Interannual variability of stratospheric zonal wind forced by the Northern lower-stratospheric large-scale waves.

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Abstract

An interactive stratospheric model was run for 13 years while being forced with the observed daily-varying northern hemisphere (NH) waves (numbers 1 to 3) on the 368K isentropic surface (which lies near 150mb) from 1980 to 1993. It reproduced much of the observed inter-annual variability (IAV) in the high-latitude monthly-mean stratospheric zonal winds during NH winter, especially in December. In the model, wave-1 played the major role in producing the high latitude IAV. In addition, observations (from 1974-95) revealed some strong anti-correlations between the large-scale 150mb stationary wave-1 amplitude and the 10mb high-latitude zonal wind during the NH early winter. It therefore seems that planetary wave variability in the lower stratosphere is the direct cause of much of the IAV in the monthly-mean stratospheric zonal wind during the NH winter (especially in December). During late winter agreement between model and observations is improved by increasing the damping of planetary waves in the tropics. Since the variability in the NH high-latitude winter zonal wind is so well modeled it does not seem likely that the high-latitude stratosphere is strongly chaotic, at least in early winter and on the time scale of a month. It also implies that if the stratospheric equatorial QBO affects the extra-tropics in December (as implied by observations) then it must do so by somehow influencing the planetary waves at 150mb. It is shown that this influence is disrupted by strong tropospheric activity, as in the early winter of 1987. The model also produces a QBO signal in the SH tropics during NH winter, due to the variability in the wave-induced cross-equatorial flow.

1 Introduction

It is well known that there is a large interannual variability in the northern winter stratospheric zonal wind (eg. Labitzke 1982, Kodera 1995), and much effort has gone into finding possible stratospheric and tropospheric causes for this variability. Part of the variability may be linked to the quasi-biennial oscillation (QBO) in the equatorial lower stratosphere which appears to affect the propagation and dissipation of extra-tropical planetary waves and hence their forcing of the zonal-mean circulation (eg. Holton and Tan 1982, Dunkerton and Baldwin 1991, Tung and Yang 1994). In addition, it is possible that the solar cycle modulates the effect of the QBO (Labitzke and van Loon 1995, Kodera 1993) by perturbing the upper-stratospheric zonal winds in early winter (Kodera 1991). Also, variations in the winter-mean stratospheric zonal winds are well correlated with the tropospheric North Atlantic Oscillation (eg. Baldwin et al. 1994) and stratospheric sudden warmings appear to be linked to blocking events in the troposphere (see eg. Kodera and Chiba 1995) though the connection is not very robust or well understood as yet.

The purpose of this paper is to investigate the role of the lower-stratospheric large scale waves in the inter-annual variability of the stratosphere and to this end it will be useful to describe now four scenarios, each of which may only partly describe the operation of the stratosphere.

(1) It may be that much of the stratospheric variability is internal to the stratosphere and that, given an annually periodic wave forcing from the lower stratosphere, the zonal wind perturbations due to the equatorial QBO and solar cycle could induce much of the extra-tropical interannual variability by affecting the propagation of extra-tropical planetary waves and their breaking in the upper stratosphere (eg. Tung and Yang 1994).

(2) However, it may be that planetary waves in the lower stratosphere are modulated by the equatorial QBO (Holton and Tan 1982, Butchart and Austin 1996). This modulation may be just an 'echo' of what is happening higher up, or it may be that it is important (since it is in the most dense part of the stratosphere) in driving the planetary-wave variability throughout the stratosphere and hence in producing the extra-tropical variability. It seems that a zonal wind perturbation in the upper stratosphere can be conveyed to the zonal wind (and hence also the planetary waves) in the lower stratosphere or troposphere via wave-mean interactions acting over a number of months (Kodera 1995, Kodera and Chiba 1995). However, the connection between stratosphere and troposphere may be more rapid if a wave becomes resonant (see eg. Tung and Lindzen 1979). Such resonance appeared to occur for wave-2 during the February 1979 sudden warming (Smith 1989). If such a resonance were common for wave-1 also, we would expect some sort of signal from the equatorial QBO to appear in the lower-stratospheric planetary waves. As discussed by McIntyre (1982) among others, this may in fact be how the equatorial QBO extends itself to high latitudes - by perturbing the stratospheric zonal wind at low latitudes and bringing about a resonance (or preventing resonance) in a high latitude planetary wave, which then affects the zonal mean state.

(3) The lower-stratospheric planetary waves may also be strongly influenced by tropospheric variability which is independent of the equatorial QBO or the solar cycle – such as the North Atlantic Oscillation (NAO) (Baldwin et al. 1994) or the December 1987 major warming (Baldwin and Dunkerton 1989).

(4) The winter stratosphere may also be partly chaotic, (Holton and Mass 1976) or the inertia of the tropical zonal wind may create a partial memory lasting for about a year (Scott and Haynes 1997). Volcanic emissions may also be important (eg. Kodera 1995).

The total stratospheric variability may then be a combination of these four factors, which would be consistent with the imperfect correlations found between the stratospheric zonal wind and the equatorial QBO (eg. Baldwin and Dunkerton 1991) or the NAO (Baldwin et al. 1994).

Whatever the case, the role of the lower stratospheric planetary waves in producing the extra-tropical variability in zonal winds could be estimated by forcing a model with the observed lower stratospheric wave amplitudes for a number of years (and without any other interannually varying forcing) and seeing how much of the interannual variability in the stratospheric winds can be reproduced. If the equatorial QBO and solar cycle influence high latitudes mainly by changing the refractive index of the upper stratosphere and thereby altering the propagation of planetary waves in the stratosphere (scenario 1 above) or if the stratosphere is strongly chaotic, has a strong memory or is often strongly perturbed by volcanic emissions (scenario 4) then we would not expect to see a good reproduction in the model of the observed variability. However, if the variability of tropospheric planetary waves is strong (scenario 3) or the equatorial QBO and solar cycle cause a large enough modulation of the extra-tropical planetary waves in the lower stratosphere (scenario 2) then we could hope to see good agreement between modeled and observed stratospheric zonal-mean zonal winds.

The model and data used will be described in section 2. Then certain correlations between the stationary waves at 150mb and the zonal wind at 10mb will be shown in section 3, for the periods March 1980 to March 1993 (which is the period over which the model was run) and from January 1974 to December 1995 (which is the total span of the data used here). These correlations suggest a strong influence of the wave amplitudes on the zonal wind. This influence is demonstrated in section 4 by running the model forced with the observed wave amplitudes in the lower stratosphere. The effect of waves 1 and 2 and the sensitivity of the results to the tropical damping of the planetary waves in the model is also investigated. In section 5 the effect of the troposphere on the lower-stratospheric waves is discussed and the possibility that the equatorial QBO affects the extra-tropical zonal winds by modulating the lower-stratospheric wave amplitudes is investigated in section 6.

2 Model, data and statistics.

2.1 The Numerical Model

The THIN-AIR two-and-a-half dimensional interactive stratospheric model (described fully in Kinnersley 1996) is used for the experiments in this paper. Briefly, it extends from the ground to about 100km using an isentropic vertical coordinate (and sigma coordinates in the troposphere) with a vertical resolution of about 3.5km, and from pole to pole with a meridional resolution of about 9 degrees. The chemistry and radiation modules are two-dimensional (zonally-averaged) which leads to a huge saving in computer resources over a three-dimensional model, but are fairly sophisticated and interact with each other and the dynamical module. The dynamical module is quasi-geostrophic and is truncated at zonal-wavenumber 3, which again saves computer resources while allowing for interaction between the zonal mean state and the large scale planetary waves. For the runs in this paper, the planetary-wave breaking parametrisation used in Kinnersley (1996) has been abandoned and the waves were acted upon by a meridional diffusion of $5x10^5$ m^2s^{-1}, which damps 2-grid-length anomalies with a time constant of about 10 days, and are damped equatorwards of 35 degrees with a time constant of 1.5 days. The influence of this tropical damping will be discussed in section 4.5. Above about 42 km, the waves were damped with a time constant of 2 days. The flux-gradient method (eg. Newman et al. 1988) was used to derive a horizontal diffusion coefficient for use with the trace gases. The replacement of the breaking parametrisation with the simpler damping just described does not degrade the model's climatological performance (as will be demonstrated in some of the results shown here, in particular figures 5 and 10) but allows us to experiment more easily with the effect of planetary wave damping in the tropics (see section 4.5).

A parametrisation of gravity waves helps to produce fairly realistic stratospheric and mesospheric winds. The interaction between the different modules in this model (the chemistry, zonal-mean, planetary wave and gravity wave modules) affects the net inter-annual variability in the model, but is not by itself a source of interannual variability (as will be discussed in section 4). The only source of interannual variability in the model is the specification from observations of the three longest planetary waves in the lower NH stratosphere.

The planetary waves are forced on the 368K isentropic surface (which lies near 150mb during high latitude winter) using the observed daily-varying data for the three longest zonal wave components. The run described in this paper is a 13 year run, forced in the NH using the observed waves from March 1980 to March 1993, while the SH wave forcing is annually periodic, using the observed waves from July 1980 to June 1981. It was decided to keep the SH wave-forcing annually periodic for two reasons. First, this reveals the effect on the SH of variations in the NH wave forcing modulating the cross-equatorial mean circulation (since the planetary wave model is quasi-geostrophic, the waves in one hemisphere cannot directly influence those in the other hemisphere). Second, when the SH wave variations were specified from observations the interannual variability in the SH of the model was much larger than observed. This was assumed to be due to the scarcity of surface pressure observations in the SH with which to build up an accurate value for geopotential height. The model was initialised from a previous model run with annually-periodic planetary wave forcing which had reached an annually periodic state (in section 4 the implications of the model reaching an annually-periodic state are discussed).

2.2 Data

The daily temperature and geopotential height data used to calculate the three longest zonal waves in Montgomery potential (the isentropic-coordinate equivalent of geopotential) on the 368K isentropic surface, which were used to force the planetary waves in the model, are the same at those used in Kinnersley (1996) (though spanning from March 1980 to April 1993 instead of from July 1980 to June 1981) and are derived from the National Meteorological Center (NMC) data set(see Clough et al. 1985). The other data used in this paper was monthly-mean zonal winds and geopotential heights on pressure surfaces from 1000mb to

10mb from January 1974 to December 1995, taken from the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) re-analysed NMC data set (Kalnay et al. 1996). This data, produced by assimilation into a state-of-the-art GCM, should be more reliable and accurate than previous NMC data sets. The geopotential heights were Fourier analysed to extract the three longest wave components in the zonal direction.

2.3 Statistical calculations.

The correlations shown throughout this paper are all calculated from monthly-mean values. The signifigance of the correlations was calculated in the following simple way. The correlation between the observed and modeled anomalies in the monthly-mean zonal wind at a certain height and latitude from 1980 to 1992 involves 13 pairs of numbers. With 13 pairs of random numbers, the probability of obtaining a correlation coefficient of greater than 0.48, 0.64 and 0.79 is 0.05, 0.01 and 0.001 respectively. This is expressed in this paper by saying that correlations of 0.48, 0.64 and 0.79 obtained over 13 years are significant at the 95% , 99% and 99.9% levels respectively. For 22 years, the 95% , 99% and 99.9% levels occur at values for the correlation coefficient of 0.35, 0.47 and 0.60.

3 Correlations between 150mb stationary waves and 10mb zonal wind

Before discussing the model runs, it is useful to see how well the observed stratospheric zonal winds are correlated with the stationary planetary wave amplitudes at certain points in the lower stratosphere. In particular, the correlation between the 10mb monthly-mean zonal-mean zonal wind and the monthly-mean geopotential wave amplitude at a certain latitude on the 150mb surface (for zonal wavenumbers 1 to 3) will be shown here. Note that this is a very simple-minded inspection - no information about wave transience or phase tilt is used in the correlations. Nevertheless, strong correlations were obtained between the high-latitude wave-1 amplitude at 150mb and the northern hemisphere 10mb zonal wind. Figure 1a shows the correlation between the 150mb wave-1 amplitude at 60N (the latitude at which the correlations were strongest) and the 10mb zonal wind from March 1980 to February 1993 (the period over which the model was run) while Fig 1b uses the period from January 1974 to December 1995. Only the contours corresponding to the 95, 99 and 99.9 per cent significance levels are plotted. The two time periods give very similar values for the significance of the correlations and so this gives us confidence that 1980-92 is not a 'special' period, and that conclusions drawn from the period 1980-92 will be valid also for the longer period.

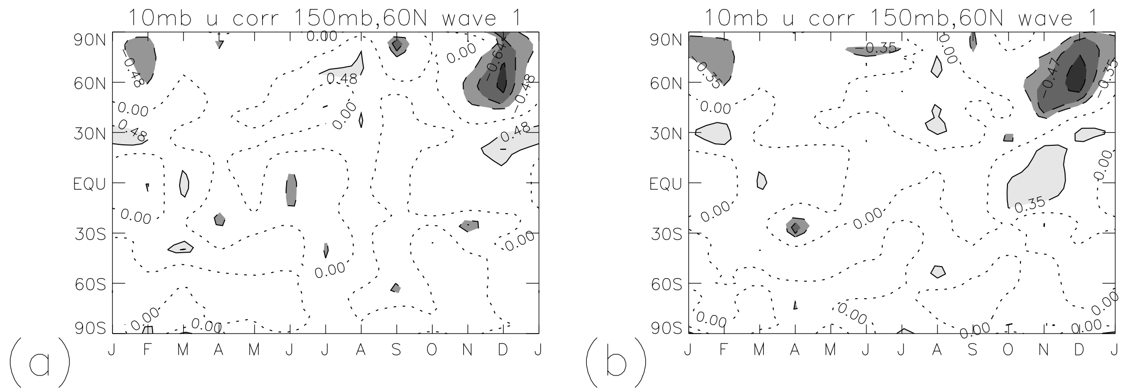

Figure 1: *Correlation between monthly-mean zonal wind at 10mb and monthly-mean stationary wave-1 amplitude at 60N, 150mb over (a) 1980–92 (contours at 0.48, 0.64, 0.79) (b) 1974–95 (contours at 0.35, 0.47, 0.60). Contours are plotted at the 95, 99 and 99.9 per cent significance levels. Dark shading indicates a negative value, light shading indicates a positive one.*

The strongest anti-correlations (which could imply that large waves are forcing the zonal wind to be weak) were obtained in December north of 40N. It is remarkable that such strong correlations (exceeding the 99.9% significance level) were obtained, since no information about wave transience or phase tilt (which are important for sudden warmings - see eg. Butchart et al. 1987) is used to obtain them. Thus while wave transience and phase tilt may be important for periods of less than a month, it seems that the stationary wave-1 amplitude at 60N and 150mb is an excellent index for the variability of the monthly-mean high-latitude NH zonal wind in December. The anti-correlation is also strong in November closer to the equator, and in February closer to the pole. This polewards propagation is reminiscent of the work of Dunkerton and Baldwin (1991) and Kodera (1991). Note that January does not have as strong an anti-correlation. Note also that at about 30N there is a positive correlation from December till February, which is consistent with the observation of a dipole in the northern winter zonal wind anomaly (eg. Dunkerton and Baldwin 1991), with the zonal wind anomaly near 60N being out of phase with the one near 30N.

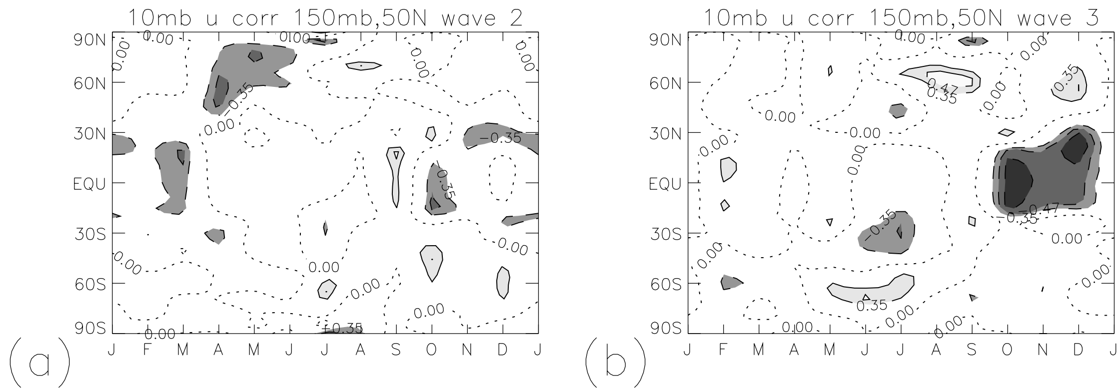

Figure 2: *(a) As figure 1b but for wave-2 at 50N, 150mb. (b) As figure 1b but for wave-3 at 50N, 150mb.*

The 150mb wave-2 amplitude at 50N (Figure 2a) is uncorrelated with the 10mb zonal wind during northern winter at high latitudes, but at lower latitudes and even in the southern tropics from December till March there are fairly large anti-correlations. The 150mb wave-3 amplitude at 50N (Figure 2b) shows a large anti-correlation with the 10mb zonal wind from October till December throughout the tropics, and also at high latitudes in January. Although figure 2 shows the correlations over the 22 year period (1974-1995), the significance of the correlations over the period of the model experiment (1980-1992) was very similar.

These anti-correlations may imply that the 150mb waves are forcing the 10mb zonal wind (stronger waves producing more wave drag on the zonal wind). Or they may be a response to the wind at 10mb or lower down (a stronger zonal wind perhaps inhibiting upward wave propagation – the Charney-Drazin criterion). Or, there may be some feedback mechanism, with the waves both responding to and forcing the zonal wind.

The above examples were mainly to suggest regions where we might expect each wave to exert an influence on the 10mb zonal wind. Actual evidence for wave-forcing of the zonal wind will be provided in the next section, from the results of several model runs. In fact the model can be regarded as a tool for combining all the information contained in the three waves and producing a result in terms of their net effect on the zonal wind.

4 Results of model runs

To see how large a degree of internal interannual variability the model has, the model was run for fourteen years with an annually-periodic planetary wave forcing (using the daily-varying July 1980 to June 1981 data). The interannual variability over the last thirteen years of the run was small – at 10mb, the standard deviation of the monthly-mean zonal winds from the modeled climatology was less than 0.2 m/s in summer and less than 0.8 m/s in winter in both hemispheres. The stratosphere of this model then is inherently non-chaotic, unlike the model of Holton and Mass (1976), perhaps because observed wave amplitudes were used here to force the stratospheric waves, and perhaps because these waves were damped in the tropical stratosphere. Different results may have been obtained if a different year's wave forcing had been used instead of July 1980 to June 1981 (although a similarly small interannual variability was obtained using the July 1987 to June 1988 wave forcing). However, since the model was able to reproduce much of the observed variability well when driven by the observed inter-annually varying wave forcing, as will be shown below, it seems that chaotic behaviour, if it happens, must at least be confined to those times and places where the model is not well correlated with observations.

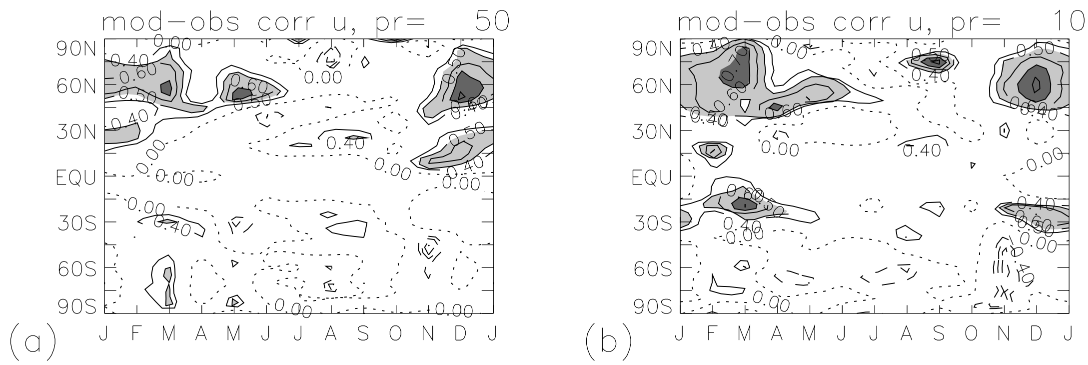

Figure 3: *Correlation between modeled and observed monthly-mean zonal wind at (a) 50mb, and (b) 10mb, from 1980-1992. (Contours at* $\pm 0.4, \pm 0.5 ...$*), Values above 0.5 are lightly shaded. Those above 0.7 are heavily shaded.*

The model was then run using the observed daily-varying waves 1 to 3 on the 368K surface from March 1980 to April 1993, starting from the March data of the last year of the model run described above. The correlation (over the 13 years from 1980 to 1992) between the modeled and observed monthly-mean zonal wind anomaly (the deviation from climatology) for each month and latitude at 50mb and 10mb is shown in figure 3, and the modeled and observed standard deviations (the r.m.s. values of the deviations from the monthly climatologies) of the monthly-mean 10mb zonal wind are shown in figure 4. These figures are discussed in the following sections.

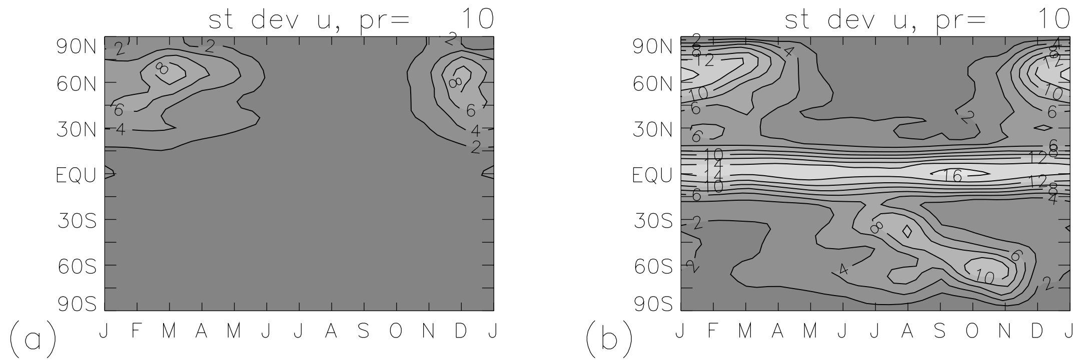

Figure 4: *Standard deviation of monthly-mean zonal wind at 10mb (a) modeled and (b) observed, in m/s.*

4.1 Extra-tropical variations.

The modeled zonal wind anomalies are well correlated with those of the observations from 50mb to 10mb and from November till March north of about 40N, though January has a poorer correlation. In this region the modeled standard deviation is comparable with that observed, though the model is generally less variable than observations, especially in January. The poor correlation and small variability in the modeled January is perhaps connected with the small correlation between stationary wave-1 and the 10mb zonal wind seen in January in figure 1(a). A comparison of modeled and observed zonal wind (figure 5) at 55N from November to March (but without January) shows that the model generally picks up the extreme behaviour of the stratosphere (for example, the early warmings of December 1984 and 1987 and the late warmings in March 1984 and 1989) while intermediate years are sometimes not modeled well. Also, the absolute values of the observed zonal wind as well as the variability are well reproduced by the model, a point which will be discussed further in section 4.5.

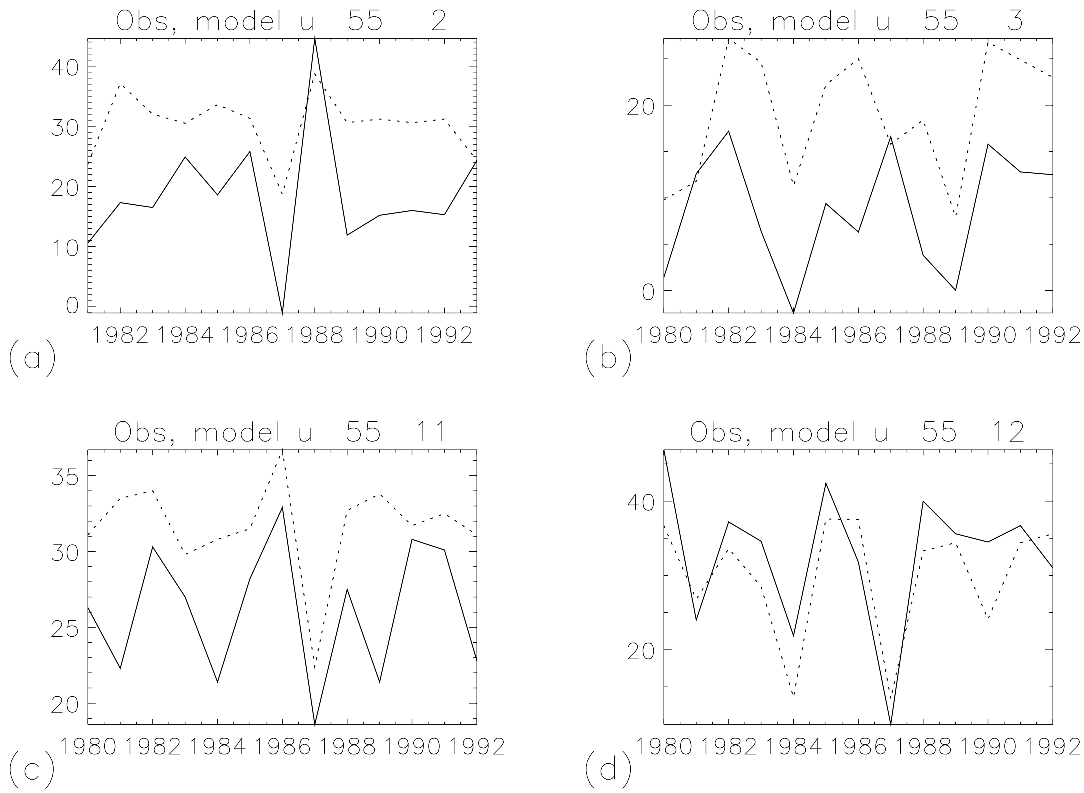

Figure 5: *Modeled (dotted) and observed (solid) 10mb zonal wind at 55N in (a) November, (b) December (c) February and (c) March.*

The agreement with observations over NH winter was better in some years than in others. The most impressive results were obtained in the winter of 1987/88, which contained a major warming in December (Baldwin and Dunkerton 1989). It can be seen (figure 6) that already in November the model agrees well with observations north of about 30N. It is remarkable that in December and January the model reproduces the westerly anomaly at low latitudes as well as the high-latitude easterly anomaly. It also captures well the polewards migration and decay of the easterly anomaly and its replacement by a strong westerly anomaly. As noted by Baldwin and Dunkerton, the sudden warming is inconsistent with the current theory of the equatorial QBO, since it occured during the QBO's westerly phase (see figure 6). Since the model does not have the observed westerly anomaly in the equatorial zonal wind and yet still simulates the extra-tropical behaviour, it suggests that the extra-tropical behaviour during winter 1987/88 was insensitive to the phase of the equatorial QBO but was instead strongly dependent on the planetary wave forcing from the lower stratosphere.

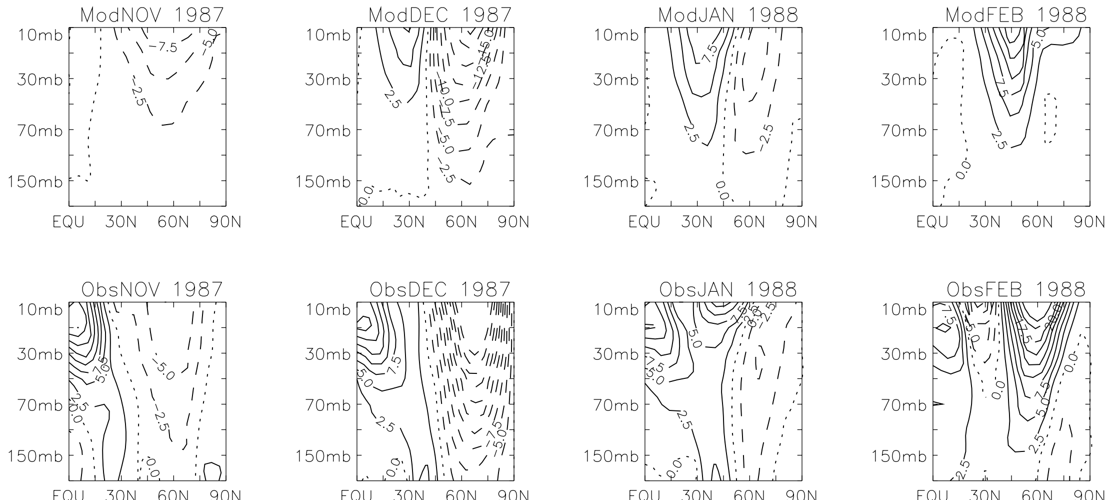

Figure 6: *Modeled (upper four panels) and observed (lower four) zonal wind anomalies from 200mb to 10mb from November 1987 till February 1988. (Contour interval 2.5m/s)*

The model has little variability below 200mb since the model troposphere is two-dimensional, does not interact strongly with the stratosphere and does not have any imposed interannual variability.

4.2 Sub-tropical variations.

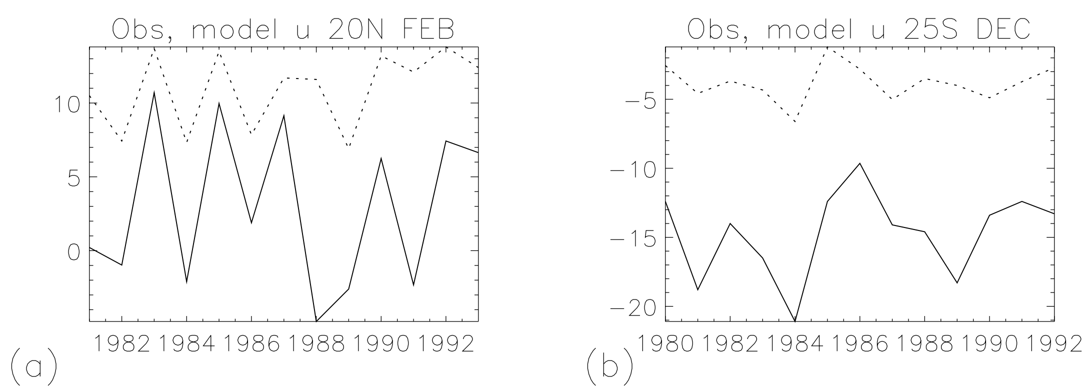

Figure 7: *(a) Observed (solid) and modeled (dotted) 10mb zonal wind anomalies at 20N in February. (b) Observed (solid) and modeled (dotted) 10mb zonal wind anomalies at 25S in December.*

At 20N in February there is a fairly strong correlation between model and observations, and the model's variability is a significant fraction of that observed (figure 7a). It is interesting that the wave forcing plays such a large role in the zonal wind variability so close to the equator where the QBO might be expected to dominate, and also that the variation produced by the waves is fairly well correlated with the 10mb zonal wind at the equator (not shown). The waves do not affect the equatorial winds significantly in the model since the variability of the equatorial wind is small in figure 4a. Therefore it would seem that the equatorial QBO at 10mb is somehow modulating the planetary waves in the lower stratosphere to produce a 10mb zonal wind variation at 20N in February which is in phase with the 10mb equatorial variation. The results of the next section show that this correlation is due to the variability in both waves 1 and 2, and so a strong correlation is not expected (nor is it evident in figures 1 or 2a) between either of the wave amplitudes and the 10mb zonal wind at 20N in February. However, since the mechanism for this correlation is not clear, and since it may be simply fortuitous, it will not be discussed further here.

4.3 Southern-hemisphere variations.

Part of the reason for varying the NH 150mb wave-forcing only (while keeping the SH wave-forcing annually-periodic) is to see its effect on the SH. At 30S in December the model is well correlated with observations and the variation is about a third of that observed (figure 7b). In this model there is no planetary-wave propagation across the equator – there is an equatorial condition of zero wave amplitude so that the geostrophic meridional wind is finite. Therefore, the only way planetary waves in the NH can affect the SH is by inducing a cross-equatorial meridional circulation. This will influence the SH zonal wind through advection of angular momentum. In the model, when the waves are large at low latitudes in the NH, the induced cross-equatorial flow is stronger and there will be a negative anomaly in the SH low-latitude zonal wind. In the real atmosphere, when the waves are large at low latitudes in the NH, waves with a small but easterly phase speed may propagate more strongly across the equator to break in the SH easterlies. Thus planetary waves in the real atmosphere may be expected to enhance a SH low latitude zonal wind anomaly caused by an anomaly in the cross-equatorial flow. This could explain the difference in amplitude between the modeled and observed anomalies. It is not unreasonable to expect easterly phase-speed Rossby waves near the equator to be produced by the growth and decay of wave forcing from the lower stratosphere. For example, a standing wave-2 disturbance in the tropics with a period of 20 days should produce waves with easterly and westerly phase speeds of about 10 m/s. The westerly phase-speed waves may be unable to propagate if they are faster than the zonal wind, but the easterly waves might propagate into the SH until they encounter their critical line.

4.4 Effect of individual zonal wave components

To see the extent to which an individual wave component can be said to be producing the interannual variability in the zonal wind at a certain time and latitude three additional runs were carried out. In the first one, only the wave-1 forcing was varied inter-annually (from 1980 to 1993) while waves 2 and 3 were annually periodic (using the 1980/81 values). The second run was similar to the first, except wave 2 was the only forcing which varied. In the third run both waves 1 and 2 varied while wave-3 was annually periodic.

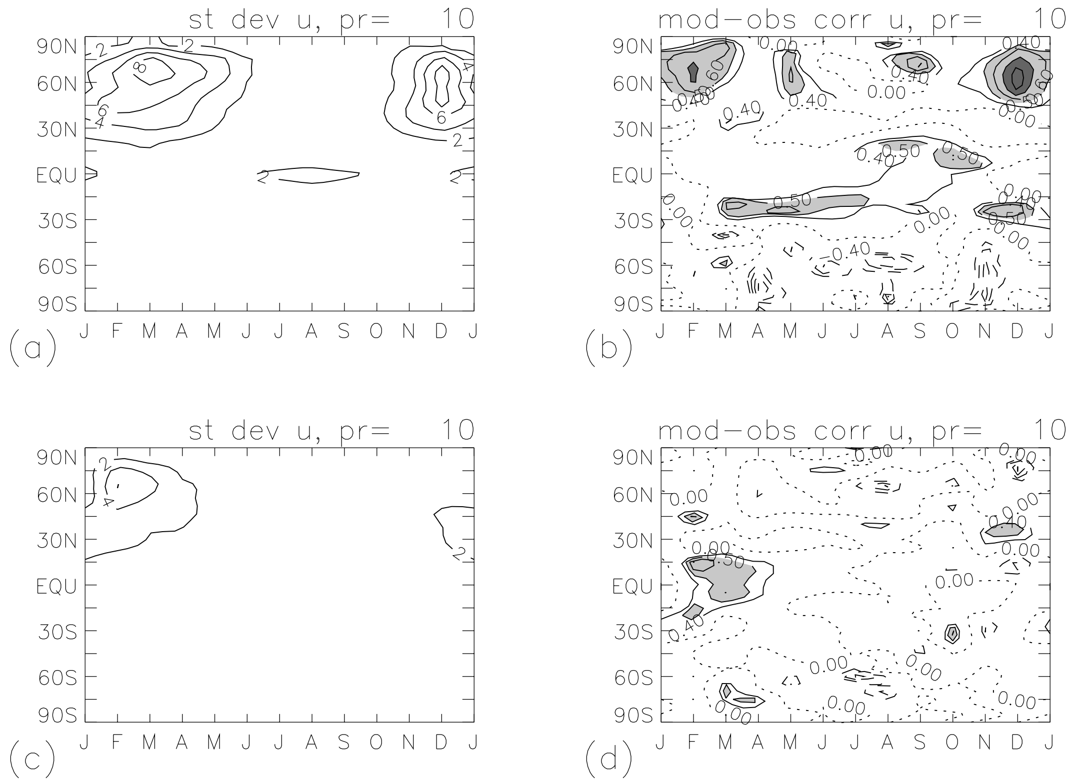

Figure 8: *(a) Standard deviation of modeled 10mb zonal wind and (b) correlation between modeled and observed zonal wind at 10mb, from 1980-1992, with only wave-1 varying from year to year. (c) and (d) as (a) and (b) but with only wave-2 varying from year to year.*

In the first run (figures 8a and 8b) the variation of wave-1 by itself reproduces fairly well by itself both the size and the phase of the zonal wind anomaly that was in the original model run north of about 50N. Also, wave-1 reproduces the correlation at about 25S in December. However, a close inspection of figures 8b and 3b reveals that the correlation at 45N from December until March is poorer in the 'wave-1 only' run, and that the late winter correlation is not quite as good. The second run, with interannually varying wave-2, has a much smaller variability (figure 8c) and shows generally poor correlation with observations (figure 8d). Neither run reproduces the correlation at 20N in February seen in the original run (figure 3b). The results of the third run (where waves 1 and 2 were both allowed to vary from year to year) was so similar to the original run that it can be said that the variability of wave-3 produces no significant variation in the modeled 10mb zonal wind.

It seems therefore that the modeled variability north of 50N and near 25S in December is due almost completely to wave-1. Including the wave-2 variability improves the performance in late winter and also near 45N from December till March. Both waves seem to be required to reproduce the variability at 20N in February.

4.5 Effect of tropical damping of planetary waves

The tropical damping of planetary waves was included for a number of reasons. First, wave breaking observed in the subtropical surf zone might be expected to remove energy from the long waves at low latitudes. Second, since the planetary waves in the model are quasi-geostropic, their behaviour at low latitudes is suspect and a damping of the waves at low latitudes might prevent unrealistic behaviour there (but only if enhanced damping there is physically realistic - as just suggested above). Third, the model was better able to simulate the inter-annual variability in the NH monthly-mean zonal wind when the damping was included.

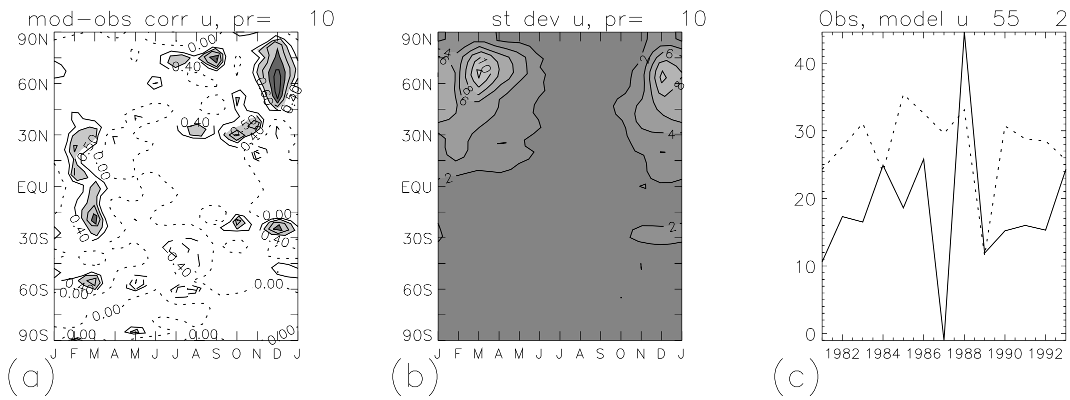

Figure 9: *(a) Correlation between modeled and observed zonal wind at 10mb, from 1980-1992, (b) standard deviation of 10mb zonal wind and (c) comparison of modeled (dotted) and observed (solid) 10mb zonal wind at 55N in February, from model with no added tropical damping of planetary waves.*

The correlation between modeled and observed 10mb zonal wind anomalies without tropical damping of planetary waves is shown in figure 9. It is seen that the NH December anomaly is still modeled well, but that the late winter anomaly is now badly modeled. The variability of the modeled 10mb zonal wind in late winter is slightly bigger without the tropical damping (figure 9b) but the large anomalies occur in the wrong years (see figure 9c).

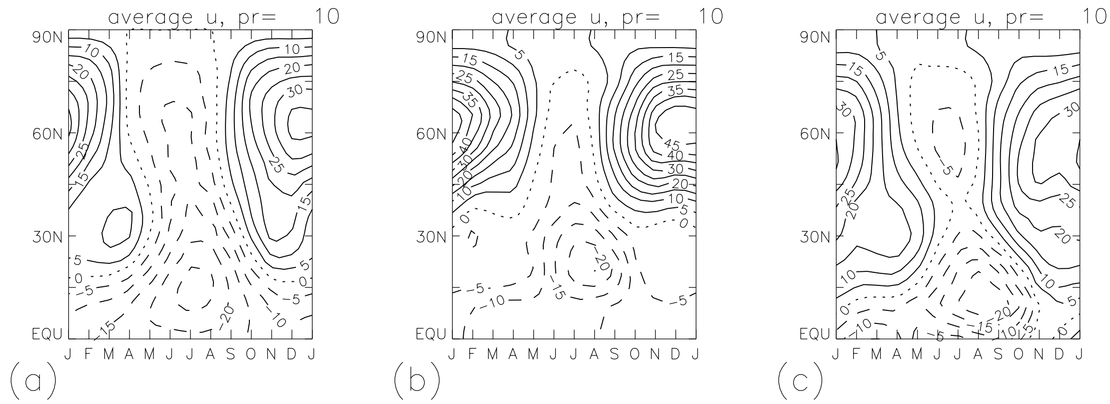

Figure 10: *Monthly-mean climatological 10mb zonal wind in NH (a) observed (b) from model with no added tropical damping of planetary waves (c) from original model.*

It is difficult to give a definite reason why better results are obtained with the tropical damping, but it appears to be connected with an improvement in the modeled NH climatological zonal wind. Figure 10 shows the observed climatological (the 1980 to 1992 average) zonal wind at 10mb and also the modeled climatological (from the modeled 1980 to 1992) wind without (fig 10b) and with (fig 10c) tropical damping. Without damping the modeled low-latitude wind is more easterly than observed and perhaps more importantly the zero-wind line is further polewards than observed. The low-latitude easterly winds in the model are caused mainly by low-latitude wave drag due to easterly phase-speed planetary waves (generated by transience in the forcing of the waves at 368K). These penetrate equatorwards of the zero-wind line and are absorbed either at their critical line or at the equator (where there is a zero-wave boundary condition). In the real atmosphere it seems that transient waves are also more important than stationary waves at low latitudes in the middle stratosphere – as can be readily seen from the calculations of Eliassen-Palm flux divergence given in Randel (1992). In the model, the tropical damping reduces the energy of these waves and hence reduces their drag on the zonal wind, allowing the zonal wind to become more westerly and bringing the zero-wind line closer to the equator. Since the position of the zero-wind line is believed to be important for the occurence of sudden warmings in middle and late winter, it seems reasonable to attribute the improvement in the model's late-winter variability to the more realistic positioning of the zero-wind line.

Since the variability of the modeled zonal wind in February appears to be sensitive to the background zonal wind, this implies that the interaction between waves and the zonal-mean state is at least as important to the evolution of the 10mb zonal wind as variation in wave-forcing from the lower stratosphere. This is consistent with the fact that the 10mb zonal wind was less strongly correlated with the amplitude of the 150mb stationary wave-1 in February than in December (figure 1).

5 Correlation between 150mb waves and tropospheric waves.

As was pointed out in the introduction, the 150mb waves may be affected both by stratospheric phenomena (eg. the QBO) and by upwards propagation of wave energy from the troposphere. Since the 10mb winds are strongly influenced by variations in the 150mb waves, it would be useful to have an estimate of the relative importance of stratospheric and tropospheric phenomena in producing the 150mb wave variability. Therefore, in this section the correlation between the 150mb waves and the tropospheric waves will be calculated, to show how strongly the 150mb waves might be influenced by the tropospheric waves. Since the 150mb wave-1 at 60N was strongly anti-correlated with the 10mb zonal wind (figure 1(a)), the correlation between the 60N, 150mb wave-1 and the 500mb wave-1 geopotential amplitude for the two periods 1979-1986 and 1974-1995 are shown in fig 10. The period 1979-86 was chosen because Kodera (1991) found a strong QBO signal near 10mb at high latitudes from October till December.

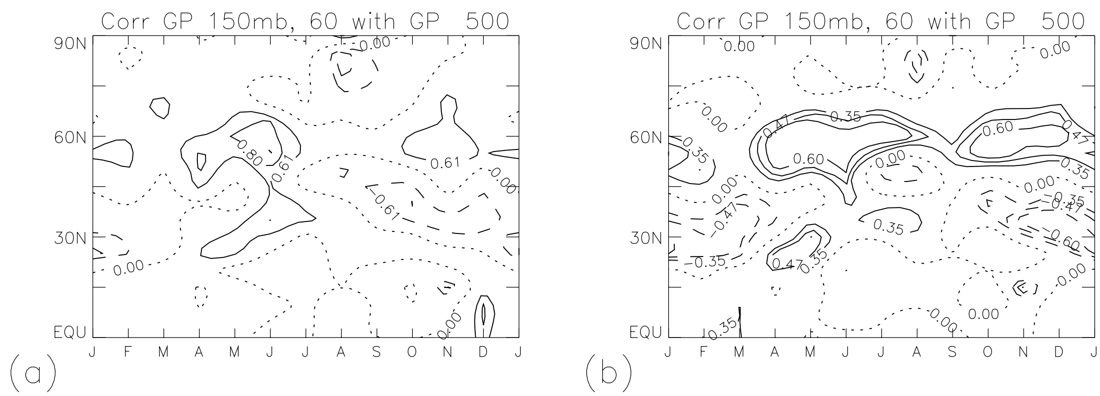

Figure 11: *Correlation between stationary wave-1 at (150mb, 60N) and stationary wave-1 at 500mb (a) from 1979–86 (contours at 0.61, 0.80 and 0.91) and (b) from 1974–95 (contours at 0.35, 0.47 and 0.60). Contours are at the 95, 99 and 99.9 percent significance levels.*

Over this period (figure 11(a)) the December 500mb wave amplitude is poorly correlated with the 150mb wave, while over the longer period from 1974 to 1995 (figure 11(b)) the correlation between wave-1 at 60N, 150mb and 60N, 500mb is significant at the 99.9% level. The reason for this strong correlation seems to lie partly in the strong tropospheric activity in late 1987 (resulting in the major warming in December 1987 - see Baldwin and Dunkerton 1989). It can be seen in figure 12(b) that December 1987 has by far the largest stationary wave-1 amplitude at 150mb over the 22 year period, and that the 500mb wave-1 amplitude is also anomalously large. Note also that October 1987 (figure 12a) also has a large stationary wave-1 amplitude at 500mb, so that the anomalous behaviour in December perhaps has its origin in the troposphere in October.

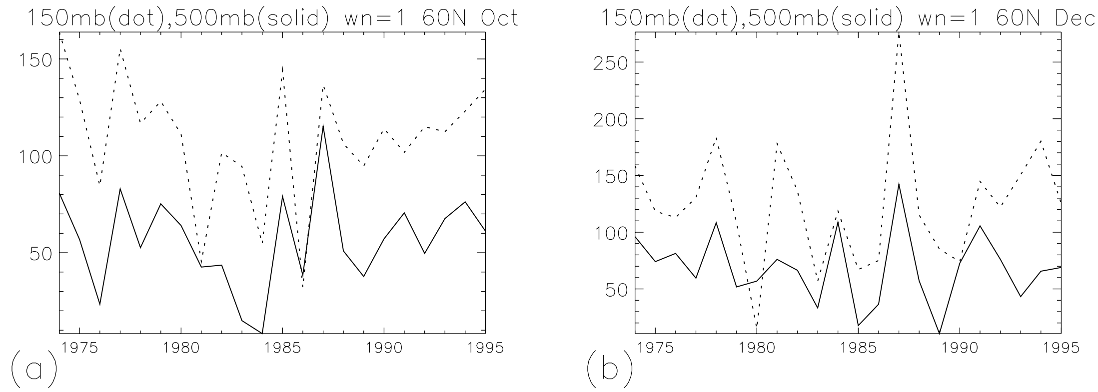

Figure 12: *Stationary wave-1 amplitude at 60N,500mb (solid), and 60N,150mb (dotted) in (a) October and (b) December.*

This anomalous behaviour in late 1987 may explain why Kodera found a strong extra-tropical QBO signal in 1979-86 – during 1979-86 there was not a strong link between the tropospheric and the lower stratospheric wave-1, and therefore the stratospheric waves could be more strongly influenced by the equatorial QBO. Over the longer period the tropospheric wave-1 was more strongly linked to the lower stratospheric wave-1 and thereby disrupted the correlation between the 10mb zonal wind and the equatorial QBO which would otherwise exist (and existed during 1979-86).

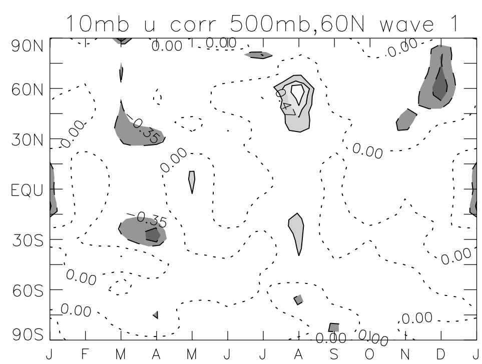

Figure 13: *Correlation between monthly-mean zonal wind at 10mb and monthly-mean stationary wave-1 amplitude at 60N, 500mb over 1974–95 (contours at 0.35, 0.47, 0.60). Contours are plotted at the 95, 99 and 99.9 per cent significance levels. Dark shading indicates a negative value, light shading indicates a positive one.*

An estimate of how strongly the troposphere affects the 10mb zonal wind is given by correlating the stationary wave-1 amplitude at 500mb and 60N with the 10mb zonal wind (see figure 13), as was done in section 3 for the waves at 150mb. It is seen that the anti-correlation in December at high latitudes is significant at the 99% level, suggesting that the tropospheric waves are playing some part in the interannual variability of the 10mb winds. However, the anti-correlation is not as strong as found for wave-1 at 150mb (compare with figure 1a).

It seems therefore that the stationary wave-1 at 150mb (which is very well correlated with the 10mb zonal wind in December) contains information from the tropospheric wave-1 but is also influenced by one or more additional factors. In the following section it will be argued that the stratospheric equatorial QBO is one of these factors.

6 Correlations between the 10mb zonal wind and the 50mb Singapore zonal wind.

Correlations of the extra-tropical zonal wind with the Singapore wind at a certain level have long been studied by many authors (eg. Holton and Tan 1982, Dunkerton and Baldwin 1991, Baldwin and Dunkerton 1991, Kodera 1991). However, the correlation is not perfect, and over certain time segments it can be poorer than others. For example, Dunkerton and Baldwin (1991) showed that the correlation between the 40mb Singapore wind and the winter mean (DJF) 10mb zonal wind at 60N was poorer over 1976-88 than it had been from 1964-75 while Kodera (1991), studying the 8-year period from 1979-86, found strong correlations from October to December between the 45mb Singapore wind and the extra-tropical zonal wind (as discussed in section 5). Using the 13 years, from 1980 to 1992, of the present data set (so that a comparison may be made with the results of the model simulation), the correlation between the 50mb Singapore wind and the 10mb zonal wind was claculated (figure 14(a)). The polewards propagation noted by Kodera (1991) can be seen. The correlation is strong in October and November but less significant in December.

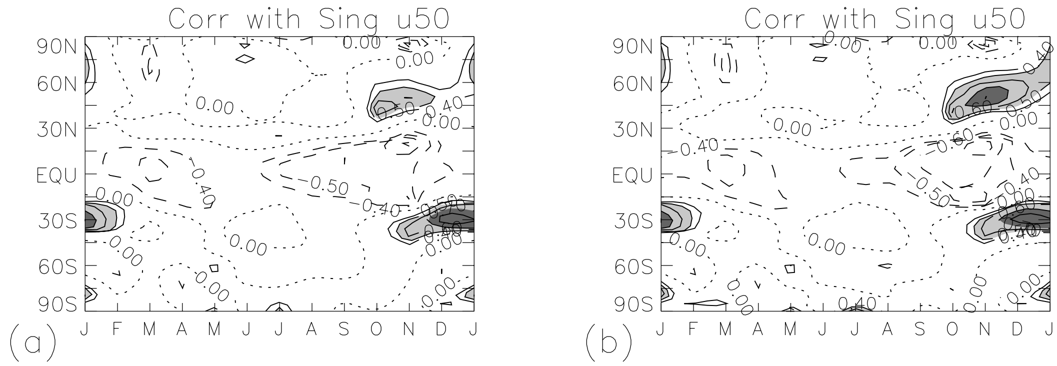

Figure 14: *Correlation between Singapore 50mb zonal wind and observed monthly-mean 10mb zonal wind (a) from 1980–92, (contours at 0.4, 0.5, 0.6, 0.7, 0.8) Values above 0.5 are lightly shaded. Those above 0.7 are heavily shaded. (b) as (a) but excluding late 1987.*

As was noted in section 5, the link between the 500mb and 150mb stationary wave-1 amplitudes was unusually strong from October to December 1987. If the troposphere was acting independently of the equatorial QBO over these months, the extra-tropical QBO signal may be improved on removing them from the analysis. This is indeed the case, as can be seen by comparing figure 14(a) with figure 14(b). The improvement in the significance of the correlations in all three months is dramatic. It therefore seems that 1987 is an anomalous year, with anomalously high wave-1 in both troposphere and stratosphere, and any such year could justifiably be excluded from an analysis for the extra-tropical QBO.

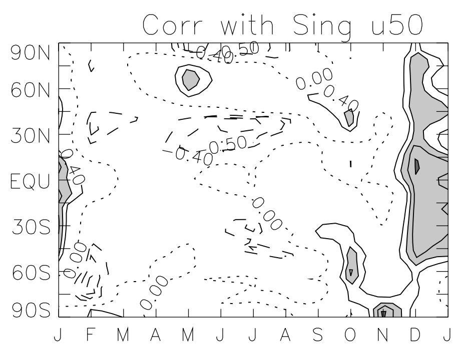

Figure 15: *Correlation between Singapore 50mb zonal wind and modeled 10mb zonal wind, (contours at 0.4, 0.5, 0.6, 0.7, 0.8). Values above 0.5 are lightly shaded. Those above 0.7 are heavily shaded.*

The correlation (after excluding late 1987, as discussed above) of the modeled 10mb zonal wind anomaly with the 50mb Singapore wind (figure 15) has some similarities and differences with that observed (figure 14b). In December the model shows a realistic correlation at 50N, which is consistent with its strong correlation with observations then (figure 3). It also implies that the high-latitude QBO in December is produced in the real atmosphere by a modulation of the planetary waves near 150mb. In November the model does not produce the strong QBO signal observed near 50N. This suggests that the QBO during November is not produced by a modulation of the 150mb waves, but is presumably produced by an interaction higher in the stratosphere. At low latitudes in December the modeled 10mb wind is correlated with the 50mb Singapore wind, in stark contrast to the observed anti-correlation. The observed anti-correlation is due to the vertical shear of the observed QBO, while in the model there is no imposed QBO at low latitudes and the planetary-wave-induced zonal wind anomaly continues unchanged in sign to the equator and well into the SH. Since the planetary waves in the model cannot propagate across the equator, the SH anomaly must be due to an anomaly in the meridional advection of angular momentum, induced by an anomaly in the NH planetary wave drag. Easterly wave drag in the NH induces a northwards mean flow (which tries to balance the drag by advecting in air with high angular momentum from the tropics). If this northwards flow extends into the SH, it will induce an easterly anomaly in the zonal wind in the SH. Therefore, an easterly anomaly in the wave drag in the NH will result in easterly anomalies in the zonal wind in the NH and in the low latitude SH. This would explain the QBO signal seen at 30S in Dec in the model. A similar signal is seen in the observations (figure 14b) and was noted by Baldwin and Dunkerton (1991) who suggested it might be caused by wave drag in the NH inducing a cross-equatorial meridional circulation in the SH. The model results here support this explanation though it is possible that the effect is amplified in the real atmosphere by wave propagation across the equator into the SH, as discussed in section 4.3.

7 Discussion and conclusions

In early winter (December in particular) the model results indicate that most of the high-latitude inter-annual variability in the monthly-mean 10mb zonal wind is a linear response to wave-1 forcing from the lower stratosphere. That the response is linear on the monthly time scale is suggested by the strong anti-correlations observed between the stationary wave-1 amplitude at 60N, 150mb and the 10mb zonal wind (section 3). Part of the variability in the forcing is due to the influence of tropospheric waves – which were particularly strong in late 1987 (section 5) – while part appears to be connected with the equatorial QBO (section 6). The relative importance of QBO and tropospheric waves to the 150mb waves (and hence to the 10mb zonal wind) in early winter is not estimated quantitatively here, but it seems that they are of about equal importance over a long time period. For example, the period from 1979 to 1986, shown by Kodera (1991) to have a strong QBO signal in the NH extra-tropics from October to December, was one where the 150mb waves were influenced more weakly than usual by tropospheric waves. When the winter of 1987/1988 (a period of strong early-winter tropospheric wave activity) is included in the analysis, the extra-tropical QBO signal is dramatically reduced.

In late winter, wave-1 forcing still drives much of the high-latitude variability in the 10mb zonal wind, but wave-2 now plays a more significant role. This is consistent with previous studies which show that a wave-2 major warming can be very dependent on a preconditioning of the zonal-mean state by an earlier wave-1 event and wave-wave interactions (eg. McIntyre 1982, Butchart et al. 1982, Palmer and Hsu 1983). The ability of the model to reproduce the late-winter behaviour is very sensitive to the amount of low-latitude damping of planetary waves. Because of the observation of strong wave breaking in the low-latitude surf-zone, it seemed reasonable to include an extra damping of planetary waves at low latitudes in the model. Damping will have an effect on the planetary waves in two distinct ways. One is to influence the growth and propagation of the waves directly. The other occurs via the waves' interaction with the zonal wind. In the model, increasing the damping beyond the background level generally decreases the drag exerted by the waves on the mean flow. This alters the mean flow and thereby influences the propagation of the waves. Since it is well known that interaction between waves and mean flow is important in the evolution of the late-winter NH stratosphere, and since adding a damping of the planetary waves in the tropical stratosphere brings the modeled zonal-mean zonal wind closer to observations (especially in its positioning of the zero-wind line) it seems that the second mechanism described above is the means by which low-latitude damping improves the model's simulation of late winter.

There is a possibility that the stratosphere is chaotic, and that given a strong but constant forcing of waves near the tropopause it will vaccillate chaotically (Holton and Mass 1976). If that were true, it should imply that it would be very difficult to obtain a reasonable correlation between observations and a model forced with the observed lower-stratospheric waves. It would also be in conflict with the results of Baldwin et al. (1994), who found strong correlations between the tropospheric NAO and the stratospheric zonal wind during northern winter. In addition, since the observed behaviour of the high-latitude stratosphere from November till March can be captured fairly well by the model, and since the model showed little inter-annual variability when there was no interannual variability in the planetary wave forcing (or in any of the other forcings) it seems that a stratosphere which does not interact with a troposphere is not strongly chaotic. The difference between this conclusion and that of Holton and Mass is perhaps due to the realistic forcing and because of the low-latitude planetary wave damping used in this model - with less planetary wave damping at low latitudes (section 4.5) the model was unable to capture the observed behaviour in late winter.

Finding correlations between certain indices (such as the 40mb Singapore wind, the tropospheric North Atlantic Oscillation (NAO) or stationary wave heights) and the state of the monthly or seasonally averaged stratosphere is conceptually useful but does not establish a causal link between the index and the stratospheric state. Also, if the state of the stratosphere depends on a combination of two or more independent indices (such as the QBO, the solar cycle and the NAO) then the correlation with one index cannot be expected to be perfect. For example, it was shown in section 6 how strong tropospheric wave activity in late 1987 disrupted the correlation of the 10mb winds with the 50mb Singapore wind. The benefit of the approach taken here is that it establishes a causal link between the planetary wave forcing in the lower stratosphere and the state of the extra-tropical stratosphere and also that it is able to combine information from the troposphere and from the equatorial QBO (since they both appear to influence the lower-stratospheric waves).

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