# 4.6 THE EFFECT OF REFLECTING SURFACES ON THE VERTICAL STRUCTURE AND VARIABILITY OF STRATOSPHERIC PLANETARY WAVES.

Nili Harnik* R. S. Lindzen

## 1 INTRODUCTION

In this work we consider the effects of an upper stratospheric reflecting surface on the vertical structure of stratospheric planetary waves. Observations of vertical wave structure reveal a variability that is consistent with downward reflection. Past studies have mostly considered the effect of lower stratospheric reflecting surfaces on blocking wave propagation into the stratosphere (e.g. Charney and Drazin, 1961). Little attention has been given to upper stratospheric reflecting surfaces which do not block wave activity completely, but affect wave structure. We expect reflection to affect wave structure because the direction of wave propagation is directly related to the tilt of the wave phase lines in the vertical-zonal plane. Also, strong downward reflection can cause wave amplitudes to peak in the stratosphere, which will otherwise grow exponentially with height due to the density effect.

We focus on two kinds of observed variations, a daily time scale variation in the phase tilt of the waves, and a seasonal time scale change in the amplitude structure. Since wave activity is observed to be episodic, with episodes lasting a few weeks (e.g. Hirota and Sato, 1969), daily phase structure changes are observed within a given episode, while seasonal amplitude changes are in fact a variation in wave structure from one episode to the other.

In this work we establish that reflecting surfaces do form in the upper stratosphere, and that downward reflection from these surfaces can have a large effect on the vertical structure of the waves, and its time evolution.

## 2 DIAGNOSING REFLECTING SURFACES

To diagnose reflecting surfaces for vertical propagation, we develop a special wavenumber diagnostic. The need for a new diagnostic arises because the index of refraction, which is commonly used, does not separate out the contribution from meridional propagation. The quasi-geostrophic PV equation on a $\beta$ plane, linearized around a zonal mean basic state, and assuming a normal mode structure in longitude, with a specified zonal wavenumber ($k$) and phase speed ($c$) is (notation is standard, see Harnik and Lindzen, 2001, for details):

$$\frac{\partial^2\psi}{\partial z^2}+\frac{N^2}{f_o^2}\frac{\partial^2\psi}{\partial y^2}+n_{ref}^2\psi=0 \tag{1}$$

The index of refraction squared ($n_{ref}^2$) is a function of the basic state and the zonal wavenumber and phase speed, and it relates to the vertical and meridional wavenumbers ($m$ and $l$, respectively) as follows:

$$n_{ref}^2=m^2+\frac{N^2}{f_o^2}l^2 \tag{2}$$

A reflecting surface for vertical propagation is the $m^2=0$ surface. In order to deduce its location from the index of refraction we need to subtract the meridional wavenumber contribution (Dickinson, 1968). Since the basic state is nonseparable in latitude and height, there is no clear way to prescribe the meridional wavenumber. While past studies have made various approximations that bring the equations to separable form (e.g. Dickinson, 1968; Schoeberl and Geller, 1977), we take a diagnostic approach, in which we solve the nonseparable equations using a model, and *diagnose* the wavenumbers from the wave solution $\psi$, as follows:

$$Re\left(\frac{\psi_{zz}}{\psi}\right)=-m^2 \tag{3}$$

$$Re\left(\frac{\psi_{yy}}{\psi}\right)=-l^2 \tag{4}$$

We test our diagnostic using a series of $\beta$ plane model runs, with a characteristic winter stratospheric basic state, and various forcings and damping fields. These runs are described in Harnik and Lindzen (2001). We find that the structure of the stratospheric waveguide is set by the basic state PV gradients, and the waveguide, in turn, sets the meridional wavenumber regardless of the forcing characteristics. At the same time, the vertical wavenumber is sensitive to the zonal wavenumber

---

*Florida State University. Correspondence address- Nili Harnik, Department of Meteorology, 54-1626, MIT, Cambridge, MA, 02139. Tel- 617-253-2092. email- nilih@tempest.mit.edu.

and phase speed of the forcing (through the index of refraction). Damping affects the vertical structure, but it hardly affects the vertical and meridional wavenumbers. The practical implication of these results is that we can use the wavenumbers of the steady state wave solution (through equations 3-4) to diagnose propagation characteristics of the *basic state*. While the existence of the waveguide is not surprising based on past studies (e.g. Matsuno, 1970), its robustness (as seen from the meridional wavenumber), and our ability to diagnose vertical propagation as clearly as we do, is striking.

## 3 OBSERVATIONS

We apply our diagnostic to observations, and test whether observed variability in wave structure, both on seasonal and daily time scales, is consistent with downward reflection from such surfaces.

For a given observed basic state, we diagnose the vertical and meridional wavenumbers, using a spherical coordinate model that spans the southern hemisphere, and has a latitudinal resolution of the operational observational product (2°). We use the observed basic state, interpolated in the vertical to the model grid, and kept constant above 0.4mb. We have a sponge layer at the top and at the equator. We use a spherical coordinate version of equation 4 (given in Harnik and Lindzen, 2001). We use the NASA/GSFC stratospheric observations data set, which is based on satellite retrievals of temperature, and has 9 levels between 100 and 0.4 mb.

We analyze observations from one randomly chosen southern hemisphere winter (1996). There were two major wavenumber one events during this winter, one during July 18-August 19, and the other in September. Figure 1 shows the latitude-height amplitude and phase structures of the time mean waves in these two periods. The temperature amplitude of the July-August wave has a single peak in the stratosphere while the September wave has two. Correspondingly, the geopotential height amplitude peaks at least 10 km lower in September. Also, the phase tilt with height is smaller in late winter. Figure 2 shows the observed zonal mean wind averaged over each of the two wave events, the stationary wave 1 index of refraction squared for the two basic states, and the meridional and vertical wavenumbers of the corresponding steady state solutions obtained using a wave 1 stationary forcing that is constant with latitude (geopotential height of 100 m). We see that the polar night jet peak weakened, and moved downward and poleward during the winter. The wavenumbers reveal a large difference in the propagation characteristics– while in August there is vertical propagation in most of the domain (evanescent regions, where $m^2 < 0$, are shaded), in September we see a turning surface at around 38.5 km in midlatitudes, where the geopotential height peaks. This suggests that the evolution of the basic state during winter is accompanied by the formation of a reflecting surface in the upper stratosphere. The vertical structure of the waves changes correspondingly, and the geopotential height amplitude peaks lower down during September.

Note that a similar poleward and downward shift of the peak of the jet and the waves has been observed in past studies (e.g. Hartmann, 1976), however, the explicit diagnosis of the change in wave propagation geometry and the formation of a reflecting surface is new. Moreover, while the changes in vertical wavenumber are obviously consistent with the vertical structure changes, the changes in the index of refraction are not. For example, from figure 2 we see that the $m^2 < 0$ surface in September coincides with the maximum in geopotential height amplitude and the node in temperature, while the $n_{ref}^2 < 0$ surface is 10-15 km higher.

We also use our diagnostic to understand daily variability in wave structure. We find that the interaction of the waves with the mean flow results in a temporary formation or downward shift of a reflecting surface (depending on whether one exists to begin with). This results in a temporary downward reflection of the waves, and the corresponding structure changes. In our talk we will show a case from August 1996, of wave 1 decelerating the flow, forming a turning surface and reflecting downwards.

## 4 DISCUSSION

An obvious question our results raise is whether downward reflection is a major source of stratospheric wave variability or whether it is specific to the winter we analyzed. Looking at the time evolution of wave structure and the basic state during other winters, as well as in past studies, there is evidence suggesting downward reflection might be quite common. Specific diagnosis of reflecting surfaces in other years, however, is needed to determine that. In any case, the consistency we find between the time evolution of the waves and the basic state provides confidence in the relevance of quasi-linear theory to the stratosphere. It is also supportive of the quality of the observations and the wavenumber diagnostics. This is important since much of the time variation of the basic state occurs at or above 5 mb, where the observations start losing reliability. The structure changes of the waves, on the other hand, are observed throughout the depth of the stratosphere.

Finally, we suggest considering the possibility of downward reflected waves affecting the troposphere. One of the striking observations in our study is that a deceleration in the upper stratosphere, and a decrease of wave amplitude at the tropopause, occur within a few days of each other throughout the winter of 1996, as well as in other years we have looked at. This may be a result of the downward reflected wave affecting its source. It is also possible, however, that the life-time of the sources of the waves and the time it takes a wave to grow enough and change the wave geometry in the upper stratosphere are similar and this is only a coincidence. A more comprehensive study, in particular, of the sources of planetary scale waves in the troposphere is needed to determine this.

## 5 REFERENCES

Charney, J. G., and P. G. Drazin, 1961. Propagation of planetary scale disturbances from the lower into the upper atmosphere. *J. Geophys. Res.* **66**: 83-110.

Dickinson R. E., 1968. Planetary waves propagating vertically through weak westerly wind wave guides. *J. Atmos. Sci.* **25**: 984-1002.

Harnik, N., and R. S. Lindzen, 2001. The effect of reflecting surfaces on the vertical structure and variability of stratospheric planetary waves. To appear in *J. Atmos. Sci.* .

Hartmann, D. L., 1976. The structure of the stratosphere in the southern hemisphere during late winter 1973 as observed by satellite. *J. Atmos. Sci.* **33**: 1141-1154.

Hirota I., and Y. Sato, 1969. Periodic variation of the winter circulation and intermittent vertical propagation of planetary waves. *J. Meteorol. Soc. Jpn.* **47**: 390-402.

Matsuno, T., 1970. Vertical propagation of stationary planetary waves in the winter northern hemisphere. *J. Atmos. Sci.* **27**: 871-883.

Schoeberl, M. R., and M. A. Geller, 1977. A calculation of the structure of stationary planetary waves in winter. *J. Atmos. Sci.* **34**: 1235-1255.

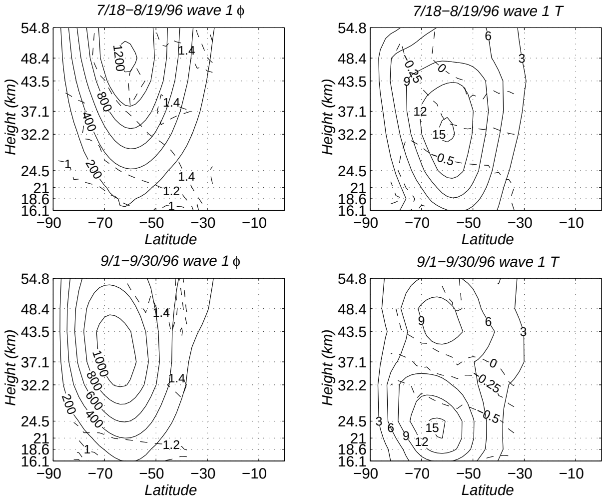

Figure 1: Time averaged wave 1 Geopotential height (left) and temperature (right) amplitude (solid) and phase (dashed), for July 18-August 19, 1996 (top) and September 1-30, 1996 (bottom). Geopotential height amplitude is in meters, temperature amplitude in °K and phase in units of $\pi$.

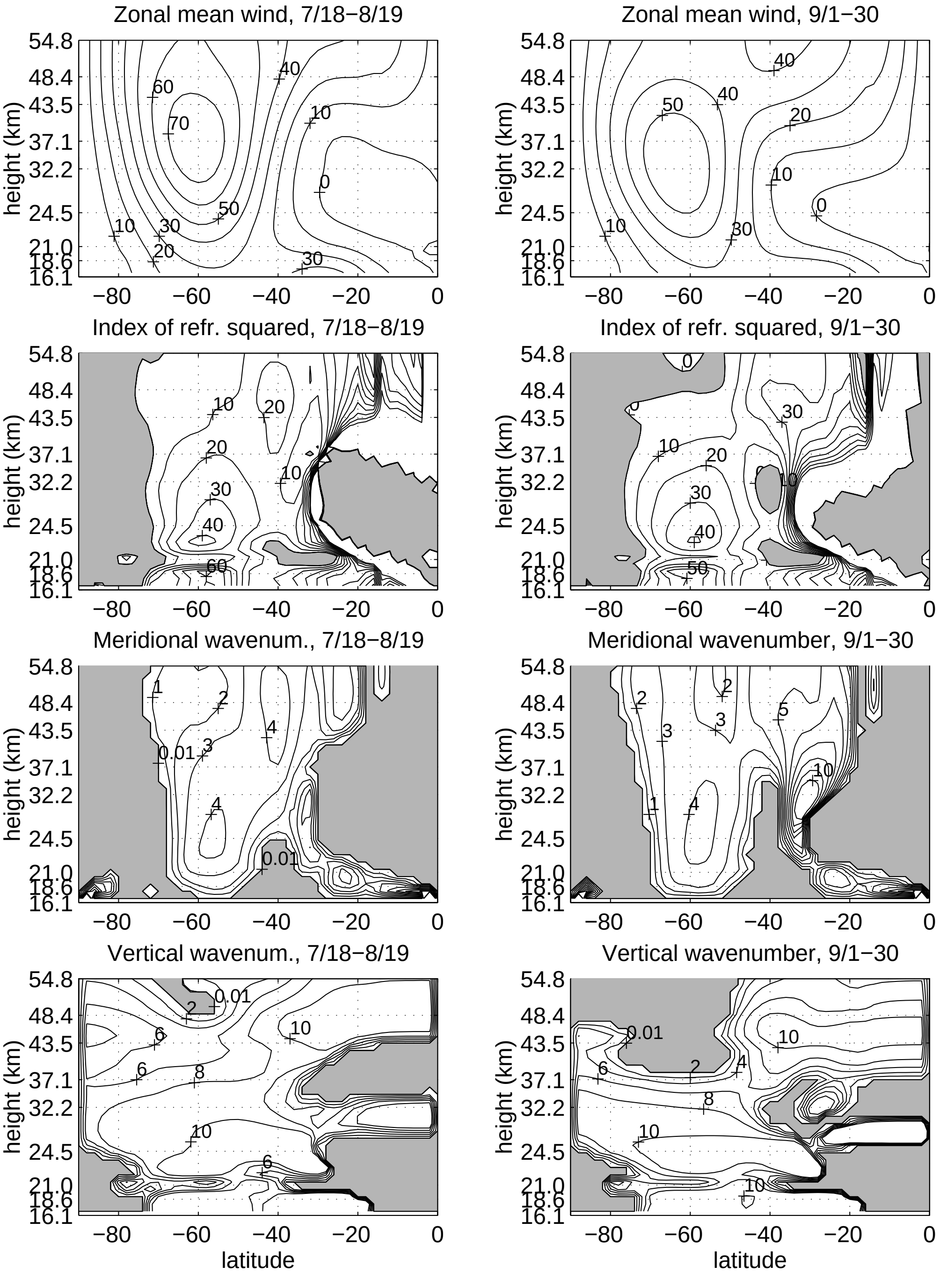

Figure 2: Top to bottom: Observed time mean of zonal mean wind, $n_{ref}^2$, and the meridional and vertical wavenumbers calculated from the steady state model solution, for July 18-August 19 (left) and September 1-30 (right), 1996. Wind in $m/s$, meridional wavenumber in $radians^{-1}$ and vertical wavenumber in $10^{-5}m^{-1}$. Negative values in the lower three rows are shaded.