THE NONLINEAR RESPONSE IN A BAROCLINIC MODEL

TO STATIONARY FORCINGS

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In accordance with the NASA provisions for research grants, a brief summary of the entire project and a cumulative bibliography is provided herein.

The first project, Roads (1981a), dealt with Namias' hypothesis that anomalous snowcover on the eastern side of the North American continent can generate an anomalous inland high pressure system and an anomalous east coast low pressure system. A significant finding of this study was that the linear stationary response of a two-level primitive equation model was inadequate, by itself, to explain the time averaged anomalies found in an equivalent non-linear model. The reason for this was that the time-averaged anomalous eddy fluxes played an important role in damping the potentially large amplitudes produced by near-resonant responses of the model. The precise mechanisms by which damping by the eddy fluxes occurs will be investigated later after the approach to resonance in a variety of models has been documented.

To this goal, the second project (Roads, 1981b) was concerned with calculating the stationary responses to Northern Hemisphere orography in a hemispheric quasigeostrophic barotropic model in solid body rotation. First the stationary linear perturbation response to the orography was calculated. The stationary mountain torque induced by these perturbations was then used to construct graphical solutions to the steady-state, wave, mean-flow interaction problem. It was shown that multiple solutions existed in the system and were near either the forcing equilibrium of the zonal forcing or near the resonance points in the system. Some of these near resonance solutions had block-like configurations with a confluence zone upstream from a large-amplitude structure consisting of a high at high latitudes and a low at low latitudes. These block-like configurations were shown to be near stable solutions of the system. Time-dependent calculations showed that the initial state and the zonal forcing equilibrium were important for determining the long-term time evolution of the system.

The third project (Roads and Somerville, 1981c) was concerned with extending these hemispheric models, one with antisymmetric and one with symmetric equatorial boundary conditions to global models. The stationary solutions in the global model and the hemispheric models were found to be different because (1) the hemispheric models lacked either the symmetric or antisymmetric waves of the global model and (2) the resonant responses were much larger in the hemispheric models. Time dependent calculations with the global and hemispheric models were also performed in order to explain a result of Somerville (1980), who found that hemispheric models produced erroneous short-term forecasts of the ultra-long waves. We determined that one reason for these errors was because the initial spectrum of global waves could be erroneously aliased onto the spectrum of waves allowed in hemispheric models and the anomalously excited propagating Rossby waves could then destroy a short-term forecast in a hemispheric model in a matter of hours.

In the fourth project, Roads (1982a,b), the forced, linear, stationary wave response to diabatic heating and orography in multi-level models extending from the surface to 100 kms on a midlatitude beta-plane channel, was described. The inviscid response was strongly influenced by the location with respect to the resonance point. On the high side of the resonance point and for the external wave, where the high side refers to values of the zonal wind, wavenumber, etc., the geopotentials were high over the mountain and low 90° to the east of the diabatic heating. Similarly, on the high side of resonance the vertical motion was upward 90° to the west of the mountains and downward over the diabatic heating. These responses shifted by 180° on the low side of resonance. In the presence of Ekman friction, highs and lows were shifted westward as the parameters change from the high side of resonance to the low side of resonance. In the presence of Newtonian cooling, these quantities were shifted eastward as the parameters change from the high side of resonance to the low side of resonance. Although the horizontal phase responses were different for forcing by orogoraphy and diabatic heating, the vertical profiles were almost the same near the resonance point. Off resonance features in the diabatic heating profile occurred because of the additional forcing in the troposphere by diabatic heating but the differences were scarcely noticeable.

As shown by Roads (1982a), these forced, stationary external waves could interact with the zonal flow in a manner similar to that found in one- and two-level models. On the high side of resonance, solutions were unstable and the zonal wind profile changed until a stable state of the low-side of resonance was present. In models with realistic zonal wind and static stability profiles, additional modes occurred which were characterized by one or two nodes in the vertical. These modes had unstable interactions on both the high and low side of resonance. the instability process was similar to observed stratospheric warmings with the westerly zonal winds changing dramatically to easterlies in a few days and then slowly returning to westerlies with a lowered stratospheric jet.

In summary, these wave-zonal-flow interaction studies demonstrated that stratospheric warmings and blocking may be described by the same basic mechanisms although different results occurred for different horizontal scales.

The other part of the completed work was done in conjunction with G. K. Vallis at Scripps (Roads and Vallis, 1982a,b). Basically, we were interested in describing climatic responses that may be influenced by cloud feedbacks. As the first step in this research, a simple energy balance climate model was constructed in order to describe the influence of the surface boundary on low-level cloudiness. As shown in this work, the surface evaporation in conjunction with the surface temperature profile could strongly-influence the cloud field and lead to increasing cloudiness in high latitudes with incrasing temperature. Further work extended the cloud model to include more vertical levels and included an explicit calculation for cloud water (Roads et al, 1982). The effect of including cloud water was clearly seen only at upper levels. This turned out to be crucial for a sensitivity expreiment involving increased CO_2 loading. Increased CO_2 levels warmed the atmosphere and generally decreased upper level cloud water which caused a reduction in the cloud-greenhouse effect. This reduced the total warming, compared with a case in which cloud cover was fixed.

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(1) Roads, J. O., 1981a: Quasi-linear blocks forced by orography in a hemispheric, quasi-geostrophic barotropic model. Mon. Wea. Rev., 109, 1421-1437.

Stationary linear perturbation responses to Northern Hemisphere orography are calculated in a quasi-geostrophic barotropic model in solid-body rotation. The stationary mountain torque induced by these perturbations is then used to construct graphical solutions to the steady-state wave, mean-flow interaction problem. It is shown that multiple solutions exist in the system and are near either the forcing equilibrium of the zonal forcing or near the resonance points in the system. Some of these near-resonance solutions have blocklike configurations with a confluence zone upstream from a large-amplitude structure consisting of a high at high latitudes and a low at low latitudes. These blocklike configurations are shown to be near stable solutions of the system. Time-dependent calculations show that the initial state and the zonal forcing equilibrium are important in determining the long-term time evolutions of the system.

(2) Roads, J. O., 1981b: Linear and nonlinear aspects of snow-albedo feedbacks in atmospheric models. J. Geophys Res., 86, 7411-7424.

Namias' hypothesis, that anomalous snowcover on the eastern side of the North American continent can generate an anomalous east coast low pressure system and an anomalous inland high pressure system, is consistent with the time-averaged anomalous response from a nonlinear, primitive equation channel model with an idealized, flat land-sea arrangement. An attempt to understand and describe this anomalous response in the nonlinear model as a linear response to anomalous diabatic heating was largely unsuccessful, primarily because the anomalous eddy fluxes were also important. This unsuccessful attempt to describe the nonlinear model's time averages by linear theory then motivated several comparisons between linear and nonlinear severely truncated quasi-geostrophic models. It was also found in these models that the eddy fluxes were extremely important for forcing or dissipating the stationary eddies.

(3) Roads, J. O. and R. C. J. Somerville, 1982: Predictability of the ultra-long waves in hemispheric and global quasi-geostrophic models. J. Atmos. Sci., 39, 745-755.

A global quasi-geostrophic barotropic model, including orography, zonal forcing and frictional dissipation, is compared to two hemispheric models, one with antisymmetric equatorial boundary conditions and one with symmetric boundary conditions. The stationary solutions in the global model and the hemispheric models are found to be different, because the hemispheric models lack either the symmetric or antisymmetric waves, and because the nonlinear feedbacks are much larger in the hemispheric models. Time-dependent calculations show that the hemispheric models can excite anomalous Rossby waves and can produce erroneous short-range forecasts in middle latitudes. We conclude that global models are preferred for making both short-range and long-range forecasts for middle latitudes.

(4) Roads, J. O., 1982a: Stable and unstable near-resonant states in multilevel, severely truncated, quasi-geostrophic models. J. Atmos. Sci., 39, 203-224.

Stationary planetary waves are investigated with severely-truncated quasi-geostrophic models extending from the surface to 100 km. For a typical winter zonal-wind profile, it is shown that large amplitude or resonant planetary waves of intermediate zonal wavenumbers (~4 or 5) occur with an equivalent barotropic structure. In the presence of Ekman friction and Newtonian damping these stationary waves have associated with them a mountain torque and temperature transport which can influence the zonal flow. In time-dependent calculations it is shown that this wave-zonal flow interaction is stable to small perturbations on the low side of resonance and unstable on the high side of resonance. Here high and low refer to large and small values of the zonal wind.

Resonant zonal wavenumbers of lower wavenumber (~2 of 3) also occur for the same zonal profile and have a node in the vertical with a small amplitude maximum near the surface and a larger amplitude maximum in the stratosphere; still lower quasi-resonant wavenumbers also occur with two nodes in the vertical. These waves destabilize the wave-zonal flow interaction on both the high and low sides of the resonance peak. This instability depends upon the presence of the orography and the basic symmetric state as Newtonian damping and surface friction are sufficient to damp the baroclinic instability associated with a linear inviscid model.

(5) Roads, J. O. and G. K. Vallis, 1982a: An energy balance climate model with cloud feedbacks. (Submitted.)

A simple two-level global climate model based on the energy balance of the atmosphere and surface is described. The model includes physically based parameterizations for: (1) exchange of heat and moisture across latitude belts and between surface and atmosphere; (2) precipitation and cloud formation; and (3) solar and infrared radiation. Predicted model fields include surface and atmospheric temperature, precipitation, relative humidity and cloudiness. The effects of cloud cover are allowed to feed back into the radiation schemes. In low latitudes, the radiative parameterizations are such that the albedo effects of cloud cover are dominant; in high latitudes, the infrared properties and albedo effects are of equal importance.

Several model integrations are described. It is found that cloudiness is generally constant with changing temperature in low latitudes. In high latitudes cloudiness increases with increasing temperature but because of compensating feedbacks by the thermal and solar radiation, the cloud feedback effect on the radiation field is small. The net global feedback by the cloud field is negative but small.

(7) Roads, J. O., G. K. Vallis and L. Remer, 1982: Cloud/climate sensitivity experiments. Invited paper presented at Fourth Biennial Ewing Symposium. (To be published).

A study of the relationships between large-scale cloud fields and large-scale circulation patterns is presented. The basic tool is multi-level numerical model comprising conservation equations for temperature, water vapor and cloud water and appropriate parameterizations for evaporation, condensation, precipitation and radiative feedbacks. Incorporating an equation for cloud water in a large-scale model is somewhat novel and allows the formation and advection of clouds to be treated explicitly. The model is run on a two-dimensional, vertical-horizontal grid with constant winds. It is shown that cloud cover increases with decreased eddy vertical velocity, decreased horizontal advection, decreasee atmospheric temperature, increased surface temperature, and decreased precipitation efficieny. The cloud field is found to be well correlated with the relative humidity field except at the highest levels. When radiative feedbacks are incorporated and the temperature increased by increasing CO_2 content, cloud amounts decrease at upper-levels or equivalently cloud top height falls. This reduces the temperatue response, especially at upper levels, compared with an experiment in which cloud cover is fixed.