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STRATIFORM CLOUDS AND THEIR INTERACTION WITH ATMOSPHERIC MOTIONS

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During the 1987-1988 academic year, we have finished three projects and we have made plans to redirect and focus our work in a proposal now being reviewed. The completed work involves study of waves on an equatorial beta-plane in shear flow, investigation of the influence of orography on the index cycle, and analysis of a model of cloud street development in a thermally-forced, sheared environment. Our proposed work involves study of boundary layer circulations supporting stratocumulus decks and investigation of how the radiative effects of these clouds modulate larger-scale flows such as those associated with the index oscillation.

Significant Accomplishments in the Past Year

1. Waves on an Equatorial Beta-Plane

The equatorial region of the oceans and atmosphere has been shown to support a variety of large-scale wave-like oscillations that are unique to this region of the globe. These waves have been shown to play important roles in such **in situ** phenomena as the Walker - El Niño circulation and the 50-day oscillation. In addition, these waves are critical in setting up so-called teleconnection patterns between the tropics and mid- and high-latitudes (Horel and Wallace, 1981). Thus, these waves, although confined to the tropics, are important in the general circulation of the atmosphere.

Numerous studies have been carried out to determine the linear structure of these oscillations in shallow water models assuming motionless background states or allowing for background winds that vary linearly with latitude (Matsuno, 1966; Bennet and Young, 1971; Lindzen, 1971). The problem with these studies is that the background flow used was highly idealized and thus was unrepresentative of the observed profile of the zonally-averaged east-west flow in most seasons. We (Aberson and Clark) have extended the above studies by allowing for much more representative background wind profiles (Aberson, 1987). One purpose of this work was to determine whether the generic Kelvin and mixed Rossby-gravity wave structures determined with the simpler zonal wind profiles still more or less remained intact in the more realistic background atmospheres. Furthermore, we sought new equatorially-trapped wave structures that could only be supported with the more realistic wind profiles. Possibly these structures could have some relevance to observed equatorial large-scale dynamical phenomena.

The profiles that we used were hyperbolic tangent and Gaussian functions for U(y), where y is north-south distance from the equator. These profiles turned out to be quite accurate representations of actual winds in certain sectors of the tropics. A broad spectrum of eigenmodes resulted from our numerical solution to the stability problem. A radiation condition was imposed as y approached $\pm$ infinity. Some of these waves were slightly modified versions of the Kelvin and mixed Rossby-gravity waves of earlier studies. A variety of new wave structures was found, however, that was unique to the background wind profile used. Some, we argued, could be discarded since they were highly sensitive to the details of U(y) or would be rapidly dissipated by friction if it were present. Others, however, could be meteorologically significant. For example, with the hyperbolic tangent wind profile with westerlies (easterlies) in the northern (southern) hemisphere and as the magnitude of U approached 10 m s^{-1} as the magnitude of y approached infinity, a disturbance that slowly propagated westward with a critical latitude near 10 degrees was found. It was mainly confined to the southern hemisphere and was slightly unstable with an e-folding time of about one month. It is very similar to the wavenumber-two structure observed by Hirota (1976) and could play an important role in driving the easterly phase of the semi-annual oscillation. With the westerly Gaussian wind profile centered at the equator, an eastward propagating mode with two amplitude maxima near critical latitudes on either side of the equator occurred. We speculate that it could be important to the Walker circulation and might also resemble some of the teleconnection patterns observed by Horel and Wallace (1981).

2. The Influence of Orography on Index Cycles

It has been shown by Lindzen et al. (1982) that index-like oscillations can occur in the atmosphere because of destructive and constructive interference between traveling free waves and topographically forced stationary waves. We (Clark and Wilson) reasoned that in a realistic atmosphere where baroclinic and barotropic instability, in addition to nonlinear wave-wave and wave-mean flow interactions can occur, it is not at all obvious that the linear Lindzen mechanism could still prevail to drive an index oscillation. We chose to use a quasigeostrophic two-layer spectral model to address the general question of what role the orography has in precipitating and fostering low frequency oscillations in eddy as well as zonally-averaged energies. A synoptic, as well as a planetary, scale disturbance was represented in the model and a Newtonian approximation to radiative driving was included. Runs of 200 and 300 days were carried out with and without orography.

Very little variance in the 20- to 30-day periodicity range was found when topography was excluded. Rather, sharp spikes in the spectrum at 7 and 10 day periods were observed. The former was due to a cyclical baroclinic exchange of energy between the synoptic-scale wave and mean flow. The latter was due to the Lindzen mechanism, that is, interference between the forced stationary wave and the traveling planetary scale wave. The problem here was that the latter mechanism did not produce slower index-like oscillations. Introduction of topography into the model broadened the energy spectrum considerably and, most significantly, introduced a peak in the variance spectrum at a period near 25 days. This peak, however, was not caused by the Lindzen wave interference mechanism. Rather, the process of form-drag instability proposed by Charney and DeVore (1979) seemed to cause the periodic, mainly barotropic, exchange of kinetic energy between the planetary wave and the mean flow. We find that, although the mechanism is not yet entirely understood, the planetary wave periodically becomes almost stationary and subsequently grows by form-drag instability. Its energy is then transferred barotropically to the mean flow. This numerical result may confirm the observations by us (Clark and Schlaak, 1988) concerning the primarily barotropic nature of the observed wintertime well-defined index oscillation of 1974/1975.

3. Cloud Street Development from Dynamic and Thermal Instabilities

At least three fundamental mechanisms leading to the development of boundary layer rolls have been proposed. The inflection point and parallel instabilities are the two dominant dynamic mechanisms and the Rayleigh-Bénard instability is the primary thermal mechanism. Under NASA sponsorship, for the past several years we have been developing nonlinear boundary layer models capable of accepting observed data in order to determine for particular atmospheric cases the mechanisms underlying roll development. We have recently published (Stensrud and Shirer, 1988) a study of the circulations developing from the inflection point instability. Hirschberg (1988), in a thesis to be completed in August 1988, has extended their model to the case of linearly varying thermal stratification. Finally, in a study sponsored by the Air Force, we are extending the Hirschberg model to the case of an arbitrarily varying stratification, with an emphasis on the influence of inversions.

In all these spectral models, the background profiles of wind or temperature are represented via their lowest order Fourier coefficients. Analysis of the stability properties of the solutions to these models allows identification of the possible modes leading to secondary circulations in the boundary layer. Preferred values of both the horizontal spacing and the orientation of the rolls are determined via the standard method of minimizing the critical values of the dynamic and thermodynamic forcing parameters. In addition, the expected values of the frequencies of the periodic solutions are determined. Hirschberg (1988) compared her model results against observations taken during the West German KonTur experiment. In two cases, when the roll circulations extended significantly into an inversion layer, her model revealed that the roll circulations were likely given by a new mode, the shear mode, that she had identified. The expected roll orientation and critical forcing values were modeled very well, but the expected street spacing and propagation rates were poorly represented. We have hypothesized that these poor results are related to the fact that the background temperature gradient is constant, and so we are now testing this hypothesis in a model with a more general background temperature profile so that the effects of the inversion can be included.

Proposed Work

1. The Index Oscillation

Our continuing study of the index oscillation will concentrate on two aspects that we consider crucial in understanding its strength and longevity, especially during the northern hemisphere winter. They are:

- the role of orographic forcing in establishing as well as maintaining the hemispheric oscillation, and
- the role of mid- and high-latitude radiative heating as modulated by periodically changing cloud cover in maintaining the oscillation against dissipative mechanisms.

Charney and Strauss (1980) demonstrated that wave-like topography in a two-layer quasigeostrophic atmosphere could stimulate growth of stationary disturbances by inducing them to tilt vertically such that they can tap the available potential energy associated with the sheared background flow. The instability occurs once the vertical shear, driven by a north-south gradient of heating, exceeds the value for which a free Rossby wave first becomes stationary (there is no mean flow in the lower layer).

Our first order of business will be to determine whether the above mechanisms can work in a simple nonlinear two-layer spectral model on a mid-latitude beta-plane to give a long-term periodicity like the index oscillation. We will also use the hemispheric spectral model to investigate in detail the mechanisms of the low-frequency oscillation noted above. Furthermore, we will introduce simple parameterizations of stratocumulus development and dissipation and the ensuing modulations of radiative heating based on our study of FIRE and global ERB data to assess diabatic feedbacks on the dynamically-driven cycle.

We have observed that stratocumulus over mid- and high-latitudes respond to periodic incursions of warm air associated with the zonal index oscillation in such a way as to modulate the field of infrared cooling. Our preliminary conclusion as to the implications of this cooling is that it reinforces the dynamically-driven oscillation. We wish to gather satellite radiance as well as conventional data for at least three years in order to more closely investigate this possibly important mechanism for coupling cloudiness with low-frequency oscillations in the atmosphere.

2. Stratocumulus Modeling

Cloud streets are one manifestation of stratocumulus decks that exist in the upper portions of the secondary circulations in the boundary layer. However, the mechanism by which these decks break up into streets remains uncertain. It is important to understand this mechanism, because, as noted in the previous section, the areal coverage of the stratocumulus deck plays an important role in modulating the index oscillation through the influence of the clouds on the large-scale radiative heat budget. Thus, we seek a detailed understanding of the dynamics of these boundary layer circulations in order to provide crucial information for modeling the structure and response of large-scale flows.

In order to provide a dataset for the study of the structure and break up of marine stratocumulus, a coordinated series of ground-based, aircraft, and satellite observations was conducted last summer west of San Diego, CA. NASA was the lead agency for this experiment, which was part of FIRE (First International Cloud Climatology Project Regional Experiment). One of us (Shirer) participated in this experiment as an observer on the NCAR Electra; indeed the data measured on this aircraft are being analyzed at Penn State. It was apparent that a common feature of marine stratocumulus is the existence of a cumulus layer below the stratocumulus. At times, these cumulus clouds penetrated into the stratocumulus deck, which coincided with the occurrence of breaks in the overcast. We propose to investigate whether the break up process may be in part dynamically caused by the coupling of the subcloud and cloud layers. We will extend a model presently being developed under the sponsorship of NSF; an early version is summarized in Laufersweiler and Shirer (1988). This new model will contain representations of net radiative heating, latent heating in two cloud layers, and arbitrary background temperature and wind profiles. We will determine the expected roll circulation spacing and orientation, and we will calculate the associated vertical transports of heat and momentum. We will attempt to identify those large-scale conditions under which stratocumulus will break up, and we will compare our results with the observations taken during FIRE.

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