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Numerical Modeling of the Global Atmosphere

Summary of Research

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This report summarizes the research we performed under the grant NAG 5-2591, which consisted of the following topics:

(a) Development and evaluation of parameterization of convective-scale downdrafts

Under this grant, we continued development and evaluation of the updraft-downdraft model for cumulus parameterization. The model includes the mass, rainwater and vertical momentum budget equations for both updrafts and downdrafts. The rainwater generated in an updraft falls partly inside and partly outside the updraft. Two types of stationary solutions are identified for the coupled rainwater budget and vertical momentum equations: (1) solutions for small tilting angles, which are unstable; (2) solutions for large tilting angles, which are stable. In practical applications, we select the smallest stable tilting angle as an optimum value. The model has been incorporated into the Arakawa-Schubert (A-S) cumulus parameterization. The results of semi-prognostic and single-column prognostic tests of the revised A-S parameterization show drastic improvement in predicting the humidity field. Cheng and Arakawa (1997a) presents the rationale and basic design of the updraft-downdraft model, together with these test results. Cheng and Arakawa (1997b), on the other hand gives technical details of the model as implemented in the current version of the UCLA GCM.

(b) Analysis of cloud properties simulated by a cloud ensemble model

We used a 2-D numerical cloud-resolving model (CRM) developed earlier for studying cumulus entrainment and associate processes. First, we analyzed the simulated data following the methods commonly used in observational studies on cumulus entrainment and confirmed that the characteristic results from observational studies can be produced using the simulated data. Second, through extensive trajectory analysis, we investigated entrainment sources and the dilution effect of entrainment on the bulk properties of each cumulus subensemble, which is identified by the stratification of simulated saturated updrafts according to their eventual heights. Then the total cloud mass flux and mean moist static energy are calculated for each subensemble, and entrainment characteristics are inferred from the cloud mass flux and in-cloud moist static energy. It was found that different subensembles do have distinguishable entrainment characteristics. All subensembles, however, are subject to the most significant dilution effect at levels immediately above cloud base. All of these results are discussed in the paper by Lin and Arakawa (1997 a, b).

(c) Statistical analysis of large-scale observed data and development of an empirical cumulus parameterization

A cumulus parameterization generally combines a cloud model with a closure assumption. The choice of a cloud model represents the "physical" aspect of the problem while the choice of a closure assumption represents the "logical" aspect. With this in mind, we performed statistical analysis of observed large-scale data to study the macroscopic behavior of moist convection. Using the method of rotated EOF (REOF) analysis applied to the vertical profiles of cumulus heating (Q_1) and cumulus drying (Q_2) diagnosed from observed large-scale heat and moisture budgets, we *empirically* classified cloud regimes and determined the characteristic normalized vertical distributions of Q_1 and Q_2 for each cloud regime. Then, for each cloud regime, we defined an empirical cloud work function, which is a combination of (the vertical profiles of) thermodynamic state variables and their vertical gradients that is strongly constrained to be near constant in observed time sequences. We constructed an empirical cumulus parameterization in this way using observations over the tropical Asian continent (Liu 1995). The parameterization is then applied to the GATE situations for verification with very encouraging results.

(d) Development and evaluation of a parameterization of orographic gravity waves

We developed a new parameterization of orographic gravity waves that takes into account the drag enhancement due to the formation of nonlinear critical layer at the lee side of mountains. The development was guided by a number of experiments performed with a numerical mesoscale model applied to a variety of orographic conditions. Based on statistical measures of the subgrid-scale orography, given as inputs additional to the mean and standard deviation of the surface height, the parameterization selectively enhances drags at the reference-level and at lower-tropospheric levels above when a nonlinear critical layer is expected to form. The basis and description of the parameterization scheme are presented by Kim and Arakawa (1995). The parameterization was then extensively evaluated in the UCLA GCM (Kim 1996). Tests of the parameterization were also made with models at other institutions such as those at CSU, NCEP, LLNL and CCSR/UT in Japan.

(e) Improved formulations of cloud-top processes in the UCLA GCM for better

simulation of starts cloud incidence and surface evaporation.

While the PBL parameterization used in the UCLA GCM can explicitly predict the starts sub layer within the PBL, the standard version of the GCM generally the starts cloud incidence almost everywhere, including the eastern subtropical Pacific of both hemispheres. This indicates that the simulated PBL is not sufficiently moist. The simulated surface evaporation, however, is not too small; in fact it is too large compared to observation. These two deficiencies strongly suggest that the PBL of the model is subject to too much drying, presumably due to the entrainment of drier air from above. Even when the rate of mass entrainment is known, however, the rate of moisture entrainment is sensitive to the way in which the humidity of entraining air is specified. This is true particularly in models with relatively coarse vertical resolution. As reported by IL and Arakawa (1997), we found that the simulation of starts cloud incidence can be drastically improved by using a specification of the humidity based on a downward extrapolation from the levels in the free atmosphere to the PBL top.

(f) Research on the vertical discretization problem in atmospheric modeling and development of a model based on a generalized vertical coordinate

When the standard Lorenz vertical grid is used, a vertical computational mode characterized by a zigzag vertical profile of the potential temperature appears in simulated results. In addition, the grid is subject to spurious baroclinic growth of short waves. Using the Charney-Phillips grid, we have constructed a new vertically discrete model based on a hybrid sigma-p coordinate, which is free from this problem while maintaining most of the advantages of the Lorenz grid such as maintaining the total energy conservation (Arakawa and Donor 1996). The paper includes a comparison between results from the new model and a model based on the standard Lorenz grid in view of the vertical propagation of gravity waves and the baroclinic growth of middle-latitude cyclones from initially-random disturbances.

g . Development of a model based on a generalized vertical coordinate

We have developed a model based on a generalized vertical coordinate, which is identical to the isentropic coordinate model of Hs and Arakawa (1990) if the coordinate is chosen to be the potential temperature everywhere. The model can be used, however, as a hybrid-coordinate model in which the coordinate is essentially sigma near the surface and wherever the stratification is unstable, and it is essentially the potential temperature for the rest of the domain with a smooth transition. The model was successfully tested in view of the growth of middle-latitude cyclones and associated fronts on a middle-latitude beta-plane. The key to the success is in the derivation and solution of the vertical mass flux equation to maintain hydrostatic consistency in the discrete model, which guarantees that the coordinate variable is single-valued and monatomic in the vertical. The design and test of the model are presented in Donor and Arakawa (1997).

1.4 Publications

Refereed articles

Kim, Y. J., and A. Arakawa, 1995: Improvement of orographic gravity wave parameterization using a mesoscale gravity wave model. *J. Atmos. Sci.*, **52,** 1875-1902.

Arakawa, A., and C. S. Donor, 1996: Vertical of the primitive equations based on the Charney-Phillips grid in hybrid σ-p vertical coordinates. *Mon. Wea. Rev.* **124,** 511-528

Kim, Y.-J., 1996: Representation of subgrid-scale orographic effects in a general circulation model: Part I Impact of the dynamics of simulated January climate. *J. Climate,* 2698-2717

Lin, C.-C., and A. Arakawa, 1997a: The macroscopic entrainment processes of simulated cumulus ensemble. Part I. Effective sources of entrainment. *J.* Atmos. Sci., **54,** 1027-1043.

Lin, C.-C., and A. Arakawa, 1997b: The macroscopic entrainment processes of simulated cumulus ensemble. Part II. Testing the entraining-plume model. *J.* Atmos. Sci., **54,** 1044-1053.

Arakawa A., 1997: Adjustment mechanisms in atmospheric models. *J. Met. Soc. Japan,* **75,** No. 1B, 155-179.

Cheng, M.-D., and A. Arakawa, 1997a: Inclusion of rainwater budget and convective downdrafts in the Arakawa-Schubert cumulus parameterization. *J. Atmos. Sci.,* **54,** 1359-1378.

Konor, C. S., and A. Arakawa, 1997: Design of an atmospheric model based on a generalized vertical coordinate. *Mon. Wea. Rev.,* **125,** 1649-1673.

Selected conference papers

Lin, C.-C., and A. Arakawa, 1995: Cumulus entrainment simulated by a cloud-resolving model. *Twenty-First Conference on Hurricane and Tropical Meteorology,* 9-13 April 1995, Miami, American Meteorological Society, 63-65.

Konor, C. S., and A. Arakawa, 1996: Development of a generalized vertical coordinate model. *Eleventh Conference on Numerical Weather Prediction,* August 19-23, 1996, Norfolk, Virginia, American Meteorological Society, 203-205.

Kim, Young-Joon, C. R. Mechoso and A. Arakawa, 1996: Impact of gravity-wave drag and envelope orography in climate simulated by a general circulation model. *Eleventh Conference on Numerical Weather Prediction,* August 19-23, 1996, Norfolk, Virginia, American Meteorological Society, 319-321.

Li, J.-L. F, and A. Arakawa. 1997: Improved simulation of PBL moist processes with the UCLA GCM. *7th Conference on Climate Variations,* February, 2-7, 1997, Long Beach, California, American Meteorological Society, 35-40.

Arakawa, A., 1997: Cumulus parameterization: an ever-challenging problem in tropical meteorology and climate modeling. *22nd Conference on Hurricanes and Tropical Meteorology,* 19-23 May 1997, Ft. Collins, Colorado, American Meteorological Society, 7-12.

Lin, C.-C., and A. Arakawa, 1997c: Some bulk properties of simulated cumulus ensemble. *22nd Conference on Hurricanes and Tropical Meteorology,* 19-23 May 1997, Ft. Collins, Colorado, American Meteorological Society, 478-479.

Technical Report

Cheng, M.-D., and A. Arakawa, 1997b: *Computational procedures for the Arakawa-Schubert cumulus parameterization.* Tech. Report 101, General Circulation Modeling Group, Department of Atmospheric Sciences, UCLA, 50 pp.

Ph.D. dissertations

Liu, Y.-Z., 1995: The representation of the macroscopic behavior of observed moist-convective processes. 227pp.