A Possible Influence of Equatorial Winds on the September 2002 Southern Hemisphere Sudden Warming Event

LESLEY GRAY AND WARWICK NORTON
Meteorology Department, Reading University, Reading, United Kingdom

CHARLOTTE PASCOE
Rutherford Appleton Laboratory, Chilton, United Kingdom

ANDREW CHARLTON
Meteorology Department, Reading University, Reading, United Kingdom

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ABSTRACT

The stratospheric sudden warming in the Southern Hemisphere (SH) in September 2002 was unexpected for two reasons. First, planetary wave activity in the Southern Hemisphere is very weak, and midwinter warmings have never been observed, at least not since observations of the upper stratosphere became regularly available. Second, the warming occurred in a west phase of the quasi-biennial oscillation (QBO) in the lower stratosphere. This is unexpected because warmings are usually considered to be more likely in the east phase of the QBO, when a zero wind line is present in the winter subtropics and hence confines planetary wave propagation to higher latitudes closer to the polar vortex. At first, this evidence suggests that the sudden warming must therefore be simply a result of anomalously strong planetary wave forcing from the troposphere. However, recent model studies have suggested that the midwinter polar vortex may also be sensitive to the equatorial winds in the upper stratosphere, the region dominated by the semiannual oscillation. In this paper, the time series of equatorial zonal winds from two different data sources, the 40-yr ECMWF Re-Analysis (ERA) and the Met Office assimilated dataset, are reviewed. Both suggest that the equatorial winds in the upper stratosphere above 10 hPa were anomalously easterly in 2002. Idealized model experiments are described in which the modeled equatorial winds were relaxed toward these observations for various years to examine whether the anomalous easterlies in 2002 could influence the timing of a warming event. It is found that the 2002 equatorial winds speed up the evolution of a warming event in the model. Therefore, this study suggests that the anomalous easterlies in the 1–10-hPa region may have been a contributory factor in the development of the observed SH warming. However, it is concluded that it is unlikely that the anomalous equatorial winds alone can explain the 2002 warming event.

1. Introduction

The stratospheric sudden warming in September 2002 was an unexpected event for several reasons. First, the amplitude of planetary wave activity in the Southern Hemisphere (SH) is normally very low, resulting in a strong westerly winter vortex that is usually relatively undisturbed. Until 2002, no midwinter sudden warming events had been recorded in the recent decades for which routine observations of the upper atmosphere have been available. This is in contrast to the Northern Hemisphere (NH), in which the polar winter vortex is regularly disturbed by breaking planetary waves and on average every 2–3 yr there is a complete breakdown of the vortex in midwinter, known as a major warming. This difference between the two hemispheres is thought to be due to various factors, such as the reduced mountainous land cover in the SH, weaker longitudinal land–sea contrast, and the presence of a nearly zonally symmetric, cold elevated surface at polar latitudes (Antarctica), all of which act to suppress sudden warmings by reducing the forcing of planetary waves and strengthening the polar-night jet.

Second, the occurrence of the SH warming event was surprising because it occurred when the equatorial
winds in the lower stratosphere, the region dominated by the quasi-biennial oscillation (QBO), were westerly, as shown in Fig. 1. In the NH, the vortex is usually more disturbed when the lower-stratospheric QBO is in its easterly phase (e.g., Baldwin et al. 2001). This has been explained in terms of the presence of a zero wind line in the NH subtropics during the QBO east phase, which confines the propagation of the planetary waves to higher latitudes and hence closer to the vortex (Holton and Tan 1980, 1982). Nevertheless, there have been major NH midwinter warmings during westerly phases of the lower-stratospheric QBO, and this has been a

Fig. 1. (a) Height time series of zonally averaged monthly mean equatorial zonal winds (m s$^{-1}$) from ERA-40. (b) Same as in (a), but after subtraction of the monthly averaged climatological values from each month. Contours are every 10 m s$^{-1}$; the thick contour is the zero wind line.
puzzle to stratospheric dynamicists since they cannot easily be explained in terms of the lower-stratospheric zero wind line, which in those years is positioned in the SH and is therefore much less of a constraint on the planetary wave propagation. Labitzke and van Loon (1988) have pointed out that these westerly phase major warmings tend to occur during periods when the 11-yr solar cycle is in its maximum phase, but the mechanism of this solar influence is unclear.

However, a recent series of studies of NH sudden warmings (Gray et al. 2001a,b; Gray 2003) has suggested that equatorial winds not only in the lower stratosphere but also in the upper stratosphere are influential. The studies noted that, although the maximum amplitude of the QBO is at around 30 km, the QBO signal actually extends to 40–50 km. They also noted that planetary waves are extremely deep structures and that sudden warming events develop first at levels near the stratopause and subsequently extend downward into the lower stratosphere. Hence there is no particular reason why only the lower-stratospheric QBO should be influential. Indeed, Gray et al. 2001b found the highest (negative) correlation of polar winter temperatures with equatorial wind direction near the stratopause level, the height region dominated by the semiannual oscillation (SAO). The maximum correlation occurred in September/October, at the beginning of NH winter around the time of the peak of the second SAO west phase and the onset of the second east phase. This suggests that the timing of this changeover may be an important factor.

In an idealized model study of flow regimes in the winter stratosphere, Gray et al. (2003, hereafter G2003) examined the influence of varying the level of tropospheric planetary wave forcing and varying the sign and strength of the equatorial winds on the timing of sudden warming events. A major result of that study was that the primary influence of both the tropospheric forcing and the equatorial wind distribution is that they change the timing of the modeled warming event(s). Strong tropospheric forcing and equatorial easterlies both served to speed up the development of the warming, while weak tropospheric forcing and equatorial westerlies slow it down. They identified three flow regimes according to the strength of the tropospheric forcing. At very low-amplitude forcing, the westerly vortex remained strong and undisturbed and never displayed a warming event within the 300-day timespan of their integrations. At high-tropospheric forcing, the modeled winter was highly disturbed and always achieved a major warming event within 100 days of the onset of the winter circulation. At intermediate forcing, there was substantial variability in the modeled response; some winters displayed strong warmings, while other winters remained undisturbed. In this intermediate regime, the equatorial wind distribution was found to be influential, with strong easterlies promoting early warmings and strong westerlies delaying them. It was suggested that the NH lies in this intermediate regime, with the equatorial wind direction having significant influence in most years, although it was noted that in some years the tropospheric forcing may be anomously high or low (possibly associated with anomalous tropospheric circulations, e.g., ENSO years) so that the winter falls into the high or low forcing regimes, respectively, and in those years the equatorial wind direction is probably less relevant.

In contrast, it was suggested that the SH was an example of the low forcing regime, in which major warmings are never observed within the available winter timespan. However, it is conceivable that the SH may actually lie at the boundary of the low and intermediate forcing regimes and that exceptionally strong tropospheric forcing or exceptionally strong easterly equatorial winds, or more likely, a combination of these two factors, could be sufficient to speed up the development of a warming, thus enabling the SH to achieve a major warming before the end of the winter.

In this paper, we use the same model as in G2003 to investigate one of these factors, namely whether the equatorial winds may have been a contributory factor to the unexpected SH sudden warming in 2002. We do not investigate the possible influence of the tropospheric forcing for the reasons given below but nevertheless stress that in all probability, it was a combination of the two factors that increased the speed of development of the warming. The model is an idealized model of the stratosphere and mesosphere only and is artificially forced with geopotential height fields at the lower boundary situated at 100 hPa. An important conclusion of the study is that the flow in the mid- and upper stratosphere modifies the Eliassen–Palm (EP) fluxes at this lower boundary and that the wave fluxes through the lower boundary should be considered as part of the response to forcing rather than the forcing per se. For this reason, we choose not to force the lower boundary of the model with the observations, since this will almost guarantee a warming event (and indeed it does, as a test run confirmed). The approach of forcing with observed geopotential heights may well be justified if the lower boundary of the model were at, say, 250 hPa since one could then be sure that the applied forcing was definitely of tropospheric origin. However, since we cannot be sure of this at 100 hPa, we choose instead to carry out our experiments with an idealized lower boundary forcing consisting of a simple zonal-mean geopotential height field with an imposed wave-number-1 perturbation that is constant in time. Further details of the forcing are provided in the relevant section. We note here that the experiments are therefore highly idealized and are not an attempt to simulate the 2002 September warming itself.

The layout of the paper is as follows: In sections 2 and 3, we describe the tools employed in the study: two observational datasets [the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF)
Re-Analysis (ERA-40) and the U.K. Met Office (UKMO) Upper Atmosphere Research Satellite (UARS) assimilated analyses and the UKMO stratosphere mesosphere model (SMM). Selected fields from the observational analyses are presented in section 4 to show that the equatorial winds in the upper stratosphere were anomalously easterly in 2002 compared with the climatology of the last 40 yr. In section 5, we describe model studies to investigate whether these anomalous winds influence the timing of the idealized modeled warming events. The results are summarized and discussed in section 6.

2. Observational datasets

a. ERA-40

The variational data assimilation system at ECMWF has been employed to make a new synthesis of the in situ and remotely sensed measurements made over the period since mid-1957, when a major improvement was made to the atmospheric observing system in preparation for the International Geophysical Year in 1958. The dataset is referred to as the ERA-40 dataset (available online at http://www.ecmwf.int/research/era; see also Randel et al. 2004). Apart from the obvious extended length of the ERA-40 dataset compared with the earlier ERA-15 dataset, a significant difference is in the use of satellite data. ERA-40 includes the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) radiances directly, while in ERA-15, retrievals of temperature and humidity were used. In addition to the traditional data used in the assimilation such as radiosonde observations, Vertical Temperature Profile Radiometer (VTPR), TOVS, and cloud motion winds (CMWs) satellite observations were used in the period 1972–88, and TOVS, Special Sensor Microwave Imager (SSM/I), European Remote Sensing Satellite (ERS), Advanced TIROS Operational Sounder (ATOVS), and CMW satellite observational analyses were used in the period 1987–2001. Post-1979, TOVS consisted of Stratospheric Sounding Unit (SSU)/High Resolution Infrared Radiation Sounder (HIRS)/Microwave Sounding Unit (MSU) plus Advanced MSU (AMSU)/HIRS from 1998 onward. The SSU and AMSU observations are predominant at upper-stratospheric levels.

The ERA-40 dataset consists of 6-hourly analyses throughout the period 1957–2001, supplemented by intermediate 3-h forecasts. The data are of high spatial resolution, with a grid spacing close to 125 km in the horizontal (T159) and with 60 levels in the vertical located between the surface and 0.1 hPa (approximately 65 km). The available data from ERA-40 not only include the conventional meteorological wind, temperature, and humidity fields, but also stratospheric ozone and ocean wave and soil conditions. The data are available on 23 standard pressure surfaces from the surface to 1 hPa. Data are also available on model levels. The figures shown in this paper are the monthly averaged data from the 6-hourly analyses on standard pressure surface data up to 2 hPa. Above that level, the model level data are used to extend the figures to 0.1 hPa. The 2002 ECMWF data shown are from the operational ECMWF analyses.

b. Met Office stratospheric analyses

Daily stratospheric analyses are available for the period 1991 to the present day from the Met Office’s data assimilation system (Swinbank and O’Neill 1994), initially prepared for validation of UARS. The data assimilation system is a development of the scheme used at the Met Office for operational weather forecasting, which has been extended to cover the stratosphere. It employs the analysis–correction scheme, as described in Lorenc et al. (1991). The data contain fields of temperature, geopotential height, and wind components, on 22 standard UARS pressure levels from 1000 to 0.316 hPa (approximately 0–55 km) and on a 2.5° latitude by 3.75° longitude grid. These fields are vertically interpolated from the model data. The model has 42 levels, with a vertical resolution in the stratosphere of about 1.6 km. The primary product is a daily analysis (at 1200 UTC) that is produced using operational observations only. For short periods of particular interest, the analyses are available at 6-hourly intervals. Assimilation experiments using UARS data in addition to operational meteorological observations have been carried out for limited periods. All data employed in this paper are from the standard data analyses only.

3. The model

The model employed in this study is the UKMO SMM. It is a global three-dimensional primitive equation model of the middle atmosphere with horizontal resolution of 5° latitude by 5° longitude and 32 vertical levels equally spaced in log pressure, giving approximately 2-km vertical resolution throughout the model domain of 16–80 km. It is a mechanistic model with temperature and horizontal winds as prognostic variables.

Radiative heating and cooling rates are computed in the model using the middle atmosphere radiation (MIDRAD) scheme (Shine 1987) with a prescribed annual-mean, global-mean carbon dioxide amount and a zonal-mean, height-resolved, monthly mean ozone climatology. 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 is employed. A simple (Rayleigh friction) relaxation scheme is used to simulate the effect of gravity wave breaking. The zonally averaged zonal winds are relaxed toward zero on a time scale varying from about 100 days in the lower stratosphere to 2 days in the mesosphere.
All experiments consisted of 20-member ensembles of 300-day duration commencing on 1 January and hence extending to the end of October. The ensemble was generated by initializing the model with data from each of the first 20 days of a previous model run (run A of Gray et al. 2001a). The lower-boundary forcing was imposed through the specified geopotential height field at 16 km. A zonally symmetric component of the geopotential height field was derived by averaging 15 yr (1980–95) of monthly zonally averaged 100-hPa geopotential heights from the UKMO TOVS satellite analysis (Bailey et al. 1993). Superimposed on this zonally averaged field was a zonally asymmetric wave forcing of the form,

\[ Z = Z_0 \exp\left[-\frac{2(\phi - \phi_0)}{30}\sin(m\lambda)\right], \]

where \( \lambda \) is the longitude, \( \phi \) is the latitude, \( \phi_0 = 60^\circ \text{S} \) is the latitude of maximum forcing, and \( m (=1) \) is the zonal wavenumber. The amplitude \( Z \) was thus a maximum at \( 60^\circ \text{S}, 90^\circ \text{E} \). A value of \( Z_0 = 250 \text{ m} \) was used, and the forcing was gradually turned on over the first 10 days of each integration and remained steady in time thereafter. The imposed latitudinal structure is similar to that seen in climatological fields of wavenumber-1 amplitudes (see Fig. 6 of Scaife et al. 2000). The imposed amplitude \( Z_0 \) is slightly larger than the climatological amplitude since taking climatological averages over a winter period smooths in time and hence underestimates the amplitude of any one forcing event. The value \( Z_0 = 250 \text{ m} \) was used since this was found to be a value that ensured a warming event some time during the modeled winter. The influence of the imposed equatorial winds from various years on the timing of that event was then examined.

In each experiment, the modeled equatorial winds were relaxed toward monthly averaged equatorial wind observations from either the ERA-40 or UKMO assimilated datasets described above. The relaxation method was identical to that employed in Gray et al. (2001a). The relaxation time scale was 5 days at the equator from the lowest level of the model up to 10 hPa, and this time scale was linearly increased with latitude (to 20 days at \( 17.5^\circ \)). Above 10 hPa, the same configuration was employed except that the equatorial time scale was gradually reduced to 0.5 day at 1 hPa (and correspondingly reduced in the subtropical latitudes) in order to reflect the reduced radiative relaxation time scales in the upper stratosphere. The maximum height range of each dataset was employed, which in both cases was well above 1 hPa, and above this level, the relaxation time scale was increased in order to achieve a smooth transition from the forced zonal winds below to the modeled winds above. To ensure consistency between model experiments, the model runs that relaxed toward ECMWF equatorial wind analyses employed operational analyses for each of the years, rather than employing a mixture of operational data for 2002 and reanalysis data for 1999 and 2000. A comparison of the operational analyses and the ERA-40 analyses for the years in question (not shown) confirmed that the two datasets were essentially the same in all of the main features.

4. The 2002 Southern Hemisphere equatorial winds

Figure 1a shows the time series of equatorial winds from the ERA-40 analysis for the period 1979–2002. We show this time period because it is the period since satellite observations of the upper atmosphere have been routinely available for assimilation. The corresponding data from the UKMO assimilated dataset for the period 1992–2002 is shown in Fig. 2a. The alternating east and west phases of the QBO are evident in the region 10–70 hPa with maximum amplitude at around 20–30 hPa. Above 5–10 hPa, the time series is dominated by the 6-monthly SAO with easterlies at solstice and westerlies at equinox. As already noted, the phase of the lower-stratospheric QBO in 2002 is westerly, with maximum winds of around 20 m s\(^{-1}\) at 30 hPa. In Figs. 1b and 2b, the seasonal cycle has been removed from the data by calculating the climatological average for each month over the displayed period and subtracting this from each individual month. In this way, the annual and semiannual periodicities are removed. The effect of this is particularly apparent above about 10 hPa (and correspondingly reduced in the subtropical latitudes) in order to reflect the reduced radiative relaxation time scales in the upper stratosphere. The maximum height range of each dataset was employed, which in both cases was well above 1 hPa, and above this level, the relaxation time scale was increased in order to achieve a smooth transition from the forced zonal winds below to the modeled winds above. To ensure consistency between model experiments, the model runs that relaxed toward ECMWF equatorial wind analyses employed operational analyses for each of the years, rather than employing a mixture of operational data for 2002 and reanalysis data for 1999 and 2000. A comparison of the operational analyses and the ERA-40 analyses for the years in question (not shown) confirmed that the two datasets were essentially the same in all of the main features.

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![Figure 1a](https://example.com/fig1a.png)

**Figure 1a.** Time series of equatorial winds from the ERA-40 analysis for the period 1979–2002. We show this time period because it is the period since satellite observations of the upper atmosphere have been routinely available for assimilation.

![Figure 1b](https://example.com/fig1b.png)

**Figure 1b.** Time series of equatorial winds from the UKMO assimilated dataset for the period 1992–2002.
hPa, and a QBO signal is now clearly evident up to at least 1 hPa with amplitude of around $\pm 5-10 \text{ m s}^{-1}$ in the ECMWF dataset. The extension of the QBO into the upper stratosphere is less clear in the UKMO dataset but is nevertheless evident in most years of the data.

The climatologies of equatorial winds that have been removed from Figs. 1a and 2a are shown in Fig. 3a for the ERA-40 dataset and Fig. 4a for the UKMO dataset. We note that the ERA-40 climatology consists of 22 yr and the UKMO climatology consists of 9 yr. The winds below 10 hPa in the climatological mean are very weak in both datasets, a result of averaging the QBO over a number of years so that the two opposite phases nearly cancel out. Above 35 km, both climatological fields clearly show the SAO. The easterly phase in January is stronger than the corresponding easterly phase 6 months later. This is consistent with other datasets of the SAO (see, e.g., Garcia et al. 1997; Dunkerton and Delisi 1997). It is thought to be due to the greater planetary wave activity in the NH that induces a stronger meridional circulation and hence stronger advection of summertime easterlies over the equator near the stratosphere level. In addition, Fig. 3b shows the climatological mean for the west phase of the QBO, determined by the sign of the equatorial wind at 40 hPa. In the formation of this climatology, the full 40 yr of the dataset have been used, to increase the number of years available for inclusion.

Removal of the seasonal cycle from the equatorial time series highlights a region of anomalously strong easterlies in 2002 in the 1–10-hPa region in both datasets (see Figs. 1b and 2b). The detailed evolution of the 2002 equatorial winds may be seen more clearly in Fig. 5a from the ERA-40 dataset and in Fig. 4b from the UKMO assimilated dataset. A comparison with the corresponding climatological fields in Figs. 3a and 4a confirms this easterly anomaly. A further comparison of the ERA-40 2002 evolution with the west phase QBO climatology (Fig. 3b) reveals that both easterly SAO phases were stronger in 2002 than in the west.
phase QBO climatology. The maximum easterlies in January/February were around 10 m s$^{-1}$ stronger in 2002, and the maximum easterlies in September were stronger by around 20 m s$^{-1}$. Indeed, in August, the month preceding the observed sudden warming, the equatorial easterlies in the region near 5 hPa were double the amplitude of the west phase QBO climatology.

The evolution of the 2002 equatorial winds in the two datasets (Figs. 4b and 5a) broadly agrees insofar as anomalously strong easterlies are present in both datasets compared with the climatologies. However, there are some differences in detail. This is particularly true of the west phase SAO in April. In the ERA-40 dataset, the westerly winds extend deeper into the atmosphere in 2002, reaching to nearly 2 hPa compared with the UKMO dataset where they reach only to 0.6 hPa. There are also some differences in the peak easterlies in January/February, both in magnitude and in the timing of the peak values. Nevertheless, despite these differences in detail, both datasets are consistent in showing anomalously easterly equatorial winds in the period leading up to the SH sudden warming in September 2002.

We also note here that the UKMO dataset suggests that the anomalously easterlies in 2002 are part of a downward progression since 2000, as seen in the time series of equatorial winds at 1 hPa shown in Fig. 6.
However, a comparison with the corresponding time series from the ERA-40 dataset in Fig. 7 does not confirm this. Interestingly, Fig. 7 shows that the anomalous easterlies in January/February were not unique, since 1975 had a similarly strong easterly anomaly and during the past decade both January 1990 and 1995 also had fairly strong easterlies. The anomalous easterlies around August/September are less common, although the second easterly peak in 1997 appears to be as strong as in 2002. However, the combination of anomalously strong easterlies in both east phases of the SAO does appear to be unusual and is not evident in any other year of the 40-yr analyses.

5. Idealized model studies

Four sets of 20-member ensembles were run, which were identical in all respects except for the equatorial wind datasets toward which the modeled equatorial winds were relaxed. In the first experiment, referred to as UKMO_2002, the modeled winds were relaxed toward the monthly averaged 2002 Met Office assimilated data fields. In the second experiment, ECMWF_2002, the modeled equatorial winds were relaxed toward the monthly averaged 2002 ECMWF operational analyses. A comparison of these two experiments ensures that our results are not specific to one dataset.

In the third and fourth experiments, ECMWF_2000 and ECMWF_1999, the modeled equatorial winds were relaxed toward monthly averaged 2000 and 1999 ECMWF operational analyses, respectively. The time series of equatorial winds in these two years are shown in Figs. 5b and 5c for comparison with 2002 (Fig. 5a). These two years were similar to 2002 insofar as they were also in a westerly phase of the QBO in the lower stratosphere, using the standard level of 40–50 hPa as the determining indicator. However, the upper equatorial stratosphere above 10 hPa was rather different in 1999 and 2000 compared with 2002. This is especially true in the 1–5-hPa height region where sudden warming events are usually initiated. In 1999 and 2000, there are westerlies in this height region between April and July/August and the following east-phase SAO in August/September 2000 is weak, reaching only \(-10 \text{ m s}^{-1}\). This contrasts strongly with 2002, where the west phase SAO in April/May barely extends down to 1 hPa, and there are strong easterlies following this, peaking at 50 m s\(^{-1}\) in August/September. The year 1999 is midway between the 2002 and 2000 evolutions. The west-phase SAO in April–June is not as strong as in 2000, and the following east-phase SAO in September is not as strong as in 2002. Hence, a comparison of ECMWF_1999 and ECMWF_2000 model winter evolutions with the ECMWF_2002 evolution will highlight whether the winter polar evolution is sensitive to differences in the equatorial height region above 10 hPa.

Figures 8, 9, and 10 show the time evolution of the south polar temperature at approximately 30 hPa from experiments UKMO_2002, ECMWF_2002, and ECMWF_1999, respectively. In all experiments, the initially warm summer temperatures in January gradually decrease as autumn progresses (January–April). The winter temperatures (May–August) are generally cold but are disrupted by minor midwinter warmings in each experiment. At the end of winter, there is a general rise in temperature in September–October forming the final warming. A detailed comparison of UKMO_2002 and ECMWF_2002 (Figs. 8 and 9) reveals an almost identical evolution to mid-April and then a series of minor

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**Fig. 7.** Time series of zonally averaged equatorial zonal winds (m s\(^{-1}\)) at approximately 1 hPa for the period 1958–2002 from the ERA-40 data (1958–2001) and ECMWF operational data (2002; monthly data).

**Fig. 8.** Experiment UKMO_2002: Time series of area-weighted temperatures (K) south of 62.5\(^\circ\)S at 32 km (approx 10 hPa). All 20-member ensembles from each experiment are shown.
disturbances, the timing of which varies between the individual ensemble members of each experiment and between the two experiments. By early May, the temperature decline has halted, and there is a steady increase from that date, reaching a maximum temperature in early July in both experiments. The peak temperatures are slightly different, with the UKMO_2002 achieving 230 K in some ensemble members, while the maximum temperatures achieved in ECMWF_2002 are 3–4 K lower. However, the ensemble-averaged timing of the warming event is very similar in the two experiments. We conclude therefore that despite minor differences in the equatorial wind time series from the two datasets, the overall response of the winter polar stratosphere to the equatorial wind distributions is robust.

A comparison of the ECMWF_2000 winter (Fig. 10) with the two 2002 experiments shows some marked differences. Most notably, the midwinter warming event is substantially delayed. The temperatures continue to decline until mid-June, and the peak temperatures are not achieved until August, around a month later than in the 2002 experiments. The different equatorial wind distribution above 10 hPa appears to have made a substantial difference. This result is consistent with previous, more idealized studies described by Gray (2003) that also showed sensitivity to the equatorial winds in the upper stratosphere. In those results, an easterly bias imposed above 40 km (approximately 3 hPa) encouraged earlier warmings, while a westerly bias slowed them down.

In the following sections, we examine in more detail the differences between the ensemble-averaged fields from the ECMWF_2002, representative of the early warming evolution and from ECMWF_2000 in which the warming event occurred approximately 1 month later.

Figure 11 shows the latitude time series of the ensemble-averaged, zonally averaged zonal winds at 40 km (approximately 3 hPa) from the two experiments, together with the difference between the ensemble means. Using the ensemble approach allows a Student’s t test to be carried out to ascertain whether the differences between the two ensemble means are statistically significant. The shading indicates regions where significance is greater than the 99% level. The first easterly phase of the SAO centered about January is on average 10 m s\(^{-1}\) more easterly in 2002 until mid-March. The SAO westerly phase around April does not extend deep enough into the stratosphere to influence the 3-hPa level in 2002, and the equatorial winds remain easterly throughout the period January–October. In contrast, 2000 has a prominent west-phase SAO in April–June so that the zero wind line extends well into the NH. The difference in wind amplitude reaches 50 m s\(^{-1}\) in this period. In Fig. 12, we show the corresponding time evolutions at 3 hPa from the ECMWF (daily operational) analyses. The patterns of evolution in the two model experiments are very similar to the observations although the timing is slightly different because the modeled warmings in 2002 occur earlier than in reality. Note in particular the difference in position of the zero wind line in Fig. 12 during April–July. In 2002, it is located in the SH subtropics at around 30°S, while in 2000 it is located in the opposite hemisphere near 0°–10°N.

Figure 13 shows the ensemble-averaged, monthly averaged height latitude cross sections of zonally averaged zonal winds for April–July from ECMWF_2002 and ECMWF_2000, together with their differences. In April, the zero wind line is displaced slightly further poleward in 2002, giving rise to an easterly anomaly at 30°S between 25–60 km, with a peak anomaly of 10 m s\(^{-1}\) at around 50 km. This upper-level anomaly intensifies through May and June as the warming develops. As shown in G2003, this easterly anomaly is also a feature of NH warmings and is a signature of the developing Aleutian anticyclone. As the anticyclone grows stronger, the easterlies associated with it in the subtropics become strong enough and extensive enough to re-
Fig. 11. Latitude time series of ensemble-averaged zonally averaged zonal winds (m s\(^{-1}\)) at 40 km (approx 3 hPa) from (top) ECMWF 2002, (middle) ECMWF 2000, and (bottom) the 2002 field minus the 2000 field. Solid contours denote westerlies, dotted contours denote easterlies, and the dashed contour is the zero wind contour. Shading on the bottom panel denotes statistical significance at the 99% level using the Student's \(t\) test.
verse the zonal-mean winds from westerly to easterly. There is also a small but significant strengthening of the polar jet in 2002 above 40 km poleward of 60°S. This is primarily due to the small shift of the vortex off the pole so that the zonal average samples more of the jet maximum region at these higher latitudes. It is a similar evolution to the “preconditioning” of the jet before a sudden warming event (see, e.g., Andrews et al. 1987).

This same evolution of an easterly anomaly developing in the subtropical upper stratosphere as a precursor to a warming event is illustrated in Figs. 14 and 15.
which show the SH monthly averaged zonal wind on the 1650-K isentropic surface (near 45 km) for May–July of each experiment. In these figures, we show a typical ensemble member from each experiment rather than an ensemble average since the latter would average out the synoptic details. The fields are plotted on an isentropic surface in order to facilitate comparisons with the corresponding Ertel potential vorticity (PV) distributions, shown in Figs. 16 and 17. Figures 14 (ECMWF_2002) and 15 (ECMWF_2000) shows a region of easterlies in both experiments in May, centered at approximately 30°S, 270°W, associated with an anticyclonic region. As the integration proceeds, this region of easterlies continues to deepen in
Fig. 14. Experiment ECMWF_2002: Monthly averaged zonal wind distributions on the 1650-K isentropic surface (approx 45 km) for (top) May, (middle) Jun, and (bottom) Jul. Solid contours denote westerlies, dotted contours denote easterlies.

Fig. 15. Same as in Fig. 14, but for experiment ECMWF_2000.
FIG. 16. Experiment ECMWF_2002: Monthly averaged Ertel PV \(10^{-6} \text{ K m}^2 \text{ s}^{-1}\) on the 1650-K isentropic surface (approx 45 km) for (top) May, (middle) Jun, and (bottom) Jul. Negative contours are dotted. Zero and positive contours are solid.

FIG. 17. Same as in Fig. 16, but for experiment ECMWF_2000.
ECMWF_2002 as it moves clockwise to approximately 180°. In ECMWF_2000, this same process takes place but over a longer time scale, taking approximately 1 month longer to reach the same amplitude. This delayed progression in ECMWF_2000 compared with ECMWF_2002 is also evident in the PV distributions in Figs. 16 and 17.

There are several differences in the zonal wind and PV distributions from the two integrations that may help to explain the delayed progression of ECMWF_2000. The PV plots in Figs. 16 and 17 show that the vortex is much broader in May (and subsequent months) in ECMWF_2000, due to the different zonal wind distribution in the subtropics. The 2002 subtropical winds are easterly throughout this period. The PV gradients at the edge of the vortex are therefore tighter in ECMWF_2002. By June, as the equatorial easterlies strengthen, there is also a ring of positive PV values at around 10°–15°S of ECMWF_2002 (Fig. 16, middle). This forms part of a spiral of positive PV air in the subtropics around the vortex edge that is drawn poleward near 30°S, 20°W into the region of the anticyclone centered on 60°S, 180°. This is an ongoing process throughout the month, as is evident from the presence of the anomalous region of positive PV air in the monthly average. In reality, this tongue of air is baroclinically unstable, and in daily plots, it consists of a series of traveling anticyclones that are advected poleward near 30°S, 20°W into the region of the anticyclone centered on 180°, as shown in Fig. 18. This process has previously been discussed in the context of NH warmings by O’Neill and Pope (1988) and G2003.

The year 2000 was selected for comparison with 2002 on the basis that although the equatorial winds in the lower stratosphere were in a west-phase QBO, similar to 2002, the equatorial winds in the upper stratosphere were quite different. The first SAO west phase in 2000 peaked at 40 m s⁻¹ at 1 hPa in June, and there was a relatively weak SAO east phase following it. In the corresponding evolution in 2002, the SAO west phase was barely evident, and a very strong easterly bias was present throughout the whole period. When compared with climatology (Fig. 3), it is evident that these two years are fairly extreme examples at opposite ends of the spectrum of observations. To provide a third example midway along this spectrum, a further model experiment, ECMWF_1999, was run. In 1999 (see Fig. 5c), the first SAO west phase in April/May and the SAO east phase following it were both midway in amplitude between 2000 and 2002. Figure 19 shows the time evolution of the polar temperatures from the 20 ensembles members of this experiment. Rather than displaying a modeled warming event approximately midway in time between the other two experiments, the results show two quite distinct patterns. In approximately one-third of the ensemble members, the early winter evolution was relatively cold, and the warming event did not occur until August. This timing is rather similar to the timing of the warmings in ECMWF_2000. In the remaining two-thirds of the ensemble, the temperatures from May onward were warmer and more disturbed, and the sudden warming event occurred 1 month earlier, in July, similar to the ECMWF_2002 evolution.

6. Summary and discussion

An examination of the ERA-40 dataset and the UKMO assimilated dataset both indicate that the
lower-stratospheric QBO (40–50 hPa) was in a westerly phase in the period leading up to September 2002. This would suggest a minimal influence on the warming event from the equatorial region since westerly QBO phases are usually associated with an undisturbed polar vortex. However, the datasets also indicate the presence of anomalously strong equatorial easterlies at upper levels (> 10 hPa) in 2002 for the whole period from January through September. The possible influence of these anomalously easterly upper-level equatorial winds has been investigated in idealized model experiments. We have suggested that the SH may lie in a flow regime at the boundary between the low and intermediate forcing regimes defined in G2003. In that case, exceptionally strong tropospheric planetary wave forcing or exceptionally strong easterly equatorial winds or, more likely, a combination of these two factors could be sufficient to speed up the development of a warming, thus enabling the SH to achieve a major warming before the end of winter.

We have employed a stratosphere–mesosphere model with a lower boundary at 100 hPa. The model experiments are highly idealized and do not seek to exactly reproduce the observed SH evolution in 2002. The amplitude of the idealized wave-1 lower boundary forcing anomaly $Z_0 = 250$ m was set at a level that ensured a warming event some time during the winter. The influence of imposed equatorial winds from various years on the timing of that event was then examined. In this way, we may see whether the 2002 equatorial winds helped to speed up the evolution of the warming, thus allowing it to take place before the end of winter. The modeled equatorial winds were relaxed toward observational analyses throughout the height region 16–65 km.

Three years of observational data were used: 2002, 2000, and 1999. All three years were in the westerly phase of the QBO at 40–50 hPa. The year 2000 was chosen for comparison since the equatorial upper-level winds (1–10 hPa) were anomalously westerly, in strong contrast to 2002 in which they were anomalously easterly. The 1999 equatorial winds were intermediate between the two extremes of 2002 (strong easterly upper-level anomaly) and 2000 (strong westerly upper-level anomaly).

All 20 ensemble members of the 2002 experiment achieved a warming event approximately 1 month earlier than in the 2000 experiment. The results therefore suggest that the anomalously easterly winds in the height region 1–10 hPa may have been a contributory factor to the observed SH warming in September 2002. This is consistent with previous model studies (Gray 2003) that showed that easterly anomalies in the upper equatorial stratosphere tended to speed up warming events whereas westerly anomalies in that height region slowed them down. Detailed comparison of the modeled evolutions of the two experiments suggest that a key component was the presence of an easterly anomaly in the equatorial/subtropical upper stratosphere in 2002 throughout the early and midwinter, which led to the early development and successful amplification of a region of anticyclonic flow in the subtropics (equivalent to the Aleutian high in the NH). The strong easterlies at the equator result in a strong horizontal wind shear and hence steep PV gradients in the SH subtropics in early winter. This will tend to act as a waveguide and so will confine any equatorward-propagating planetary waves. The proximity of a zero wind line means that the waves will tend to break. As the waves break, tongues of positive PV are advected from the equatorial/subtropical region, around the edge of the vortex and then poleward toward the anticyclonic region as shown in Figs. 16, 17, and 18.

The state of the 1999 equatorial winds in the upper stratosphere was midway between 2000 and 2002, that is, the first SAO west phase was not as weak in the region 1–10 hPa as in 2002 (which had a strong easterly anomaly), but neither was it as strong as in 2000. Similarly, the following SAO east phase was not as strongly easterly as in 2002, but it was stronger than in 2000. Interestingly, the 1999 experiment did not produce warming events whose timing was midway between those of 2000 and 2002. Instead, approximately one-third of the 20-member ensemble followed an evolution similar to 2000, with a late warming event, and the remaining two-thirds produced a relatively early warming event similar to those in the 2002 experiment. The enforced equatorial wind distribution in these different ensemble members was identical, and the only differences were the small differences in initial conditions used to produce the ensemble.

As noted for the NH, this 1999 result can be interpreted in terms of the bifurcation diagram of Yoden (1987). For very small or large tropospheric wave forcing/equatorial wind influence, there is likely to be only one stable solution, and the modeled stratosphere will go to it regardless of the initial conditions. For intermediate equatorial influence (as in 1999) or intermediate tropospheric forcing (as shown in the example of G2003), there appear to be multiple stable states. The initial conditions then become more important in determining which of the stable states the model approaches. We suggest that the state of the subtropical upper stratosphere in early winter is a crucial region for this process. If the early winter evolution happens to favor the early development of the anticyclonic flow in the subtropics and hence an easterly anomaly in this region, the winter is more likely to move into a disturbed regime. Conversely, an early winter evolution that results in a westerly anomaly in this region is more likely to remain undisturbed.

Although we conclude that the easterly anomaly in the equatorial upper stratosphere in early winter may have been a contributory factor in the warming event, we cannot wholly discount the possible influence from the small differences in the lower stratosphere since the equatorial winds were imposed at all heights between...
16 and 65 km. Possible experiments were considered in which identical winds in the equatorial lower stratosphere were retained and only the upper-level winds varied. However, these were not carried out because of the problems associated with the joining of data from different years and resulting discontinuities at the levels at which they are joined.

It is not clear why the observed upper-level equatorial winds in 2002 were so anomalously easterly. A brief examination of the two observational datasets suggests that strong east phases of the SAO have been observed before (Figs. 6–7), but the combination of two consecutive strong east phases, resulting in almost a year of anomalous easterlies, is more unusual. The east phase of the SAO is thought to be due to a combination of horizontal advection of summer easterlies across the equator by the meridional circulation and to momentum forcing by planetary and gravity wave breaking at low latitudes. It is well known that the strength of the meridional circulation is primarily determined by wave forcing, so that one might expect strengthened easterlies throughout the SH in mid- to late winter (July–September) as the warming event developed. However, it is not immediately clear that this mechanism can explain the strengthened easterlies in early winter (May–June), nor the unusually strong easterlies in the previous summertime (January/February) since the previous NH winter, although disturbed, was not unusually so. More research in this area would be helpful in resolving this question.

Finally, we reiterate that it is most likely that the unexpected SH warming in September 2002 was a combination of a number of possible factors, including anomalous tropospheric forcing and anomalously easterly equatorial winds. Indeed, the 1999 experiment suggests that equatorial winds in previous years may also have been conducive to a sudden warming event, but this did not occur in reality, suggesting that other factors are also required. Further work with more sophisticated models and experiments is desirable in order to further understand the complicated behavior of the real atmosphere.

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