AD-781 525

A NUMERICAL STUDY OF CLOUD GROUPS

Y. Ogura

Illinois University
Urbana, Illinois

30 September 1973

FINAL REPORT OF THE
LABORATORY FOR ATMOSPHERIC RESEARCH
MARCH 15, 1971 - SEPTEMBER 30, 1973

ARPA Order Number: 1748

Program Code Number: 62706D

Name of Contractor: University of Illinois

Effective Date of Contract: March 15, 1971

Contract Expiration Date: September 30, 1973

Amount of Contract: $436,410.00

Contract Number: DAHC04-71-C-0016

Principal Investigator: Professor Y. Ogura

Telephone Number: 217-333-2192

Project Scientist: Professor Y. Ogura

Telephone Number: 217-333-2192

Short Title of Work: A Numerical Study of Cloud Groups

Sponsored by
Advanced Research Projects Agency
ARPA Order No. 1748

15

Summary of the Results

As described in the proposal, the main objectives of this research contract were:

a. to develop realistic models for an individual thunderstorm cell, and

b. to investigate the relationships between the large-scale meteorological fields and cumulus cloud ensembles so that the parameterization for cumulus clouds in a global circulation model may be improved on a more scientifically sound basis.

A list of publications produced is attached (no technical reports were produced). Because all the works done during the period of the research contract have been either published in scientific journals or widely distributed in the preprint form, it would be appropriate in this final report to summarize the major conclusions we have obtained and to describe how each article listed was motivated to contribute to the overall goal of the research project.

1. Modeling of an individual cloud.

Here are two specific objectives in this area. One is to develop a fully three-dimensional cumulus cloud model and the other to investigate the interaction between dynamical and microphysical processes in the life cycle of a thunderstorm cell. The growth and fallout processes of precipitation interact with the updraft which in turn controls the amount and development of hydrometeers. Therefore, the inclusion of microphysical processes is important to successful simulation of the evolution of cumulus clouds with time. On the other hand, if we are interested not in the detailed description of an individual cloud but in the collective effect of cumulus clouds on the evolution of the large-scale motion, it is not advisable to include too much complicated microphysical processes into the cloud model for the obvious reason that prohibitingly large amounts of computer time is required.

We have developed one-, two-, and three-dimensional cumulus models. One-dimensional models are least demanding for computer time and most convenient to be incorporated into a global circulation model. However, restricting the problem to one-dimension involves crude assumptions concerning the dynamics. Two-dimensional cloud models assume axisymmetric or slab-symmetric. An axisymmetric model is more free from the restrictions imposed in a one-dimensional model. However the axisymmetric model is unable to incorporate the effect of the vertical wind shear, a factor which is believed to be important in the development of severe local storms. The two-dimensional slab-symmetric model can accomodate the vertical shear. However, as shown in Publication No. 8., the simulated slab-symmetric cloud evolves with time quite differently from the simulated axisymmetric cloud. Moreover the irrevocably three dimensional nature of the severe convective storm has been known for many years. Even the allegedly two dimensional squall line often appears as a row of individual storms, each with decidely three dimensional structure.

The strategy we have taken in our study of dynamics and physics of an individual cloud was to use one- and two-dimensional models with non-parameterized microphysical processes and examine the accuracy of the existing (such as Kessler's) parameterization schemes for microphysical processes. A three-dimensional simulation was made with parameterized microphysical processes.

In Publication No. 6, we have developed a one-dimensional cloud model including the following microphysical processes: condensation/evaporation, stochastic coalescence, sedimentation and drop breakup. The ice phase of water is ignored and only the nucleation process is parameterized. A total of 61 mass categories, corresponding to radii from 4μm to 4mm, are used to determine the drop size distribution. Convection is initiated in a conditionally unstable atmosphere which represents tradewind conditions, and long time integrations of the model are performed to cover the entire life cycle of a simulated cumulus cloud. Some aspects of maritime warm cumulus and rainfall seem to be simulated realistically, such as the sudden onset of large-drop rain in convective showers.

Two-dimensional axisymmetric and slab-symmetric models with Kessler's parameterized microphysical processes are developed in Publication No. 4 and 8. The main conclusion in Publication No. 4 is that the deviation from the environmental pressure can be ignored in determining the saturation vapor pressure. This conclusion makes an iterative calculation in determining the saturation vapor pressure unnecessary and reduces the computer time needed for simulating the deep cloud.

As stated earlier, a comparison between axisymmetric and slab-symmetric models is made in Publication No. 8, and the result confirms in general the conclusion reached by previous studies: the updraft in an axisymmetric model grows more vigorously than in a slab-symmetric model for the same environmental and initial conditions: The ratio of the maximum speed of the compensating downdraft outside the cloud to the maximum updraft is significantly larger than that in an axisymmetric model; and the compensating downdraft in a slab-symmetric model spreads in space more widely than in an axisymmetric model.

In addition, we have developed a new finite-difference scheme which we call the modified upstream scheme for integrating the governing partial differential field and to investigate how the cloud population is controlled by the large-scale fields.

For this purpose, a method was devised in Publication No. 9 whereby the spectral distribution of vertical mass flux associated with cumulus clouds was determined from observed large-scale variables. This method combines the observed large-scale heat and moisture budgets and a simple model of the physical processes occuring within the cloud ensembles.

The method was first applied to the averaged summer time conditions over the Marshall Islands in the western Pacific. The result shows the presence of thebimodal distribution of the vertical mass flux at the cloud base in terms of the cloud top height. One group of clouds penetrates up to the 200-300 mb level and another group stays below the 600 mb level, wh le relatively few cloud top lie between 400 mn and 600 mb. The total percentage area covered by all clouds is found to be a few percent and the vertical velocity inside the cloud at the cloud base is estimated to be somewhere near 1 m sec^{-1} for most clouds. Because the observed large-scale averaged upward velocity at that level is of the order of 0.1 cm sec^{-1}, this result indicates that the total mass entering into ascending clouds through the cloud base is one order of magnitude larger than the mass brought into the subcloud layer by large-scale convergence. This excess mass is compensated by the downward motion with velocity of 1 cm sec^{-1} in the order of magnitude in the region between clouds at the cloud base.

In Publication No. 13, the method proposed in Publication No. 9 is applied to the averaged easterly wave disturbances in the Western Pacific based on Reed and Recker's (1971) data set to determine the cloud mass flux distribution in various weather conditions, ranging from disturbed conditions in the trough region to a relatively undisturbed condition in the ridge region. The results show that shallow clouds are present practically everywhere in the wave disturbances, even in the ridge region where the large-scale vertical motion is downward. In contrast, deep clouds penetrating into the layer above the 500 mb level are present in a significant amount only in the region near the trough axis (most intense in the region east of the trough axis). More quantitatively, while the total mass flux associated with all cumulus clouds at the cloud base level is not correlated with the low-level large scale convergence, the mass flux due to deep clouds is found to increase linearly with the increase of low-level large-scale convergence. This would suggest that the generation and maintenance of shallow clouds and deep clouds are controlled by separate mechanisms. The daily rainfall estimated on the basis of the computed convective mass flux is compared with observations with fairly good agreement.

3. Works in closely related areas

3.1 A multi-level moist primitive equation model

Because one of the objectives of the research project was to develop a parameterization scheme representing the collective effect of cumulus clouds on the evolution of the large-scale motion, it was felt necessary to have a multi-level moist primitive model ready for use at our research group to test the parameterization scheme which we intended to develop.

Accordingly, in Publication No. 5, we have developed a 6-layer primitive equation model in the σ-coordinate system and applied it to investigate the genesis and development of an intermediate scale cyclone. Here the intermediate scale cyclone has a typical horizontal scale of 1,000 km and is generated on an extended front or develops as secondary members of a cyclone family.

The baroclinic development of large scale extratropical disturbances with typical scale of several thousand kilometers is now well understood. Its characteristics as described by the baroclinic instability theories agree well with those observed in the real atmosphere and the evolution of these disturbances have been successfully simulated by several authors using geostrophic or primitive models. It has been many years since forecast for synoptic scale weather system based on the dynamic method became operational.

However, operational numerical prediction fails frequently to predict the genesis and development of intermediate scale cyclones and the dynamics of those cyclones are only poorly understood. We have therefore attempted to simulate these cyclones using our primitive model. The result shows some agreement between the simulated cyclone and observed on.

We are currently revising this primitive equation model so that it has a finer vertical resolution in the lower portion of the troposphere. This is desirable for investigating the dynamics of meso-scale convective system.

3.2 Development of a variable grid scheme

The primary objective of Publication No. 1 is to investigate the feasibility of using a variable grid in the numerical integration of hydrodynamic problems which requires more resolution in certain parts of the fluid than in others. A familiar example is meso-scale or medium-scale systems embedded in a larger scale atmospheric circulation.

We have developed a shallow-fluid model with a varible grid and applied this model to investigate air flow across the (idealized) Andes Mountain as an initial and boundary value problem. The Andes are roughly 4.75 km high between 9 and 33°S and only about 200 km wide on their western slope. We introduced a continuously variable map factor in the east-west direction: the grid interval is 500 km far away from the mountain and 50 km at the crest. The scheme is found to be quite stable.

3.3 A study of dynamics of the planetary boundary layer

It is well recognized that the proper inclusion of the planetary boundary layer (PBL) into a numerical model is important for successful simulation of large scale motions. There have been relatively few theoretical studies on the effects of inertial acceleration on the flow structure of a PBL even with the simplification of neutral stratification. However, the unique role of inertial acceleration can hardly be overstated. As long as it is not identically zero everywhere, it gives rise to horizontal convergence or divergence within the PBL. The associated vertical motion constitutes an efficient coupling between the boundary layer and the "free" flow above.

Therefore, in Publication No. 2, we have investigated the three-dimensional flow of a steady, neutral, horizontally inhomogeneous PBL driven by an imposed rectlinear flow, with a large cross-wind shear, over a surface of uniform roughness.

3.4 A generalization of the CISK theory

A long-standing problem in the dynamics of the tropical atmosphere has been to explain how the latent heat released in cumulonimbus clouds (due to Conditional Instability of the First Kind) can sometimes be harnessed to provide energy for the growth of disturbances on the synoptic scale. The theory of Conditional Instability of the Second Kind (CISK), formulated by Charney and Eliassen (1964), Ooyama (1964) and Ogura (1964), has provided a dynamical mechanism through which such cooperative growth can begin to be understood.

In the CISK theory, the essential link connecting the large scale flow with the primary heat source is the assumption that the rate of heating can be parameterized in terms of the large scale convergence of moisture. Since moisture content is normally highest in the planetary boundary layer, the moisture convergence is closely related to the boundary layer convergence of mass. In the papers referred to above, the boundary layer pumping was described by an Ekman formula, which related the frictionally induced pumping to the vorticity of the flow above the boundary layer.

In Publication No. 10, the CISK theory is generalized by incorporating an explicit solution of the time-dependent boundary layer equations for the case of exponential growth and allowing the interior flow to be unbalanced. Two separate modes of solution are found, which are termed CISK of Types A and B. CISK of Type A is a generalization of the well known CISK solution and CISK of Type B is a new solution. The mean thermodynamic parameter of the tropical atmosphere favor Type A CISK. However, the range of parameters required for the existence of Type B CISK would seem to be attainable. This may help to explain why the ITCZ cloud bands, though normally found away from the equator, are sometimes observed on the equator.

4. Graphics Development and Use

During the past several years we have been concerned about the graphical display of data at Illinois' ARPANET node. This concern developed as we began remote numerical simulations using the IBM 360/91 at UCLA in the latter months of 1972. Of particular importance was the need for contour displays of data fields. These contours were to be used for analysis of the generated data and for this task the Gould electrostatic printer-plotter was suitable. At this time we also began the process of purchasing a plotter for more precise and ledgible graphical output.

Our initial programming effort began during the summer of 1972 when the FORTRAN contour routines used on the CDC 6600/7600 system at the National Center for Atmospheric Research were adapted by us for use on the IBM 360/75 campus computer. These routines were then transferred from the ARPANET node next door at the Center for Advanced Computations (CAC) to UCLA's 360/91 in the Fall. Routines for creating the intermediate standard network graphics file (NGP) and the Gould device file were written by CAC and Laboratory staff, and by November 1972 we were using the IBM 360/91 to generate not only contour pictures, but also vector plots of wind fields and HIDE or surface plots of calculated data from any network site to a Network TENEX system.

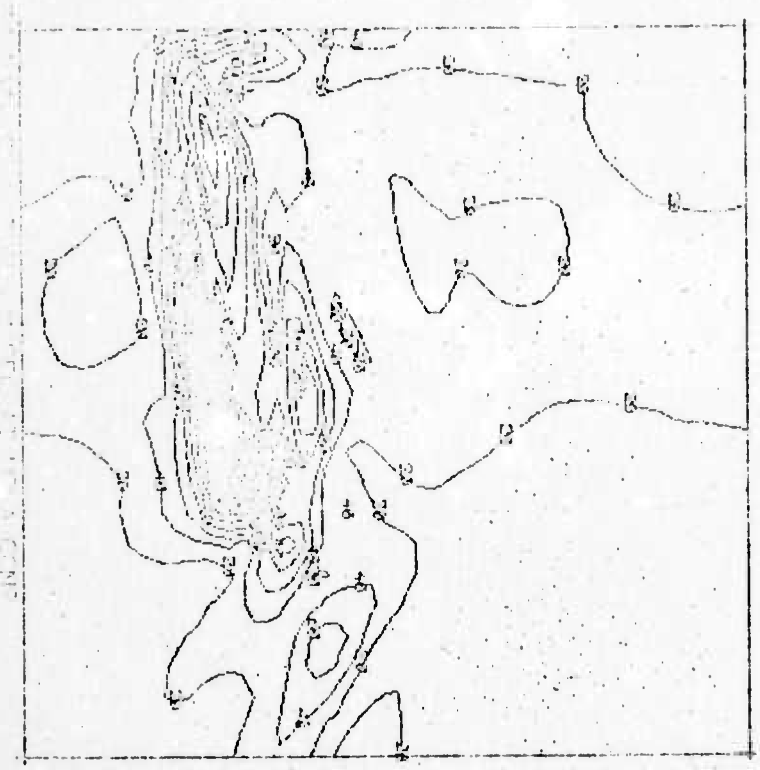
The data for each field to be displayed is placed in a separate file on the TENEX system by the user. The user may interact in specifying the parameters needed for the type of display desired. This is done through a command language that approaches natural expression and includes command fillout and possible command inquiry A typical sequence of events might be

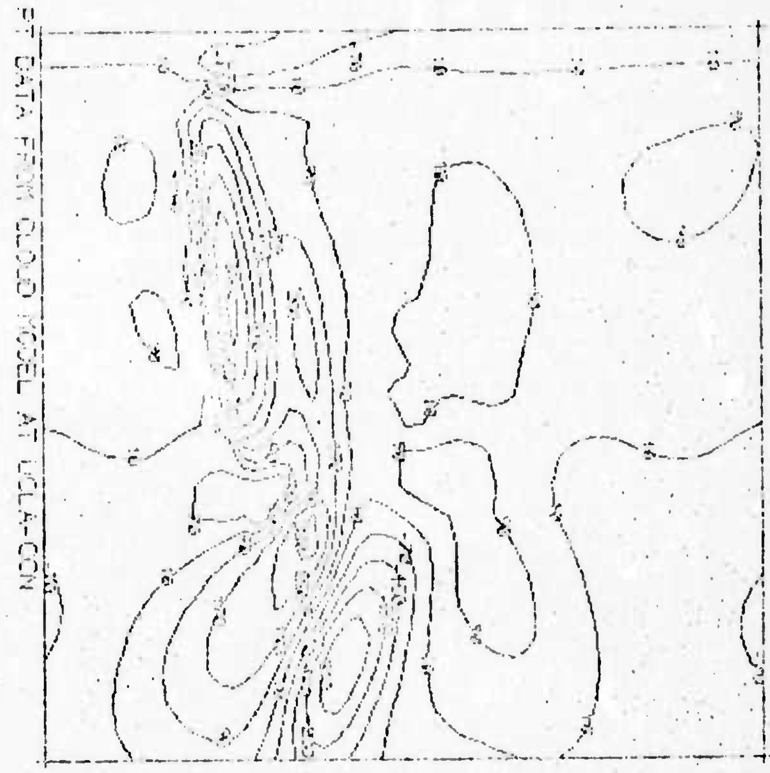
1. Display an initial contour on the Computek.
2. Modify contour interval or other parameters for a more helpful display.
3. Display new contour again on the Computek.
4. Go back to 2 if you are not satisfied.
5. Make a hard copy on the Gould or ZETA for later use or take a polaroid picture.

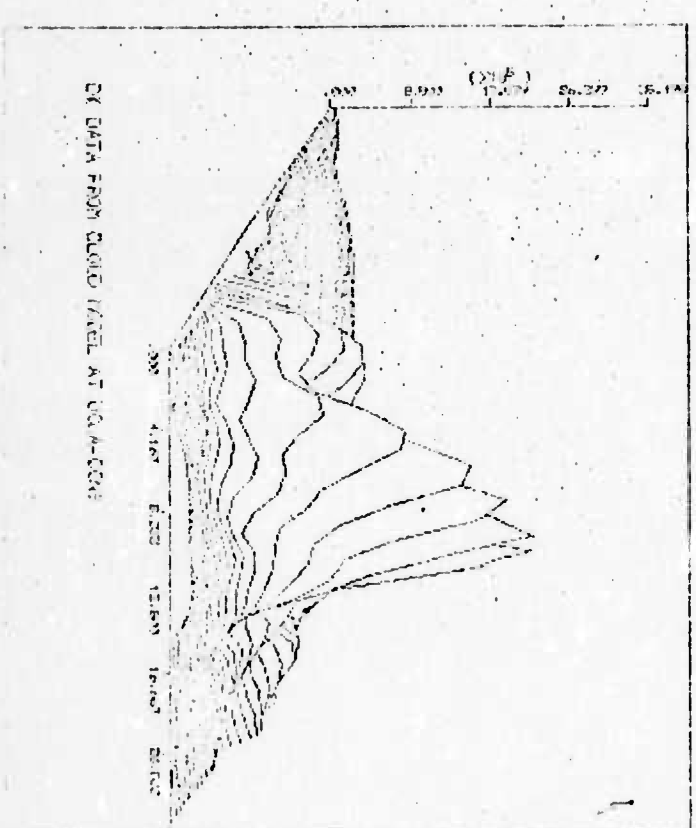
Features include the ability to title pictures, to draw one contour picture over another and to show more than one contour picture in the display area (see attached figure).

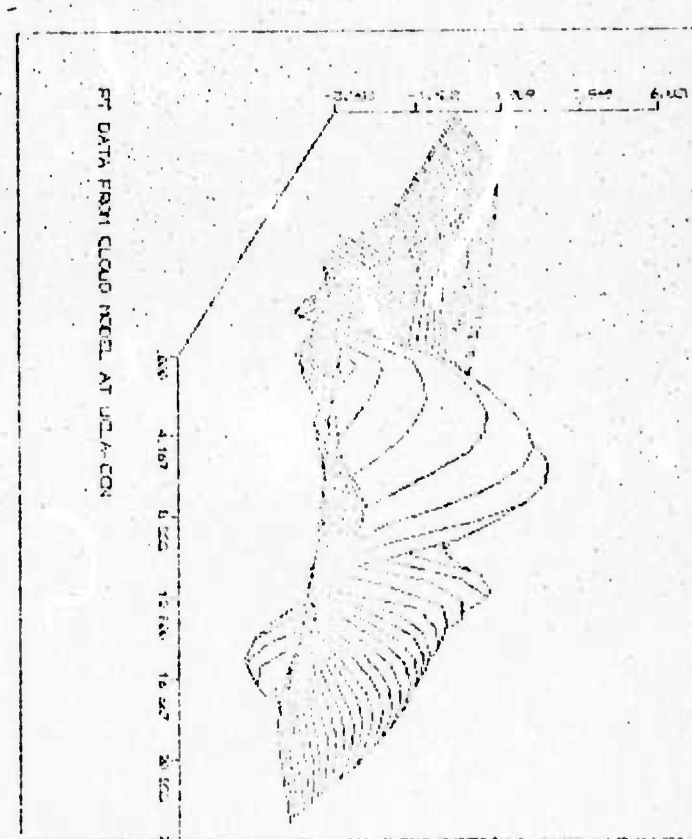
The creation of a Gould picture requires a significant amount of computation. A large part of this computation can by user's choice be done on the UCLA IBM 360/91 through an improved TENEX remote job entry system (RJS) that we wrote. By October, 1973, most of the components of the interactive system were developed and in the final debugging stage.

The ZETA plotter had not been used extensively by October, 1973, after its installation in the late spring of 1973. There was still some hardware difficulties. Nor was it well integrated into ANTS (the ARPA Network Terminal System at CAC). It was used primarily in connection with the NASA/USGS contract work involving the color display of raw and interpreted ERTS (Earth Resources Technology Satellite) data.




FT DATA FROM CLOUD MODEL AT UCLA-CON




FT DATA FROM CLOUD MODEL AT UCLA-CON

List of Publications

1. A numerical Shallow-Fluid Model Including Orography with a Variable Grid, I. Vergeiner and Y. Ogura. J. Atmos. Sci., 29, (1972), 270-284.

2. Steady, Neutral Planetary Boundary Layer Forced by a Horizontally Non-Uniform Flow, by M.-K. Mak, J. Atmos. Sci., 29 (1972), 707-717.

3. Cumulus Modeling and Parameterization, by Y. Ogura. Rev. Geophys. Space Phys. (accepted for publication).

4. The Pressure Perturbation and the Numerical Modeling of a Cloud, by R. Wilhelmson and Y. Ogura. J. Atmos. Sci., 29 (1972), 1295-1307.

5. Numerical Simulation of the Development of the Intermediate Scale Cyclone in the Moist Model Atmosphere, by T. Nitta and Y. Ogura. J. Atmos. Sci., 29, (1972), 1011-1024.

6. The Development of Warm Rain in a Cumulus Model, by Y. Ogura and T. Takahashi, J. Atmos. Sci., 30 (1973), 262-277.

7. The Numerical Simulation of a Thunderstorm Cell in Two- and Three-Dimensions, by R. Wilhelmson (1972) Ph.D. Thesis, University of Illinois.

8. A Comparison Between Axisymmetric and Slab-symmetric Cumulus Cloud Models, by S.-T. Soong and Y. Ogura. J. Atmos. Sci., 30, (1973). 879-893.

9. Diagnostic Determination of Cumulus Cloud Populations From Observed Large-Scale Variables, by Y. Ogura and H.-R. Cho., J. Atmos. Sci., 30, (1973) 1276-1286.

10. A Generalization of the CISK Theory, By J. R. Bates, J. Atmos. Sci., 30, (1973), 1509-1519.

11. Numerical Simulation of Warm Rain Development in an Axisymmetric Cloud Model, by S.-T. Soong, (in preparation).

12. The Life Cycle of a Thunderstorm in Three Dimension, by R. Wilhelmson, (in preparation).

13. A Relationship Between the Cloud Activity and the Low-Level Convergence as Observed in Reed-Recker's Composite Easterly Waves, by H.-R. Cho and Y. Ogura, (in preparation).

Advanced degrees earned

Robert Wilhelmson, Ph.D., June 1972, Department of Computer Science. Thesis "The Numerical Simulation of a Thuderstorm Cell in Two- and Three-Dimensions".