JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. D4, PAGES 4539–4551, FEBRUARY 27, 2000

A model study of the influence of the quasi-biennial oscillation on trace gas distributions in the middle and upper stratosphere

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Abstract. The dominant tracer transport processes in the equatorial and subtropical latitudes of the middle and upper stratosphere are investigated. Distributions of water vapor in Northern Hemisphere winter from the Microwave Limb Sounder onboard the Upper Atmosphere Research Satellite are employed, together with a three-dimensional Stratosphere Mesosphere Model that incorporates a representation of the quasi-biennial oscillation (QBO). The model reproduces the observed tracer distributions, in particular a "staircase" feature that is present in northern winter of 1992 (easterly QBO phase) but not in 1993 (westerly QBO phase). This feature is highly asymmetric about the equator. The model circulation is diagnosed to show that while the induced QBO circulation in the lower stratosphere of the model is relatively symmetric about the equator, in the middle and upper stratosphere it is highly asymmetric and in the correct sense to give rise to the staircase feature. Model experiments are compared in which trajectories are advected by (1) the full three-dimensional circulation and (2) the residual mean circulation only, thereby removing the local effects of isentropic mixing by planetary waves on the trajectory distributions. These confirm the importance of advection by the QBO circulation at equatorial and subtropical latitudes. However, sharpening of the tracer gradients at the subtropical edge of the surf zone by the action of planetary waves is shown to be important in the formation of a subtropical "cliff" between 10 and 20 mbar at 20°-30°N. The model results also suggest that the prominence of the summer subtropical peak in easterly phase years compared with westerly phase years is not entirely due to increased summer upwelling of the large-scale global circulation caused by the stronger planetary wave driving. The depression of the winter half of the equatorial peak by the local asymmetric QBO circulation is also shown to be important.

1. Introduction

The Upper Atmosphere Research Satellite (UARS) has provided a number of excellent data sets of long-lived trace gases, notably nitrous oxide (N2O), methane (CH4), water vapor (H2O), and hydrogen fluoride (HF). Global observations of these gases over a number of years provide essential validation data against which to test both the accuracy of our global circulation models of the atmosphere and theoretical ideas of large-scale transport processes.

The UARS mission, with its reasonable spatial resolution and relatively long lifetime, has provided evidence of significant interannual variability, which may be associated with the quasi-biennial oscillation (QBO). In this paper, we examine the interannual variability of tracer distributions in the Northern Hemisphere subtropics. We use a computer model that includes a representation of the QBO to simulate features in the tracer distributions observed by UARS in the Northern Hemisphere winter and investigate the transport processes that give rise to those features. In particular, we address whether the equatorial and subtropical distributions and their interannual variability are primarily due to advection by the QBO circulation or the result of isentropic mixing by midlatitude planetary waves.

Paper number 1999JD900302.
0148-0227/00/1999JD900302$09.00

1.1. Observations

In the tropics and subtropics the distribution of long-lived trace gases is dramatically affected by circulations associated with the semi-annual oscillation (SAO) and the quasi-biennial oscillation (QBO) [*Gray and Pyle*, 1986, 1989; *Trepte and Hitchman* 1992; *Hitchman et al.*, 1994]. The mean meridional circulations associated with these oscillations have relative upwelling (downwelling) associated with easterly (westerly) shear zones at the equator. These induced circulations affect the tracer distributions, so for example, a "double peak" tracer distribution is associated with a westerly equatorial shear zone.

The UARS measurements of H_2O from the Microwave Limb Sounder (MLS) [*Barath et al.*, 1993], N_2O from the Cryogenic Limb Array Etalon Spectrometer (CLAES) [*Roche et al.*, 1993] and H_2O, CH_4 and HF from the Halogen Occultation Experiment (HALOE) [*Russell et al.*, 1993] have indicated an unexpected distribution in Northern Hemisphere winter/early spring [*Dunkerton and O'Sullivan,* 1996; *O'Sullivan and Dunkerton* 1997; *Gray and Russell*, 1999] , which is present only in the so-called easterly phase of the QBO, i.e., when the equatorial zonal winds at 30-50 mbar are easterly. The feature is a "staircase" structure, as illustrated in Plate 1a, which shows the version 4 water vapor (H_2O) distribution in February 1992 from MLS. Note that although only data of a single day are shown, the feature is evident throughout the winter. See, for example, *O'Sullivan and Dunkerton* [1997] who show a February/March average. We show data

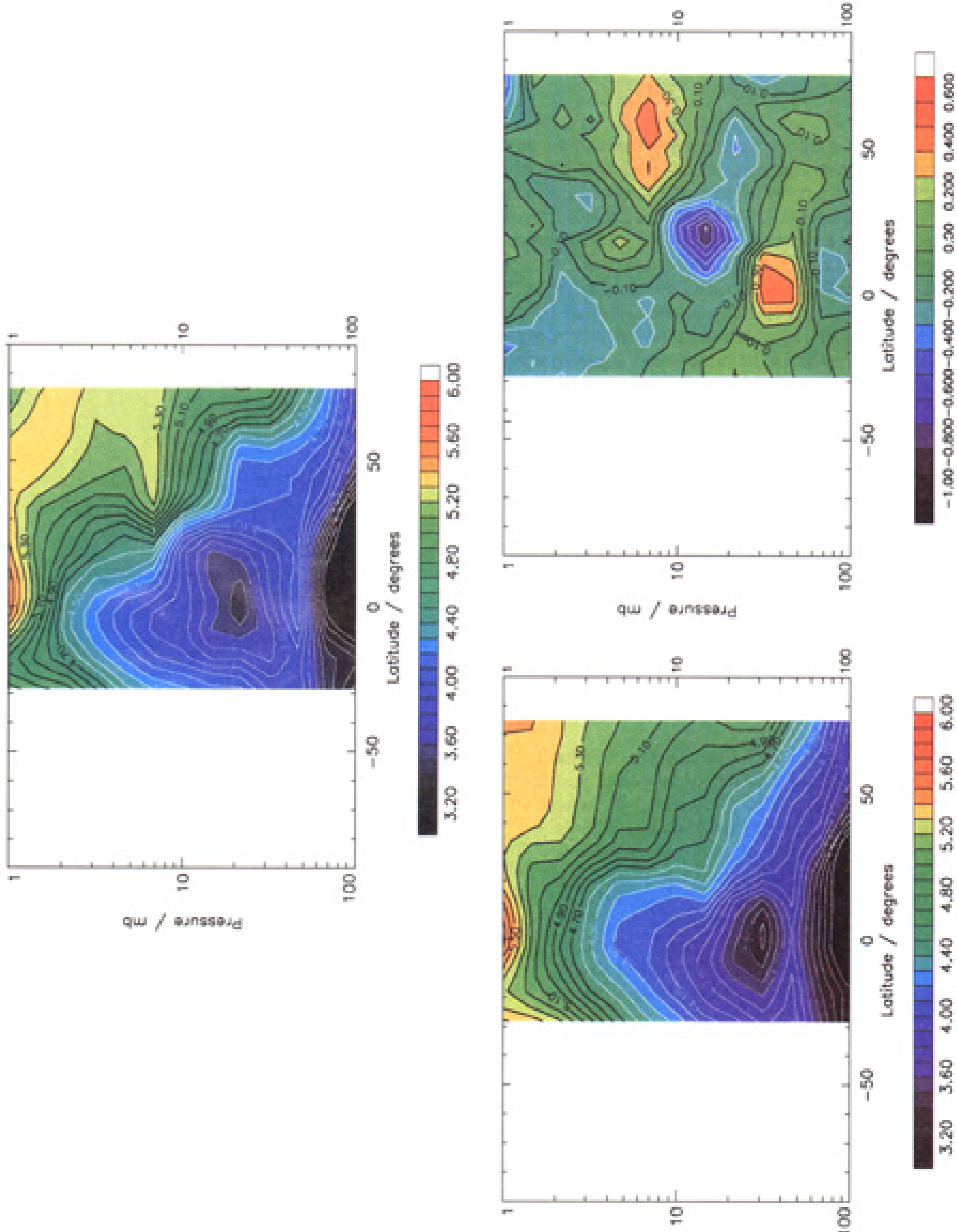

Plate 1. Latitude - height zonal averaged cross section of MLS H_2O: (a) February 24 1992, (b) February 24 1993, (c) difference between the two distributions i.e. plate 1a minus 1b. Contour interval is 0.1 ppmv.

of a single day in order that diagnosis is not confused by averaging over a feature that is slowly descending with time.

The "staircase" feature consists of:

(1) an asymmetrical off-equatorial peak in the tracer isolines (water vapor minimum) in the summer hemisphere above approximately 8 mbar with steep isolines over the equator forming a vertical "equatorial cliff"; (2) a region of almost horizontal isolines forming a "subtropical ledge" between 8-15 mbar and 0°-20°N, which is also asymmetric, being present only in the Northern Hemisphere; (3) a region of almost vertical isolines forming a "subtropical cliff" in the Northern Hemisphere between approximately 20°-30°N and 8-20 mbar; (4) a region of horizontal contours in the surf zone between 30°-60°N and 8-20 mbar forming a "midlatitude ledge"; (5) steep isolines poleward of 60°N between 10 and 70 mbar at the edge of the polar vortex forming an "edge-of-vortex cliff".

For comparison purposes, we show in Plate 1b the MLS H_2O distribution from the same period in the following year 1993 and in Plate 1c the difference between the 1992 and 1993 distributions. There is no sign of the staircase feature, neither in Plate 1b nor at any other time during the winter of 1993. The "staircase" feature appears to be a consistent feature of the Northern Hemisphere when the QBO is in its easterly phase. *Dunkerton and O'Sullivan* [1996] have shown that the feature is also present in CLAES N_2O data in 1992. *Gray and Russell* [1999] have shown that the feature is present in HALOE H_2O, CH_4, and HF data in January 1992, 1994, and 1996 (all "easterly" QBO phase years) but not in 1993, 1995 or 1997 ("westerly" QBO phase years). Although we concentrate on the Northern Hemisphere data in this paper, the same feature is also present in the Southern Hemisphere winter period.

1.2. Asymmetry

The "staircase" feature in Plate 1a is remarkably asymmetric about the equator. This appears at first to be inconsistent with tracer advection by the meridional circulations induced by the SAO or QBO, which theory predicts to be symmetric about the equator. Indeed, *O'Sullivan and Dunkerton* [1997] noted that the observations were in marked contrast to the symmetric SAO- and QBO-induced circulations described by *Gray and Pyle* [1986, 1989] and *Trepte and Hitchman* [1992]. They concluded from this and other evidence that the distribution of tracers in the subtropics below about 10 mbar must be dominated by the QBO-modulated planetary wave isentropic mixing, with the easterly QBO winds preventing planetary wave radiation into the tropics, so a strong tracer gradient is generated in the winter subtropics at the edge of the surf zone.

However, the asymmetric nature of the tracer observations is not, in fact, inconsistent with tracer advection by the induced SAO and QBO meridional circulations. Although the SAO and QBO signals dominate the equatorial zonal wind distributions it does not automatically follow that this is true in the meridional plane. The SAO and QBO meridional circulations are, in fact, relatively weak circulations superimposed on an annual meridional circulation that is strongly asymmetric. It is therefore possible that this background asymmetric circulation will modulate the QBO and SAO transport circulation in some way to produce net QBO and SAO signals in tracer distributions that are asymmetric.

Indeed, observations of the QBO signal in column ozone are highly asymmetric about the equator [*Hasebe,* 1983; *Lait et al.*, 1989; *Bowman,* 1989; *Tung and Yang,* 1994a; *Randel and Cobb,* 1994]. The data display an off-equatorial column ozone QBO anomaly which develops in both Northern and Southern Hemispheres during the local winter / spring season. A number of attempts were made in the past to explain the asymmetric nature of these anomalies [*Gray and Pyle,* 1989; *Holton,* 1989; *Hamilton,* 1989; *Gray and Dunkerton,* 1990; *Tung and Yang,* 1994b], some of which invoked advection by the mean circulation, while others suggested that the influence of the QBO on planetary wave propagation and hence on isentropic mixing was responsible. More recent analyses of the height distribution of the QBO in Stratospheric Aeorsol and Gas Experiment (SAGE) ozone [*Randel and Wu* 1996] and other trace gases [*Randel et al.* 1998] have added to the evidence that the QBO signal in trace gases is highly asymmetric.

1.3. Recent Studies

In an analysis of the QBO signal in the meridional circulation of the UK Meteorological Office (UKMO) model-assimilated observations, *Randel et al.,*[1999] derived QBO anomalies in zonal wind, temperature, and residual circulation from the UKMO analyses [*Swinbank and O'Neill*, 1994, Figure 18]. Their derived temperature and residual circulation anomalies in each year are highly asymmetric about the equator, exhibiting a single circulation between 2 and 20 mbar rather than the expected two-cell symmetric QBO circulation.

In a series of two-dimensional modeling experiments, *Jones et al.* [1998] and *Kinnersley* [1999] have demonstrated a mechanism in which the induced symmetric QBO circulations are advected by the annual meridional circulation preferentially into the winter hemisphere. Through the Coriolis parameter dependence in the thermal wind equation, this has the effect of preferentially strengthening the local QBO circulation in the winter hemisphere. This nonlinear advection is therefore a source of asymmetry in the resultant QBO and SAO meridional circulations that could account for the asymmetry in the circulation derived by *Randel et al.* [1999] and could also be responsible for the asymmetry of the observed tracer distributions in plate 1a.

In view of these recent developments in our understanding of the QBO mean circulations and their asymmetry, it seems appropriate to reexamine the UARS tracer distributions. We pay particular attention to the formation of the asymmetric "staircase" feature described above and whether the components of the staircase feature are produced primarily by advection by the mean circulation or by processes associated with isentropic mixing due to midlatitude planetary waves.

In this paper, we concentrate on the upper staircase features 1-3, i.e. the off-equatorial summer peak and "equatorial cliff," (feature 1) the "subtropical ledge" between 0°-20°N and 8-15 mbar (feature 2) and the "subtropical cliff" of steep isolines at 20°-30°N and 8-20 mbar (feature 3). In fact, the isolines in the latter region have steep slopes right down to 50 mbar. However, we will concentrate here on the upper part of feature 3 between 8 and 20 mbar only. The lower region 20-50 mbar has already been studied in detail by *Gray and Russell* [1999], who showed that the steeper isolines in the northern subtropics in 1992 below about 20 mbar are due primarily to advection by the QBO circulations. However, their analysis showed that isentropic mixing becomes increasingly important above 20 mbar. It was not clear from their study, which used only observational data, whether advection or mixing was the dominant process above 20 mbar. In this paper, we therefore extend their study by using both observational data and computer model simulations to examine the region above 20 mbar. We employ a three-dimensional model of the stratosphere and mesosphere to simulate the observed tracer distributions and then use it to diagnose the dominant mechanisms that produce the staircase feature in the model.

The layout of the paper is as follows: The model formulation is described in section 2. In section 3, trajectory distributions from the main model run are described, including the simulation of the staircase feature. The transport mechanisms giving rise to the feature are examined in section 4, including a detailed examination of the residual mean circulation anomaly associated with the QBO. In section 5, the conclusions from the model study are applied to the interpretation of the main differences in the MLS H_2O distributions in 1992 and 1993. Finally, in section 6, the study and its major conclusions are summarized.

2. Model

The model employed in this study is the UKMO Stratosphere Mesosphere Model (SMM). It is a global three-dimensional primitive equation model of the middle atmosphere [*Fisher,* 1987; *Butchart et al.*, 1982; *Marks,* 1988; *O'Neill and Pope,* 1988; *Fairlie et al.*, 1990; *Farrara et al.*, 1992; *Fisher et al.*, 1993; *Rosier and Lawrence,* 1999; *Scaife and James,* 1999]. It has horizontal resolution of 5° latitude, 3.75° longitude and 32 vertical levels equally spaced in log pressure between 100 mbar and 0.01 mbar giving approximately 2 km vertical resolution. It is a mechanistic model with temperature and horizontal winds as prognostic variables and a lower boundary located near the tropopause at which 100 mbar (16 km) geopotential height fields are specified as the bottom boundary condition. These are obtained from daily stratospheric analyses from the UKMO assimilated data set [*Swinbank and O'Neill*, 1994] which are then linearly interpolated to provide a continuously varying lower boundary forcing. Radiative heating and cooling rates are computed using the MIDRAD scheme [*Shine,* 1987, *Shine and Rickaby*, 1989] with prescribed climatological, zonally symmetric CO_2 and ozone. A leapfrog integration scheme is used with fourth-order accuracy in the horizontal and second order accuracy in the vertical. A time step of 240 s was employed.

A simple Rayleigh friction scheme is used with a relaxation timescale varying from about 100 days in the lower stratosphere to 2 days in the mesosphere in order to simulate the effect of gravity wave breaking. In addition to this, a QBO was included in the model using a technique introduced by *Gray and Ruth* [1993]: the modeled zonal winds at the equator below 10 mbar were slowly relaxed towards monthly averaged observed winds from Singapore radiosonde measurements. The relaxation time employed was 10 days close to the equator and smoothly and rapidly increased poleward of this in order to produce a realistic QBO zonal wind distribution in the region approximately 20° either side of the equator which smoothly merged with the models own winds at mid-latitudes. Similarly, above 10 mbar the relaxation times were increased in order to achieve a smooth transition from the forced zonal winds below 10 mbar to the modeled winds above 10mbar.

In the experiments described in this paper, the model was run for the period November 1991 to June 1993, using the corresponding daily geopotential heights derived from the UKMO-assimilated data set for the lower boundary forcing and the corresponding monthly averaged Singapore winds to ensure the correct phase of the equatorial QBO. The model was initialized with horizontal wind and temperature data for November 1991, also taken from the UKMO-assimilated data set [*Swinbank and O'Neill*, 1994]. In the region of the upper mesosphere for which assimilated data were not available, data from the COSPAR International Reference Atmosphere (CIRA) data set [*Barnett and Corney* 1985a, b] were merged with the assimilated data.

Figure 1 shows the height time series of equatorial winds in the model. In January 1992 the easterly QBO phase has reached its maximum amplitude at around 25 ms^{-1} at 20 mbar

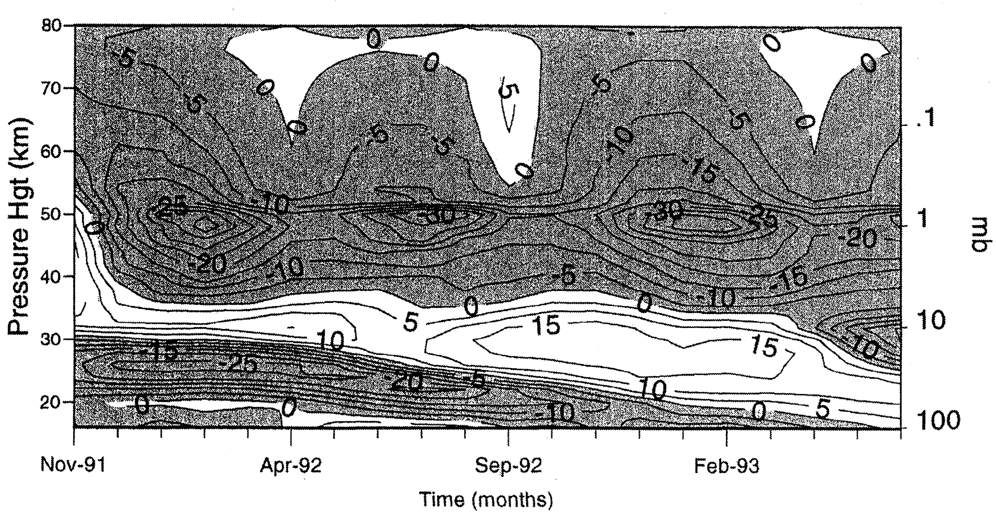

Figure 1. Height-time series of modeled zonally averaged zonal wind at the equator. Contour interval 5 ms^{-1}.

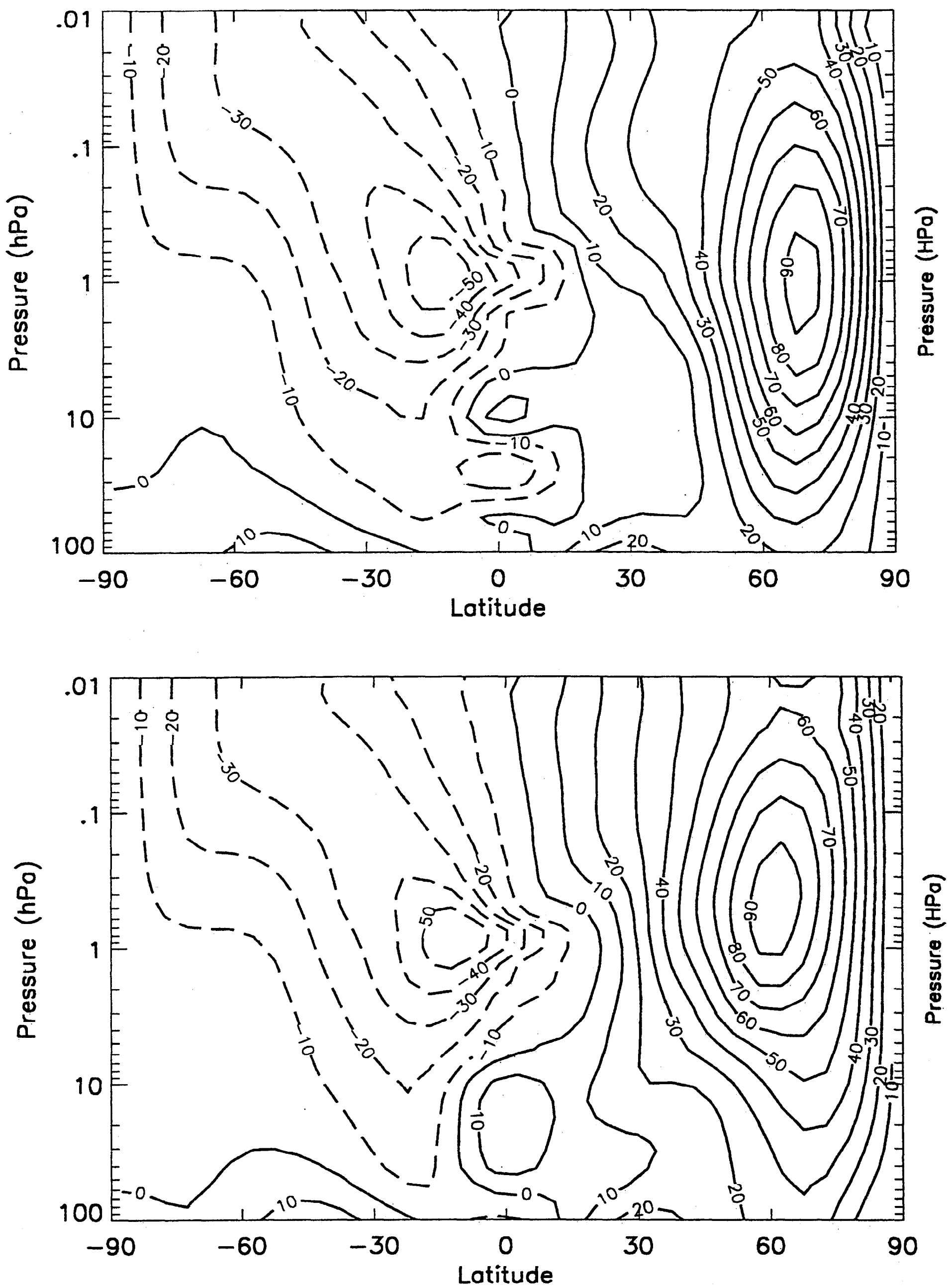

Figure 2. Height-latitude cross-section of monthly averaged, zonally averaged zonal winds in (a) January 1992 and (b) January 1993. Contour interval 10 ms^{-1}.

and the next incoming westerly phase is evident above 10 mbar. In January 1993, on the other hand, the westerly QBO phase dominates the lower stratosphere with westerlies present in the range 8-80 mbar, reaching a maximum amplitude of 15 ms^{-1}. These differences are more clearly seen in Figure 2 which shows the zonal wind cross sections for the two Januaries. The incoming westerly phase above 10 mbar in January 1992 is manifested by alternating layers of easterlies and westerlies at the equator. Note that in Figure 2 the initial wind distribution between 1 and 10 mbar was westerly, due to the presence of the semiannual oscillation (SAO) westerlies, but in the subsequent integration, the SAO westerlies do not extend sufficiently deep into the stratosphere because the model does not include a parameterization of the appropriate wave forcing nor is its resolution sufficiently high to generate this internally. Nevertheless, the model does exhibit a SAO with weak easterlies during equinox and stronger easterlies during solstice. Since the study concentrates on the evolution during the solstice period, we do not consider the lack of penetration of the westerlies to be a problem.

In Figure 3 we show the latitude time series of the zonal winds at 10 mbar. This compares well with the corresponding evolution of the UKMO-assimilated model fields [e.g., *O'Sullivan and Dunkerton*, 1997, Figure 1] apart for the timing of the onset of QBO westerlies in 1991/1992. *O'Sullivan and Dunkerton* [1997] noted the discrepancy between obser-

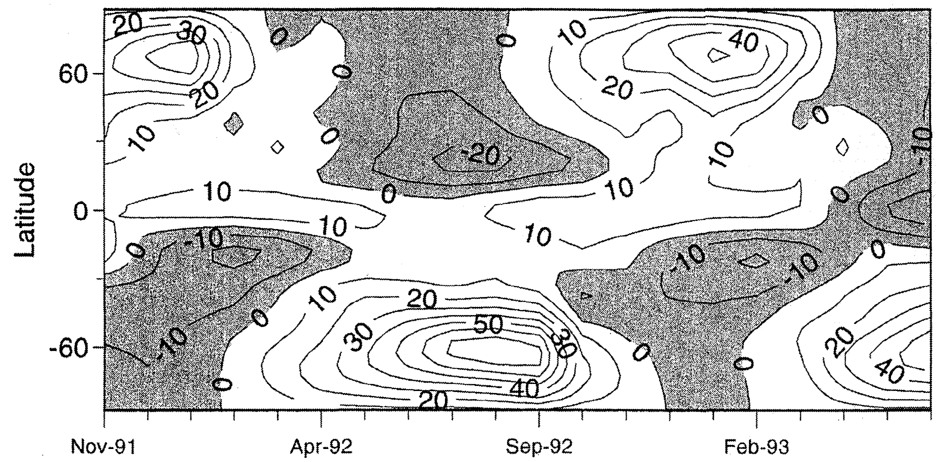

Figure 3. Latitude time series of monthly averaged, zonally averaged zonal winds at 10 mbar. Contour interval 10 ms^{-1}.

vations in this period. The Singapore winds reverse to westerlies at 10 mbar in November 1991, the UARS High-Resolution Doppler Imager (HRDI) winds reverse in April 1992 [*Ortland et al.*, 1996] and the UKMO-assimilated winds reverse in September 1992 [*Swinbank and O'Neill*, 1994]. Since the modeled equatorial winds are tied to the Singapore data, the equatorial winds are already westerly at 10 mbar at the beginning of the integration in November 1991.

3. Model Trajectory Distributions

To study global scale tracer transport, Lagrangian trajectories were included in the model runs. These consisted of approximately 2000 parcels initialized on an equal area grid on each of 17 pressure surfaces uniformly spaced in log pressure between 0.05 mbar and 60 mbar, giving good global coverage. The trajectories were initialized in November 1991, and an analysis of the resulting trajectory transport in winter 1991/1992 during the following 3-4 months was carried out. The trajectories were then reinitialized to identical positions in the following November (1992), and the trajectory transport in the winter of 1992/93 was analyzed in the subsequent 3-4 months in an identical fashion, so exact comparisons could be made between the parcel distributions in the two winters.

Plate 2a shows a zonal cross section of the initial trajectory positions in November 1991 and 1992 color-coded according to their initial pressure surface. The distributions on February 24 1992 and 1993, 3-4 months after their initialization, are shown in Plates 2b and 2c respectively. These may be compared with Plates 1a and 1b.

The overall morphology of the modeled trajectory distributions in Plate 2 and the differences between the two years are realistic when compared with the observational data in Plate 1, especially at low latitudes. The 1992 distribution has a marked staircase feature that is strongly asymmetric. For example, the yellow and pale orange trajectories, which correspond to trajectories that were initialized at 15 mbar and 24 mbar, have ascended on average to 5-6 mbar and 12 mbar in the southern subtropics over the course of the 3-4 months leading up to February 1992. This corresponds well to the subtropical maximum in the summer hemisphere in the MLS data. In the northern subtropics, between approximately 0° and 20°N, however, the average level of these trajectories plunges to 12 mbar and 18 mbar, thus forming an "equatorial cliff" similar to feature 1 in the data. The distribution between 0° and 20°N is relatively flat, corresponding well to the "subtropical ledge" feature 2. At 20°-30°N the pressure level of these trajectories once again plunges to around 30-50 mbar, forming a "subtropical cliff" corresponding to feature 3. Thus a distinctive staircase feature is evident in February 1992 which is very similar to the MLS data in Plate 1a. In 1993 the modeled trajectories do not exhibit a staircase feature, in good agreement with the MLS data in Plate 1b.

The trajectory plots in Plate 2 are built up simply by plotting every trajectory at its appropriate latitude and pressure coordinate, starting at the higher pressure values first and proceeding layer by layer to the lower-pressure level trajectories. In this way, although giving a good visual presentation of the distribution, there is scope for the "later" trajectories to obscure the earlier ones to some extent. Although this problem can be minimized by using small plotting symbols, it cannot be avoided altogether. In order to show more clearly the presence of the staircase feature in the 1992 model run and the lack of it in 1993, Figure 4 shows the February 1992 and 1993 distributions of only those trajectories that were initialized on the 15 mbar pressure surface. They are therefore identical to the yellow trajectories in Plate 2. The distributions of the trajectories in the two years are quite different. There is a marked staircase feature in 1992 with a distinctive "ledge" between 0° and 20°N at around 12 mbar and "cliffs" over the equator and at 20°-30°N. None of these features is present in 1993, which shows a distribution that gently slopes from around 8 mbar at the equator to 40 mbar at middle and high latitudes.

4. Residual Mean Circulation

In Figure 5 we show the vector representation of the January 1992 residual circulation minus the January 1993 residual circulation. The circulations were derived using the standard transformed Eulerian mean (TEM) formulation. We choose to show the monthly mean differences for January since it is the circulation in the previous months that will have determined

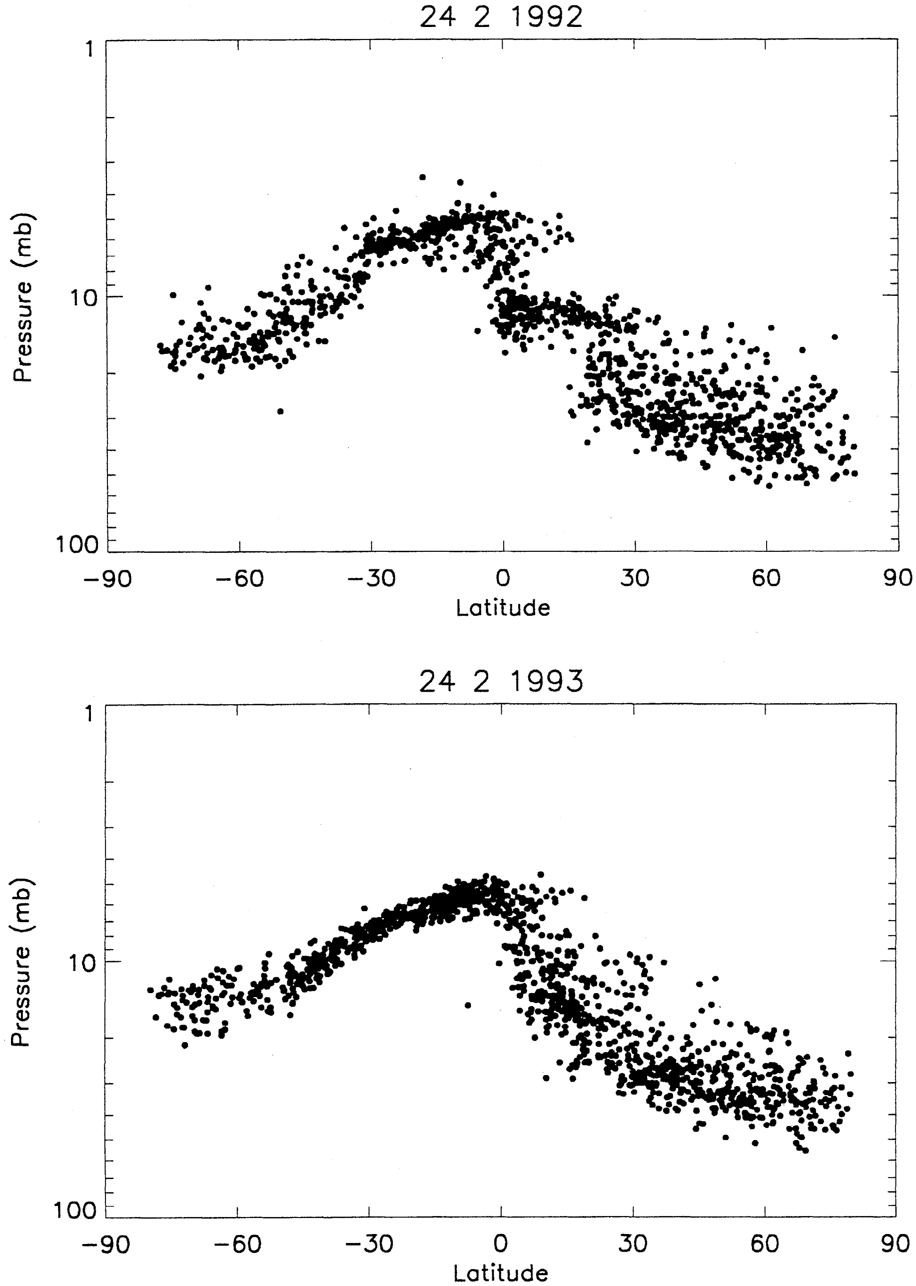

Figure 4. Height-latitude distributions on February 24 (a) 1992 and (b) 1993 of those parcels initialized on the 15 mbar level.

the tracer and trajectory distributions in February shown in Plates 1 and 2. There is a pattern of stronger descent at high northern latitudes below 1 mbar in 1992 than in 1993 and stronger meridional flow from the equator to these higher latitudes in the region of the stratopause at around 1 mbar. The 1992 summer-to-winter meridional circulation in the stratosphere, during which the QBO was in its easterly phase in the lower stratosphere, is therefore stronger than the following westerly phase year. This is in good agreement with previous modeling and theoretical studies [e.g., *Hess and O'Sullivan,* 1995; *Tung and Yang*, 1994b] which have shown that the forcing of the largescale mean meridional circulation by the action of midlatitude planetary waves is stronger during easterly phase years due to latitudinal confinement of the surf zone.

To determine whether the 1992 staircase feature in the model is due in any way to the action of isentropic mixing at midlatitudes tightening the tracer gradients at the subtropical edge of the surf zone or whether it is due to advective transport by the QBO circulation, a further trajectory calculation was performed. In parallel with the set of trajectories shown in Plate 2 which were advected by the full three-dimensional winds, a second set of trajectories was established. They were initialized in an identical fashion to the original trajectories but were subsequently advected by the modeled residual-mean circulation instead of the full three-dimensional winds. The TEM circulation was calculated at each model time step specifically for this purpose. In this way, we have eliminated any local influence on the trajectory distributions of isentropic mixing due to the presence of planetary waves.

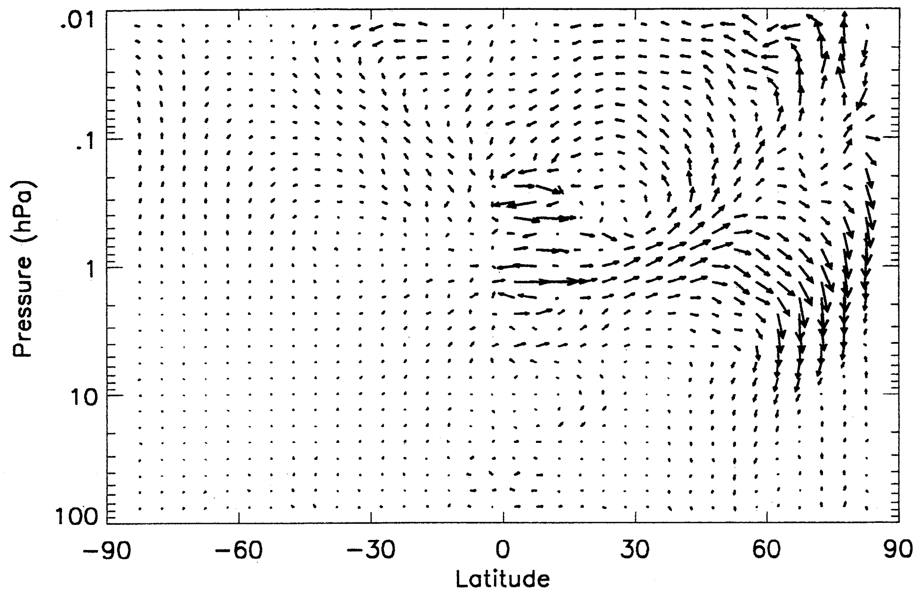

Figure 5. Latitude-height cross section of the modeled monthly averaged residual-mean circulation for January 1993 subtracted from the equivalent January 1992 field. The residual circulation components are represented by vector arrows of arbitrary scaling.

The distributions in February of the trajectories that had been initialized on the 15 mbar pressure surface are shown in Figure 6. Those advected by the residual mean circulation only are shown as crosses and the full 3-D wind trajectories (i.e., those shown in Figure 4) have been superimposed as dots for easy comparison. The residual-mean trajectory distributions have captured very well the distributions at equatorial and subtropical latitudes between 5 and 15 mbar in both years. Examination of the corresponding plots for those trajectories initialized on the other pressure surfaces (not shown) confirms that the residual circulation alone is able to reproduce the equatorial cliff (feature 1) and the subtropical ledge (feature 2). This is good evidence that these features are not caused by mixing processes associated with midlatitude planetary waves. On the other hand, the residual circulation trajectories do not reproduce the subtropical cliff (feature 3) at 20°-30°N, and this is discussed further below.

In Figure 7 the 15 mbar residual circulation trajectories from each year (i.e., those marked as crosses in Figures 6a and 6b) are plotted in the same axes in order to more easily compare them. There is virtually no difference between the two distributions in the Southern Hemisphere. The model results therefore suggest that the increased upwelling in the summer subtropics driven by stronger planetary wave driving in the easterly QBO phase may not be particularly great. Examination of Figure 5 also supports this since there is very little difference in the magnitude of the residual circulation anomaly in the southern subtropics. The major difference between the two years lies in the northern subtropics between 0° and 30°N. This suggests that the depression of the trajectories (or mixing ratio isopleths) in the winter subtropics by the QBO circulation and hence the suppression of the winter side of the equatorial bulge may be a significant factor in the shift of the equatorial peak into the summer hemisphere.

Figure 7 suggests that a strongly asymmetric anomalous circulation in the northern subtropics in 1992 compared to 1993 is required in order to explain the equatorial cliff and subtropical ledge. Relative descent just north of the equator is required at around 10-20 mbar together with equatorial outflow at 0° and 20°N around 20 mbar and a return arm with relative ascent at 10-20 mbar and 20°-30°N and equatorial inflow at the upper levels between 0° and 20°N above 15 mbar.

Figure 8 shows an expanded section of figure 7 in which only the vectors below 5 mbar are plotted. The magnitudes of the vectors have been increased, so their directions are clearer. At the lower levels of 40-60 mbar the direction of the equatorial circulation anomaly is as predicted by theory, with upward arrows indicating stronger equatorial ascent in 1992 (easterly QBO phase) than in 1993 (westerly QBO phase). However, at the higher levels in Figure 8 between 10 and 30 mbar there is relative equatorial descent in 1992 compared to 1993, signifying the presence of the next incoming westerly QBO phase in 1992. In the subtropics of the Northern Hemisphere there is a well-formed "return arm" of the QBO circulation with anomalously strong ascent in the northern subtropics. However, in the Southern Hemisphere subtropics, this return circulation in the subtropics is not present at all in December (not shown), and although present in January, it is much weaker than the corresponding Northern Hemisphere circulation. Hence at these levels there is substantial asymmetry in the induced QBO circulation. The sense of the anomalous circulation in Figure 8 is precisely that required to explain the 1992/1993 differences in trajectory distributions shown in Figure 7 and hence also to explain the presence of the equatorial cliff (feature 1) and subtropical ledge (feature 2) in the 1992 MLS H_2O distributions shown in Plate 1a. This asymmetry is in the same sense as in the two-dimensional models of *Jones et al.*, [1998] and *Kinnersley* (1999) caused by the nonlinear advection of zonal momentum. It also agrees well with the asymmetric circulations derived from UKMO-assimilated data by *Randel et al.* [1998, Figure 18].

The local equatorial QBO circulation at 10-30 mbar shown in Figure 8, which is responsible for the subtropical ledge (feature 2) at 8-20 mbar, extends only as far as 30°N. Pole-

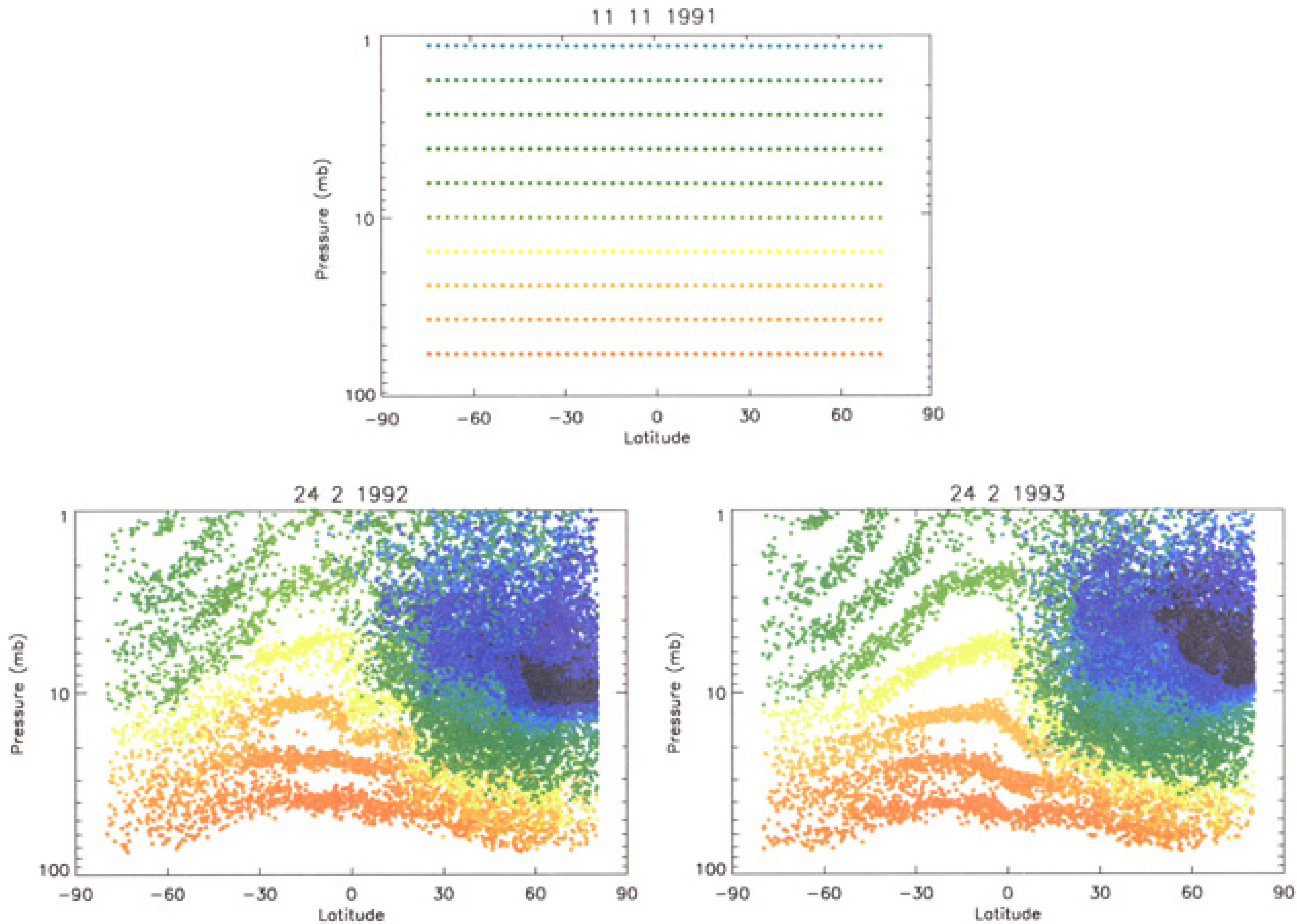

Plate 2. Height latitude distributions of the modeled parcel distributions (a) the initial distribution in November of each winter, (b) February 24 1992, easterly QBO phase, (c) February 24 1993, westerly QBO phase.

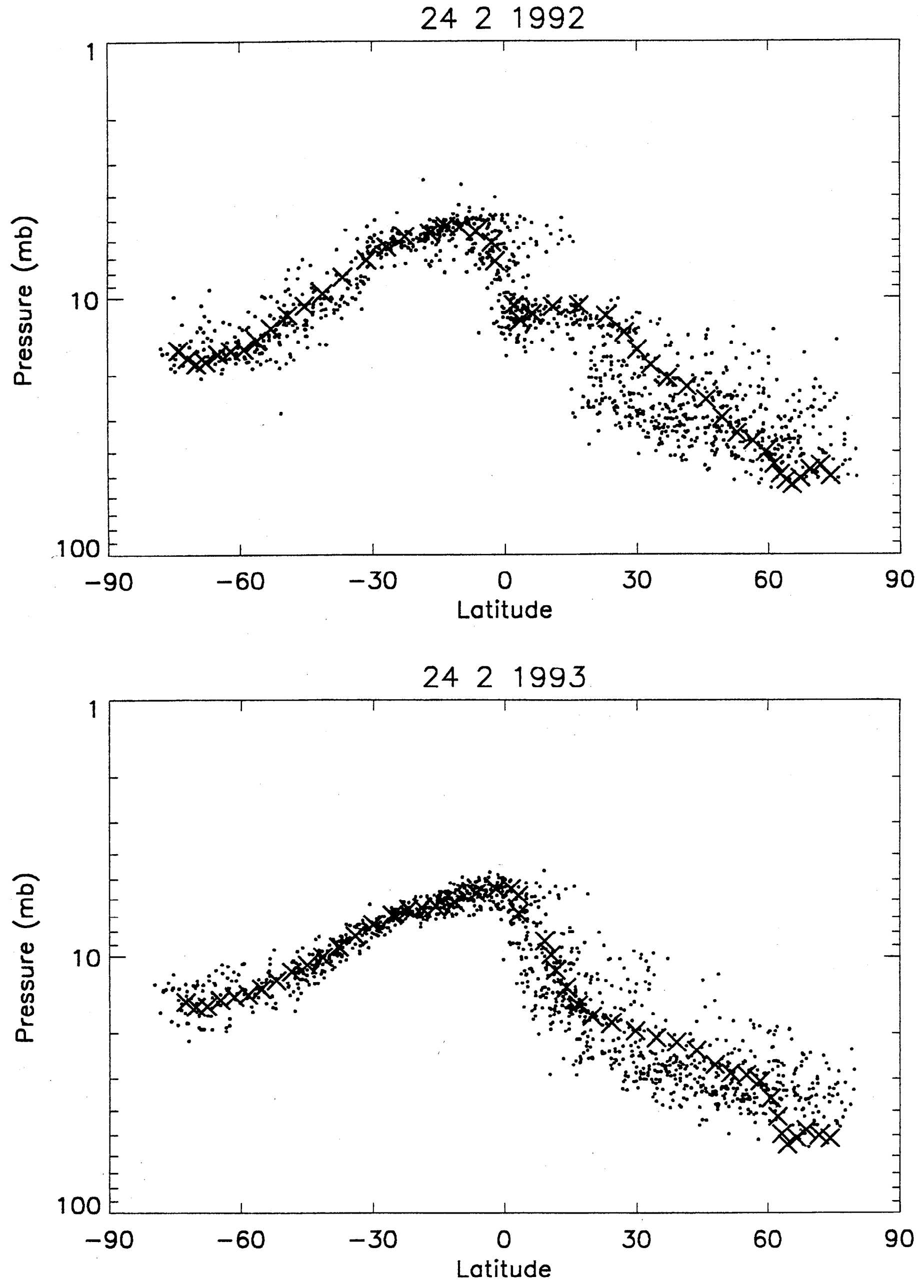

Figure 6. Modeled parcel positions on February 24 (a) 1992 and (b) 1993 for those trajectories initialized on the 15 mbar level and subsequently advected by the full three-dimensional circulation (dots) and the residual mean circulation (crosses).

ward of this, there is a general descent in midlatitudes which both Figures 5 and 8, show is stronger in 1992 than in 1993. Hence it is possible that the subtropical cliff (feature 3) could simply reflect the northward extremity of the QBO circulation, i.e., the northward edge of the subtropical ledge. On the other hand, the cliff could be due to erosion by the action of planetary waves, whereby strong tracer gradients develop at the subtropical edge of the surf zone. *Gray and Russell* [1999] found an increasingly important role for isentropic mixing associated with planetary waves in determining the subtropical tracer distributions above 20 mbar. The more effective mixing in the easterly QBO phase serves to flatten the isolines at midlatitudes but sharpen the isentropic tracer gradients at the poleward and equatorward edge of the surf zone [*McIntyre*, 1982; *Norton*, 1994]. This, in turn, will steepen the isoline slopes in the zonally averaged distribution if the mixing occurs throughout an extended height region of the atmosphere.

The trajectories that were advected by the full three-dimensional winds capture reasonably well the "subtropical cliff" (feature 3 at 20°-30°N and 8-20 mbar in 1992. Although the cliff is not easily seen in the multiple pressure level trajectory plot of Plate 2b because of the problem of overplotting of later trajectories, it is clearly evident in the 15 mbar trajectories (Figure 4a). The fact that the residual circulation trajectories (crosses in Figure 6a) do not capture the subtropical cliff at all well suggests that differential vertical advection at the northward extremity of the local QBO circulation is not

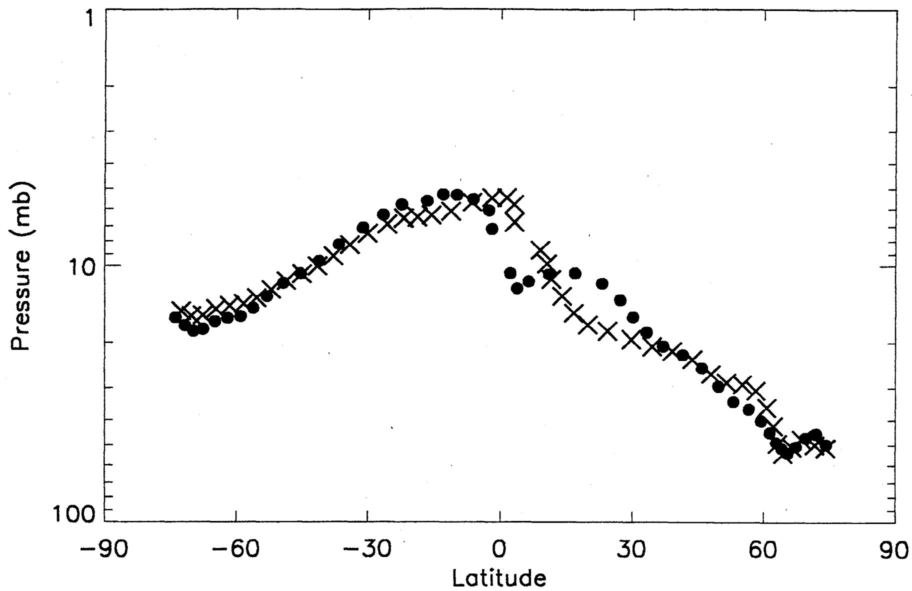

Figure 7. Height-latitude distributions on February 24 1992 (dots) and 1993 (crosses) of those parcels initialized on the 15 mbar level and subsequently advected by the residual circulation. This plot is therefore identical to the distributions marked by crosses in each of figures 6a and 6b.

sufficient to account for this subtropical cliff. The model diagnostics therefore suggest that isentropic mixing at the subtropical edge of the surf zone is also important in producing the steep isolines in the subtropics in the region 10-20 mbar.

5. 1992/1993 Difference Plots

O'Sullivan and Dunkerton [1997] have calculated H_2O and N_2O "difference" plots by subtracting the 1993 February/March fields from the corresponding fields for the same period in 1992. Plate 1c shows a similar plot for MLS H_2O on February 24. The main features of plate 1c are identical to those shown by *O'Sullivan and Dunkerton* [1997] and consist of a large negative H_2O anomaly centered at approximately 20°N and 10-20 mbar plus two positive anomalies, one over the equator at 30-60 mbar and one poleward of 40°N centered around 6-8 mbar.

The positive anomaly at the high northern latitudes is most likely the result of increased descent at high latitudes in the 1992 easterly QBO phase compared with 1993, as suggested by O'Sullivan and Dunkerton. The sign of the anomaly agrees well with the difference plots of the modeled large-scale residual circulation shown in Figure 5. The anomalously strong high-latitude descent in 1992 compared with 1993 will advect air with higher mixing ratios from above.

The large positive anomaly over the equator at 30-60 mbar is associated with a region of relatively wet air in 1992 centered at 50 mbar (see Plate 1a) compared with 1993 (Plate 1b). The pattern of alternating wet and dry layers in the equatorial lower stratosphere is associated with the annual cycle in tropopause temperatures [e.g. *Mote et al.*, 1995, 1996]. The relatively moist layer in 1992 at 30-60 mbar is at the level of increased equatorial ascent associated with the easterly shear zone (see Figure 8). The increased equatorial ascent will

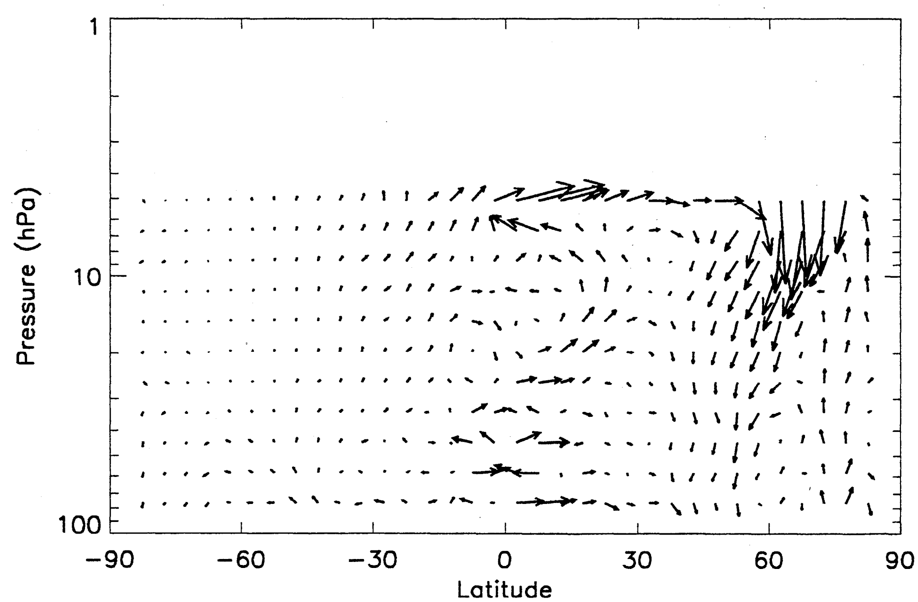

Figure 8. As for Figure 5 but showing only the circulation below 5 mbar in order to highlight the equatorial and subtropical circulations in the stratosphere.

serve to propagate the pattern of alternating moist and dry air upward more rapidly in 1992 than in 1993. In addition, there may be a QBO signal in the tropical tropopause temperatures contributing to this signal. A more extensive examination of the nature and amplitude of this anomaly is outside the scope of this paper.

The negative anomaly centered at 20°N and 10-20 mbar is around twice the amplitude of the positive anomalies. *O'Sullivan and Dunkerton* [1997] attributed this to the effect of the QBO winds on the subtropical extent of wave breaking and hence to isentropic mixing. We suggest that a comparison of the MLS data in Plates 1a and 1b clearly indicates that this difference anomaly is due to the presence of the subtropical ledge in 1992 in the region 8-15 mbar, 0°-20°N, which is not present in 1993. We have shown that the origin of this subtropical ledge is advection by the local QBO circulation. We therefore propose that the large negative anomaly at 20°N, 10-20 mbar is in fact due to the presence of the subtropical ledge in 1992 caused by the advection of low water vapor from the equator by the QBO circulation in the easterly QBO phase. We suggest that this large anomaly at 20°N has a separate origin from the tail of a much smaller amplitude negative anomaly that extends downward and poleward from 20°N to middle and high latitudes in Plate 1c. This latter "tail" of weakly negative anomaly is probably the result of enhanced meridional mixing by planetary waves in 1992 compared to 1993, as suggested by O'Sullivan and Dunkerton.

6. Summary

The main features and year-to-year variations in the zonally averaged H_2O distributions at equatorial and subtropical latitudes observed by MLS have been described and modeled. A notable feature in the Northern Hemisphere winter is a "staircase" feature described in detail in section 1, which is present in 1992 (Plate 1a) during the easterly QBO phase but not in 1993 (Plate 1b) during the westerly QBO phase. The equatorial and subtropical components of this feature are (feature 1) an asymmetric off-equatorial peak in the tracer isolines in the summer hemisphere above 8 mbar with steep isolines over the equator forming a vertical "equatorial cliff", (feature 2) a region of almost horizontal isolines forming a "subtropical ledge" between 8-15mbar and 0°-20°N which is also asymmetric, being present only in the Northern Hemisphere, and (feature 3) a region of almost vertical isolines forming a "subtropical cliff" in the Northern Hemisphere between 20°-30°N and 8-20 mbar. The presence of this staircase feature in QBO easterly phase years but not in westerly phase years is fairly well established throughout the UARS period [*Gray and Russell*, 1999].

In a model experiment for the period 1991-1993 in which the correct phase of the equatorial zonal wind QBO was prescribed, the staircase feature in 1992 and its absence in 1993 was reproduced (Plate 2 and Figure 4). Diagnosis of the residual circulation in the model showed that there were three main QBO-induced circulations: (1) the global scale circulation with stronger descent in the winter hemisphere during the easterly QBO phase due to increased planetary wave forcing, (2) below 30 mbar, a low-latitude QBO circulation which is fairly symmetric about the equator, and (iii) above 30 mbar, a low latitude circulation which is highly asymmetric about the equator and is strongest in the winter hemisphere, consistent with the recent work of *Jones et al.* [1998], *Randel et al.* [1999] and *Kinnersley* [1999].

A model experiment was performed in which parcel trajectories were advected (1) by the full three-dimensional circulation and (2) by the modeled residual circulation alone, so in the latter experiment, the local influence of planetary waves on the trajectories, i.e., isentropic mixing processes and the resulting tightening of gradients at the subtropical edge of the surf zone, was eliminated. Analysis of these model runs has indicated the following conclusions:

1. The "equatorial cliff" above 8 mbar (feature 1) and the Northern Hemisphere "subtropical ledge" at 8-15 mbar, 0°-20°N (feature 2) are both reproduced when only the residual circulation is used to advect the trajectories, showing the dominance of advection by the local QBO circulation in determining these features.
2. Advection of trajectories by the residual circulation alone does not reproduce the "subtropical cliff" at 8-20 mbar, 20°-30°N (feature 3). Its simulation required the inclusion of planetary waves, which increase the isentropic gradients of the tracers at the subtropical edge of the surf zone. This indicates the importance of planetary wave processes in the region 8-20 mbar.
3. The summer hemisphere subtropical peak in long-lived tracer distributions, which is prominent in easterly QBO phase years but not in westerly phase years, may not be entirely a result of increased subtropical upwelling caused by the increased planetary wave driving of the large-scale circulation, as is often assumed. The model diagnosis suggests that the appearance of the off-equatorial summer peak is also due to the depression of the winterside of the equatorial bulge. This depression is due to the smaller-scale local QBO circulation, which is highly asymmetric about the equator.
4. The largest difference in the H_2O distributions between the two years is a negative anomaly centered at 20°N, 10-20 mbar, as highlighted by the difference plots in Plate 1c. We propose that this is caused by advective transport of dry air from the equator by the local QBO circulation in 1992 and is not a result of isentropic mixing processes, as suggested by *O'Sullivan and Dunkerton* [1997].

Acknowledgments. This work was supported by the U.K. Natural Environment Research Council. I should like to extend my thanks to Hugh Pumphrey and the MLS team for the availability of such high-quality data, to Barbara Naujokat for the Singapore wind data, to Richard Kennaugh, Euain Drysdale, and Brian Lawrence for technical assistance in using the model, and to Tim Dunkerton and two anonymous referees for their comments on an early draft of the paper.

References

Barath, F. T., et al., The Upper Atmosphere Research Satellite Microwave Limb Sounder instrument, *J. Geophys. Res., 98*, 10,751-10,762, 1993.

Barnett, J. J., and M. Corney, Middle atmosphere reference model derived from satellite data, Middle Atmosphere Program, *Handb. MAP, 16*, 47-85, 1985a.

Barnett, J. J., and M. Corney, Discussion on variability in time and space: Planetary waves, climatological distribution, Middle Atmosphere Program, *Handb. MAP*, *16*, 86-137, 1985b.

Bowman, K. P., Global patterns of the quasi-biennial oscillation in total ozone, *J. Atmos. Sci., 46,* 3328-3343, 1989.

Butchart, N., S. A. Clough, T. N. Palmer, and P. J. Trevelyan, Simulations of an observed stratospheric warming with quasi geostrophic refractive index as a model diagnostic, *Q. J. R. Meteorol. Soc., 108*, 475-502, 1982.

Dunkerton, T. J., and D. J. O'Sullivan, Mixing zone in the tropical stratosphere above 10 mbar. *Geophys. Res. Lett., 23*, 2497-2500, 1996.

Fairlie, T. D. A., M. Fisher, and A. O'Neill, The development of narrow baroclinic zones and other small scale structure in the stratosphere during simulated major warmings, *Q .J. R. Meteorol. Soc.*, *116*, 287-315, 1990.

Farrara, J. D., M. Fisher, C. R. Mechoso, and A. O'Neill, Planetary scale disturbances in the southern hemisphere during early winter, *J. Atmos. Sci.*, *49*, 1757-1775, 1992.

Fisher, M., The Met. O. 20 Stratosphere Mesosphere Model, *Dyn. Climatol. Tech. Note* 52, Meteorol. Off., Bracknell, England, 1987.

Fisher, M., A. O'Neill, and R. Sutton, Rapid descent of mesospheric air into the stratospheric polar vortex. *Geophys. Res. Lett.*, *20*, 1267-1270, 1993.

Gray, L. J., and T. J. Dunkerton, The role of the seasonal cycle in the quasi biennial oscillation of ozone, *J. Atmos. Sci.*, *47*, 2429-2451, 1990.

Gray, L. J, and J. A. Pyle, The semi-annual oscillation and equatorial tracer distributions, *Q. J. R. Meteorol. Soc.*, *112*, 387-407, 1986.

Gray, L. J, and J. A. Pyle, A two-dimensional model of the quasi-biennial oscillation in ozone, *J. Atmos. Sci.*, *46*, 203-220, 1989.

Gray, L. J., and J. M. Russell III, Interannual variability of trace gases in the subtropical winter stratosphere, *J. Atmos. Sci.*, *56*, 977-993, 1999.

Gray, L. J., and S. Ruth, The modelled latitudinal distribution of the ozone QBO using observed equatorial winds, *J. Atmos. Sci.*, *50*, 1033-1046, 1993.

Hamilton, K., Interhemispheric asymmetry and annual synchronisation of the ozone quasi biennial oscillation, *J. Atmos. Sci.*, *46*, 1019-1025, 1989.

Hasebe, F., Interannual variations of global total ozone revealed from Nimbus 4 BUV and ground-based observations, *J. Geophys. Res.*, *88*, 6819-6834, 1983.

Hess, P. G., and D. O'Sullivan, A three dimensional modeling study of the extratropical quasi biennial oscillation in ozone, *J. Atmos. Sci.*, *52*, 1539-1554, 1995.

Hitchman, M. H., M. McKay, and C. R. Trepte, A climatology of stratospheric aerosol, *J. Geophys. Res.*, *99*, 20,689-20,700, 1994.

Holton, J. R., Influence of the annual cycle in meridional transport on the quasi biennial oscillation in total ozone, *J. Atmos. Sci.*, *46*, 1434-1439, 1989.

Jones, D. B., H. R. Schneider, and M. B. McElroy, Effects of the quasi-biennial oscillation on the zonally averaged transport of tracers, *J. Geophys. Res.*,*103*, 11,235-11,249, 1998.

Kinnersley, J. S, On the seasonal asymmetry of the low and middle latitude QBO circulation anomaly, *J. Atmos. Sci.*, 56, 1140-1153, 1999.

Lait, L. R, M. R. Schoeberl, and P. A. Newman, Quasi-biennial modulation of the Antarctic ozone depletion, *J. Geophys.Res.*, *94*, 11,559-11,571, 1989.

Marks, C. J., Linear wavetrains in models of the stratosphere, *Q. J. R. Meteorol. Soc.*,*114*, 297-323, 1988.

McIntyre, M. E., How well do we understand the dynamics of stratospheric warmings?, *J. Meteorol. Soc. Jpn. 60*, 37-65, 1982.

Mote, P. W, K. H. Rosenlof, J. R. Holton, R. S. Harwood, and J. W. Waters, Seasonal variations of water vapor in the tropical lower stratosphere, *Geophys. Res. Lett.*, *22*, 1093-1096, 1995.

Mote, P. W., K. H. Rosenlof, M. McIntyre, E. S. Carr, J. C. Gille, J. R. Holton, J. S. Kinnersley, H. C. Pumphrey, J. M. Russell, and J. W. Waters, *J .Geophys. Res.*,*101*, 3989-4006, 1996.

Norton, W. A., Breaking Rossby waves in a model stratosphere diagnosed by a vortex following coordinate system and a technique for advecting material contours, *J. Atmos. Sci.*, *51*, 654-673, 1994.

O'Neill, A., and V. D. Pope. Simulations of linear and nonlinear disturbances in the stratosphere, *Q. J. R. Meteorol. Soc.*, *114*, 1063-1110, 1988.

Ortland, D. A., W. R. Skinner, P. B. Hays, M. D. Burrage, R. S. Lieberman, A. R. Marshall, and D. A. Gell, Measurements of stratospheric winds by high-resolution Doppler imager, *J. Geophys. Res.*, *101*, 10,351-10,363, 1996.

O'Sullivan, D., and P. Chen, Modeling the QBO's influence on isentropic tracer transport in the subtropics, *J. Geophys. Res.*, *101*, 6811-6821, 1996.

O'Sullivan, D., and T. J. Dunkerton, The influence of the quasi-biennial oscillation on global constituent distributions, *J. Geophys. Res.*, *102*, 21,731-21,743, 1997.

Randel, W. J., and J. B. Cobb, Coherent variations of monthly mean column ozone and lower stratospheric temperature, *J. Geophys. Res.*, *99*, 5433-5447, 1994.

Randel, W. J., and F. Wu, Isolation of the ozone QBO in SAGE II data by singular decomposition, *J. Atmos. Sci.*, *53*, 2546-2559, 1996.

Randel, W. J., F. Wu, J. M. Russell, and A. Roche, Seasonal cycles and QBO variations in stratospheric CH_4 and H_2O observed in UARS HALOE data, *J. Atmos. Sci.*, *55*, 163-185, 1998.

Randel, W. J., F. Wu, R. Swinbank, J. Nash, and A. O'Neill, Global QBO circulations derived from UKMO stratospheric analyses, *J. Atmos. Sci.*, *56*, 457-474, 1999.

Roche, A. E., J. B. Kumer, J. L. Mergenthaler, G. A. Ely, W. G. Uplinger, J. F. Potter, T. C. James, and L. W. Sterrit, The cryogenic limb array etalon spectrometer (CLAES) on UARS: Experiment description and performance, *J. Geophys. Res.*, *98*, 10,763-10,776, 1993.

Rosier, S. M., and B. N. Lawrence, The January stratospheric sudden warming : A role for tropical inertial instability?, *Q. J. R. Meteorol. Soc.*, in press, 1999.

Russell, J. M. III, L. L. Gordley, J. H. Park, S. R. Drayson, W. D. Hesketh, R. J. Cicerone, A. F. Tuck, J. E. Frederick, J. E. Harries, and P. J. Crutzen, The Halogen Occultation Experiment, *J. Geophys. Res.*, *98*, 10,777-10,797, 1993.

Scaife, A. A., and I. N. James, Response of the stratosphere to interannual variability of tropospheric planetary waves, *Q. J. R. Meteorol. Soc.*, in press, 1999.

Shine, K. P., The middle atmosphere in the absence of dynamical heat fluxes, *Q .J. R. Meteorol. Soc.*, *113*, 603-633, 1987.

Shine, K. P., and J. A. Rickaby, Solar radiative heating due to absorption by ozone in *Proceedings of the Hampton, Va., Quadrennial Ozone Symposium* edited by P. Fabian and R. Bojkov, pp. 597-601, A. Deepak, Hampton, Va., 1989.

Swinbank, R., and A. O'Neill, A stratosphere troposphere data assimilation system, *Mon. Weather Rev.*, *122*, 686-702, 1994.

Trepte, C. R., and M. H. Hitchman, Tropical stratospheric circulation deduced from satellite aerosol data, *Nature*, *355*, 626-628, 1992.

Tung, K. K., and H. Yang, Global QBO in circulation and ozone, I, Re-examination of observational evidence, *J. Atmos. Sci.*, *51*, 2699-2707, 1994a.

Tung, K. K., and H. Yang, Global QBO in circulation and ozone, II, A simple mechanistic model, *J. Atmos. Sci.*, *51*, 2708-2721, 1994b.

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(Received October 23, 1998; revised April 28, 1999; accepted May 7, 1999.)