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Final Report to the National Aeronautics and Space Administration for

Studies of

Trade-Wind Cloudiness and Climate

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Accomplishments

1. Closed mesoscale cellular convection (MCC) consists of mesoscale cloud patches separated by narrow clear regions. Strong radiative cooling occurs at the cloud top. Shao and Randall (1996) used a dry two-dimensional Bousinesq model is used to study the effects of cloud-top cooling on convection. Wide updrafts and narrow downdrafts are used to indicate the asymmetric circulations associated with the mesoscale cloud patches. Linear analysis of the model indicates only that the longest waves are most unstable, and gives no indication of asymmetric convection cells in the linear convective regime. A weakly nonlinear analysis suggests the presence of downdrafts that are narrower than the updrafts, but this effect is not very pronounced for reasonable values of parameters. Fully nonlinear numerical simulations show that strong cloud-top cooling can generate highly asymmetric mesoscale cells corresponding to closed MCC. Nonlinear processes play essential roles in generating and maintaining closed MCC. Based on the numerical results, a conceptual model was constructed to suggest a mechanism for the formation of closed MCC over cool ocean surfaces.

2. A new method to estimate the radiative and evaporative cooling in the entrainment layer of a stratocumulus-topped boundary layer has been developed by Shao et al. (1997). The mixing process was represented by the concentrations of a conserved tracer, rather than by the mixing fraction χ used in previous studies. This approach avoids the uncertainty inherent in calculating χ . The new method explains why the evaporative cooling estimated from data is sensitive to the values of jumps of temperature and moisture across the inversion as determined from data, while the radiative cooling is not. The sensitivity of the evaporative cooling to the jumps makes its comparison with the radiative cooling inconclusive, and so only the maximum possible evaporative cooling (MPEC) was considered. The method was applied to a set of large-eddy simulation (LES) results and to a set of tethered-balloon data obtained during FIRE. It was shown that for the LES results the average MPEC is larger than the average radiative cooling, while for the FIRE data the average radiative cooling and MPEC are about the same. The evaporative cooling depends more strongly on the extent of mixing than does the radiative

cooling. The two important parameters in the method (i.e., the saturation mixing ratio and the probability density function of the mixed parcels) are used to parameterize the fractional cloudiness.

3. Chen et al. (1996, 1998) developed a stratocumulus-capped marine mixed layer model which includes a parameterization of drizzle based on the use of a predicted cloud condensation nuclei (CCN) number concentration. The autoconversion process is parameterized in terms of an assumed droplet size distribution. The accretion and sub-cloud evaporation processes are parameterized following Redelsperger and Sommeria. Aerosol particles are divided into two modes, representing the small nucleation mode and the CCN mode, respectively. Both number and mass balances are considered. Two steady states were obtained, as in the model of Baker and Charlson. The lower steady state CCN number concentration corresponds to the typical marine time boundary layer. The higher steady state CCN number concentration is regarded as the continental air mass case. A difference between the results of Chen et al. (1996, 1998) and those reported by Baker and Charlson is that the former obtain a smoother transition between these two states. This result supports some observations that suggest there is no sharp transition between the drizzling and non-drizzling steady states of CCN number concentration in the marine boundary layer. The model was tested using ASTEX data, and the results show that the boundary layer's macroscopic structure is sensitive to the CCN number concentration. When the CCN number concentration increases, the drizzle rate decreases, so that the boundary-layer cloud remains thick. When the CCN number concentration decreases, the drizzle rate increases and as a result the boundary-layer cloud becomes thinner.

4. We have developed, implemented, and tested a very elaborate new stratiform cloudiness parameterization for use in GCMs (Fowler et al. 1996; Fowler and Randall 1996 a, b). The parameterization was initially incorporated into the CSU (Colorado State University) GCM, and is now being ported to the CSM (Climate System Model) which has been developed at the National Center for Atmospheric Research (NCAR).

5. Xu and Randall (1996 a) demonstrated that probability density function (PDF)-based cloudiness parameterizations and large-scale relative humidity (RH)-based cloudiness parameterizations are regime-dependent when applied to large-scale models. As an alternative to these conventional RH- and PDF-based approaches, Xu and Randall (1996 b) proposed a very simple cloudiness parameterization, and tested it using simulations of observed tropical cloud systems and subtropical stratocumuli with the UCLA cloud ensemble model. The parameterization uses the large-scale average condensate (cloud water and cloud ice) mixing ratio, \bar{q}_l , as the primary predictor, and the large-scale relative humidity, \overline{RH} , as a secondary predictor. The cloud amount, C_s , is assumed to satisfy

$$C_s = \overline{RH}^p \left[1 - \exp \left(-\alpha \frac{\bar{q}_l}{[(1 - \overline{RH})q^*]^\gamma} \right) \right], \quad (1)$$

where q^* is the saturation water vapor mixing ratio, and coefficients α , p , and γ are semi-empirical constants which were statistically determined from simulations of tropical cloud systems. An evaluation of the parameterization was performed using *independent* simulations of subtropical stratocumuli (Xu and Randall, 1996 b), and this evaluation has now been repeated using ARM data. The validity of the approach and the sensitivity to cloud regime and horizontal-averaging distance was investigated by Xu and Randall (1996 b).

6. Finally, we have developed a new, mechanistic parameterization of the effects of cloud-top cooling on the entrainment rate (Randall et al. 1998). The theory is formulated in terms of an “effective inversion strength,” which is the true inversion strength minus a correction for cloud-top cooling. The predictions of the theory agree well with large-eddy simulation results. The parameterization has been implemented in the CSU GCM, with good results.

Personnel Partially Supported by This Grant

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Refereed Publications

Chen, A., S. Kreidenweis, and D. A. Randall, 1998: Incorporation of Aerosol Physics and Drizzle Into a Simple Marine Stratocumulus Model. In preparation for the *Quarterly Journal of the Royal Meteorological Society*.

Fowler, L. D., D. A. Randall, and S. A. Rutledge, 1996: Liquid and Ice Cloud Microphysics in the CSU General Circulation Model. Part 1: Model Description and Simulated Microphysical Processes. *Journal of Climate*, **9**, 489-529.

Fowler, L. D., and D. A. Randall, 1996 a: Liquid and Ice Cloud Microphysics in the CSU General Circulation Model. Part 2: Simulation of the Earth's Radiation Budget. *Journal of Climate*, **9**, 530-560.

Fowler, L. D., and D. A. Randall, 1996 b: Liquid and Ice Cloud Microphysics in the CSU General

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- Randall, D. A., D.-M. Pan, and P. Ding, 1996: Quasiequilibrium. Paper presented at the *NATO Advanced Study Institute's Workshop on The Physics and Parameterization of Moist Atmospheric Convection*, Kloster Seeon, Germany, August 5-15, 1996. To be published by Springer-Verlag in the NATO ASI series, 1997.
- Randall, D. A., M. A. Branson, and C.-H. Moeng, 1998: The effects of cloud-top radiative and evaporative cooling on stratocumulus entrainment. In preparation for the *Quarterly Journal of the Royal Meteorological Society*.
- Shao, Q., and D. A. Randall, 1996: Closed Mesoscale Cellular Convection Driven by Cloud-Top Cooling. *Journal of the Atmospheric Sciences*, **53**, 2144-2165.
- Shao, Q., D. A. Randall, and C.-H. Moeng, 1997: A new approach to determine the radiative and evaporative cooling rates in the entrainment layer of a stratocumulus-topped boundary layer. *Quarterly Journal of the Royal Meteorological Society* (in press).
- Xu, K.-M., and D. A. Randall, 1996 a: A semi-empirical cloudiness parameterization for use in climate models. *Journal of the Atmospheric Sciences*, **53**, 3084-3102.
- Xu, K.-M., and D. A. Randall, 1996 b: Evaluation of statistically based cloudiness parameterizations used in climate models. *Journal of the Atmospheric Sciences*, **53**, 3103-3119.

Non-Refereed Publications

- Randall, D. A., 1995: Parameterization of Subgrid-Scale Stratiform Cloudiness Associated with

- Convection. Paper presented at the *Fall AGU*, San Francisco, California, December 11-15, 1995.
- Randall, D. A., Q. Shao, and M. Branson, 1997: Representation of Clear and Cloudy Boundary Layers In Climate Models: Status and Prospects. Paper presented at the *Colloquium of the Royal Netherlands Academy of Arts and Sciences on Clear and Cloudy Boundary Layers*, Amsterdam, August 1997.
- Chen, Aidong, S. M. Kreidenweis and D. A. Randall, 1996: Studies of Stratocumulus Cloud, Drizzle and Aerosol Interactions. *Atmospheric Science Paper No. 603*, Colorado State University.
- Shao, Q. and D. A. Randall, 1995: The Effects of Cloud-Top Processes on Convection in the Cloud-Topped Boundary Layer. *Atmospheric Science Paper No. 573*, Colorado State University, 270 pp.
- Fowler, L. D., and D. A. Randall, 1997: Fractional cloudiness in the CSU general circulation model. Paper presented at the *IAMAS and IAPSO Joint Assembly*, Melbourne, Australia, July 1-9 1997.
- Xu, K.-M. and D. A. Randall, 1997: Statistical-equilibrium states of radiative-convective systems over the tropical oceans. Paper presented at the *22nd Conference on Hurricanes and Tropical Meteorology of the American Meteorological Society*, Fort Collins, CO, 19-23 May 1997.
- Xu, K.-M., and D. A. Randall, 1995: Use of Explicit Simulation of Cloud Ensembles for Developing a Cloudiness Parameterization. Paper presented at the *IUGG Symposium on Clouds, Convection, and Large-Scale Land Surface Processes*, Boulder Colorado.