Stratospheric Vacillations and the Major Warming over Antarctica in 2002

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ABSTRACT

The conditions that lead to the major warming over Antarctica in late September 2002 are examined. In many respects, the warming resembled wave-2 warmings seen in the Northern Hemisphere; the winter cyclonic circulation was split into two smaller cyclones by a large amplitude planetary wave disturbance that appeared to propagate upward from the troposphere. However, in addition to this classic warming mechanism, distinctive stratospheric vacillations occurred throughout the preceding winter months. These vacillations in wave amplitude, Eliassen–Palm fluxes, and zonal-mean zonal winds are examined. By comparison with a numerical model experiment, it is shown that the vacillation is accompanied by a systematic weakening of the westerly winds over the season. This preconditions the Antarctic circulation, and it is argued that it allows anomalously strong vertical propagation of planetary waves from the troposphere into the stratosphere. By contrast, a survey of previous winters shows that stratospheric westerlies usually vary much more gradually, with vacillations only occurring for short periods of time, if at all, in a given winter.

Similar vacillations in a numerical model of the stratosphere only occur if the forcing amplitude is above a certain value. However, the level of winter-mean wave activity entering the stratosphere during 2002 is not unprecedented, and there is still some uncertainty over the cause of the onset and persistence of the vacillation and, ultimately, the major warming.

1. Introduction

The winter stratosphere is characterized by a westerly circulation around a cold polar vortex. In the 1950s, it was discovered that this orderly state of affairs in the Northern Hemisphere is interrupted from time to time by sudden stratospheric warmings (Scherhag 1952), in which the westerly flow is disrupted and the temperature rises by up to several tens of degrees in a few days. The strength of these stratospheric warmings varies considerably. To distinguish between strong and weak events, a major warming is defined as one in which, at 10 hPa or below, the temperature increases poleward of 60° latitude and the zonal-mean westerlies are reversed. When the circulation only reverses in the upper stratosphere, the event is classified as a minor warming. Minor warmings also occur in the Southern Hemisphere, sometimes more than once in a winter. However, until 2002, a major warming had not been observed in the Southern Hemisphere (e.g., Andrews et al. 1987; Roscoe et al. 2005).

Zonal wind at 60°S and the mean meridional temperature gradient at 10 hPa from 60°S to the South Pole are shown in Fig. 1 for September 2002 [all data are from Met Office assimilated analyses (Swinbank and O'Neill 1994) unless otherwise stated]. The mean zonal wind is westerly and around 50 m s^{-1} for the first 20 days of the month, before rapidly decelerating and reversing on 25 September. The temperature gradient appears to reverse more readily, with two weaker reversals before a stronger reversal on 20 September. Both of the criteria for a major warming were therefore first met on 25 September when the 10-hPa mean zonal wind and the meridional temperature gradient were reversed, and late September 2002 represents the first major warming observed in the Southern Hemisphere since records began in 1957. It is possible that Southern Hemisphere major warmings have occurred on previous occasions, before the advent of modern observing systems. However, since no major warmings have been observed in the modern era, this is clearly a rare event. During the winter of 2002, prior to the warming, there was also a marked series of wind vacillations in the upper stratosphere and unusually weak westerlies (Fig. 2b). We return to these features in later sections.

2. Possible factors contributing to the warming

a. The quasi-biennial oscillation

Following the discovery of a modulation of the northern winter vortex strength by the quasi-biennial oscil-

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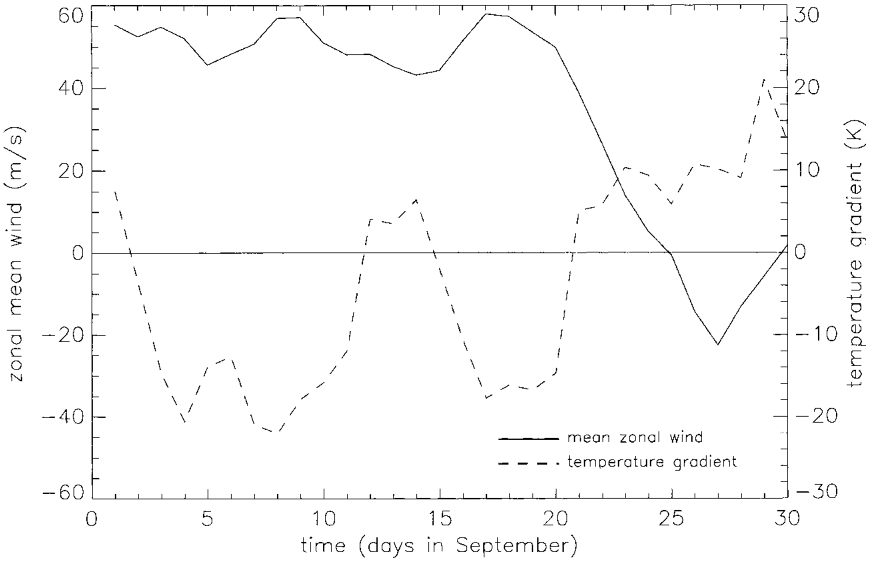

FIG. 1. The 10-hPa time series of mean zonal wind at 60°S and mean temperature gradient from 60° to 90°S.

lation (QBO; Holton and Tan 1980), various authors have also related the strength of the southern polar vortex to the phase of the QBO (e.g., Butchart and Austin 1996; Baldwin and Dunkerton 1998). As well as a weaker vortex, it seems that major warmings are also more common in the Northern Hemisphere during the easterly phase of the QBO (e.g., Hamilton 1998). It is possible that the QBO could have contributed to the conditions for the Antarctic major warming of 2002. However, the lower-stratospheric QBO was in the westerly phase throughout the winter period and September in 2002, and this phase of the QBO is, on average, associated with a strong and undisturbed vortex.

b. A wave packet from the troposphere

Close to the middle of September, a large planetary-scale wave pulse was produced in the troposphere. The vertical component of the Eliassen–Palm (EP) flux shows a large pulse appearing in the lower troposphere near 60°N on 16 and 17 of September (Fig. 3a). It is difficult to distinguish a feature in the troposphere responsible for this pulse of planetary waves, however, apparent progression of the pulse upward from the troposphere to the stratosphere on a time scale of a few days can be seen in Fig. 3 (although it does not grow monotonically with height), and its arrival in the stratosphere corresponds to the timing of the major warming (cf. Figs. 1 and 2).

This picture of the warming conforms to the Matsuno (1971) mechanism of a major warming generated by a pulse of Rossby wave activity propagating upward from the troposphere, and subsequent dissipation through interaction with a critical line in the mean flow. In this particular case, the size of the pulse of wave activity at 100 hPa is unprecedented when compared to previous southern winters (Fig. 4, top). Possible reasons for this include a large pulse of planetary waves from the lower troposphere, a large pulse of planetary wave activity generated in situ in the upper troposphere by nonlinear interactions of baroclinic eddies (Scinocca and Haynes 1998), and anomalous propagation of waves into the lower stratosphere because of preconditioning.

We first note that there was no anomalously large pulse of wave activity in the lower troposphere just before the warming (Fig. 4, bottom). In this region, there was a pulse in Fz, but it was smaller than some of those found in previous years, which, of course, did not give rise to major warmings.

Second, although EP fluxes from planetary waves show a peak near the tropopause on 21 September (Fig. 3a), synoptic-scale waves show only small values in the upper troposphere at this time (Fig. 3b). The EP flux from synoptic-scale eddies does however peak on 13 September, and as this decreases, planetary wave fluxes increase at the same level in the lower troposphere. A modified Scinocca and Haynes (1998)–type mechanism could therefore be important in providing the source of planetary waves in the lower troposphere. This is unlikely to be the main cause of the warming however, as larger planetary wave pulses often occur at this level (see, e.g., the pulse on 2 September in Fig. 3a).

We examine the vortex for preconditioning using a diagnostic related to the refractive index. Figure 5a suggests that in the period up to the warming in September 2002, there were anomalously large values of the re-

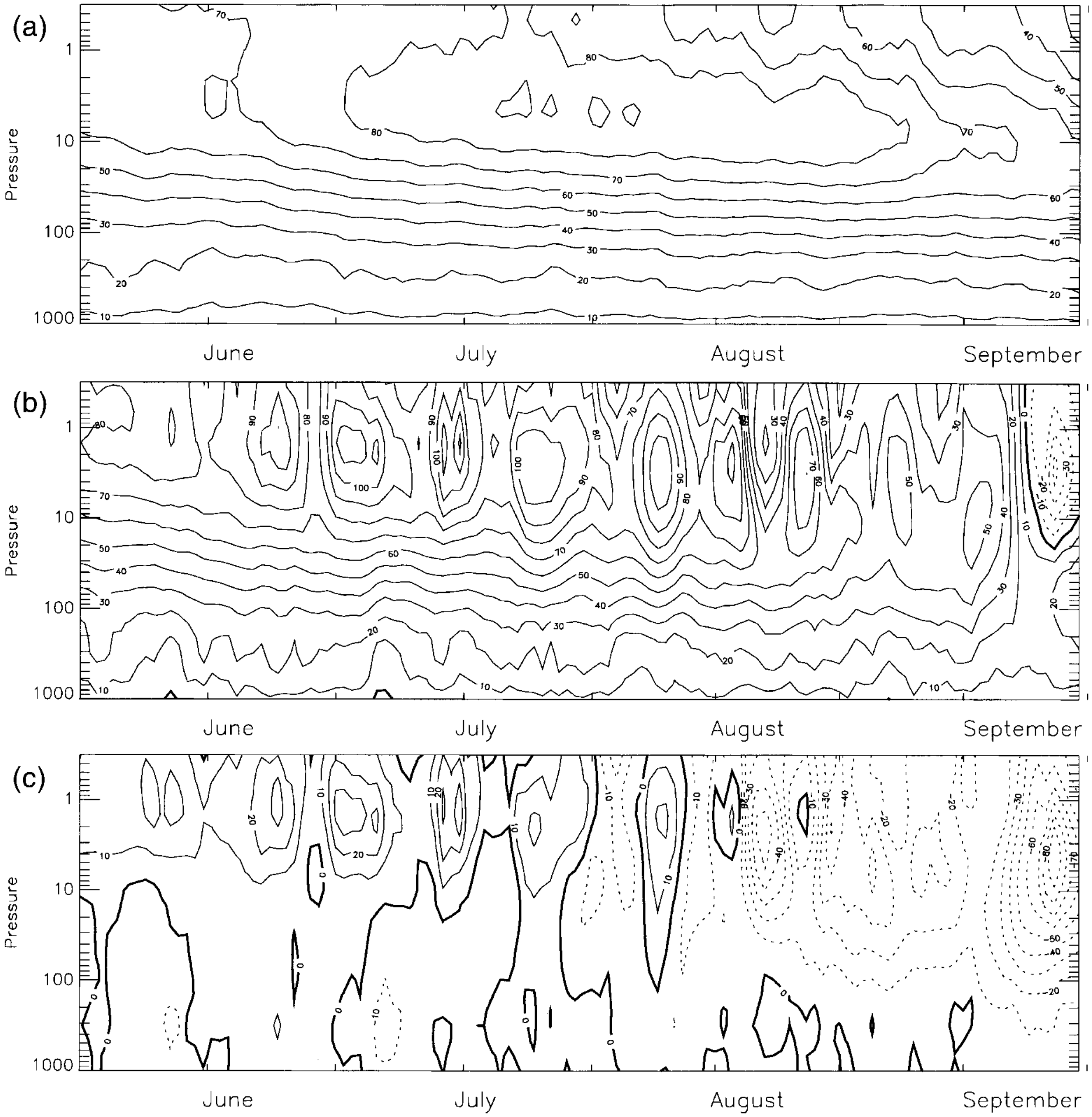

FIG. 2. Zonal winds (m s^{-1}) from (a) the mean of 10 previous Southern Hemisphere winters from 1992 to 2001, (b) the winter of 2002, and (c) the difference between (b) and (a). Zonal averages at 58.75°S are shown for the period from 1 Jun to 30 Sep.

fractive index for planetary waves in the lower stratosphere over Antarctica. For a given source amplitude of upward-propagating waves, and assuming the Wentzel–Kramers–Brillouin–Jeffreys (WKBJ) theory holds, we then expect larger magnitude EP fluxes to move into the lower stratosphere [e.g., Butchart et al. 1982, their Eq. (25)], at least partly explaining the anomalously large pulse in the upper troposphere. Further evidence of preconditioning comes from the area of the vortex. By examining a number of cases, Baldwin and Holton (1988) showed that the area enclosed by a potential vorticity (PV) contour in the midstratosphere is usually a good measure of preconditioning of the stratosphere for a warming. Figure 5b shows that, compared to 2001, which is a more typical year with a strong polar-night jet (Fig. 6), a systematic reduction in the area of the vortex in the midstratosphere occurred from late June onward, confirming the idea that preconditioning of the vortex began some weeks in advance.

In summary, although the wave packet at 100 hPa

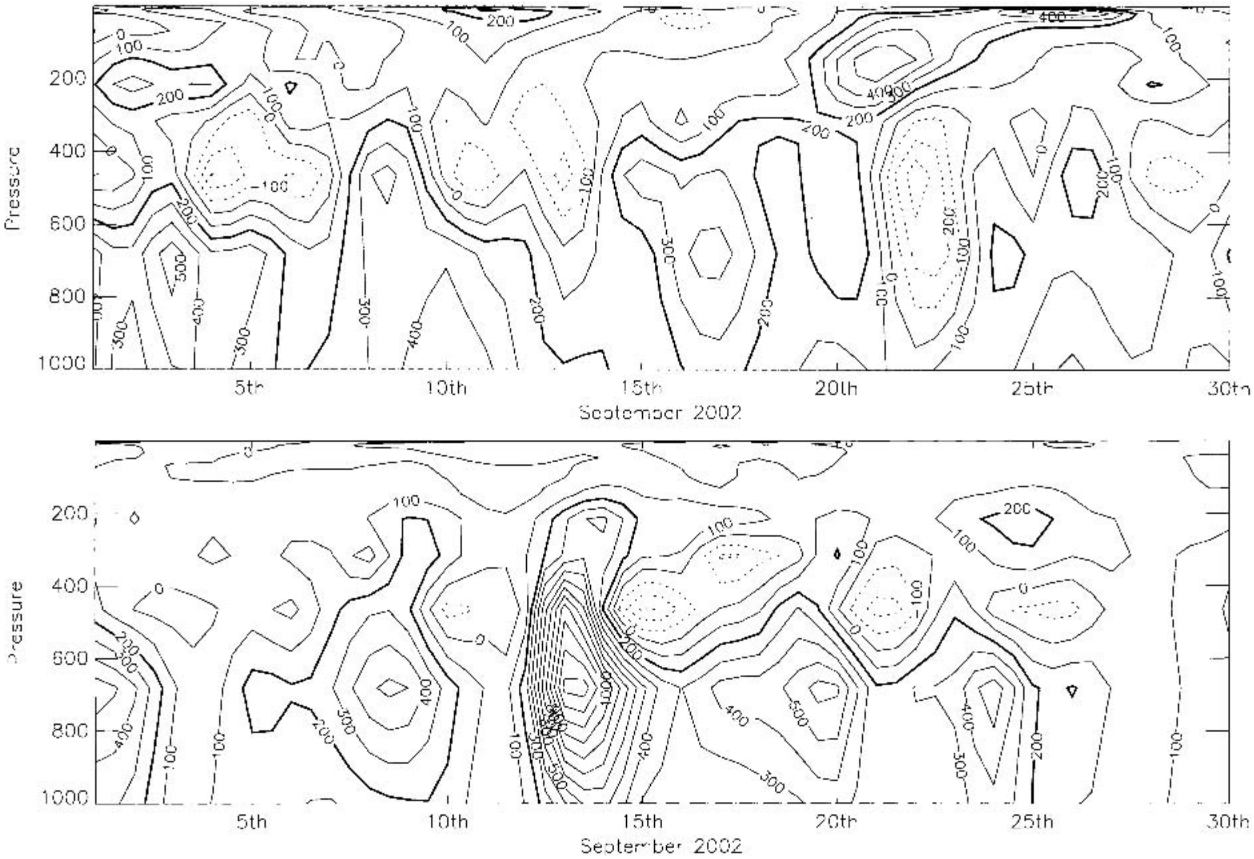

FIG. 3. Time series of the vertical component of the EP flux scaled by $1/P^{1/2}$, where P is pressure, for Sep 2002 for (top) planetary-scale waves 1–4 and (bottom) synoptic-scale waves 5–12 averaged over 50°–70°S. Units are $\mathrm{kg}^{1/2}\ \mathrm{m}^{1/2}\ \mathrm{s}^{-1}$.

appears to have been the trigger for the warming, the large amplitude at this level is more consistent with a highly preconditioned vortex leading to increased refractive index in the lower stratosphere and enhanced propagation of planetary waves from the troposphere than an exceptionally large pulse of wave activity from the lower troposphere or strong nonlinear interaction of baroclinic eddies near the tropopause.

c. Persistent winter vacillations

A whole hierarchy of numerical models has shown distinct stratospheric regimes that are either steady or vacillating. The vacillations were first found in a beta-channel model of the zonal wind and a single zonal wave as a function of height (Holton and Mass 1976). Using slowly varying wave forcing, Chao (1985) showed how the major warmings in this model could be viewed in terms of catastrophe theory. Yoden (1987) also showed that increased wave forcing can lead to a transition to sudden warmings by a Hopf bifurcation from a steady state to a perfectly periodic vacillating solution (Hopf 1942; Ott 1993). Vacillations have since been found in models with less spectrally truncated meridional and zonal structure (Scott and Haynes 2000; Chen et al. 2001) and fully 3D mechanistic models of the middle atmosphere (Scaife and James 2000). Finally, stratospheric vacillations have also been shown to occur in a comprehensive general circulation model (GCM; Christiansen 2000). When high levels of planetary wave forcing are emanating from the troposphere, almost all of these models also exhibit a strong vacillation between easterly and westerly winds that resembles a series of major warmings. Similarly, all of the models show an asymptotic approach to quasi-steady conditions when the wave forcing from the troposphere is very low. In models in which latitudinal structure is well represented, another vacillation is found with amplitudes of around 10 m s^{-1} and periods of around 5–10 days. It occurs with moderate levels of planetary wave forcing, and this weaker vacillation has been identified as likely to play an important role in the interannual variability of the Southern Hemisphere stratosphere (Scaife and James 2000). In contrast, interannual variability in the Northern Hemisphere is dominated by the occurrence/nonoccurrence of major warmings.

Figure 6 shows the evolution of winds in the polar-

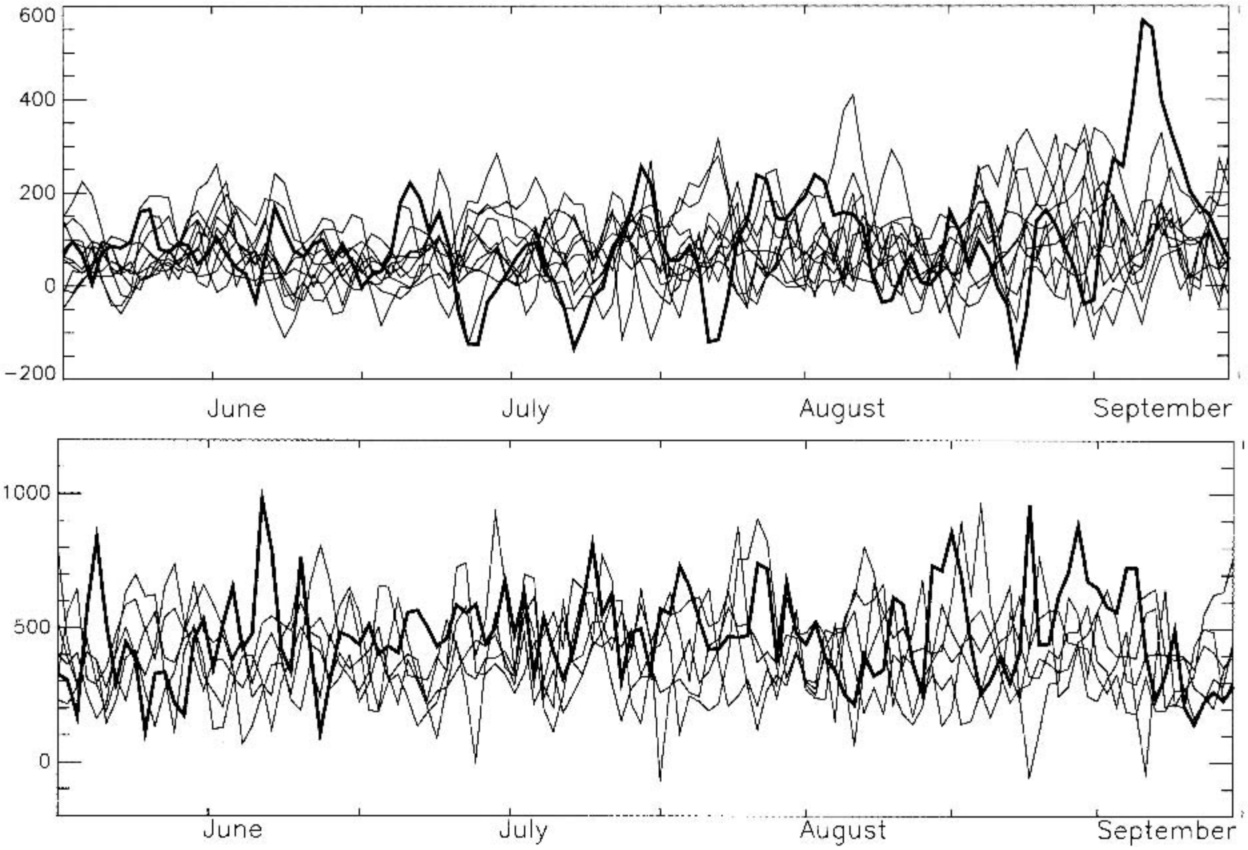

FIG. 4. Time series of the vertical component of the EP flux for 1 Jun–30 Sep for each year from 1992 to 2002 from assimilated analyses. Averages between 51.25 and 71.25S are shown at 100 hPa (upper) and 681 hPa (lower). Units are kg$^{1/2}$ m$^{1/2}$ s^{-1} and the flux is scaled by $1/P^{1/2}$.

night jet in the Antarctic stratosphere for 10 consecutive winters from 1993 to 2002. Although some pulses in wave activity occurred as early as May in 2002 (Newman and Nash 2005), distinctive vacillations with amplitude around 20 m s^{-1} began around day 20 (20 June 20) and continued throughout the winter while the zonal winds systematically decreased, and potential vorticity diagnostics showed that the vortex was eroded to an unusually small area (Fig. 5). Similar vacillations are occasionally found in other winters but only exist for short periods, for example, around day 90 of 1995 and day 60 of 1996. It seems that the Southern Hemisphere stratosphere therefore does spend time in both quasi-steady and vacillating regimes as suggested by Scaife and James (2000), but that most of the time it is spent in the low forcing, quasi-steady regime, as was the case throughout 2001, for example. The winter of 2002 is therefore highly unusual both in spending several months in the vacillating regime and ultimately producing a major warming. It is tempting to suggest that the major warming could have been predicted many weeks in advance because of the unusual persistence of the vacillating regime.

Figure 2b shows the vertical extent of the wind vacillations through the 2002 winter. The vacillation appears to be localized in the upper stratosphere, and the maximum amplitude occurs near the maximum in the polar-night jet. There is little phase difference in the vacillation at different heights in the upper stratosphere and the peak amplitude descends with time, following the seasonal descent of the jet core down through the stratosphere (Fig. 2a). Similar features were noted in the modeled vacillation described by Scaife and James (2000).

The vacillations are also visible in other flow parameters. Time series of the amplitudes of geopotential wave 1 and wave 2 in the extratropics show matching vacillations that tend to be out of phase with the wind vacillation (Fig. 7), although the phase relationship between vacillations in wave-1 and wave-2 amplitude shows some variation and the wave-2 component is substantially weaker than the wave-1 component.

d. Comparison with model vacillations

Very similar vacillations, but with about half the amplitude in the wave fields and zonal mean winds, were found in the idealized simulation with a hydrostatic

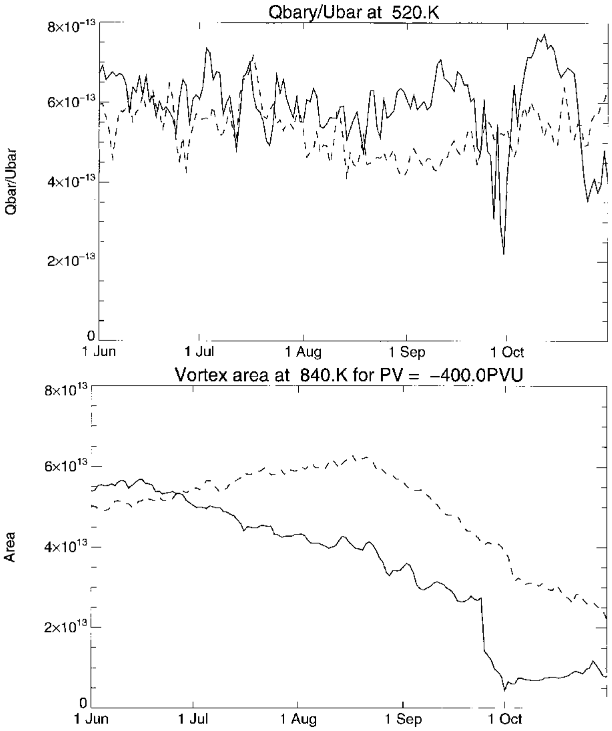

FIG. 5. Time series of the meridional gradient of PV [in PV units (PVU), where 1 PVU = 1.0 × 10^{-6} m^2 s^{-1} K kg^{-1}] divided by (top) the zonal-mean wind over 60°–75°S with negative values set to zero in the average [large values indicate large values of refractive index for planetary waves (e.g., Butchart et al. 1982)] and (bottom) the area enclosed by the −400 PVU contour on the 840-K potential temperature surface (m^2).

primitive equation model (Scaife and James 2000, their Figs. 2 and 4). Figure 8 shows how the stratosphere can also produce this response to a realistic increase in planetary wave amplitudes in the 100-hPa geopotential height field. In this case from an increase in wave amplitudes caused by the El Niño–Southern Oscillation (ENSO). When the model is forced at 100 hPa with relatively small geopotential height wave-1 amplitudes (constructed from years with weak ENSO activity, i.e., neither El Niño nor La Niña), the zonal wind near the core of the polar-night jet tends to approach an almost steady regime with strong winds approaching 100 m s^{-1}. Such winds often occur during normal Southern Hemisphere conditions as shown in Fig. 6. However, when the stronger wave-1 amplitudes are used to force the model, the stratospheric winds begin to vacillate with amplitude around 10 m s^{-1} and period of a week or so. Also note how the vacillation at this higher level of forcing is accompanied by a slow reduction in the strength of the mean winds, so that after 120 days, even without any imposed seasonal cycle, the polar-night jet is substantially weaker in the larger wave amplitude forcing case.

In these simulations, with steady wave forcing, individual periods of the vacillation correspond to the generation and dissipation of a single anticyclone that migrates poleward and eastward with time (Scaife and James 2000). This can be seen in the distribution of PV on mid- to upper-stratospheric potential temperature surfaces on occasions in 2002, particularly late in the winter. Similar events have been considered as traveling waves constructively interfering with the stationary waves in the stratosphere (Hirota et al. 1990). On other occasions, a relatively stationary anticyclonic eddy appears to grow in situ during a vacillation period. In either case, the geopotential height in the center of the anticyclone is a maximum when the zonally averaged zonal wind is a minimum. It is also worth mentioning that shortly after these times, the vertical component of the EP flux in the lower stratosphere is negative, suggesting the possibility of downward-propagating waves. The occurrence of periods when the vertical component of the EP flux is negative in the lower stratosphere (Fig. 4) at times of enhanced planetary wave amplitudes in the stratosphere suggests that the resonance mechanism of Plumb (1981) also cannot be ruled out as playing a role in 2002.

The similarity between the idealized simulations in Fig. 8 and the winds in 2002 and a cold undisturbed year such as 2001 (see Fig. 6) is striking. Winds from the weaker forcing experiment and the 2001 winter both show a slow approach to an almost steady regime with

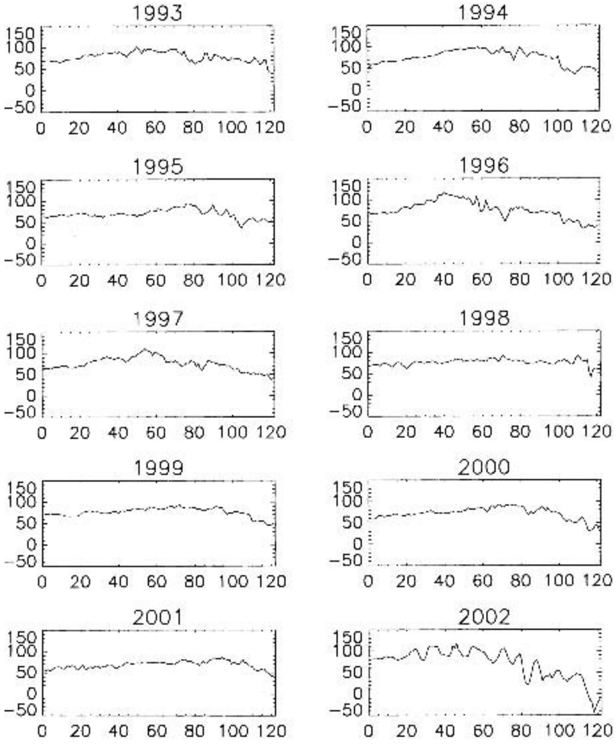

FIG. 6. Zonal winds (m s^{-1}) from previous Southern Hemisphere winters. Zonal averages at 1 hPa and 60°S are shown for 120 days starting from 1 Jun.

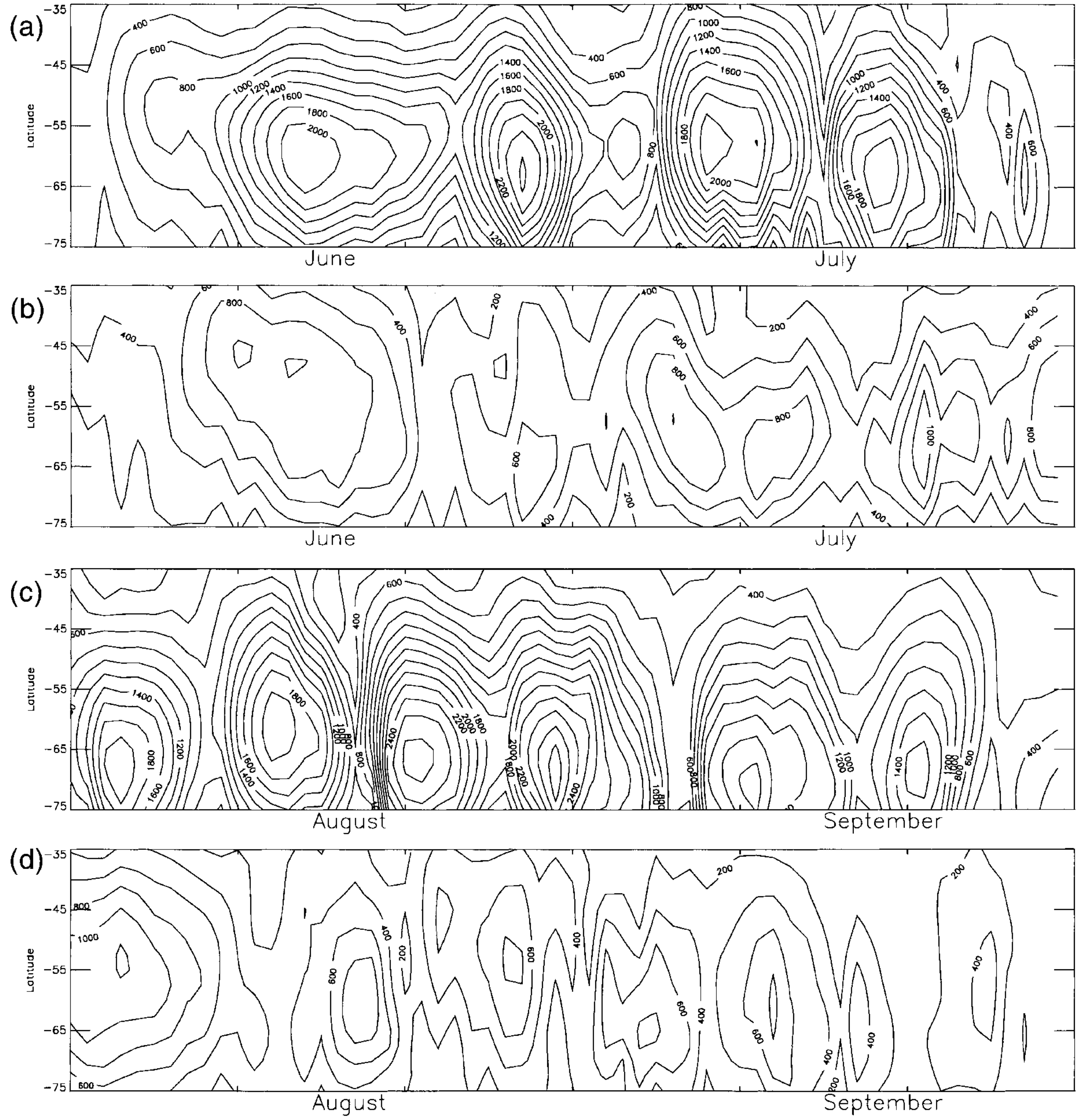

FIG. 7. Geopotential height amplitudes (m) of waves 1 and 2 at 1 hPa for the period from (a), (b) 1 Jun until 31 Jul and (c), (d) 1 Aug until 30 Sep.

very strong westerlies, whereas the stronger forcing experiment and the 2002 case both show a similar vacillation over a period corresponding to several months and a systematic decline in the strength of the mean wind, so that by day 120 of the idealized simulations (Fig. 8), and by early September in observations (Fig. 6), the jet is substantially weakened in the vacillating regime.

It is also worth noting that a moderate ENSO event occurred in 2002 and was becoming well developed through southern winter. Given the striking similarity between the idealized model simulations and the evolution of the polar-night jet in 2001 and 2002, we examine the 100-hPa geopotential height for wavelike anomalies in winter 2002. Figure 9 shows that the 2002 anomaly consisted of a predominantly wave-2 pattern of geopotential height anomaly around 60°S with maxima just south of the tip of South America and southeast of Africa. The quasi-stationary wave pattern normally found in the Southern Hemisphere

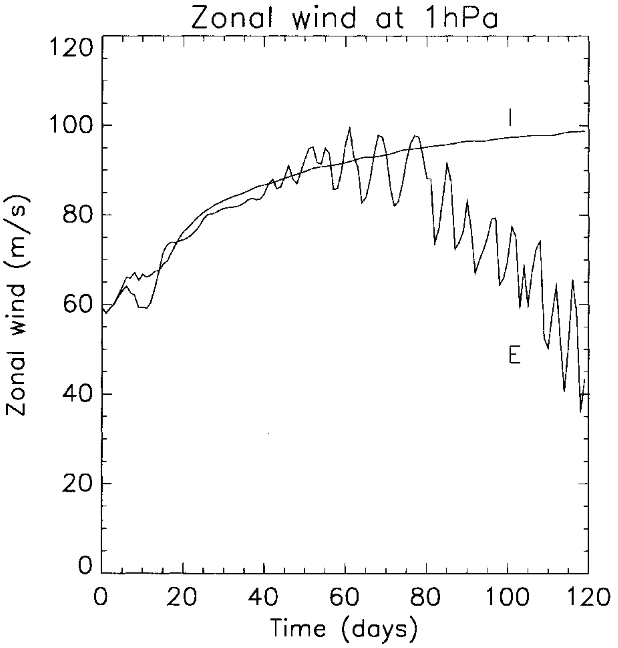

FIG. 8. Zonal winds (m s^{-1}) from perpetual Jan simulations with large wave-1 amplitude forcing from El Niño periods (E) and weaker wave amplitude forcing from intermediate periods with little ENSO activity (I). Zonal averages at 1 hPa and 60° latitude are shown.

(Fig. 9a) is strengthened over the South Pacific in 2002, and this corresponds to an increase of around 20% in the amplitude of stationary waves compared to the mean over recent years (Fig. 9d). This is consistent with the expected increase in steady wave forcing, but we note that larger stationary planetary wave amplitudes have occurred in other recent years. A full explanation of the increased wave forcing in 2002 has to also include traveling waves. To include all waves, Fig. 10 shows the total seasonal mean EP flux. The total forcing at 100 hPa in 2002 is close to the maximum over recent years, and unlike the wave packet in September, the strong winter mean forcing near the tropopause in 2002 is consistent with anomalously strong waves at lower levels (see the values for 681 hPa). Only 1996 matches the strength of winter mean waves seen near the tropopause in 2002, and the 1996 winter also showed some periods of vacillation (Fig. 6).

3. Conclusions and prospects for future major warmings in the Southern Hemisphere

The Antarctic stratospheric circulation entered a vacillating regime similar to that identified in Scaife and James (2000), for the whole of the winter in 2002. This can be explained as a response to more vigorous planetary waves near the tropopause. We showed how this vacillation is associated with a systematic weakening of the polar-night jet by some tens of m s^{-1}. The substantial reduction in the area of the polar vortex and the increased refractive index for planetary waves in the lower stratosphere also indicate that it was strongly preconditioned by September compared to the same date in previous, undisturbed years, such as 2001. Provided that the 100-hPa conditions are given, this preconditioning of the polar-night jet is not a necessary condition for the major sudden warming to occur, as shown by Manney et al. (2005), and we agree that the warming was ultimately caused by the strong pulse of planetary waves at 100 hPa. However, we suggest that the pulse of waves at 100 hPa is itself likely to be sensitive to the stratospheric preconditioning, since as we have shown, similar or larger strength pulses in the lower troposphere in previous years did not grow to such large amplitude in the lower stratosphere. We suggest that preconditioning played a crucial role in allowing the very large wave pulse to form near the tropopause just before this major warming.

We therefore sought to explain the preconditioning of the vortex. This appears to be because of the wave amplitude forcing from below being large enough to force a persistent vacillation throughout the winter that resembles the vacillation in idealized model experiments (Scaife and James 2000). Short periods of similar vacillating behavior are seen in previous years, but in none of the past 10 yr did the vacillation begin as early, or persist for as long, as it did in 2002. This is in spite of similar levels of total wave forcing near the tropopause in 1996, for example. The cause of such persistent vacillations in 2002 is therefore still unclear. In particular, the cause of the onset of the vacillation in early winter deserves further study, and it may be related to the unusually strong westerlies and large vortex area in early June (see Figs. 5 and 6).

In addition, although it was thought to be a model deficiency, early versions of the stratosphere–troposphere configuration of the Met Office Unified Model (a comprehensive GCM) have also reproduced the occasional Southern Hemisphere major warming (Butchart and Austin 1998). The latest versions of this model with interactive ozone and parameterized nonorographic gravity wave drag also occasionally produced "anomalous" Southern Hemisphere warmings. Figure 11 compares results from a 20-yr run of the model with 11 yr of observations. The integration represents the period 1980–1999 and is similar to that described in Butchart et al. (2003) except that the version of the model used included a new chemical transport scheme (J. Austin 2002, personal communication). There were also small changes to the radiation scheme. In the 20 yr of model simulation, there were two extreme years in which there were rapid increases in the South Pole temperatures in midwinter (Fig. 11b) and large, rapid deceleration of the zonal-mean winds

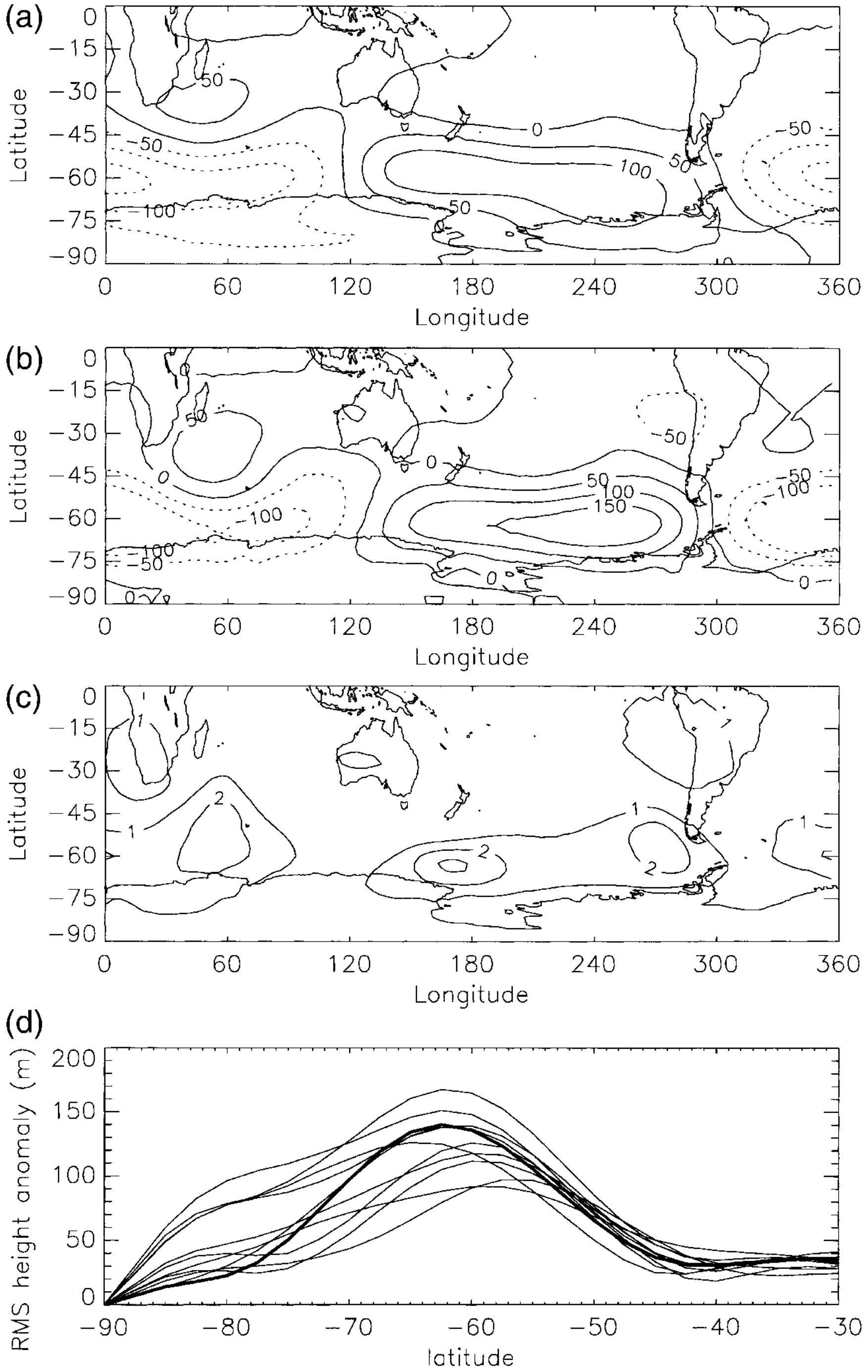

FIG. 9. Seasonal geopotential height fields for Jun–Jul–Aug at 100 hPa: (a) climatological stationary waves (1992–2001), (b) stationary waves for 2002, (c) anomaly in 2002 divided by interannual standard deviation, and (d) zonally averaged rms departure from the zonal mean at 100 hPa as a function of latitude for the past 11 yr, with 2002 in bold and the mean dashed. Units are m throughout.

(Fig. 11d). However, in contrast to the observed event of September 2002, these model warmings occurred earlier in the winter (mid-August), and though the temperature rise was much greater than that in September 2002 (cf. Figs. 11a and 11b), there was no complete reversal of the zonal-mean zonal wind at 60°S and 10 hPa. Another difference is that the modeled warmings were forced by wave 1 rather than wave 2.

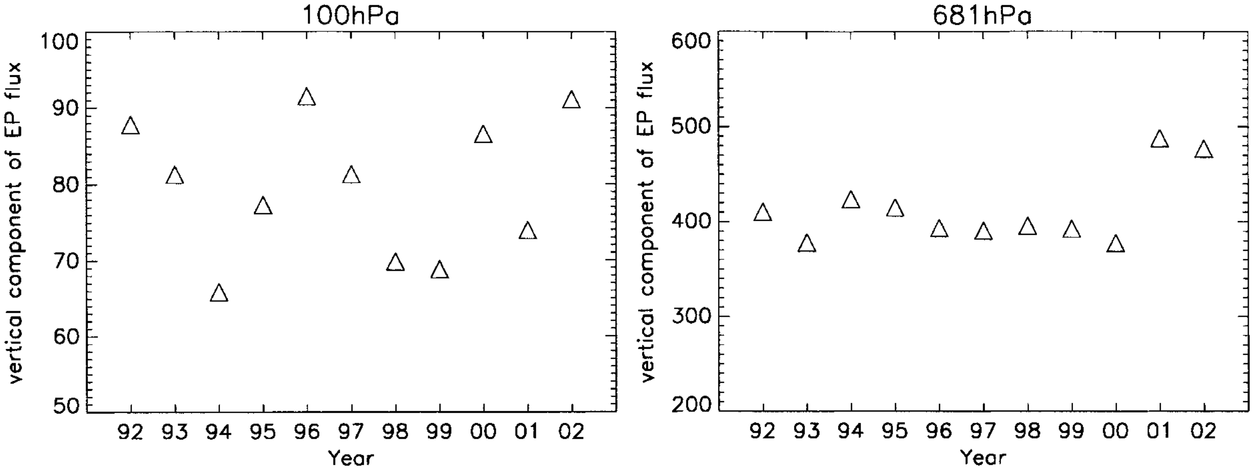

FIG. 10. Winter means of the instantaneous daily vertical component of the EP flux at (left) 100 and (right) 681 hPa calculated from Met Office assimilated analyses. Units are kg$^{1/2}$ m$^{1/2}$ s^{-1}.

Despite this difference, there is also some evidence of vacillating behavior prior to the main events, and had we paid more attention to the model, we may have realized that the Southern Hemisphere stratosphere is not far from the conditions required to produce a major warming. It would also be interesting to carry out a perturbation experiment on a previously disturbed Southern Hemisphere winter such as 1989, using a numerical model with slightly amplified tropospheric waves to test if a major warming would result. If so, the unexpected events of 2002 might have been anticipated.

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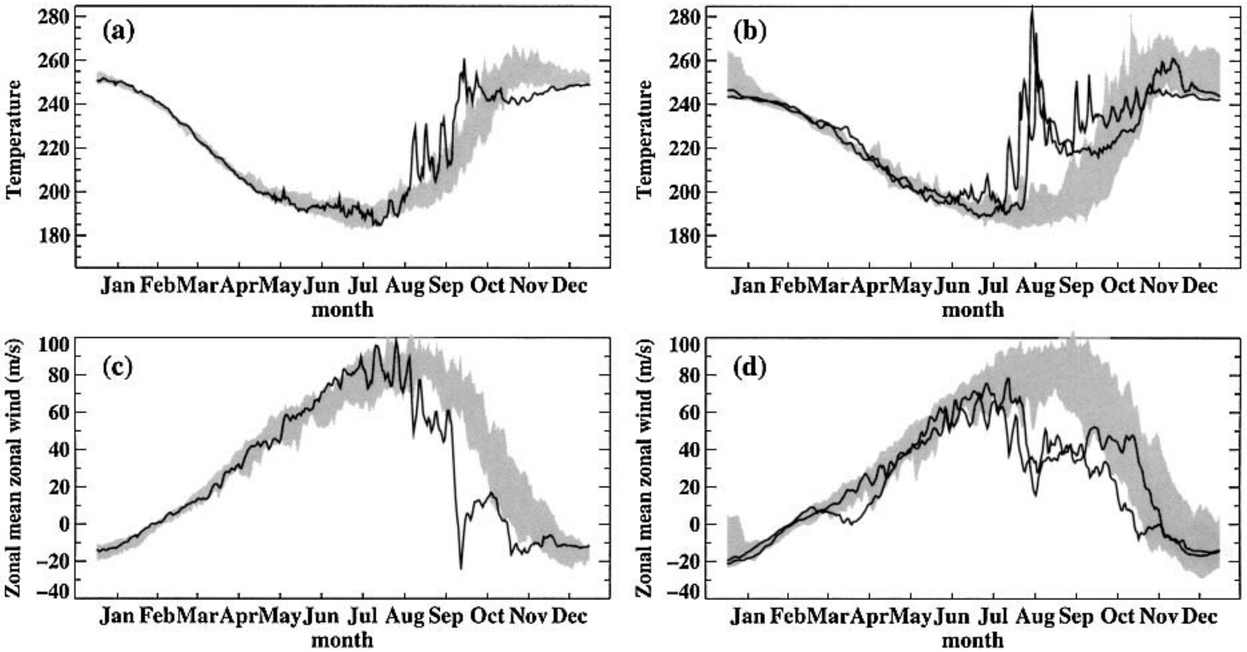

FIG. 11. Daily South Pole temperatures (K) and zonal-mean zonal wind (m s^{-1}) at 10 hPa for (a), (c) Met Office assimilated fields for 1992–2002. Values for 2002 are shown by the solid curve, and the shading is the envelope of values for the remaining 10 yr. (b), (d) The 20 yr of model simulation 1980–99. Values for 1983 and 1992 are given by the two solid curves, and the shading is the envelope of values for the remaining 18 yr.

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