500-hPa geopotential height over East Asia, which indicate a weaker East Asian trough, tend to appear only in the easterly QBO phase winters (Figure 7b). Also, the amplitude of these height anomalies tend to be stronger compared to that in the all wave activity composite (Figure 4c). However, in the westerly QBO phase there are no significant variations in East Asian trough (Figure 7a), and high values are only significant over the North Pacific. As a weaker trough indicates the weakening of cold air intrusion into East Asia, the results in Figure 7 are consistent with the modulation of

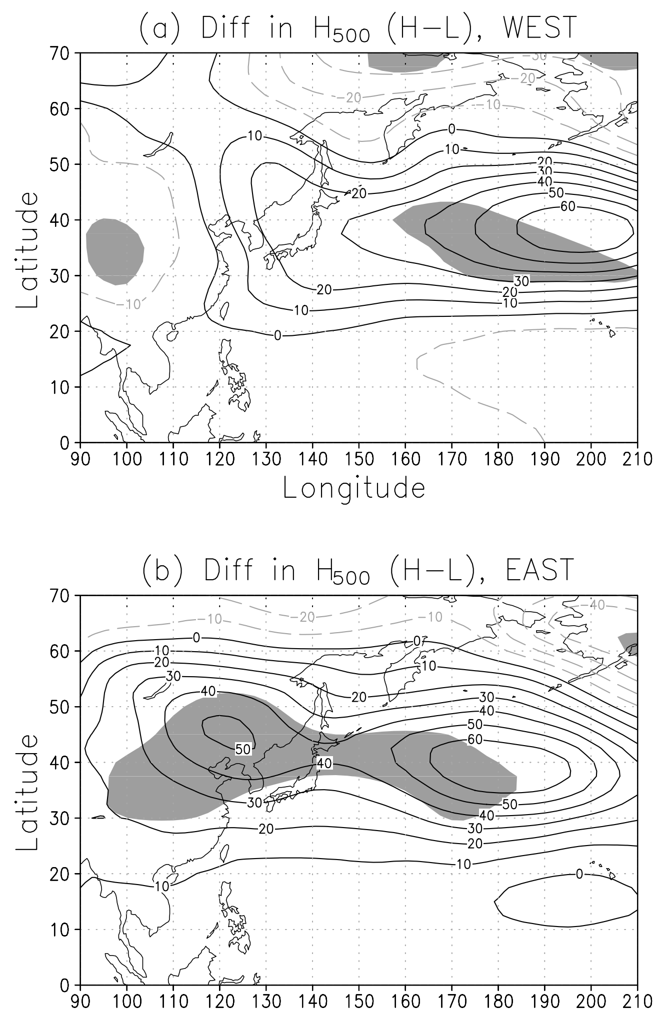

Figure 7. As in Figure 6, but for DJF 500-hPa geopotential height. Contour interval is 10 gpm.

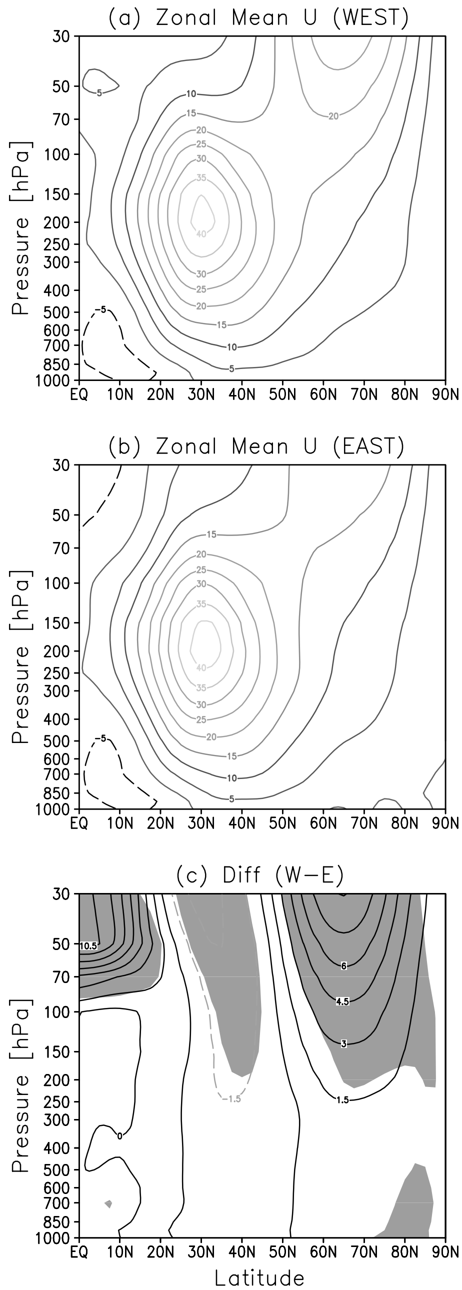

Figure 8. Composite patterns of DJF zonal-mean zonal winds for (a) the 14 westerly QBO phase winters and (b) the 13 easterly QBO phase winters as shown in Table 1, and (c) the difference between westerly and easterly phases (west minus east). Contour intervals are 5 ms^{-1} in (a) and (b) and 1.5 ms^{-1} in (c), with negative values shown by dashed contours. Shadings in (c) indicate significant values at the 95% confidence levels.

the surface temperature variations over East Asia in association with the planetary wave activity by QBO.

5. A Possible Physical Mechanism

[16] One issue that needs to be addressed is why the tropospheric planetary wave activity and East Asian winter climate relationship is dependent on the QBO winds in tropical stratosphere. The QBO has a significant influence on the intensity of the polar vortex in the winter stratosphere [e.g., *Ruzmaikin et al.*, 2005; *Hampson and Haynes*, 2006]. Hence we make the composite of DJF zonal-mean zonal winds ($\bar{u}$) separately for 14 westerly and 13 easterly QBO phases (see Table 1). Comparing Figures 8a and 8b, it's evident that the subtropical westerly jet stream is increased but the polar jet stream becomes weaker in the easterly QBO phase. For example, the wind at 50-hPa is nearly 25 m/s at the core of polar night jet when the QBO is westerly, whereas it is only about 15 m/s when the QBO is easterly. In fact, the difference between these two composites (Figure 8c) displays a meridional dipole in extratropical stratosphere. Significant positive and negative values extend downward to the tropopause region around 65°N and 35°N, respectively. The result is consistent with the previous findings on the relationship between the QBO and the polar night jet [e.g., *Baldwin et al.*, 2001 and references therein].Therefore in the westerly phase of QBO the polar night jet becomes stronger and the subtropical jet becomes weaker near the tropopause. On the contrary, the QBO favors a weaker stratospheric polar vortex and a stronger subtropical jet in the upper troposphere during the easterly phase.

[17] Two mechanisms have been proposed to explain the influence of QBO on the stratospheric polar vortex. One is that the QBO determines the position of the critical line and the width of waveguide, which influence the propagation of planetary waves [*Holton and Tan*, 1980]. The other is related to the QBO-induced meridional circulation, which can penetrate to middle and high latitudes via the wave flux and thus influences the extratropical circulation directly [*Kinnersley*, 1999; *Kinnersley and Tung*, 1999]. Both processes involve a wave mean flow interaction. Hence the cross-sections of EP flux vectors for the westerly and the easterly QBO phase winters and their difference are shown in Figure 9, respectively. In both westerly and easterly phases planetary waves propagate upward from the lower boundary at midlatitudes, and split into two branches in the upper troposphere with one branch moving equatorward and the other propagating into the stratosphere (Figures 9a–9b). In the difference field (Figure 9c), the upward propagation of planetary waves into the stratosphere is significantly reduced, due to enhanced zonal mean flows in the stratosphere. Therefore compared to the westerly phases, the easterly phases of QBO correspond to stronger upward propagation of planetary waves. In subtropical (30–40°N) upper troposphere, the equatorward wave flux is enhanced, possibly due to the weakened subtropical jet in the westerly QBO phase.

[18] The QBO modulation mechanism may be revealed by the composite patterns of the EP flux divergence in latitude-height cross sections for the high minus low wave indices in the QBO westerly and easterly phases (Figure 10). In both the difference fields, a dipole-like pattern exists over the midlatitude troposphere, with a divergence center (positive value) to the north and a convergence center (negative value) to the south. In addition, positive values appear along the polar waveguide at the lower stratosphere. This structure is very similar to the one that is composed based on all the high and low wave index cases [see *Chen et al.*, 2005, Figure 2c]. Compared to the QBO westerly composite, both the divergence and convergence centers of the dipole tend to

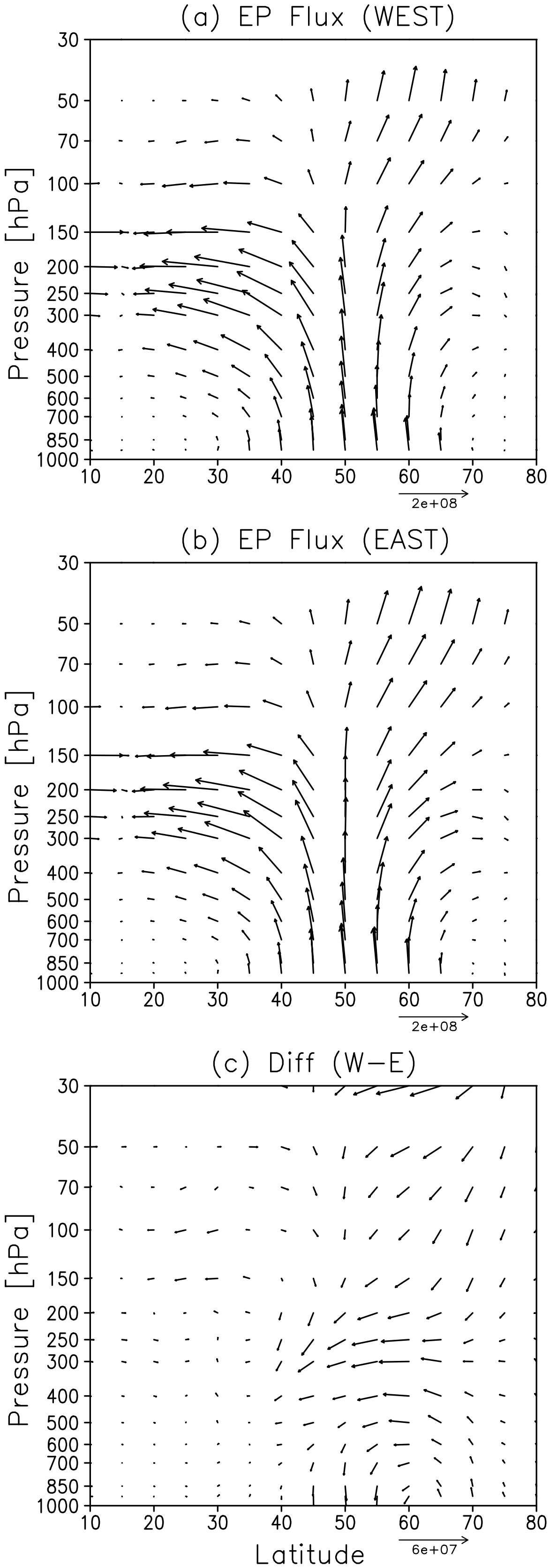

Figure 9. As in Figure 8, but for the cross-sections of EP flux vectors. The vertical coordinate is scaled by an inverse of the air density.

be enhanced in the easterly phases of QBO. This implies that the amplitude of interannual variations of tropospheric planetary wave activity tends to be enhanced in the QBO easterly phase winters.

[19] The increase of the wave flux divergence in the northern part of the dipole in the easterly phase might be related to the enhanced upward wave flux into the stratosphere in association with the decrease of the zonal mean wind in the stratosphere. Previous investigations indicated that the strength of zonal wind near the tropopause determines the transmission of the vertically propagating waves. The decrease in stratospheric zonal wind may thus enhance

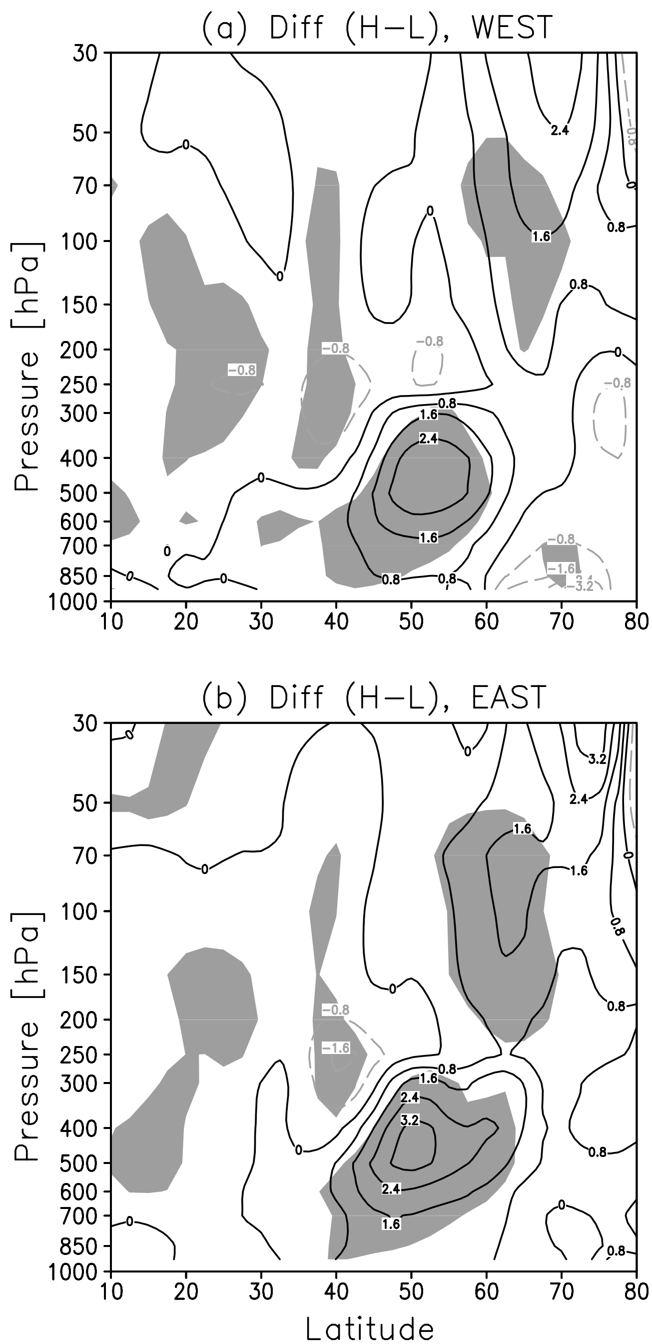

Figure 10. As in Figure 6, but for DJF EP flux divergence. Contour interval is 0.8 ms^{-1} day^{-1}.

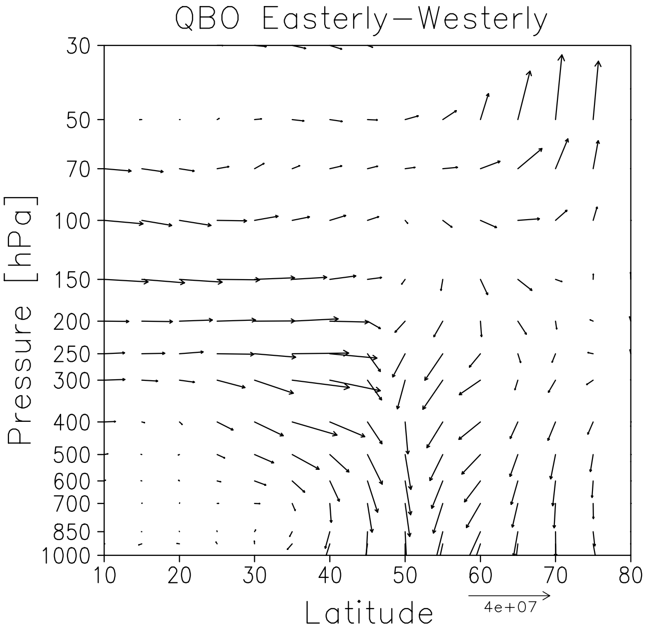

Figure 11. Composite differences of the cross-sections of EP flux vectors between easterly and westerly phases (east minus west) for the difference between high and low wave index winters. The vertical coordinate is scaled by an inverse of the air density.

the upward EP flux. On the other hand, the enhanced subtropical jet during the QBO easterly phase may favor a more zonally oriented waveguide, preventing/reducing the equatorward propagation of the wave flux. As a result, anomalous northward fluxes in the upper troposphere tend to converge into the southern part of the dipole (Figure 11). Thus a combined effect of the subtropical and polar stratospheric zonal winds associated with the easterly (westerly) phase of QBO leads to enhanced (reduced) EP flux divergence dipole structure and thus the variations of tropospheric planetary wave activity. With this physical mechanism, one may expect a larger difference between the high and low wave activity winters in the easterly phases than in the westerly phases of the QBO as shown in section 4.

[20] We further examine the zonal wave number (WN) 1–3 patterns of sea level pressure (SLP) fields under the modulation of the tropical QBO winds. It turns out that the WN 1 and 2 patterns may be significantly influenced. Figures 12 and 13 present the composite differences in the WN 2 and the WN 1 patterns between the high and low wave activity winters classified by QBO phases based on Table 1. Whereas the SLP patterns in both the westerly and easterly phases are similar, the amplitude is stronger in the easterly phase (Figure 12). Compared to the westerly QBO phase, the WN 2 patterns tend to shift westward and northward in the easterly phase. Moreover, the WN 1 patterns depict much stronger and significant differences in its amplitude (Figure 13). When the WN 1 patterns are linearly superimposed to the WN 2 patterns, the pressure gradient tend to be decreased more significantly over the continent of northeastern Asia in the easterly than the westerly QBO phase (Figure not shown). Hence the warming in northeastern Asia may be much stronger than in the North American in the easterly phase winters. Comparing to the WN 1 and 2, the WN 3 is little influenced by the QBO (Figure 14). This is dynamically reasonable, since the stationary planetary waves of WN 1 and 2 can readily propagate into the stratosphere whereas those of WN 3 could not [e.g., *Charney and Drazin*, 1961; *Chen et al.*, 2003].

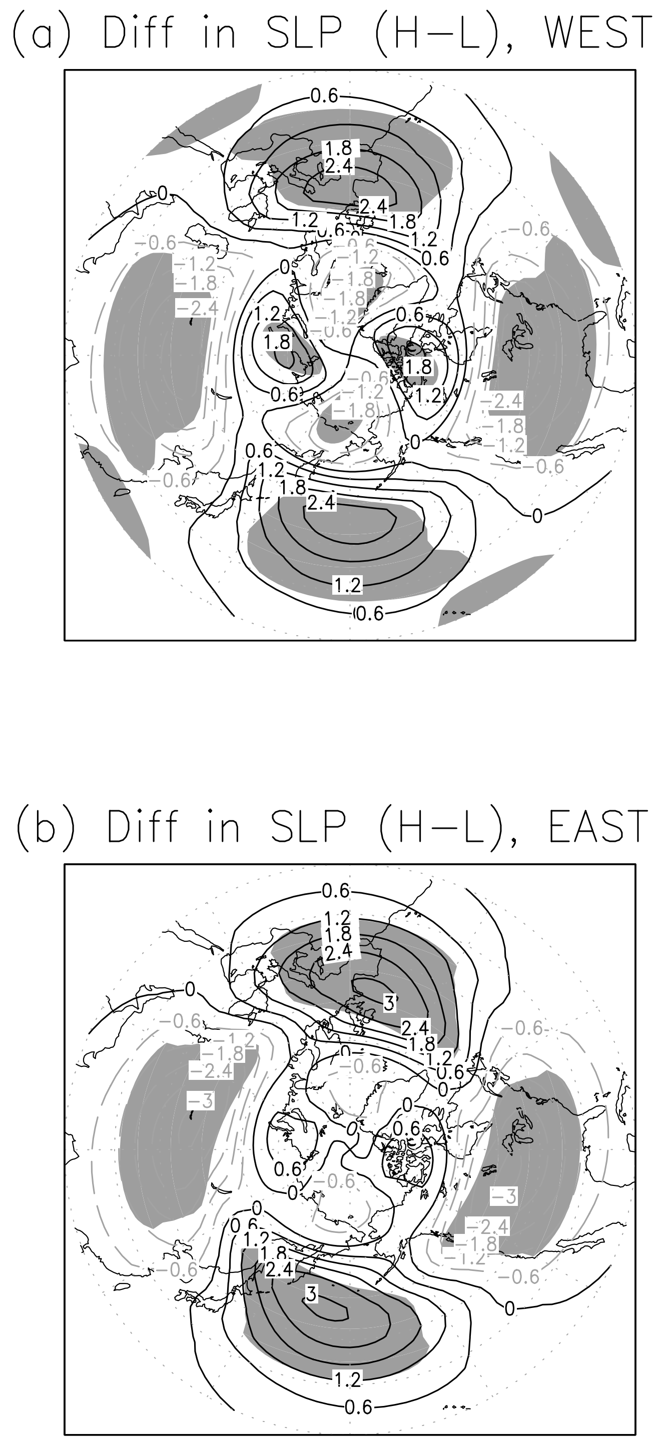

Figure 12. As in Figure 6, but for the zonal wave number-2 distribution of DJF sea level pressure. Contour interval is 0.6 hPa.

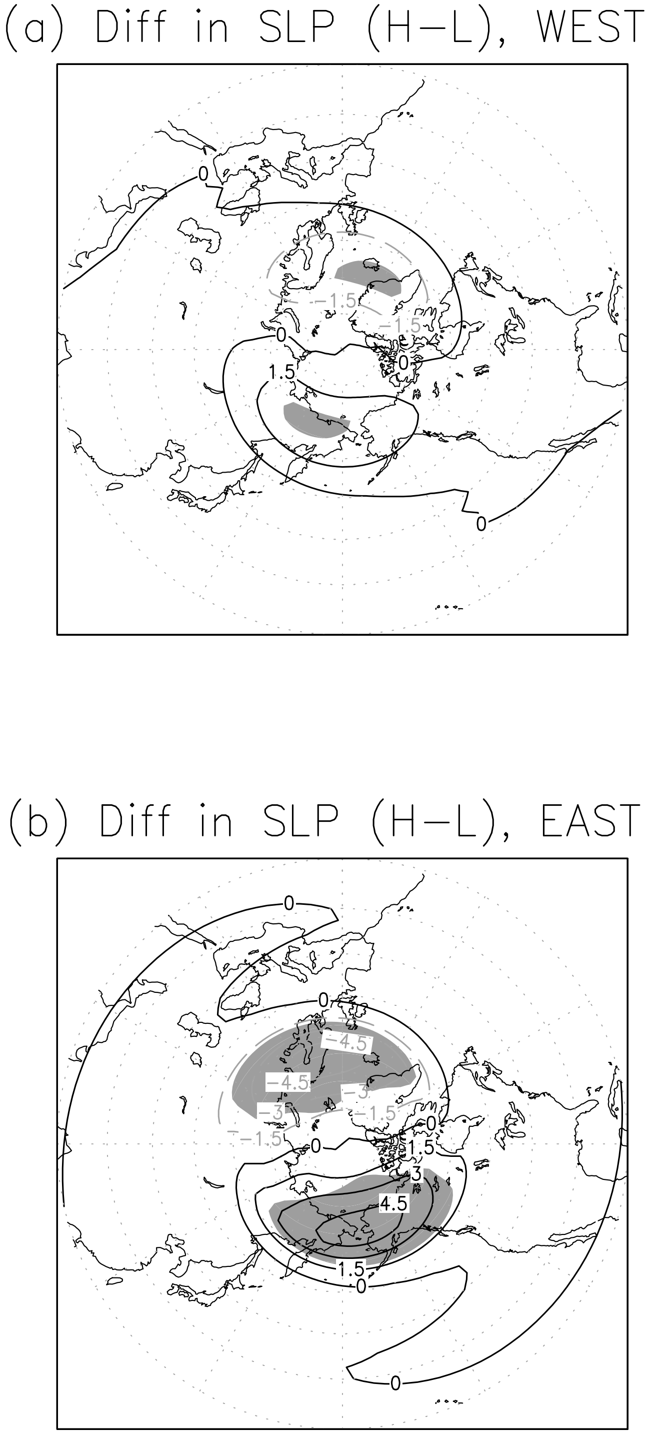

Figure 13. As in Figure 12, but for the zonal wave number-1 pattern. Contour interval is 1.5 hPa.

[21] Finally, the proposed physical mechanism may be tested by using an index of the stratospheric polar night jet, or an index of the subtropical jet. Figures 15a–15b presents the regression (contours)/correlation (shading) map of 850-hPa temperature upon the wave index in the westerly and the easterly QBO phase winters, respectively. It is evident that there are only marginal correlations over northeastern Asia during the westerly QBO phase (Figure 15a). However, significant correlation appears in Asia with a regressed positive value of 1.5°C over the region of 50°N–57°N, 110°E–125°E during the easterly QBO phase (Figure 15b). This is generally consistent with the composite results shown in Figure 6. We further show the regression (contours)/correlation (shading) map of 850-hPa temperature upon the wave index in the strong and the weak polar night jet winters in Figures 15c–15d. The index of the stratospheric polar night jet is defined as

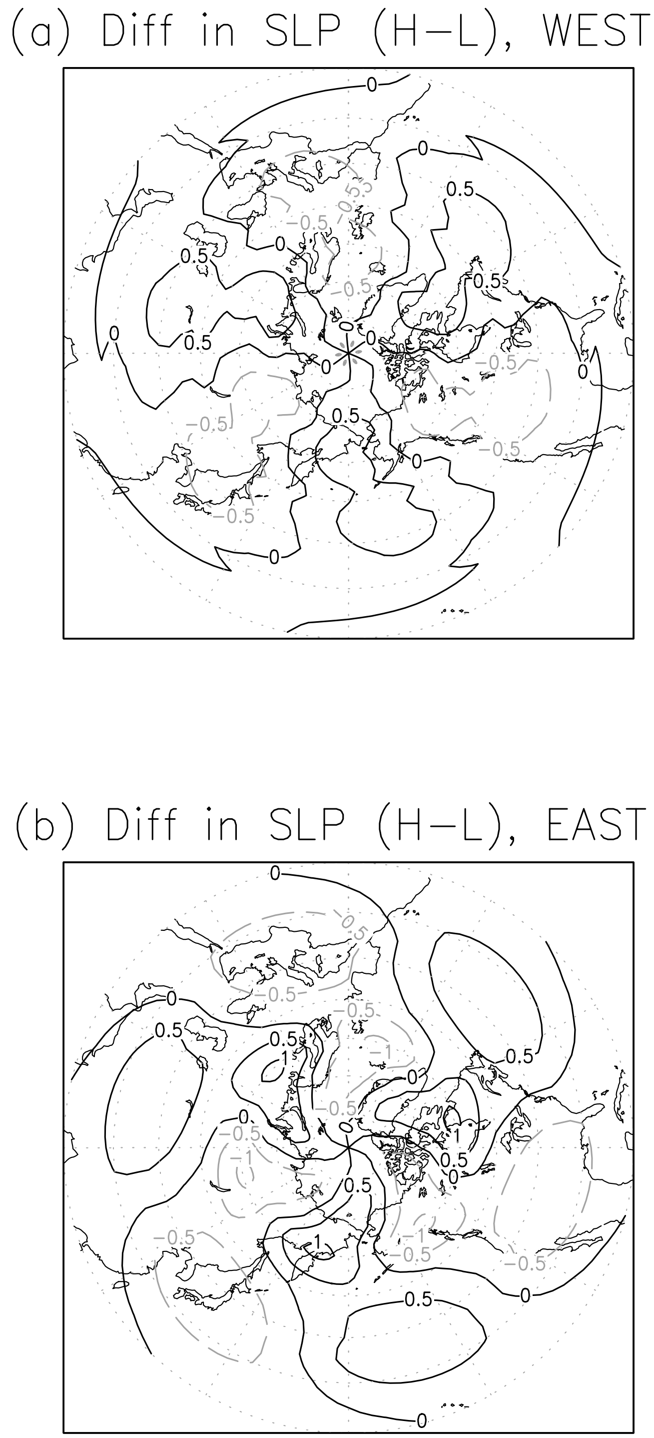

Figure 14. As in Figure 12, but for the zonal wave number-3 pattern. Contour interval is 0.5 hPa.

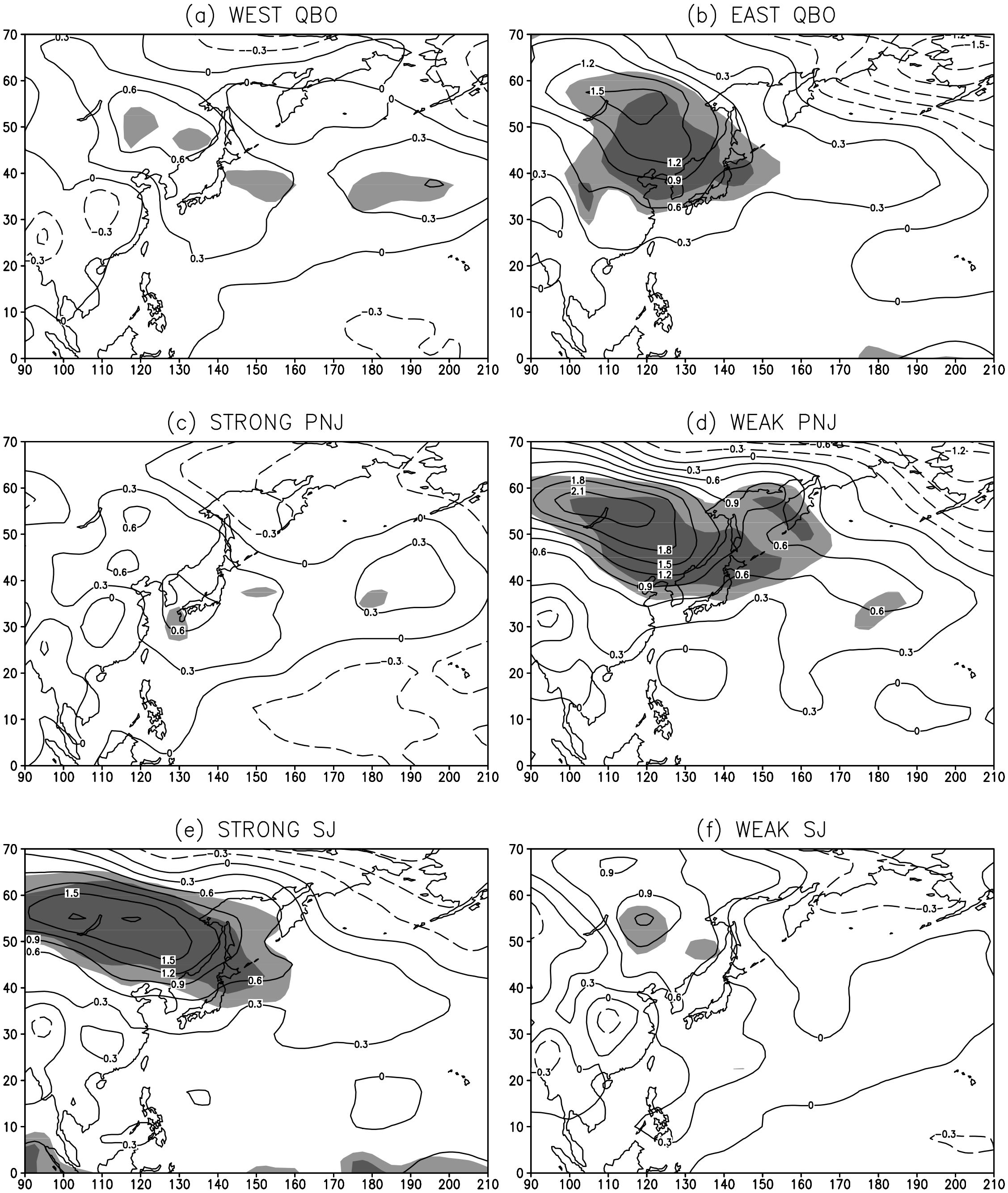

Figure 15. Regression (contours)/correlation (shading) maps of 850-hPa temperature upon the wave index in (a) the westerly and (b) the easterly QBO phase winters, (c) the strong and (d) the weak polar night jet winters, and (e) the strong and (f) the weak subtropical jet winters. Contour intervals are 0.3°C. The shading indicates that the correlation is significant above the 95%- (light) and the 99%-level (dark), respectively.

the 50-hPa zonal mean zonal wind at 65°N. We select the strong and weak cases as the DJFs in which absolute normalized values of jet are larger than 0.5. Based on this criterion, 16 strong and 15 weak jet winters are picked out, respectively. Only in the weak polar night jet cases the wave activity and the lower tropospheric temperature are significantly related over northeastern Asia (Figure 15d). Particularly, comparing Figures 15b and 15d we find that the robust signals are expanded and the regressed values become larger when the polar night jet index is used. Similarly, we define an index of the subtropical jet as the 150-hPa zonal mean zonal wind at 35°N. Also, 15 strong and 17 weak jet winters are chosen with a criterion of its absolute normalized values larger than 0.3. The regression (contours)/correlation (shading) map of 850-hPa temperature upon the wave index is presented in the strong and the weak subtropical jet winters in Figures 15e–15f, respectively. Again, the relationship between wave activity and 850-hPa temperature becomes more pronounced. In these cases, the significant warming associated with high wave activities appears in northeastern Asia in the presence of strong subtropical jet winters (Figure 15e). This result also supports the proposed physical mechanism. Therefore the QBO modulation of the relationship between the tropospheric stationary planetary wave activity and the East Asian winter climate may be attributed to the indirect influence of the QBO induced polar and subtropical stratospheric zonal winds changes.

6. Conclusions and Discussion

[22] An apparent relationship between the tropical QBO winds in the stratosphere and the effect of the tropospheric stationary planetary wave activity on the East Asian winter climate in the Northern Hemisphere has been explored. Findings suggest a preference for the remarkable warming in northeastern Asia in response to high wave activity in the easterly phase of the QBO, and for the reduced and insignificant warming in northeastern Asia but the significant cooling in central and southern China in the westerly phase of the QBO. During the easterly phase winters the East Asian trough at 500-hPa tends to be significantly weakened. Hence the cold wave intrusion into East Asia may be reduced. On the contrary, there are no significant variations in the East Asian trough in the westerly QBO phase winters.

[23] The QBO modulation of the relationship between the tropospheric planetary wave activity and East Asian winter climate appears to result from the indirect influence of the QBO via the extratropical stratospheric circulation changes. In the easterly QBO phase winters, the polar night jet becomes weaker and favors the upward wave flux into the stratosphere, whereas the subtropical jet becomes stronger near the tropopause and reduces the southward wave propagation. These tend to enhance the divergence of EP flux in the polar region and the convergence in subtropical troposphere, comparing the high wave activity winters to the low wave activity winters. In this case, the variations of tropospheric planetary wave activity may be enhanced (reduced), and as a result, the differences in the East Asian climate anomalies become larger (smaller) and robust (insignificant).

[24] Further analysis on the individual planetary waves indicates both WN 1 and 2 in the sea level pressure field may be significantly modulated by the tropical QBO winds. This is consistent with previous knowledge that only stationary planetary waves of WN 1 and 2 can propagate into the stratosphere in the Northern Hemisphere winter. The present findings extend earlier ones [e.g., *Chen et al.*, 2005] by emphasizing the modulation effect of QBO on the tropospheric planetary wave activity - East Asian winter monsoon relationship, which is practically useful for climate prediction. By comparing the vertical propagation of zonal WN 1 in the Northern Hemisphere winter during either an anomalously strong or weak polar vortex, *Perlwitz and Graf* [2001] found the different propagation characteristics. In the weak stratospheric polar vortex winters the upward propagation of waves from the troposphere into the stratosphere was the dominating feature, whereas the downward and southward refraction of wave energy was observed in the strong polar vortex winters. These results also support our explanation on the QBO modulation of the relationship between the tropospheric planetary wave activity and East Asian winter climate.

[25] The modification of the stratosphere on tropospheric extratropical circulation may also involve synoptic eddies [*Shepherd*, 2002; *Limpasuvan et al.*, 2004; *Wittman et al.*, 2004]. Probably, the significant cooling in central and southern China associated with the planetary wave activity in the QBO westerly winters is linked to this synoptic wave activity. The refracted planetary waves by the anomalously strong polar night jet may induce complex interaction with the tropospheric synoptic waves, particularly in the westerly phase of the QBO.

[26] Due to the limit of the data period, only a few cases of anomalous wave activity winters classified by the QBO westerly and easterly phases are selected. Further studies with more samples from a general circulation model may be done in the future. However, the model used should have a realistic stratospheric QBO simulation in order to obtain the correct relationships. Unfortunately, most of the current climate models are unable to correctly simulate the QBO and are biased toward a too strong polar winter vortex, which may underestimate the effect of the tropospheric planetary wave activity on East Asian winter climate anomalies.

[27] **Acknowledgments.** Part of this research was done when W. Chen visited IPRC. This work is supported by the Chinese Key Developing Program for Basic Sciences (Grant 2004CB418303) and the National Natural Science Foundation of China (Grants 40523001 and 40575026). IPRC is partially sponsored by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). This is SOEST contribution number xxxx and IPRC contribution number xxx.

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