Proc. Indian Acad. Sci. (Earth Planet. Sci.), Vol. 104, No. 4, December 1995, pp. 579–606.

Sensitivity of the tropical nonlinear stationary Kelvin and Rossby waves to the vertical structure of heating

R KRISHNAN and S V KASTURE*

National Centre for Medium Range Weather Forecasting, New Delhi 110003, India
*Theoretical Physics Division, Physical Research Laboratory, Ahmedabad 380009, India

MS received 12 October 1994; revised 27 September 1995

Abstract. Idealized experiments using linear (LM) and nonlinear (NM) multilevel global spectral models have been carried out to investigate and understand the impact of nonlinearities on the stationary wave response in the tropical atmosphere and its sensitivity to the vertical profile of heating. It is found that nonlinearities exert a dominant influence on the low-latitude stationary Kelvin and Rossby waves particularly in the vicinity of the forcing region. Our study shows that nonlinear effects on the upper tropospheric response produce prominent eastward displacement of the anticyclonic vorticity and horizontal shifts of the maximum equilibrium divergence relative to the prescribed heating. These changes due to nonlinear terms are found to be quite sensitive to the vertical structure of diabatic heating. The strongest nonlinear effects are found to occur when the vertical level under consideration is strongly forced from below. Detailed vorticity budget calculations indicate that stronger nonlinear contributions from stretching and horizontal advection of relative vorticity favour the generation of upper tropospheric anticyclonic circulation and its eastward displacement. Larger vertical advection and twisting terms appear to oppose the generation of upper tropospheric anticyclonic vorticity. It is found that the nonlinear terms which affect the vorticity generation in the upper levels are crucially controlled by the vertical profile of heating.

The mid-tropospheric response due to deep convective heating in the NM is characterized by anomalous equatorial westerlies in the low-latitude Rossby regime and exhibits prominent ageostrophic motions. Such nonlinear effects appear probably because of a vertical shift of the low level circulation anomalies in the NM. In the case of shallow convective heating the occurrence of anomalous zonal flows and ageostrophic motions in the low latitude regions of the NM takes place near the level of the maximum heating. Our study shows that large heating amplitudes and small vertical gradient of heating at a given vertical level together favour generation of anomalous zonal flows and ageostrophic motions in the near equatorial regions. These anomalous basic flows in the low-latitudes have implications on the propagation of transients from the tropics to midlatitudes. Non-linear effects on the lower tropospheric stationary waves are prominently seen in the case of strong low level heating which produces a large strengthening of the lower tropospheric cyclonic anomalies that exhibit distinct eastward shifts in the NM relative to the LM.

Keywords. Vorticity; advection; stretching; ageostrophic.

1. Introduction

It is well known that the tropical atmosphere is characterized by a strong zonally asymmetric distribution of diabatic heating. Observational findings by Ramage (1968) and Krueger and Winston (1974) reveal that deep convective heating occurs predominantly over three zones in the tropics located over South America, equatorial Africa and the 'maritime' continent of Indonesia. It is the longitudinal variation in the distribution of heat sources and sinks that drives the planetary scale circulations in the tropical atmosphere. Matsuno (1966) for the first time obtained the various normal modes of the tropical atmosphere using a shallow water system of equations on an equatorial β-plane. Gill (1980), in his pioneering work, calculated the stationary wave response induced by an isolated tropical heat source using a linear shallow water anomaly model. He examined the anomalous stationary wave response, for a single vertical baroclinic mode, forced by idealized tropical atmospheric heating. His solutions elegantly explained the planetary scale circulation anomalies in terms of the stationary Kelvin and Rossby waves. In a subsequent study, Phlips and Gill (1987) pointed out that the zonal scale of the forced equatorial waves was essentially controlled by the linear dissipation term which was a tunable parameter in their model. They showed that when a weak damping was used in the model the stationary Kelvin and Rossby waves had a greater zonal extent. But in the presence of strong dissipation these stationary waves were localized near the forcing region.

1.1 *Linear and nonlinear stationary wave response*

The dynamics of large scale motions in the tropics can be studied as a problem of determining the wave response induced by tropical diabatic heating. Theoretical studies by Matsuno (1966), Webster (1972), Gill (1980), Simmons (1982) and many others have greatly contributed towards our present understanding of the equatorial wave dynamics and the nature of thermally forced response in the tropical atmosphere. The studies of Webster (1972) and Gill (1980) were essentially based on linearized calculations. The main shortcoming in Gill's model, was the use of strong Rayleigh friction and Newtonian cooling terms which had an e-folding decay time of about 2·5 days. Apparently the physical processes which can have such strong damping time-scales are still not clearly understood. Simmons (1982) examined both linear and nonlinear responses but his solutions were constrained by the climatological basic state. There are a few important studies that have addressed the role of nonlinear terms on the forced tropical motions. Hendon (1986) investigated the nonlinear time-mean response forced by an idealized heat source, of varying strengths, using a 2-level model. He used a damping term having a decay time-scale of 5 days only at the bottom level of the model. He found that the upper level anticyclones in the nonlinear response were displaced eastward when the forcing amplitude was strong. Van Tuyl (1986) studied the linear and nonlinear stationary responses of the tropical atmosphere by considering various cases of mass forcings. He found that the nonlinear effects were significant only when the zonally symmetric forcing was added to the wave-like component. He observed strong zonal flows near the equatorial region which resulted from wave-mean flow interactions. Studies by Sardeshmukh and Held (1984), Sardeshmukh and Hoskins (1985) and Hendon (1986) indicate that nonlinear dynamics play a crucial role in determining the observed time-mean vorticity balance in the tropical upper troposphere.

1.2 *Motivation*

There is still considerable potential and justification for understanding the role of nonlinear dynamics on the thermally forced flows in the tropical atmosphere. A preliminary scale