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STRATIFORM CLOUDS AND THEIR INTERACTION WITH ATMOSPHERIC MOTION

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During 1989 and 1990, we have seen the publication of two papers and the submission of a third for review on work supported primarily by the previous contract, NAS8-36150; the delivery of an invited talk at the SIAM Conference on Dynamical Systems in Orlando, Florida; and the start of two new projects on the radiative effects of stratocumulus on the large-scale flow. The published papers discuss aspects of stratocumulus circulations (Laufersweiler and Shirer, 1989) and the Hadley to Rossby regime transition in rotating spherical systems (Higgins and Shirer, 1990). The submitted paper (Haack and Shirer, 1990) discusses a new nonlinear model of roll circulations that are forced both dynamically and thermally. The invited paper by H.N. Shirer and R. Wells presented an objective means for determining appropriate truncation levels for low-order models of flows involving two incommensurate periods; this work has application to the Hadley to Rossby transition problem in quasi-geostrophic flows (Moroz and Holmes, 1984). The new projects involve the development of a multi-layered quasi-geostrophic channel model for study of the modulation of the large-scale flow by stratocumulus clouds that typically develop off the coasts of continents. In this model the diabatic forcing in the lowest layer will change in response to the (parameterized) development of extensive fields of stratocumulus clouds. To guide creation of this parameterization scheme, we are producing climatologies of stratocumulus frequency and we will correlate these frequencies with the phasing and amplitude of the large-scale flow pattern. We discuss the above topics in greater detail below.

SIGNIFICANT ACCOMPLISHMENTS IN THE PAST YEAR AND FOCUS OF CURRENT RESEARCH

1. A Low-Order Model of Stratocumulus Circulations

Laufersweiler and Shirer (1989) present a new model of stratocumulus circulations. Latent heating effects are parameterized via the no-entrainment assumption, in which upward motions below cloud base are assumed to be dry adiabatic, while upward and downward motions above cloud base are assumed to be moist adiabatic. A stability analysis of the motionless solution shows that there is a preferred mode for which a horizontal wavenumber selection criterion leads to activation of two additional latent heating terms in the moist spectral model. Examination of the resulting convective solutions reveals that the associated patterns are asymmetric: the downdrafts are horizontally narrower and more intense than the updrafts. Evidence that such circulation patterns characterize marine stratocumulus-topped boundary layers has been given by Nicholls (1988). We will use the results from this model and two new ones under development to guide our study of stratocumulus cloud interactions with the large-scale flow.

2. Transitions from Hadley to Rossby Flows

A highly idealized, nonlinear, vertically continuous, rotating, spherical model of global-scale flow is investigated by Higgins and Shirer (1990) to study the transitions from two-dimensional steady Hadley flows to three-dimensional, temporally periodic Rossby flows. Although this subject has been thoroughly covered in channel and cylindrical systems, it has not been addressed very much in spherical ones. The forcing values for the Hadley to Rossby transition are found to be satisfactorily approximated by the low-order system and agree well with those given by the higher resolution model of Henderson (1982). The most significant transitional behavior that differed from that seen in rotating annuli is that the upper Hadley transition curve is not found in the rotating spherical one. This result agrees with that of Henderson (1982) as well as with that of Miller and Fehribach (1990). In addition, they show that the heating rates for the regime transition curves are realistic only when an effective eddy viscosity, whose use was originally proposed by Dutton (1982), is used to represent the sub-Hadley scale dissipation rates. These ideas will be applied in the analysis performed during our current study.

3. Dynamically and Thermally Forced Roll Vortices

Boundary layer rolls can draw their energy from both the background wind shear and surface heat fluxes. With NASA support we have been developing a series of models (Shirer, 1980, 1986; Stensrud and Shirer, 1988) of these roll circulations; the fourth in the series (Haack and Shirer, 1990) is the first to combine both the dynamic and the thermal mechanisms into one model in order to obtain a more complete description of the possible mode transitions. Three types of modes are found, two dynamic and one thermal. The most significant nonlinear effect that they identify involves the modifications of the background wind and temperature profiles by the rolls. The rolls transport heat vertically so as to bring the boundary layer toward neutral stratification, while momentum is transported vertically so as to add constant shear ($\partial U/\partial z = k$) to the background cross-roll wind profile $U(z)$. Such shear must be removed from observed wind profiles before they can be used to study the dynamical forcing of the roll modes. The manuscript is currently being revised for resubmission this fall.

4. Transitions to Quasi-Periodic Flows

Transitions within the Rossby regime are characterized by vacillation involving flows of two different horizontal wavenumbers. These vacillating flows are found for parameter values near the curves bounding the regions of single-wavenumber, propagating Rossby waves. Moroz and Holmes (1984) explain the onset of this vacillatory behavior as a bifurcation from a temporally periodic Rossby wave to a quasi-periodic one. Such bifurcations can be identified by analysis of the stability of the steady Hadley solution and the identification of double Hopf bifurcation points from which two different temporally periodic Rossby wave solutions emanate. Choosing an appropriate truncation level for a model capable of capturing this type of bifurcation requires an objective procedure. H.N. Shirer and R. Wells are working on such a procedure, which follows one proposed by Kloeden (1986). Preliminary results based on study of rotating convection were presented by H.N. Shirer in an invited paper delivered at the SIAM Conference on Dynamical Systems in May 1990. In this problem, certain spectral coefficients are found to be crucial for properly describing the branching behavior, while others are much less important. The techniques developed in this study will have eventual application to the choice of truncation level for the quasi-geostrophic channel model that is currently being developed.

5. Stratocumulus Modulated Quasi-Geostrophic Flow

Development of a new multi-layered, three-dimensional, quasi-geostrophic channel model of flow responding to the development of stratocumulus clouds in the lowest layer has begun; this is the project for MS student Barbara J. Kratz. Initially the model will have four layers, one for the boundary layer, two for the troposphere and one for the stratosphere (Fig. 1). In the horizontal, half of the domain will be over a continent and half over an ocean. The three-dimensional quasi-geostrophic potential vorticity equation will be integrated in time in the inner layers to give values of potential vorticity $\nabla_H^2\psi + R\partial^2\psi/\partial z^2$, where ψ is the quasi-geostrophic stream function, z is height, and R is a constant. The thermodynamic equation will be integrated

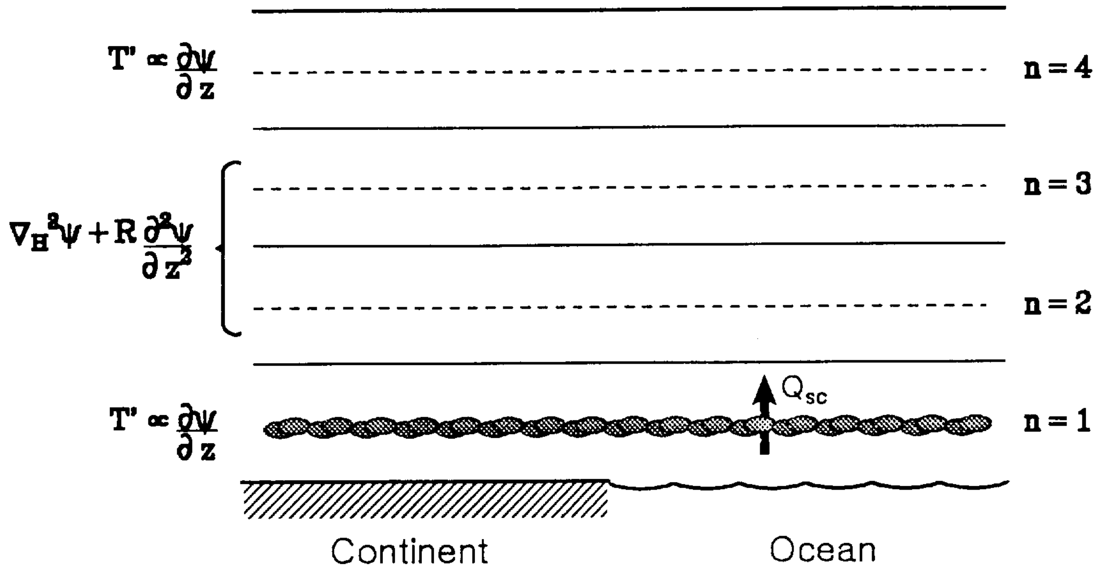

Fig. 1. Cross section of the domain for the model of stratocumulus-modulated quasi-geostrophic flow. The variables that are predicted at each time step before application of the Lindzen and Kuo (1969) scheme are noted by each layer.

in the lowest and highest layers to give values for $\partial\psi/\partial z$. In the bottom layer, this equation will contain a diabatic heating term representing the radiative forcing by a field of stratocumulus clouds. Inclusion of such forcing is motivated by the results of Clark and Schlaak (1988), whose observations demonstrated a link between the index oscillation and the formation of stratocumulus clouds at high latitudes. A truncated spectral expansion based on that used by Vickroy and Dutton (1979) will describe the horizontal variations within all four layers of the new model, while finite differences will represent the vertical coupling between the layers. At each time step, the numerical technique of Lindzen and Kuo (1969) will be utilized to obtain values of ψ in each layer. These values will be found from the values of $\partial\psi/\partial z$ and the interior potential vorticity, which as noted above will be determined from the thermodynamic equation in the bottom and top layers and the potential vorticity equation in the inner layers. The effects of stratocumulus clouds will be parameterized by linking the form of the diabatic forcing term in the lowest layer to the flow pattern given by ψ in all of the layers. In the first year of the grant, we have concentrated on developing the model code for each layer and on preliminary examination and implementation of the vertical coupling routine.

6. Stratocumulus Cloud Climatology

We have begun study of the spatial patterns of stratocumulus cloud frequency for the continental United States and the nearby oceans. An undergraduate student, Charles Pavloski, is developing the necessary numerical codes for accessing the ten-year database of surface and upper air data that we have archived on our departmental computer system. An example of the stratocumulus frequency for April 1990 is given in Fig. 2. Only those stations reporting at least 75% of the time were included in this figure. Maxima along the northeast Atlantic coast, as well as along the northwest and southwest Pacific coasts and the Texas coast, are clearly seen. Minima occur off the southeast Atlantic coast and over the desert southwest of the United States. These climatologies, once correlated with the flow aloft, will provide the basis for the stratocumulus parameterization to be used in the new quasi-geostrophic model.

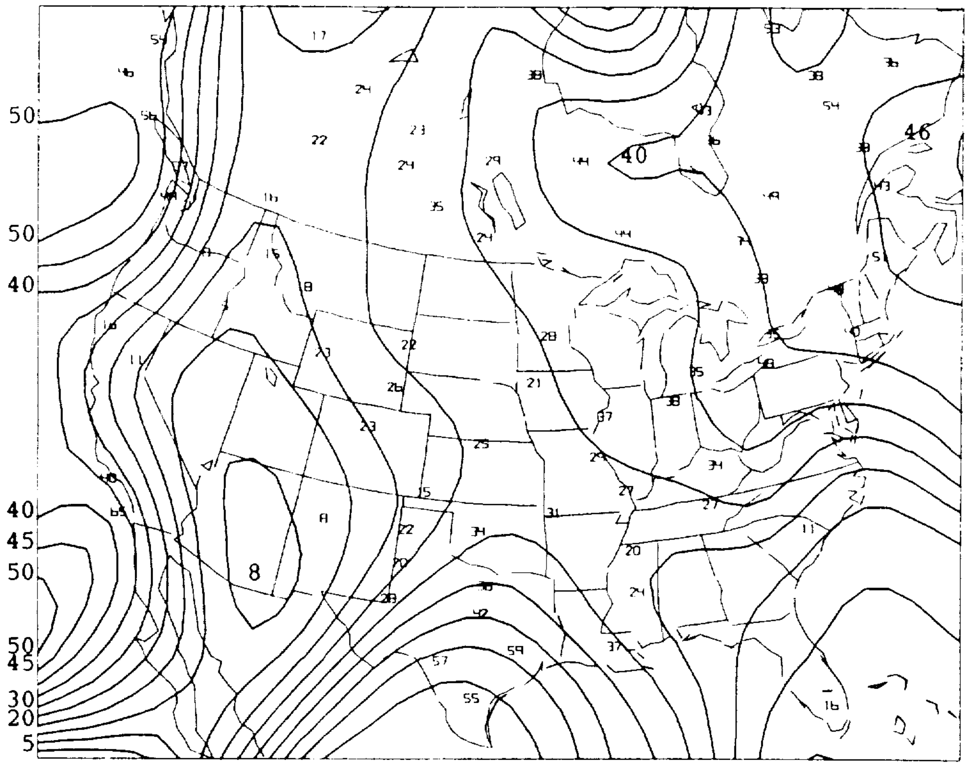

Fig. 2. Observed stratocumulus frequency for April 1990. A station must have reported at least 75% of the time for its data to be included in the analysis.

PLANS FOR NEXT YEAR

1. Stratocumulus Modulated Quasi-Geostrophic Flow

During the next year we will continue developing and testing the numerical algorithms in the new quasi-geostrophic channel model. Once these algorithms work, we will determine the forcing parameter values for the onset of nonlinear Rossby waves and we will determine the horizontal and vertical structures of these waves. Both surface-based and internal diabatic forcing effects will be considered and the results compared with those of previous studies. Based on the results of the stratocumulus climatology project, we will develop a parameterization of the radiative forcing by the stratocumulus. We envision basing this parameterization on the flow pattern near the coast of the continent. For example, in the winter, stratocumulus clouds are expected off the east coast during episodes of low-level cold advection, as evidenced by inspection of satellite pictures. Northwesterly flow aloft is usually associated with cold advection at the surface that produces stratocumulus clouds over the warmer oceans near the east coast of a continent, while the formation of these clouds typically leads to additional radiative cooling of the troposphere from below. Thus, when the model solutions exhibit northwesterly flow, a simple parameterization would produce diabatic cooling in the lowest layer over the western oceanic portion of the domain. Once this parameterization is developed, it will be incorporated into the model and the behavior and sensitivity of the solutions will be examined, with emphasis given to whether or not certain regimes of flow are favored when the stratocumulus modulation is included.

2. Stratocumulus Cloud Climatology

Work on developing the stratocumulus cloud climatology will continue, with emphasis given to associating several-day-long maxima and minima over the oceans with the average flow aloft. First, cases having relatively stationary flow patterns will be identified. For these stationary periods the observed stratocumulus frequencies will be compared with the average phase and amplitude of the height fields aloft. From these results, we will develop a parameterization of the diabatic forcing in the lowest layer by linking the phasing of the height fields on the eastern and western coasts with the observed stratocumulus frequencies. This parameterization will be incorporated into the quasi-geostrophic model and its solutions will be investigated, as discussed above.

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