NASA Conference Publication 2200

The Numerical Studies Program for the Atmospheric General Circulation Experiment (AGCE) for Spacelab Flights

Summary results of a meeting held in
Boulder, Colorado
April 14-15, 1981

NASA

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The Numerical Studies Program for the Atmospheric General Circulation Experiment (AGCE) for Spacelab Flights

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National Aeronautics
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Scientific and Technical
Information Branch

1981

PREFACE

A spherical baroclinic flow experiment which will model the large-scale circulations of the Earth's atmosphere has been proposed to NASA Headquarters, Office of Space and Terrestrial Applications, for Spacelab flights. The experiment is known as the Atmospheric General Circulation Experiment (AGCE). In the experiment gravity will be simulated by a radial dielectric body force. The experiment must be performed in a low gravity environment such as orbiting Spacelab to allow the dielectric force to be dominant. The major objective of the AGCE is to study nonlinear baroclinic wave flows in spherical geometry. Thus, the apparatus must be designed such that strong baroclinic instability can be realized. This requirement means that numerical models must be developed which will accurately predict the basic axisymmetric states and the stability of these states. In addition, a three-dimensional, fully nonlinear, numerical model of the AGCE based on the complete set of equations is required. The AGCE numerical design studies program is underway, and it was the purpose of this meeting to review the work achieved to date.

The meeting was organized by Dr. William W. Fowlis of the Space Sciences Laboratory, NASA, Marshall Space Flight Center, Alabama, and by Dr. M.H. Davis of the

Universities Space Research Association in Boulder, Colorado. The meeting was held on April 14 and 15, 1981, at the National Center for Atmospheric Research in Boulder, Colorado.

The purpose of these proceedings is to present concise reports of the speakers' presentations. References have been included with some of the individual reports; and, in addition, a list of publications of the NASA/MSFC, Geophysical Fluid Dynamics Group, Fluid Dynamics Branch has been attached. These references will enable the interested reader to pursue further any particular topic.

This meeting was sponsored through funding from the Global Weather Research Program of the Office of Space and Terrestrial Applications, NASA Headquarters, Washington, D.C., under contract NAS8-34008 to Universities Space Research Association.

MEETING PROGRAM

SCIENTIFIC REVIEW MEETING OF THE NUMERICAL STUDIES PROGRAM FOR THE ATMOSPHERIC GENERAL CIRCULATION EXPERIMENT (AGCE) FOR SPACELAB FLIGHTS

April 14, 1981

I. Presentations

1.	Overview	William W. Fowlis, NASA/MSFC	8:30 - 9:00 AM
2.	The AGCE Apparatus	William W. Fowlis, NASA/MSFC	9:00 - 9:30 AM
3.	Spherical Hydrostatic Models: Basic States and Stability	Robert Gall and Tim Miller, University of Arizona	9:30 - 10:15 AM
	Coffee		10:30 - 10:45 AM
4.	Cylindrical Annulus Models	Fred Leslie, NASA/MSFC	10:45 - 11:30 AM
	Lunch		11:30 - 1:00 PM
5.	Spherical Models: Basic States and Stability	Glyn Roberts, USRA, NASA/MSFC	1:00 - 2:00 PM
6.	The Three-Dimensional Spherical Model for the AGCE	Basil Antar, University of Tennessee Space Institute	2:00 - 2:45 PM
	Coffee		2:45 - 3:15 PM
7.	Model Verification Studies Using Accurate Measurements of Spin-Up	Jae M. Hyun, NRC, NASA/MSFC	3:15 - 4:00 PM

April 15, 1981

Presentations (continued)

8.	Description of Stripped-Down Spectral GCM	Eric Pitcher, University of Miami	9:00 - 9:30 AM
9.	Review of Current Stripped-Down GCM Studies	John E. Geisler, University of Miami and Robert Malone, DOE, Los Alamos	9:30 - 10:30 AM
	Coffee		10:30 - 11:00 AM

II. Discussion

This part of the program has been left unstructured. Group discussion of relevant topics is suggested. It is expected that the following will be discussion topics:

1. Comparison of the model results.
2. Value of the GCM studies for the AGCE.
3. Difficulties in formulating the three-dimensional, nonlinear, spherical model for the AGCE.

The meeting will finish formally about 3:00 PM on April 15, 1981. However, some people will be staying longer in Boulder and it is anticipated that discussions will continue until about 5:30 PM.

LIST OF ATTENDEES

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<u>TABLE OF CONTENTS</u>

1. OVERVIEW

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NASA, Marshall Space Flight Center
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Introduction

Since the late 1940's a substantial amount of experimental and theoretical work has been devoted to the study of baroclinic flows in a rotating and differentially heated cylindrical annulus of liquid. Much has been learned from this work about baroclinic instability and much insight into the behavior of large-scale atmosphere dynamics has been achieved. In particular, the experimentalists produced regime diagrams which show the conditions under which different flow types occur. These types are axisymmetric flows, steady wave flows, simple unsteady periodic wave flows (vacillations) and irregular flows. Theoreticians have produced models of the basic axisymmetric states and the stability of these states has been examined to give theoretical regime diagrams.

A valuable extension of the previous experimental work in cylindrical geometry would be to create a spherical model. For such a model a radial body force to simulate gravity is required. Such a force can be achieved by dielectric effects on a liquid in the presence of a large voltage, but in the terrestrial laboratory it cannot be made large enough to overwhelm gravity. However, in an orbiting vehicle like Spacelab, this dielectric force will dominate.

The GFFC and the Proposed AGCE

Two spherical geophysical fluid flow model experiments which exploit the radial dielectric force are being prepared for Spacelab flights. A spherical convection experiment known as the Geophysical Fluid Flow Cell (GFFC) has been assigned to Spacelab 3. In this experiment the liquid will be held between two concentric spheres in the form of a spherical capacitor on which is applied a large AC voltage. The liquid will also be subjected to rotation and a convectively unstable radial temperature gradient. In the AGCE the liquid will again be held between concentric rotating spheres in the presence of a large voltage, but for this experiment the liquid will be subjected to a stable radial temperature gradient and an unstable latitudinal gradient. The AGCE has been proposed for flights beyond Spacelab 3. Fig. 1.1 shows the scientific teams for both the GFFC and the AGCE and Fig. 1.2 is a schematic drawing showing the essentials of the proposed AGCE apparatus.

The AGCE Design Program

The approach taken for the AGCE design has been to proceed on a broad scientific front so that as well as producing engineering specifications for the AGCE apparatus, a body of relevant scientific knowledge will be acquired for interpreting and understanding the AGCE results and for relating these results to real atmospheric flows. Such knowledge will also be valuable for the formulation of well-posed experiments with the AGCE apparatus. In this context, a considerable number of analytical basic state and stability studies with simple rectilinear models have already been performed and nearly all of this work is available in published papers or reports. Although this work has deepened our qualitative understanding of baroclinic processes, it cannot be used for quantitative design studies for the AGCE apparatus. The mathematical difficulties associated with spherical geometry, nonseparability and nonlinearity mean that for the determination of the apparatus specifications, numerical models must be used. The numerical design studies program for the AGCE is underway and it was the purpose of this meeting to review the work performed to date. The objectives of the design program are to specify dimensions for the apparatus, physical properties for the liquid and imposed external conditions such that baroclinic instability will be realized and substantially nonlinear wave flows achieved.

The Presentations

In this section the presentations are listed and some background given. (Some of the speakers when preparing their reports made small changes in their titles from those given in the original program. In the list below and in the reports that follow, the authors' changes have been retained but the numbering of the presentations remain the same as in the program. Note that one report covers Presentations 8 and 9.)

2. The AGCE Apparatus.

Although this review is concerned with numerical modeling, we felt that a description of the requirements of the apparatus and of the hardware as it is perceived at this stage would be valuable for the modeling effort. A Feasibility Study contract for the AGCE instrument is underway at the present time.

3. Hydrostatic Calculations of Axisymmetric Flow and Its Stability for the AGCE Model.

When the AGCE design program was started, it was realized that some preliminary apparatus specifications would be required for the Feasibility Study before the complete numerical models could be proposed. Consequently, it was decided to proceed with simpler numerical hydrostatic models. Eventually, by comparison with the complete models, the importance of the nonhydrostatic effects will be assessed. Since all large-scale numerical, meteorological modeling makes the hydrostatic assumption, this work also brings the AGCE effort closer to atmospheric modeling research. The results of this work have been used as inputs to the Feasibility Study.

4. Cylindrical Annulus Models.

To develop spherical, axisymmetric basic state and stability codes for the AGCE designs effort, it was originally decided to adapt to spherical geometry a two-dimensional, cylindrical code based on the Navier-Stokes equations. The code was developed by Alex Warn-Varnas. As part of a systematic checking of this code we planned to compare its predictions with previous numerical results on cylindrical basic states and with experimental results on stability. (These latter results have never been quantitatively confirmed by theory.) This presentation deals with our progress in this effort. However, we decided recently, because the Warn-Varnas code is somewhat out-of-date, to build the required basic state and stability codes again from scratch and to repeat the above effort with the new codes.

5. Spherical Models: Basic States and Stability.

Spherical axisymmetric basic state and stability codes based on the full equations are being developed using the latest techniques. Because many computer runs will have to be made with these codes to generate the required AGCE apparatus specifications, accurate and rapid convergence is required. These codes will also be easily adaptable to cylindrical geometry so that checks based on previous work can be performed.

6. The Three-Dimensional Spherical Model for the AGCE.

The basic state and stability codes are necessary for the AGCE apparatus designs but in order to interpret the fully developed wave flow a spherical, three-dimensional, fully nonlinear code based on the complete equations is also required.

7. Model Verification Studies Using Accurate Measurements of Spin-Up.

The Geophysical Fluid Dynamics Laboratory of NASA/MSFC has available a laser Doppler velocimeter system for making accurate flow measurements in rotating systems. These measurements are being used to check our numerical codes. A substantial amount of code verification has already been done in cylindrical geometry and we are planning to make measurements of spin-up in spherical geometry to check the spherical codes. As well as being of value to the AGCE program, this effort also amounts to fundamental work in rotating fluid dynamics.

8. and 9. Preliminary Regime Diagrams on a Sphere with a Simplified General Circulation Model.

In the early planning stages for the AGCE, it was decided that the simplest and most direct way of obtaining a spherical, numerical, three-dimensional model of the AGCE, would be to strip-down an existing general circulation model (GCM). Further examination revealed that this was not so and that in order to have a quantitative numerical model it was necessary to start from the beginning. However, it is clear that a stripped-down GCM will be a very valuable part of the total AGCE program. It will assist in linking the AGCE to GCM modeling and to real atmospheric dynamics. In fact, knowledge of the behavior of a stripped-down GCM is a salient omission in GCM modeling. This work will make fundamental contributions to global weather and climate studies.

GEOPHYSICAL FLUID FLOW CELL (GFFC)

PRINCIPAL INVESTIGATOR:	John Hart	(Univ. of Colorado)
CO-INVESTIGATORS:	Juri Toomre	(Univ. of Colorado)
	Peter Gilman	(NCAR/HAO)
	George Fichtl	(NASA/MSFC)
	William Fowlis	(NASA/MSFC)

ATMOSPHERIC GENERAL CIRCULATION EXPERIMENT (AGCE)

PRINCIPAL INVESTIGATOR:	William Fowlis	(NASA/MSFC)
CO-INVESTIGATORS:	George Fichtl	(NASA/MSFC)
	John Geisler	(Univ. of Miami)
	Robert Gall	(Univ. of Arizona)
	Basil Antar	(Univ. of Tennessee Space Institute)

FIGURE 1.1 SPACELAB EXPERIMENTS SCIENTIFIC TEAMS

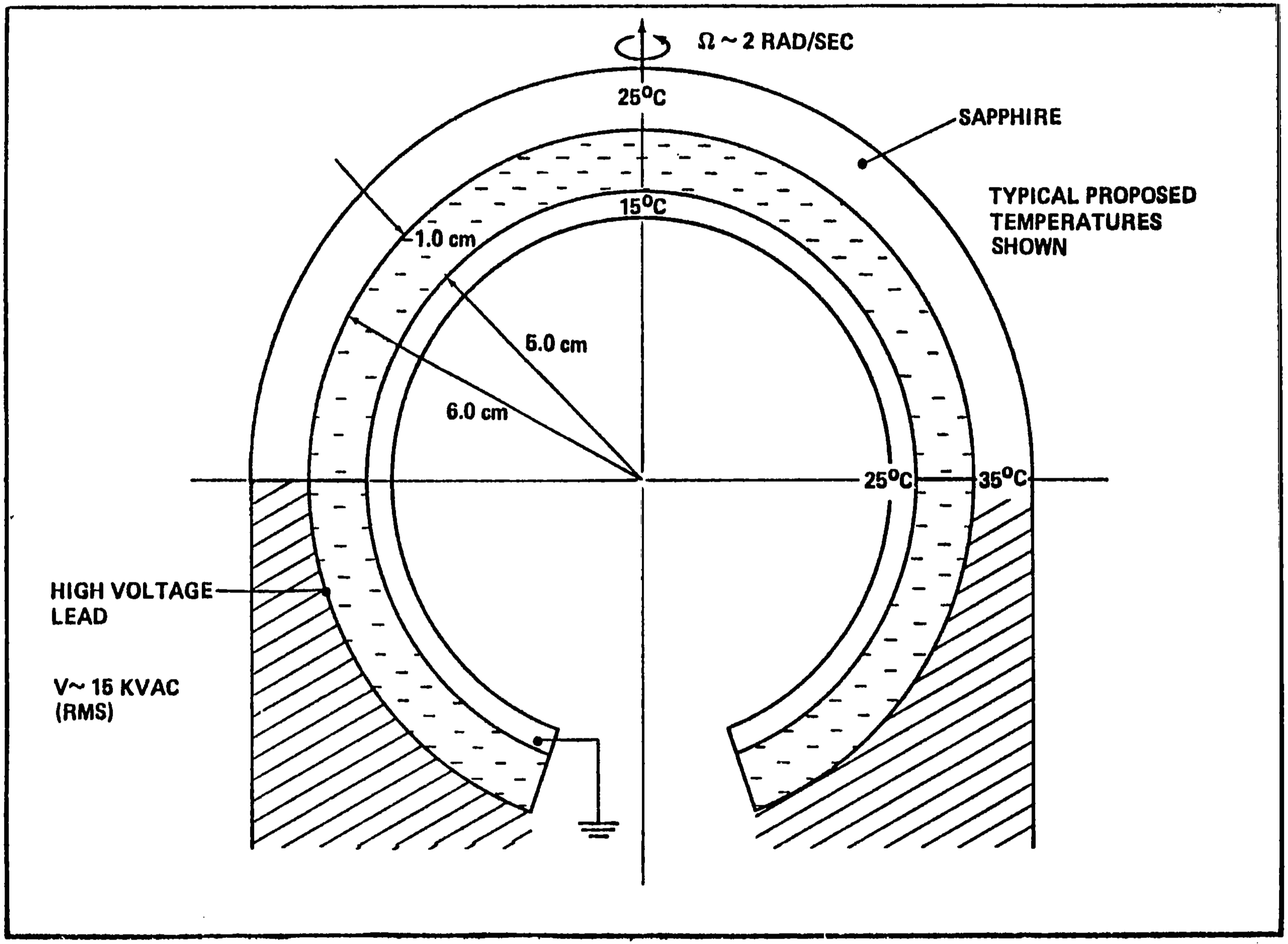

FIGURE 1.2 SCHEMATIC DRAWING OF THE PROPOSED AGCE APPARATUS.

2. THE AGCE APPARATUS

William W. Fowlis

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Introduction

The AGCE apparatus has been proposed as an instrument to extend previous experimental work on baroclinic flows in cylindrical geometry to spherical geometry. The instrument must be flown in Spacelab to allow the radial dielectric body force which simulates gravity to be dominant. Fig. 1.2 of the Overview shows the essential configuration of the proposed apparatus. Some preliminary values of dimensions and imposed conditions are included.

Measurement Techniques

It is desired to measure flow and temperature. Clearly, because of the large AC voltage and the ease of disturbing the relatively small volume of liquid, the measurement problem is not trivial. For flow measurement in the GFFC a photochromic dye marker technique was developed and it is planned to use this method for the AGCE instrument also. For the GFFC temperature measurement, a Schlieren system adapted to the geometry of the instrument was developed. The surface of the inner sphere was made reflective and the incident light normal so that the light passed back from the test volume instead of passing through. A set of aplanatic lenses was designed to image the curved object surface on a flat plane for photography. This method cannot be used for the AGCE apparatus (see below). These measurement techniques are discussed in Ref. 2.1 and Fig. 2.1 is a drawing of the GFFC instrument.

The Special AGCE Problem

In order to have clearly defined polar, midlatitude and equatorial regions, the AGCE requires larger spheres than the GFFC and an aspect ratio of about 0.2. The dimensions of the spherical gap in the GFFC are: inner radius = 2.4 cm and outer radius = 3.3 cm; the proposed tentative dimensions for the AGCE are: inner radius = 5 cm and outer radius = 6 cm. The optical, thermal and electrical requirements for the outer sphere for both the GFFC and the AGCE dictate that sapphire must be used. Thus, the feasibility of obtaining a larger sapphire hemisphere must be examined. Further, the larger spheres mean that the already large lenses used for the GFFC must be increased still more. This is not practical. Therefore, a new concept for temperature measurement must be sought.

The preliminary baroclinic instability studied indicated that to achieve a strongly nonlinear waveflow regime, a larger value of the dielectric body force (g_E) than that used for the GFFC is required. The expression for g_E is:

$$g_E = \frac{2\varepsilon\gamma}{\rho\alpha}\left(\frac{R_I R_O}{\Delta R}\right)\frac{V^2}{r^5},$$

where ε is the dielectric constant and ρ is the density, γ and α are the thermal coefficients for ε and ρ, respectively, R_I and R_O are the inner and outer radius, $\Delta R = R_O - R_I$, V is the applied voltage and r is the radius. The only practical way to increase g_E is to increase ε and/or V. Thus, suitable liquids with higher values of ε and compatible photochromic dyes should be sought and higher voltage sources should be examined.

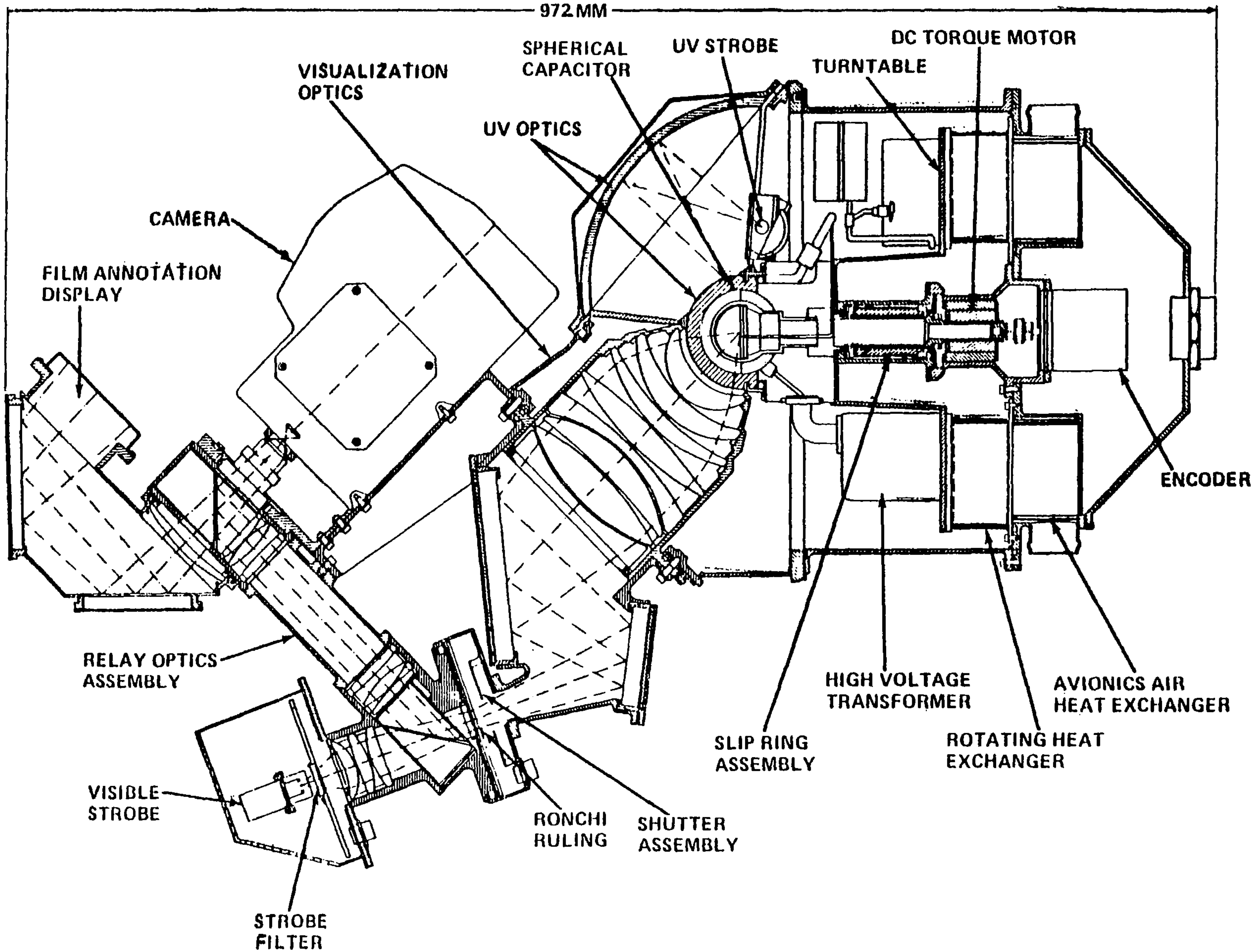
The Feasibility Study

These special problems of the AGCE apparatus design led to the award of a six month Feasibility Study contract to General Electric Co's Space Division, Valley Forge, PA during December, 1981. Fig. 2.2 shows the Feasibility Study task list. Preliminary results from the Feasibility Study indicate that an optical scanning device to measure the temperature is feasible. Fig. 2.3 shows the essentials of this scanner. Clearly, optical folding of this device is required for implementation, but this should not be a serious problem.

References

2.1 Fowlis, W.W. 1979. Optical Engineering, 18, 281.

FIGURE 2.1 THE GFFC INSTRUMENT



1 - SURVEY OF DIELECTRIC LIQUIDS

2 - HIGH VOLTAGE AND HIGH FREQUENCY SOURCES

3 - DUST REMOVAL

4 - OBSERVATION OF THE FLOW AND DATA STORAGE

5 - OPTICAL FIELD OF VIEW

6 - THERMAL CONDITIONS

7 - CONTROL OF THE TOTAL APPARATUS

8 - MATERIAL FOR THE OUTER SPHERE

9 - CONFIGURATION OF THE APPARATUS

10 - THE AGCE APPARATUS DESIGN AND FABRICATION COSTS

FIGURE 2.2 AGCE FEASIBILITY STUDY TASK LIST

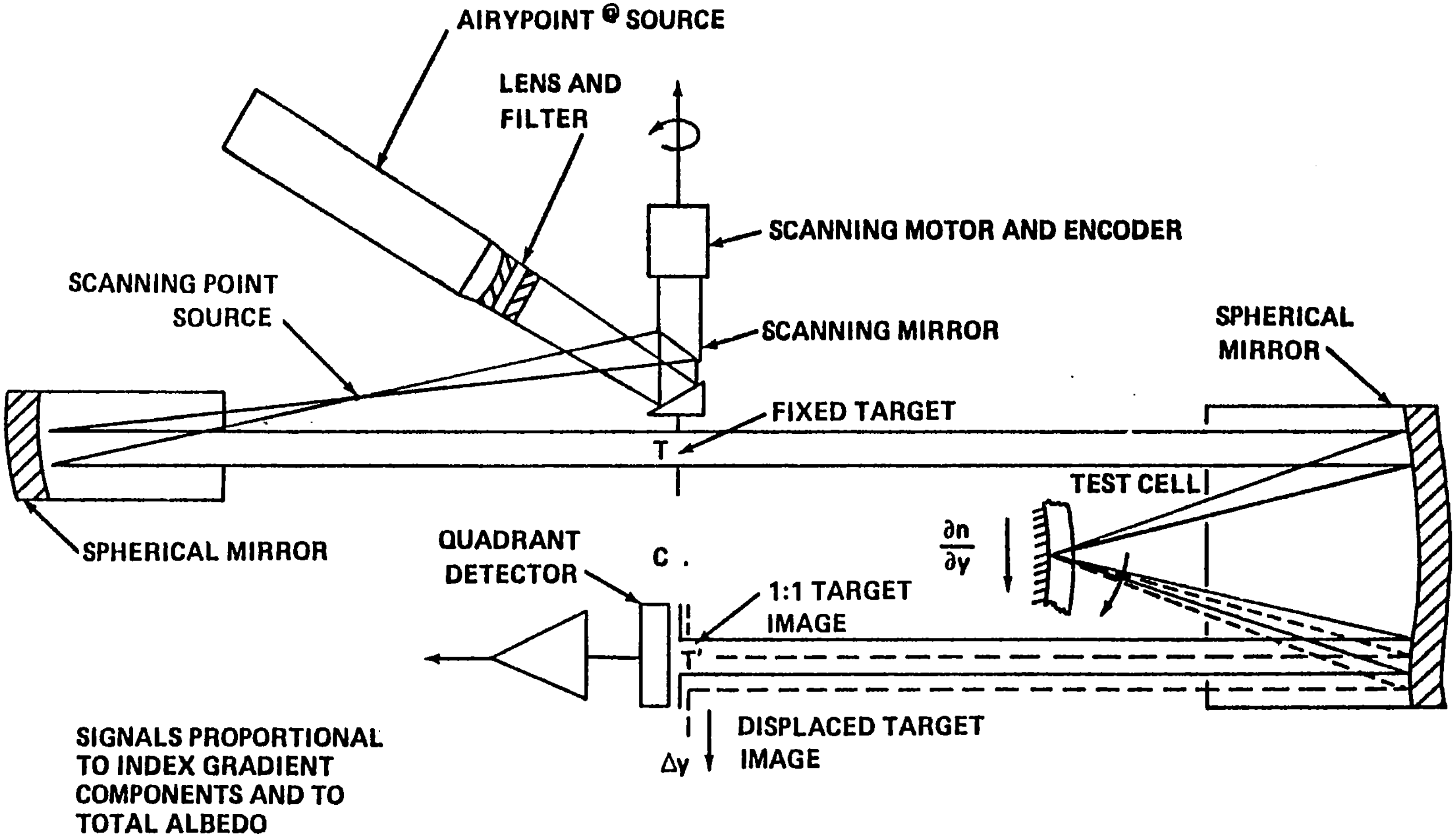


FIGURE 2.3 THE AGCE SCANNER CONCEPT (UNFOLDED)

3. HYDROSTATIC CALCULATIONS OF AXISYMMETRIC FLOW AND ITS STABILITY FOR THE AGCE MODEL

by

Timothy L. Miller
and
Robert L. Gall

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The ultimate purpose of this set of calculations is to determine where baroclinic waves might be expected in the AGCE apparatus by the use of numerical hydrostatic primitive equation models. This will be accomplished by using an axisymmetric primitive equation model to compute, for a given set of experimental parameters, a steady state axisymmetric flow and then testing this axisymmetric flow for stability using a linear primitive equation model.

The hydrostatic model has the advantage that it is fairly inexpensive to run. The cost for the axisymmetric model is about one second of CYBER-175 computer time per second of experimental time. This is for a stretched grid of moderate resolution, with three points in the interior of the Ekman layer for the case of $\Omega = 3$. (The Ekman layer is thicker for lower rotation rates.)

At the NCAR workshop, some axisymmetric flows were presented, and also some preliminary stability calculations. Steady axisymmetric flows have been calculated for rotational rates $\Omega = 0, 1, 2$ and 3 (radians per second). Stability calculations were completed for just one of these cases, $\Omega = 3$.

Initial and Boundary Conditions

The temperature was held constant at the inner and outer walls. On the outer, it was 35°C at the equator and 25°C at the pole. On the inner, it was 25°C at the equator and 15°C at the pole. On both, the temperature distribution was linearly interpolated in between. The condition of zero heat flux was assumed at the equator and polar walls. A physical wall was assumed at the equator; horizontal velocities were assumed to be zero there, at the pole and at the horizontal boundaries. The initial condition was that the interior had a temperature distribution interpolated linearly in between the inner and outer walls, and the fluid was in solid rotation ($\bar{V} = 0$).

Results of the Axisymmetric Calculations

Without rotation, the predicted steady-state flow is entirely in the meridional plane. There is a Hadley circulation with fluid moving northward at the top and southward at the bottom. Maximum vertical motion is at the pole in the downward direction. There is upward motion near the equator. Meridional speed increases poleward, consistent with the mass convergence that occurs in the spherical shell.

With rotation (see Fig. 3.1), there is a zonal flow caused by the Coriolis deflection, which is eastward in the outer part of the domain and westward closer to the inner sphere. Meridional flow becomes confined mostly to the horizontal Ekman layers, which become thinner with increasing rotation. The maxima in the meridional and zonal flows move away from the pole with increasing rotation.

Preliminary Linear Stability Calculations

A very simple quasi-geostrophic model has been utilized for a preliminary test of the stability of the predicted axisymmetric flow to perturbations with longitudinal and vertical dependence. Results of calculations performed for three columns (each of a different latitude) for $\Omega = 3$ were presented. Unstable modes were present for virtually all wavelengths and at all three columns. There were at least three types of unstable modes.

One was "deep", resembling the "Eady Mode" while the others tended to be mostly confined to the upper or lower portions of the spherical shell. It is expected that the growth rates predicted by a full, primitive equation linear model will be comparable to those for the "deep" mode predicted by this simple model for the column containing the zonal jet. This primitive equation linear model is currently under construction.

Figure Legend

Contours of temperature (in degrees C) and velocity (cm/sec) fields. Eastward velocity is "u", northward is "v", and radial (upward) is "w". "Delta" is the contour interval. Dashed contours denote negative values; the first solid contour is the zero contour.

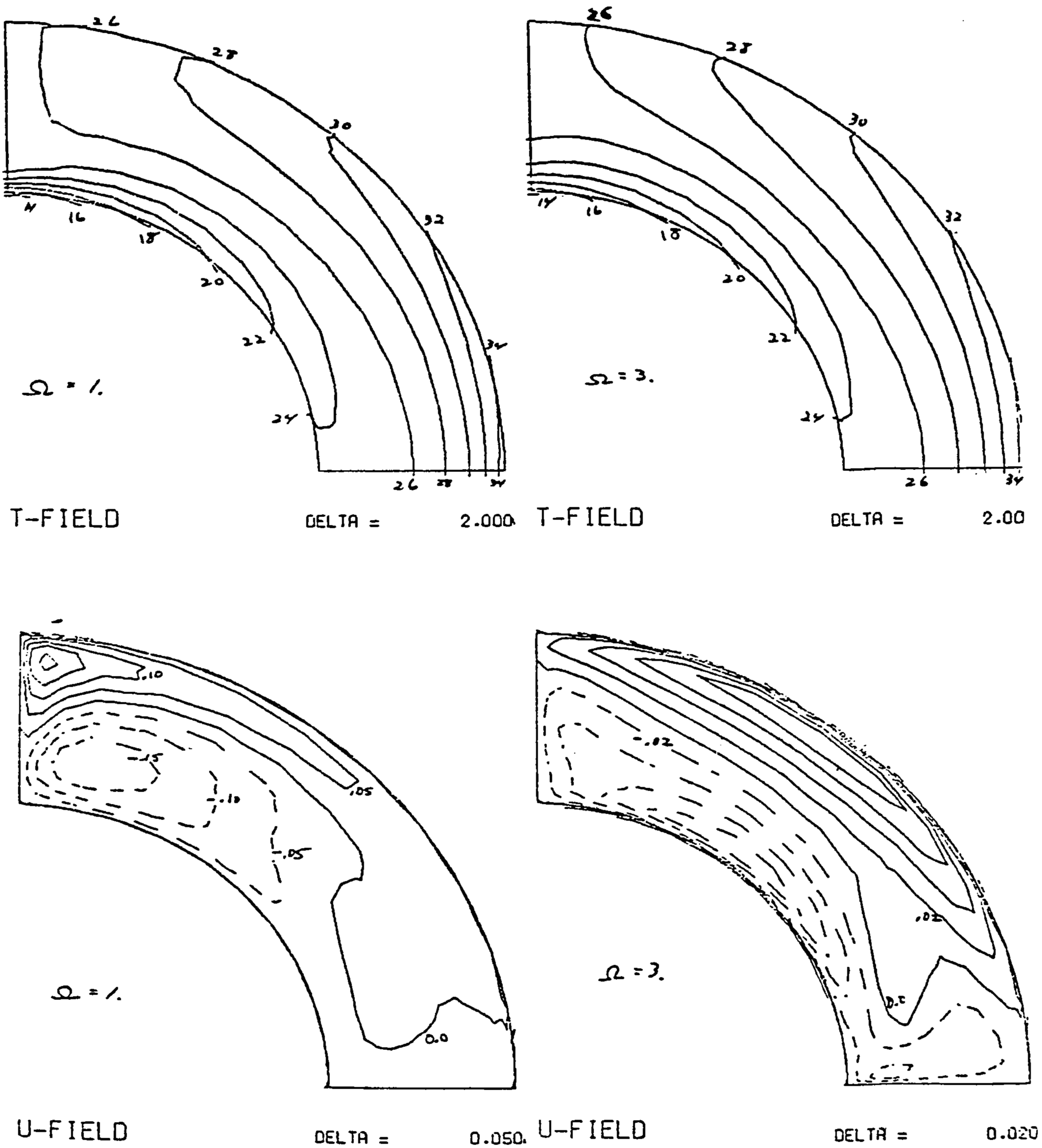
T-FIELD
DELTA = 2.000
T-FIELD
DELTA = 2.00
U-FIELD
DELTA = 0.050
U-FIELD
DELTA = 0.020

FIGURE 3.1a

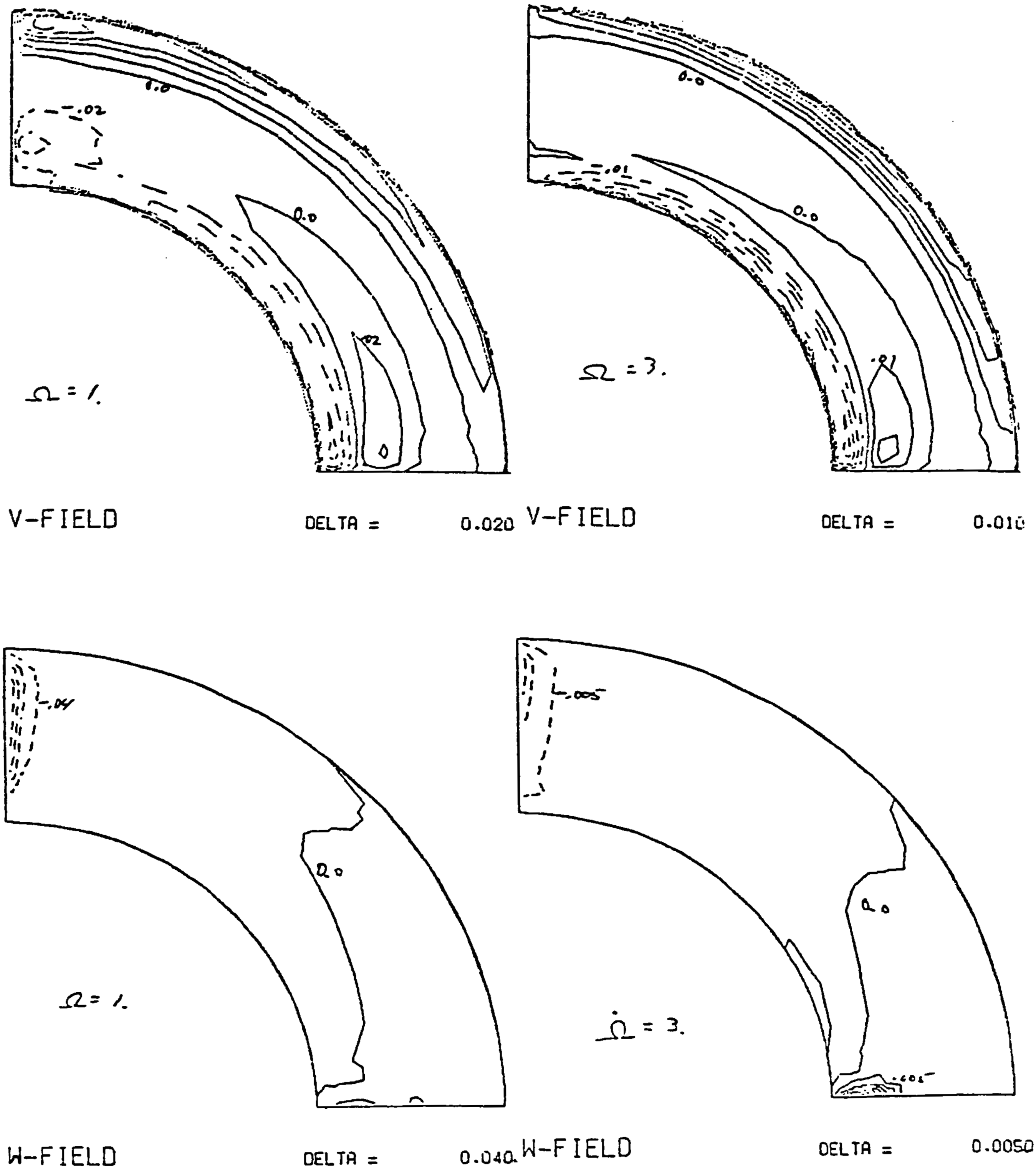
V-FIELD
DELTA = 0.020
V-FIELD
DELTA = 0.010
W-FIELD
DELTA = 0.040
W-FIELD
DELTA = 0.0050
0.0
0.0
0.0
0.0
0.0
0.0

FIGURE 3.1b

4. CYLINDRICAL ANNULUS MODELS

Fred Leslie

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In an effort to determine numerically the stability diagram for the AGCE, the cylindrical code of Warn-Varnas (Ref. 4.1) was to be modified for linear stability and adapted to spherical geometry. The code was to compute axisymmetric basic states and then test their stability to zonal disturbances. This report briefly describes the Warn-Varnas code and presents some of the basic state results.

The code solves the Boussinesq Navier-Stokes equations (in flux form) along with the temperature and continuity equations in a cylindrical coordinate system rotating about a vertical axis. Axial symmetry and constant coefficients of expansion, viscosity and thermal conductivity are assumed. The vertical sidewalls are maintained at prescribed temperatures while the top and bottom are thermal insulators.

The computations are made on a staggered grid and linear averaging is used for points not containing the variable of interest. The grid is stretched by the function tanh (bi) where i is the grid point number and b is a stretching parameter based on the Ekman number, such that at least five grid points lie within the Ekman layer.

Typically, a 42 x 42 grid was used, although some calculations were performed on a 26 x 26.

The leap-frog scheme is used for time differencing. When only a steady state solution was of interest, the time step was frequently adjusted to be about as large as the CFL stability criterion would allow. If time evolution of the flow was important, then a smaller fixed time step was used. The nonlinear terms are center-differenced and nondivergence is incorporated. The Dufort-Frankel scheme is used for the diffusion terms. The Coriolis terms are differenced in the manner of Gareth Williams so as not to contribute energy to the fluid. Finally, the buoyancy and pressure gradient terms are center-differenced. The scheme is approximately second order accurate except for the diffusion terms. Stability is maintained by the CFL limit as well as time restrictions based on the rotation rate and the Brant-Vaisala frequency. Pressure is determined from a Poisson equation formed from the radial and vertical equation. This equation is solved using ADI and optimized iteration parameters based on the nature of the grid (Ref. 4.3). Initially, the fluid was taken in solid body rotation with the container and with a temperature conduction profile.

For the purpose of validating the model, comparisons were made with the cylindrical annulus basic states devised by Williams (Ref. 4.4). In particular, runs were made for the same parameters as Williams' Case A3. This case is specified by: a free surface, inner radius = 3.68 cm, outer radius = 6.02 cm, fluid (water) depth = 5 cm, rotation rate = 1.342 rad/sec, imposed horizontal temperature difference = 29°C. (These values give a flow in the upper symmetric region of the regime diagram.) The model predictions, after running for 151.5 sec. of experimental time, are shown in Fig. 4.1. Fig. 4.1a shows the stream function, 4.1b the temperature and 4.1c the zonal flow. Fig. 4.2 shows Williams' results for the same conditions and time. The agreement is excellent. The code has also been used to model spin-up and the results compared with laboratory measurements (see Report 7).

To assist the Feasibility Study (see Report 2) in the design of the temperature control system for the AGCE, the Warn-Varnas code was run in a cylindrical form which approximated as closely as possible the spherical AGCE geometry (see Fig. 1.2, Report 1). A cylindrical annulus of silicone fluid 1 cm deep was considered. The inner cylinder radius was reduced to nearly zero while the outer cylinder radius was made to be the mean distance from equator to pole on the AGCE apparatus (8.64 cm). The small inner cylinder is required for numerical stability (Ref. 1.1); a free-slip boundary condition was used for the vertical velocity at the inner cylinder. The temperature along the bottom varied linearly from 15°C to 25°C and along the top from 25°C to 35°C. The sidewalls were insulators. The upper surface was taken as a rigid boundary. The cylinder was rotated at a rate of 2.094 rad/sec. The results obtained after running for a time of 210 sec. are shown in Fig. 4.3.

Since more up-to-date and efficient codes are now being developed for the AGCE design studies (see Report 5), this work with the Warn-Varnas code will not be continued beyond this stage.

References

4.1 Warn-Varnas, A., Fowlis, W.W., Piacsek, S. and Lee, S.M. (1978) J. Fluid Mech., 85, 609.

4.2 Williams, G.P. (1969) J. Fluid Mech., 37, 727.

4.3 Wachpress, E.L. (1966) Iterative Solutions of Elliptic Systems, Prentice-Hall, NY.

4.4 Williams, G.P. (1967) J. Atmos. Sci., 24, 144.

FIGURE LEGENDS

FIGURE 4.1a The stream function for Williams' Case A3. The maximum value is 0.310, the minimum 0 and the contour interval 0.03.

FIGURE 4.1b The temperature for Williams' Case A3. The contour interval is .1 of the imposed temperature difference.

FIGURE 4.1c The zonal velocity for Williams' Case A3. The maximum value is 2.31 cm/sec, the minimum -0.581 cm/sec. The contour interval is 0.3 cm/sec.

FIGURE 4.2 Williams' results for his Case A3. Stream function, temperature and zonal velocity are shown.

FIGURE 4.3a The stream function for the cylindrical approximation to the AGCE apparatus. The maximum value is .0186, the minimum 0 and the contour interval .002.

FIGURE 4.3b The temperature for the cylindrical approximation to the AGCE apparatus. The contour interval is .1 of the maximum imposed temperature difference.

FIGURE 4.3c The zonal velocity for the cylindrical approximation to the AGCE apparatus. The maximum value is .0667 cm/sec, the minimum -.0674 cm/sec. The contour interval is .015 cm/sec.

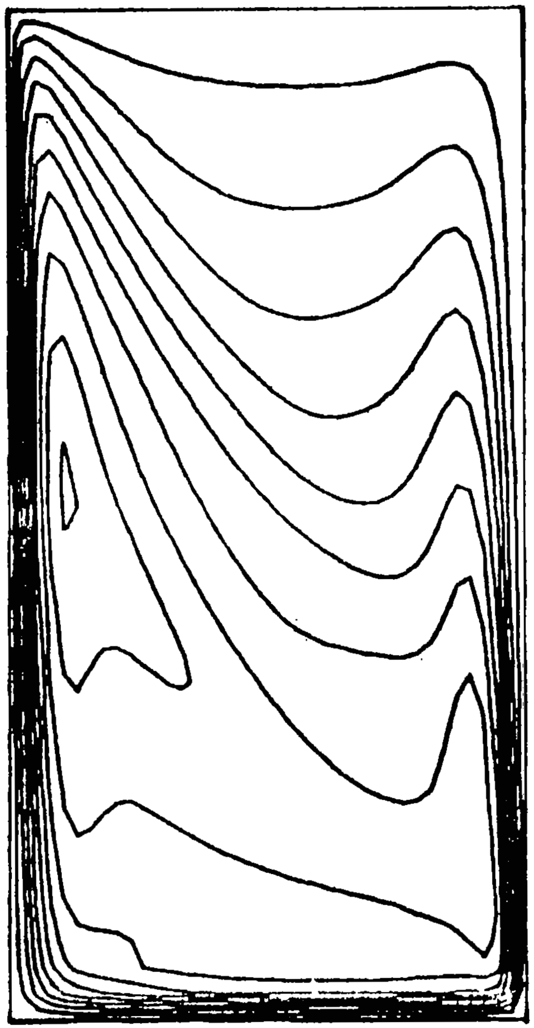


FIGURE 4.1a CASE A3
STREAM FUNCTION
TIME = 151.5 SEC

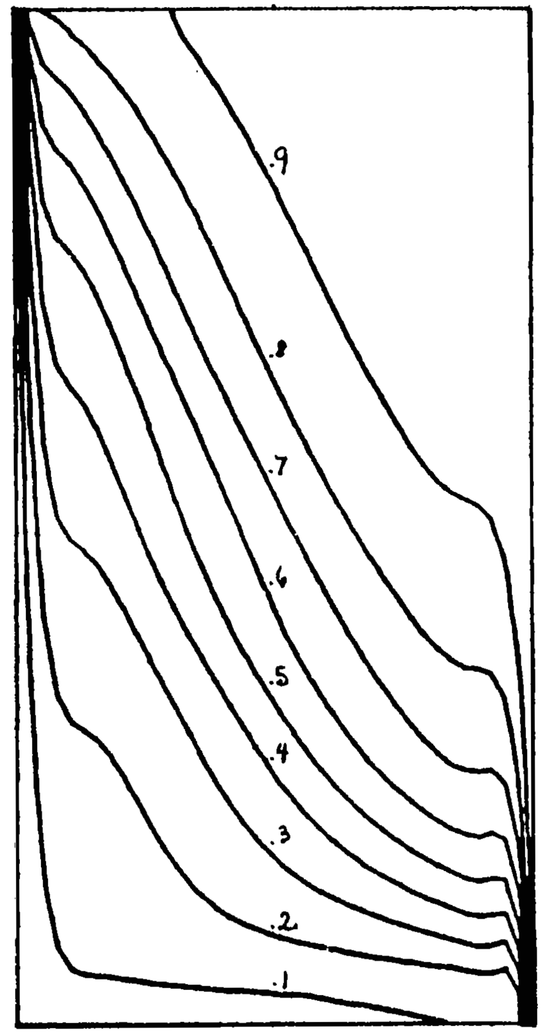


FIGURE 4.1b CASE A3
TEMPERATURE
TIME = 151.5 SEC

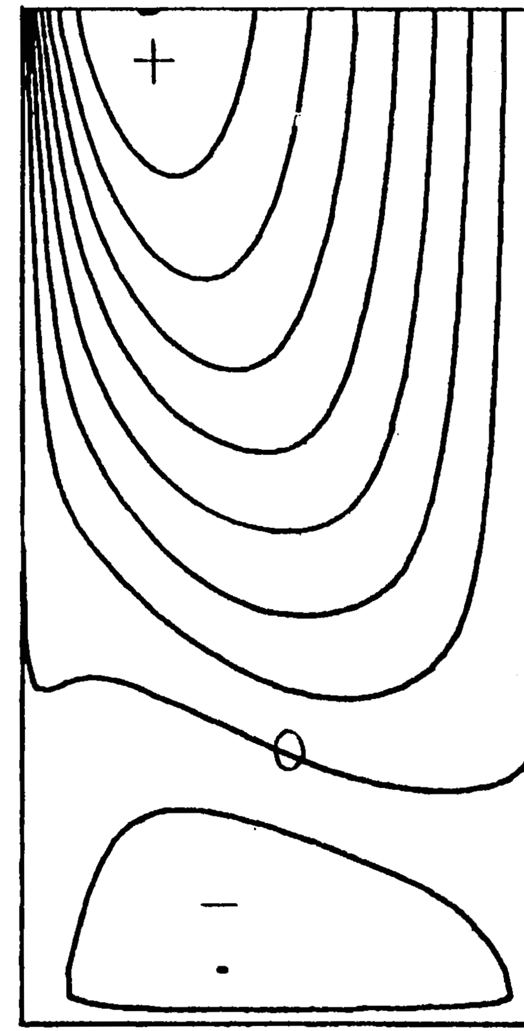
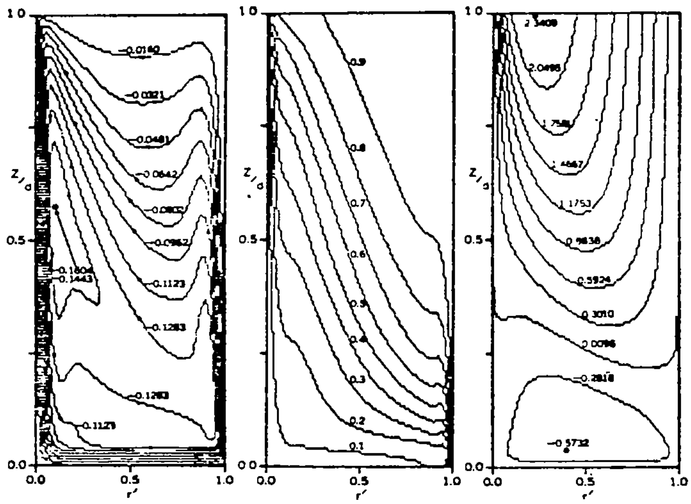


FIGURE 4.1c CASE A3
ZONAL VELOCITY
TIME = 151.5 SEC



t = 151.5

FIGURE 4.2

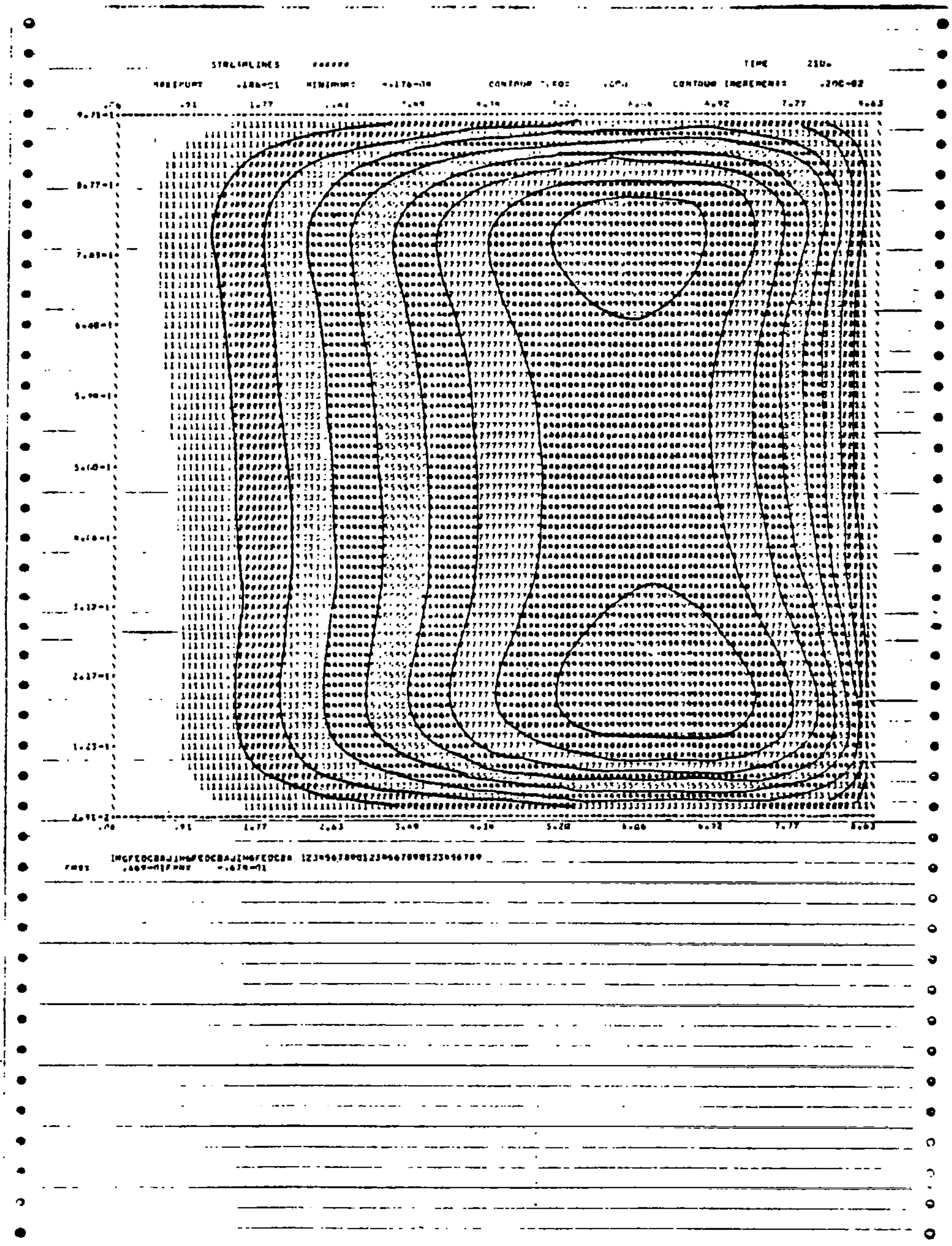


FIGURE 4.3a

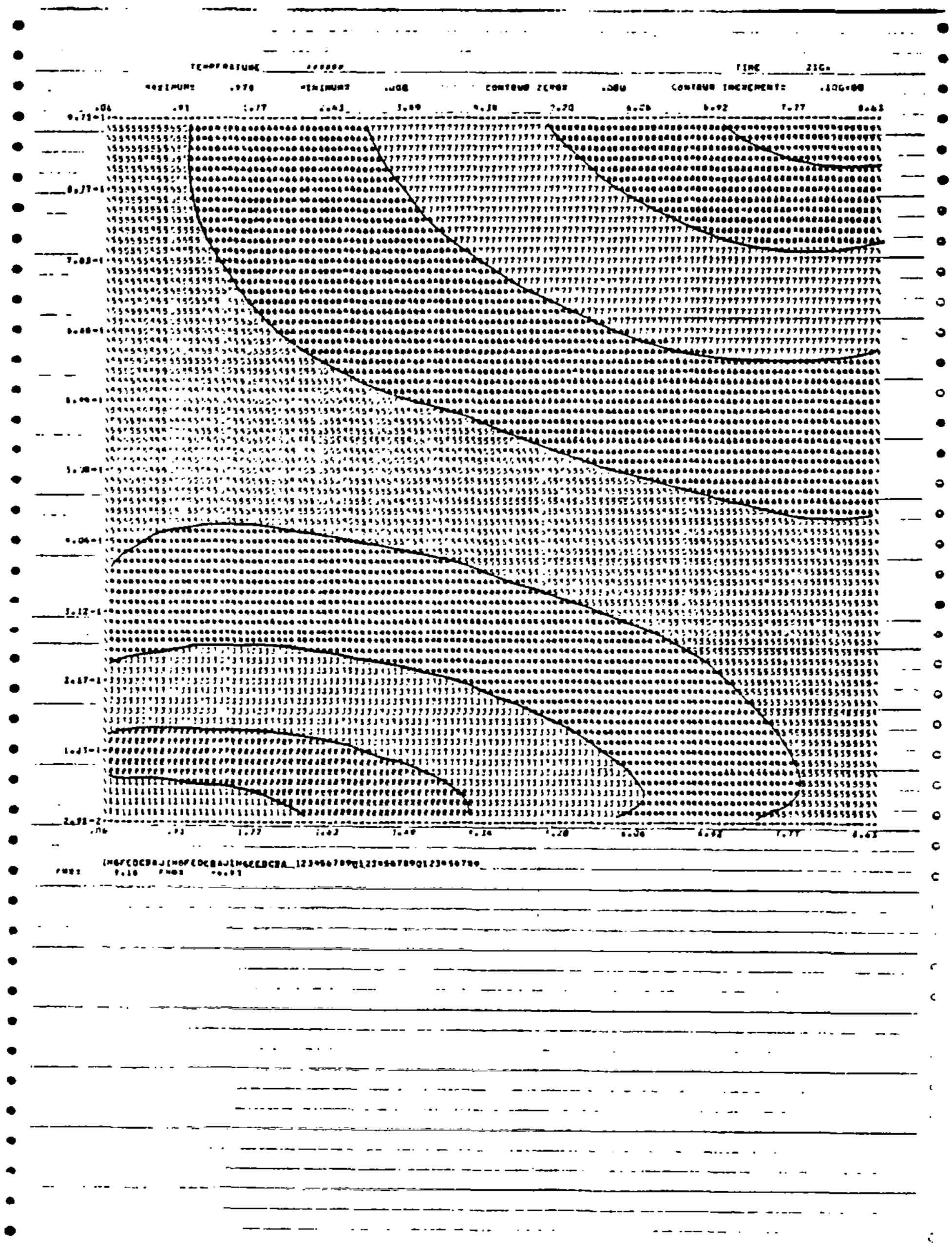


FIGURE 4.3b

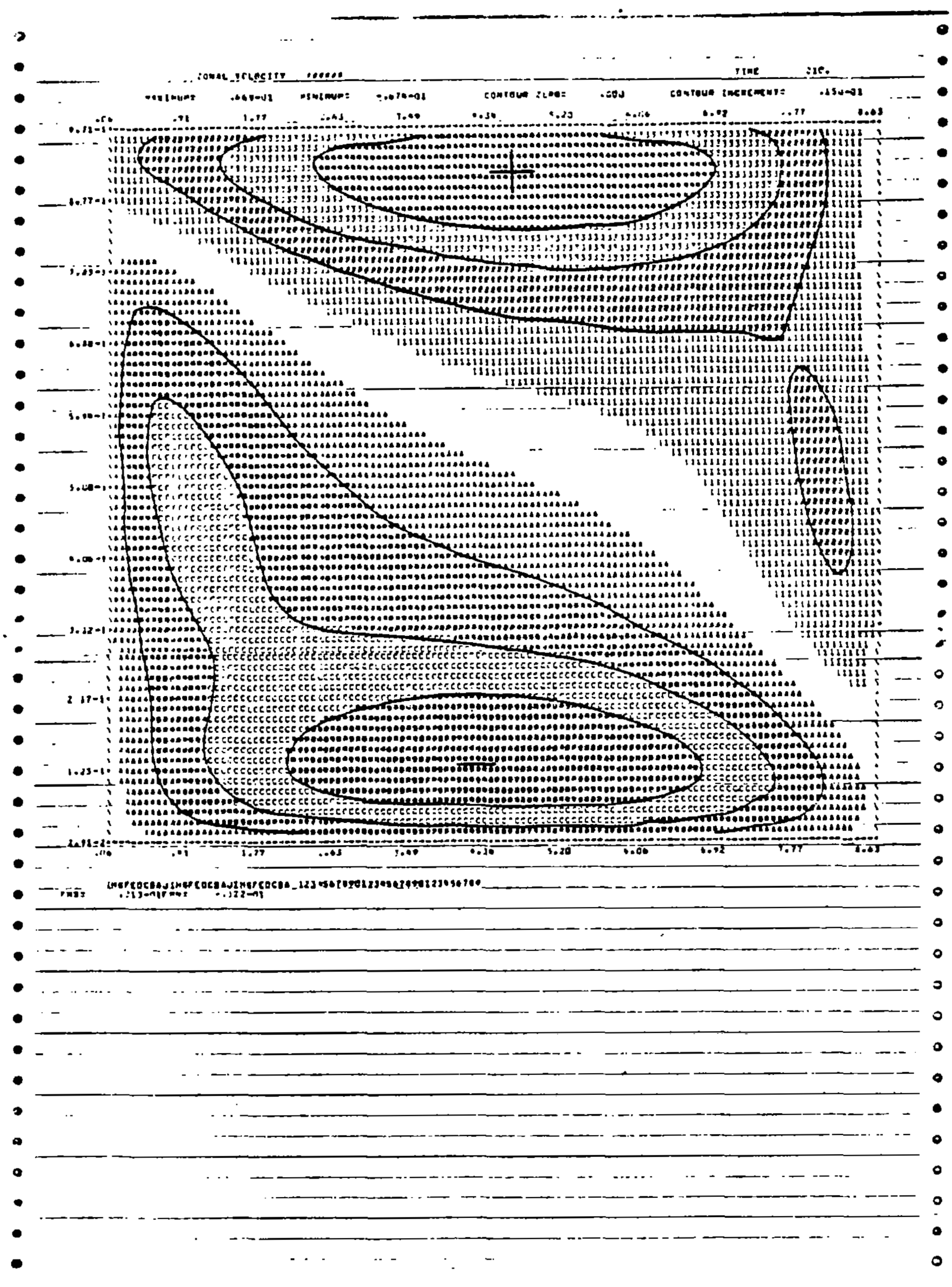


FIGURE 4.3c

5. SPHERICAL MODELS: BASIC STATES AND STABILITY

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Introduction

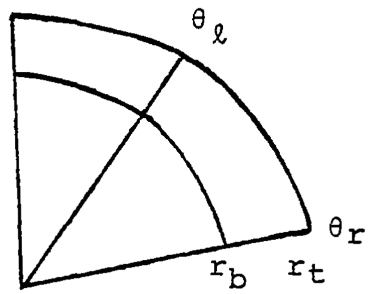
This program, begun in March 1981, is a numerical study of steady axisymmetric basic states in a spherical cap and of their stability to azimuthally varying perturbations of different wave numbers. We are still at a planning stage, and no results are yet available. In this report, we outline the main features of the planned computer code and numerical methods.

Equations

The equations are the ordinary convection equations for a rotating incomprehensible Boussinesq fluid. The thermal diffusivity is a constant, but the kinematic viscosity may be a function of temperature. The buoyancy acceleration is $b\nabla\phi$. Here b is normally αT, but may include a quadratic term for certain fluids. The gravitational potential ϕ has up to three terms, corresponding to dielectric radial gravity, the centrifugal force, and terrestrial gravity for preliminary tests. The equations are written in spherical polar coordinates.

Domain

The axisymmetric cap domain is illustrated in the figure. The inner and outer spheres have radii r_b and r_t,



and the polar angle is between θ_ℓ and θ_r. The left boundary is normally the axis. The right boundary may be at the equator, or at 150° (leaving a 30° cone for hardware). These boundaries allow an annulus geometry, by making the inner radius very large, and the angle boundaries correspondingly small.

Boundary Conditions

The solid boundaries have zero velocity. Appropriate boundary conditions are applied at the axis. The code will allow the options of free-slip or symmetry boundaries, but there will be no normal flow.

The four boundaries have either zero normal temperature derivative or imposed temperature. The imposed temperature is defined by the corner temperatures, assuming linearity in r and in one of the three functions θ, θ^2 and $\cos 2\theta$. The last function has appropriate symmetry at the equator and pole.

Nonuniform Mesh

A nonuniform finite difference mesh in r and θ is used to provide adequate resolution in the thin boundary layers without wasting mesh points in the interior. The mesh spacing is proportional to the product of the distances from chosen points just outside the boundaries.

Spatial Representation of Axisymmetric Equations.

The placement and staggering of the variables on the mesh, and the relative placement of the boundaries, minimizes the required averaging and facilitates the time representation. A flux representation of the advection terms is used to avoid nonlinear instability. Central differences are used for all derivatives. The representation is chosen to conserve representations of heat, temperature squared, momentum, angular momentum, and potential energy, as far as these are conserved by the equations.

Spatial Representation of Linear Disturbances

The equations for zonally varying linear perturbations of an axisymmetric basic state are represented in the same way. The variables are complex functions of θ and r, with azimuthal dependence $\exp(im\lambda)$ understood.

Iteration for Steady Axisymmetric Solution

The iteration method is based on implicit time stepping, but uses time steps which are different for temperature and velocity, and which are proportional to the mesh spacing so that they are smaller in the boundary layers. Without this method, excessively many iterations are required for convergence, especially for the interior temperature. Advection, diffusion, and the Coriolis force are treated by an alternating direction implicit method. This first stage of an iterative step uses an extrapolated pressure from previous steps. In the second stage, the new flow is made incompressible using a correction pressure field which is obtained by solving a Poisson equation. For this equation, an efficient ADI iterative method is used.

Iterative Method for the Stability Analysis

The fastest growing or slowest decaying linear eigenmode, for a given axisymmetric basic state and zonal wave number, is found by an iterative method closely related to that described above. Terms $-pT$ and $-p\underline{u}$ are added to the right hand sides, where p is the complex growth rate eigenvalue, and is updated after each iteration step. When a steady solution is obtained, the real part of p is the required growth or decay rate.

6. THE THREE-DIMENSIONAL SPHERICAL MODEL FOR THE AGCE

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The objective of the present task is to develop an accurate numerical model of the Atmospheric General Circulation Experiment (AGCE). Since such a model will serve both as a design and diagnostic tool for the AGCE, as well as for conducting numerical experiments which otherwise cannot be performed by AGCE, the numerical code has to be extremely versatile. The code in its final form will solve the complete three-dimensional, nonlinear Navier-Stokes energy equations with the Boussinesq approximation. As indicated, the code will be versatile in that it will allow for any thermal boundary conditions and any external forcing in the form of rotation and body forces. Also, the code will allow for variable thermodynamic coefficients.

It was decided that such a code is best developed in three stages in such a way that each stage would add to the complexity of the code. The first stage of the development will be to solve for the axisymmetric flow in the spherical annulus under the conditions of the AGCE. This will be the simplest version of the code in that it will solve the two-dimensional form of the governing equations. The results of this stage will help in the understanding of the steady basic flow field of the AGCE, if any exists. The second stage will add in the complexity of the code by solving for the instability of the two-dimensional basic state and study the organized waveflow if such a state exists. Finally, by including a complete spectrum of Fourier modes in the azimuthal direction, the fully three-dimensional nonlinear flow field will be analyzed.

The specific numerical method used in the final code will be a mixed finite-difference-spectral technique. Due to the specific geometry of the AGCE (spherical annulus) spectral methods are ideally suited, especially in the latitudinal and azimuthal directions. However, a finite difference approximation will be used in the radial direction and time. The spectral technique will be comprised of a double Fourier-Chebyshev expansion, where the Chebyshev polynomial expansion will be used in the latitudinal direction. This is necessitated by the existence of solid boundaries across the spherical gap at some preassigned latitudinal direction. In the azimuthal direction, the Fourier expansion will be used; which is best suited due to the periodicity of the geometry and the boundary conditions, and since it is expected that the fully three-dimensional flow field will develop wavey motion in that direction.

As for the finite differencing, a semi-implicit technique will be used with the proper grid stretching near the walls.

At the present time the code is being constructed for the time-dependent axisymmetric flow in the spherical annulus without latitudinal walls. However, for this code a special Fourier series in the latitudinal direction is being used which incorporates the Fast Fourier Transform to speed up the calculations. The finite difference solution will be implicit for the diffusion terms and explicit for the nonlinear terms. Once this code is verified and is running, the Chebyshev polynomial expansion in the latitudinal direction will be incorporated to allow for the latitudinal walls. Thus, to date the project is well into the first stage of the development which will be completed soon.

7. MODEL VERIFICATION STUDIES USING ACCURATE MEASUREMENTS OF SPIN-UP

Jae M. Hyun, NRC, NASA/MSFC

A computer code (Ref. 7.1) to generate numerical solution for axisymmetric rotating fluid in a cylinder has been obtained and amended for routine use at MSFC (see Report 4). The numerical simulations used the Navier-Stokes equations in axisymmetric form and employed finite-difference techniques on both constant and variable grids. The purpose of this work is to check the reliability and accuracy of this numerical code for spin-up flows in a cylinder by comparing the numerical results against high-resolution laser-Doppler velocimeter (LDV) measurements of the azimuthal flows. After the code was verified by cross-checking it against the laser measurements, the numerical solutions were analyzed in detail to gain further insight into the fundamental questions analyzed in rotating fluid dynamics. The following four categories of spin-up flows have been studied:

A. Linear Homogeneous Spin-Up.

The spin-up flows in a cylinder of a homogeneous fluid under small Rossby numbers have been simulated by use of this code (Ref.7.1). The results exhibit excellent agreement with LDV measurements. The agreement is good not only for the overall decay of the azimuthal flow, but also for the amplitudes and phases of the weakly excited inertial modes. The results also establish that the theoretical analysis (Ref. 7.2) gives an accurate description of the overall azimuthal flow decay. It is important to note that in linear homogeneous spin-up the azimuthal velocity in the interior decays essentially as solid-body rotation.

B. Linear Stratified Spin-Up.

A modified version of this code was used to obtain numerical solutions for spin-up flows under small Rossby numbers of a thermally stratified fluid in a cylinder with insulating sidewall (Ref. 7.3). Comparisons of the numerical results against LDV measurements showed excellent agreement, establishing the reliability and accuracy of the code for stratified problems. It is found that, in agreement with previous work, the azimuthal flow decays significantly faster than the prediction of the theory (Ref. 7.4). It has been shown in Ref.7.3 that viscous diffusion in the interior, which has more pronounced effects in stratified flow, is the cause of the discrepancy with the theory.

C. Nonlinear Homogeneous Spin-Up.

The problem of spin-up from rest in a cylinder of a homogeneous fluid was examined numerically using this code (Ref.7.5). Again, comparisons of the numerical results against LDV measurements show excellent agreement, demonstrating the accuracy of this code for nonlinear problems. Attention was focused in Ref. 7.5 on the structure of the moving front, which separate the interior flow into two distinctive regions. By performing systematic diagnostic studies of each term in the azimuthal momentum equation, radial profiles were displayed of the behavior of the various dynamic effects near the front. The limitations of the previous analytical models become apparent in light of the comprehensive flow data produced by the present numerical solutions.

D. Nonlinear Stratified Spin-Up.

A preliminary run was made using this code to simulate spin-up from rest in a cylinder of a stratified fluid. Accurate LDV measurements are not available for this problem, but exploratory experiments have been reported (Ref. 7.6). There is a question of non-axisymmetry in stratified spin-up from rest after the bow-shaped front reaches the cylinder axis. The numerical results, however, appear to be in good agreement with the descriptions provided by the exploratory experiments for at least up to the usual homogeneous spin-up time scale.

References

7.1 Warn-Varnas, A., Fowlis, W.W., Piacsek, S. and Lee, S.M. (1978) J. Fluid Mech., 85, 609.

7.2 Greenspan, H.P. and Howard, L.N. (1963) J. Fluid Mech., 17, 385.

7.3 Hyun, J.M., Fowlis, W.W., and Warn-Varnas, A. (1981) Accepted for publication in the J. Fluid Mech.

7.4 Walin, G., (1969) J. Fluid Mech., 36, 289.

7.5 Hyun, J.M., Leslie, F., Fowlis, W.W., and Warn-Varnas, A. (1981) in preparation.

7.6 Greenspan, H.P. (1980), Geophys. Astrophys. Fluid Dyn., 15, 1.

8. PRELIMINARY REGIME DIAGRAM ON A SPHERE WITH A SIMPLIFIED GENERAL CIRCULATION MODEL

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I. INTRODUCTION

In the Atmospheric General Circulation Experiment (AGCE) apparatus a fluid is confined between co-rotating spheres in the presence of a simulated radial gravity and a meridional temperature gradient on the inner sphere. This situation is much closer to the atmosphere than is the traditional laboratory analogue, which consists of an annulus of fluid confined between co-rotating cylinders oriented parallel to terrestrial gravity. Surprisingly little effort has been devoted to the theoretical modeling of flows in the laboratory annulus, either for design studies or for understanding of the data, a situation due in large part to the limited capability for numerical simulation of fluid flow existing 20 years ago when laboratory annulus experiments were in vogue. The capability does exist today and in view of the cost and scope of the AGCE it must be utilized to generate information for design and to interpret experimental results.

Our objective is to provide results from numerical model studies that will be useful for design considerations and which can be accumulated to form the body of basic knowledge necessary for application of the AGCE data to the understanding of atmospheric problems. Our philosophy is that the most efficient way to obtain a computer model suitable for this objective is to modify an existing general circulation model (GCM) of the atmosphere rather than to develop such a model from first principles. Here we briefly outline the GCM and what we have done to modify it. This is followed by a presentation of recent results we have obtained.

II. THE MODEL

The model we have chosen to modify is currently the official GCM at the National Center for Atmospheric Research (NCAR). For this reason, even though its development has involved several people at several institutions, we refer to it hereafter as the NCAR model. Fig. 8.1 provides a description of the model. Several papers documenting the model and verifying its output against atmospheric data sets are in preparation.

We have modified the model by removing various physical components until what remains is a code that solves the nonlinear primitive equations on a sphere. Thus, we have removed most of what is seen in Fig.8.1 including topography, retaining only the spectral dynamics, diffusion, and dry convective adjustment. The reason for dropping all the physics and retaining only the bare dynamics is that we wish to operate the model in the laboratory mode (more specifically, in the AGCE mode). In this modified version the GCM is not an exact model of the AGCE apparatus, but it is much closer to it than any other model we are aware of. A secondary but important effort arising from this drastic pruning of the model is a speeding up of the model run time. An additional benefit of using this GCM, as against developing a model from scratch, is that we can make use of the diagnostic package that comes with the model to display the results.

We are currently operating the model with a rhomboidal truncation at $M = 7$ rather than $M = 15$, thereby gaining a factor of 8 in run time. It is not expected that we can explore much of the geophysically relevant portions of parameter space with the $M = 7$ truncation, but we can explore a good deal of the parameter space that has been covered in the classical laboratory annulus experiments. We have retained the full 9 levels of vertical resolution.

The forcing in our model is a prescribed meridional temperature distribution at the lower boundary. This boundary is flat and there is no division into land and sea. We have chosen the simplest possible way of getting this heat up into the atmosphere: we erect standard temperature profiles at each latitude, thereby creating an equilibrium temperature field T_{EQ}, and then relax to this field by a linear law, that is, by inserting a term $-(T-T_{EQ})/\tau$ on the right hand side of the thermodynamic equation. We operate the model by selecting a rotation rate and a meridional temperature gradient and "spinning-up" the model from an isothermal, at-rest initial condition. What takes place subsequently in the model is the creation of a meridional over turning whose associated jets (for non-zero rotation) may become baroclinically unstable. A wave field then evolves to some essentially steady state or goes into some mode of vacillation.

Repeated trials of the spinup process just described is the mode of the classical laboratory annulus experiment. In such an experiment, the investigator notes whether the resulting motion field is axially symmetric or whether (via baroclinic instability) the axially symmetric field has waves superimposed on it. If waves are found, their characteristic and their behavior are noted. This information is then entered on the "regime diagram" where the two parameters are a thermal Rossby number and a Taylor number. In this diagram the boundary between the region of waves and the region of axially symmetric motion has a distinctive shape; and, for example, the subregion of the wave region where a vacillation occurs has been mapped out.

With some assumptions, the thermal Rossby number can be considered proportional to the static stability of the fluid, S, and the square root of the Taylor number can be considered proportional to a quantity ε^2/δ, where ε is the ratio of the horizontal temperature difference to the vertical temperature difference and δ is the Ekman number. Linear baroclinic instability models containing Ekman damping have been employed in f-plane and β-plane geometry to map out stability boundaries in the parameter space of S versus ε^2/δ. Such a map constitutes a "theoretical" regime diagram.

There is agreement to within one order of magnitude between the location of the f-plane stability boundary in the theoretical regime diagram and the boundary of the wave regime in regime diagrams obtained from laboratory annulus experiments. The only model presently available for generating theoretical regime diagrams in fully spherical geometry is the one we are describing here. We now present results from a first set of experiments with this model that shows what we believe to be a segment of the boundary separating the wave regime from the axially symmetric regime.

III. RESULTS

Before examining our theoretical regime diagram, we discuss the motion field in a few specific cases, considering first the case of zero rotation (that is, a non-rotating earth). In all cases we take the imposed equator to pole temperature difference to be 40° K. The initial condition is that of an isothermal atmosphere at rest, but with a random perturbation over the globe in the initial surface pressure field which is necessary if waves are to subsequently grow from baroclinic instability. Fig. 8.2 shows contours of zonally-averaged vertical motion ($\omega = dp/dt < 0$ corresponds to upward motion) in the zero rotation case (point E in Fig. 8.6). There is evidently a Hadley cell extending from equator to pole. The upward branch of this cell has maximum ω of about 7×10^{-4} mb sec^{-1}. There are no zonal jets, and there is no wave activity.

We next discuss a case (point Q Fig. 8.6) with rotation rate of 4×10^{-5} sec^{-1}, which is a little more than half the geophysical value. Fig. 8.3 shows the zonally-averaged zonal wind, time-averaged over geophysical days 40.5 to 50. As determined by the vertical velocity pattern (not shown) the width of the Hadley cell in this case is 30° of latitude in each hemisphere. Fig. 8.4 is a southern hemisphere polar projection of the 500 mb height field which shows that significant wave activity is present and that there is regular eastward propagation of the pattern. Visual inspection of the time history of the run shows that this wave pattern has arisen from instability and is by day 50 varying relatively slowly in amplitude. Fig. 8.5 is a power spectrum of this wave activity. It shows that in the northern hemisphere the activity is predominately zonal wave 3 and in the southern hemisphere is predominately zonal wave 4. The difference between hemispheres is presumably a consequence of the difference in the (random) pattern of initial conditions and has the interesting implication that one global run with this model really provides two independent realizations of the flow pattern. Fig. 8.5 also shows that the wave activity is predominately confined to the region between 30 and 70 degrees, which is poleward of the axes of the subtropical jets.

We turn finally to discuss Fig.8.6, which shows the points we have so far obtained on the regime diagram. Each point is coded with a "station symbol" that is defined in the upper right hand corner of the figure. This shows, clockwise from upper left, the width of the Hadley cell, an identification letter, the latitude of the westerly jet, the magnitude of the jet, the amplitude of the zonal component of the perturbation wind field at 300 mb (a measure of wave activity), and the zonal wave number where this activity is maximum. As can be seen in the figure, in going from point Q to point P there is a drop from 3.5 m sec^{-1} to 0.01 m sec^{-1} in the wave activity. A comparable drop is to be found for pairs (B,N) and (C,M). This is the basis for drawing the solid line and claiming that it is the boundary separating the wave regime from the axially symmetric regime. This curve is continued upward and to the right on the basis of the fact that in going from C to D the width of the

Hadley cell increases from 50 degrees to 90 degrees. Substantial wave activity remains at point D, however, so that more runs are needed in this area to find out exactly where the boundary lies.

At the lower right of the figure is a hatched region where the spectrum of linear growth rates from baroclinic instability models extends well past our present truncation at zonal wave 7. That this region is indeed inaccessible with the present model is confirmed by the run denoted by X, which showed a very large accumulation of wave amplitude at zonal wave 7.

We have not yet made runs long enough to unambiguously identify any vacillation. Along with the more detailed examination around point D as mentioned above, some longer runs are our next objective. This highlights another advantage of using a GCM for these studies: all of the 50 day runs so far have been saved on history tapes; and we can continue them by using the model state at 50 days as the initial condition.

SPECTRAL GCM

- SPECTRAL DYNAMICS
  - M=15 TRUNCATION (48x40 GRID)
  - SEMI-IMPLICIT TIME INTEGRATION SCHEME
  - VECTORIZED FFT
- 9 VERTICAL LEVELS, σ COORDINATES
- REALISTIC LAND-SEA-ICE DISTRIBUTION
- REALISTIC TOPOGRAPHY (SMOOTHED)
- NCAR RADIATION PACKAGE
  - SOLAR AND IR RADIATIVE TRANSFER
  - PREDICTED CLOUDINESS
  - SURFACE ALBEDO VARIES GEOGRAPHICALLY
- CONVECTIVE ADJUSTMENT AND CONDENSATION
- BULK PARAMETERIZATION OF SURFACE STRESS, SENSIBLE AND LATENT HEAT
- HORIZONTAL AND VERTICAL DIFFUSION
- SURFACE TEMPERATURE OVER LAND FROM ENERGY BALANCE; FIXED OVER OCEAN
- NO SURFACE HYDROLOGY

FIGURE 8.1

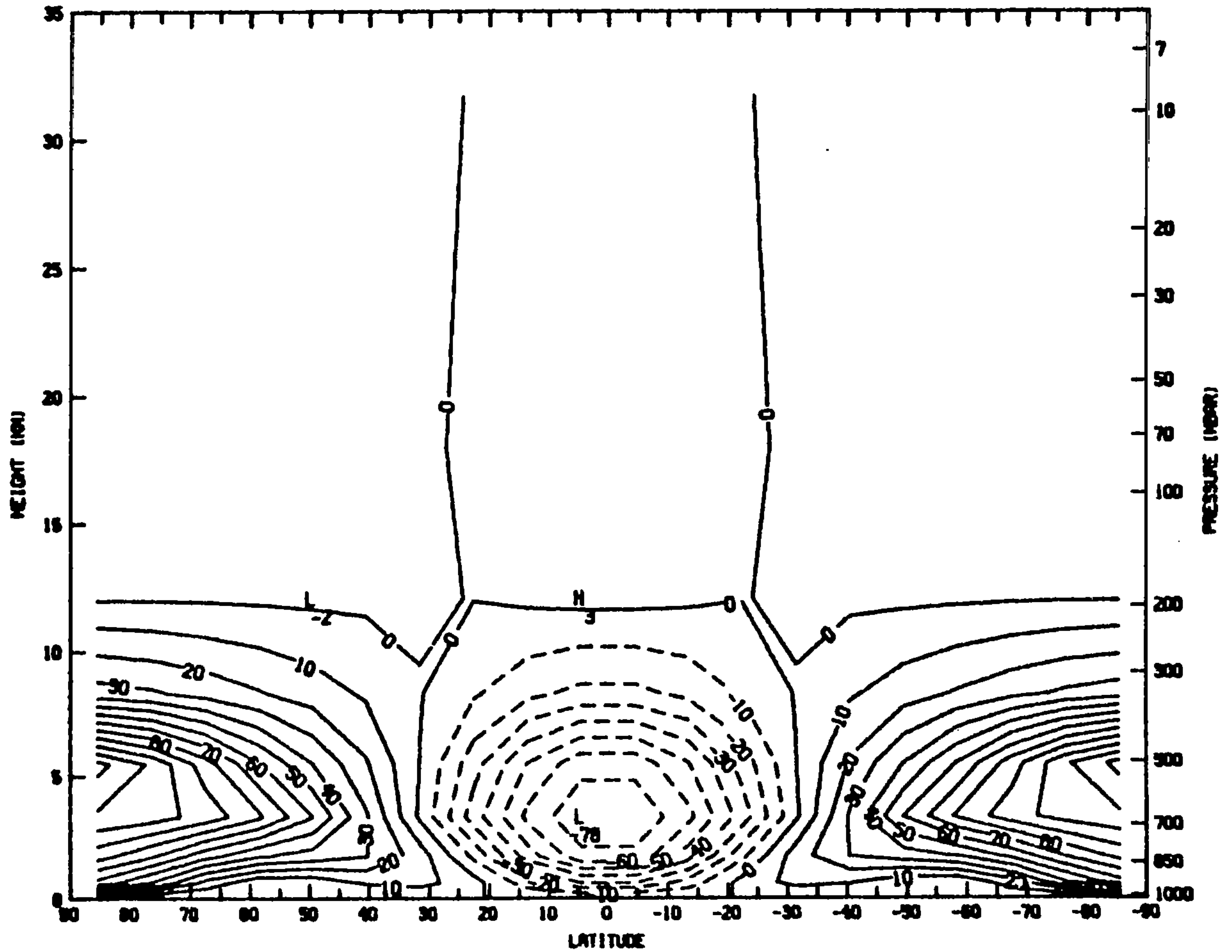
TE...ØMEGA=O SPINUP FRØM REST WITH LARGE RANDØM PERTURBATIØNS.

	NRSTRT	NFILE	KØUNTF	TØTTIM(S)	RUNDAT	RUNTIM
CURRENT	-8	1	972	3.499E+06	03/31/81	13 53 02
RESTARTF	0	1	972	3.499E+06	03/31/81	12 05 52
RESTARTL	0	1	1200	4.320E+06	03/31/81	12 05 52
INITIAL	0	0	0	0.000E+00	03/31/81	NØ TAPE

GCMPP	
THIS RUN	VERSIØN
03/31/81	03/23/81
13 53 02	15 07 42
PPS3K	PPS3K

INPUT FIELDS AVERAGED

DAYS 40.5 TØ 50.0 ØMEGA - VERTICAL VELØCITY (MB/S) ZØNAL AVERAGE



CØNTØUR FRØM -0.70000E-03 TØ 0.12000E-02 CØNTØUR INTERVAL ØF 0.10000E-03 PT(3.3)= 0.53380E-03 LABELS SCALED BY 0.10000E+08

FIGURE 8.2

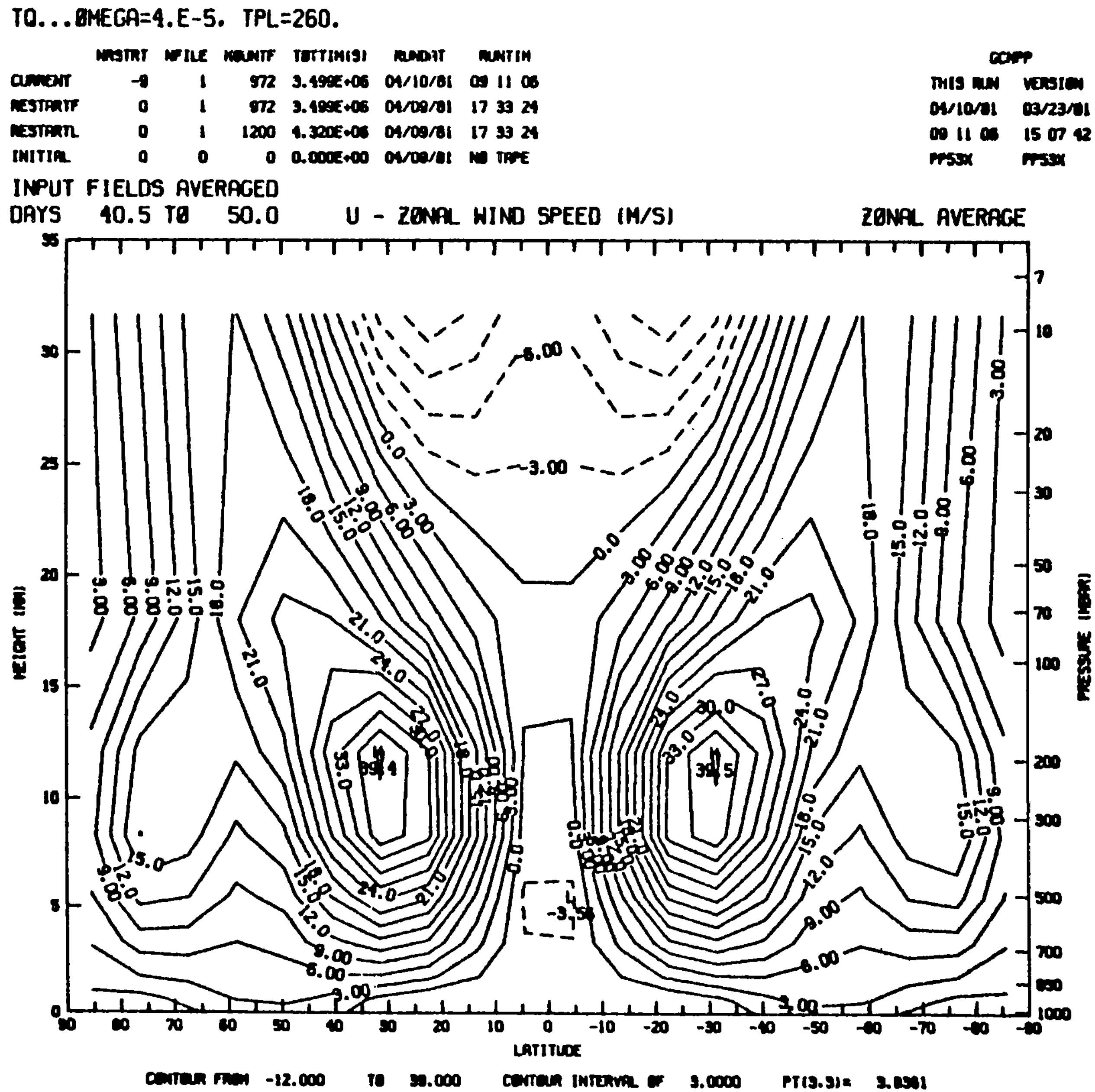

TQ...ØMEGA=4.E-5. TPL=260.
NRSTRT NFILE NCOUNTF TOTTIM(S) RUNDAT RUNTIM
CURRENT -9 1 972 3.499E+06 04/10/81 09 11 06
RESTARTF 0 1 972 3.499E+06 04/09/81 17 33 24
RESTARTL 0 1 1200 4.320E+06 04/09/81 17 33 24
INITIAL 0 0 0 0.000E+00 04/09/81 NO TAPE
GCMPP
THIS RUN VERSION
04/10/81 03/23/81
09 11 06 15 07 42
PP53X PP53X
INPUT FIELDS AVERAGED
DAYS 40.5 TØ 50.0
U - ZØNAL WIND SPEED (M/S)
ZØNAL AVERAGE
HEIGHT (KM)
PRESSURE (MBAR)
LATITUDE
CONTOUR FROM -12.000 TO 39.000 CONTOUR INTERVAL OF 3.0000 PT(3,3)= 3.8361

FIGURE 8.3

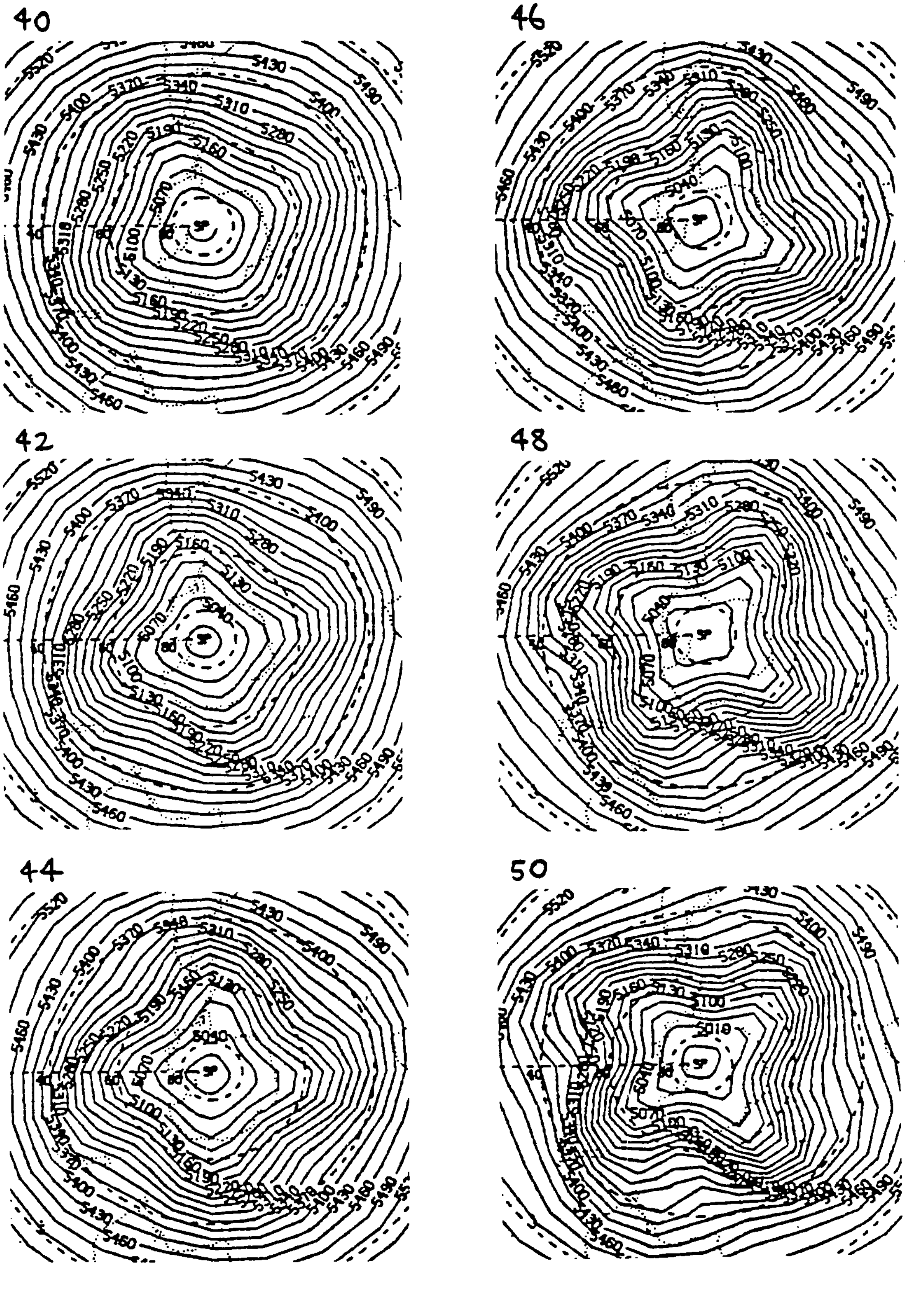


FIGURE 8.4

TQ...ØMEGA=4.E-5, TPL=260.

	NRSTRT	NFILE	KØUNTF	DAY	TØTTIM(S)	RUNDAT	RUNTIM	INPUT FILE FILTERING		SPECPP	
CURRENT	-11	1	1200	50.0	4.320E+06	04/10/81	09 04 13	TEMPØRAL	UNFILTERED	THIS RUN	VERSIØN
RESTARTF	0	1	1200	50.0	4.320E+06	04/09/81	17 33 24	SPATIAL	UNFILTERED	04/10/81	03/23/81
RESTARTL	0	1	1200	50.0	4.320E+06	04/09/81	17 33 24			09 05 13	16 28 55
INITIAL	0	0	0	0.0	0.000E+00	04/09/81	NØ TAPE			SPCX	SPOK

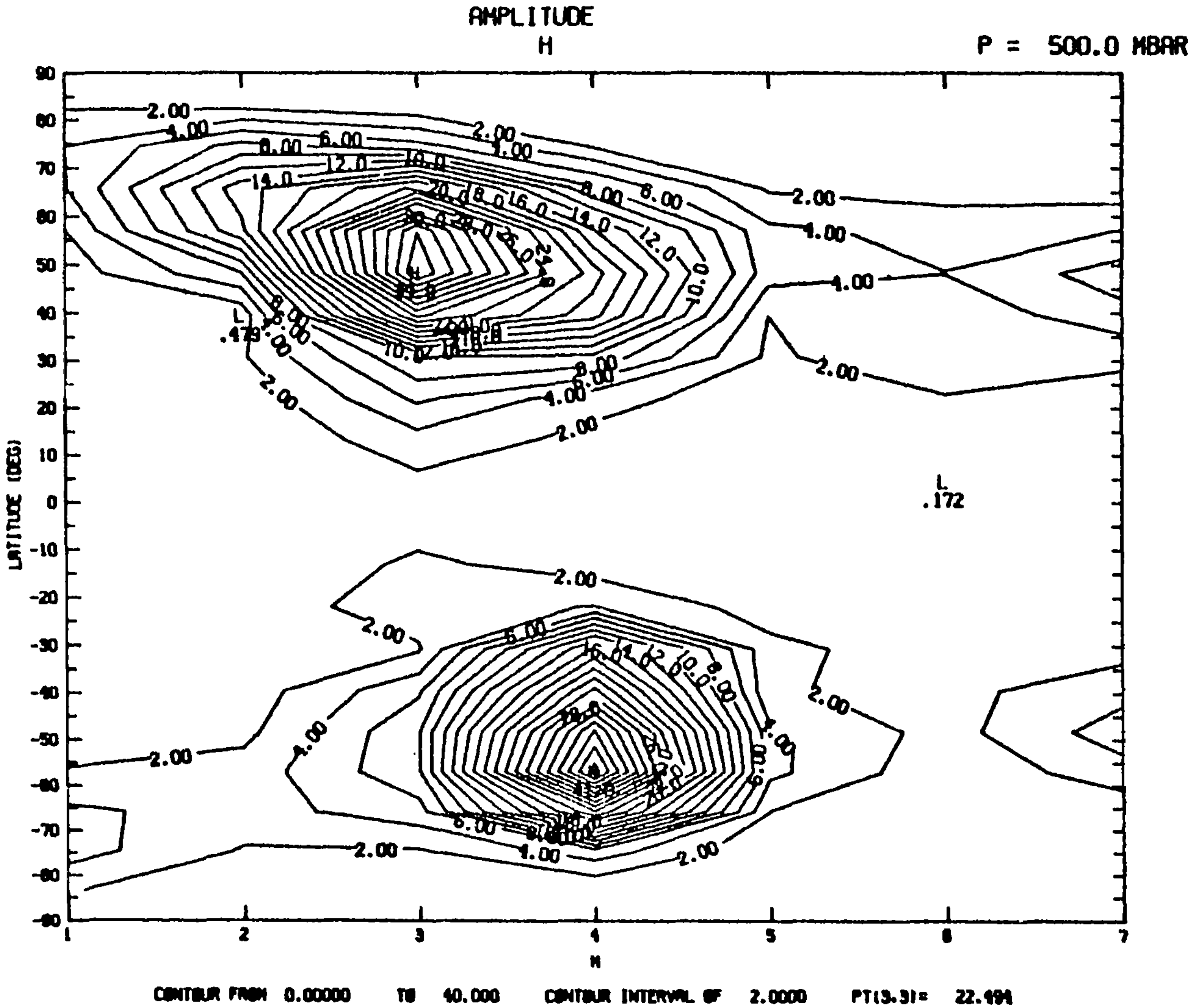
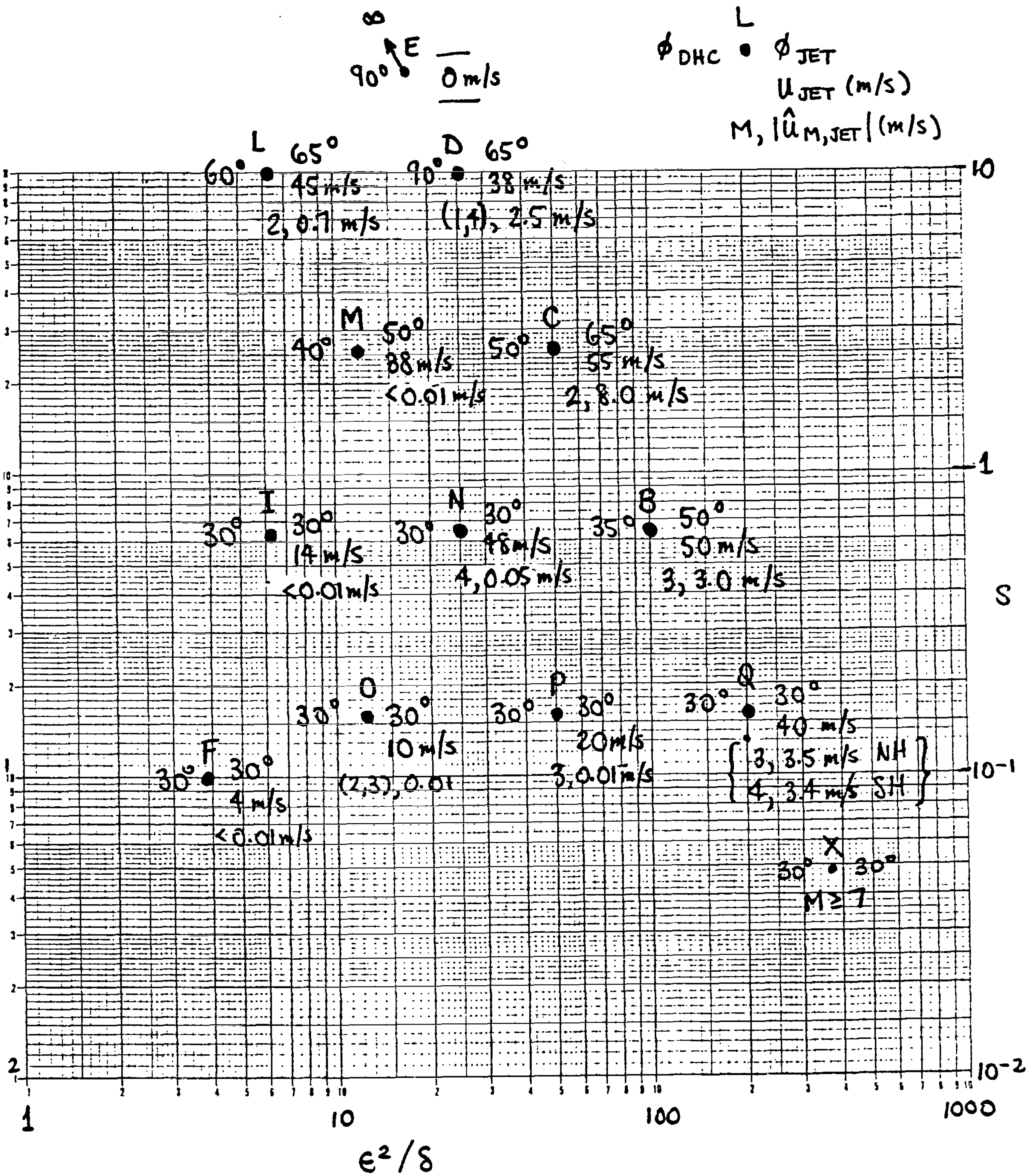


FIGURE 8.5



E
90°
0 m/s
L
ϕ_{DHC} • ϕ_{JET}
U_{JET} (m/s)
M, $|\hat{u}_{M,JET}|$ (m/s)
L 60° 65° 45 m/s 2, 0.7 m/s
D 90° 65° 38 m/s (1,4), 2.5 m/s
M 40° 50° 88 m/s <0.01 m/s
C 50° 65° 55 m/s 2, 8.0 m/s
I 30° 30° 14 m/s <0.01 m/s
N 30° 30° 48 m/s 4, 0.05 m/s
B 35° 50° 50 m/s 3, 3.0 m/s
O 30° 30° 10 m/s (2,3), 0.01
P 30° 30° 20 m/s 3, 0.01 m/s
Q 30° 30° 40 m/s 3, 3.5 m/s NH 4, 3.4 m/s SH
F 30° 30° 4 m/s <0.01 m/s
X 30° 30° M ≥ 7
10
1
10^{-1}
10^{-2}
S
1
10
100
1000
ϵ^2/δ

FIGURE 8.6

PUBLICATIONS OF THE GEOPHYSICAL FLUID DYNAMICS GROUP

NASA, Fluid Dynamics Branch, Space Sciences Laboratory,

Marshall Space Flight Center

1977

1. Geophysical Fluid Flow Model Experiments in Spherical Geometry. W.W. Fowlis and G.H. Fichtl. Proceedings of the Third NASA Weather and Climate Program Science Review. NASA Conference Publication 2029, Paper No. 32, pp 177-181, 1977.

1978

1. Numerical Solutions and Laser Doppler Measurements of Spin-Up. A. Warn-Varnas, W.W. Fowlis, S. Piacsek and S.M. Lee. Journal of Fluid Mechanics, 85, Part 4, pp 609-639, 1978.

2. The Effects of Curvature and Viscosity on Baroclinic Instability. A Two-Layer Model. W.W. Fowlis and S. Arias. NASA Technical Paper 1328, 25 pp, 1978.

1979

1. A Study of the Expected Effects of Latitude-Dependent Rotation Rate on Laboratory Geophysical Flow Experiments. J.E. Geisler and W.W. Fowlis. Proceedings of the Fourth NASA Weather and Climate Program Science Review. NASA Conference Publication 2076, Paper No. 40, pp 241-245, 1979.

2. Remote Optical Techniques for Liquid Flow and Temperature Measurement for Spacelab Experiments. W.W. Fowlis. Optical Engineering, 18, 3, pp 281-286, 1979.

3. Theoretical Regime Diagrams for Thermally Driven Flows in a Beta-Plane Channel. J.E. Geisler and W.W. Fowlis. Journal of the Atmospheric Sciences, 36, 8, pp 1530-1541, 1979.

4. Geophysical Fluid Dynamics. W.W. Fowlis. Proceedings of the Workshop on Spacecraft Dynamics as Related to Laboratory Experiments in Space. NASA/MSFC, May 1979.

5. The Geophysical Fluid Flow Experiment. B.G. Broome, G.H. Fichtl and W.W. Fowlis. Proceedings of the Huntsville Electro-Optical Technical Symposium and Workshop, Huntsville, May 1979.

6. The Effect of the Non-Uniform Wind Shear on the Intensification and Reflection of Mountain Waves. J.M. Hyun and M.U. Kim. Journal of the Atmospheric Sciences, 36, 12, 1979.

7. The Wave Structures of the Eady Model of Baroclinic Instability. J.M. Hyun and W.W. Fowlis. NASA Technical Paper 1548, 21 pp, 1979.

1980

1. Baroclinic Instability with Variable Gravity - A Perturbation Analysis. A.C. Giere and W.W. Fowlis. NASA Technical Paper 1586, 29 pp, 1980.

2. Influence of Solidification on Surface Tension Driven Convection. B.N. Antar, F.G. Collins and G.H. Fichtl. International Journal of Heat and Mass Transfer, 23, pp 191-201.

3. Eigenvalues of a Baroclinic Stability Problem with Ekman Damping. B.N. Antar and W.W. Fowlis. Journal of the Atmospheric Sciences, 37, 6, pp 1399-1404, 1980.

4. Review of Rotating Fluids in Geophysics, Academic Press, New York, 1978. W.W. Fowlis. EOS, Transactions of the American Geophysical Union, 61, 39, 1980.

5. Sullivan's Two-Celled Vortex. F.W. Leslie. American Institute of Aeronautics and Astronautics Journal, 18, 10, p 1272.

6. Theoretical Regime Diagrams for Thermally Driven Flows in a Beta-Plane Channel in the Presence of Variable Gravity. J.E. Geisler and W.W. Fowlis. NASA Technical Memorandum 78316, 18 pp, 1980.

7. Baroclinic Instability of a Fluid in a Rotating Channel. B.N. Antar and W.W. Fowlis. (Abstract) Bulletin of the American Physical Society, 25, 9, p 1077.

8. The Applicability of the Piecewise Linear Current Profile in the Baroclinic Instability Problem. J.M. Hyun. Journal of the Meteorological Society of Japan, 58, 6, 1980.

9. Baroclinic Instability with Variable Static Stability - A Design Study for a Spherical Atmospheric Model Experiment. A.C. Giere and W.W. Fowlis. Geophysical and Astrophysical Fluid Dynamics, 16, pp 207-224, 1980.

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16. ABSTRACT

The Atmospheric General Circulation Experiment (AGCE) proposed for Spacelab flights is a spherical baroclinic flow experiment which will model the large-scale circulations of the Earth's atmosphere. Because the major objective of the AGCE is to study nonlinear baroclinic wave flows in spherical geometry, the apparatus must be designed so that strong baroclinic instability can be realized. Therefore, numerical models must be developed which will accurately predict the basic axisymmetric states and the stability of these states, in addition to the requirement for a three-dimensional, fully nonlinear, numerical model of the AGCE based on the complete set of equations. The AGCE numerical design studies program is under way, and this document summarizes the results of a meeting held in Boulder, Colorado, April 14-15, 1981, to review the work achieved to that date.

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