12B.1 ON THE STRUCTURES AND ENERGETICS OF LARGE-SCALE CONVECTIVELY COUPLED GRAVITY WAVES: A NORMAL MODE PERSPECTIVE

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1. INTRODUCTION

The origin and dynamics of convectively coupled equatorial waves are currently not well understood. To address this problem, we perform a normal mode analysis of large-scale [O(1000 km)] convectively coupled gravity waves simulated using a two-dimensional (2D) cloud resolving model (CRM). Specific research questions to be addressed are as follows:

Question 1: Which vertical normal modes appear most prominently in the simulated wave's dynamical structures, and what are the phase relationships between these modes?

Question 2: What are the relative roles of deep convective, shallow convective, and stratiform heating processes in maintaining the energy in these modes?

Answers to these questions provide a basis for assessing theories of coupled wave instability, including wave-CISK and the stratiform instability theory of Mapes (2000).

2. SIMULATION OVERVIEW

We use the CRM of Khairoutdinov and Randall (2003) to conduct a 15-day simulation of radiative convective equilibrium in a large-scale, 2D domain extending 8192 km in the horizontal with a spatially uniform SST and a spatially uniform radiative cooling profile. To eliminate possible interactions between convection and a domain-averaged mean flow, the horizontal winds at each grid point are uniformly relaxed to zero on a four-hour time scale. The effects of planetary rotation are not considered.

Results of the simulation reveal the "spontaneous" development of two large-scale convectively gravity waves (not shown). The waves propagate to the right at phase speeds of about 16 m s^{-1}, and are composed of smaller-scale cloud clusters that propagate to the left. As with previous CRM work by Grabowski and Moncrieff (2001), we find that the structures and phase speed of the simulated waves strongly resemble observations of convectively coupled Kelvin waves (e.g. ,Straub and Kiladis 2002). Temperature anomalies associated with the waves exhibit a cold "boomerang"-like structure, with the elbow of the boomerang located in the upper troposphere. Convection associated with the waves is strongest when air is anomalously cool in the lower troposphere, anomalously warm in the middle troposphere, and anomalously cool at the level of the tropopause.

3. NORMAL MODE ANALYSIS

The simulation is analyzed by projecting model output onto the normal modes of the model's base state atmosphere, calculated using the algorithm of Fulton and Schubert (1985). Results show that the boomerang-like structure of the waves can be regarded as the superposition of two bands of normal modes: a band of slow modes with phase speeds in the range16-18 m s^{-1} and a band of fast modes with phase speeds in the range 35-45 m s^{-1}. Convection associated with the waves is in phase with geopotential anomalies of the slow modes, and in quadrature with those of the fast modes (see Fig. 1).

These phase relationships, as well as the phase speed of the simulated waves (close to that of the slow modes), broadly support the stratiform instability theory of Mapes (2000). Here, however, the large-scale waves arise through an unstable interaction between convection and modes with phase speeds in the range 16-18 m s^{-1}, rather than 23-25 m s^{-1}. Also, as demonstrated in Fig. 2b, deep convective heating processes, as well as stratiform heating processes, play an important role in maintaining the energy of the slow modes. Shallow convective heating processes strongly remove energy from these modes, consistent with Mapes' model.

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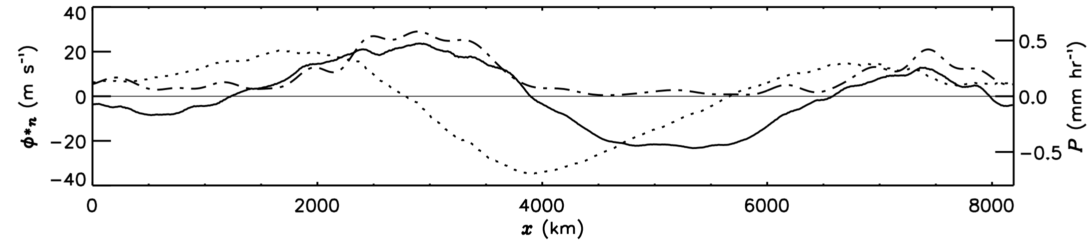

Figure 1. Zonal distributions of the surface precipitation rate (dot-dashed), geopotential anomalies of the fast modes (dotted), and geopotential anomalies of the slow modes (solid), averaged in a reference frame moving with the large-scale waves at 16 m s^{-1}. Note: geopotential anomalies have been normalized by their respective phase speeds (i.e., $\phi^*_n \equiv \phi_n / c_n$).

4. IMPLICATIONS

A current challenge in numerical climate prediction is to improve atmospheric GCMs so that they more realistically simulate tropical variability. Our results suggest that in order to meet this challenge cloud parameterizations must accurately represent microphysical processes within stratiform anvil clouds, as well as cumulus clouds. They also suggest that closure algorithms of cloud parameterizations must be sophisticated enough to capture the strong sensitivity of convective cloud ensembles to thermodynamic forcing by higher-order vertical normal modes. In Mapes' (2000) model, this strong sensitivity is predicted to occur whenever variations in convection are primarily regulated by variations in CIN. Most state-of-the-art closure algorithms, however, neglect the role of convective initiation processes in regulating convection amount, suggesting a possible avenue for their improvement.

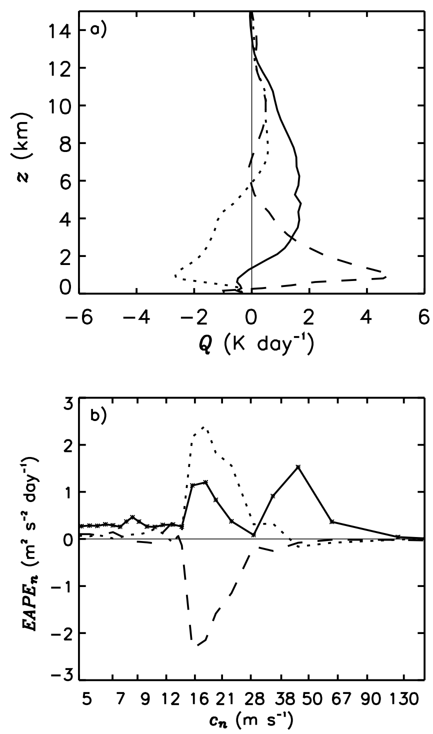

Figure 2. Domain- and time-averaged convective heating profiles (a) and energy production spectra (b) in deep convective (solid), stratiform (dotted), and shallow convective (dashed) regions of the simulation.

5. REFERENCES

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