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STRATOSPHERE - TROPOSPHERE COUPLING IN THE LEAD-UP TO STRATOSPHERIC SUDDEN WARMINGS

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1 INTRODUCTION

Major Stratospheric Sudden Warmings occur almost every winter in the Northern Hemisphere, however in the Southern Hemisphere only one such warming has been observed to date, in September 2002. This difference between the stratospheric winter evolution in the respective hemispheres has mainly been attributed to the difference in land-ocean distribution and topography which favors the generation of stationary planetary-scale Rossby waves of zonal wave numbers 1 and 2 in the Northern Hemisphere. Those are the major wavenumbers associated with sudden warmings, corresponding to displacement (wave-1) and splitting (wave-2) events. In the Southern Hemisphere, planetary waves are generally weaker than in the north, with wave-1 being quasi-stationary while wave-2 is dominated by eastward-traveling components. The strong Antarctic suden warming in 2002 exhibited a strong wave-2 signature. The question arises as to what caused the waves to become so large during this exceptional event.

Several mechanisms have been proposed to be able to force large amplitude traveling waves of long wavelengths in the extratropical atmosphere in the absence of strong surface forcing. The first hypothesis is the generation of long waves by tropospheric baroclinic instability of these waves (Hartmann (1979)). A second hypothesis is the generation of long waves by nonlinear wave-wave interaction between synoptic-scale baroclinic eddies in the upper troposphere (Scinocca and Haynes (1998)). Kushner and Polvani (2005) have attributed a major stratospheric warming in a spectral core model with no longitudinal variability to the second mechanism.

This paper will explore further the possibility for baroclinic instability of long waves in a model atmosphere where such waves are not explicitly forced at the surface. In particular, it will be explored if waves produced by this mechanism are able to grow large enough to cause significant stratospheric variability such as sudden warmings.

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2 MODEL SETUP

The model used in this study is the spectral core of a general circulation model of intermediate complexity (GFDL model). We are following the model setup as specified in Polvani and Kushner (2002) in hybrid coordinates (they use σ coordinates). This setup includes a linear relaxation towards a zonal mean equilibrium temperature profile which corresponds to the Held and Suarez (1994) profile in the troposphere with an asymmetry about the winter hemisphere, and a cooling over the winter pole in the upper stratosphere. We use a $\gamma = 4K/km$ lapse rate for the winter stratospheric cooling [for the definition and use of γ see Polvani and Kushner (2002)], which corresponds to a strong Southern Hemisphere - like polar vortex. The model runs have no seasonal cycle but are run in constant winter conditions.

We are presenting a comparison of three model runs: The first run is a control run with no surface forcing or truncation. We then compare the control run to both a mountain run and a truncated run as explained below.

For the topography run, the only difference to the control run is a surface mountain forcing. We are using the settings for "run 9" by Gerber and Polvani (2009), which they term their "most realistic run" in terms of the frequency and strength of the sudden warmings produced. This run uses wave-2 topography centered at $45°$ latitude with a height of $3000m$ in order to force planetary waves.

For the truncated run the only difference to the control run is a truncation in wavenumber space to zonal wave-2 and a mean flow only. Variations of zonal wavenumber 1 as well as zonal wavenumbers 3 and higher are set to zero throughout the atmosphere at every time step, which yields a model atmosphere where only zonal wave-2 is allowed to propagate and interact with the mean flow. Like the control run, the truncated run has no longitudinally varying forcing.

3 RESULTS

As expected, the stratospheric variability in the control run is significantly reduced as compared to the real atmosphere due to the lack of planetary wave forcing. The control run yields a very strong polar vortex with mean winds around $100m/s$ at its center, with a standard devi-

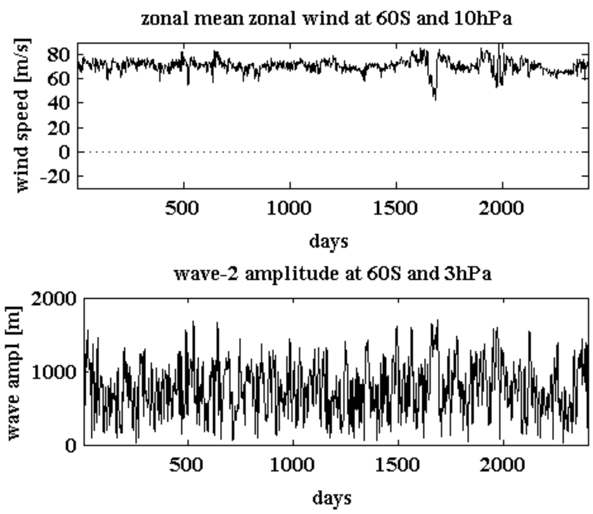

Figure 1: Control run: Timeseries of zonal mean zonal wind $[m/s]$ at $60°S$ and $10hPa$ (top) and wave-2 amplitude $[m]$ at $60°S$ and $3hPa$ (bottom) for a 2300-day period of the model run.

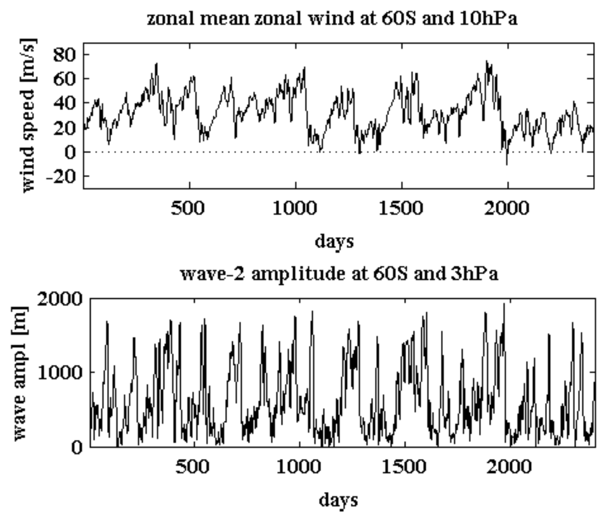

Figure 2: Same as figure 1 but for the topography run.

ation of $5m/s$ over the entire run. Zonal wave-2 reaches large mean amplitudes of $750m$ due to the strong wave propagation into the polar vortex. Adding a topographic forcing significantly changes the variability in the run. The mean wind at the polar vortex reduces to $57m/s$ with a standard deviation of $15m/s$ over the entire run, while the waves reach similar mean amplitudes as compared to the control run.

Along with its greater stratospheric variability the topography run exhibits 14 major warmings over a length of about 10,000 days, while the control run does not exhibit any major warmings. The stratospheric wave-2 amplitude timeseries for the control run looks white noise - like (Figure 1), while the topography run exhibits frequent persistent events of high wave amplitude which are followed by a strong weakening of the polar vortex at $60°S$ and $10hPa$ (Figure 2). Events of shorter persistence occur in the control run and lead to minor decelerations of the mean flow.

Surprisingly, the truncated run (with no topography) displays behavior similar to that of the topography run. The truncated run exhibits a similar number of warmings (13) over the same runtime as the topography run, and it shows a similar frequency and strength of sudden warmings (Figure 3). Again, high wave-2 amplitude persistence is observed preceding strong weakenings of the mean flow. These sudden warmings are produced by strong wave-2 events comparable to the topography run, although wave-2 is not explicitly forced in this run. We will argue in the discussion that baroclinic instability of wave-2 is responsible for these strong wave events.

4 DISCUSSION

Significant stratospheric variability including major warmings is observed in the truncated run indicating that another mechanism apart from topography is able to force large planetary-scale waves, at least in the truncated model setting. The results suggest that this mechanism is tropospheric baroclinic instability of long waves. Most other mechanisms can be eliminated due to the truncated nature of the model run, especially interaction between synoptic-scale waves aggregating into long planetary scales as well as interaction between planetary- and synoptic-scale waves. In addition, several features of the waves indicate their origin is from baroclinic instability: waves with long zonal wavelengths can become synoptic scale in terms of their total horizontal wavelength by adopting a large meridional wavenumber, and by being confined to high latitudes (Hartmann (1979)). Figure 4 shows a composite of all major warmings in the truncated run, indicating a small meridional scale of the wave which usually spans the entire extratropical atmosphere. For propagation into the strong stratospheric winds, these effects have to be accompanied by an increase in the meridional scale of the wave when entering the stratosphere (Charney and Drazin (1961)), as indicated by figure 5 for the day of the warming.

The only difference between the truncated run and the control run is the truncation itself, which eliminates eddies of synoptic zonal scale. Therefore, this comparison undermines an interpretation of nonlinear interaction between synoptic-scale waves as being the primary mechanism forcing the long waves. Rather, in these experiments, it is direct long-wave generation by baroclinic instability; interaction with synoptic scales has the effect of weakening both the long waves and the consequent stratospheric variability.

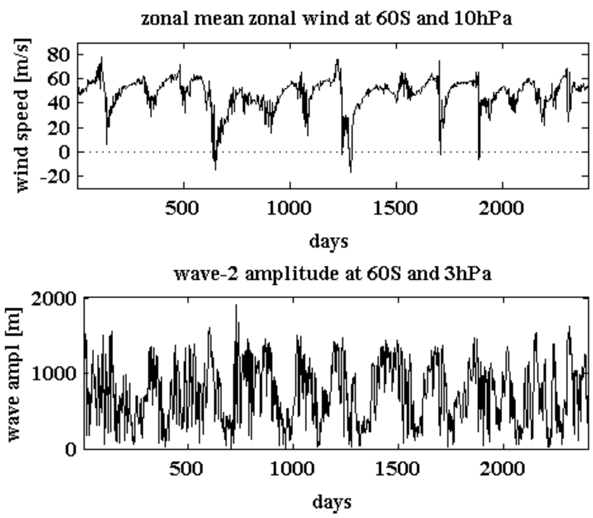

Figure 3: Same as figure 1 but for the truncated run.

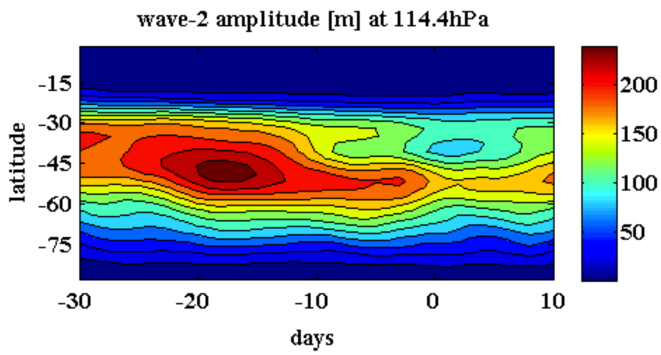

Figure 4: Wave-2 amplitude $[m]$ at $114hPa$ in a composite of all major warmings in the truncated run. Day 0 corresponds to the day when the zonal mean zonal wind becomes negative at $10hPa$ and $60°S$ (WMO criterion).

5 SUMMARY

We have found zonal wave-2 baroclinic instability in a spectral core model truncated to wave-2 and a mean flow and with no longitudinally varying forcing. Long wave baroclinic instability induces significant stratospheric variability including major stratospheric warmings. The frequency and strength of these warmings is similar to those produced by a mountain forcing associated with a realistic Northern Hemisphere climatology.

In the presence of synoptic eddy forcing, tropospheric baroclinicity is reduced and the instability of wave-2 is weakened. Baroclinic instability of long waves may therefore need to be considered as a forcing of realistic planetary-scale waves which are able to induce major stratospheric variability or even sudden warmings.

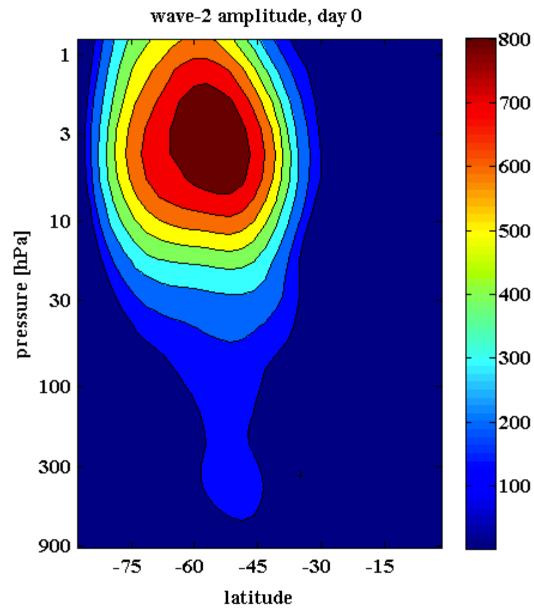

Figure 5: Wave-2 amplitude $[m]$ in latitude and height for a composite of all major warmings in the truncated run for day 0 (according to the WMO criterion).

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