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Modeling the August 2002 minor warming event

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[1] Hindcasts of the Southern Hemisphere minor stratospheric warming and mesospheric cooling event of August 2002, made with a new high altitude version of the Navy's operational forecast model, are compared with temperatures acquired by SABER (Sounding of the Atmosphere using Broadband Emission Radiometry). Results show realistic hemispheric evolution of both the stratospheric warming and mesospheric cooling over a 10-day time period. Use of Rayleigh friction to model mesospheric gravity wave drag shows improvement in the upper mesosphere over a hindcast without Rayleigh friction. The limited vertical extent of the main mesospheric cooling signature disagrees with the Liu and Roble (2002) model results but is supported by SABER temperature observations (Siskind et al., 2005). Examination of 3D EP-flux vectors over the 10-day forecast suggests that the planetary wave responsible for the warming/cooling event originated from a horizontally localized region of the troposphere.
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1. Introduction

[2] Several studies have used General Circulation Models (GCMs) to examine major sudden stratospheric warming (SSW) events, usually for the Northern Hemisphere [*O'Neill*, 1980; *Yoden et al.*, 1999]. More recently, *Liu and Roble* [2002] used a high altitude GCM that enabled them to study the mesospheric cooling (MC) thought to accompany SSWs. While MCs have been observed during SSWs in the past, questions remain about the factors that control the magnitude and vertical extent of the cooling [*Siskind et al.*, 2005].

[3] Here we report on a forecast (hindcast) of a minor SSW and its accompanying MC using a GCM with a fully resolved troposphere, stratosphere, and mesosphere. This minor warming event occurred in August 2002, during a Southern Hemisphere (SH) winter that was unusually disturbed, culminating in September 2002 with the first major SSW ever observed in the SH [*Allen et al.*, 2003]. The August 2002 SSW/MC event was chosen for this study because SABER, on NASA's TIMED (Thermosphere Ionosphere Mesosphere Energetics and Dynamics) satellite, was observing the polar SH middle atmosphere at this time. Furthermore, the SSW on 23 August 2002 was isolated in time by relatively undisturbed flow both 5 days before and 5 days after.

[4] This paper presents results of a first, baseline, study that shows the potential of global numerical weather prediction (NWP) models with a well-resolved middle atmosphere to forecast a realistic SSW/MC event.

2. Model and Data Description

[5] The GCM at the heart of the Navy Operational Global Atmospheric Prediction System, NOGAPS [*Hogan and Rosmond*, 1991], has been extended to higher altitudes as part of a research effort to extend the vertical forecasting range [*Eckermann et al.*, 2004; *McCormack et al.*, 2004]. This NOGAPS-ALPHA (Advanced Level Physics and High Altitude) GCM has already shown improvement over the 2002 operational system in predicting the dynamical evolution of the major SSW in September 2002 (D. R. Allen et al., NOGAPS-ALPHA simulations of the 2002 Southern Hemisphere stratospheric major warming, submitted to *Monthly Weather Review*, 2005).

[6] For this study, 10-day hindcasts were run, initialized at 00 UTC on 8 August 2002 (day 230). The initial conditions were taken from the Navy's operational analysis up to 10 hPa and a special Navy stratospheric analysis (STRATOI) from 10 hPa to 0.4 hPa. Above 0.4 hPa, analyses were progressively relaxed to climate initial conditions based on the COSPAR International and UARS Reference atmospheres [*Eckermann et al.*, 2004]. These climate conditions specify a zonally averaged state, so that no realistic planetary waves exist in the model's mesosphere at the initial time. However, SABER observations showed the mesospheric temperatures to be nearly zonally symmetric at this time.

[7] Several runs were examined that used different top model pressures, Rayleigh friction (RF) specifications, and horizontal resolution. All runs showed a similar minor stratospheric warming and associated mesospheric cooling. For conciseness, only the results for two runs are shown: one with RF and one without. The RF profile is taken from *Butchart and Austin* [1998] and has a peak damping time of about 2 days in the upper mesosphere. Here RF is used as a crude proxy for the sub-grid scale momentum forcing produced by gravity wave breaking. This gravity wave drag (GWD) is an important component of the mesospheric momentum budget. Both runs used a triangular truncation of 79 (T79, horizontal resolution ~1.5°) and 68 vertical levels from the surface to 100 km (constant vertical resolution in the middle atmosphere of ~2 km).

[8] Temperatures from these NOGAPS-ALPHA GCM runs are compared with temperature observations by the

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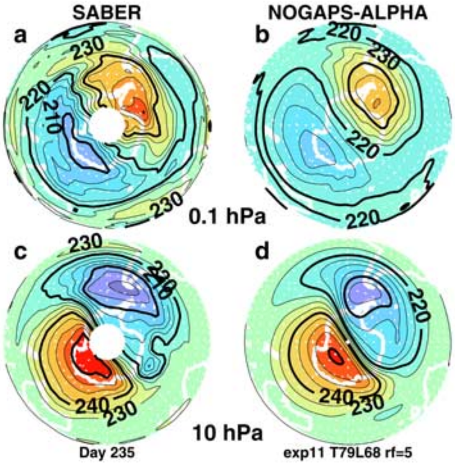

Figure 1. Temperature (K) on 23 August 2002 for a) SABER and b) NOGAPS-ALPHA 5-day forecast at 0.1 hPa, and for c) SABER and d) NOGAPS-ALPHA 5-day forecast at 10 hPa. Southern Hemisphere polar orthographic projections with 0° longitude on the right. The contour interval is 5K. The SABER temperature profiles over 24 hrs have been binned and smoothed. The NOGAPS-ALPHA forecasts valid on 00, 06, 12, and 18 UTC 23 August 2002 and initialized on 00 UTC 18 August 2002 have been averaged. NOGAPS-ALPHA results include Rayleigh friction. A bias of 15K has been subtracted from the NOGAPS-ALPHA 0.1 hPa temperatures (b) for comparison of the wave temperature structure.

SABER instrument on TIMED. SABER scans the limb, acquiring raw radiances from the CO_2 emission at 15 μm with ~2 km vertical resolution. *Mertens et al.* [2004] report good agreement between retrieved SABER temperatures and independent observations [see also *Siskind et al.*, 2005].

3. Results

[9] Figure 1 shows polar plots of SABER temperatures and the NOGAPS-ALPHA 5-day forecast temperatures at 0.1 hPa and 10 hPa for 23 August 2002. A 15 K bias was subtracted from the model temperatures at 0.1 hPa to facilitate comparison of the wave patterns. The temperature patterns show that the warm and cold phases of a large-amplitude wave-1 planetary wave are out of phase between the stratosphere and mesosphere. Despite the climatological initial conditions used by NOGAPS-ALPHA in the mesosphere, after 5 days the forecast temperature patterns have developed a planetary wave pattern that is similar to the observations.

[10] The wave pattern is further illustrated in Figure 2, as well as the effect of RF on the model forecast. Including RF (Figure 2b) decreases the warm and cold temperature anomalies above 0.1 hPa seen in Figure 2a and cools the cold air pool in the lower mesosphere (1–0.1 hPa) at 180°E, in better agreement with the SABER observations (Figure 2c). The addition of RF slows the mean winds at upper levels, effectively lowering the mesospheric planetary-wave critical level [*Sassi et al.*, 2002] and limiting the height of planetary wave propagation. These plots also show the phase tilt with height and the temperature phase reversal between the stratosphere and mesosphere seen in Figure 1.

[11] The time history of the SSW/MC event over the South Pole is presented in Figure 3 by plotting zonally averaged temperatures at 80°S for the model runs with and without RF (Figures 3a and 3b) and for the SABER observations (Figure 3c), over the 10 days of the model forecasts. Temperatures at the initial time have been subtracted from each panel to highlight the SSW/MC. For the case without RF the model temperatures in the lower mesosphere begin cooling over the first 2 days of the forecast. For the model run with RF, the lower mesosphere does not cool as much in the early days of the forecast in better agreement with the SABER observations. This suggests the importance of mesospheric GWD for producing the polar descent necessary to balance the radiative cooling in the model. After about 3 days with little temperature change, the model run with RF quickly develops an SSW/MC, with temperature anomalies at the pole peaking at about day 5 of the forecast, in good agreement with the SABER observations. At longer times the forecast diverges more from the observations: however, the forecast still captures the decay of the temperatures back closer to the initial conditions in the final 5 days, in overall agreement with the observations. The SABER observations suggest that the MC is shallow and only extends to ~80 km. The model forecast with RF also shows the most intense cooling region occurring below ~80 km.

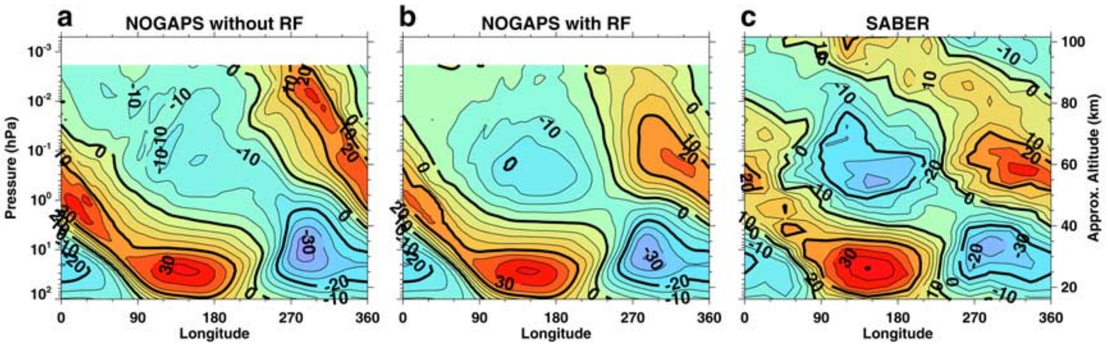

Figure 2. Temperature deviations from the zonal mean (K) at 60°S (55–65°S average) plotted as a function of longitude and pressure (100–0.0005 hPa) on 23 August 2002 for a) NOGAPS-ALPHA 5-day forecast without RF, b) NOGAPS-ALPHA 5-day forecast with RF, and c) SABER observations. Upper (sponge) levels of model not plotted.

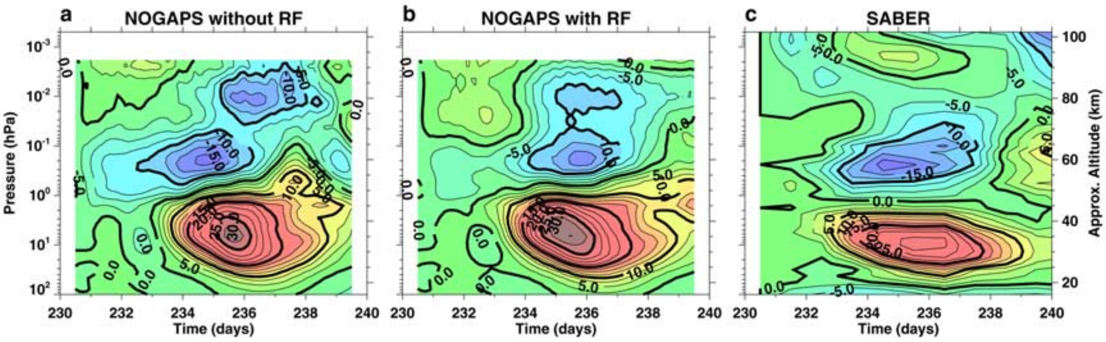

Figure 3. Zonal mean temperature changes (K) at 80°S as a function of time (18–28 August 2002) and pressure for a) NOGAPS-ALPHA 5-day forecast without RF, b) NOGAPS-ALPHA 5-day forecast with RF, and c) SABER observations. The contour interval is 2.5K. The NOGAPS-ALPHA forecasts have been smoothed with time using a 12 hr boxcar average and are not plotted at the beginning and end. Daily averaged SABER observations are plotted at 12 UTC.

[12] Figure 4 shows the vertical and latitudinal structure of the warming by plotting the zonal mean temperature change (23 August minus 18 August 2002) and the perturbation of the residual mean stream function (21 to 23 August 2002 average) taken from the model run with RF. The zonal mean temperatures in both the model (Figure 4a) and the SABER observations (Figure 4b) reveal not only the large SSW/MC event at high latitudes but also reversed temperature changes equatorward of 60°S. This suggests a two cell residual mean circulation pattern that is verified by the perturbation residual mean stream function calculated for the model (Figure 4a), with upward and downward circulation regions corresponding to temperature cooling and warming regions respectively. Note that the averaged residual mean circulation over the 10-day model forecast has been subtracted in this plot; examination of the full residual mean circulation (not shown) associates the MC mainly with a reduction in the normal downward circulation near the pole with very little mean upward residual circulation occurring.

[13] The 3D EP-flux formulation of *Plumb* [1986] can give some insight into the origin of the planetary wave activity responsible for this SSW/MC. Figure 5 shows a longitude-altitude cross section of the vertical and longitudinal 3D EP-flux (vectors) and the amplitude of the vertical component (contours) calculated over the 10 days of the model forecast with RF. The vectors show a region of enhanced upward-tilted fluxes near the tropopause at ~15°W. There is also an upward region in the lower stratosphere near 60°E with a weaker downward region centered at ~120°W. This latitudinal structure in the upward component of the 3D EP-flux can be seen in the polar plots of Figure 6, where the localized structure at 100 hPa (Figure 6b) implies a localized tropospheric epicenter for the planetary wave event, and where the larger amplitude upward and smaller amplitude downward regions at 10 hPa suggest that, while most of the wave activity is from below, there may be wave reflection in some regions.

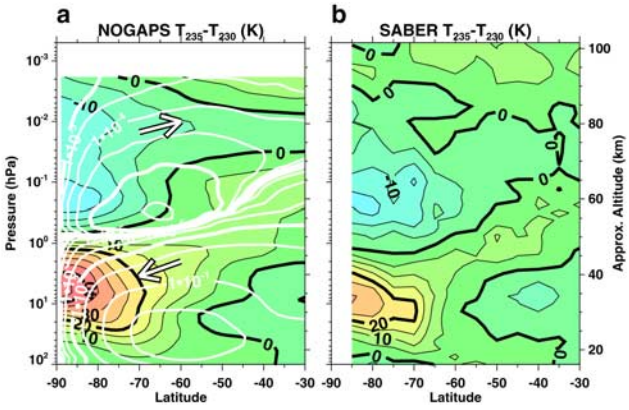

Figure 4. Zonal mean temperature change (K) on 23 August 2002 for a) NOGAPS-ALPHA 5-day forecast with RF and b) SABER observations. The NOGAPS-ALPHA perturbation residual mean stream function ($\times 10^{10}$ Kg s^{-2}, white contours, contour levels: $[-3, -1, 0, 1, 3] \times 10^{-[1,2,3,4,5]}$) averaged over the 3–5 day forecast is also shown in a).

4. Discussion and Conclusion

[14] The NOGAPS-ALPHA hindcast runs with RF for 18–28 August 2002 show a zonally averaged mesospheric cooling (MC) in response to a minor SSW that is confined

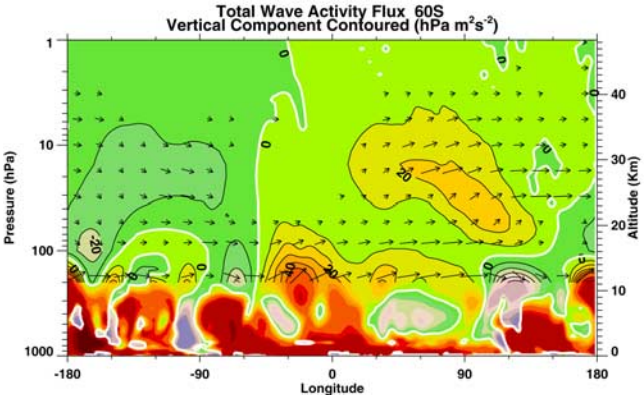

Figure 5. Vertical component of the 3D EP-flux (colored contours, contour interval: 10 hPa m^2 s^{-2}) and the longitudional and vertical component of the 3D EP-flux (vectors) over the 10-day NOGAPS-ALPHA forecast with RF.

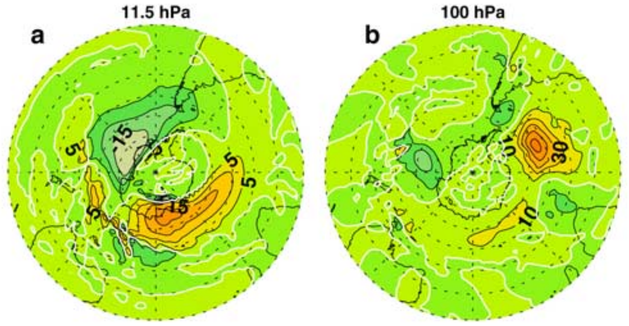

Figure 6. Vertical component of the 10-day average NOGAPS-ALPHA 3D EP-Flux at a) 11.5 hPa and b) 100 hPa. The contour intervals are a) 5 and b) 10 hPa $m^2 s^{-2}$.

within the lower mesosphere (Figures 3b and 4a) in agreement with the SABER observations presented here and by *Siskind et al.* [2005]. This differs from the strong cooling throughout the mesosphere found by *Liu and Roble* [2002] in their model runs. In the upper mesosphere and lower thermosphere, the SABER observations show a warming [*Siskind et al.*, 2005]. Future development of a higher NOGAPS-ALPHA model is needed to model and study such upper mesospheric responses to SSWs.

[15] Our results are important because they show that some aspects of mesospheric coolings can be generated without GWD during SSWs. However, our conclusions are tempered by the lack of an explicit mesospheric GWD parameterization in our model calculations. The improvement in the simulation with RF suggests that GWD controls the vertical structure of the MC response. This improvement was seen in both the wave structure (Figure 2) and zonal mean thermal state (Figure 3) and occurred because RF lowers the mesospheric critical line for planetary-waves propagating slowly eastward and reduces the upward group velocity for stationary planetary waves. Thus, the vertical propagation of the waves is limited in altitude. *Sassi et al.* [2002] found that GWD-generated mesospheric critical lines were necessary for obtaining realistic breaking planetary-wave structures. The differences between the SSW/MC vertical structure calculated by *Liu and Roble* [2002] and that recorded here by SABER may lie in the nature of the gravity wave spectrum used in the TIME-GCM run that controls mean wind and planetary wave evolution.

[16] 3D EP-fluxes calculated from model runs (Figures 5 and 6) suggest that the middle atmosphere planetary waves responsible for the SSW/MC originated mainly from a localized region of the troposphere. Figure 6b shows a localized enhancement of upward EP-flux at lower levels similar to the results shown by *Nishii and Nakamura* [2004] for the Southern Hemisphere major warming that occurred during September 2002. Together these results suggest that a similar circulation anomaly in the tropophere may be responsible for both the August and September 2002 SSW events.

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