

A Statistical Analysis on the Effects of the Equatorial QBO on the Extratropical Stratosphere and Troposphere Based on Large Samples of Daily Data

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Abstract

The 46-year daily data of NCEP/NCAR Reanalysis are analyzed to investigate the effects of the equatorial quasi-biennial oscillation (QBO) on the large scale dynamics in the extratropical stratosphere and troposphere. Composites of the data in northern winter months with respect to the westerly or easterly phase of the QBO show that the stratospheric polar vortex is colder and stronger in the westerly phase in accord with previous studies. Statistical significance of the composite difference is tested by the large sample method with roughly 2000-day dataset for each phase of the QBO. Independence of serial daily data is taken account of by evaluating an effective time between independent samples. As a result, the most significant composite difference of the temperature is found near the tropopause in high latitudes, although the frequency distributions of the temperature for the two phases of the QBO overlap each other heavily.

1. Introduction

The QBO dominates the variability of the equatorial stratosphere (e.g., Baldwin et al. 2001). Observational studies on the relationship between the phase of the QBO and the winter stratospheric circulation can be traced back to the pioneering work by Holton and Tan (1980): When the phase of the QBO is defined with respect to the equatorial zonal wind at the levels around 50 hPa, the stratospheric polar vortex is weaker, warmer and more disturbed during winters in the easterly phase of the QBO. Major stratospheric sudden warming (SSW) events tend to occur more frequently in the easterly phase (Labitzke 1982).

Naito et al. (2003) investigated the effects of the equatorial QBO on stratospheric sudden warming (SSW) events, by performing perpetual winter integrations with a simplified three-dimensional global circulation model of the atmosphere in which zonal momentum forcing was imposed in the equatorial stratosphere to mimic a westerly or easterly phase of the QBO. In a series of experiments to sweep a parameter of the equatorial wind forcing from a case with strong westerly to a case with strong easterly through a case with zero forcing, statistical and dynamical characteristics of SSW events showed systematic dependence on the equatorial wind forcing. Composite analysis for a large number of the obtained SSW events was made to describe daily evolution of the temperature field during the events, particularly the aftereffect to the lower levels. The statistical significance of the composite difference was tested with the large sample method. A significant difference between the cases with westerly wind forcing

and the other cases with easterly wind forcing was detected even in the troposphere in high latitudes.

In the present study, the statistical difference depending on the phase of the QBO in the 46-year daily data of the real atmosphere is investigated on the basis of the large sample method. In order to take account of the independence of serial daily data, an effective time between independent samples is evaluated. Attention is focused on winter months in the Northern Hemisphere.

2. Data and method of analysis

Daily data of the NCEP/NCAR Reanalysis for 46 years (January 1958–December 2003) are used. The data of the zonal mean temperature [T] and of the zonal mean zonal wind [u] are analyzed for the northern winter months (December, January and February).

Monthly data of the zonal wind in the equatorial stratosphere from 1953 up to the present (courtesy of Dr. Naujokat) are used to define the phase of the QBO. A “Westerly (W)” or “Easterly (E)” phase is determined for each winter according to the equatorial wind which is averaged between the 40-hPa and 50-hPa levels for three months from December to February as was in the previous study (Naito and Hirota 1997). Consequently 26 winters (2316 days) are categorized in “W”, and 21 winters (1834 days) are categorized in “E”. A possible QBO effect which may originate near 1 hPa (Gray et al. 2001) is not examined in the present study.

Statistical significance of the difference between the two composites for “W” and “E” is tested by the large sample method. A statistic

$$Z \equiv [\bar{W} - \bar{E}] / \sqrt{(\sigma_w^2/N_w) + (\sigma_e^2/N_e)}, \quad (1)$$

is a standard normal variable if N_w and N_e are sufficiently large, and is used as an index of the statistical significance of the difference between two means (Hoel 1984). Here \bar{W} and \bar{E} are averages, σ_w^2 and σ_e^2 are variances, and N_w and N_e are sample sizes in the category of “W” and “E”, respectively. The statistical significance of the difference is 90%, 99%, 99.9% or 99.99%, when $|Z|$ is 1.28, 2.33, 3.09 or 3.72, respectively.

In order to take account of persistence of the sequential daily data, the sample sizes N_w and N_e are replaced by effective sample sizes $N'_w \equiv N_w t_0 / T_0$ and $N'_e \equiv N_e t_0 / T_0$, and hence Z is replaced by

$$Z' \equiv Z \sqrt{t_0 / T_0}. \quad (2)$$

Here the sampling time t_0 is 1 day in the present case, and an effective sampling time T_0 can be estimated according to the theory considering the first-order Markov process to satisfy $\rho_i = \exp(-2\tau/T_0)$, where ρ_i is serial correlation coefficient and τ is the lag (Laurmann and Gates 1977).

In the present analysis, T_0 is defined as twice the shortest lag τ (day) for which ρ_i falls below $1/e$, for each

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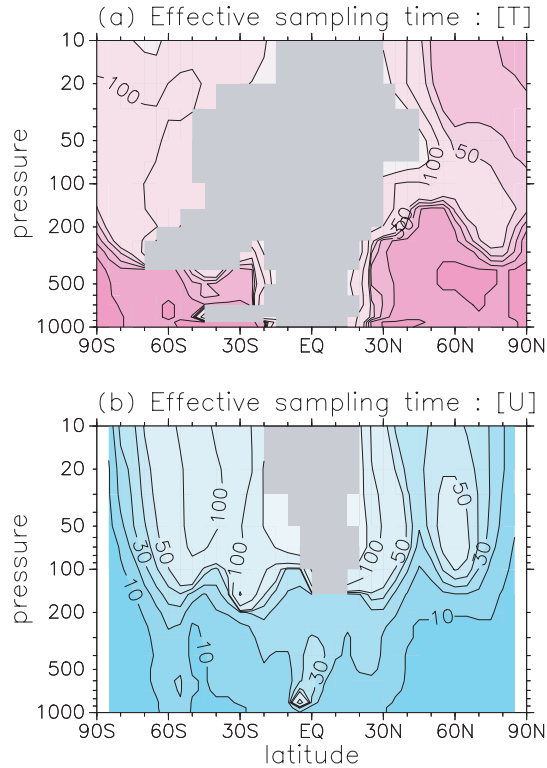


Fig. 1. Latitude-height sections of the effective sampling time T_0 evaluated for (a) $[T]$ and (b) $[u]$. Contours are drawn at 10, 20, 30, 40, 50, 100, 200 (days). Grid points with T_0 greater than 300 days are masked by gray shade.

of $[T]$ and $[u]$ in every data point on the meridional plane. Whole 46-year time series are used to calculate ρ_c after the climatological annual cycle is subtracted. The resultant T_0 is shown in Fig. 1. In the extratropical troposphere, T_0 for $[T]$ is shorter than 20 days. There is a sharp increase in T_0 around the tropopause, above which T_0 is longer than 50 days. In the tropics, T_0 is longer than 100 days. As for $[u]$, T_0 is shorter than 20 days in the extratropical troposphere, around 20 to 100 days in the extratropical stratosphere, and longer than 100 days in the tropical stratosphere.

3. Results

3.1 Composite difference

Figure 2 shows the composite difference (i.e., the 2316-day average in “W” minus the 1834-day average in “E”) of the zonal mean temperature $[T]$ and the zonal mean zonal wind $[u]$ in the northern winter months.

The composite difference of $[u]$ around 30–50 hPa over the equator is positively large by the definition of the QBO phases. The composite difference of $[T]$ over the equator is positive around 70 hPa and negative around 20 hPa, and the secondary positive difference of $[T]$ appears around 35°N, 20 hPa; these composite differences in $[T]$ are consistent with the difference in $[u]$ in terms of the thermal-wind relationship. This pattern of the composite difference in $[T]$ is due to the meridional circulation associated with the QBO as illustrated by Plumb and Bell (1982).

The negative difference of $[T]$ in the polar stratosphere implies lower temperature in “W” due to less

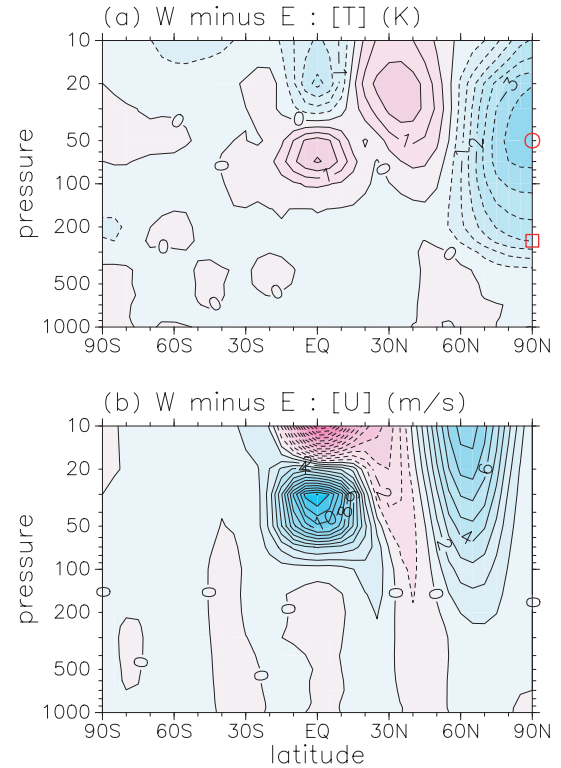


Fig. 2. Latitude-height sections of the composite difference (“W” minus “E”) of (a) $[T]$ and (b) $[u]$. Contour intervals are 0.5 K and 1 m s⁻¹, respectively. The two red marks indicate the data points of frequency distributions shown in Fig. 4.

frequent occurrence of SSW events, which is consistent with the previous studies (e.g., Labitzke 1982). The largest difference of $[T]$ is about 4 K at 90°N, 50 hPa (denoted by the red circle), and the difference decreases as the altitude decreases below 50-hPa level; it is about 2 K at 90°N, 250 hPa (denoted by the red square).

The positive difference of $[u]$ at high latitudes in the stratosphere implies stronger polar night jet in “W”, which is also consistent with the previous studies (e.g., Dunkerton and Baldwin 1991). The largest composite difference of $[u]$ appears at the core of the polar night jet at the top level of the dataset; the difference at 60°N, 10 hPa is about 8 m s⁻¹. The pattern in the stratosphere displays a dipole changing sign around 40°–45°N. The high-latitude positive anomaly and the subtropical negative anomaly penetrate the troposphere, although the difference becomes small. This was also noted by Dunkerton and Baldwin (1991).

3.2 Statistical significance

Figure 3 shows the statistical significance of the composite difference in percentage, on the basis of Z' taking account of the effective sampling time T_0 . The sign of the plotted value of the significance is set to the same as the sign of the composite difference shown in Fig. 2.

Figure 3a shows that the composite difference for $[T]$ is significant not only in the QBO region but also in the middle and high latitude stratosphere. The significance is particularly high around the tropopause in high latitude; the maximum is 99.9985% at 90°N, 250 hPa. The composite difference is most significant near the tropopause whereas the maximum of the composite

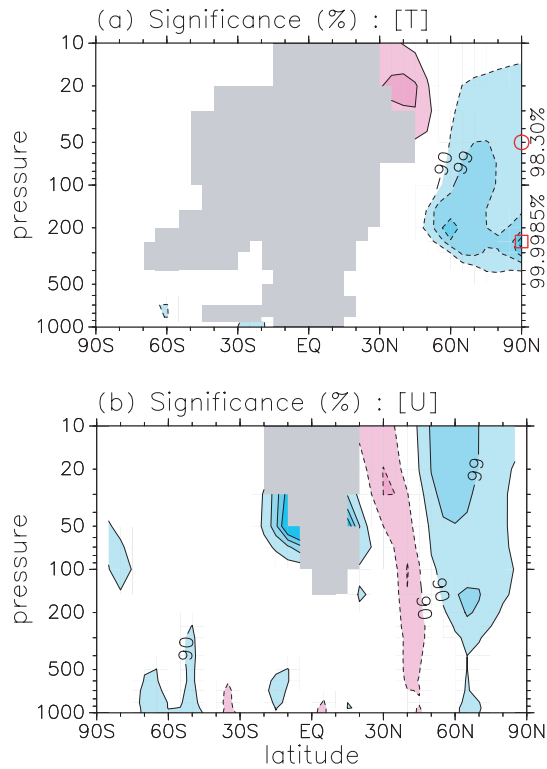


Fig. 3. Latitude-height sections of the statistical significance of the composite difference in (a) $[T]$ and (b) $[u]$. Contours are drawn at ± 90 , ± 99 , ± 99.9 , and ± 99.99 (%); a negative sign of the significance indicates the negative difference. Gray shade is the same as in Fig. 1.

difference is at 50 hPa. The large effective sample sizes related to the short T_0 at 250 hPa (shorter than two weeks) compared with the long T_0 at 50 hPa (longer than a month) allows the smaller composite difference to have higher significance at 250 hPa. The secondary maximum of the significance appears around 60°N near the tropopause in association with the latitudinal change in T_0 .

Composite difference of $[u]$ is most significant at 50 hPa over the equator, where the phase of the QBO was defined (Fig. 3b). The positive difference around 60°N and the negative difference around 30°N are also significant in the stratosphere and the troposphere. The significance is higher than 99% around 60°N in the stratosphere. The significance is still higher than 90% through the troposphere around 40°N and around 65°N , although the absolute value of the difference is less than 1 m s^{-1} (Fig. 2b). The high significance of the composite difference in the troposphere is partly due to the short T_0 (10–20 days) in the troposphere compared with the long T_0 (50–100 days) in the stratosphere; we have larger effective sample sizes in the troposphere.

3.3 Frequency distribution

Figure 4 shows two examples of frequency distributions of the polar temperature at 50 hPa and at 250 hPa, for each dataset in “W” or in “E”. These two data points are indicated by the red marks in Figs. 2 and 3.

The frequency distributions of $[T]$ at 90°N , 50 hPa (Fig. 4a) are very skew and far from the fitted Gaussian curves, especially in “W”. This skewness is related to a long tail of a few warm days during SSW events against a mass of ordinary cold days in the winter polar strato-

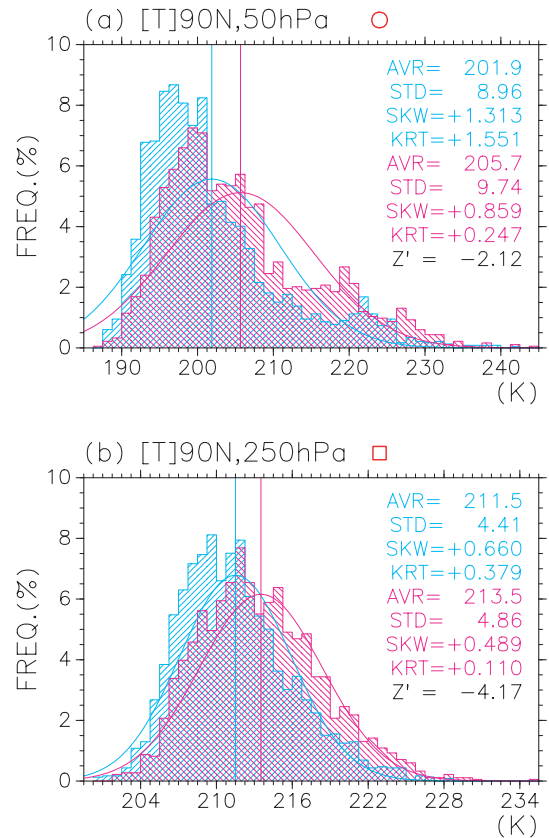


Fig. 4. Frequency distributions of $[T]$ (a) at 90°N , 50 hPa and (b) at 90°N , 250 hPa, for each of the dataset in “W” (cyan) and the dataset in “E” (magenta). Widths of the bins are 1.25 K and 0.75 K, respectively. A vertical line and a curve indicate the average and the fitted Gaussian distribution for each dataset. The values of average, standard deviation, skewness, and kurtosis are written in cyan or magenta for each dataset. The value of Z' is written in black.

sphere. Reflecting less frequent occurrence of SSW events in the westerly phase of the QBO, the average of $[T]$ in “W” is about 4 K lower than in “E”, and the skewness in “W” is about 1.5 times as large as in “E”. Note also that the mode value is about 2.5 K lower in “W”. The two frequency distributions overlap each other heavily because of the relatively large standard deviations (about 9–10 K) compared with the difference between the two averages (4 K). The index of the statistical significance Z' is -2.12 , which means that the composite difference has the significance of 98.30% as shown in Fig. 3a.

The frequency distributions of $[T]$ at 90°N , 250 hPa (Fig. 4b) are more close to the Gaussian curves than at 50 hPa. The overlap of the two frequency distributions is as heavy as at 50 hPa, because of the relatively large standard deviations (about 4–5 K) compared with the difference between the two averages (2 K). However, the index of the statistical significance Z' reaches -4.17 owing to the smaller T_0 , indicating the most significant (99.9985%) composite difference as shown in Fig. 3a.

4. Concluding remarks

The composite difference in the extratropical strato-

sphere and troposphere between the two categories of the westerly and easterly phases of the QBO was investigated with the 46-year daily data of the NCEP/NCAR Reanalysis. Focusing attention on winter months in the Northern Hemisphere, 2316-day data were available in the westerly phase of the QBO, while 1834-day data in the easterly phase.

The composite analysis showed that the stratospheric polar vortex is colder and stronger in the westerly phase. The results are fundamentally consistent with the previous studies based on the monthly averaged data for a shorter period (e.g., Holton and Tan 1980). In the present study, statistical significance of the composite difference was tested by the large sample method. The independence of serial daily data was taken account of by evaluating the effective sampling time. The composite difference of $[T]$ is larger in the polar stratosphere (the maximum is about 4 K at 90°N, 50 hPa) and most significant around the tropopause. The highest value of the significance reaches 99.9985% at 90°N, 250 hPa, partly due to the large effective sample sizes related to the short effective sampling time T_0 (10–20 days) in the troposphere. The composite difference of $[u]$ displays a dipole pattern in the stratosphere changing sign around 40°–45°N; the pair of the positive and negative anomalies extends down to the troposphere. The pair of the anomalies of the composite difference of $[u]$ is significant in the stratosphere (>99%) and in the troposphere down to the surface (>90%).

The frequency distributions of $[T]$ at the polar stratosphere showed large skewness due to a few warm days during SSW events. The skewness is larger and the averaged temperature is lower in the westerly phase, because of less frequent occurrence of SSW events. While the frequency distributions overlap each other heavily, the composite difference of $[T]$ at the pole is very significant even near the tropopause (Fig. 4b).

The dipole pattern illustrated in the composited $[u]$ (Fig. 2b) in low-frequency atmospheric variations is not unique to the influence of the QBO (Baldwin et al. 2001). Thompson and Wallace (2000) showed the leading mode of variability of the northern extratropical troposphere and stratosphere is characterized by deep, zonally symmetric or “annular” structure, which has a node around 45°N similar to the pattern shown in Fig. 3b. Haigh (1999) carried out GCM experiments on the solar impact on climate, and showed the differences in zonal mean zonal wind between a run representing solar minimum and each of the other runs representing solar maximum. There is a dipole structure near 55°S, indicating a poleward shift in the subtropical westerly jet, and a similar poleward shift in the jet can be seen in the northern hemisphere in her result. Kodera (1995) made composite analysis assuming four possible causes: solar activity, QBO, volcanic aerosols, and trends. The results of composite analysis show that in November, anomalous zonal mean zonal wind is found in accordance with the assumed forcings in different regions in the stratosphere. As winter progresses, however, anomalous patterns in zonal mean zonal wind become similar by forming a dipole-type pattern and extend down into the troposphere. The similar patterns in the zonal mean zonal wind shown by their studies suggest that the effect of the external forcings on the low-frequency atmospheric variations tends to be amplified by the coupling of the internal variations in the stratosphere and the troposphere mainly through planetary wave dynamics, although wave behavior was not examined in the present study.

The statistical method used in the present study can be applied to test the effects not only of the QBO but also of such other external forcings on the dynamical

variability in the stratosphere and troposphere.

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