Sensitivity of the boreal winter circulation in the middle atmosphere to the quasi-biennial oscillation in MAECHAM5 simulations

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[1] The polar vortex in the Northern Hemisphere exhibits high intraseasonal and interannual variability which, to some degree, may be controlled by the quasi-biennial oscillation (QBO) in the tropical stratosphere. Here we analyze the QBO signal in the Northern Hemisphere polar vortex in a model simulation using the general circulation model MAECHAM5 (Middle Atmosphere European Center Hamburg Model), which simulates the QBO as an internal mode of variability. Composites have been computed for the westerly and easterly QBO phases from early winter to late winter (November–December, December–January and January–February) of a 50-year experiment containing 20 complete QBO cycles. This method identifies tropical and midlatitude patterns in wind and temperature that are related to the secondary meridional circulation of the QBO extending towards the winter pole. In the tropics, significant QBO signature is observed in the mesosphere up to 0.05 hPa only in early winter and mainly in the easterly QBO phase forced by the parameterized gravity waves-mean flow interaction. At high latitudes, MAECHAM5 shows a significantly warmer (colder) polar stratosphere in the easterly (westerly) QBO phase at 30 hPa accompanied by a weaker (stronger) polar vortex in the late winter months, from December to February (December to January) in the easterly (westerly) phase of the QBO. In early winter there is no significant change in temperature and zonal mean zonal wind in the polar stratosphere. The analysis of EP fluxes shows a different behavior between QBO phases, with changes in the waveguide. Wave propagation occurs upwards and polewards in the easterly QBO phase at 30 hPa, while waves are refracted equatorward in the westerly phase. No relationship has been found between the tropical QBO and the final warming at the end of the boreal winter.

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1. Introduction

[2] The QBO signature in zonal-mean zonal wind and temperature in the tropical stratosphere has been widely analyzed using different data sets such as rawinsonde observations and satellite measurements [*Angell and Korshover*, 1962; *Hamilton*, 1984; *Dunkerton and Delisi*, 1985; *Naujokat*, 1986; *Ortland et al.*, 1996]. In the extra-tropics, strong evidence that the QBO influences the extra-tropical northern stratosphere was presented first by *Holton and Tan* [1980, 1982]. Following works found a strong relation to the 11-year solar cycle during January and February, suggesting that solar influence modifies the QBO signal during late winter and *Naito and Hirota* [1997] confirmed these findings and showed that a robust QBO signal is also present during November and December. Nevertheless, the high natural variability in relation to the few decades of observations makes it difficult to identify significant QBO signals in wind, temperature or geopotential [*Holton and Tan*, 1980; *van Loon and Labitzke*, 1987] (discussion in *Baldwin et al.* [2001]). Further, the QBO is only a minor contributor to the extratropical variability that evolves due to internal dynamics of the atmosphere and perturbations by El Nino [*Calvo et al.*, 2004; *Garcia-Herrera et al.*, 2006], the 11 year solar cycle [*Labitzke*, 1987; *Labitzke and van Loon*, 1988; *Gray et al.*, 2004; *Labitzke*, 2005] or volcanic eruptions [*Barnes and Hofman*, 1997, 2001]. The detection of QBO signals in observations or analyses therefore is difficult. Thus, using numerical experiments is a useful method that allows separating some of the complications in the observations. In this sense, works by *Gray et al.* [2004], *Pascoe et al.* [2006], and *Naito and Yoden* [2006] have investigated the effects of the QBO on polar latitudes using GCMs and the results did show variations in the behavior of the polar vortex in relation to the equatorial winds. However, these models impose a QBO from artificial momentum forcings and are run for perpetual winter conditions. Prescribed QBO structures are typically simplified, neglecting for example sea-

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Table 1. Winters (November–December) Selected to Compute the Composites for the Westerly and Easterly QBO Phases in MAECHAM5 Experiment

	Year
QBO/W	1981, 1984, 1986, 1991, 1996, 1998, 2003, 2008, 2010, 2013, 2015, 2018, 2023, 2025
QBO/E	1980, 1985, 1987, 1990, 1992, 1995, 1997, 1999, 2002, 2004, 2009, 2014, 2016, 2019, 2022, 2024

sonal modifications of the QBO. *Niwano and Takahashi* [1998] did internally generate a QBO in their model and found differences between QBO phases at polar latitudes. However, the QBO in their model showed relevant deficiencies such as a too short period and a high asymmetry between west and east QBO phases.

[3] The general circulation model MAECHAM5 is able to simulate internally a realistic QBO in the tropical stratosphere by internal resolved and parameterized wave mean-flow interaction [*Giorgetta et al.*, 2002, 2006]. Here, we analyze climate simulations of MAECHAM5 with the aim to identify anomalies in the extratropical circulation in winter in relation to the QBO cycle. Therefore, we will study the QBO signature focusing on middle and high latitudes in the Northern Hemisphere at different winter periods from early to late winter and we will extend the vertical domain of previous analyses up to the mesosphere. The MAECHAM5 experiment will allow us to isolate the QBO signature from other sources of variability in the stratosphere in extratropics, which facilitates its study.

[4] The paper is arranged as follows: section 2 gives a short description of the model and the experiment together with the methodology that has been followed. The QBO signature is described in section 3, section 4 analyzes the QBO forcing in the lower mesosphere while section 5 studies the wave-mean flow interaction at middle and high latitudes. Section 6 summarizes the main conclusions.

2. Data and Methodology

2.1. MAECHAM5

[5] The Middle Atmosphere configuration of the ECHAM5 model (MAECHAM5) has been used in this work. Detailed descriptions of ECHAM5 and MAECHAM5 are found in *Roeckner et al.* [2003] and *Manzini et al.* [2006], respectively. MAECHAM5 has been run in two different vertical resolutions and several boundary conditions. The experiment employed in this study spans up to 0.01 hPa (or about 80 km) in the vertical domain, with 90 vertical levels. In the stratosphere, the vertical resolution is approximately 700 m between the tropopause and 42 km height, and better than 1 km up to the stratopause [*Giorgetta et al.*, 2006, Figure 1]. The horizontal resolution is T42 with 128 $\times$ 64 grid points (longitude versus latitude). Sea surface temperature (SST) and sea ice distribution are prescribed as lower boundary conditions following the monthly mean climatology of the period 1979–1996 (AMIP2 data set), so that direct El Niño or La Niña influences are excluded. The simulation using the SST and ice climatology was integrated over 50 years, labeled as years 1978 to 2027. This experiment excludes any external interannual forcing as for example effects of the 11-year solar cycle or volcanic eruptions. By construction, interannual variability in the simulated circulation can only be explained by internal variability including the QBO, which is the most important interannual oscillatory mode of the model system.

2.2. Composites

[6] Monthly-mean data from 1979 to 2027 have been composed for westerly and easterly phases of the QBO in three different winter periods, early winter (November–December, ND), middle winter (December–January, DJ) and late winter (January–February, JF). The first year of the experiment has been disregarded. To compute the composites, the QBO index at 30 hPa has been used as a previous analysis (not shown) revealed that the most intense response of the extratropical winter stratosphere to the QBO in MAECHAM5 was observed when using that level. Although the zonal wind at Singapore has typically been used as the QBO index, we have employed the zonal-mean zonal wind as it shows high zonal symmetry at 30 hPa.

[7] A full early winter November–December was merged into the QBO/W (or QBO/E) phase whenever November or the November–December average of the equatorial zonal mean zonal wind at 30 hPa is higher (lower) than 10 m/s (-10 m/s). Positive values indicate westerly winds. The composite for each QBO phase has been computed as the average of all winter months included in each group. The following January and February months have been used to compute the composites for middle and late winter. We have used composites in early winter (ND) as a reference for the QBO phase since previous studies showed that the midlatitude and high latitude atmosphere seems to be more sensitive to the QBO in that period [*Labitzke*, 1987; *Dunkerton and Baldwin*, 1992; *Baldwin and O'Sullivan*, 1995; *Naito and Hirota*, 1997]. Table 1 shows the selected winters for each QBO phase.

[8] When necessary, the significance of the signal related to the QBO has been tested by a Monte-Carlo method. With this aim, composites have been computed using random ND, DJ or JF sequences from the whole data series from 1979 to 2027 and gathering them into groups with the same number of winters as in the QBO composite we want to test. Then, the composites are computed taking the values in early, middle or late winter of those years. This procedure has been repeated 1000 times and the leading random distribution plotted. A preliminary analysis revealed that 1000 times was enough to estimate the distribution of probability properly. The sample follows a normal distribution and so, the threshold above or below which the values in the QBO composites are considered 95% significant lies at the 5% tails ($\pm$1.96 standard deviation from the mean) in the Monte-Carlo distribution.

2.3. ERA-40

[9] In some cases, monthly mean data from ERA-40 reanalysis [*Simmons and Gibson*, 2000] for the period 1958–2000 have been composed with respect to the QBO phase to compare with composites from MAECHAM5. Due to the high asymmetry observed in the QBO index at 30 hPa in ERA-40 data, ND months have been included in the QBO/W (QBO/E) phase whenever the equatorial zonal

Table 2. As in Table 1 to Compute the Composites for ERA-40 Data From 1958 to 2000

	Year
QBO/W	1959, 1961, 1963, 1966, 1971, 1975, 1977, 1980, 1982, 1985, 1987, 1990, 1992, 1994
QBO/E	1958, 1962, 1965, 1970, 1972, 1974, 1976, 1979, 1981, 1983, 1986, 1989, 1991, 1996

mean zonal winds in November or in the ND average are above (below) 5 m/s (−15 m/s) which is different from the criteria chose to compute the composites in the GCM. Table 2 shows the years selected in this fashion to compute the composites.

3. QBO Signature

3.1. QBO Signal in the Zonal-Mean Zonal Wind

[10] Figure 1 shows the composites of the zonal-mean zonal wind U in ND, DJ and JF computed as explained in section 2 for the westerly and easterly QBO phases at 30 hPa. The alternation of up to five regions with westerly and easterly winds is observed in the equatorial atmosphere, with a clear presence of the QBO in the equatorial stratosphere throughout the winter. The main difference from early to late winter in tropics lay in the QBO westerly jet observed in the tropical stratopause in the westerly phase of the QBO. It extends without zero wind line to the winter hemisphere westerly jet, gets weaker in DJ and even disappear in JF in the QBO/W. In the extratropics, the patterns show westerly winds in the winter hemisphere and easterlies in the summer hemisphere above 40 hPa. The evolution and extension of the extratropical winter jet towards higher latitudes and lower altitudes reported elsewhere [e.g., *Kuroda and Kodera*, 1999; *Kodera and Kuroda*, 2002] is also observed in both QBO phases. The climatology of the simulated zonal mean zonal wind in winter months is compared with ERA-40 data in *Giorgetta et al.* [2006].

[11] Figure 2 shows the same composites for the zonal-mean zonal wind anomalies U′ with respect to the model climatology for each period (ND, DJ, JF) in zonal-mean zonal wind U_c. Light and dark shading show the 95% significant positive and negative anomalies according to the Monte-Carlo test explained above. The anomalies cleary show the domain of the QBO with vertically propagating jets of significant amplitude in the equatorial stratosphere, and related signals outside of this domain.

[12] In the lower and middle stratosphere in early winter (ND), anomalous significant westerly (easterly) winds are located between 50 and 10 hPa, with easterlies (westerlies)

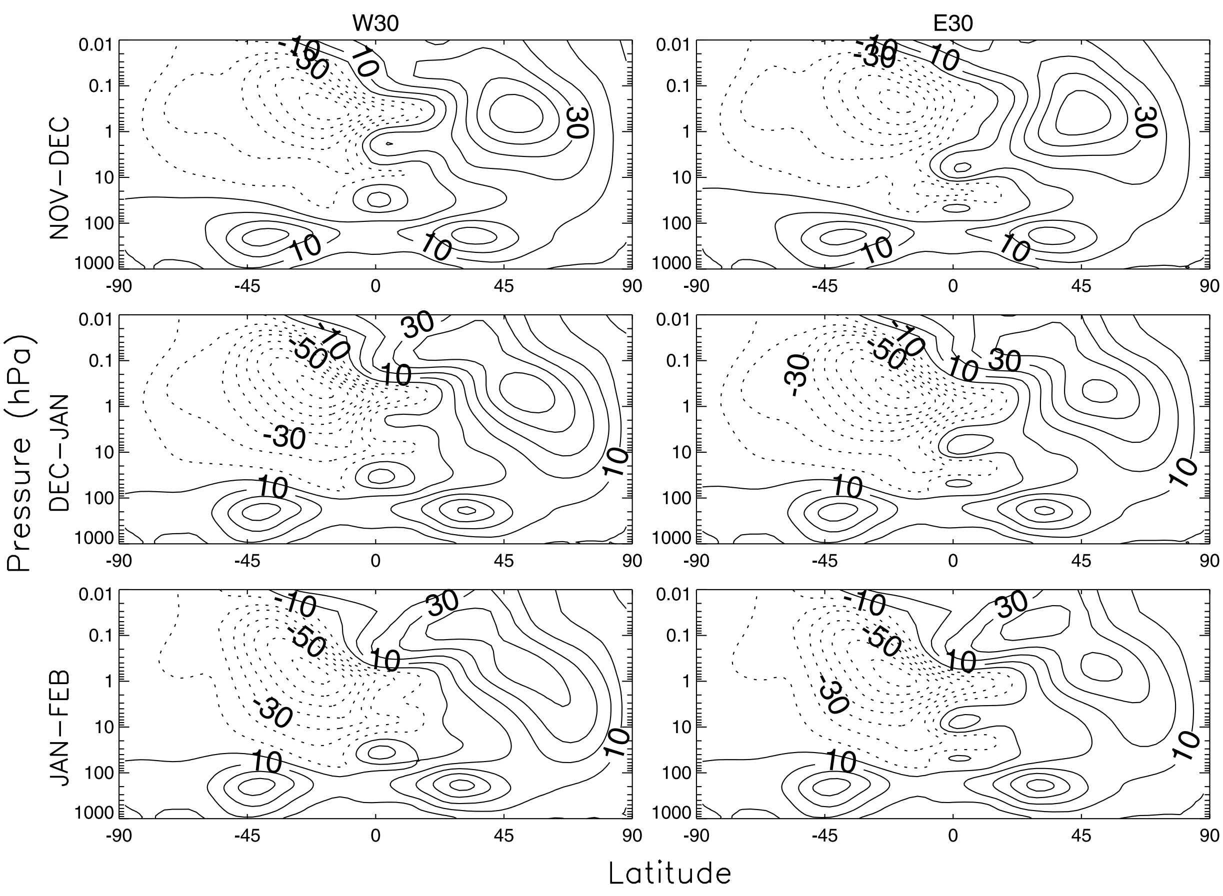

Figure 1. Composites of the zonal mean zonal wind with respect to the westerly phase (left) and easterly phase (right) of the QBO for November–December (above), December–January (middle) and January–February (below) from MAECHAM5 experiment. Contours are drawn every 10 m/s. Solid (dotted) for westerly (easterly) wind anomalies.

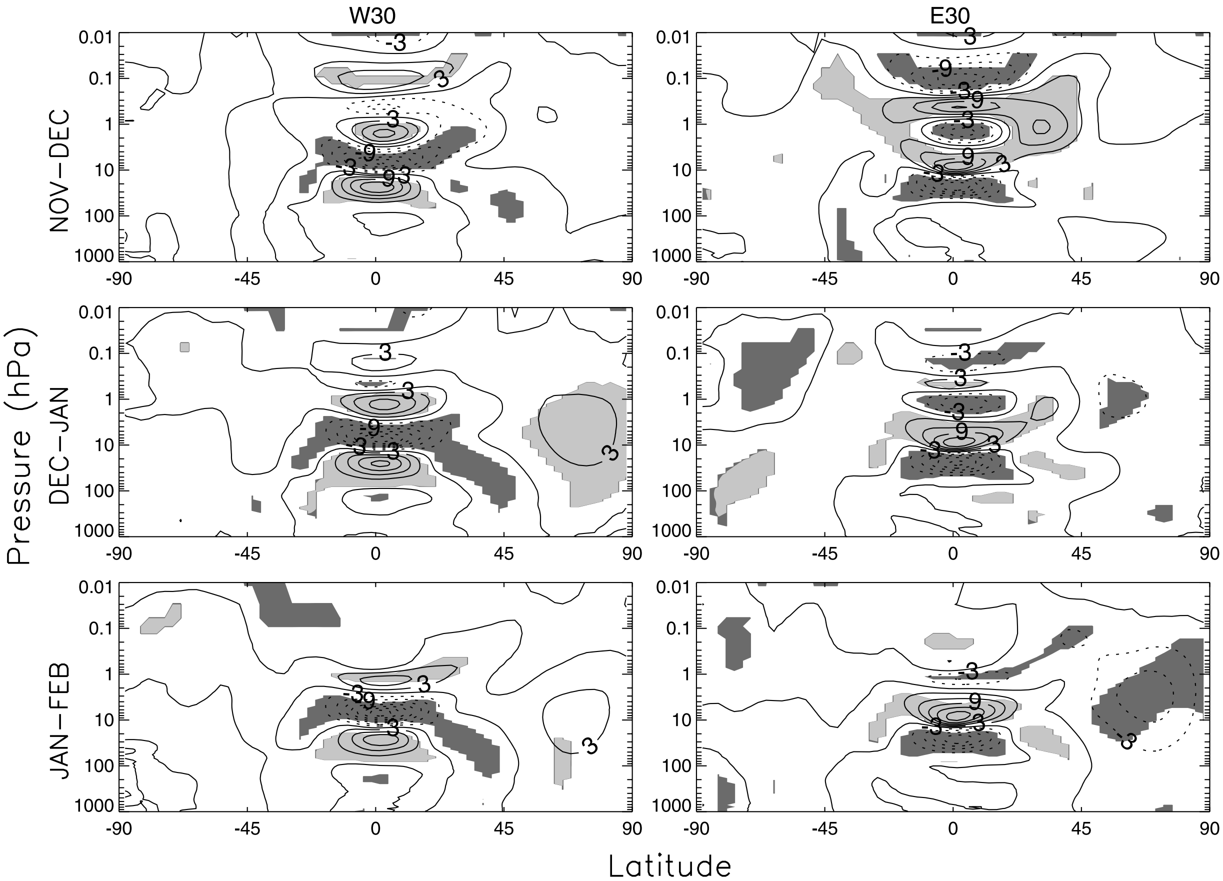

Figure 2. Composites of the zonal mean zonal wind anomalies with respect to the westerly phase (left) and easterly phase (right) of the QBO for November–December (above), December–January (middle) and January–February (below) from MAECHAM5 experiment. Shadowed regions indicate statistical significant anomalies at 95% confidence level. Light (dark) gray for westerly (easterly) significant values. Contours are drawn every 3 m/s.

between 10 and 3 hPa during the QBO/W (QBO/E) phase. Above them, a third cell with westerlies (easterlies) is located between 3 and 1 hPa. Maximum values are about 15 m/s in the first two regions and about 6 m/s in the third one. Two more equatorial zonal wind anomalies are observed in the lower mesosphere. Easterly (westerly) anomalies are found at QBO/W (QBO/E) between 0.7 and 0.3 hPa and westerly anomalies above them from 0.3 to around 0.05 hPa. Contrary to the QBO signature in the stratosphere, relevant differences are found between phases apart from the change of sign. Both jets show significant anomalies in the easterly phase with largest values of 12 m/s while only the uppermost is significant in the westerly phase and values do not go beyond 6 m/s. As winter evolves, the significant signal observed in the lower mesosphere weakens. In late winter, JF, hardly any significant anomaly is observed above 1 hPa. Therefore, the tropical mesosphere seems to be susceptible to QBO perturbations in early winter but not in late winter, and mainly in the easterly phase of the QBO. An extended analysis and discussion of the QBO signal in the lower mesosphere will be done in section 4.1.

[13] Outside the tropics, the anomalies U′ extend to the subtropics in the Northern Hemisphere up to about 40°N. They span upwards in ND, from about 3 to 1 hPa (0.2 hPa) in the westerly (easterly) QBO phase and downwards in DJ and JF, between 100 and 10 hPa. At high latitudes, westerly significant anomalies about 3 m/s are observed in DJ from 12 to 1 hPa in the westerly QBO phase. In the easterly QBO phase, easterly significant anomalies and thus, a weaker polar vortex, is observed in DJ and JF evolving from higher heights and lower latitudes (about 1 hPa and 55°N) in DJ to a wider region from 10 to 1 hPa at higher latitudes in agreement with the displacement of the polar vortex anomalies in winter [*Kuroda and Kodera*, 1999; *Kodera and Kuroda*, 2002]. Maximum anomalies are above 6 m/s.

[14] This anomalous pattern is consistent with works by *Holton and Tan* [1980, 1982], who found weaker (stronger) winds in the polar night jet during the easterly (westerly) phase of the QBO at 50 hPa., *Dunkerton and Baldwin* [1991] and *Baldwin et al.* [2001]. So, the amplitude in U′ is similar to that found, for example, by *Dunkerton and Baldwin* [1991] or *Hamilton* [1998] for DJF in observations and in experiments with artificially forced QBO jets respectively. The QBO signature in zonal mean zonal wind in MAECHAM5 has also been compared with results from the ERA-40 reanalysis [*Simmons and Gibson*, 2000]. Figure 3 shows the composites of U′ computed in the same fashion as in Figure 2 with ERA-40 data from 1958 to 2000. The vertical height in ERA-40 allows the comparison with

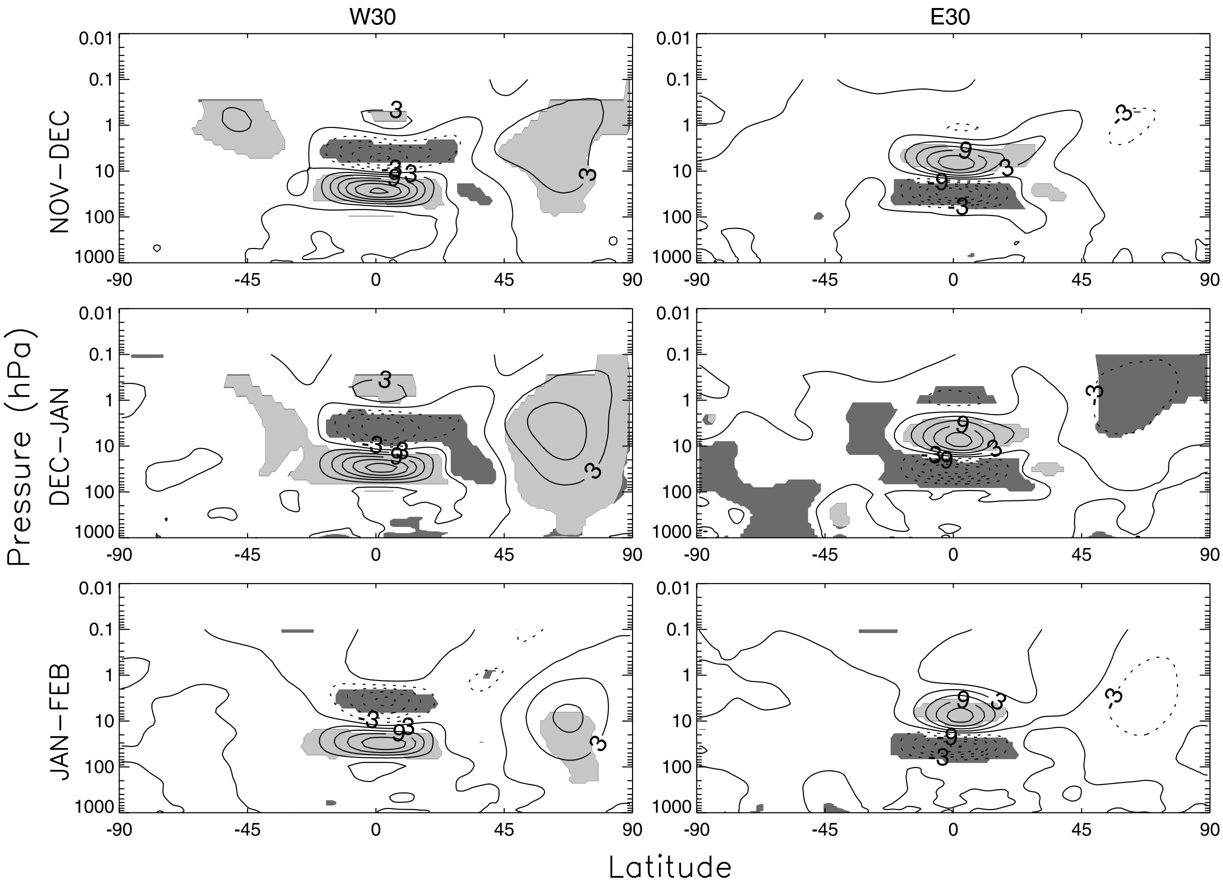

Figure 3. As in Figure 2 for zonal mean zonal wind anomalies from ERA-40 data for the period 1958–2000.

MAECHAM5 results below 1 hPa. In the tropical stratosphere, the three-fold structure clearly observed in the model agrees well with that obtained from ERA-40 data as in works by *Gray et al.* [2004]; and *Pascoe et al.* [2005], although slightly larger anomalies are observed in ERA-40. A detailed comparison between winds in MAECHAM5 and ERA-40 in this region was discussed by *Giorgetta et al.* [2006]. In extratropics, the intensification (weakening) of the polar vortex observed in QBO/W (QBO/E) in MAECHAM5 results is also seen in ERA-40 data; however, the timing and intensity vary. So, the anomalous acceleration of the polar vortex during QBO/W is more intense in ERA-40 and takes longer than in MAECHAM5, significant signal is observed throughout the winter. On the contrary, the weakening observed in QBO/E is not so intense as in the model and occurs only in DJ in ERA-40 while it is observed from DJ to JF in the model.

[15] Therefore, the comparison between MAECHAM5 and ERA-40 results show an overall agreement. However, some differences appear and in this sense, we should bear in mind that a direct comparison between the model and reanalysis is complicated. The analyzed periods are different; the QBO cycles differ as well as the relative phases of QBO an annual cycle. In additon, ERA-40 includes additional sources of variability such as volcanoes or ENSO present in the real atmosphere but not included in the experiment used from MAECHAM5. These other phenomena also have an effect on the stratospheric circulation and make more difficult to compare the QBO signal mainly in extratropics where the QBO is not the main source of variability. In any case, the QBO signal at high latitudes will be analyzed in depth in section 4.2.

3.2. QBO Signal in the Zonal-Mean Temperature and the Secondary Meridional Circulation

[16] The anomalous positive or negative wind shear originated in the tropics as a result of the QBO generates anomalies in temperature at those latitudes [*Randel et al.*, 1999]. Figure 4 shows the composites of the zonal-mean temperature anomalies T’ for ND, DJ and JF for the westerly and easterly QBO phases. Light and dark shading display 95% significant anomalies according to a Monte-Carlo test.

[17] In the tropics, alternating regions with positive and negative anomalies are observed in the tropics in both QBO phases and correspond well with the regions of positive and negative vertical wind shear observed in Figure 2. The latitudinal width of the cells seems to increase with height, from 10°S to 10°N in the stratosphere to 15°S to 15°N in the lower mesosphere. The largest anomalies reach values up to 1.5 K in QBO/W and 2 K in QBO/E in the stratosphere while larger maximum values are observed in the lower mesosphere (2 K in the QBO/W and 3 K in the QBO/E). As in the U' anomalies, the descending of the anomalies from early to late winter is well reproduced in both phases. In the lower mesosphere, the largest significant signal occurs in ND, decreases in DJ and almost disappears in JF.

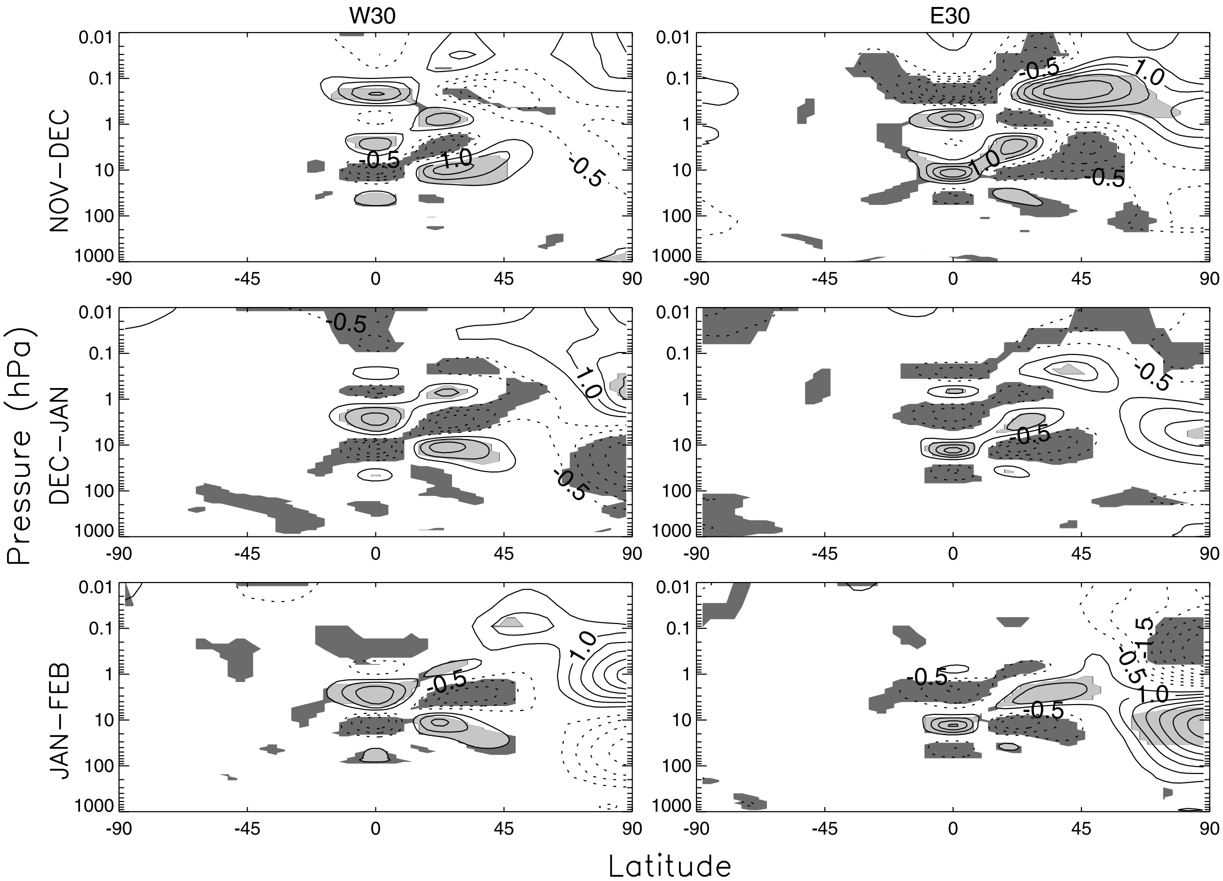

Figure 4. As in Figure 2 for zonal mean temperature anomalies. Contours are drawn every 0.5K. Light (dark) gray for positive (negative) significant anomalies.

[18] The anomalies observed in the equatorial region have their counterpart anomalies in the subtropics in the Northern Hemisphere, resulting from the secondary circulation of the QBO that extends northward in this season. The QBO signature shows again significant regions with alternating negative and positive signs up to the lower mesosphere in ND and up to the stratopause in JF. Hence, at 40°N, the vertical profile of temperature anomalies is dominated by these major signals of opposite sign, which have here much larger vertical scales than the QBO jets at the equator. The out-of-phase behavior in the tropical region is a robust feature of the QBO signature and the model results are in good agreement with those from UKMO stratospheric assimilation data [*Randel et al.*, 1999] and NCEP-NCAR reanalysis studies from 200 to 10 hPa [*Ribera et al.*, 2004].

[19] Besides the anomalies in the tropical and subtropical region, QBO related temperature anomalies T' are observed at high latitudes in the Northern Hemisphere. In the westerly phase of the QBO, cold anomalies are observed at polar latitudes throughout the winter but are significant only in DJ over a region located between 100 and 10 hPa. Maximum values are above 2 K. In the easterly phase, warm anomalies related to a weaker polar vortex are observed, being significant also in DJ but mostly in JF where the largest values go beyond 3.5 K. An anomalous significant cooling is also observed around 1 hPa forming a dipolar structure, as required by dynamics. The descending of the anomalies in the polar region from early winter to late winter is clearly seen as it is the displacement of the largest anomalies from middle latitudes in ND to high latitudes in DJ and JF.

[20] Figure 5 shows the composite of zonal mean temperature anomalies from ERA-40 data from 1958 to 2000. In the tropics, the agreement is very good up to 10 hPa with slightly larger anomalies in ERA-40 in the lower stratosphere as discussed by *Giorgetta et al.* [2006] for the deseasonalized temperature signals of the QBO. At high latitudes, during the QBO/W, anomalous cooling is significant in DJ between 100 and 10 hPa as observed in MAECHAM5. The cooling is still significant in JF but over a smaller region. The maximum anomalies are about 3 K, 1 K larger than in the model. Above the cooling, an anomalous warming is observed centered at 1 hPa. In the QBO/E, the anomalous significant warming is observed in both the model and reanalysis with about the same amplitude, maximum of 3.5 K. However, it appears earlier than in the model (DJ instead of JF), and at higher heights, between 10 and 1 hPa as occurred in zonal mean zonal wind anomalies (Figure 3). The top of the reanalysis does not allow to see any significant cooling above it. Thus, it seems that the extratropical response to the easterly phase of the QBO is observed slightly later in the model than in the reanalysis, while in QBO/W the anomalous cooling observed in the polar stratosphere is more intense in ERA-40 than in MAECHAM5. MAECHAM5 results are also in good agreement with other studies as *Dunkerton and Baldwin* [1991], who found differences up to 6 K between

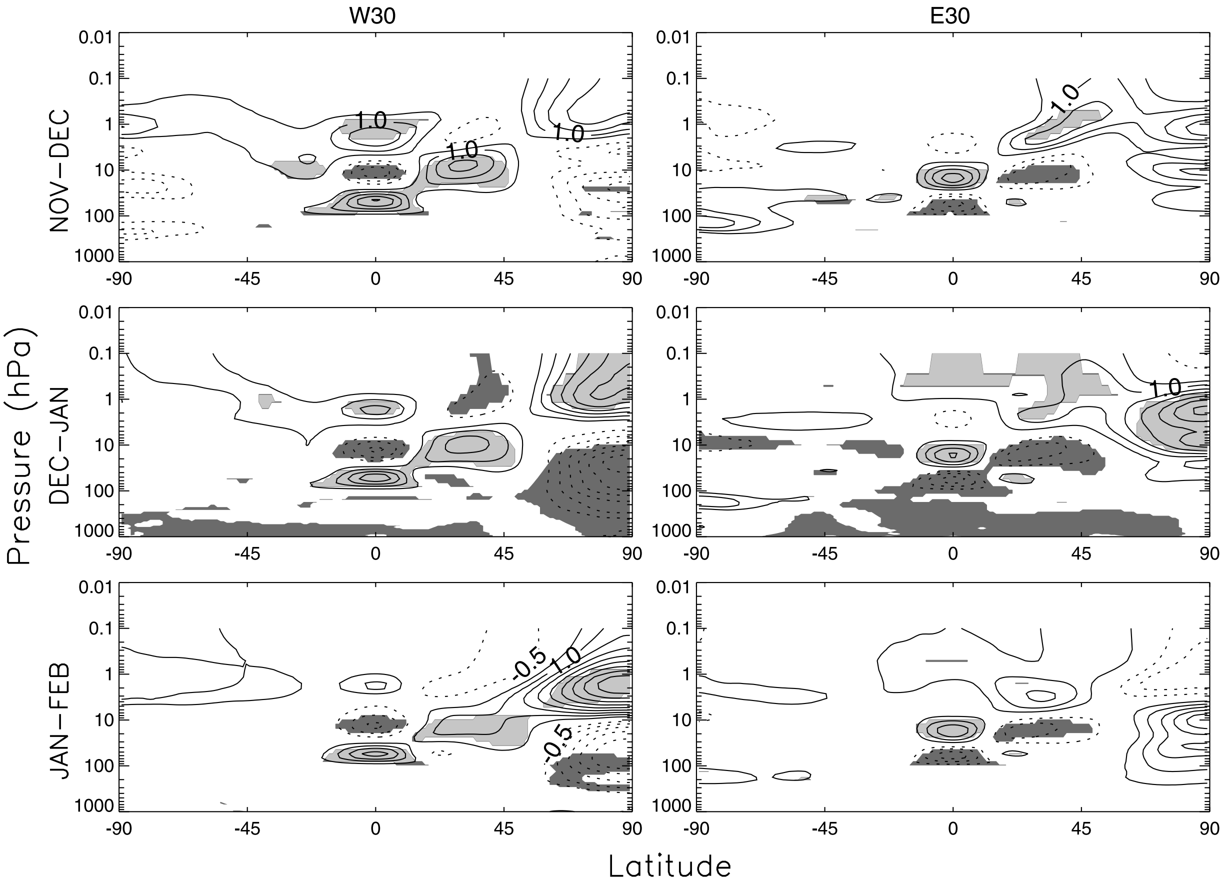

Figure 5. As in Figure 4 for zonal mean temperature anomalies from ERA-40 data for the period 1958–2000.

easterly and westerly QBO phases in DJF in the North Pole using National Meteorological Center data (NMC), which is comparable with our 5.5 K in MAECHAM5 computed as the difference between QBO/E and QBO/W in JF and DJ, respectively.

[21] The anomalies in wind and temperature observed in the tropical and subtropical region show the behavior of the mean meridional circulation of the middle atmosphere modified by the secondary meridional circulation of the QBO. This circulation is characterized by sinking (rising) motion anomalies at the equator in westerly (easterly) shear zones accompanied by a maximum (minimum) in temperature in this region to maintain the thermal wind balance [*Plumb and Bell*, 1982; *Randel et al.*, 1999; *Baldwin et al.*, 2001; *Ribera et al.*, 2004]. In addition, out-of-phase anomalies occur in the subtropics related to the return branches of the secondary meridional circulation of the QBO.

[22] Residual circulation anomalies have been studied by compositing the anomalies in mass stream function based on the transformed Eulerian mean velocities v* and w* for ND, DJ and JF in westerly and easterly QBO phases (Figure 6). Light and dark shading denote clockwise and anti-clockwise circulation respectively. In the tropical region, five closed circulation cells are observed in early winter (ND) from 100 to 0.1 hPa while the uppermost cell disappears in late winter (DJ). The descending of the anomalies is observed from early to late winter, except for the uppermost mesospheric cell that is not observed in JF. The largest anomalies are observed in the second and third cells located between 12 and 1 hPa, which corresponds with the largest significant anomalies in temperature (see Figure 4). So, for instance, the second cell in QBO/W (about 10 hPa) shows rising in tropics and sinking in subtropics and is accompanied by anomalous cooling at the equator and anomalous warming at subtropics. The opposite occurs in QBO/E. Unlike to the equinox seasons, the solstice season, in particular in boreal winter, shows tropical circulation cells extending predominantly to the winter hemisphere. The intensity of the upper cells is stronger in the easterly phase, again in good agreement with the distribution of significant anomalies in zonal wind and temperature. As expected, the location and signs of these anomalous cells are totally consistent with the anomalies in zonal-mean zonal wind and temperature observed in Figures 2 and 4 in the tropical region and evidence the modulation of the mean meridional circulation by the QBO.

[23] Outside the tropics, Figure 6 shows anomalies in the circulation in the Northern Hemisphere middle upper stratosphere at high latitudes that corresponds with the descending branch of the mean meridional circulation towards the boreal hemisphere. While in the westerly phase of the QBO the anomalies in the residual circulation go upwards at polar latitudes, indicating a weaker stratospheric branch; in the easterly phase the anomalies are downwards and thus, the climatological sinking is even more pronounced. Thus,

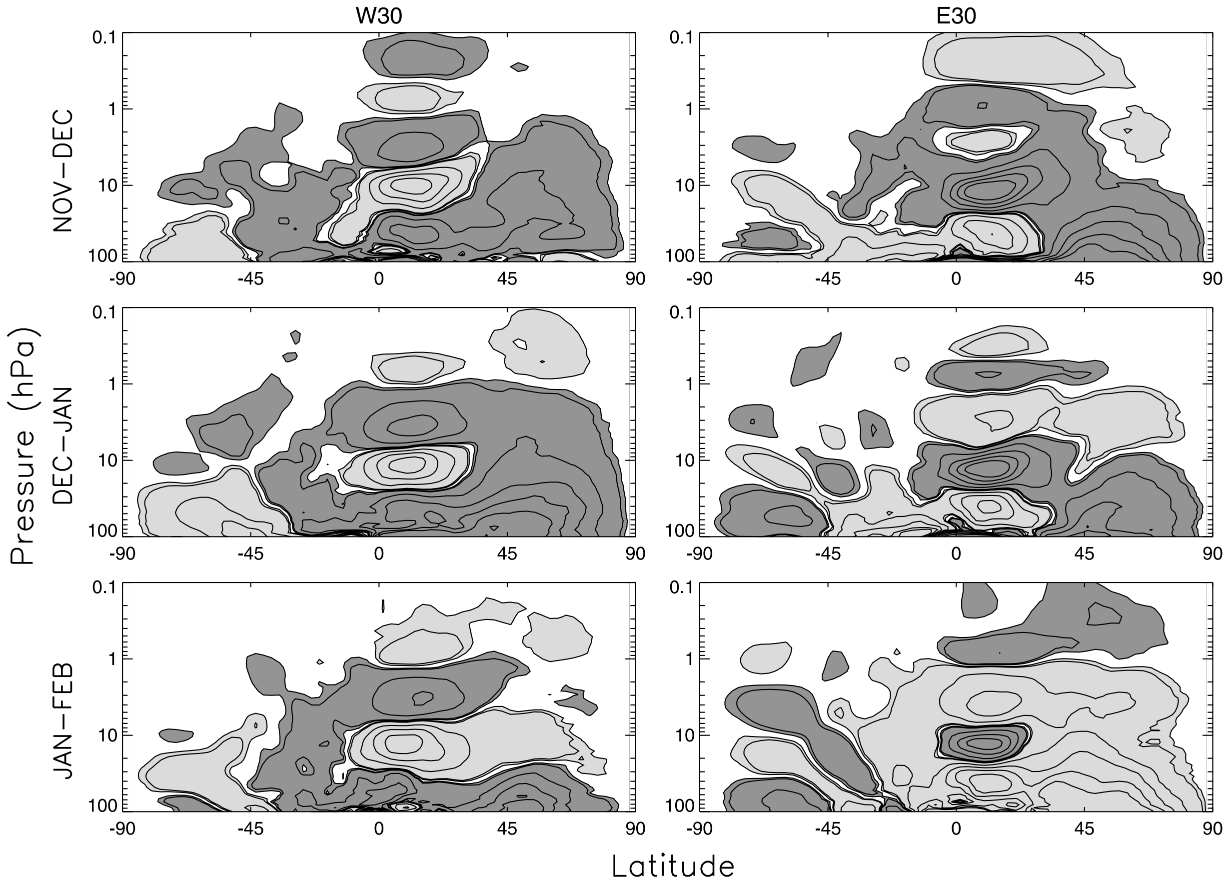

Figure 6. As in Figure 2 for mass stream function anomalies. Contours are drawn at ±5, 10, 50, 100, 150, 200 $\times$ 10^6 kg/s. Light (dark) gray for clockwise (anticlockwise) anomalies.

the warming related to the descending of air in the North Pole intensifies, in agreement with the composites of temperature. DJ in QBO/W and JF in QBO/E are the periods with the strongest anomalies in the mass stream function and the widest anomalous regions throughout the stratosphere, which is also consistent with the occurrence of the maximum significant anomalies in temperature (Figure 3).

4. Forcing of the Simulated QBO in the Lower Mesosphere

[24] The vertical structure of MAECHAM5 and the top of the model at higher heights (0.01 hPa) compare to other data sets have allowed detection of QBO signature in the lower mesosphere. Results from zonal mean zonal wind, temperature and mass stream function discussed in section 3 show this signature in early and middle winter (ND and DJ) but not in late winter. In this section, we will analyze the dynamical mechanisms involved in the occurrence of the QBO in this region.

[25] The QBO in the tropics is the result of the wave-mean flow interaction and the advection acting on the zonal momentum. In MAECHAM5 wave-mean flow interaction includes both resolved waves up to the truncation limit in the model (wave number 42 in this experiment) and the parameterized effects of the gravity waves interaction with the resolved wind. Thus, the total tendency of the zonal-mean zonal wind U can be expressed as the sum of the tendencies due to resolved wave mean interaction, diagnosed as the divergence of the Eliassen-Palm flux, the gravity wave drag and the advection due to residual circulation. The computation of these three processes and their net effect on the tropical stratosphere is discussed in depth in *Giorgetta et al.* [2006]. Here, we will extend their analysis up to the top of the model and will focus in results on the lower mesosphere.

[26] Figure 7 shows a comparison of different sources of anomalous tendencies at the equator, composited for the westerly and easterly phases of the QBO in early winter and late winter. Vertical profiles at other equatorial latitudes show similar results. Above 1 hPa, the EP flux divergence and advection almost compensates each other at any height and so the net forcing in the lower mesosphere is mainly due to gravity wave drag. This occurs in both QBO phases throughout the winter. However, the comparison between ND and JF shows a more intense net forcing in early winter in agreement with results from zonal mean zonal wind, temperature and mass stream function anomalies showed in section 3. In early winter, the total forcing peaks at 0.2 hPa showing a positive tendency of 0.4 m/s/day in QBO/W while in QBO/E the net forcing is westwards and slightly larger than in QBO/W (−0.55 m/s/day). These peaks indicate the descending of the westerly (easterly) zonal mean zonal wind anomalies in the QBO/W (QBO/E). In QBO/E, a second maximum of positive forcing is observed

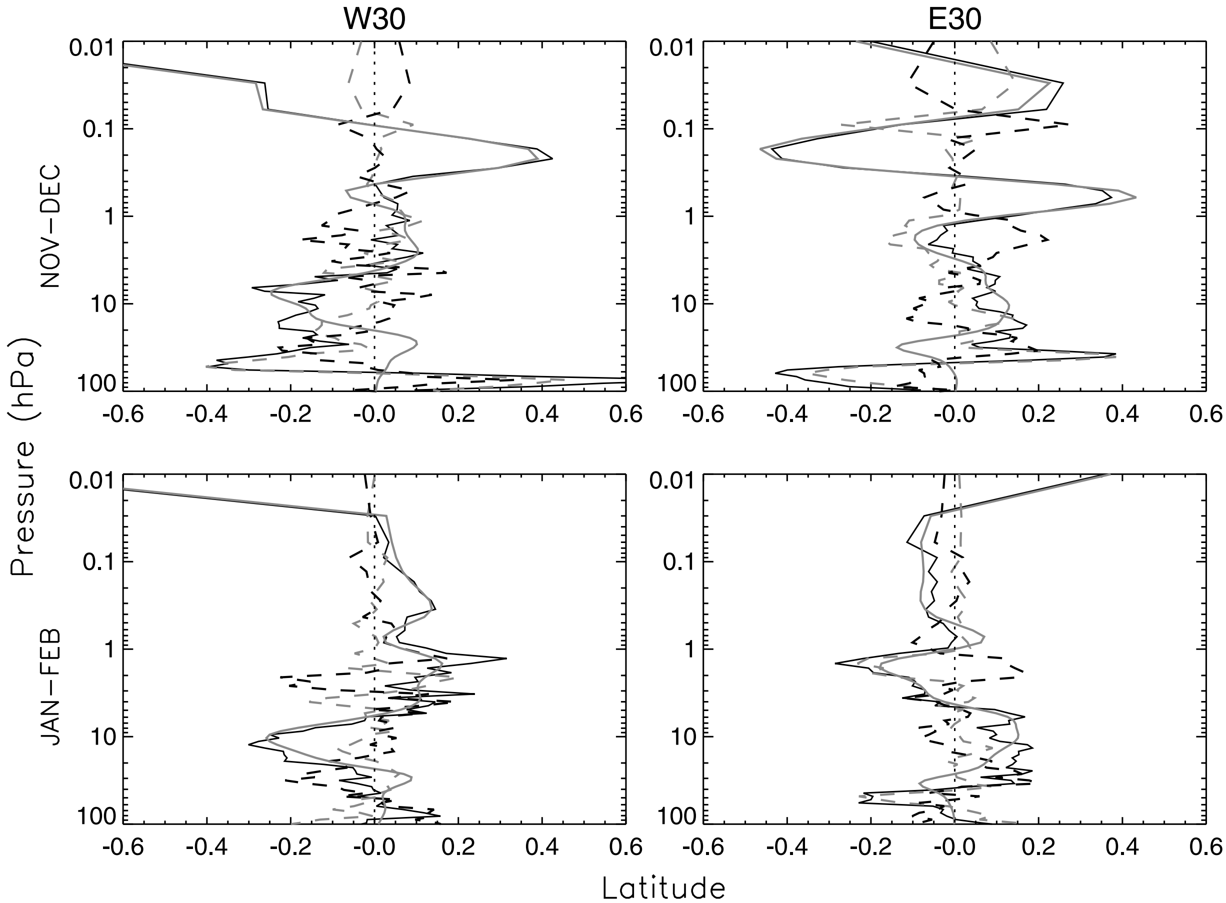

Figure 7. Vertical profile at the equator of the anomalous tendencies (dU/dt) by resolved wave mean flow interaction (black dashed), advection (gray dashed), parameterized gravity wave drag (gray solid) and their sum (black solid) for the composite westerly phase (left) and easterly phase (right) in November−December (above) and January−February (below). Tendencies are in m/s/day.

about 0.5 hPa in accordance with the anomalous positive vertical shear observed in Figure 2.

[27] Therefore, the analysis of the tendencies in the zonal mean zonal wind indicates that the QBO in the lower mesosphere is mainly caused by the interaction of the parameterized gravity waves with the resolved wind. The QBO signature in this region is observed mainly in early winter and shows larger anomalies in the easterly QBO phase as a result of a more intense gravity wave drag.

5. Wave−Mean Flow Interaction at High Latitudes

[28] The modulation of the extratropical Rossby waves by the QBO is a possible mechanism to explain QBO signals in wind and temperature in the polar region. Quasi-stationary planetary waves are able to propagate into the middle atmosphere only where winds are westerly and weaker than a critical value [*Charney and Drazin*, 1961]. Thus, as the phase of the QBO changes in tropics and subtropics, the position of the boundary line between westerly and easterly zonal-mean zonal wind varies and so, the effective channel where the waves propagate upwards and the regions where they dissipate and deposit momentum are modified [*Baldwin et al.*, 2001; *Edmon et al.*, 1980; *Karoly and Hoskins*, 1982; *Salby and Callaghan*, 2003]. This is specifically the case in the upper stratosphere, where westerlies extend from the North Pole to the Southern Hemisphere when the QBO is in westerly phase at these levels, but only to about 15°N when the QBO is in easterly phase (Figure 1).

[29] Our previous analysis of the zonal-mean zonal wind and temperature in the Northern Hemisphere polar regions seems to corroborate this reasoning: a significant stronger (weaker) vortex and cooler (warmer) polar stratosphere is observed when the winds are westerlies (easterlies) in the tropics at 30 and 1 hPa (see Figures 2 and 4). To look into this mechanism, composites of the Eliassen-Palm flux and its divergence have been analyzed in ND, DJ and JF. The EP flux components are defined in the transformed eulerian mean framework [e.g., *Andrews et al.*, 1987, equations (3.5.3a) and (3.5.3.b)] as:

$$F_\phi = \rho_0 \cdot a \cdot \cos\phi\left(\overline{u}_z \cdot \overline{v'\theta'}/\overline{\theta}_z - \overline{v'u'}\right) \tag{1}$$

$$F_z = \rho_0 \cdot a \cdot \cos\phi\left\{\left[f - (a\cdot\cos\phi)^{-1}\cdot(\overline{u}\cdot\cos\phi)_\phi\right]\overline{\cdot v'\theta'}/\theta_z - \overline{w'u'}\right\} \tag{2}$$

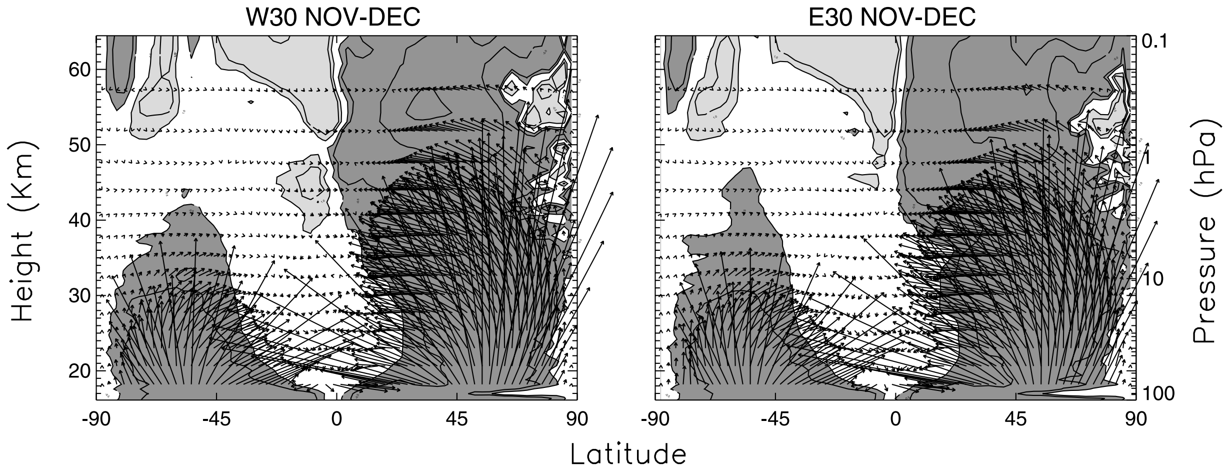

Figure 8. Composites of the EP flux (arrows) and its divergence (contours) full fields at westerly (left) and easterly (right) QBO phase in November–December. (F_z/F_ϕ = 30.) Contours are drawn at ±0.5, 1, 5 and 10 m/s/day. Light (dark) shaded for positive (negative) divergence larger than ±0.5 m/s/day.

where ρ_0 is density, a is the earth's radius, ϕ is latitude, z is log-pressure height, f is the Coriolis parameter, (u, v) is zonal and meridional wind and θ is potential temperature. Bars and primes denote the zonal mean and eddy components, respectively.

[30] The EP flux cross sections are useful in this sense, as the EP flux can be interpreted as a measure of the wave propagation from one height and latitude to another while its divergence is a precise measure of how the resolved waves in the model will force changes in the background

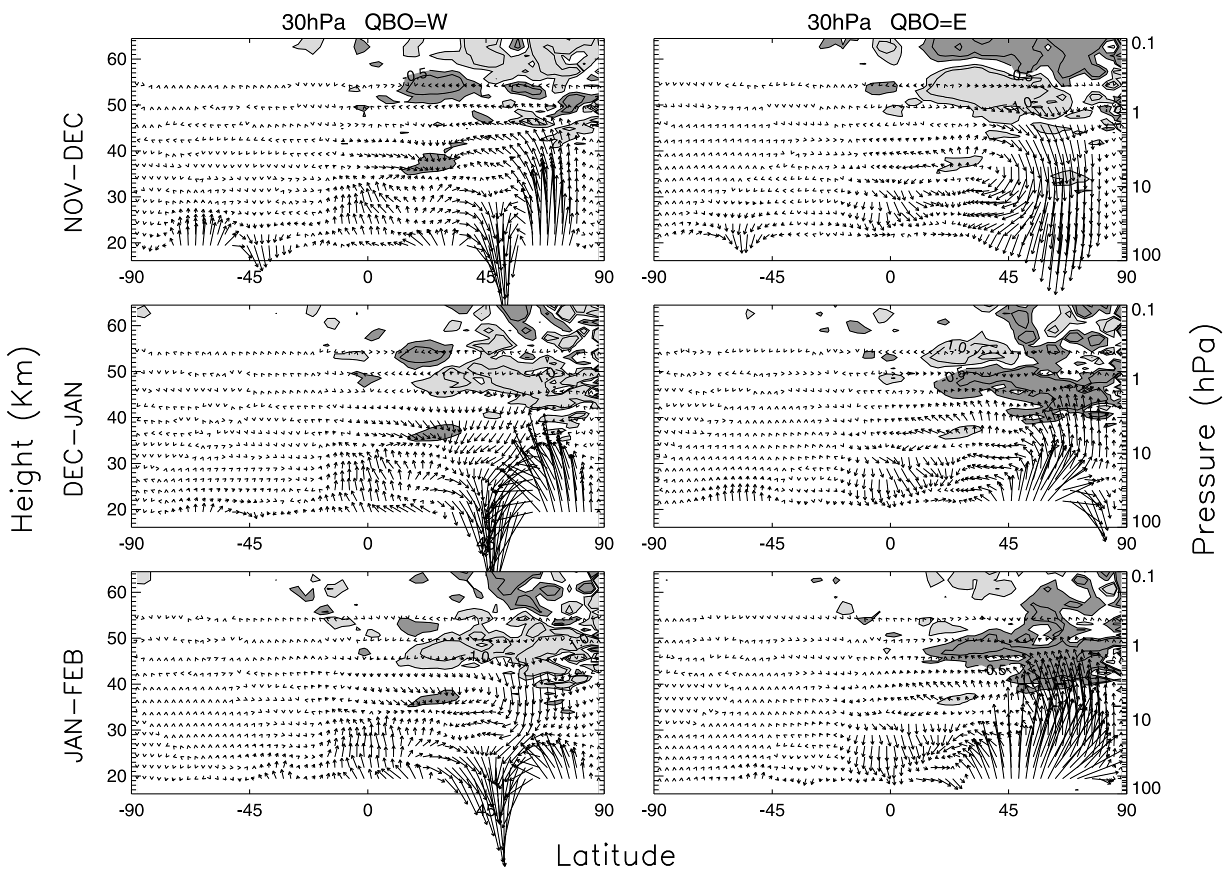

Figure 9. Composites of the EP flux anomalies (arrows) and its divergence (contours) at westerly (left) and easterly (right) QBO phase in November–December (above), December–January (middle) and January–February (below). (F_z/F_ϕ = 180.) Contours are drawn at ±0.5, 1, 5 and 10 m/s/day. Light (dark) shaded for positive (negative) divergence larger than ±0.5 m/s/day.

atmosphere [*Dunkerton*, 2003]. Figures 8 and 9 display composites of the EP flux (arrows) and its divergence (contours) full fields and anomalies at QBO/W and QBO/E.

[31] The composites of the full EP flux fields in ND (Figure 8) show the characteristic pattern in boreal winter for both QBO phases: intense upward wave propagation in the Northern Hemisphere and wave refraction towards lower latitudes at high heights. Further, negative values of the EP flux divergence and their maximum in the middle atmosphere indicate the dissipation of the waves and their effect on the background flow. The same pattern is observed in full fields in DJ and JF (not shown).

[32] The composites of the EP flux anomalies (Figure 9) do allow us to see differences between the two phases, especially at middle and high latitudes. In the QBO/W composite, upward propagation anomalies are observed between 70°N and 90°N while downward anomalies are observed between 40°N and 70°N generating a downward/upward pattern in the EP flux anomalies. From early to late winter this pattern evolves in such a way that the maximum height of upward anomalies at high latitudes decreases from 1 hPa in ND to 30 hPa in JF and downward anomalies are observed instead in the upper stratosphere. Anomalies in the divergence of the EP flux exceeding 1 m/s/day (shaded regions in the figure) occur only in the subtropics at about 0.5 hPa and in high latitudes at about 1 hPa. The high latitude anomalies at 1 hPa in QBO/W are positive, such that the total westward forcing is reduced (see Figure 7). Thus, the anomalous positive divergence does not reflect a real acceleration of the background flow but less intense EP flux convergence observed in the full field.

[33] In the QBO/E composite, upward EP fluxes are reduced in high latitudes below 1 hPa in ND as downward anomalies are observed there. However, in DJ and JF upward fluxes increase at high latitudes between 100 and 1 hPa. Anomalies in the divergence of the EP flux are qualitatively opposite to those for the QBO/W composite, especially in DJ and JF. In those months the full westward forcing in QBO/E at high latitudes about 1 hPa is stronger than in the climatology. Hence, the comparison of the composites for QBO/W and QBO/E, and the climatology of this experiment shows that the westward forcing by resolved wave mean-flow interaction on the zonal mean Northern Hemispheric vortex is intensified in the E30 case, and reduced in the W30 case. This forcing is concentrated on a layer between 3 and 0.5 hPa, northward of 45°N.

[34] Therefore, MAECHAM5 EP flux anomalies clearly show the different behavior of the wave propagation and dissipation depending on the QBO phase. In the westerly QBO phase, at polar latitudes the upward propagation occurs towards the subtropics in the lower stratosphere while it is reduced in the middle upper stratosphere. The westward forcing observed above is also reduced which intensifies the polar vortex, makes the meridional circulation weaker and the polar stratosphere warmer. The largest anomalies in the EP flux and its divergence observed in DJ corroborates the significant anomalies observed in wind and temperatures. In the easterly QBO phase, the upward propagation of planetary scale waves is intensified to the North Pole in ND and DJ throughout the stratosphere up to about 1 hPa where the largest values in the EP flux convergence are observed increasing the westward forcing. This momentum deposition decelerates the polar vortex, and then the meridional circulation is intensified which makes the polar stratosphere warmer in those months.

[35] These results indicate that the QBO simulated by MAECHAM5 modulates properly the wave propagation in the Northern Hemisphere. These anomalies are part of the relationship that included zonal wind, zonal temperature and circulation anomalies showing an overall agreement.

[36] Finally, the possible influence of the tropical QBO in the warming observed at Polar latitudes at the end of the boreal winter has been studied here by compositing the zonal mean temperature in March with respect to the east and west QBO phase during the November–December. The anomalous warming is in fact observed in the polar regions although the signal is not significant according to the Monte Carlo simulation. This seems to indicate that that warming is not related to the phase of the QBO. However, this does not necessarily mean that both phenomena are not related. A deeper study of these phenomena would imply the analysis of individual final warming events and the use of daily data, which is out of the scope of this work.

6. Conclusions

[37] The signature of the quasi-biennial oscillation has been investigated in a 50-year simulation with MAECHAM5 focusing on middle and high latitudes in the middle atmosphere in boreal winter. Composites at westerly and easterly QBO phases (choosing the QBO index at 30 hPa) have been analyzed for the winter periods: November–December (ND), December–January (DJ) and January–February (JF). These are the main conclusions from this study:

[38] 1. MAECHAM5 reproduces accurately the QBO signature in the tropical and subtropical regions. The model simulates the threefold out-of-phase structure according to observations [*Gray*, 2003]. Beyond that pattern, significant anomalies are observed in the lower mesosphere mainly in the easterly QBO phase. These mesospheric anomalies reach their largest values in early winter, ND, get weaker in DJ and are not observed in late witner, JF. The QBO in this region is mainly forced by the interaction of the parameterized gravity waves with the resolved wind which is much more intense in the early winter. Thus, QBO anomalies in the zonal-mean zonal wind are observed up to 60 km in November–December.

[39] 2. The anomalies in the zonal mean zonal wind are accompanied by the corresponding anomalies in the zonal mean temperature, which shows the modulation of the averaged mean meridional circulation by the QBO. The MAECHAM5 residual circulation anomalies show the pattern of the secondary meridional circulation. Several cells are observed in the tropical and north-subtropical region with sinking (rising) motion at the equator in the westerly (easterly) shear zones accompanied by a maximum (minimum) in temperature at the equator. Out-of-phase anomalies in the subtropics are associated to the return branches. As in zonal mean zonal wind anomalies, QBO related anomalies in zonal temperature and residual circulation are observed in the tropics up to the lower mesosphere only in the early winter months.

[40] 3. At high latitudes, the relationship first established by *Holton and Tan* [1980, 1982] is well reproduced by the model. The north polar stratosphere is characterized by a stronger (weaker) polar vortex and colder (warmer) polar stratosphere during the west (east) QBO phase accompanied by a weakening (intensification) of the polar stratospheric branch of the Brewer Dobson circulation in the winter hemisphere. Contrary to the QBO signal in the tropical mesosphere, the significant anomalies are observed at high latitudes in middle and late winter. In particular, the polar vortex is more perturbed in QBO/E (larger anomalies) and these anomalies reach their maximum later in the winter than in QBO/W (JF versus DJ).

[41] 4. MAECHAM5 results show an overall agreement with those from ERA-40 data in the perturbation patterns but differences in intensity and timing. So, the polar vortex is more perturbed in QBO/W than QBO/E in ERA-40 while the opposite is observed in MAECHAM5. Maximum anomalies are observed in DJ in QBO/W as in the model but earlier in QBO/E (DJ versus JF). In any case, a direct comparison between the reanalysis and the model is complicated as different periods have been considered to composite, QBO cycles differ and additional sources of variability in addition to the QBO are included in ERA-40.

[42] 5. The anomalies observed in MAECHAM5 in the polar region in middle and late winter seem to be due to a different behavior of the planetary wave propagation according to the QBO phase. So, when westerlies are observed at 30 and 1 hPa (QBO/W), upward wave propagation is enhanced at middle and high latitudes up to 10 hPa and then waves are refracted towards the subtropics. Then, above 10 hPa the upward propagation is less intense than climatology as well as the negative EP flux divergence, which intensifies the polar vortex. On the contrary, in the QBO/E waves cannot propagate towards lower latitudes as easterly winds are located at 30 and 1 hPa in the tropics. As a result, the upward propagation at polar latitudes is enhanced up to the stratopause where waves dissipate and deposit easterly momentum. This makes the polar vortex weaker than in the climatology. Therefore, MAECHAM5 results support the assumption that a great part of the extratropical QBO signature occurs through the modulation of the Rossby wave propagation by the QBO as changes in the zonal-mean winds in tropics modify the effective waveguide.

[43] **Acknowledgments.** The experiment was carried out on the SX-6 supercomputer at the German Climate Computing Center DKRZ.

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