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STRATOSPHERE - TROPOSPHERE COUPLING BY PLANETARY WAVES

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1 INTRODUCTION

The stratosphere and the troposphere exhibit a strong coupling during the Northern Hemisphere winter season. This coupling is particularly strong during the formation of major or minor Sudden Stratospheric Warmings (SSW), which are extreme events in the stratosphere associated with a weakening of the polar vortex and a warming of the polar stratosphere. This strong stratospheric variability may be accompanied by tropospheric flow anomalies, as suggested by e.g. Baldwin and Dunkerton (2001). Due to the comparatively longer memory of the lower stratosphere relative to the troposphere, stratospheric signals may help increase tropospheric predictability after SSW events. However the mechanism leading to these warmings is not yet fully understood.

A great deal is known about the influence of the troposphere onto the stratosphere. Planetary Rossby waves account for the main part of the large-scale vertical coupling in the extratropical atmosphere and can cause large deviations from radiative equilibrium in the stratosphere. In order to examine the mechanism leading to warmings, looking at planetary wave propagation prior to warmings is a good starting place.

Several studies have found strong wave-1 amplitude anomalies at and below the stratospheric polar vortex prior to SSW events: Labitzke (1981) has found wave-1 anomalies prior to several warmings in radiosonde data as well as early satellite observations. Limpasuvan et al. (2004) have found similar precursors for a composite of sudden warmings in the NCEP reanalysis.

This paper explores the role of the mutual coupling of the stratosphere and the troposphere in terms of planetary wave forcing prior to sudden warmings. This is done by employing ERA40 reanalysis data as well as a general circulation model of intermediate complexity (a spectral core model) to model stratospheric variability in the form of sudden warmings.

2 DATA AND MODEL SETUP

a. *Reanalysis Data*

The reanalysis data used in this study is the ERA40 reanalysis project (Uppala et al. (2006)) at 2.5 degrees horizontal resolution and with 23 levels between the surface and 1mb. [As a comparison, the NCEP reanalysis data uses 17 pressure levels between the surface and $10mb$.] We are using daily data for the satellite era 1979-2001. There are 14 major warmings present in this period according to the WMO criterion for sudden warmings which requires a wind reversal at $60°N$ and $10hPa$. Seven of these warmings are splitting events (according to the Charlton and Polvani (2007) algorithm) and will be used for comparison with the model results described below.

b. *Spectral Core Model*

The model used in this study is the spectral core of a general circulation model of intermediate complexity, the GFDL model. We are following the model setup as specified in Polvani and Kushner (2002). 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 are here 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 $45°N$ with a height of $3000m$ in order to force planetary waves.

As a difference to their run, we are here running the model using a hybrid vertical coordinate system (they use σ coordinates) as well as $T30$ resolution (they use $T42$).

The model was run with no seasonal variation for 8000 perpetual January days. This run includes 10 major warmings according to the WMO criterion, as well as many minor warmings. All model warmings are classified as splitting events.

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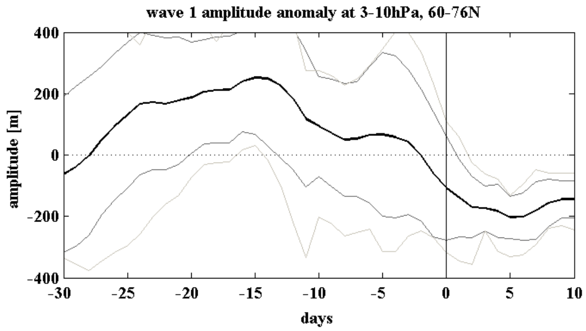

Figure 1: ERA40 composite timeseries of all splitting events. Daily wave-1 amplitude anomalies are shown at the time of the sudden warming (day 0) at a mean of 3-10hPa and 60-76N. The black solid line is the composite wave amplitude anomaly, the lighter gray line is the composite plus/minus the standard deviation, and the lightest gray lines are the maximum and minimum values for every day of the composite.

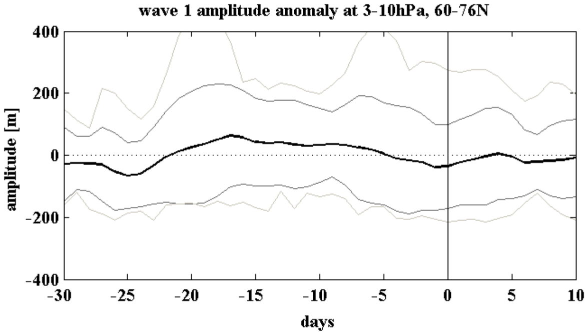

Figure 2: Same as figure 1, but for the model timeseries.

3 RESULTS FROM ERA40 ANALYSIS

The reanalysis data was analyzed in terms of wave-1 and higher wave number amplitude anomalies prior to all observed splitting and displacement events. Splitting and displacement is classified as in Martius et al. (2009), according to the Charlton and Polvani (2007) algorithm.

Figure 1 shows the wave-1 amplitude anomalies for a composite of all 7 splitting events during the period 1979-2001. A large positive wave-1 anomaly occurs about 2 weeks prior to the SSW, where the vertical line on day 0 indicates the day when the WMO criterion is fulfilled.

Wave-1 precursors can be shown to exist for both splitting and displacement warmings [not shown here], which supports the finding that there exists no significant distinction between splitting and displacement events (Coughlin and Gray (2009)).

4 RESULTS FROM MODEL ANALYSIS

As for the reanalysis data, the model data was analyzed for wave-1 and higher wave number anomalies. Surprisingly, wave-1 precursors similar to those in the reanalysis data were found for the model warmings, although wave-1 is not explicitly forced in this model. The splitting date (day 0 in the figure) is determined according to the WMO criterion (wind reversal at $60°N$ and $10hPa$).

Figure 2 shows the wave-1 amplitude anomalies at the polar vortex maximum for a composite of all 10 splitting events present in the model run. Wave-1 reaches amplitudes comparable to the ones of wave-2 [not shown here]. In particular, wave-1 has a positive anomaly about 2 weeks prior to the splitting event which is significant at the 85% level.

The positive wave-1 anomaly prior to the warming event in the model results is weaker than in the ERA40 reanalysis. We would expect this based on the fact that wave-1 is known to be strongly forced in the real atmosphere by the Northern Hemisphere topography and heating patterns, while the model includes wave-2 topography only and no thermal forcing.

5 DISCUSSION

We suggest that the wave-1 precursor observed in both reanalysis as well as in model simulations may be necessary (although not sufficient) for a sudden warming to happen. In the real world, a strong wave-1 signal can often be identified in the form of a strong stratospheric Aleutian anticyclone. As this anticyclone grows stronger it strips potential vorticity away from the vortex which by this mechanism weakens and shrinks in size. In addition to weakening the polar vortex this mechanism may sharpen the potential vorticity gradient at the edge of the polar vortex. This could then form a strengthened wave guide which will allow forced waves from below to propagate upward more effectively. This will further weaken the vortex and thereby eventually lead to a sudden warming event.

In the model simulations, a similar mechanism could be acting, where a wave-1 anomaly may arise through interaction with synoptic-scale waves [Scinocca and Haynes (1998)] or by an asymmetry of the upward propagating wave-2 produced by interaction with the mean flow. Once the vortex is sufficiently weakened by the positive wave-1 amplitude anomaly, the forced wave-2 signal will be able to propagate upward more efficiently which will finally lead to the destruction of the polar vortex. This is also supported by the finding that all model warmings are splitting events.

6 SUMMARY

Stratospheric Sudden Warmings are the most striking deviations from the radiative equilibrium circulation in the stratosphere. Stratospheric variability is to a major part forced in the troposphere, but the stratosphere plays a role in controlling the amount of wave activity propagating upward. The main part of this large-scale vertical coupling in the extratropical atmosphere is accounted for by planetary Rossby waves, which are suggested to be the main driver of variability in the stratosphere, as well as the dominant cause for SSW events.

Several studies have found strong wave-1 amplitude anomalies at and below the stratospheric polar vortex prior to SSW events. We have found a similar wave-1 signal prior to sudden warmings in both ERA40 reanalysis data as well as a spectral core model capable of producing a realistic frequency of SSW events. This suggests a pre-conditioning of the vortex prior to the warmings, or even an evolution into a state that favors sudden warmings.

In reanalysis data, this wave-1 pulse can be observed about 2 weeks prior to SSW events for both splitting and displacement events. Strong wave-1 amplitudes are expected as they are forced in the troposphere. The particular model used shows a similar wave-1 anomaly prior to warmings although only wave-2 is explicitly forced at the surface.

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