Tropospheric and equatorial influences on planetary-wave amplitude in the stratosphere

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[1] Using 49-year NCEP/NCAR reanalysis data we examine two possible factors affecting the amplitudes of extratropical planetary waves in the stratosphere: tropospheric influence and equatorial Quasi-Biennial Oscillation (QBO) modulation. Our results show that the QBO modulation on wave amplitudes is statistically significant only for wavenumber-1 in early winter. The variability of wavenumber-2 amplitude is mainly determined by tropospheric forcing. The effect of the solar cycle on planetary-wave amplitude is also discussed. *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342), 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions

1. Introduction

[2] It has long been thought that the equatorial Quasi-Biennial Oscillation (QBO) might have a significant influence on extratropical circulation in the stratosphere. Based on the theoretical speculations that the critical layer may act as a reflector for stationary planetary waves [*Tung and Lindzen*, 1979; *Tung*, 1979; *Killworth and McIntyre*, 1985], *Holton and Tan* [1980, 1982] (hereafter HT80 and HT82) suggested that the equatorial QBO, by altering the width of the extratropical waveguide, may affect the amplitude of the planetary waves at mid and high latitudes. This so-called Holton-Tan mechanism was supported by the observational results of HT80 and HT82, who found that in early winter wavenumber-1 amplitude in the extratropics was larger, and zonal wind was weaker, in the easterly phase of the QBO, than in the westerly QBO phase. *Dunkerton and Baldwin* [1991] found that the Eliassen-Palm fluxes are also modulated by the QBO in early winter. *Dunkerton et al.* [1988] showed that major sudden warmings almost never occurred when the equatorial winds were ‘‘deep westerly’’, consistent with the speculation of [*McIntyre*, 1982], although the easterly QBO phase did not consistently lead to major sudden warmings. The behavior of wavenumber 2 in winter, also reported by HT80, does not appear to be consistent with the Holton-Tan mechanism.

[3] *Labitzke* [1987] and *Labitzke and van Loon* [1988] noted that major warmings can occur in the west QBO phase during solar maxima. Using 37-year National Meteorological Center (NMC) and Freie Universität Berlin datasets, *Naito and Hirota* [1997] found that HT80’s results, valid for 1962/63–1977/78, failed to hold in 1978/79–1993/94. They conjectured that such a difference is due to the effect of the 11-year solar cycle because HT80’s period happens to contain two solar minima and one maximum, while the second period covers one solar minimum and two maxima. They therefore suggested that HT80’s result could not be valid in general, it being applicable only to periods with more solar minima than maxima.

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[4] The purpose of the present paper is to clarify the observed manifestations of the Holton-Tan mechanism using longer-time data. In addition to studying the QBO modulation, we are particularly interested in the influence of tropospheric forcing on planetary-wave amplitudes in the stratosphere, and also the possible effect of the solar cycle. The data used here are 49-year (November 1952–March 2001) monthly-mean geopotential heights from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR). The QBO winds are the monthly-mean Singapore winds from B. Naujokat [*Naujokat*, 1986]. The solar flux data are based on the plot in *Naito and Hirota* [1997].

2. QBO Composites

[5] HT80 divided the winter season into ‘‘early winter’’ (November–December, ND) and ‘‘late winter’’ (January–March, JFM). Using 16-year NMC data, they composited amplitudes of wavenumber 1 and 2 in the two categories according to the phase of the equatorial QBO, as measured by the sign of the mean zonal wind at 50 mb at Balboa, Canal zone (9°N). They found that in early winter, wavenumber 1 amplitude at 50 mb is about 40% greater in the easterly category than in the westerly category, with statistical significance of 99% in a student t-test. After adding up 6 more years, they found that the difference of wavenumber 1 amplitude between the two categories increased to 50%, with significance of 99.9%.

[6] We have repeated the HT80 calculation using 49-year NCEP/NCAR reanalysis data. The phase of the equatorial QBO is defined the same way at 50 mb, but using Singapore winds [*Naujokat*, 1986]. Figures 1a and b show the results for wavenumber 1. Consistent with the finding of HT80, the composite amplitude of wavenumber 1 at 50 mb is larger, by about 20%, in early winter (Figure 1a) when the QBO phase is easterly, at significance level of about 97%. In late winter, the difference of wavenumber-1 amplitudes between the two QBO phases is not statistically significant (Figure 1b), which is also consistent with HT80.

[7] HT80 found that in later winter wavenumber-2 composite amplitude was about 60% stronger during the westerly phase of the equatorial QBO, with significance of 96%. However, when four additional years were added to the sample, they found that the significance level dropped to about 90%. They suspected that the wavenumber-2 signal might be a result of sampling fluctuations, and suggested that a substantially longer time series may be required for a definitive answer. Our result for wavenumber 2 using the 49-year data is presented in Figures 1c and d. In both early and late winter, the differences of wavenumber-2 amplitude at 50 mb between the two QBO phases are too small to be statistically significant, consistent with HT80’s conjecture. For the 16-year data used by HT80, three of the 8 years in their easterly category (1966, 1971, 1977) had anomalously small amplitudes of wavenumber 2 in late winter. It is these extremely small amplitudes which lead to the much smaller composite wavenumber-2 amplitude of the

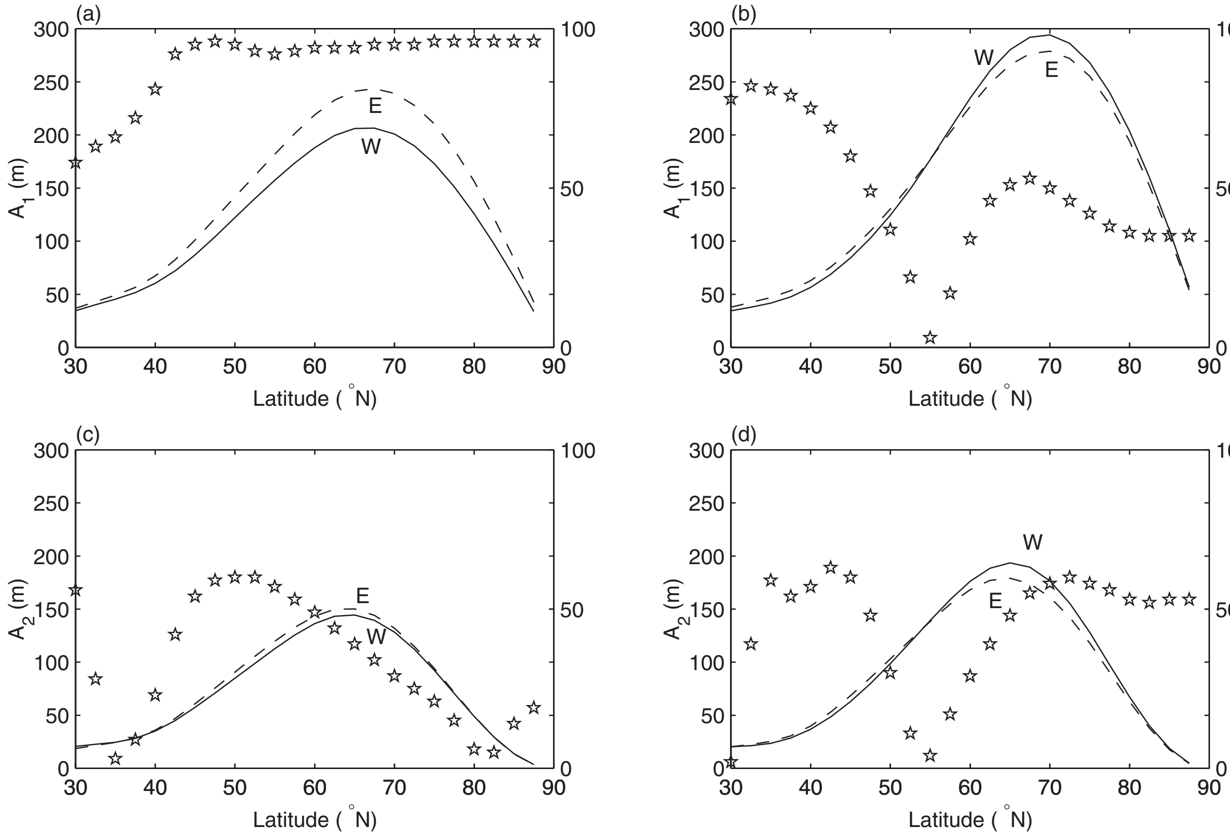

Figure 1. Meridional profiles of wavenumber-1 and 2 amplitudes at 50 mb. W (solid-line) and E (dashed-line) indicate HT80's westerly and easterly categories, respectively. Significance (%) of student's t-test, marked by ☆, is scaled on the right-hand-side vertical axis. (a) November–December (ND) mean, wavenumber 1, (b) January–March (JFM) mean, wavenumber 1, (c) ND mean, wavenumber 2, and (d) JFM mean, wavenumber 2.

easterly category when compared to that of the westerly category. Such occurrences are rare in our 49-year time series.

[8] *Naito and Hirota* [1997] argued that the equatorial QBO modulation on wavenumber-2 amplitude could be uncovered when the solar cycle effect was included. They found that for their MIN solar flux group (solar 10.7-cm flux less than $120 \times 10^{-22} Wm^{-2}Hz^{-1}$) wavenumber-2 amplitude is significantly larger in early winter when the QBO wind is easterly, while in late winter the amplitude is larger when the QBO wind is in the opposite direction (see their Table 1). *Dunkerton and Baldwin* [1992] also found that the modulation of QBO influence by the solar cycle is prominent in late winter (February only). The Naito and Hirota's late winter results can be reproduced using NCEP/NCAR data for the same 37 years as theirs (Figure 2a). However, the difference of wavenumber-2 amplitude becomes not significant when the longer-time series (1953–2001) is used (Figure 2b). This is probably because their 37-year series is not sufficiently long. According

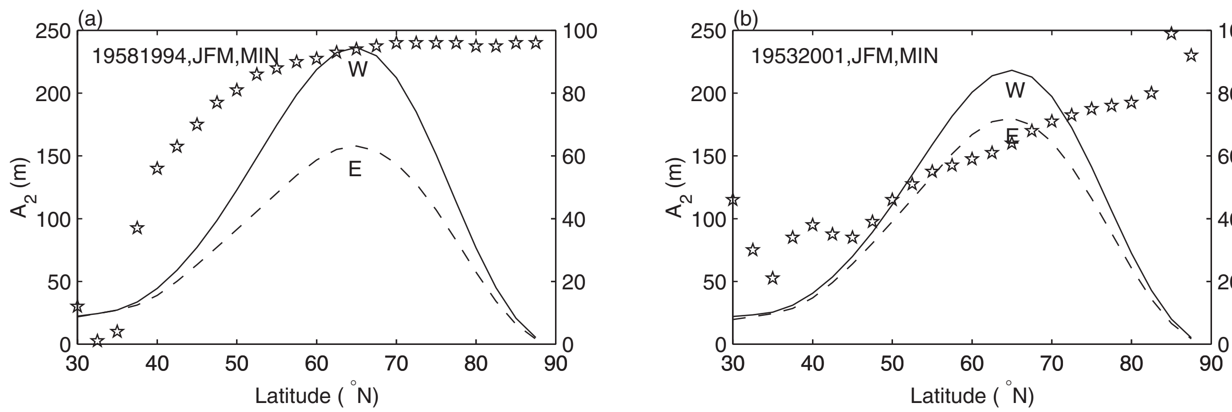

Figure 2. JFM mean meridional profiles of wavenumber-2 amplitudes at 50 mb for Naito and Hirota's MIN solar flux group. (a) Naito and Hirota's period (1958–1994), (b) 1953–2001.

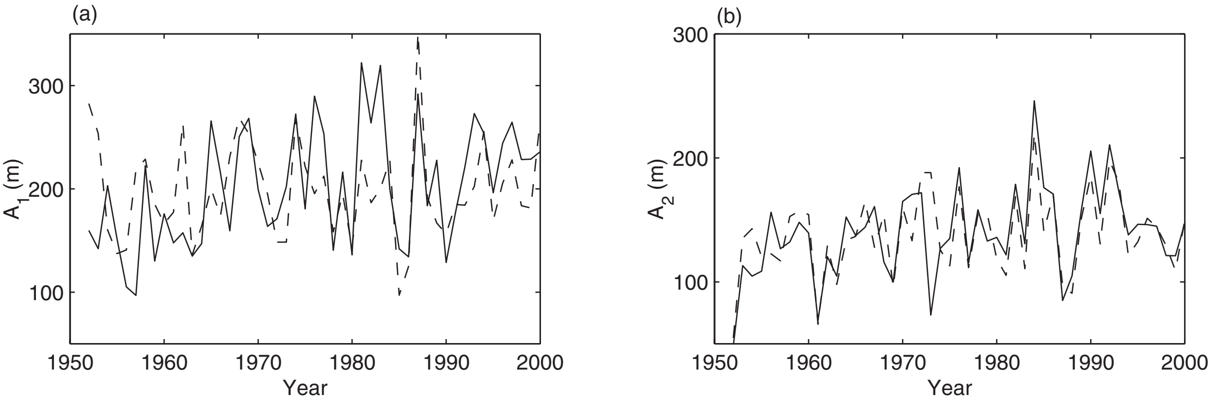

Figure 3. ND mean amplitudes at 60°N vs. years at 50mb (solid-line) and 150 mb (dashed-line). (a) Wavenumber 1, (b) wavenumber 2. In (a) and (b) wave amplitudes at 150 mb are multiplied by 1.5 and 1.1, respectively, for ease of comparison with wave amplitudes at 50mb.

to Naito and Hirota's classification at 50 mb, each of their four groups includes a very small number of years. For example, there were only 6 of their 37-years that belong to the group of "early winter, minimum solar flux, and easterly QBO phase".

3. Tropospheric Influence

[9] The composites in the previous section were done without regard to tropospheric forcing. To identify the influence from tropospheric forcing, we evaluate vertical correlations of wave amplitudes between 150 and 50 mb.

[10] Figure 3a shows wavenumber-1 amplitudes at 150 and 50 mb at 60°N, averaged over ND, as a function of years. The correlation coefficient of the time series between the two levels is about 0.47, at 99.9% significance level. This modest correlation implies that there still exists room for other factors, such as the equatorial QBO, to modify its amplitude during its upward propagation from the tropopause to 50 mb.

[11] One may inquire whether the significant QBO difference of the composite wavenumber-1 amplitudes at 50 mb in early winter arises from such amplitude difference at 150 mb. To clarify this, we calculate composite wavenumber-1 amplitudes at 60°N at 150 mb, yielding 136 and 129 meters for the easterly and westerly categories, respectively. The difference between them is not significant (at 43% significance level). Therefore, the significant difference of wavenumber-1 amplitude at 50 mb is not due to tropospheric forcing or to the QBO modulation on tropospheric forcing. Moreover, we have also calculated the ratio of wavenumber-1 amplitudes between 50 and 150 mb. The ratio is $221/136 \approx 1.63$ and $187/129 \approx 1.45$ for the easterly and westerly categories, respectively. This means that during its upward propagation from 150 mb to 50 mb wavenumber-1 amplitude grows faster when the QBO wind is easterly.

[12] The situation for wavenumber 2 is different. Figure 3b shows that ND mean wavenumber-2 amplitude at 150 and 50 mb are strongly correlated, with a correlation coefficient of about 0.75. Therefore, wavenumber 2 is mainly determined by tropospheric forcing. The composite amplitudes at 150 mb are 134 and 119 meters for the two QBO categories. The difference is not significant (at 93% significance level). The amplitude ratios between 50 and 150 mb: $147/134 \approx 1.10$ and $133/119 \approx 1.12$ for the easterly and westerly categories, respectively, are almost identical. The growth of wavenumber-2 amplitude is not affected by the QBO phase during its upward propagation from the troposphere to stratosphere.

[13] It can be seen from Figure 3 that the ND-mean amplitude of wavenumber 2 does not grow as much as wavenumber 1 as it propagates upward from 150 mb to 50 mb. It appears that, at least for the two-month mean, wavenumber 2 is reflected more than wavenumber 1 during its upward propagation. This may explain why wavenumber 2 is not modulated by the equatorial QBO in a significant way, and also why wavenumber 2 is so vertically coherent.

[14] For late winter (JFM, figures not shown), the vertical correlation for wavenumber-1 amplitude is about 0.29, at 97.5% significance level, smaller than that in early winter. Note that this weaker correlation is not a result of a stronger QBO modulation in late winter. The vertical correlation of wavenumber-2 is about 0.94, which is larger than in early winter. This again implies that wavenumber-2 amplitude in the stratosphere is determined by tropospheric forcing, and that the equatorial QBO has little effect on wavenumber-2 amplitude.

4. Conclusions

[15] We have re-examined the influences of the QBO and troposphere on the extratropical planetary-wave amplitudes in the lower stratosphere using 49-year NCEP/NCAR reanalysis data. Our findings are: (1) For both early and late winter, wavenumber-2 amplitude in the stratosphere is mainly determined by tropospheric forcing, and is little affected by the equatorial QBO. The solar cycle effect on wavenumber-2 amplitude was also found to be not significant. (2) The equatorial QBO has statistically significant modulation on wavenumber-1 amplitude in early winter, and the amplitude is generally about 20% larger when the QBO wind is easterly. In late winter, the QBO modulation is not significant. Both results are consistent with HT80.

[16] It appears likely that the Holton-Tan mechanism is applicable only in early winter. In late winter, the westerly waveguide configuration is altered drastically by the occurrence of major sudden warmings, which may overwhelm the QBO influence. As a result, the difference of wavenumber-1 amplitudes between QBO phases becomes not significant.

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