Tropical SST Preconditioning of the SH Polar Vortex during Winter 2002

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ABSTRACT

The response of the Southern Hemisphere (SH) polar atmosphere to the tropical sea surface temperature (SST) during the 2002 winter–spring season is investigated by using a general circulation model (GCM). The SH stratospheric winter of 2002 was particularly unusual, characterized by a weaker-than-normal polar vortex during the whole season. It also registered, at the end of September, the first major warming yet observed in the SH. This event is unexpected in the SH, and it is supposed to be induced by a "preconditioning" of the polar vortex starting at the beginning of the winter. Atmospheric GCM experiments with prescribed SST boundary conditions are performed. The sensitivity of the Antarctic dynamics to the tropical SST of 2002 (a year characterized by an El Niño event of moderate intensity) is studied, and the uniqueness of the 2002 tropical oceanic condition is investigated through the comparison of the simulated response of the climatic system to 2002 and 1997 tropical SST (1997 being a year with a strong El Niño event). Model results highlight a primary role played by the tropical SST of 2002 in the development of the peculiar characteristics of the Antarctic dynamics during the winter months that appears to be a necessary condition for the generation of the anomalous destabilization of the polar vortex during the following spring. Results for June 2002 show a strong generation of vertically propagating waves resulting from the tropical SST that, through the perturbation of the westerly jet at middle latitudes, produces a preconditioning of the polar vortex by affecting the wave refraction index. The particular structure of the tropical SST anomalies during the winter of 2002 is thought to have influenced the subsequent preconditioning of the stratospheric vortex.

1. Introduction

The meteorology of the SH stratosphere during the winter and spring of 2002 was highly unusual and was characterized by a particularly warm and weak polar night jet (Newman and Nash 2005). These anomalous conditions resulted from a series of wave events, which took place over the course of the winter and led, in late September, to the first recorded stratospheric major warming over the Antarctic. Although the 2002 event was accurately forecast (Simmons et al. 2005), little is understood of those conditions thought to be influential in the subsequent stratospheric warming. Newman and Nash (2005) proposed the following two possible causes: 1) an excessive tropospheric wave forcing and 2) an anomalous mean flow that allowed moderate tropospheric waves to more easily propagate into the stratosphere. They estimated a level of wave activity entering the stratosphere during 2002 that was not unprecedented, although stronger than the climatology. Linked with this, an anomalously strong wavenumber 1 was seen at both high and low latitudes in the lower troposphere. Scaife et al. (2005) highlighted the presence of the anomalously large values of the refractive index for planetary waves in the lower stratosphere over Antarctica during September. Also, Manney et al. (2005) examined the refraction of large-scale waves in a model simulation of September 2002 and highlighted a broad corridor of upward and poleward propagation throughout the stratosphere prior to the warming. Harnik et al. (2005) found that the anomalous conditions of the winter of 2002 began as early as the end of the SH autumn, with a deceleration of the subtropical winds. These appear to have enhanced the poleward focusing of wave activity in the mid- and upper stratosphere during the rest of the winter. Uncertainties over the cause of the onset of the vortex preconditioning and, ultimately, of the major warming still persist. Various authors have related the strength of the southern polar vortex to the phase of the quasi-biennial oscillation (QBO; e.g., Butchart and Austin 1996; Baldwin

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and Dunkerton 1998). However, the westerly phase of the lower-stratospheric QBO throughout the 2002 winter period should be, on average, associated with a strong and undisturbed vortex (Scaife et al. 2005). Gray et al. (2005) explored the sensitivity of the polar vortex to the equatorial winds in the upper stratosphere, suggesting that the anomalous easterlies in the 1–10-hPa region may have been a contributing factor in the development of the SH major warming, but this alone cannot explain the observed event. During recent years, increasing evidence suggests that the climate response to the tropical SST conditions extends to mid-high latitudes. Recent studies (e.g., Camp and Tung 2007; Sassi et al. 2004) have highlighted the influence of El Niño–Southern Oscillation (ENSO) conditions on the winter polar stratosphere of the Northern Hemisphere (NH). McPhaden (2004) evidenced, in the evolution of the El Niño event that characterized the 2002/03 period, a peak phase during October–December and weaker signals during May and July. Grassi et al. (2005, 2006) studied the effect of the tropical SST changes on the SH polar stratosphere. They proposed that there is a teleconnection mechanism driven by the perturbation of the tropical waves generated by deep convection during winter, which in turn affects the mean flow and the wave refraction properties at higher latitudes.

Here, a state-of-the-art global atmospheric model is used to simulate the response of the SH polar dynamics to the tropical SST of 2002. The goal of this work is to point out the crucial role played by the tropical SST in the development of the peculiar atmospheric situation during the Antarctic winter of 2002. In this paper the tropical SSTs of 2002 are identified as being important for the "preconditioning" of the Antarctic polar vortex and for its subsequent destabilization during spring.

2. Model and experiments

The numerical model used in this work is the National Center for Atmospheric Research (NCAR) Community Atmospheric Model, version 2 (CAM2; Boville and Bretherton 2003; Zhang et al. 2003). The model resolution is T42 (about 2.8° × 2.8°), with 26 vertical layers in a hybrid-sigma coordinate system, ranging from the surface to 2.917 hPa, with a vertical resolution varying from 1.1 km in the stratosphere to 3–4 km in the upper levels. The boundary conditions that are necessary to perform the model simulations consist of monthly mean values of SST, sea ice, and ozone. In a first run case, named "end90s," we reproduced a generic situation representative of the end of the 1990s. From the standard boundary dataset provided with the model, that is, a merged product based on the monthly mean Hadley Centre Global Sea Ice and Sea Surface Temperature dataset version 1 (HadISST1) and version 2 of the National Oceanic and Atmospheric Administration weekly optimum interpolation (OI.v2) SST analysis (Hurrell et al. 2008), SST and sea ice data appropriate for the period studied were calculated. In a second and third case, named "02sstTR" and "97sstTR," we modified the tropical (i.e., between 30°S and 30°N) SST field by introducing monthly data representative of 2002 and 1997, respectively, based on the Kaplan SST version 2 data (Kaplan et al. 1998). The tropical SST, introduced in case 02sstTR, has maximum anomaly values of about 1.5 K in the Indo-Pacific region. Figure 1 shows tropical SST values for June. Relative to the end90s case, positive SST anomalies tend to be located in the eastern and western Pacific, in cases 97sstTR and 02sstTR, respectively. For the ozone, global seasonally varying data of concentrations appropriate for 1979 and trend values between 1979 and 1997, based on Randel and Wu (1999), have been used to calculate an ozone field representative of the end of the 1990s. This field has been used in all of the performed experiments.

When evaluating a GCM, it is important to isolate a model response to external variability (variations in the SST boundary conditions) from its own internal variability. Each experiment comprises 10 yr of integration performed by using seasonally varying SST repeated between the years. This approach allows, through a statistical evaluation of the results, the selection of the externally forced signal (i.e., statistically significant differences in means between the perturbed and the background simulations, where the significance is assessed at the 95% level using a two-sample t test) from the internal model variability.

We primarily focus on the analyses of the results sampled every 10 days, saved as instantaneous and 10-day-averaged values. More specific analyses of the temporal variability of the convective activity and of the presence of warming events required daily values of the dynamical fields for selected periods.

3. Simulation results

a. *Atmospheric impact of 2002 tropical SST on SH polar latitudes*

The impact of the 2002 tropical SST on the SH atmospheric dynamics has been calculated in terms of the difference between the 02sstTR and end90s simulated cases. In fact, these simulations use the same boundary conditions, representative of the situation at the end of the 1990s, and differ only in the tropical SST forcing between 30°S and 30°N. Following Newmann and Nash

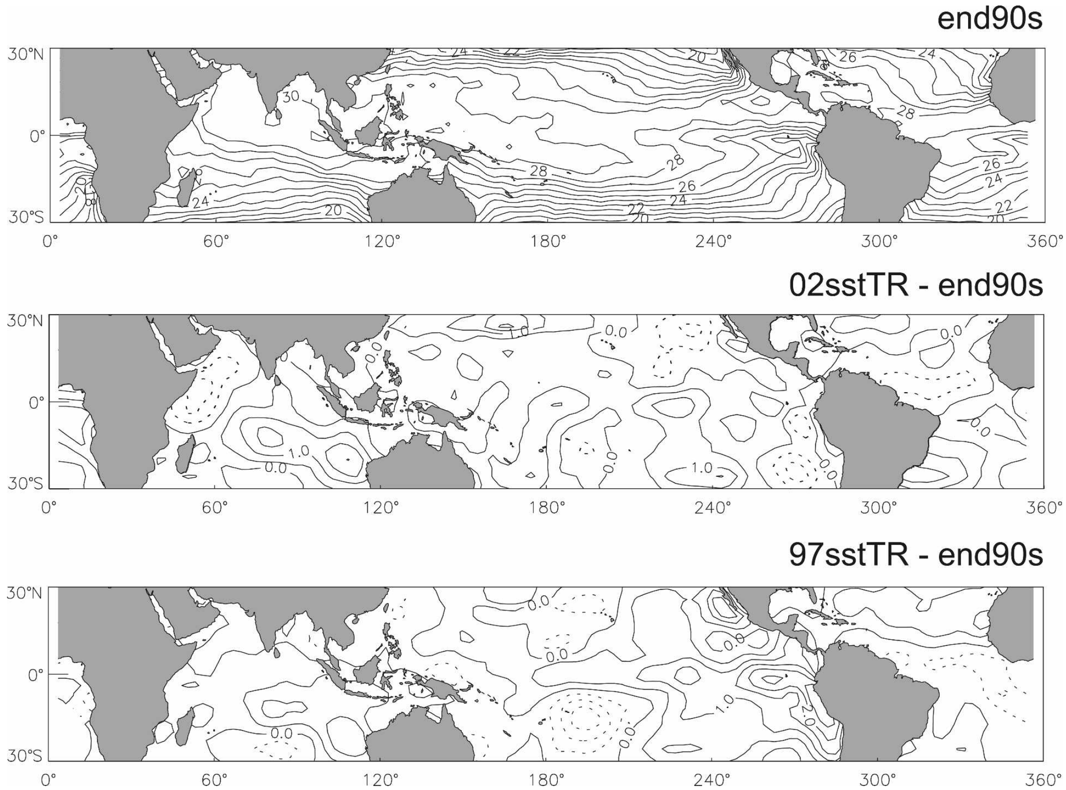

Fig. 1. (top) Tropical SST values for the end90s case, and tropical SST anomalies relative to the end90s case for the (middle) 02sstTR and (bottom) 97sstTR cases. Contour intervals are (top) 1° and (middle and bottom) 0.5°C. SST fields are shown for June.

(2005), the seasonality of the vertical structure of the simulated polar vortex has been calculated as temperature variation near the edge of the vortex (i.e., averaged between 55° and 75°S) and zonal-mean zonal wind perturbation averaged over 20°–90°S (Fig. 2). The 2002 tropical SST induces a destabilization of the polar vortex, starting from June, that progressively grows from the end of August, reaching its maximum during October, with a zonal warming of about 8 K around 30 hPa and a zonal wind deceleration of about 14 m s^{-1} in the upper model levels. The high level of significance of both positive values of temperature anomalies and negative values of zonal wind anomalies indicates that the perturbation of the dynamic field acts to systematically destabilize the polar vortex in the perturbed 02sstTR case. This effect leads to the following various stratospheric warming events during spring: a minor warming (diagnosed in terms of temperature inversion poleward of 65°S at 10 hPa for 2 days or more) in 5 of the 10 yr of integration and a major warming (defined as in Andrews et al. 1987) in 1 yr of integration of the 02sstTR case. This last event arises at the beginning of October and is characterized by zonal winds of approximately -20 m s^{-1} at 10 hPa and 65°S and maximum temperature around 240–250 K in the polar stratosphere. These results are particularly surprising considering the absence of both major and minor warming events in the 10-yr simulation of the end90s case. Further investigations are required in order to identify the possible origin of such unexpected effects.

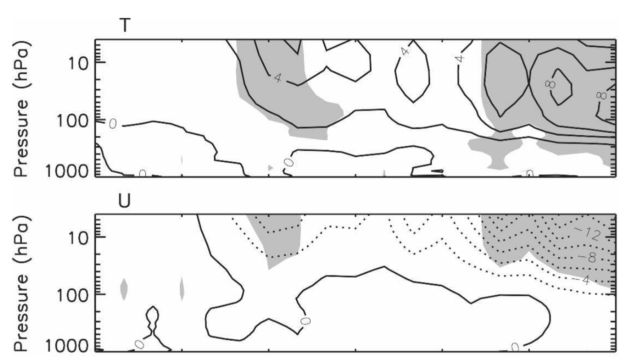

Fig. 2. Anomaly values, calculated as mean difference between the 02sstTR and end90s cases, from 1 May to 31 Oct of (top) temperatures, averaged over 55°–75°S, and (bottom) winds, averaged over 20°–90°S. Contour intervals are 2 K for the temperatures and 2 m s^{-1} for the winds and negative contours are dashed. Shading indicates significant changes at the 95% level.

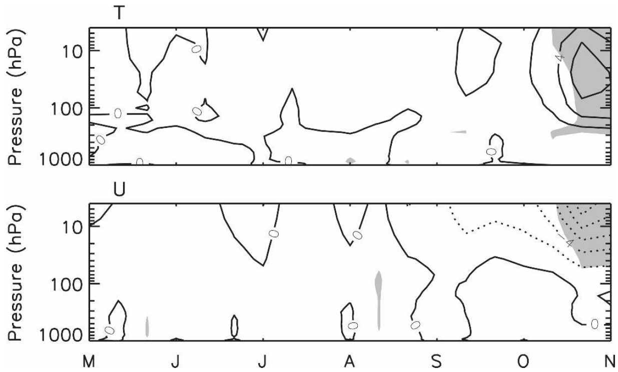

FIG. 3. Same as in Fig. 2, but for the 97sstTR minus end90s case.

b. *2002 and 1997 tropical SST: Compared analysis of the induced atmospheric perturbation during SH winter*

During 2002 the Pacific Ocean at tropical latitudes has been characterized by an El Niño event of moderate intensity (McPhaden 2004). To study the possible link between the polar vortex perturbation and the presence of El Niño, the dynamical response to the tropical SST appropriate for 1997, a year characterized by a particularly intense El Niño event, has been considered through the analysis of the 97sstTR simulation. Figure 3 shows the temperature variation near the edge of the vortex (i.e., averaged between 55° and 75°S) and the zonal-mean zonal wind perturbation averaged over 20°–90°S in terms of the mean difference between the 97sstTR and end90s cases. This time, a statistically significant effect, with maximum anomaly values of 6 K in temperature and -10 m s^{-1} in zonal wind, arises only during October. Moreover, in the 10-yr simulation tropical SST appropriate for 1997 does not produce any warming events during the spring period. The strongest difference between the 02sstTR and 97sstTR cases seems to be related to the timing of the anomaly, starting at the beginning of winter in the 02sstTR case and only during spring in the 97sstTR case. The cause of the early development of the described anomalies in the 02sstTR case is investigated by looking at the model variable "T tendency–Zhang–McFarlane moist convection" (ZMDT), which represents the temperature tendency resulting from the net latent heat released during condensation of air masses in deep convection. The standard deviation (SD) of ZMDT is an indicator of the efficiency of the time-dependent heating in exciting equatorial waves with spatial and temporal characteristics that match those of the heating variability (see, e.g., Ricciardulli and Garcia 2000). The temporal evolution/vertical structure of the perturbation of SD(ZMDT), calculated as the mean difference between the 02sstTR and 97sstTR cases, is shown in the top of Fig. 4 for the months of June and July. The graphic shows a pulse of convective driving during June, corresponding to an increase in the 02sstTR case of the convectively induced planetary waves, which are able to propagate vertically in the stratosphere of the winter hemisphere. Figure 4 (middle) shows the increase, in the 02sstTR case with respect to the 97sstTR case, of the Eliassen–Palm flux vertical component (i.e., the meridional eddy heat flux) across the tropopause. This flux, in turn, affects the SH zonal wind at middle latitudes. In particular, the stronger wave forcing during June will reduce stratospheric westerlies. In fact, normally vertically propagating waves weaken the lower-stratospheric jet, and a strengthening in the generation of those waves will result in a negative zonal wind anomaly around 40°S (Fig. 4, bottom).

The possibility that seems to emerge from this analysis is that, during June 2002, tropical SSTs generated stronger-than-usual vertically propagating waves that perturbed the westerly jet at middle latitudes. We suggest that this signal produced a preconditioning of the polar vortex that initiated a destabilization of the vortex during spring. Indications supporting these hypotheses are given by the analyses in Fig. 5. These plots define anomalies with respect to the end90s case 10-yr mean. These include 2 yr chosen from the 02sstTR case and a typical year from the 97sstTR case (hereafter I, II, and III, respectively). Simulation I leads to a major warming during October, while simulation II produces no warming. For each simulation, Figs. 5 (a)–(c) (upper panels) show the atmospheric response in terms of latitudinal/temporal evolution of the induced zonal wind anomalies at model level corresponding to 37 hPa. To better highlight evidence for the polar vortex preconditioning, the evolution of the perturbation (sampled every 10 days) has been studied starting from May. Figures 5 (a)–(c) (lower panels) show the corresponding temporal evolution of the tropospheric anomalies of SD(ZMDT). In all of the cases, the zonal winds show a negative anomaly that arises during winter and persists until spring. During winter, the presence of the negative zonal wind anomaly is consistent with a general positive anomaly of SD(ZMDT). This suggests a stronger driving of the convectively induced waves in both the 02sstTR and 97sstTR cases with respect to the background, which is probably related to the presence of the El Niño events. However, in both simulations of the 02sstTR case, the positive anomalies of SD(ZMDT) are found earlier than in the 97sstTR case (June instead of July), resulting in a perturbation that impacts the zonal wind field earlier. In simulation I, in particular, this

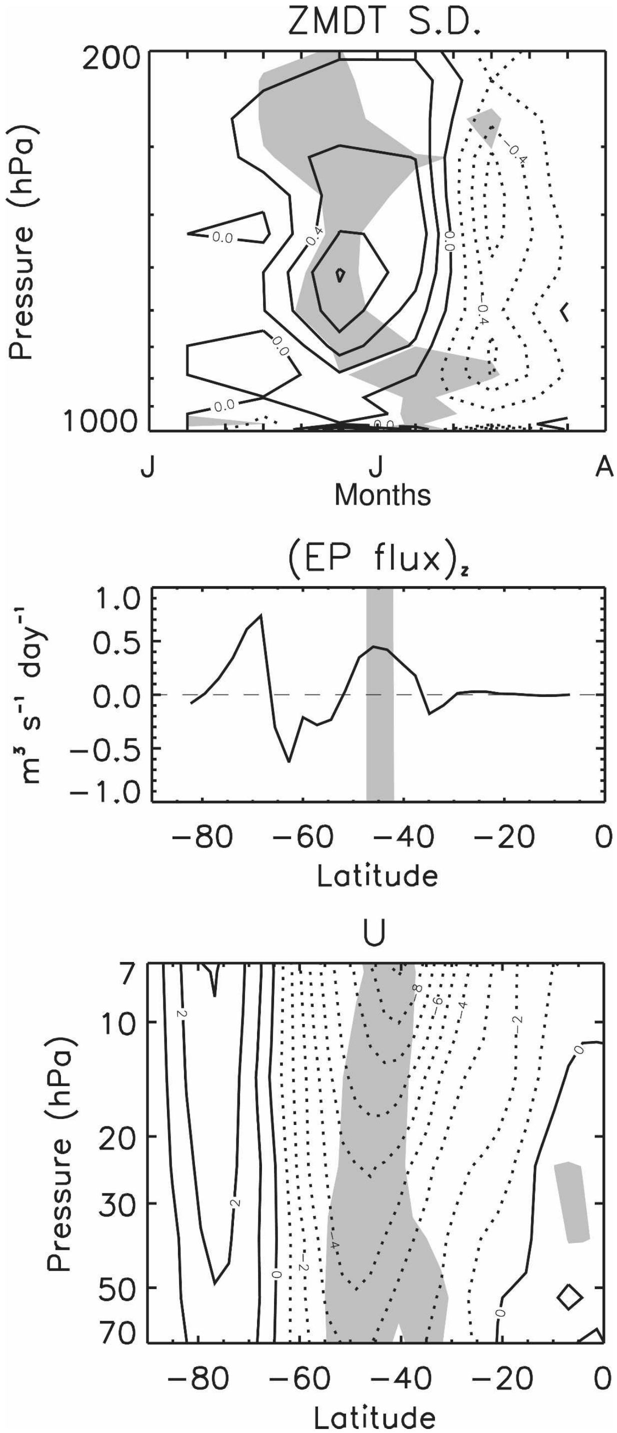

FIG. 4. Mean difference between the 02sstTR and 97sstTR cases of (top) tropospheric values of SD(ZMDT), zonally averaged over latitudes from 30°S to 30°N for June and July (1×10^{-6} K s^{-1}); (middle) the vertical component of the EP flux across the tropopause during June (m^3 s^{-1} day^{-1}); and (bottom) meridional zonal mean values of the zonal wind component for the end of June (m s^{-1}). Shading indicates significant changes at the 95% level.

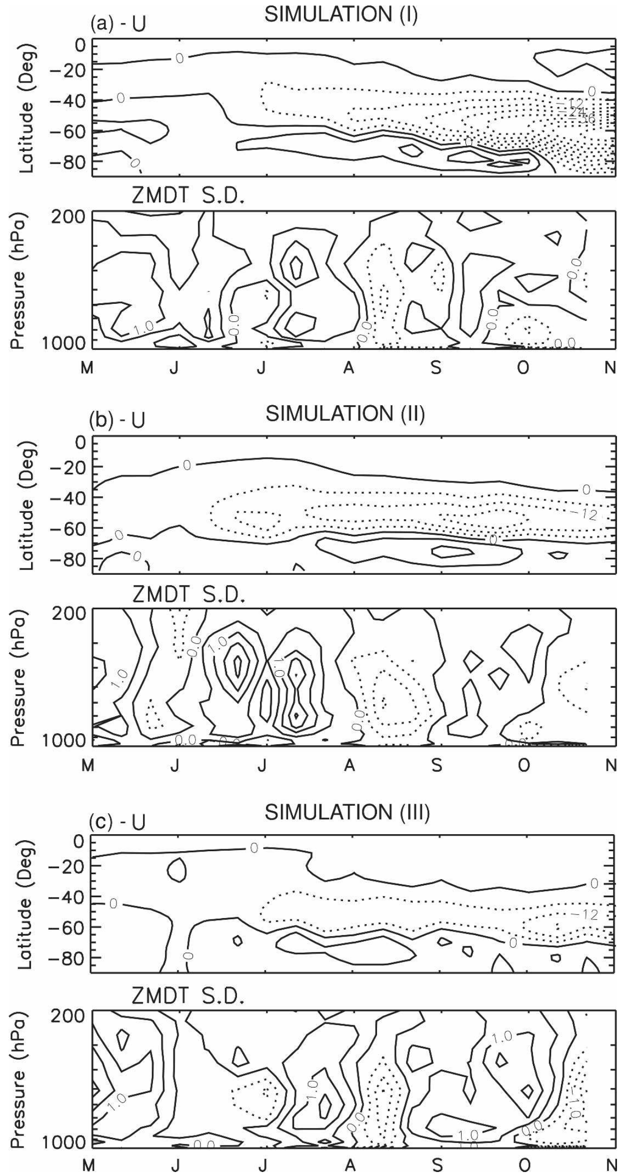

FIG. 5. Zonal mean departures from the mean of the end90s case, calculated for 2 yr of the 02sstTR case (I and II) and 1 yr of the 97sstTR case (III) and plotted from 1 May to 31 Oct of [(a), (b), (c) upper panels] the latitudinal pattern of zonal wind (contour intervals are 3 m s^{-1}) and [(a), (b), (c) lower panels] the standard deviation of tropospheric temperature tendency resulting from deep convection (units are 1×10^{-6} K s^{-1} and contour intervals are 0.2; data are zonally averaged over latitudes from 30°S to 30°N). Negative contours are dashed. See text for details.

perturbation progressively grows and moves to higher latitudes during the winter–spring period, investing the polar latitudes during October. Therefore, the strong destabilization of the polar vortex during spring seems to be related to the early preconditioning of the polar vortex during the beginning of the winter. However, in order to better understand the different evolution of

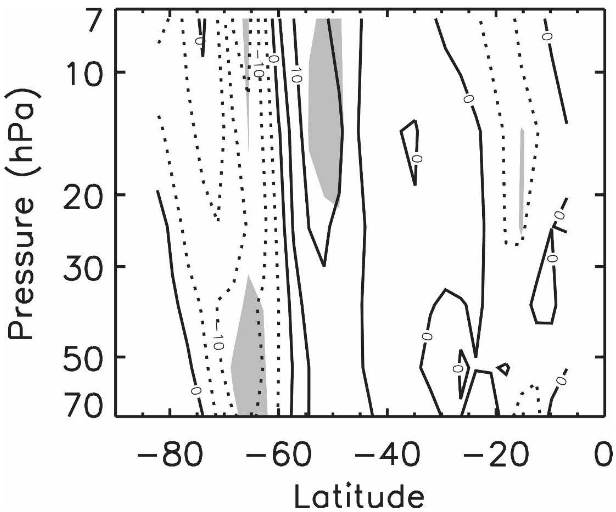

FIG. 6. Mean percentage change (%), between the 02sstTR and 97sstTR cases of the quasigeostrophic wave refractive index for zonal wavenumber 1 during August. Shading indicates significant changes at the 95% level.

the signals on the zonal wind during the end of winter/beginning of spring in each simulation, further analyses have been performed.

c. Preconditioning and polar vortex evolution during spring

We studied the anomalies of the wave refractive index (calculated as in Chen and Robinson 1992) in the 02sstTR case with respect to the 97sstTR case. Figure 6 shows a positive anomaly in the refractive index in a region around 50°S, relating to differences in flow during June–July. This pattern of the refractive index favors the propagation of waves toward this region. We suggest that tropical SST-induced waves, through the perturbation of the westerly jet at middle latitudes, could have produced a preconditioning of the polar vortex by affecting the wave refractive index and subsequently the distribution of vertically propagating waves. The lack of a strong perturbation of the polar vortex in the 97sstTR case should be related to the less intense focusing of the upward-propagating waves toward high latitudes.

A closer investigation of the 02sstTR case leads to the identification, in the presence of such preconditioning, of favorable conditions for the generation of a major warming event. The upper plots of Fig. 7 show the anomalies of the divergence of the Eliassen–Palm flux (div-EP) calculated, following Randel et al. (1987), for the end of August and for simulations I and II. These plots show evidence of an oscillation of the div-EP anomalies northward and southward of 60°S, characterized by an opposite phase in simulations I and II. These results can be explained by pointing out that the maximum positive anomaly of the refractive index, shown in Fig. 6, affects the pattern of the upward-propagating waves by deflecting them, respectively, either northward or southward if the waves propagate in a region located either southward or northward of the latitude corresponding to the maximum. Therefore, in simulation I, the region of convergence of the Eliassen–Palm flux southward of 60°S would result from a wave forcing that is stronger in the region northward than in the region southward of 60°S. The opposite pattern in simulation II would follow from the prevalence of the wave forcing southward of 60°S. While the div-EP anomalies relative to simulation I are associated with a tendency to a high-latitude deceleration of the zonal flow, and then to a high-latitude shift of the zonal wind negative anomalies, those anomalies relative to simulation II produce a confinement to the middle latitudes of the jet deceleration. These tendencies are also evident in the bottom plots of Fig. 7, showing a southward propagation of the positive anomaly of the refractive index in simulation I with respect to simulation II, resulting from the shift of the zonal wind anomaly and producing a progressive focusing toward higher latitudes of the upward-propagating waves. The arising of warming events during spring appears to be triggered by the latitudinal distribution of the upward-propagating waves.

In this framework, during 2002, the tropical SST tendency to generate stronger-than-normal vertically propagating waves during June could have produced strong negative anomalies on the lower-stratospheric jet that led to the activation of a mechanism of wave-mean flow interaction. In fact, these anomalies were able to affect the distribution of the vertically propagating waves at middle latitudes in the following period by perturbing the wave refractive index in such a way that the anomalies moved poleward. The poleward movement could have affected the vertically propagating waves still more, producing still further poleward movement of the anomalies, which reach the highest latitudes at the beginning of October. The convective driving in June is therefore a key factor and appears to be a necessary, though not sufficient, condition for the generation of the major warming during the following spring. The possible origin of the anomalous convectively induced tropical waves, in relation to the anomalous characteristics of the tropical SST of 2002, remains an open issue.

The peculiarity of the oceanic condition of 2002 seems related more to the spatial pattern of the SST anomalies than to the strength of an El Niño event that

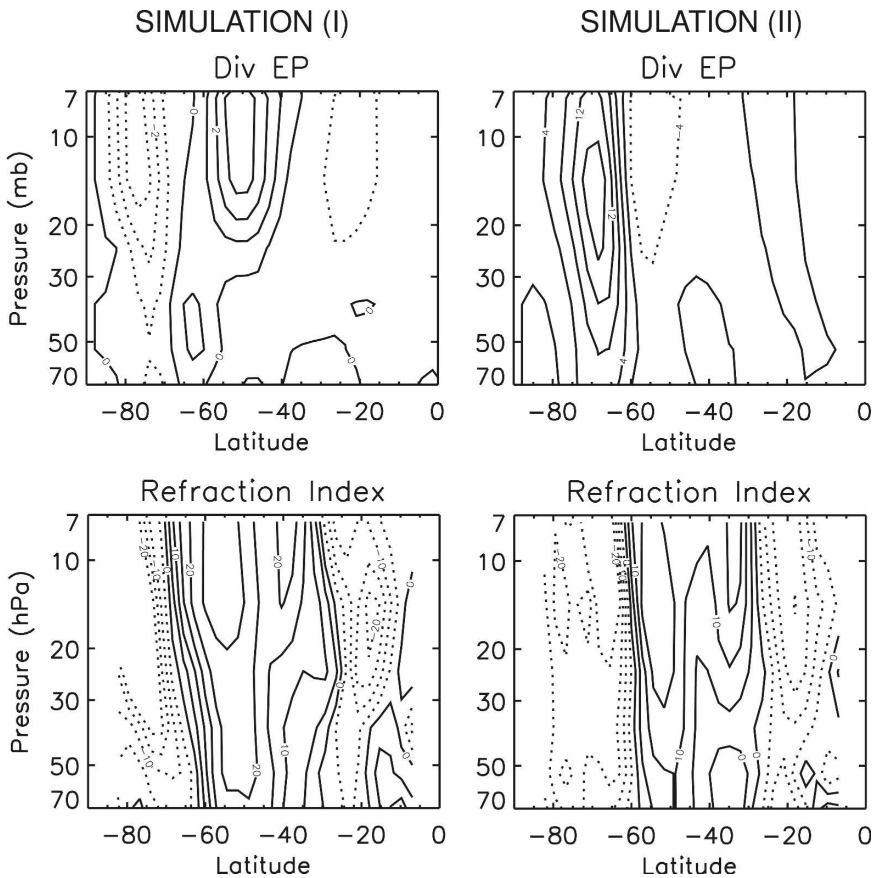

FIG. 7. Zonal mean meridional departures from the mean of the end90s case, calculated, at the end of August, for simulations I and II of (top) the divergence of Eliassen–Palm flux (m s^{-1} day^{-1}) and (bottom) the quasigeostrophic wave refractive index for zonal wavenumber 1 (%).

was of moderate intensity. These anomalies are typically concentrated farther east along the equator in the Pacific Ocean, but during 2002 they were instead located in the central region of the equatorial Pacific, with maximum SST values around 170°W (McPhaden 2004). Figure 1 highlights SST anomalies in this region during June that are even higher in the 02sstTR case than in the 97sstTR case. This can be related to the simultaneous effect of a westward displacement of the spatial pattern of the El Niño anomalies, combined with a warming of the Indian and western Pacific Oceans consistent with a greenhouse gas forcing that was unprecedented during 1998–2002 (Hoerling and Kumar 2003). Our hypothesis is that the SSTs of 2002, because of their spatial localization in a region corresponding to the area of maximum large-scale climatological ascent, strongly affected the wave generation (Lachlan-Cope and Connolley 2006). To test this hypothesis two runs have been carried out for the austral winter period (June–August) by perturbing the SST tropical boundary conditions with an idealized 2-K anomaly in a 20° × 20° box centered, in one case ("02_like"), at 0° latitude and 170°W longitude, and in another case ("97_like") at 0° latitude and 145°W longitude. Figure 8 shows the perturbation of SD(ZMDT)

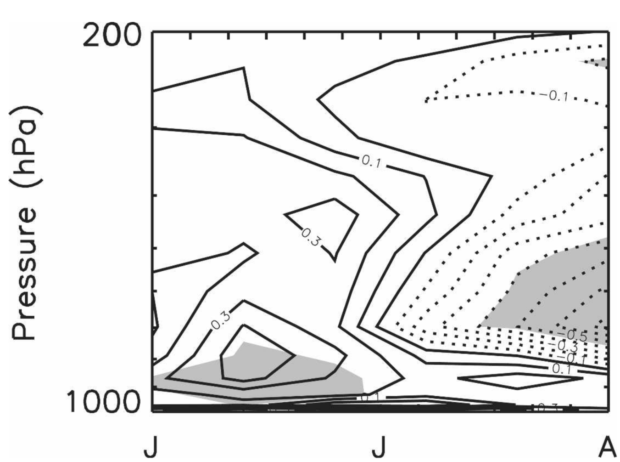

FIG. 8. Same as in Fig. 4 (top), but for the 02_like case minus the 97_like case.

calculated between the 02_like and 97_like cases. The increase during June indicates the presence of a stronger convective driving in the 02_like case, induced by the westward shift of the SST anomalies. This preliminary study suggests the unusual pattern of the 2002 SST anomalies as possible origin for the discussed anomalous preconditioning of the SH stratospheric polar vortex. Such an issue requires further investigations and is a topic of ongoing research.

4. Discussion and conclusions

The influence of tropical SST on the SH polar vortex during 2002 has been studied. The simulations highlight a key role played by the tropical SST in the development of the peculiar situation that characterized the Antarctic stratosphere during 2002. Results suggest that 2002 tropical SSTs in June could have been responsible for an unusual increase of the convectively generated tropical waves, and then for a negative perturbation of the subtropical jet. This signal on the zonal flow could then have activated a teleconnection mechanism with the highest latitudes during the following winter–spring period leading to a destabilization of the polar vortex at the end of September/beginning of October. The analysis highlights the unusual pulse of convective driving during June as a condition for the arising of the stratospheric warming during spring, in the presence of a favorable pattern of middle–high-latitude wave forcing. However, it should be considered that, because of known model underestimation of the temporal variability of convective activity (Ricciardulli and Garcia 2000), a more correct reproduction of the strength of the tropical forcing resulting from SSTs could probably enhance the percentage of warming events in the perturbed 02sstTR simulation.

Even if the link between the 2002 stratospheric warming and the SH vortex preconditioning has been already suggested in previous works (see, e.g., Scaife et al. 2005), this paper indicates for the first time the tropical SSTs, and in particular the peculiar structure of their anomalies during the winter of 2002, as a possible origin of such preconditioning. Similarly to Grassi et al. (2006), this study indicates the arising of a signal on the subtropical jet at middle latitudes during winter and the subsequent poleward translation of this signal as a possible cause of the perturbation of the southern polar vortex during spring.

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