What Causes the Seasonal Cycle of Stationary Waves in the Southern Stratosphere?

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ABSTRACT

Stationary planetary waves in the southern stratosphere display a characteristic seasonal cycle. Previous research based on a one-dimensional model suggests that this behavior is mainly determined by seasonally varying transmission properties of the atmosphere with respect to wave propagation. The issue is investigated with the help of a hemispheric, linear, quasi-geostrophic model. It reproduces well some of the observed qualitative features and is internally consistent in the sense that its seasonal wave cycle can be explained in terms of varying wave transmission properties of the mean circulation. On the other hand, the model does not yield the observed seasonal cycle. Despite considerable sensitivity to modifications in the basic-state wind and dissipation parameterization, the model could not be reasonably fit to reproduce the observed seasonal cycle. Possible reasons for the model deficiency are put forward. In summary, even though suggestive, the present study is not entirely conclusive about the degree to which the observed cycle is determined by wave transmission properties alone.

1. Introduction

Stationary planetary waves in the stratosphere exhibit a characteristic seasonal behavior. For illustration, Fig. 1 shows the climatological seasonal cycle of the stationary wave of zonal wavenumber 1 at two different pressure levels. To first approximation, wave activity is absent in the summer hemisphere, whereas one observes strong wave activity in the winter hemisphere. As is well known, the one-dimensional beta-plane model of Charney and Drazin (1961) explains the wave behavior in the stratosphere through wave transmission properties of the underlying atmosphere, which are determined by the mean circulation.

More recently, noticeable differences in the circulation between the two hemispheres have become apparent (Hirota et al. 1983). A closer look at Fig. 1 shows for instance that the waves in the southern stratosphere are considerably weaker than in the northern stratosphere. They also display a distinct relative wave minimum in mid-winter (Randel 1988). Even though the data—especially in the Southern Hemisphere—have to be considered with care, Grose and O'Neill (1989) found that the basic fields like temperature and winds can be qualitatively trusted. They show that zonal-mean winds as derived from LIMS (Limb Infrared Monitor of the Stratosphere) and from SSU (Stratospheric Sounding Unit), respectively, differ only by a few meters per second. Therefore, we consider the *qualitative* features, which we concentrate on in this study, as real.

A simple one-dimensional, nonlinear model by Plumb (1989) suggests the *hypothesis* that the different seasonal wave behavior in the two hemispheres can essentially be explained through differences in wave propagation according to the ideas of Charney and Drazin. The interhemispheric differences in Plumb's model arise from the fact that in his simulation the Southern Hemispheric waves stay in a linear regime, while in the Northern Hemisphere there is substantial wave–mean flow interaction, which reduces the strength of the mean westerlies. Another possible source of stratospheric seasonal variation is the varying tropospheric forcing. This, however, appears to be an insufficient explanation for the substantial seasonal variation in stratospheric wave amplitude (a factor of 4.9 at the 10 mb level for the time range April through October), since the seasonal variation of the wave in the troposphere is comparatively moderate (a factor of 1.7 at the 200 mb level for the same time period).

The above hypothesis of varying transmission properties is based on a beta-plane model, which allows only for vertical wave propagation. Yet, since the work of Charney and Drazin (1961), numerous studies (e.g., Matsuno 1970; Karoly and Hoskins 1982; Lin 1982; Nigam and Lindzen 1989) have shown that hemispheric geometry, basic-state wind field curvature, and meridional in addition to vertical wave propagation play an essential role in the propagation of waves. In these studies, the refractive index is introduced as a quantity of key importance and as a useful diagnostic for wave propagation in the meridional plane. If the hypothesis holds true, the refractive index, too, should display a seasonal cycle corresponding to the observed

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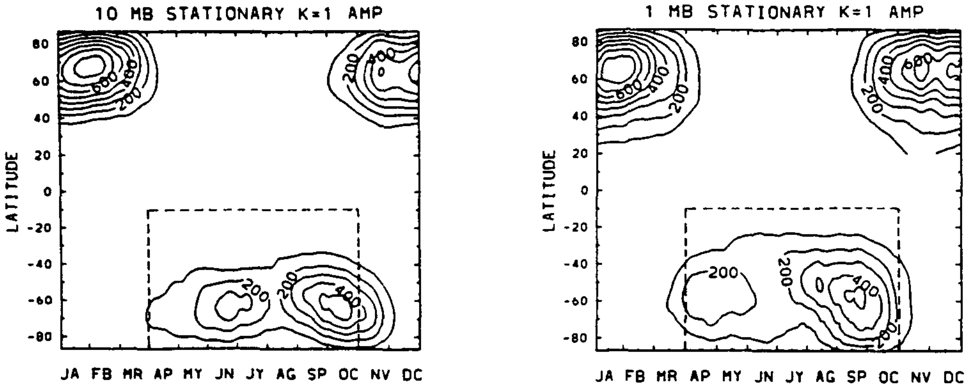


FIG. 1. Seasonal cycle (latitude–time section) of stationary wave amplitude (in m) for zonal wavenumber 1 at 10 mb (left panel) and 1 mb (right panel). Contour interval: 100 m. The dashed line indicates the region covered by the model (Fig. 4). Data used are climatological monthly means. The figure is taken from Randel (1987).

wave cycle. The latter proposition, however, is challenged by observations: even though the mean *winds* vary substantially, the *refractive index* displays no substantial overall variation throughout the winter season (Randel 1988). This behavior is plausible, since the refractive index is essentially the ratio of the quasi-geostrophic potential vorticity gradient and the mean wind. Months with stronger mean winds turn out to have stronger potential vorticity gradient, and hence the two effects tend to cancel each other.

The discrepancy between the hypothesis and the observed behavior of the refractive index motivated us to reexamine planetary wave propagation with special attention to the seasonal cycle of wave propagation in the Southern Hemisphere. The present note gives a brief overview. A more detailed description of the model used and its results can be found in Wirth (1990).

2. The model

To investigate the issue, we use a linear, quasi-geostrophic, hemispheric model for stationary waves, essentially following Matsuno (1970). The model prescribes a zonally symmetric basic state, simulates forcing by specifying the wave at the lower boundary, and solves for the wave in the whole domain under consideration. Matsuno and subsequent investigators (Simmons 1974; Schoeberl and Geller 1977; see also Schoeberl et al. 1979; Lin 1982; Karoly and Hoskins 1982; part of these studies use primitive equations instead of quasi-geostrophic theory) have shown that this type of model is able to qualitatively simulate essential features of Northern Hemispheric wintertime stationary waves. On the other hand, a more detailed comparison between such models and relevant data reveals quantitative discrepancies and further limitations (Austin 1982, 1983). We therefore do not aim for a quantitatively correct simulation. Yet, we hope to include enough realism such as to reproduce the essential features of planetary wave propagation, especially the seasonal cycle. The major improvement over Plumb's one-dimensional model (Plumb 1989) is that we allow for meridional in addition to vertical wave propagation and include realistic wind shear.

The quasi-geostrophic potential vorticity equation is linearized about a purely zonal basic-state flow, for which we use climatological monthly mean zonal-mean winds from Randel (1987). Since the stationary waves in the southern stratosphere are dominated by the lowest wavenumber (Randel 1988), we restrict our study to zonal wavenumber 1. In order to model the seasonal behavior of the Southern Hemisphere winter, we consider subsequent months, ranging from April through October. For each month, the problem is treated as stationary. This is a reasonable approximation to the extent that the basic state varies slowly as compared with the time required to establish a stationary wave. The latter should be satisfied to a good approximation in the present situation. Similarly, since the wave amplitudes are smaller and show less interannual variability in Southern Hemisphere winter than in Northern Hemisphere winter (Randel 1987), the use of a linear model and the use of climatological monthly mean data is a priori expected to be a fair approximation for a qualitative simulation of the wave propagation behavior.

With the above approximations, the model dynamics reduces to one single elliptic partial differential equation for the wave behavior:

$$\mathcal{L}\Psi + \nu_S\Psi = 0, \qquad (1)$$

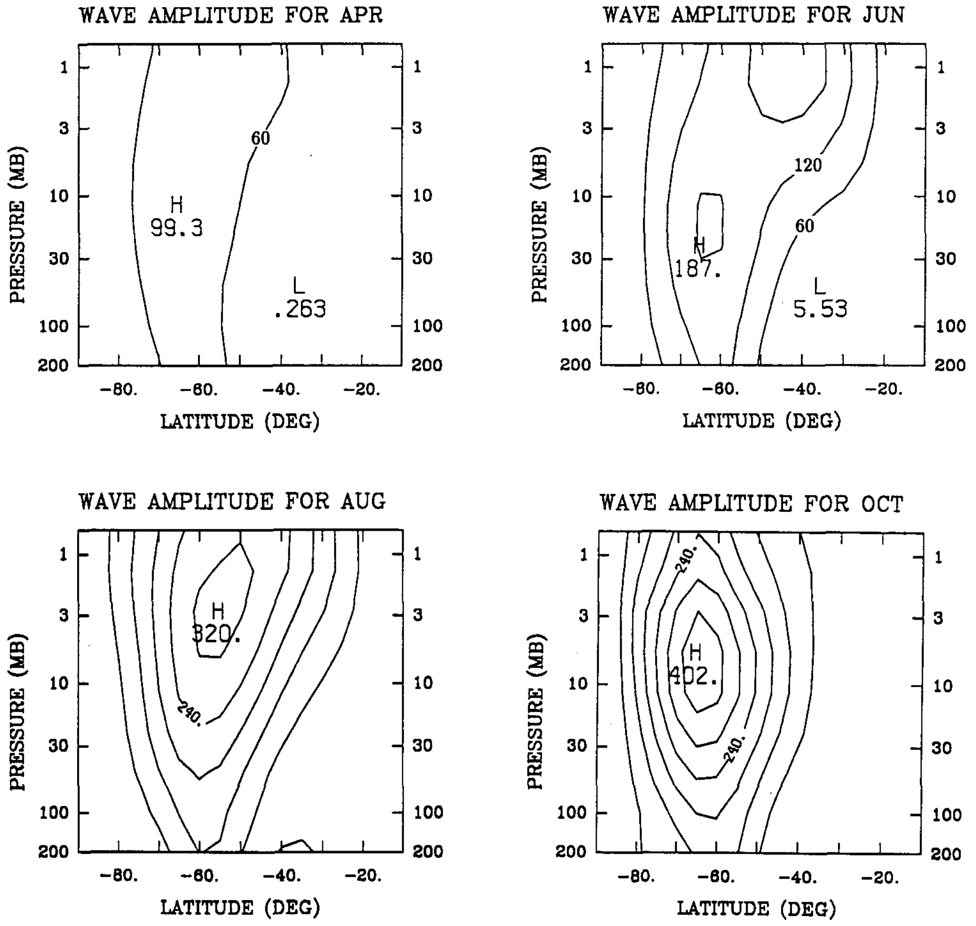
where Ψ is proportional to the perturbation stream function, $\mathcal{L}$ is an elliptic, second-order differential operator in latitude and altitude (similar to the operator of Matsuno 1970), and ν_S is the refractive index square (simply called the "refractive index" in the following).

Dissipation is implemented as Rayleigh friction and Newtonian cooling, using the same damping coefficient α for both. Guided by estimates for the Newtonian cooling coefficient (Leovy 1984), α is chosen to be $\alpha = 0.05\ \mathrm{day}^{-1}$ below 48 mb, $\alpha = 0.2\ \mathrm{day}^{-1}$ above 0.7 mb, and linear and continuous in between. With this form of dissipation the refractive index is complex, which prevents the singularity of the equation at critical levels, i.e., where the basic-state velocity vanishes. The domain under consideration extends in altitude from 200 mb up to 0.7 mb and in latitude from the South Pole to 10° southern latitude (denoted as 10°S or $-10°$ in the following). At the lower boundary, we prescribe the solution for Ψ (both amplitude and phase) as derived from Randel's (1987) data. The natural boundary condition at the South Pole is $\Psi = 0$. Since the overall propagation of the waves is upward and equatorward, for the upper and equatorward boundary a radiation condition would seem to be the best choice. However, in order to circumvent related technical difficulties, we instead use sponge layers and zero Dirichlet boundary conditions beyond the sponges. The model results are both qualitatively and quantitatively insensitive to the precise treatment of critical levels and boundary conditions (Wirth 1990).

For numerical implementation, the equation is discretized on a 5° by 5 km grid (latitude by altitude) using finite differences. Interpolation of the data from Randel's dataset onto the present grid uses bicubic splines. The resulting algebraic system of equations is solved with the help of a direct solver (based on Lindzen and Kuo 1969). To test the sensitivity of the model results with respect to the numerical resolution, the number of gridpoints was doubled in both altitude and latitude. The differences in the results turned out to be negligible.

3. Model results and interpretation

The model wave amplitude for different months is presented in Fig. 2, while the corresponding observed wave amplitude is shown in Fig. 3. Comparison of the two figures indicates that our model simulates well the qualitative features of the observed wave for the later


WAVE AMPLITUDE FOR APR

WAVE AMPLITUDE FOR JUN

WAVE AMPLITUDE FOR AUG

WAVE AMPLITUDE FOR OCT

FIG. 2. Model wave amplitude (in m) for zonal wavenumber 1 in meridional sections for every other month. Contour interval: 60 m. Note that the lower boundary is at 200 mb.

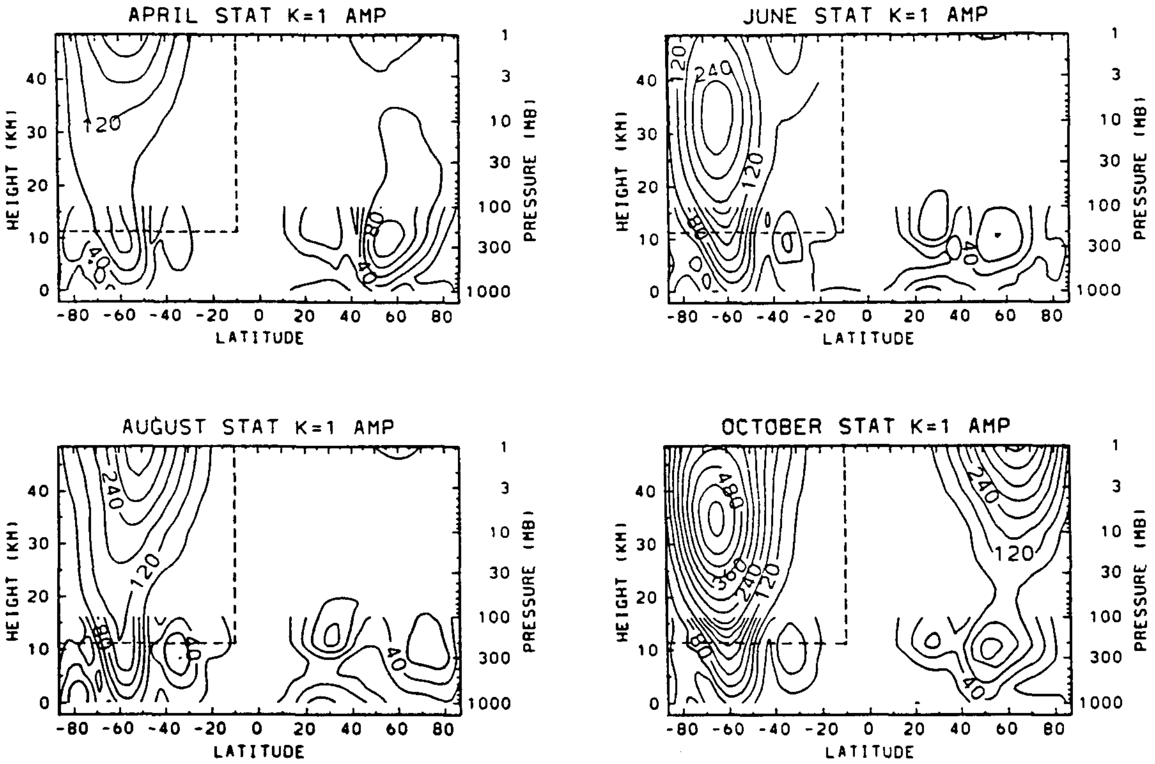


FIG. 3. Observed wave amplitude (in m) for zonal wavenumber 1 in meridional sections for every other month. Contour interval: 60 m above 100 mb, 20 m below 100 mb. Note that the lower boundary of the data is at 1000 mb. The dashed line indicates the region covered by the model (Fig. 2). The figures are taken from Randel (1987).

winter months (August through October). In both observations and model, the wave amplitude increases with altitude in the lower and middle stratosphere, and the so-called polar night jet descends and shifts poleward. As for the latter feature, the wave amplitude mimics the basic-state zonal wind field (cf. Simmons 1974). This mimicking behavior turns out to be a rather robust property in the present model. The direction of the Eliassen-Palm flux (no figures shown here) indicates overall upward and equatorward wave propagation for all months, which is in qualitative agreement with observations. The success of the model in late winter suggests that, despite the relatively large wave amplitudes in those months (Mechoso et al. 1988), the climatological behavior in the Southern Hemisphere is essentially captured by a linear model (cf. Plumb 1989).

However, in earlier winter months the agreement between model and observations is rather poor. For instance, the observed wave amplitude in April increases with altitude, but it is approximately constant with height in the model. Similarly, the model wave in June exhibits qualitative differences in comparison with the observed amplitudes. Correspondingly, the seasonal cycle of the model wave amplitude (Fig. 4) is qualitatively different from the observed cycle (Fig. 1). The model does not yield the observed relative minimum in mid-winter. Instead, it shows a continuous increase in wave amplitude until late winter. Since the simulation is better in late than in early winter, it appears that the main deficiency of the model is the "missing" relative wave maximum in early winter.

The seasonality of the wave's phase at 60°S is shown in Fig. 5. The model (Fig. 5b) gives a fair representation of the observed phase behavior (Fig. 5a): both model and observations display westward phase tilt with height and a seasonal change from small (June and July) to large (September and October) vertical phase tilt. The latter feature suggests a qualitative difference between the early winter and the late winter wave maximum (Randel 1988). The seasonal change in phase tilt, however, is much less pronounced in the model than in the observations. Similarly, the model vertical phase tilt is overall smaller than observed.

Concerning the early winter maximum there are reasons to question whether it is unambiguously related to quasi-stationary wave activity. (C. R. Mechoso 1990, private communication): observational evidence suggests that large eastward traveling transients develop in the southern stratosphere during early winter in certain years. These transients can contribute to the monthly mean wave field. On the other hand, our model does not account for traveling transients. In fact, it turns out that the model response can vary consid-

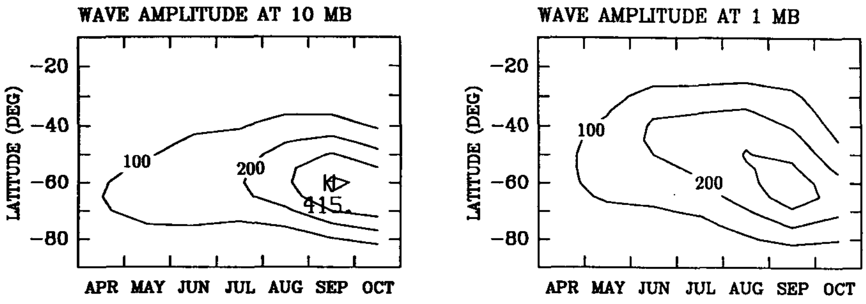


FIG. 4. Seasonal cycle (latitude–time section) of the model stationary wave 1 amplitude (in m) at 10 mb (left panel) and 1 mb (right panel). Contour interval: 100 m.

erably with phase speed for slowly traveling waves (Austin 1982). Furthermore, the early winter circulation in the southern stratosphere reveals substantial interannual variability (Geller and Wu 1987). The use of climatological monthly mean fields might therefore be misleading.

Despite the aforementioned discrepancies in early winter, the overall model performance encourages a closer analysis to address the questions raised in the introduction. We find that the model results can be consistently interpreted on the basis of refractive index diagnostics, i.e., in terms of wave transmission. For illustration, Fig. 6 shows the basic-state wind field and the refractive index for the two months April and October. The main features of the refractive index are negative values toward the pole and equatorward of the critical lines, a ridgelike structure in higher latitudes, a local low altitude minimum in midlatitudes and an overall increase toward the equator. In spite of the overall similarity of the refractive index for different months (as pointed out by Randel 1988), the following more detailed structures turn out to be of key importance: for easy upward wave propagation, and hence for large stratospheric wave amplitude, the higher latitude ridge (acting as a wave guide, see Karoly and Hoskins 1982; Lin 1982) should be well pronounced and reach down all the way to the forcing level; in addition, the low-level midlatitude minimum (inhibiting wave propagation) should be weak and located more towards the equator. The importance of the low-level refractive index can be illustrated in a plot of its seasonal cycle (Fig. 7). The figure considers only latitudes between 80° and 40°S, where the main forcing is located. The similarity with the seasonal cycle of the model wave amplitude (Fig. 4) is apparent. In connection with a sensitivity study (see below), we modified the basic states for the different months in such a way that the low-level refractive index had a two-peaked structure with a minimum in mid-winter. Admittedly, for this purpose the modifications had to be somewhat arbitrary and unrealistic. Nevertheless it was interesting to note that the resulting wave response showed qualitatively the same two-peaked structure. This, again, demonstrates the importance of the low-level refractive index.

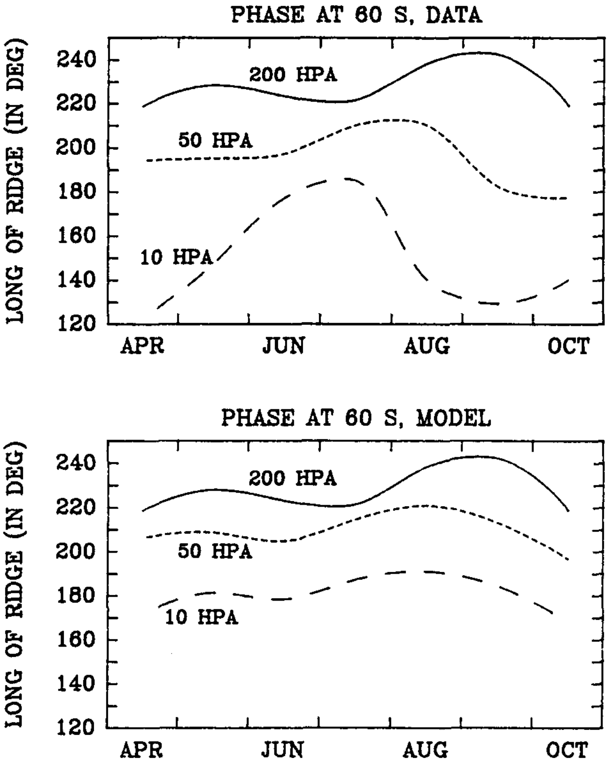


FIG. 5. Seasonality in phase (longitude of ridge) of stationary wave 1 at 60°S for various pressure levels. (a) data (from Randel 1988), (b) model.

In summary, accepting the above suggested key features in the refractive index, the seasonal cycle of the model's wave appears plausible in the light of the observed seasonal cycle of the basic state. On the other hand, these results draw into question Plumb's explanation of the seasonal cycle. Note, e.g., that in both April and October the wind maximum in the considered domain is about 50 m s^{-1}. The dramatic differences in wave response between April and October (see Fig. 3) thus cannot be explained by a one-dimensional

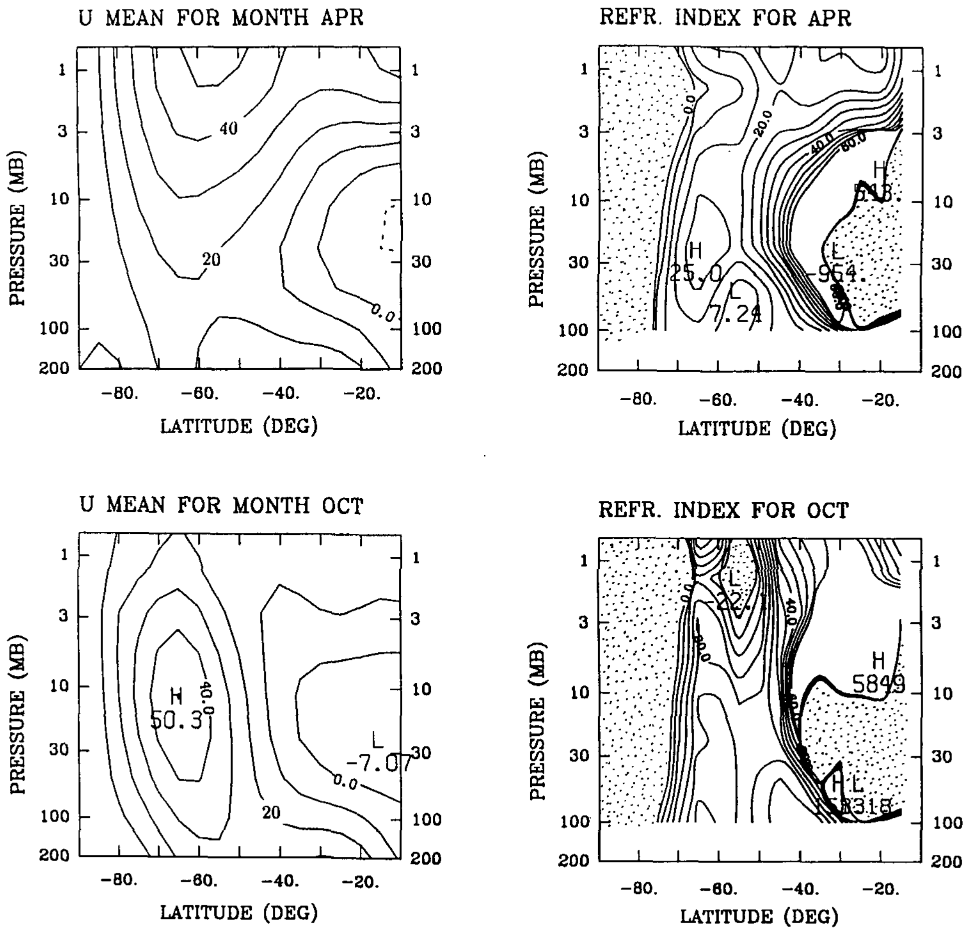


FIG. 6. Basic-state zonal wind (in m s^{-1}; left row) and refractive index (dimensionless; right row) for April and October, meridional sections. Contour interval: 10 m s^{-1} for the zonal wind, 5 for the refractive index. For the refractive index only contours between 0 and 60 are drawn and areas of negative refractive index are stippled.

consideration of wave propagation relying only on the mean wind.

Since there is considerable sensitivity of the model response with respect to variations in the basic state (cf. Schoeberl and Geller 1977), it is important to check the robustness of our results with respect to such variations. We considered a great variety of basic-state modifications and examined the modified response. Particular sensitivity was found with respect to modifications which affect the low-level winds and the jet-structure of the wind field. Modifying the basic-state wind in the middle and upper stratosphere resulted in less dramatic changes, and often the response could be rationalized in terms of the mimicking tendency mentioned above. For the low-level modifications, weaker winds generally result in higher low-level refractive index and hence, according to our consistent interpretation, in increased wave amplitudes. To check the sensitivity of our results with respect to the exact treatment of forcing, we replaced our "realistic" lower boundary condition by a constant boundary condition with no seasonal cycle and with no variation in latitude. The qualitative wave behavior turned out to be unchanged. Therefore we conclude that the (weak) seasonal cycle in forcing plays a minor role and that the

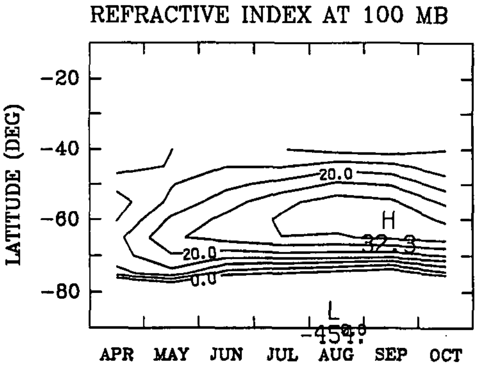


FIG. 7. Seasonal cycle (latitude–time section) of the refractive index (dimensionless) at 100 mb in the latitude range between 80° and 40°S. Contour interval: 5. No negative contours are drawn.

(very pronounced) seasonal cycle of the model response must essentially be attributed to a corresponding cycle in wave transmission properties. Also the sensitivity of the model with respect to variation in the damping coefficient was extensively examined. Even though there is some sensitivity (cf. again Schoeberl and Geller 1977; Schoeberl et al. 1979), the seasonal wave cycle always turns out to have only one peak in late winter. To summarize, the modifications studied here do not suggest that the discrepancies between model and observations can entirely be explained in terms of model sensitivity to the basic-state zonal wind, to forcing, or to dissipation parameterization.

4. Summary and conclusions

The present work studies the seasonal cycle of stationary planetary waves in the southern stratosphere, using a linear, hemispheric model for wave propagation. The model simulates well the qualitative features of the wave dynamics for late winter months. In the higher stratosphere, the wave amplitude displays a strong tendency to mimic the basic-state zonal wind field. The model wave can consistently be interpreted with the help of the refractive index, i.e., in terms of the transmission properties of the underlying atmosphere. Specific features in the refractive index turn out to be of key importance, in particular its behavior in the lower stratosphere.

The pronounced seasonal cycle of the model wave is mostly determined through varying transmission properties; the weak tropospheric cycle plays hardly any role. The present model draws into question a qualitative explanation for the seasonal cycle, which relies on the one-dimensional Charney-Drazin model.

However, in early winter, there are qualitative discrepancies between the model results and observations. As a consequence, the observed seasonal cycle is not captured by the model. Possible reasons for the missing wave maximum in early winter may be the existence of a transient traveling wave and interannual variability. Also, one might question the accuracy of the winds derived from satellite data. In particular for the latitude band between 40° and 60°S, there are few ground-based data. In fact, the model results show considerable sensitivity to modifications of the lower stratospheric wind in middle latitudes. However, no set of modified basic states was found that was able to reproduce the observed qualitative features of the waves including their seasonal cycle. A more systematic, albeit more cumbersome, approach would be solving the nonlinear, inverse problem. Because of the discrepancies, the present study is not entirely conclusive about the cause of the observed seasonal cycle, even though it strongly suggests that the variation in transmission properties plays a major role.

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