Nonlinear Stationary Wave Maintenance and Seasonal Cycle in the GFDL R30 GCM

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ABSTRACT

In this study, the climatological stationary wave maintenance is examined from nonlinear perspective using the GFDL R30 GCM outputs, a fully nonlinear stationary wave model, and a linear stationary wave model. The primary focus of the study is on the nature of the stationary nonlinearity and relative contribution to the total nonlinearity by various factors, such as heating, orography, and the interaction between flows forced by heating and orography. It is found that both the nonlinear effect of the diabatic heating and the nonlinear interaction between flows forced by orography and diabatic heating are important contributors toward the total stationary nonlinearity in northern winter and summer. Some regional features, such as the anticyclone off the northwest coast of North America in winter and the southwestern U.S. summer anticyclone, are entirely due to the nonlinear interaction between flows forced by heating and orography.

Consistent with the linear stationary wave maintenance, the diabatic heating is the most dominant forcing mechanism in the Tropics and the Southern Hemisphere (SH) throughout the seasonal cycle in the nonlinear framework. Over the Northern Hemisphere (NH) extratropics during northern winter, however, the role of the orographic forcing is comparable to that of diabatic heating due to its strong nonlinear interaction with flows forced by heating and transients. This contrasts significantly with the conclusion drawn from the direct nonlinear responses in which the orography is much less important than the diabatic heating. The regional feature of the ridge over northwestern North America in northern winter is found to be largely due to the presence of orography.

The effect of transients in the nonlinear model, including the nonlinear interaction of transients with flows forced by heating and orography, shows a wave train over the Pacific–North American region (PNA) that resembles the atmospheric response to El Niño. This differs considerably from that in the linear view as well as that of the direct nonlinear response to transients. Furthermore, it is found that the inclusion of orography or transients in the total stationary wave forcing improves the spatial pattern simulation of the GCM stationary waves for both hemispheres in their respective winter months.

1. Introduction

The scientific question of the maintenance mechanisms for the climatological stationary waves has been investigated for the past half century. During the last two decades, great improvements have been made in our understanding of the structure and maintenance of the climatological stationary waves. In addition to many observational studies, various models were employed in the past to reproduce and explain the essential features of the climatological stationary waves in observations (see Held 1983 for a review). Due to deficiencies in observational data and models used, however, the maintenance mechanisms of the climatological stationary waves are not completely understood, especially with regard to the nonlinear nature of the stationary waves.

To investigate the maintenance of the climatological stationary waves, linear stationary wave models (e.g., Charney and Eliassen 1949; Hoskins and Karoly 1981; Nigam et al. 1986, 1988; Valdes and Hoskins 1989; Ting and Held 1990; Ting 1994; among others) have been widely used to diagnose the relative importance of forcings, for example, orography and land–sea thermal contrasts. In the linear stationary wave theory, stationary eddies are generated when the zonal mean flow is subjected to the various zonally asymmetric forcings. With the high quality observational and/or general circulation model (GCM) data and more sophisticated linear modeling tools, the ability to faithfully reproduce the climatological stationary waves in GCM and observations enhanced greatly in the recent years. The relative importance of the individual forcings can be determined by examining the linear model response to each of the individual forcings.

Although the linear stationary wave model has been a successful diagnostic tool, it has its limitations. The atmosphere is intrinsically nonlinear, thus the linear divisions among different forcings are not entirely realistic. For example, the response to diabatic heating induces flow changes, which will alter the effect of orography (mechanical forcing). The importance of station-
ary nonlinearity in maintaining regional climatological stationary wave features has been pointed out in many previous studies. For example, by including an extra term representing nonlinearity in the linear model, Valdes and Hoskins (1989) illustrated the importance of nonlinearity in maintaining the ridge over and upstream of western North America in both lower and upper troposphere during northern winter. With a linear stationary wave model, Ting (1994) found that the stationary nonlinearity forcing accounts for the Geophysical Fluid Dynamics Laboratory (GFDL) GCM summertime anticyclone over North America, which is known to have important impacts on precipitation over the United States. Ting (1994) further proposed that the nonlinearity is possibly caused by the nonlinear interaction between flow forced by diabatic heating and local orography. The crucial role of nonlinearity in the maintenance of stationary waves suggested by the linear model supports that a more thorough understanding of the nature of the nonlinearity is needed. While it is possible to measure the overall effect of stationary nonlinearity in the atmosphere using the linear model (e.g., Valdes and Hoskins 1989; Ting 1994), it is impossible to identify the nonlinear effect of each individual forcing and the nonlinear interaction among different forcing components with the linear model alone. A fully nonlinear stationary wave model is necessary to achieve that purpose.

Fully nonlinear models of various forms have been used in many previous studies to examine the nonlinear effect of orography. Manabe and Terpstra (1974) inferred the role of orography based on the comparison between a GCM experiment with realistic orography and one with a flat lower boundary. The advantage of using a GCM is that the complicated physical processes and nonlinear interaction can be incorporated. However, with GCMs alone, one cannot separate the total effect of orography into the part due to the mechanical effect of the orography and the part forced by the changes of diabatic heating and transient forcing that result from the presence of orography. Valdes and Hoskins (1991) constructed a nonlinear stationary wave model based on primitive equations and iterative method to examine the steady nonlinear solution of the atmospheric response to earth orography. They found that nonlinearity modifies significantly the linear response to orography in both spatial pattern and amplitude. With an idealized GCM and a linear stationary wave model, Cook and Held (1992) examined the nonlinearity induced by idealized orography with different heights and found that nonlinearity becomes more dominant for increasing mountain heights. The prominent effects of the nonlinearity are amplitude saturation and the dominance of poleward wave propagation. By using a quasigeostrophic nonlinear model, Ringer and Cook (1997) investigated the factors controlling the nonlinearity in mechanically forced stationary waves by orography, such as orographic height and shape, surface wind, vertical wind shear, and meridional temperature gradient. They found that nonlinearity should be more important in summer than winter due to weaker surface wind and vertical wind shear in summer. All of the above studies concluded the significant modification of the linear stationary wave response to orography by nonlinearity.

Compared to the nonlinearity by orography, there was much less research work done on the nonlinear effect of diabatic heating and the interaction between flows forced by orography and heating. This is mainly due to the technical difficulties in constructing a nonlinear stationary wave model that converges when subjected to the diabatic forcing. One exception is the study of Ting and Held (1990), who used an iterative nonlinear stationary wave model similar to that in Valdes and Hoskins (1991), but subjected to the tropical heating associated with zonally asymmetric sea surface temperature in an idealized GCM. Due to the idealized nature of the problem, the nonlinear model is able to converge and thus a fully nonlinear solution is obtained. The results in Ting and Held (1990) showed that there are significant modifications of the linear model response to diabatic heating due to nonlinear effect. Recently, techniques have been developed to use time-evolving primitive equation nonlinear model to obtain a steady-state nonlinear solution. Hoskins and Rodwell (1995) obtained a reasonably good simulation of the global circulation during northern summer using the time-dependent model approach. They found that the nonlinear interaction between orography and diabatic heating is important for a realistic simulation of the low-level monsoon flow. Ting and Yu (1998) used the same approach and compared the linear and nonlinear model responses to tropical heating at different longitudes. A recent study by Ringler and Cook (1999) found the importance of the nonlinear interaction between heating and orography in the Northern Hemisphere extratropics, using a nonlinear quasigeostrophic model.

Although the nonlinear effects of orography and diabatic heating as well as their interaction have been studied in the past, there is no previous research that provides a complete diagnostics of the nonlinear stationary wave maintenance. Given the useful insights provided by the linear stationary wave diagnostics (e.g., Valdes and Hoskins 1989; Ting 1994; Wang and Ting 1999), it is desirable to repeat the diagnostics using a fully nonlinear model. In our study, a time-dependent fully nonlinear model based on the primitive equations is employed for the nonlinear stationary wave diagnostics. We utilize data from the GFDL GCM rather than observational reanalysis because GCM output provides more dynamical consistency and is thus easier to verify using the nonlinear model. With the combined use of a linear stationary wave model and a fully nonlinear model, this study aims at the investigation of the maintenance mechanisms and seasonal cycle of the global and regional stationary wave features in the GFDL GCM, with the primary focus laid on the nature of stationary
The specific questions this study attempts to address are the following.

- What is the nature of the stationary nonlinearity in the GFDL GCM climatological stationary wave maintenance—that is, which factor(s) has(have) the major contribution to the total stationary nonlinearity?
- Within the nonlinear framework, what is the relative importance of orography, diabatic heating, and transients in the maintenance of the GCM climatological stationary waves?
- What are the causes for the regional climatological stationary wave features, such as the ridge over northwestern North America in boreal winter, the Tibetan anticyclone, and the anticyclone over the North America in boreal summer?

The datasets and the analysis tools are briefly described in section 2. The GFDL GCM climatological stationary waves are compared to the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis climatological stationary waves in section 3. Section 4 presents a brief account of the linear model simulations of the stationary waves. The nonlinear model results are presented and discussed in section 5. Finally, the conclusions are given in section 6.

2. Data and methodology

a. Data

The GCM output used in this study are taken from the 100-yr control experiment with prescribed climatological sea surface temperatures of the climate group GCM at GFDL. The GCM has rhomboidal wave number 30 truncation in the horizontal and 14 unevenly spaced sigma levels in the vertical (R30L14). The model has realistic seasonal cycle and predicted clouds. This particular experiment also uses smoothed orography, which is designed to avoid the Gibbs ripples due to spectral truncation of orography as discussed in Navarra et al. (1994) and Lindberg and Broccoli (1996). The effect of smoothed orography is mainly to produce a more realistic precipitation field (Lindberg and Broccoli 1996). In this study, the GCM climatological stationary waves and their forcings are obtained by averaging data from the last 50 yr of the 100-yr run. There are very little differences between the 50- and the 100-yr mean climatology. The stationary waves in this study are represented by the zonally asymmetric streamfunction field to emphasize the amplitude in the Tropics and the subtropics. The results are shown at two σ levels, that is, \( \sigma = 0.257 \) and \( \sigma = 0.866 \), which are referred to as the upper and lower tropospheric levels, respectively.

Before performing linear and nonlinear model simulations, the climatological stationary waves in the GCM are compared to those in observations. In this study, the NCEP–NCAR reanalysis (Kalnay et al. 1996) is used to represent observations. The reanalysis climatological stationary waves are obtained by taking the 52-yr (1948–99) mean based on horizontal wind fields.
b. Nonlinear stationary wave model

Similar to Ting and Yu (1998), the nonlinear model employed in this study is a time-dependent fully nonlinear model based on three-dimensional primitive equations in sigma (σ) coordinates. The model has the same spatial resolution as the GFDL GCM, that is, R30L14. It is essentially the dynamical core of the GFDL GCM except that the model variables are deviations from a prescribed zonal mean or zonally varying basic state. Unless otherwise stated, the basic state used in this study is the zonal mean state from the 50-yr average GCM data for each month. To obtain a quasi-steady solution, model-generated transients are suppressed by strong dampings. Therefore, a quasi-steady solution can be obtained after integrating for a sufficiently long time. The forcings for the nonlinear model include orography, diabatic heating, and transient vorticity and heat fluxes. The GCM orography and diabatic heating are directly obtained from the GCM dataset. The transient forcing is residually derived based on the basic equations in sigma coordinates. For further details on the nonlinear model, please refer to the appendix of Ting and Yu (1998).

The damping employed in the nonlinear model includes Rayleigh friction. Newtonian cooling and biharmonic diffusion. A 35 (25)-day Rayleigh friction is applied to u(v) in the top seven levels for all 12 months. For the lowest seven levels, the Rayleigh friction coefficients are obtained by linearly regressing the vertical diffusion of momentum against the horizontal velocity in the GCM. For simplicity, Rayleigh friction coefficients obtained this way are named optimum Rayleigh damping coefficients, since they provide the best possible approximation to that in the GCM. Due to small differences among the optimum Rayleigh friction coefficients for different months, the 12-month average is chosen as Rayleigh damping coefficients for all months in the nonlinear model. The Rayleigh friction coefficients used in nonlinear model are

\[
\frac{\partial u}{\partial t} = \cdots - \kappa_u u \quad \frac{\partial v}{\partial t} = \cdots - \kappa_v v
\]

where

\[
\kappa_u = (7^{*}35.0, 35.0, 29.0, 23.0, 1.0, 0.5, 0.3)^{-1} \text{ (days)}^{-1} \quad \text{and}
\]

\[
\kappa_v = (7^{*}25.0, 23.0, 14.0, 6.5, 6.0, 1.0, 0.3, 0.15)^{-1} \text{ (days)}^{-1},
\]

from the top to the surface atmospheric levels. A 15-day Newtonian cooling is applied to all levels in the thermodynamic equation. The biharmonic diffusion is applied to the vorticity, divergence and thermodynamic equations with a coefficient of \( \nu_k = 1 \times 10^7 \text{ m}^4 \text{ s}^{-1} \), which is 10 times stronger than that in the GCM. The stronger biharmonic diffusion is necessary to suppress the transient eddies in the nonlinear model and to obtain a quasi-steady-state solution. In addition, a 3-day zonal mean damping is included to suppress the zonal mean variability in the nonlinear model.

c. Linear stationary wave model

For the purpose of comparison as well as to quantitatively determine the nonlinear effect, a linear stationary wave model is also employed in this study. The linear model is the same as that utilized in Wang and Ting (1999). It has the same spatial resolution as those in the GFDL GCM and the nonlinear model, that is, R30L14. The model linearizes about the zonal mean basic state based on the 50-yr average GCM data for each month. The forcings included in the linear model are orography, diabatic heating, transient forcing, and stationary nonlinearity. The first three forcings are the same as those in the nonlinear model. The stationary nonlinearity forcing, which represents the stationary nonlinear wave–wave interaction, is also included in the linear model as an additional forcing. The linear model response to the stationary nonlinearity forcing can be considered as the overall stationary nonlinear effect in the GCM. To be consistent with the nonlinear model and facilitate the comparison between the linear and the nonlinear model results, the same damping coefficients as those employed in the nonlinear model are used in the linear model. The linear model forcings are exactly the same as those in the nonlinear model, except the stationary nonlinearity forcing, which is computed from the GCM stationary waves (see Ting 1994).

3. GCM climatological stationary waves

To evaluate the climatological stationary waves simulated in the GFDL GCM, we compare the GCM-simulated climatological stationary waves against those in the NCEP–NCAR reanalysis. Two measures are used for this comparison. The first is an area-weighted spatial pattern correlation \( r \) between the stream functions for the climatological stationary waves in the GCM (\( \psi_{\text{GCM}}^* \)) and those in the reanalysis (\( \psi_{\text{obs}}^* \)).

\[
r = \frac{\int_A (\psi_{\text{GCM}}^* \psi_{\text{GCM}}^* \cos \theta) \ d\lambda \ d\theta}{\left( \int_A (\psi_{\text{GCM}}^* \cos \theta)^2 \ d\lambda \ d\theta \right)^{1/2} \left( \int_A (\psi_{\text{obs}}^* \cos \theta)^2 \ d\lambda \ d\theta \right)^{1/2}},
\]

where \( A \) is the area over which the spatial pattern correlation is calculated and \( \lambda \) and \( \theta \) represents longitude and latitude. The second is the zonal root-mean-square (rms) amplitude of the climatological stationary waves,

\[
rms(\psi^*) = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} \psi_{\text{rms}}^2 \cos \theta \ d\lambda}.
\]
Figure 2. Zonal root-mean-square streamfunction amplitude of the GFDL GCM climatological stationary waves at (a) $\sigma = 0.257$, (b) $\sigma = 0.866$, and that of the NCEP–NCAR reanalysis 52-yr climatological stationary waves at (c) $\sigma = 0.257$, (d) $\sigma = 0.866$. Contour interval is $1 \times 10^6$ m$^2$ s$^{-1}$. Values greater than $8 \times 10^6$ m$^2$ s$^{-1}$ in (a) and (c) and greater than $5 \times 10^6$ m$^2$ s$^{-1}$ in (b) and (d) are shaded.

Figure 1 shows the spatial pattern correlation $r$ between climatological stationary waves in the GCM and those in the NCEP–NCAR reanalysis as a function of vertical levels and month of the year for the stationary waves over the whole globe (Fig. 1a) the Northern Hemisphere, (NH; Fig. 1b), and the Southern Hemisphere, (SH; Fig. 1c). In general, the GFDL GCM simulates fairly well the stationary waves at the upper ($\sigma \sim 0.1–0.3$) and lower ($\sigma > 0.7$) levels in northern summer and throughout the troposphere in northern winter, with a pattern correlation exceeding 0.8 (Fig. 1a). Relatively low correlations ($r < 0.7$) are found at midlevels during north-
ern summer and the transitional seasons. This is similarly seen in the NH stationary wave correlations (Fig. 1b). In the SH (Fig. 1c), low correlations are again found in austral summer and transitional seasons, but they are more widespread than those in the NH. Despite the relatively low correlations for the above-mentioned areas, the pattern correlations are above 0.5 in general. This indicates a reasonable agreement between the GCM and the NCEP–NCAR reanalysis in terms of stationary wave patterns. To determine how well the GCM simulates the observed stationary wave strength, the GCM rms stationary amplitude at both lower and upper levels (Figs. 2a,b) is compared to its counterpart in the reanalysis (Figs. 2c,d). The gross features of the reanalysis stationary wave amplitude are captured by the GFDL GCM. These include the double maximum in northern winter upper troposphere and a single maximum in NH summer for both the upper and lower troposphere. There are, however, significant discrepancies between the GCM stationary wave amplitude and that in the reanalysis. The most distinct difference is that the GCM considerably overestimates the observed stationary wave strength in the Tropics during northern summer for both lower and upper levels. As will be discussed in more detail later, the overestimation in the GCM is a result of the overestimation of the response to tropical heating in the GCM. Other discrepancies include a wider latitudinal extent of the northern summer maximum at both the upper and lower levels and a slight underestimation of the extratropical maximum at upper level during northern winter in the GCM. Despite the above differences between the GCM and the reanalysis, the GFDL GCM gives a reasonably good simulation of the observed stationary wave amplitude. Goswami (1998) illustrates that this GCM provides a realistic simulation of the monsoon circulation over India and Southeast Asia. Given the many advantages of the GCM data, it is useful to examine the forcing mechanisms of the GCM climatological stationary waves, in particular, the nonlinear nature of the stationary wave maintenance.

4. Linear model simulation

When the linear model is subjected to the total stationary wave forcing taken from the GCM, including orography, diabatic heating, transients, and stationary nonlinearity, we expect the linear model to give an exact reproduction of the GCM stationary waves, provided that the dissipation parameterization in the linear model is accurate. The spatial pattern correlation between the linear model response to the total forcing and the GCM stationary waves is shown in Fig. 3. The correlation is almost everywhere above 0.8, indicating a good consistency between the linear model and the GCM. Figure 3 can be compared to Fig. 11 in Wang and Ting (1999), which shows the same spatial pattern correlation as in Fig. 3, but based on the NCEP–NCAR reanalysis. The higher spatial pattern correlation in Fig. 3 illustrates again the advantage of using the GCM output over observational reanalysis in stationary wave modeling. The imperfect correlation in Fig. 3 can be attributed to the inaccuracy of the dissipation parameterization used in
the linear model. The stationary wave amplitude simulated by the linear model when subjected to total forcing (not shown) also compares well to the GCM amplitude (Figs. 2a,b).

To illustrate the importance of the stationary nonlinearity, linear model response to the total forcings without the stationary nonlinearity—that is, orography, diabatic heating, and transients—is computed. The spatial pattern correlation between this linear model response and the GCM stationary waves is shown in Fig. 4. The pattern correlation is much lower in Fig. 4 compared to Fig. 3, indicating a nontrivial contribution of the stationary nonlinearity to the GCM stationary wave maintenance. The lower spatial pattern correlation is particularly true for all levels in the NH from October to April and middle levels during northern summer. For NH summer, the spatial pattern correlation remains high at both lower and higher levels in Fig. 4 compared to Fig. 3. This suggests that stationary nonlinearity plays a more important role during NH cold months. For SH, the reduction of correlation in Fig. 4c is not as dramatic as for NH, particularly for austral winter months. Thus, nonlinearity is not as important a factor in SH stationary wave maintenance as in NH, a conclusion confirmed by the nonlinear model in section 5. To further explore the relative role of stationary nonlinearity forcing compared to other forcings in maintaining the GCM climatological stationary waves, the amplitude of the linear model response to each individual forcing for all 12 months is shown in Fig. 5 for the upper level. It is clear from Fig. 5 that diabatic heating dominates the GCM climatological stationary waves in the tropics for all months. Comparing Fig. 5a to Fig. 2a, it is easily seen that the overestimation of stationary wave amplitude in the tropics in GCM is largely due to the effect of diabatic heating. In the NH extratropics, however, the four forcings are of comparable importance in contributing to the GCM climatological stationary waves in terms of both the spatial pattern (not shown) and stationary wave amplitude, although the latitude of maximum amplitude is farther north of that in Fig. 2a. This differs from the conclusions in Wang and Ting (1999) based on the NCEP–NCAR reanalysis, where diabatic heating is more dominant than other forcings in the NH extratropics during northern winter. The difference in conclusions mainly results from the fact that the NCEP–NCAR reanalysis heating is stronger than the GCM heating in the NH extratropics during northern winter. Similar conclusions regarding the relative importance of the four individual forcings in maintaining the GCM stationary waves apply to the lower level. Note that the stationary nonlinearity in Fig. 5d is more important for the NH stationary wave strength during the cold months than that in the summer and the SH, consistent with the conclusion drawn from the spatial pattern correlation.

The streamfunction pattern of the linear model response to the stationary nonlinearity at the upper level is shown in Fig. 6 for January (Fig. 6a), April (Fig. 6b), July (Fig. 6c), and October (Fig. 6d). In January, the main features are a dipole over the western Pacific with an anticyclone to the east and a cyclone to the west, and an anticyclone centered over the northwestern coast of North America. The ridge over northwestern North
Fig. 5. Zonal root-mean-square streamfunction amplitude of the linear model response to (a) diabatic heating, (b) orography, (c) transients, and (d) stationary nonlinearity at $\sigma = 0.257$. Contour interval is $1 \times 10^6$ m$^2$ s$^{-1}$. Values greater than $5 \times 10^6$ m$^2$ s$^{-1}$ are shaded.

America contributed by stationary nonlinearity as shown in Fig. 6a is consistent with the findings in Valdes and Hoskins (1989). Figure 6a also indicates that stationary nonlinearity enhances the jet over central Pacific, a feature not noted in earlier studies. In July (Fig. 6c), the main features due to stationary nonlinearity are the anticyclone centers over northeastern Asia and western United States, each accompanied by a cyclonic center farther to the east. The high over the United States is consistent with the findings in Ting (1994), who used a different version of the GFDL GCM. For the two transitional months (Figs. 6b,d), the main features due
Fig. 6. Linear model streamfunction response to the GCM stationary nonlinearity forcing at \( \sigma = 0.257 \) for (a) Jan, (b) Apr, (c) Jul and (d) Oct. Contour interval is \( 5 \times 10^6 \text{ m}^2 \text{s}^{-1} \), and negative values are shaded.
to stationary nonlinearity are similar to that in January, but with weaker amplitude. The notable feature in both cases is the contribution to an enhanced jet over the North Pacific. Figure 6 illustrates clearly the important role of stationary nonlinearity in maintaining many regional stationary wave features in the NH, particularly in northern winter. The exact cause of the stationary nonlinear effect, however, is not clear from the linear model. This question will be explored in detail using the fully nonlinear model in the next section.

5. Nonlinear model simulations

When the nonlinear model is subjected to the zonal mean climatological GCM basic state, the stationary wave forcings, that is, global orography, diabatic heating, transient vorticity, and heat flux convergences, and specified damping parameters, a quasi-steady state can be reached after about 25 days. The average of day 31 to day 50 responses is chosen as the nonlinear stationary wave solution in this study.

To illustrate how well the nonlinear model simulates the GCM climatological stationary waves, the spatial pattern correlation between the GCM stationary waves and the nonlinear model response to the sum of orography, diabatic heating, and transient forcing is shown in Fig. 7. Figure 7 should be compared to Fig. 4, which shows the same spatial pattern correlation but for the linear model response. Note that Fig. 7 should not be compared to Fig. 3, since Fig. 3 illustrates the dynamical consistency between the linear model and the GCM, rather than a true nonlinear solution. Compared to the linear results in the NH (Fig. 4b), the spatial pattern correlation for the NH in the nonlinear simulation (Fig. 7b) increases uniformly throughout the troposphere and for all months. This is particularly true during northern winter months. The correlation is relatively low during the spring and fall in the lower troposphere, though. For the SH (Fig. 7c) where linear model works relatively well, the improvements by the nonlinear model in spatial pattern correlation are mainly at the lowest model levels.

In the midtroposphere, however, the correlation deteriorates in the nonlinear model simulation compared to the linear model solution during the transitional seasons. The poor pattern correlation at the surface for the SH atmosphere in the nonlinear model simulation (Fig. 7c) is mainly due to the SH orographic forcing, especially the Antarctic. The removal of SH orography increases the spatial correlation significantly at the surface (Fig. 7d) but decreases the pattern correlation at other lower levels. Over the whole globe (Fig. 7a), the nonlinear model results are much better than the corresponding linear model results based on spatial pattern correlation. It is thus worthwhile to examine further the nature of the stationary nonlinearity using this nonlinear model.

The overall nonlinear effect in the GCM generated by the nonlinear model can be obtained by subtracting the linear model response to the sum of orography, diabatic heating, and transient forcing from the nonlinear model response to the sum of these three forcings. Figure 8 displays the overall nonlinear effect generated by the nonlinear model at \( \sigma = 0.257 \) for January (Fig. 8a), April (Fig. 8b), July (Fig. 8c) and October (Fig. 8d). Figure 8 can be compared to the linear model response to the GCM stationary nonlinearity forcing at the upper level (Fig. 6). There is a clear similarity between Fig. 8 and Fig. 6 for all months, particularly in January. The wave train–like pattern extending from the western North Pacific toward north and then east to southeast United States in January (Fig. 8a) is strikingly similar to the corresponding one in Fig. 6a. All main features in April and October in Fig. 6 are reproduced in Fig. 8 with slightly different amplitude. In July (Fig. 8c), the anticyclonic center over northern Asia and that over the U.S. continent are again similar to the corresponding ones in Fig. 6c. The similarity between Fig. 6 and Fig. 8 indicates that the nonlinear model approach taken in this study is truly able to represent the stationary nonlinearity in the GCM. Thus the nature of the stationary nonlinearity in the GCM can be determined by the nonlinear model.

The stationary nonlinear effect in Fig. 8 may be contributed by several factors, such as the nonlinear orographic effect, nonlinear diabatic heating effect, and the nonlinear interaction between flows forced by orography and heating, among others. The importance of nonlinear orographic forcing has been emphasized in many previous studies (Cook and Held 1992; Valdes and Hoskins 1991). The nonlinear interaction between flows forced by diabatic heating and orography has been suggested in Ting (1994) to be responsible for the summertime anticyclone over North America. To separate the different components of the nonlinear effect, we make use of both the linear and nonlinear model responses as follows,

\[
NE(f_1) = NLIN(f_1) - LIN(f_1) \quad \text{and} \quad \tag{1}
\]

\[
NE(f_1, f_2) = NLIN(f_1 + f_2) - NLIN(f_1) - NLIN(f_2) \quad \tag{2}
\]

where \( NE(f) \) represents nonlinear effect due to forcing \( f \), \( NE(f_1, f_2) \) the nonlinear effect due to the interaction between flows forced by forcing \( f_1 \) and \( f_2 \), and \( NLIN(f) \) and \( LIN(f) \) the nonlinear and linear model responses to forcing \( f \), respectively. Using the above notation, the nonlinear model response to the sum of diabatic heating \( f_1 \), orography \( f_2 \), and transients \( f_3 \) can be decomposed into seven different parts in the nonlinear framework,

\[
NLIN(f_1 + f_2 + f_3) = NLIN(f_1) + NLIN(f_2) + NLIN(f_3) + NE(f_1, f_2) + NE(f_1, f_3) + NE(f_2, f_3). \quad \tag{3}
\]
Fig. 7. Area-weighted spatial pattern correlation between the GFDL GCM zonally asymmetric streamfunction fields and the nonlinear model streamfunction response to the sum of diabatic heating, orography and transients over (a) the global domain, (b) the NH domain, (c) the SH domain, and (d) the SH domain but without the SH orography in the forcing. Contour interval is 0.1. Values greater than 0.8 and less than 0.6 are dark and lightly shaded, respectively.
Fig. 8. The zonally asymmetric streamfunction difference between the nonlinear model response to the sum of diabatic heating, orography and transients and the linear model response to the same forcing, a measure of the stationary nonlinear effect, at $\sigma = 0.257$ for (a) Jan, (b) Apr, (c) Jul, and (d) Oct. Contour interval is $5 \times 10^6$ m$^2$s$^{-1}$ and negative values are shaded.
Given that the linear model response can be simply decomposed into the following, 
\[
\text{LIN}(f_1 + f_2 + f_3) = \text{LIN}(f_1) + \text{LIN}(f_2) + \text{LIN}(f_3),
\]
thus the nonlinear effect of the total forcing (Fig. 8) can be decomposed into the following seven parts,
\[
\text{NE}(f_1 + f_2 + f_3) = \text{NLIN}(f_1 + f_2 + f_3) - \text{LIN}(f_1 + f_2 + f_3)
= \text{NE}(f_1) + \text{NE}(f_2) + \text{NE}(f_3) + \text{NE}(f_1, f_2) + \text{NE}(f_1, f_3) + \text{NE}(f_2, f_3) + \text{NE}(f_1, f_2, f_3).
\]
(5)
In the following sections, we will discuss the contributions due to each of the terms in Eq. (5) for January and July.

In addition, we also assess the total effect (TE) due to one individual forcing, say \( f_1 \), in the following way,
\[
\text{TE}(f_1) = \text{NLIN}(f_1) + \text{NE}(f_1, f_2) + \text{NE}(f_1, f_3) + \text{NE}(f_1, f_2, f_3),
\]
(6)
which is equivalent to the difference between the responses to forcings with and without \( f_1 \),
\[
\text{TE}(f_1) = \text{NLIN}(f_1 + f_2 + f_3) - \text{LIN}(f_1 + f_2 + f_3).
\]
(7)
Therefore, the total effect of one forcing not only includes the nonlinear response to that forcing, but also includes the nonlinear interaction between flows forced by that forcing and the rest of the forcings.

\textbf{a. Nonlinear effect of diabatic heating}

The linear and nonlinear model responses to global diabatic heating are shown in Fig. 9 for January (Figs. 9a,b) and July (Figs. 9c,e) at the upper level. Also shown in Fig. 9 are the differences between the linear and nonlinear model responses to the heating in January (Fig. 9c) and July (Fig. 9f), which illustrate the nonlinear effect of diabatic heating as in Eq. (1). In January, the main difference between the linear and nonlinear responses is the enhancement of the NH extratropical centers, particularly over the North Pacific region. There is also a slight eastward shift of the quadrupole centers over the tropical Pacific in the nonlinear model result (Fig. 9b). These nonlinear effects of diabatic heating are shown clearly in the difference map (Fig. 9c), which appears as a wave train–like structure emanating from the western tropical Pacific along a “great circle” route all the way to the tropical Atlantic. As a result of the eastward shift of the tropical quadrupole centers, the subtropical jet is enhanced over the central Pacific. The results here are consistent with the model response to idealized tropical GCM heating in Ting and Held (1990). In July, the difference between the linear and nonlinear model responses is rather subtle. The only significant difference is the eastward extension of the South Asian anticyclone in the nonlinear model. The contribution of nonlinear effect by diabatic heating to the total stationary nonlinearity can be determined by comparing Figs. 9c,f to the total nonlinear effect in Figs. 8a,c. The comparison indicates that the nonlinear effect of diabatic heating is clearly a significant contributor to the total nonlinear effect in Fig. 8. There are large differences between Fig. 8a and Fig. 9c, however, suggesting that other nonlinear effects are important in January.

\textbf{b. Nonlinear effect of orography}

Similar to Fig. 9, we compare in Fig. 10 the linear and nonlinear model responses to orography, and the differences between the linear and nonlinear solutions to orography for January and July at the upper level. In January, the difference between the linear and nonlinear responses is the weakening of the southeastward wave train emanating from the Tibet and the strengthening of the wave train propagating northeastward. This is consistent with earlier findings based on idealized orography (Cook and Held 1992) and realistic orography (Valdes and Hoskins 1991). In July, both the linear and nonlinear model responses to orography are rather weak and the difference is as strong as the linear and nonlinear model responses themselves. As pointed out in Ringler and Cook (1997), due to weak surface wind, the atmospheric response to orography may be weak, but highly nonlinear. The results in Fig. 10 confirm their speculation. Although nonlinearity modifies the linear response to orography significantly in both January and July, the contribution to total nonlinear effect by orography is relatively weak based on the comparison between Figs. 10c,f and Figs. 8a,c. Thus the direct nonlinear effect due to orography is not important in explaining the total nonlinear effect in Fig. 8.

\textbf{c. Nonlinear effect of transients}

Figure 11 shows the linear and nonlinear model responses to transient heat and momentum flux convergences, and the differences between the linear and nonlinear responses for January and July. Transients in this study are defined as the submonthly time scale eddy activities. In both January and July, the main responses are in the winter hemisphere where the stronger transient eddies are located. The general patterns of the responses to transients are very similar for the linear and nonlinear models. The main features are an intensification of the jet stream at the jet exit region and a weakening of the jet at the entrance region. This is particularly evident in January over the NH. The only nonlinear modification is the intensity change of the centers at various locations. By comparing Figs. 11c and 11f to the total nonlinear effect in Figs. 8a and 8c, the nonlinear effect of the transients forcing is rather weak.
Fig. 9. The streamfunction responses to global diabatic heating at $\sigma = 0.257$ based on (a), (d) the linear model, (b), (e) the nonlinear model, and (c), (f) the difference between the nonlinear and the linear model responses. The left panels are for Jan and the right panels for Jul. Contour interval is $5 \times 10^5$ m$^2$ s$^{-1}$ and negative values are shaded.

d. Other nonlinear effects

As shown in Eq. (5), there are four nonlinear interaction terms that contribute toward the total nonlinear effect in Fig. 8. If the process is completely linear, then the nonlinear interaction terms will be identically zero. Thus a nontrivial interaction term represents nonlinear interference between flows forced by different forcings. The contributions of each of the interaction terms are shown in Fig. 12 for January and July. The most important contributor to the total nonlinearity in Fig. 8 is the interaction between flows forced by orography and diabatic heating (Figs. 12a,e). In January (Fig. 12a), the nonlinear interference between heating and orography accounts for a very large fraction of the total nonlinearity in Fig. 8a. This is particularly true for the ridge centered at the west coast of North America, which is almost entirely due to the nonlinear interaction of flows forced by heating and orography. The nonlinear inter-
action between flows forced by heating and transients (Fig. 12b), and between those by orography and transients (Fig. 12c) are relatively insignificant, similar to the nonlinear effects of orography and transients. The three-way interaction term (Fig. 12d) is surprisingly large, considering the negligible effect of the interaction between flows forced by transients and another forcing, either orography or diabatic heating. As will be shown in section 5e, Fig. 12d is the dominant contributor toward the total effect of transients. The main effect of the three-way interaction term is a wavetrain pattern extending from East Asia to North America. In July (Fig. 12e), the nonlinear interaction between flows forced by heating and orography is of smaller magnitude than the nonlinear effect of diabatic heating (Fig. 9f) over Tibetan Plateau. The main effect of this nonlinear interaction is a slight northward shift of the Tibetan anticyclone. Over North America, however, the nonlinear interaction between flows forced by heating and orography is entirely responsible for the weak anticy-
clone center over the United States. This is consistent with earlier finding (Ting 1994) that stationary nonlinearity is the main forcing mechanism for the North American anticyclone in summer. The results here further point toward that the anticyclone is caused by the nonlinear interaction between flows forced by heating and orography, rather than the direct thermal forcing as is the case of the Tibetan anticyclone. All other nonlinear interaction terms are relatively weak compared to the interaction between flows due to heating and orography in July.

e. Nonlinear stationary wave maintenance

Given the above discussion on the importance of nonlinear effect, it is worthwhile to examine the nonlinear stationary wave maintenance as compared to that in the linear framework. The role of each forcing in maintaining the stationary waves from nonlinear perspective is much more complex than that in the linear framework. The complexity arises from the sophisticated nonlinear interactions of flow forced by one particular forcing with that by the rest of the forcings. Thus, there are different
ways to measure the importance of each individual forcing in maintaining the stationary waves in a nonlinear framework. For example, the role of orography can be obtained as the nonlinear response to orography, as shown in Figs. 10b and 10e, or as the difference of nonlinear responses to total stationary wave forcing with and without orography [Eq. (7)]. The advantage of the first approach is its easy comparison to the linear model results, whereas the advantage of the second approach is the inclusion of all possible effects of orography, that is, the nonlinear interaction between flows forced by orography and other forcings as well as the direct nonlinear response to orography. In the following, we will show the stationary wave maintenance in both ways.

Fig. 12. The zonally asymmetric streamfunction difference due to the nonlinear interaction between flows forced (a), (c) by diabatic heating and orography, (b), (f) by diabatic heating and transients, (c), (g) by orography and transients, and (d), (h) and by diabatic heating, orography, and transients at $\sigma = 0.257$ for Jan (left panels) and Jul (right panels). Contour interval is $5 \times 10^9$ m$^2$ s$^{-1}$ and negative values are shaded.
Figure 13 illustrates the zonal mean stationary wave amplitude as measured by the zonal root-mean-square of the streamfunction responses to global diabatic heating (Fig. 13a), orography (Fig. 13b), transients (Fig. 13c), and the nonlinear interaction terms due to interference between flows forced by heating and orography (Fig. 13d), heating and transients (Fig. 13e), orography and transients (Fig. 13f) and the three-way interaction term (Fig. 13g) at the upper level. Figure 13 can be compared to the corresponding linear model results in Fig. 5. In general, the nonlinear model results in Fig. 13 are showing a consistent picture as the linear model results in that the diabatic heating is the most dominant forcing throughout the seasonal cycle in the Tropics. The role of orography (Fig. 13b) is relatively weak in both the linear and the nonlinear cases. The significance of transients (Fig. 13c) is mainly in the winter hemisphere and stronger than that of the orography. The nonlinear interaction between flows forced by orography and heating (Fig. 13d) is significant in both winter and summer toward the stationary wave maintenance. It is the most dominant contributor in NH extratropics. The amplitudes of the nonlinear interactions between flows forced by heating and transients (Fig. 13e) and between those by orography and transients (Fig. 13f) are relatively weak. The contribution by the three-way interaction term is also not trivial in winter extratropics, as shown in Fig. 12d.

Figure 13b may indicate that orography is not an important forcing mechanism in maintaining the stationary waves in the NH extratropics. This is not entirely true, however, if one considers the nonlinear interaction between flows forced by orography and other forcings. To represent the effects of orography and other individual forcings in a more realistic way, Fig. 14 illustrates the zonal root-mean-square amplitude of the total effect of heating, orography, and transients as measured by the difference between nonlinear model responses to total stationary wave forcing with and without one particular forcing (Eq. 7). In another word, the amplitude for orography in Fig. 14b is obtained as the amplitude of the sum of nonlinear model response to orography (Fig. 13b), nonlinear interactions between flows forced by orography and heating (Fig. 13d), between those by orography and transients (Fig. 13f), and between those by orography, heating and transients (Fig. 13g). Although the tropical amplitude is again dominated by the effect of heating in Fig. 14a, the effect of orography (Fig. 14b) increased many times of the direct nonlinear model response to orography (Fig. 13b) in the NH winter extratropics. While the NH extratropical amplitude in Fig. 14a has increased due to the inclusion of nonlinear interaction between flows forced by heating and other forcings, the total effect of orography in Fig. 14b is comparable to the total effect of heating in NH extratropics. Although Fig. 13 gives the impression that transients is more important than orography, it is opposite in Fig. 14, where the effect of orography becomes more dominant. The comparison of Fig. 13b with Fig. 14b illustrates nicely that the dynamical forcing of the orography can be much stronger than the direct linear or nonlinear model responses to orography. It is more commonly speculated that the indirect effect of orography is mainly associated with its influence upon heating and transients. Our results show that the pure dynamical interaction among different forcings can be equally, if not more, important than the indirect thermal effect of the mountains, particularly in winter.

It is interesting to compare the spatial pattern of the direct nonlinear model response to one individual forcing to that of the total effect of that forcing. The total effects of diabatic heating, orography, and transients in January at the upper level are shown in Fig. 15. The total effect of orography (Fig. 15b) is the sum of the direct nonlinear response to orography (Fig. 10b) and the nonlinear interactions between flows forced by orography and other forcings (Figs. 12a,c,d). Clearly the total effect of orography is dominated by the nonlinear interaction between flows forced by diabatic heating and orography. The difference between Fig. 15b and the direct nonlinear model response to orography (Fig. 10b) is apparent. While the amplitude of the direct nonlinear model response to orography is almost negligible, the amplitude of the total effect of orography (Fig. 15b) is rather significant. This is particularly true over the PNA-Atlantic sector, where the amplitude of the orographic effect is slightly stronger than that of diabatic heating (Fig. 15a). In particular, the ridge centered at the northwestern coast of North America is largely due to the existence of the orography. Similarly, there are large differences between the direct nonlinear model response to transients (Fig. 11b) and the total effect of transients (Fig. 15c), especially in spatial structures. Figure 15c is the sum of the direct nonlinear model response to transients (Fig. 11b) and the nonlinear interactions between flows forced by transients and other forcings (Figs. 12b,c,d). The difference in spatial structure between Fig. 15c and Fig. 11b is mainly due to the three-way interaction term (Fig. 12d). While the direct nonlinear model response to transients has very little amplitude over the North American land areas, the effect of transients in Fig. 15c shows an anticyclone center over North America. This anticyclone, along with the low center over the Gulf of Alaska, and the low over the Southeast United States forms the familiar wavetrain pattern over the PNA that resembles the atmospheric response to El Niño (Held et al. 1989; Ting and Hoerling 1993; Hoerling and Ting 1994, among others). This consistency between the effect of transients in maintaining the climatological stationary waves and the role of transients in atmospheric response to El Niño supports the notion that storm track change during El Niño plays a central role in its impact on extratropical atmosphere (Held et al. 1989). The effect of diabatic heating (Fig. 15a), a dominant forcing mechanism in the tropical region, is similar to the direct nonlinear model response.
Fig. 13. Zonal root-mean-square streamfunction amplitude of the nonlinear model response to (a) diabatic heating, (b) orography, (c) transients, and the nonlinear interactions between flows forced by (d) orography and diabatic heating, (e) diabatic heating and transients, (f) orography and transients, and (g) diabatic heating, orography, and transients at $\sigma = 0.257$. Values greater than $5 \times 10^6$ m$^2$ s$^{-1}$ are shaded.
Fig. 14. Zonal root-mean-square streamfunction amplitude of the total effects of (a) diabatic heating, (b) orography, and (c) transients at \( \sigma = 0.257 \). Values greater than \( 5 \times 10^6 \text{m}^2\text{s}^{-1} \) are shaded.
to diabatic heating (Fig. 9b) in most regions except the NH extratropics. The difference is mainly due to the nonlinear interaction between flows forced by diabatic heating and orography (Fig. 12a).

Another way to view the importance of orography and transients is to compute spatial pattern correlations between the GCM stationary waves and the nonlinear model response without that particular forcing, such as shown in Fig. 16 for no-orography and no-transients cases. The pattern correlations are shown in Fig. 16 for global (Figs. 16a,d), NH (Figs. 16b,e), and SH (Figs. 16c,f) domains, respectively. When comparing Fig. 16 to the corresponding spatial pattern correlation between GCM stationary waves and the nonlinear model response to total forcing (Fig. 7), several conclusions can be drawn. First, the NH winter correlation is substantially reduced in the middle levels when there is no orography (Fig. 16b) or no transient (Fig. 16e) forcings. For the NH summer months (May–September), the spatial pattern correlation is substantially reduced in the middle levels when there is no orography or no transient forcings. For SH, the conclusions are somewhat different with regard to the role of orography. The spatial pattern correlation does not deteriorate much when there is no orography (Fig. 16c) compared to that with orography (Fig. 7c), consistent with Fig. 7d. It is not clear whether this result is a reflection of the insignificant role of orography in maintaining the SH stationary waves, or the limitation of the nonlinear model in simulating the SH stationary waves. On the other hand, when taking the transient forcing out, the spatial pattern correlation in SH reduces significantly in the midlevels (Fig. 16f), especially for SH cold months (May–September). Thus the role of transients in maintaining the stationary waves in SH seems to be consistent with that in NH. The global correlation is a combination of the results in NH and SH, showing a reduced correlation in northern winter months (November–February), but improved correlation for the transitional months due to SH contribution in the case of no-orography (Fig. 16a). In the case of no transients (Fig. 16d), there is a uniform reduction in spatial pattern correlation. It is thus clear that orography is very important for the maintenance of northern winter stationary waves in the NH, and transients is important for both northern winter and southern winter stationary wave maintenance.

6. Summary and discussion

In this study, we examined the nonlinear stationary wave maintenance using GFDL GCM outputs and a fully nonlinear stationary wave model combined with a linear stationary wave model. The main advantage of using the GCM output rather than observational analysis/reanalysis is the dynamical consistency between the GCM stationary waves and the stationary wave forcings. The method can be equally applied to the observational analysis/reanalysis provided that the observed stationary waves are dynamically consistent with their derived forcings. Linear modeling of the observed stationary waves using NCEP–NCAR reanalysis has been conducted earlier (Wang and Ting 1999). The novel aspect of the current study is the use of a nonlinear stationary wave model that can realistically simulate the GCM’s stationary waves. Thus the previous unanswered questions concerning the nature of stationary nonlinearity and the nonlinear stationary wave maintenance can be readily investigated using the nonlinear model.

The GFDL GCM simulates well the observed sta-
Fig. 16. Spatial pattern correlation between the GFDL GCM zonally asymmetric streamfunction and the nonlinear model responses to the total forcing without orography over (a) the global domain, (b) the NH domain, (c) the SH domain, and to the total forcing without transients over (d) the global domain, (e) the NH domain, and (f) the SH domain. Contour interval is 0.1 and values greater than 0.8 and less than 0.6 are dark and lightly shaded, respectively.

Stationary waves as represented by the NCEP–NCAR 52-yr reanalysis. The nonlinear model is found to reasonably reproduce the GCM stationary waves, especially for winter and summer months in both hemispheres. The only exception is in the SH during transitional months (March, April, October, and November) in the midtroposphere. The poor simulation in SH during the transitional months is due mainly to the presence of SH orographic forcing, for reasons not completely understood. Furthermore, the nonlinear model is found to reproduce very well the total stationary nonlinear effect in the GCM. While the linear model can only reveal the total effect of stationary nonlinearity in the GCM, the nonlinear model is capable of revealing in detail the...
nature of the stationary nonlinearity. Both the nonlinear effect of the diabatic heating and the nonlinear interaction between flows forced by orography and diabatic heating are found to be important for the stationary nonlinearity in northern winter and summer. The nonlinear interaction between flows forced by heating and orography in NH winter is the most important contributor to the total stationary nonlinearity in the GCM, particularly over the west coast of North America. The nonlinear interaction between flows forced by heating and orography is almost entirely responsible for the summer anticyclone over North America. The nonlinear effect of the diabatic heating and that of orography are consistent with earlier results of idealized nature (Cook and Held 1992; Valdes and Hoskins 1991; Ting and Held 1990). Although the nonlinear response to orography modifies the corresponding linear solution considerably, it has a relatively small contribution to the total stationary nonlinearity effect. The nonlinear response to transients is mainly to modify the amplitude of the linear responses to the transient forcing in the winter hemispheres.

A more realistic measure of the role of each forcing in maintaining the stationary waves is to examine the nonlinear model response to total stationary wave forcing with and without that particular forcing. For example, while the direct nonlinear model response to orography is small, the interaction between flows forced by orography and other forcings, diabatic heating in particular, renders the effect of orographic forcing comparable to that of diabatic heating in the NH extratropics during winter. This conclusion differs considerably from the picture we obtain by the direct nonlinear responses to individual forcings, where the role of orography is much weaker than that of diabatic heating in the extratropics in NH winter. Diabatic heating is the most dominant forcing mechanism in the tropics and the SH throughout the seasonal cycle, consistent with the linear model results. The effect of transients also shows interesting contrasts to the direct linear or nonlinear model response to transients. While the direct response to transients shows only a local response over the storm track region, the total effect of transients including nonlinear interactions shows a wave train over the Pacific/North American region that resembles the atmospheric response to El Niño. This finding reconciles the often puzzling picture of the completely different role played by transients in maintaining the climatological stationary waves and that in maintaining the anomalous stationary waves, such as during El Niño events. By examining the spatial pattern correlation, it is found that the inclusion of orography in the total stationary wave forcing improves significantly the pattern correlation in NH winter months. The role of orography, however, does not improve the spatial pattern correlation significantly in the SH. On the other hand, the inclusion of transient forcing improves pattern correlation for both hemispheres in their corresponding winter months.

The important role of the nonlinear interaction between flows forced by diabatic heating and orography can be understood in the following way. The direct linear model response reflects the effect of zonal mean surface wind blowing over the mountains and generating stationary waves. In the nonlinear model, the surface wind from the zonal mean climatological basic state as well as those induced by the orography itself are allowed to interact with the orography, thus the nonlinear effect of orography is taken into account. When the effect of diabatic heating is included in the nonlinear model, the flow interacting with orography is due to the zonal mean climatological flow, the flow forced by diabatic heating and that forced by orography. Thus the total flow interacting with orography is much stronger than in both the linear and the nonlinear orographic forcing cases. This is confirmed in Fig. 17, which shows the nonlinear model response to orography when the model basic state includes the zonal mean climatological flow plus the nonlinear model response to the sum of heating and transients in January. The similarity between Fig. 17 and Fig. 15b, which shows the total effect of orography including the nonlinear interaction between flow forced by orography and other forcings [Eq. (6)], indicates that the modification of flow around orography is indeed the mechanism for the nonlinear interaction between flows forced by orography and other forcings. Similarly, one can obtain Fig. 15c by solving the nonlinear model when it is subjected to the transient forcing superimposed on the basic state consisting of the zonal mean climatological flow and the nonlinear response to the sum of heating and orography (not shown). The important contribution in this case by the three-way interaction (Fig. 12d) indicates that the presence of both the heating- and orography-forced flows is important to realistically estimate the total effect of transients. In another word, if there were no orography, the effect of transients in maintaining both the climatological stationary waves and the anomalous stationary waves such as those during an El Niño would be different.

![Fig. 17. The nonlinear model streamfunction response to orography when the basic state consists of the zonal mean climatological flow plus the nonlinear model response to the sum of diabatic heating and transients at $\sigma = 0.257$. Contour interval is $5 \times 10^4$ m$^2$ s$^{-1}$ and negative values are shaded.](image-url)
Niño event would be very much different from the earth atmosphere, due to the lack of nonlinear interaction such as shown in Fig. 12d. This further emphasizes the effect of orography in maintaining not only the climatological stationary waves, but also the anomalous stationary waves, such as those during an El Niño event, in NH winter.

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