NASA Contractor Report 3766

Alternative Experiments Using the Geophysical Fluid Flow Cell

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National Aeronautics
and Space Administration

**Scientific and Technical
Information Office**

1984

1. INTRODUCTION

The Geophysical Fluid Flow Cell (henceforth GFFC) is an experiment that was designed to take advantage of the zero gravity environment of the Spacelab to effect studies of rotating convection in a spherical shell with radial gravity. The radial gravity is possible because in the absence of the imposed uniform gravitational acceleration that dominates the terrestrial laboratory, other forces that mimic buoyancy can be substituted. In the GFFC, a hemispherical shell of dielectric fluid is subject to a radial electric field. The resulting polarization forces are in the radial direction and directly proportional to the density of the dielectric fluid. Thus, a radially oriented buoyancy force is simulated in a manner that is exactly analogous to that occuring in planetary atmospheres and oceans. Unfortunately, however, this dielectric buoyancy or dielectric gravity is rather weak for applied fields that don't cause breakdown in the fluid. Thus it is necessary to conduct experiments using it in the zero-gravity environment. The uniform gravity of Earth, would, for example, completely dominate the motions in the GFFC, and these motions would not be good models for the geophysically interesting problems.

The GFFC was designed to generate a dielectric gravity as large as possible with available materials and safety factors taken into account. This neccessitates a small inner radius of the hemispherical fluid shell, since the electric field goes like 1/radius^2, and a small gap width, since this enhances the field for a given applied electric potential. On the other hand, fluid motions of interest (instability, bifurcations, and turbulence or chaos) occur at low effective viscosity or high Reynolds number. Thus the gap of the hemispherical annulus cannot be made too small. The GFFC was optimized for the study of

a particular class of problems that are of great scientific interest and that allowed the simplest GFFC configuration in terms of engineering, state of the art materials, and flow visualization.

The problems to be studied in the first flight of the GFFC on Spacelab III are concerned with the effects of rotation on thermal convection driven by a statically unstable thermal heating. This heating is either constant on each hemisphere, or can vary in latitude. Of principal interest are the wavenumber selection mechanisms, the orientation (bandedness) of the convection cells, the time dependence of the convection, and the possible generation of any differential rotation. The technical advantages of studying these problems are:

1. It is easy to get well into the supercritical region of parameter space. This includes parameters that are well beyond the reach of computer flow models with adequate resolution.

2. The direct buoyancy driven convective flow (as compared with slantwise or baroclinic instability) has a large signature in both thermal gradients and velocity. Thus it is relatively easy to observe using Schlieren and dye deformation techniques.

3. The expected experiment time scales, while of order 1 hour, are not so long as to be impractical given the orbit times and power restrictions on the Spacelab.

It is natural to ask the question, could the GFFC be used to study any other global flow problems of fundamental scientific interest. Substantial resources have been invested in the construction of the GFFC, and given that reflights might be made at relatively low cost, it would be of great benefit to the community if the GFFC could

be used productively in other areas. This study addresses this question. Our rational for evaluating the potential of alternative experiments (e.g. other than the direct convection experiments, that might themselves benefit from reflight) is based on the following constraints:

1. That the experiments make a contribution to fundamental scientific issues.

2. That the flows, at least for some parameters, be beyond the foreseeable access by numerical computation. There is now reasonable confidence in computer simulations of large-scale hydrodynamic flows up to certain resolution. There are questions of numerical viscosity and thermal diffusion at the small scales, as well as problems in some models at singularities (like the pole), but many models have been tested against both other models and terrestrial laboratory experiments. Thus we want to be sure we can learn something fundamental from the GFFC that we might not expect to get from numerical modelling. This is a fuzzy issue because all numerical results are to a certain extent model dependent, whereas the experimental conditions are well defined with known representations of viscosity and diffusion. Nonetheless, we don't want to do experiments that simply are to be used to verify numerical models!

3. That the experiments be done with minimal modification to the existing GFFC. That is, we don't want to have to rebuild the apparatus in any substantial way. The kinds of changes that might be tolerable, and done at very low cost, include things like software adjustments, insertion of obstacles in the working fluid gap, changing the fluid to one with different properties, etc. Certainly any mechanical changes to the spheres or to the optics system would be only justified by

an extremely strong (almost sensational) proposal.

This study is organized in the following manner. Section 2 outlines the capabilities of the GFFC as configured for the thermal convection experiments. This review is not meant to be exhaustive as the engineering details of the GFFC have been published elsewhere. Section 3 addresses the question of the expected meridional and zonally symmetric circulations one might expect in the GFFC when heated in various statically stable configurations. Then in section 4 we study the stability of the computed zonal flow in order to demonstrate that baroclinic instability problems are not feasible in GFFC. Section 5 extends the results of section 3 to suggest an oceanographic experiment that seems to satisfy the above constraints.

2. CHARACTERISTICS OF THE GFFC

Figure 1 shows a schematic of the GFFC instrument (from the GFFC crew training handbook, INT012). The working spheres are rotated on a turntable. They are heated and cooled by thermoelectric devices mounted on the turntable, with overall cooling by avionics air. Flow visualization is by back-focus Schlieren and photochromic dye injection. Images are recorded on 16mm film through a complex optical path. Essentially hemispherical data coverage is implemented. The Schlieren measures the radially averaged horizontal temperature field as a function of latitude and longitude. The dye lines are injected radially, span the fluid gap, and successive frames of film record their deformations. Data gathering sensitivity is about .5 degrees centigrade for the Schlieren , and between about .01 and
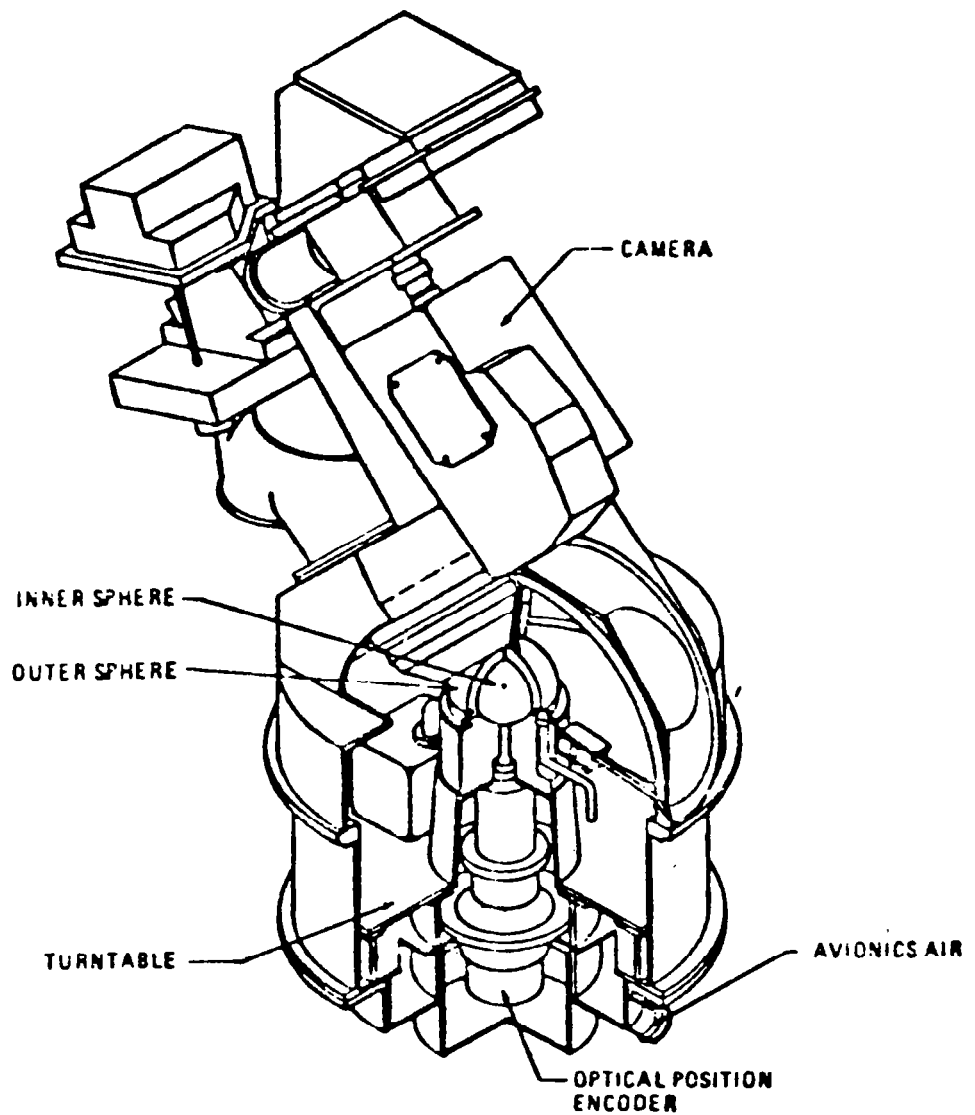
GFFC EXPERIMENT

Figure 1

and 1cm/sec for the dye lines. The high dye line figure depends on the rotation rate. Since dye is injected on the opposite side of the sphere from the camera, the sphere must rotate 180^0 before a photo can be taken. At high flow rates, the dye can deform so much as to be impossible to photograph in a short time. Thus, 1 cm/sec velocities can only be recorded via dye if the rotation period is short (e.g. 2 sec.).

Figure 2 shows a cross-section of the working fluid region. The fluid is contained within rigid boundaries. The spherical surfaces are conductors, while the radial equatorial boundary is an insulator. The inner radius is R_i and the outer radius is R_o. The gap-width D is just the difference in these two radii. The applied temperatures T_o and T_i can be programmed to vary with latitude. Typically the pole is hotter than the equator when this is done. The following list summarizes the capabilities and currently used fluid parameters of the GFFC.

R_i = inner radius = 2.402cm

R_o = outer radius = 3.300cm

D = gap width = .898cm

ν = kinematic viscosity = .0065cm^2/sec

ρ = basic fluid density = .761 gm/cm^3

α = coefficient of thermal expansion = .00134 C^{-1}

κ = thermal diffusivity = .00090 cm^2/sec

Ω = rotation rate (about .025 to 3.14 rad/sec)

T_i and T_o: radial gradient $T_i - T_o$ = 0 to 30^{0*}

latitudinal (ϕ) gradient = 0 to 20^0

max-min temperatures at any point 50^0 and 20^0

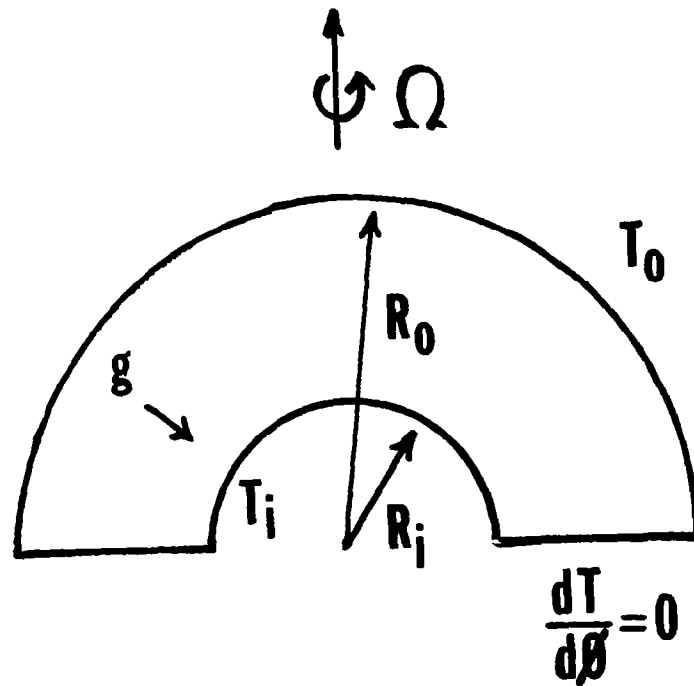* 10^0 minimum driving required for adequate Schlieren sensitivity

FIGURE 2   CROSS SECTION OF THE GFFC.

It is useful to go through the calculation for the dielectric radial gravity g. There is a potential across the gap

$$V \cdot R_i (R_o/r - 1) \sin\omega t / D$$

where r is the radius and ω is the excitation frequency. This leads to a radial electric field

$$E = R_i R_o V \sin\omega t / D r^2$$

so that $\qquad \nabla E^2 = 4(R_i R_o V/D)^2/r^5.$

Now the effective dielectric gravity is $g_{em} = \epsilon \nabla \underline{E}^2/2$, where ϵ is the dielectric constant of the silicone oil (2×10^{-11} mks), and the underbar denotes a time average. Thus

$$g_{em} = 2\epsilon (R_i R_o V_{rms}/D)^2/\rho r^5$$

It is seen that g_{em}, henceforth simply g, goes up as the applied voltage squared, and decreases as r^5. The 5'th power dependence is not significantly different from a 2'nd power dependence with the present gap. Figure 3 gives the dielectric gravity, scaled by the square of the applied rms voltage. The range of voltage in the GFFC is 40v to 10kv. This gives a maximum _outer_ value of 1 m/sec^2. The inner value is a factor of 5 bigger. In the following we will take the average maximum value to be 2m/sec^2.

The other important parameters for flow problems in the GFFC are the Prandtl number $P_r = 7.0$, the aspect ratio $\beta = R_1/D = 2.67$ and some measure of the viscosity. The Taylor number is $T_a = f^2 D^4/\nu^2$. A related dimensionless quantity of importance is the Ekman number $E = \sqrt{T_a}^{-1}$. Here f is the Coriolis parameter 2Ω. Figure 4 shows the inverse Ekman numbers obtainable in GFFC as a function of the rotation period of the apparatus τ_Ω. This period is 1 to 255 seconds. The smallest Ekman number is of order .001, or $\sqrt{E}$ of order .03.
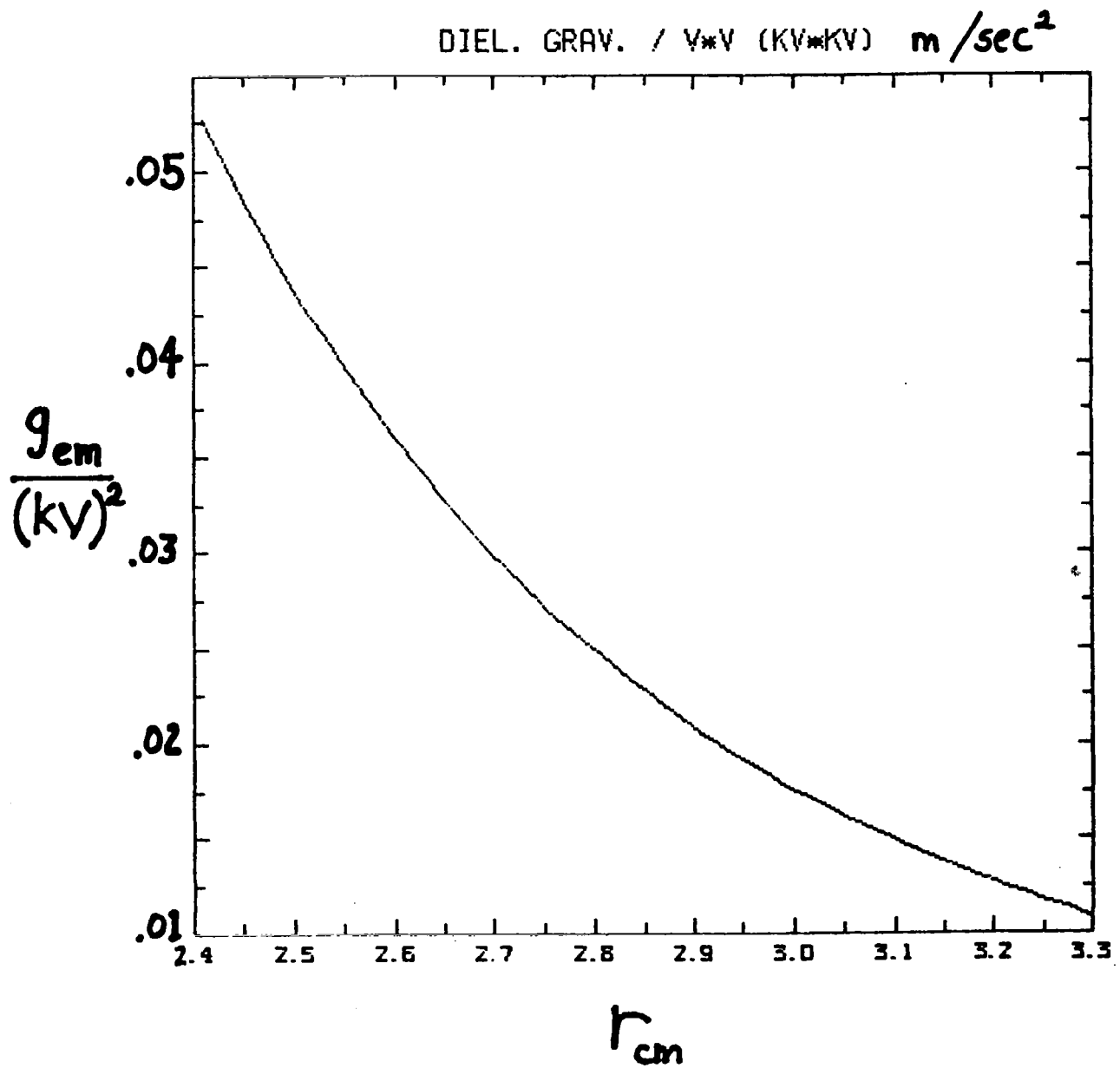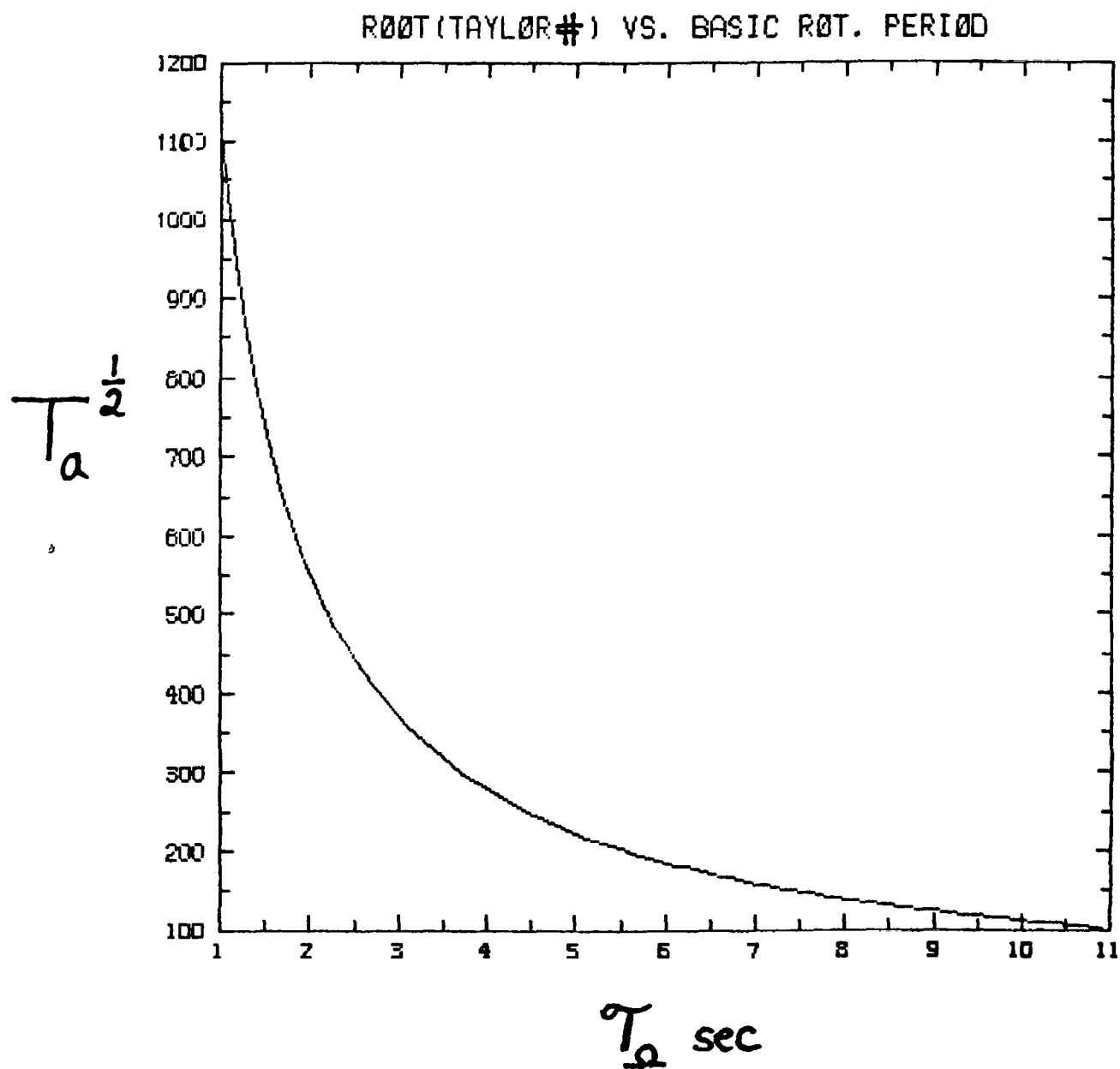
Figure 3

DIEL. GRAV. / V*V (KV*KV) m/sec^2

$\dfrac{g_{em}}{(kV)^2}$

r_{cm}

Figure 4

ROOT (TAYLOR #) VS. BASIC ROT. PERIOD

Finally, some measure of the flow strength is required. A suitable one is the thermal Rossby number based on the applied lateral temperature gradient at the boundaries ∇T, and assuming geostrophic and hydrostatic balance. This is

$$R = g\alpha\nabla TD/f^2L^2,$$

where L is measure of the horizontal length scale of the motion (or of ∇T). The accessible values of R are given in figures 5 and 6 for two values of ∇T and a range of L. It is noted that strong quasi-geostrophic flows (R about .3 is my definition of this range) occur typically for small L=2D or so. Thus we conclude that really strong non-linear motions in a baroclinic flow will happen only if the motions are confined to a channel at mid- or high-latitude.

Given these numbers it is possible to use previous stability results of Antar and Fowlis (1980) or Giesler and Fowlis (1979) to show that baroclinic instability might just be possible in a mid-latitude channel in the GFFC at the extreme conditions (1sec period, 30 degrees). However, it is by no means clear that a simple basic state based on the thermal wind will be accurate at these conditions in the interior of the fluid. For this reason, and because of it interest for the oceanographic case of section 5, we proceed to look at the zonally symmetric circulation expected in the GFFC with latitudinal boundary heating.

3. SYMMETRIC CIRCULATIONS

Because small L flows are the only ones that give big enough R for non-linear baroclinic instability (at least potentially), we start by considering an idealized mid-latitude channel model. This is shown in figure 7. A standard scaling is used for the basic equations, and
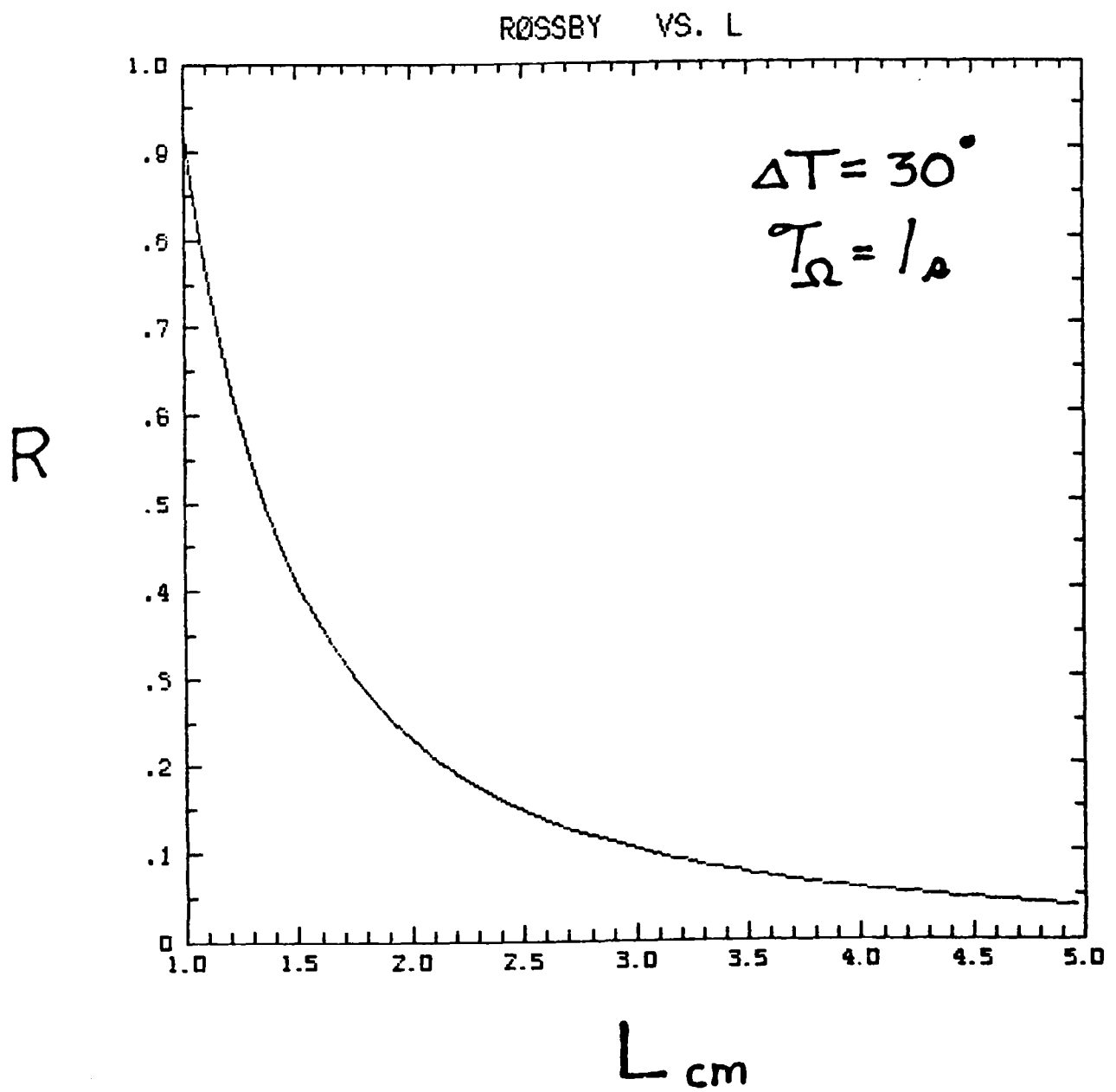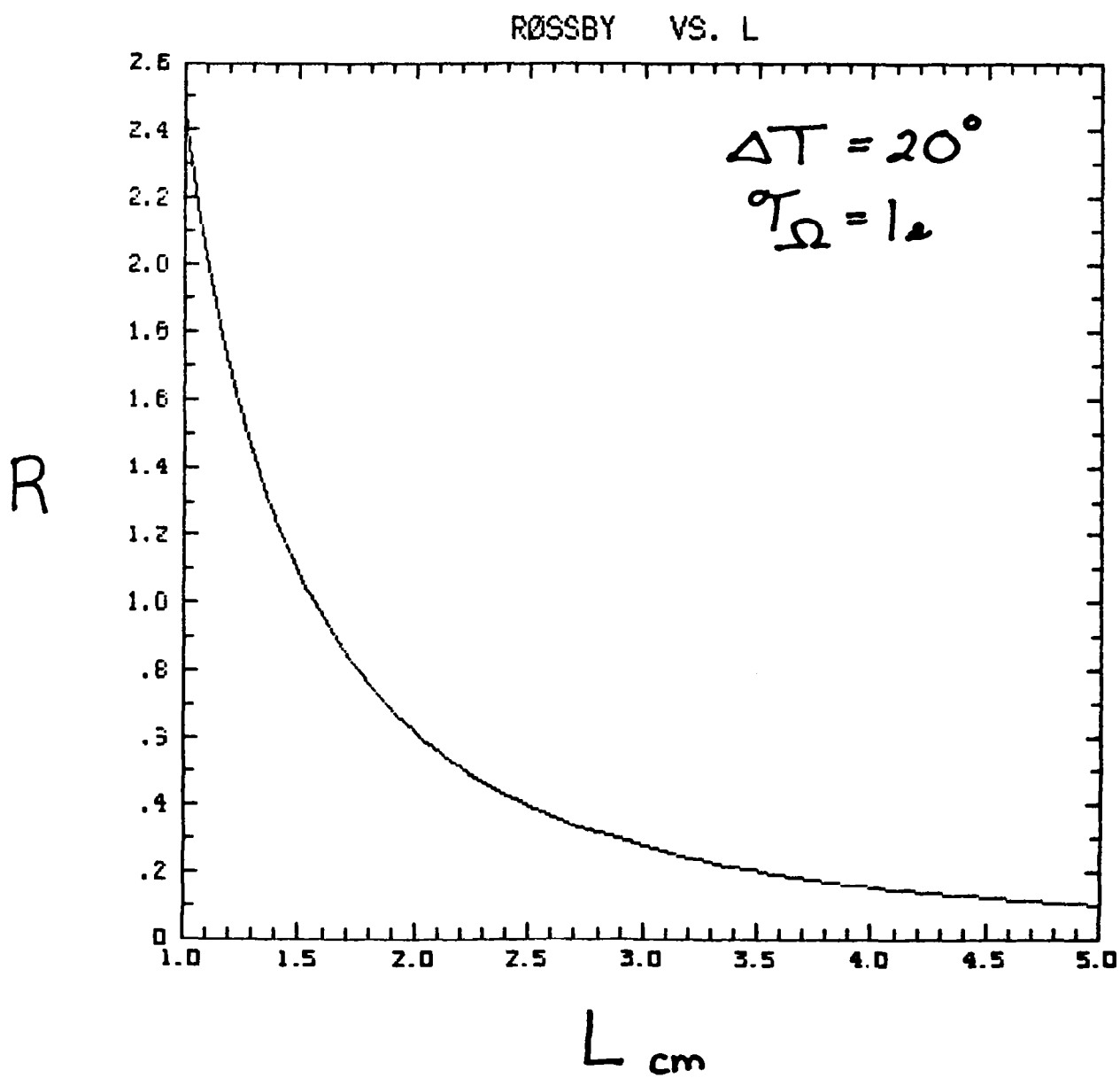
Figure 5

ROSSBY   VS. L

$\Delta T = 30^{\circ}$

$T_{\Omega} = 1_{\rho}$

R

L_{cm}

Figure 6

RØSSBY   VS. L

$\Delta T = 20°$
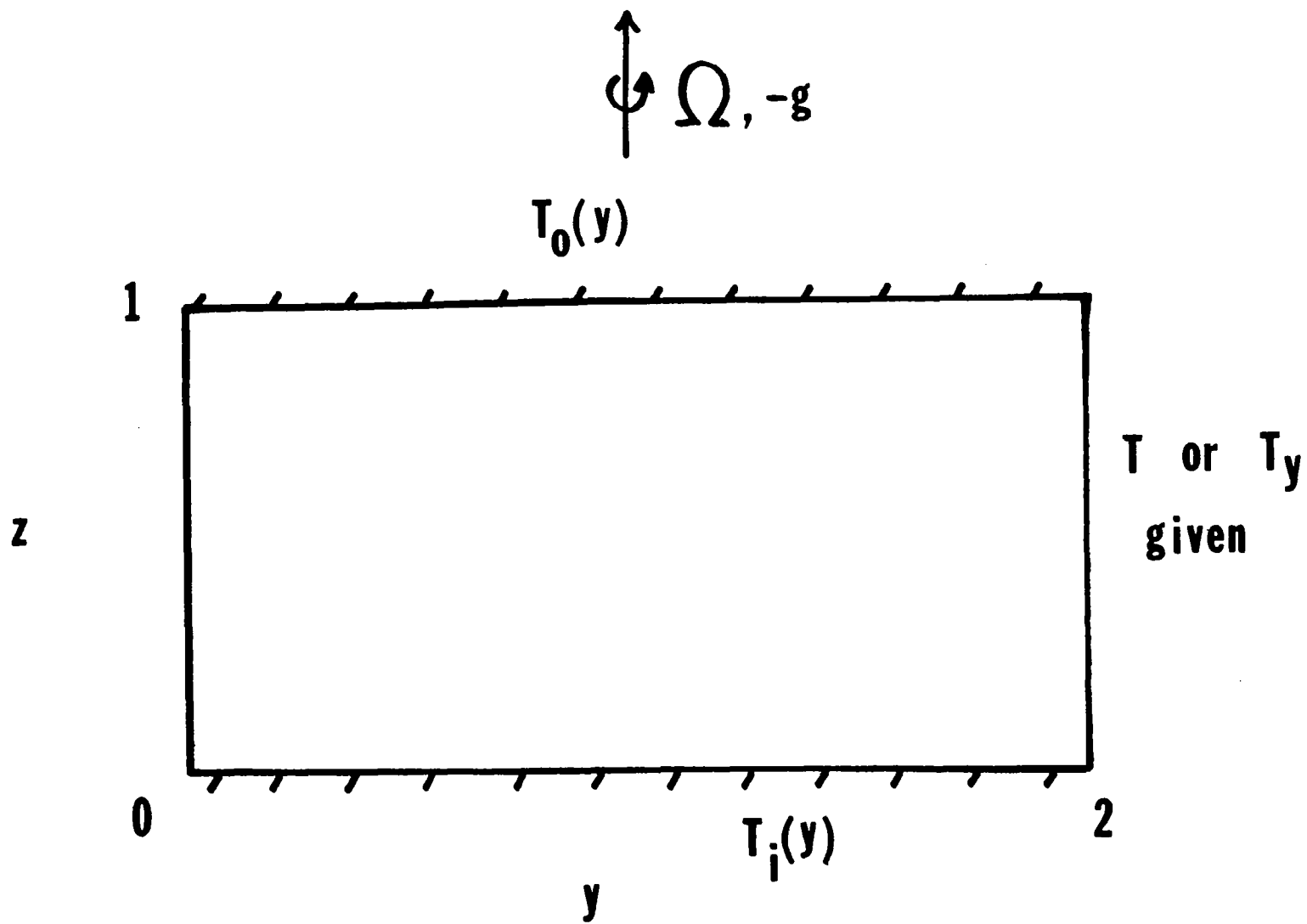
$\mathcal{T}_{\Omega} = 1_{\mathbf{a}}$

R

L cm

Figure 7. Cross-section of mid-latitude slot.

it is easily shown (c.f. Holton, 1979) that a local cartesian coordinate system is accurate enough for our purposes. Hence y corresponds to latitude, z to radius, and the motion is assumed independent of x. The upper and lower surfaces have applied temperature distributions, and the vertical endwalls can be either insulating or conducting (how one would make a thermally conducting radial wall in the GFFC with the 10kv across the gap is not at all clear to me). The horizontal boundaries are viscous no-slip, but the vertical boundaries are just impermeable in our simple model. We consider motions only on an f-plane for now.

The goal is to compute the zonally (x) symmetric flow in the slot as a function of the external parameters. This is a problem of long-standing interest in geophysical fluid dynamics, yet a solution for arbitrary forcing is not available. Our approach has been suggested in bits and pieces by Barcilon and Pedlosky (1967), Daniels (1976), Hignett et al. (1981), and Killworth and Manins (1980).

For small R and E the interior of the box will be geostrophic and hydrostatic. There will however be Ekman boundary layers along the two horizontal surfaces and these will generate Ekman suction velocities

$$w = \mp \sqrt{(E/2)} \cdot \partial u / \partial y \qquad (1)$$

at z=0,1 respectively where u is the x-invariant zonal wind. This suction will persist unless the thermal stratification gets to be extremely big (Barcilon and Pedlosky 1967). Thus the interior vertical velocity scale is $\sqrt{E}$ compared with the a priori thermal wind scale. The x momentum equation then suggests that the interior meridional velocity v will be of order E or R/E whichever is less. Thus, on the f-plane, the meridional circulation is very <u>weak</u>, much smaller than that given by simple continuity scaling where v~w~$\sqrt{E}$ for order 1 aspect ratios.

The interior momentum equations in the small R,E limit reduce simply to the thermal wind balance,

$$\partial u/\partial z = -\partial T/\partial y \qquad (2)$$

Now the general thermal equation

$$vT_y + wT_z = \kappa \nabla^2 T \qquad (3)$$

requires v and w, the meridional and vertical velocities. But since v is much less than w (taking $R \approx \sqrt{E}$ say) we only need to find w(y). But continuity suggests

$$w_z = -v_y \approx 0$$

again because of the smallness of v. Thus w(y) can be simply found from (1) and (2). It is, for constant g,

$$w'(y) = (T_z|_1 - T_z|_0)/(2^{3.5} + \varepsilon(T|_1 - T|_0)) \qquad (4)$$

Combining (4) with (3) gives the non-dimensional non-linear equation

$$\nabla^2 T = \varepsilon w'(y) \cdot T_z(y,z) \qquad (5)$$

The key parameter here is ε (not to be confused with the dielectric constant used earlier),

$$\varepsilon = RP_r/\sqrt{E} \qquad (6)$$

The physical situation described by this model is shown in figure 8. The zonal flow u is in thermal wind balance, but the thermal distribution itself is determined by an advective-diffusive balance. The thermal wind generates vertical velocities via the Ekman suction, and these can compress the diffusive effects on T into a thermoclinic layer. The meridional velocity v is so weak as to have little influence on the temperature distribution problem. It is clear that only if ε is small will the interior thermal wind scaling hold up!

Equation (5) is solved by an iterative relaxation procedure. Actually a modified version of (5) is used that includes horizontal thermal advection in the Ekman layers, but this process is effective only on the 10% level. Figures 9a,b,and c show the resulting

thermal distributions for a conducting right hand boundary and an insulating left hand wall, with a cosine gradient of T along the bottom and a uniform top temperature. Case (a) shows the T field when the advection terms in (5) are arbitrarily suppressed. Figures 9b and 9c show how the downwards vertical velocity suppresses the thermal field into a boundary layer along the lower wall. At $\epsilon = 3$ this layer is already quite thin, meaning that the zonal velocity field u, that responds to T_y will not fill much of the box. Note that our extreeme GFFC paramters give $R \cdot P_r \approx 1$ so $\epsilon \sim 1/\sqrt{E} \approx 10$. It would appear that the thermal wind scaling will break down, and that the zonal flow will be weaker and more structured in the interior than one would think at first, based on using the boundary T gradient in the thermal wind law.

A similar situation occurs with variable g. The model is a bit more involved for this case and although the derivation is not presented in detail it follows the spirit of that given above. Figure 10 shows that the predicted zonal flow, for the same boundary conditions as above, decreases substantially as ϵ increases.

If one looks closely at equation (5) it is obvious that asymmetries in the thermal boundary conditions will accentuate the advective term, whereas if $T_{0z} = T_{1z}$, say, the advective effect will be minimized. Unfortunately, flux conditions at boundaries are very difficult to achieve in practice. However relaxing the end conditions to insulating, and providing a similar gradient of temperature along the top and bottom boundaries does help. Figure 11 shows the thermal fields for these conditions. It is clear that at $\epsilon = 10$ the thermocline layer is not yet as strong as in the previous case at $\epsilon = 3$. Figure 12 shows the predicted zonal flows for this heating. At $\epsilon = 30$ the interior vertical shear has decreased by a factor of 3 or so

from what would be expected by thermal-wind scaling. Figure 13 shows a typical w distribution.

Solutions of this simplified symmetric circulation model suggest that the thermal wind scaling used in stability analyses of GFFC type flows may be substantially in error if the paramter ε is larger than about 1. However, this is a parameter one would like to be large in order to promote instability (strong driving, low friction, see (11)).

One full numerical computation was run for the zonally symmetric flow in the GFFC under the maximum stress conditions (largest Taylor number and maximum applied thermal gradients). We wanted to get some idea of how big a zonal circulation or thermal wind would be generated. The numerical model treats $1/r^5$ gravity along with all the boundary conditions in the actual GFFC. It is described in Hart (1976) where results from it were successfully compared with terrestrial laboratory experiments. Figure 14 shows the resulting steady solution. The R in the figure is actually a Rayleigh number, not the thermal Rossby number defined earlier, but the forcing corresponds to 20^0 from equator to pole, and a stable radial gradient of 5^0C. The thermal contours are inverted because the Rayleigh number is negative (stably stratified), so to interpret the temperature it is necessary to multiply the values shown in 14b by -1. A stable pool develops in the equatorial 'stratosphere' so there is a meridional jet parallel to the axis of rotation (14c). The rest of the meridional circulation is confined primarily to boundary layers. The zonal flow is strongest at high and mid-latitudes and nearer the inner sphere where g is biggest. The strength of the zonal wind is about half that given by a thermal wind scaling based simply on the boundary condition. Whether or not this zonal wind might be baroclinically unstable is the topic of the next section.
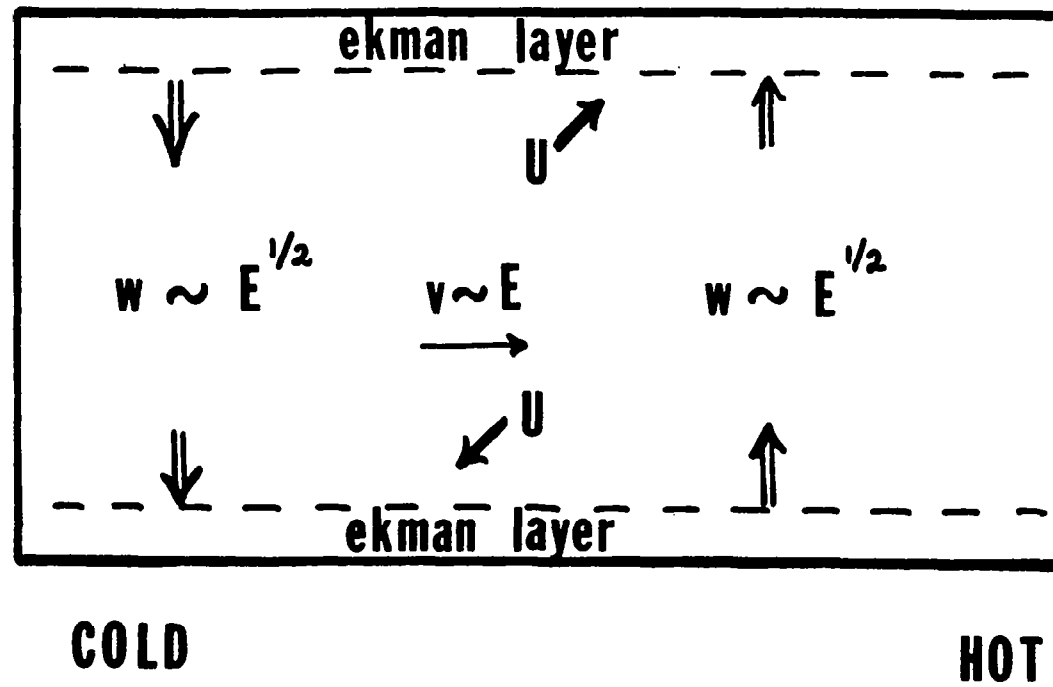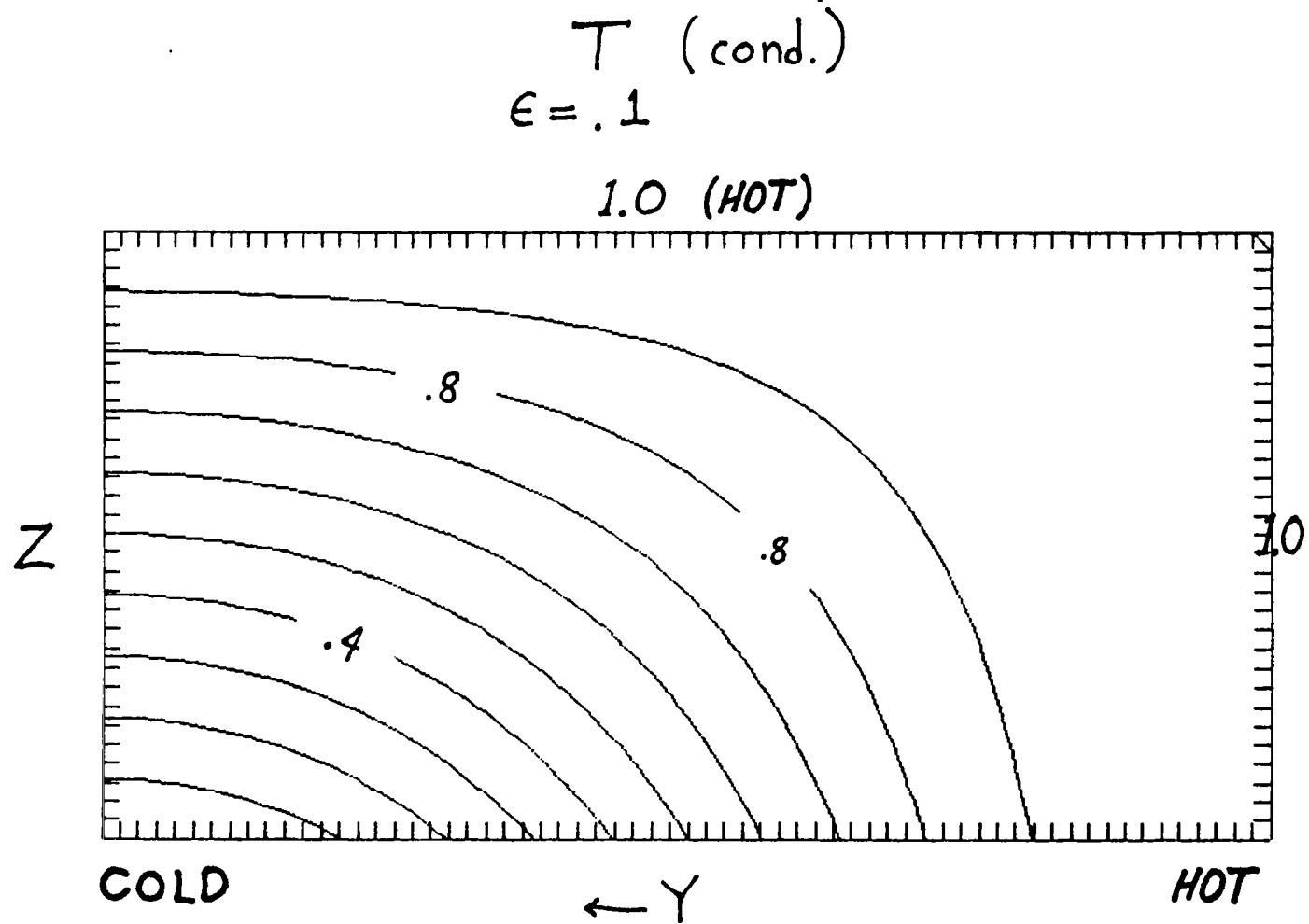
Figure 8. Physical structure of convection driven by non-uniform heating

Figure 9a. Zonally symmetric temperature field.
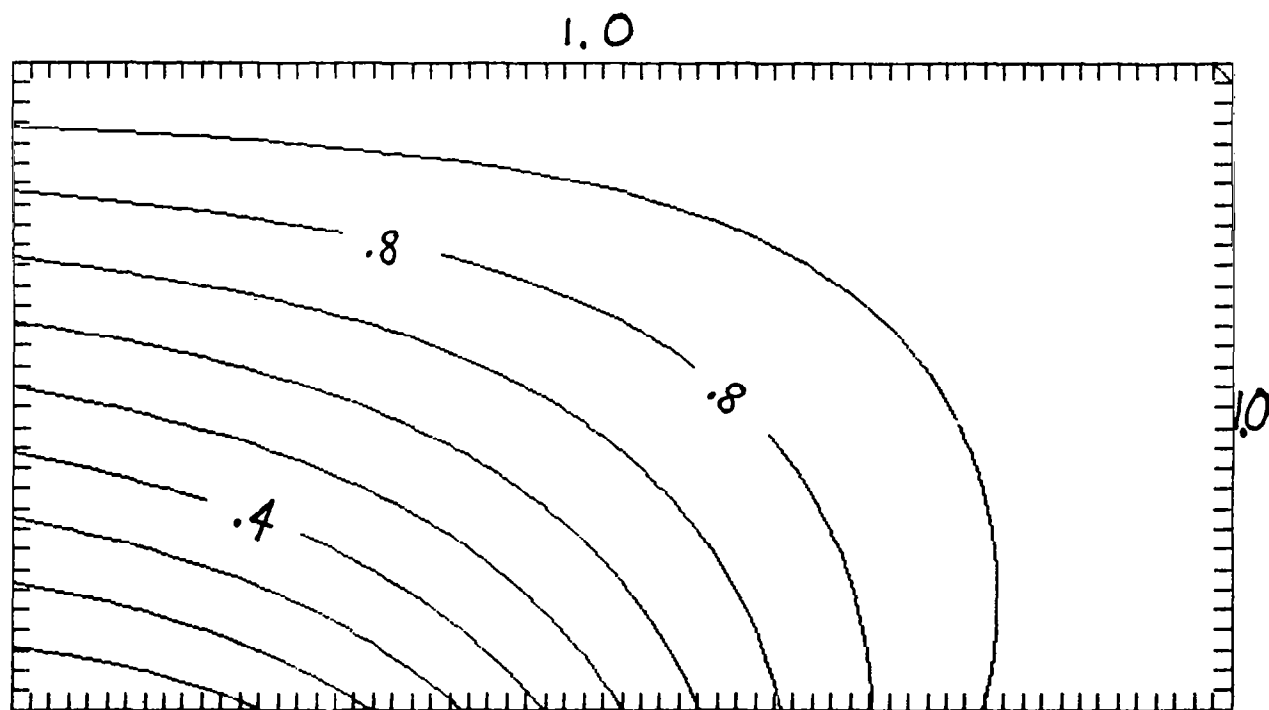
T (cond.)

$\epsilon = .1$

1.0 (HOT)

.8

.8

Z

.4

10

COLD

← Y

HOT

Figure 9b.

Figure 9c.

T

$\epsilon = 3$

1.0

.8

.8

.4

1.0

← Y
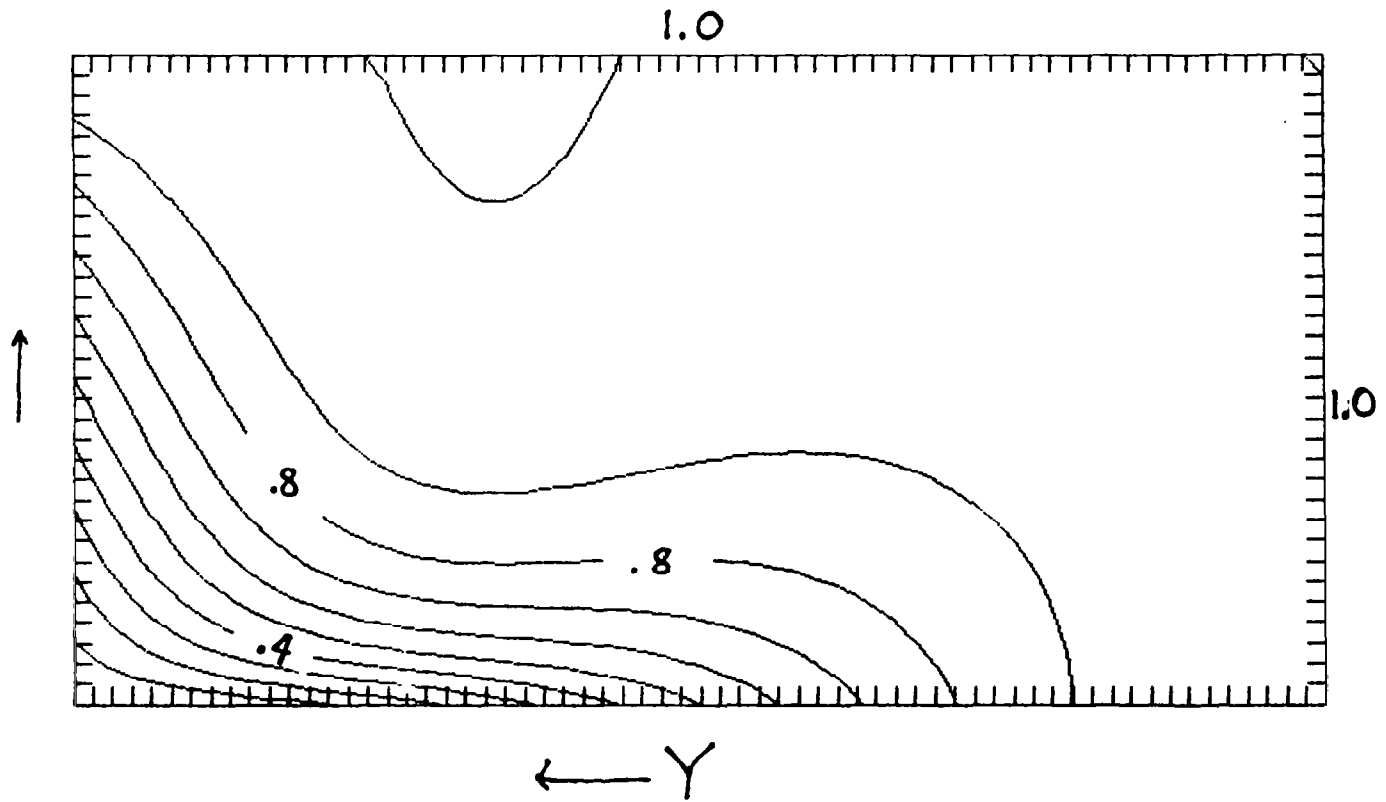
$$\epsilon = .5$$

HORIZ VELOCITY Y=.5

$\overline{U}(.5,z)$

Z
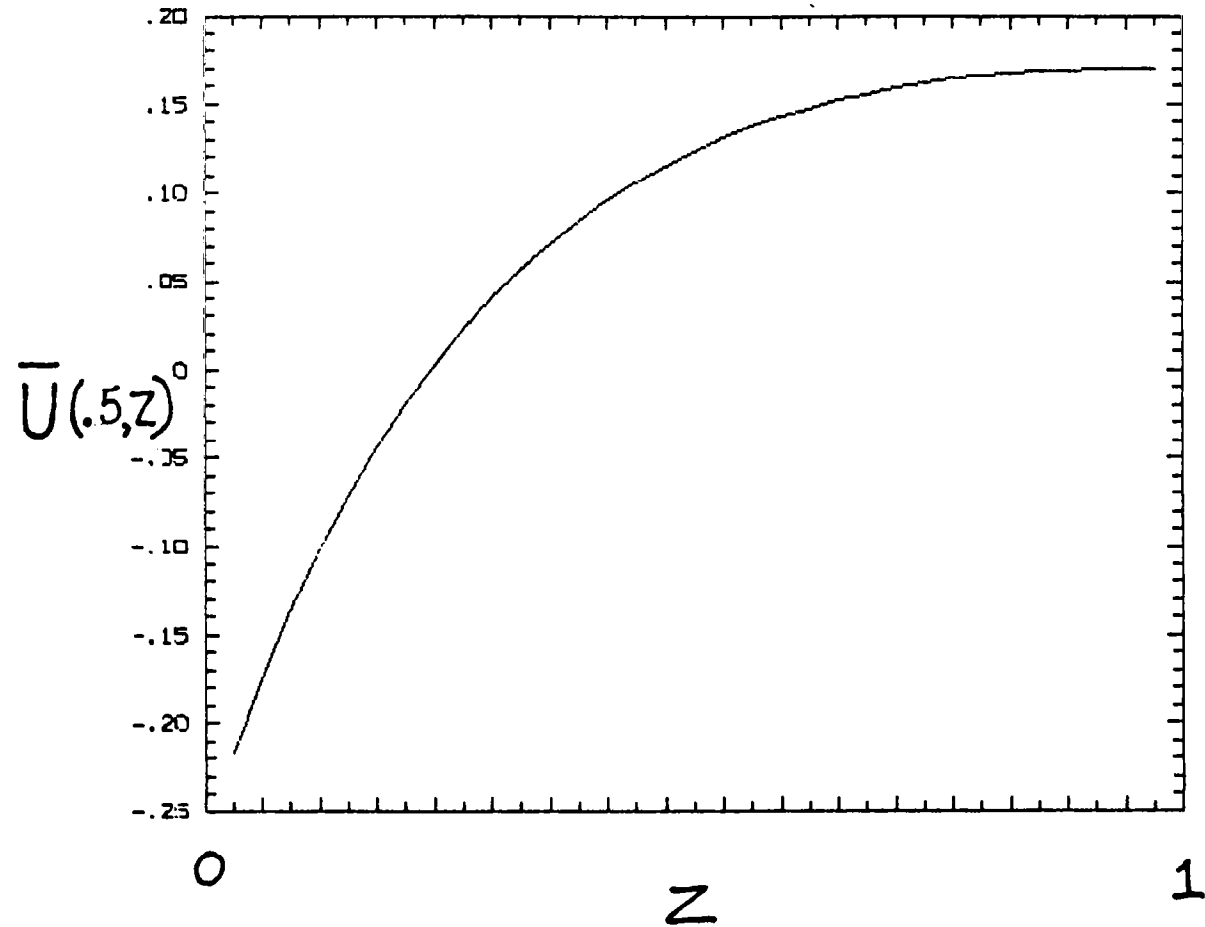
Figure 10b.

$\epsilon = 3$

HORIZ VELOCITY Y=.5

$\overline{U}(.5,Z)$

Z
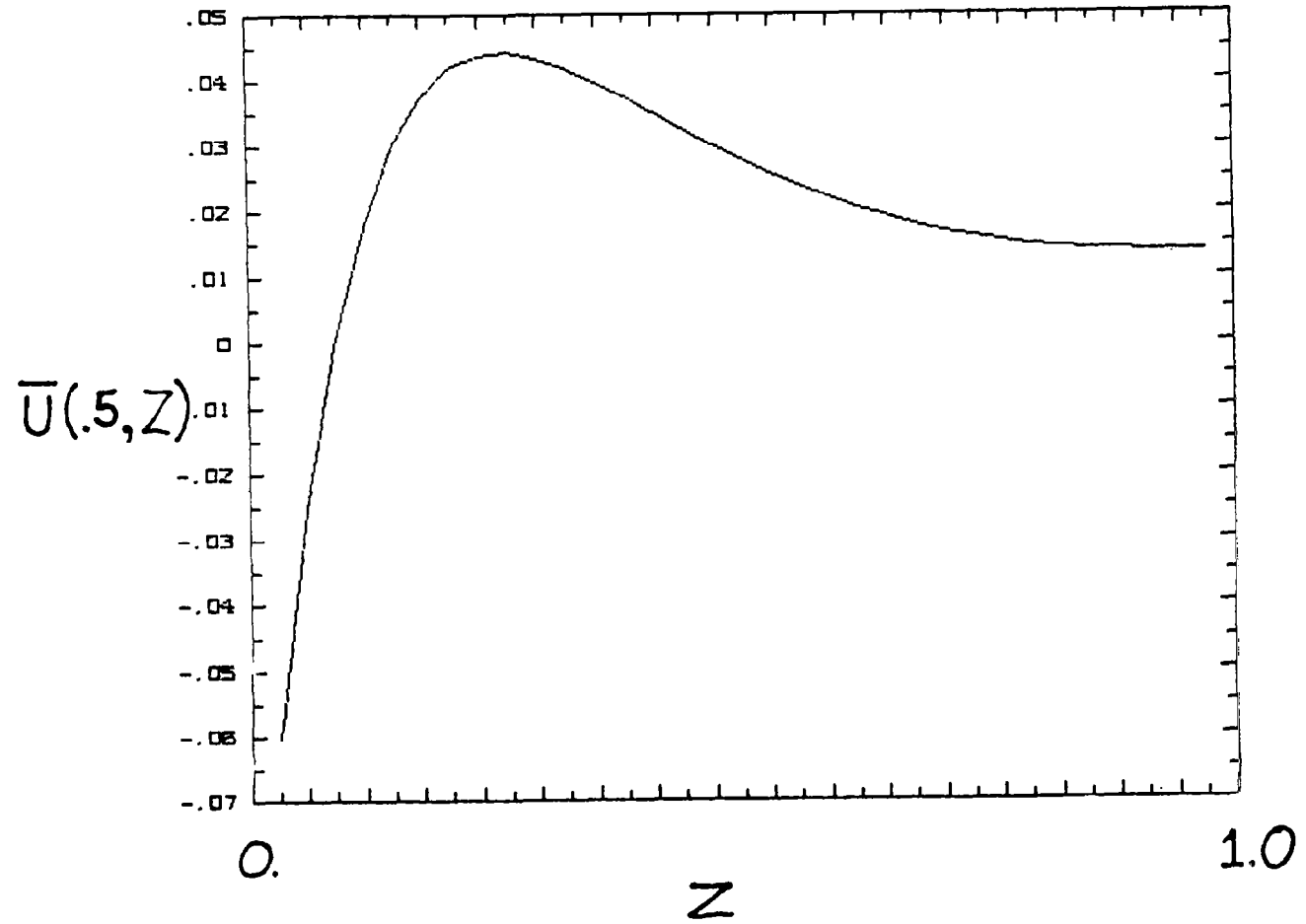
T (conductive)
$\epsilon = 10$
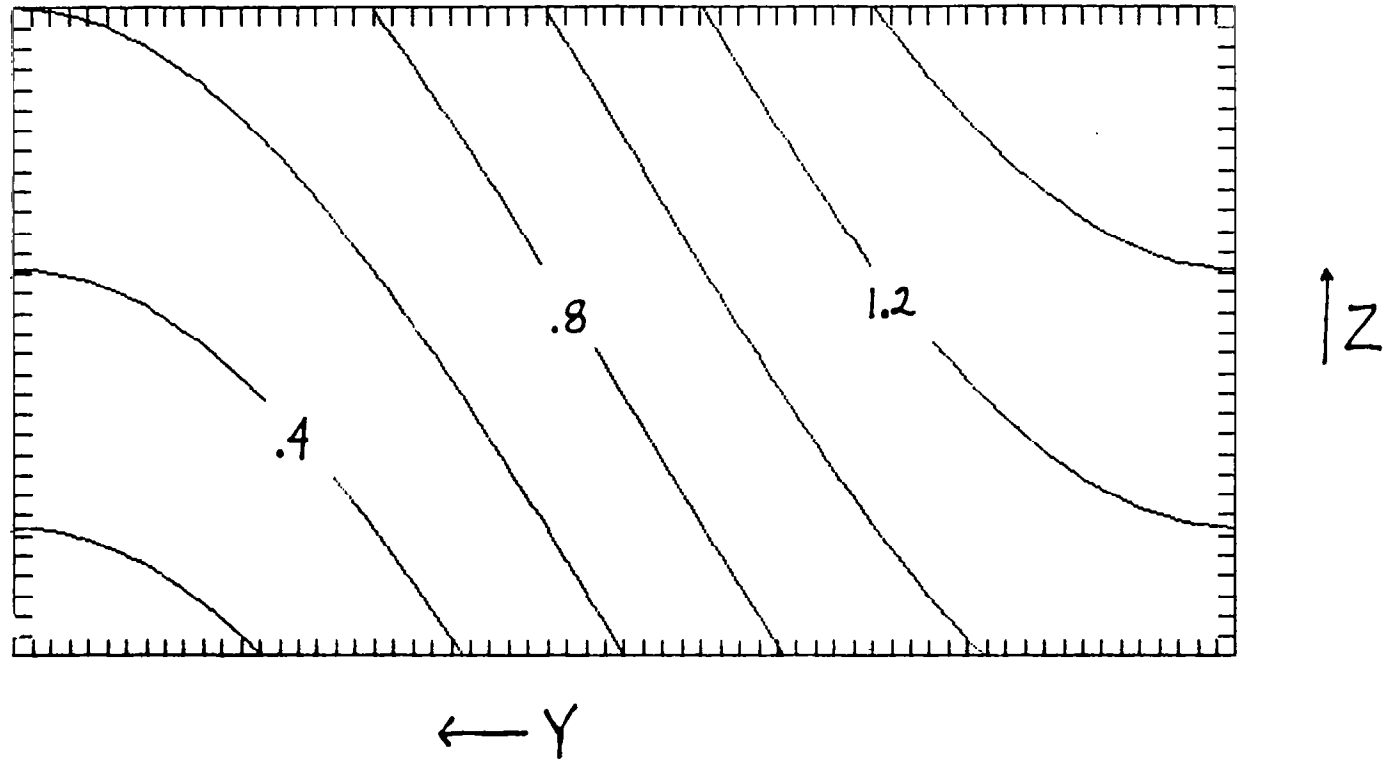
Figure 11a.

Figure 11b.

Figure 12.

HØRIZ VELØCITY Y=.5

Figure 13.

VERTICAL VELOCITY

W

Y

O

2.0

Figure 14a.

CASE =   1   01

T   =   0.500E+06

R   =   -0.500E+06

P   =   7.000

BETA =   2.670

DIFFERENTIAL ROTATION UO

CONTOUR FROM -800.00   TO   1400.0   CONTOUR INTERVAL OF   100.00   PT(3.31= -36.195

Figure 14b.

CASE = 1   01

T   = 0.500E+06

R   = -0.500E+06

P   = 7.000

BETA = 2.670

TOTAL TEMPERATURE FIELD

CONTOUR FROM -4.8000   TO 5.4000   CONTOUR INTERVAL OF 0.60000   PT(3 31= 3.2598

Figure 14c.

CASE =   1   01

T   =   0.500E+06

R   =   -0.500E+06

P   =   /.000

BETA =   2.670

MERIDIONAL CIRCULATION
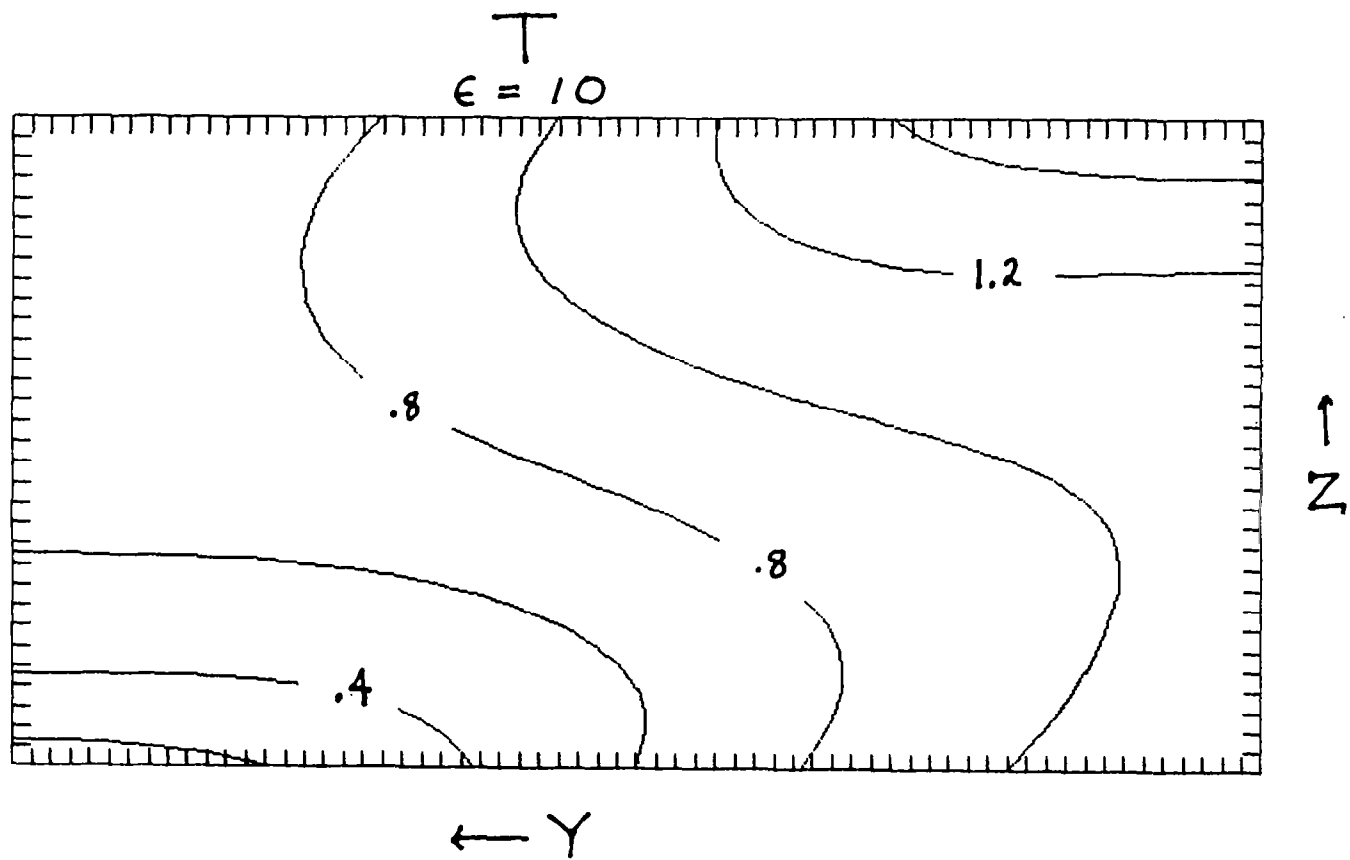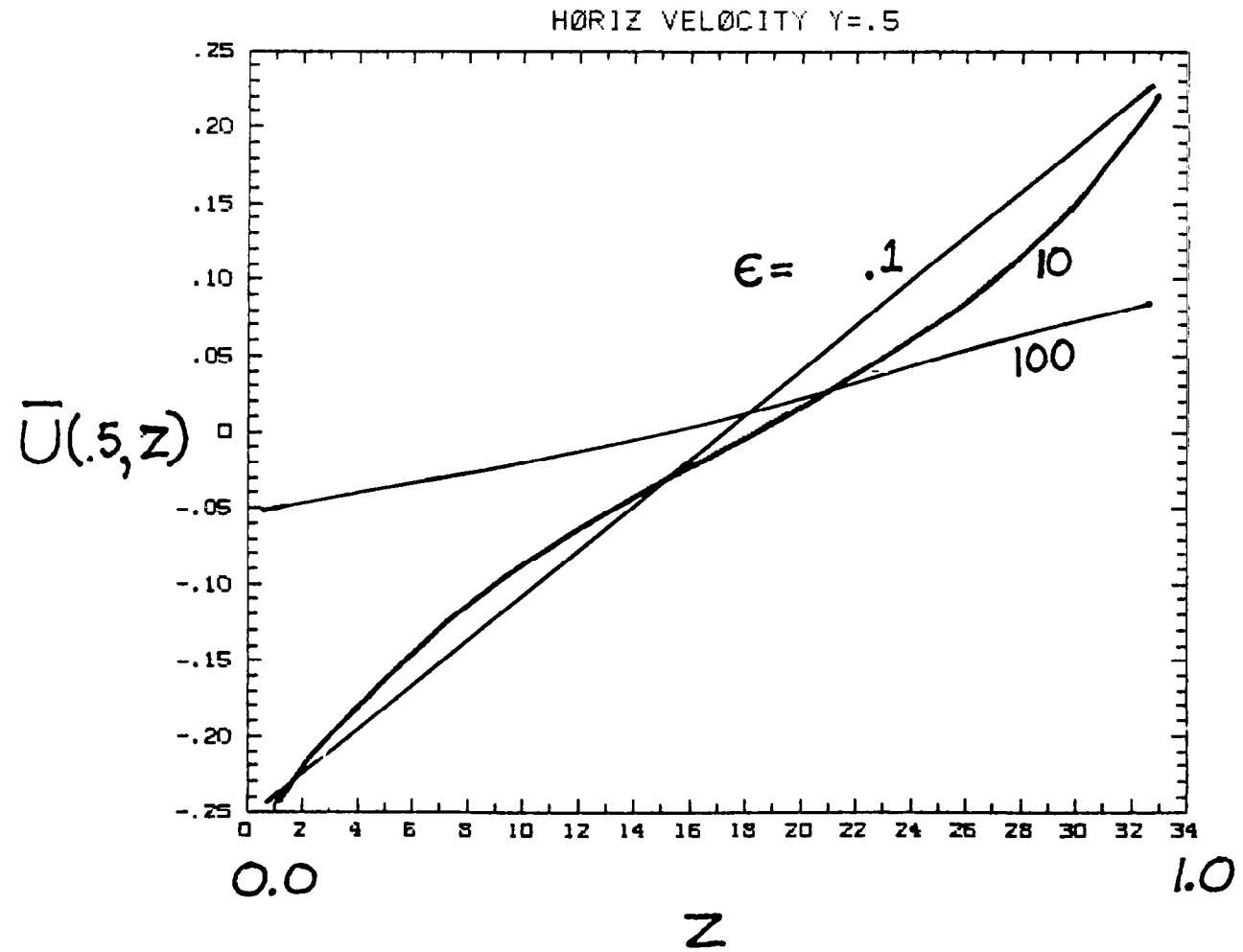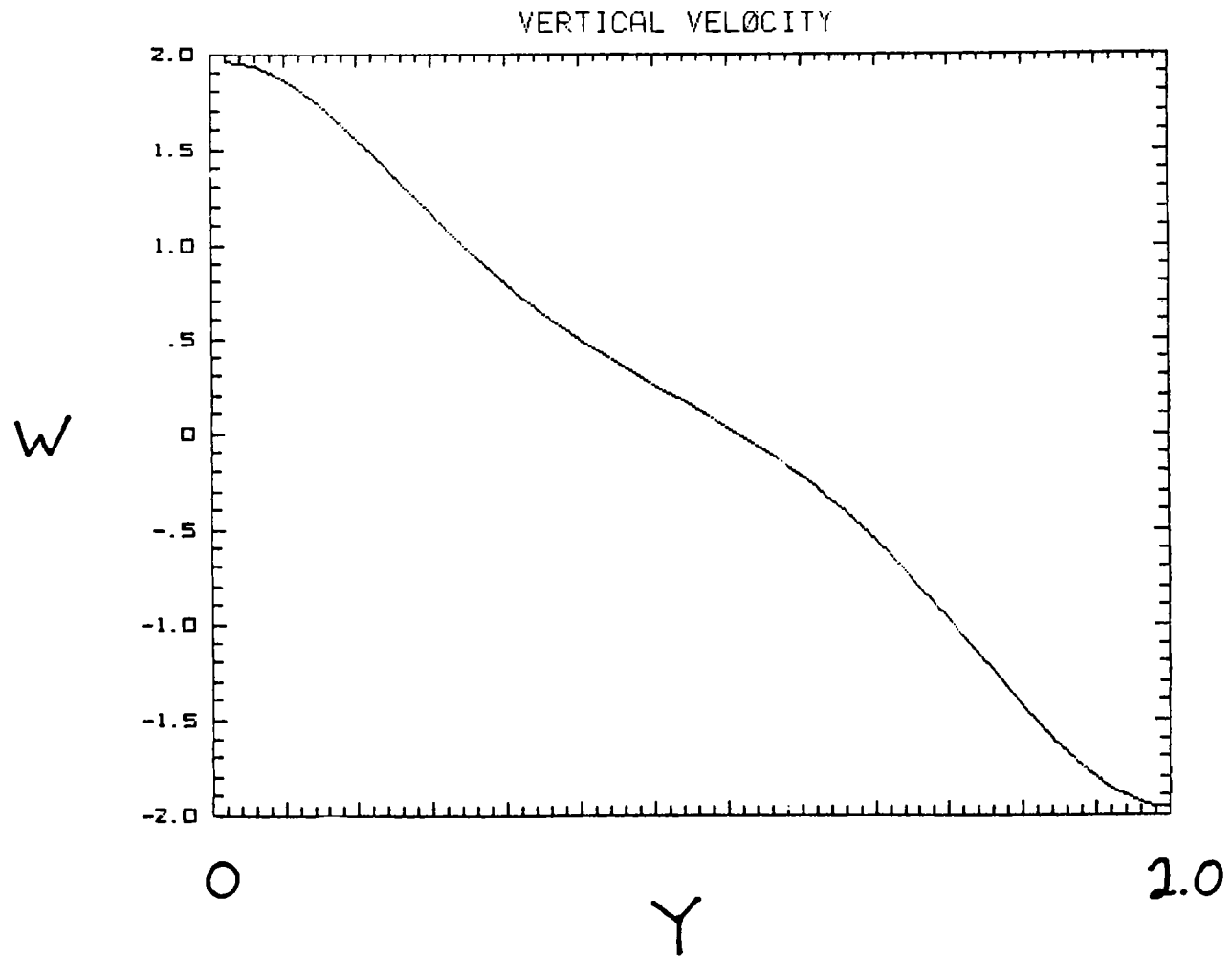
4. STABILITY OF THE SYMMETRIC CIRCULATION

It is the intent of this section to address the question of baroclinic stability of the basic zonal flows of the previous section. In particular we would like to know if a flow can be sufficiently unstable that one might expect strongly non-linear motions will develop. Not only are these strongly non-linear waves of fundament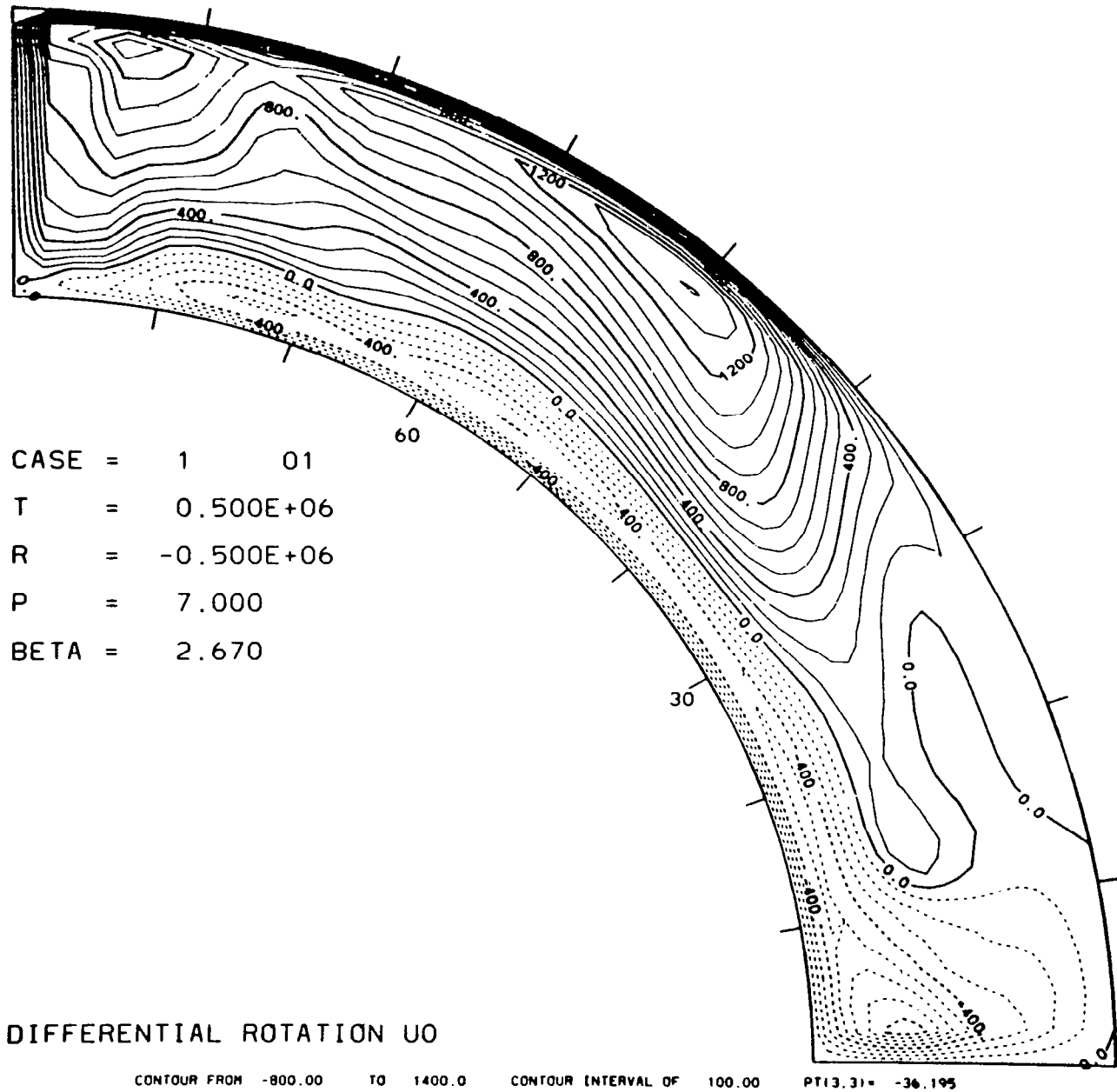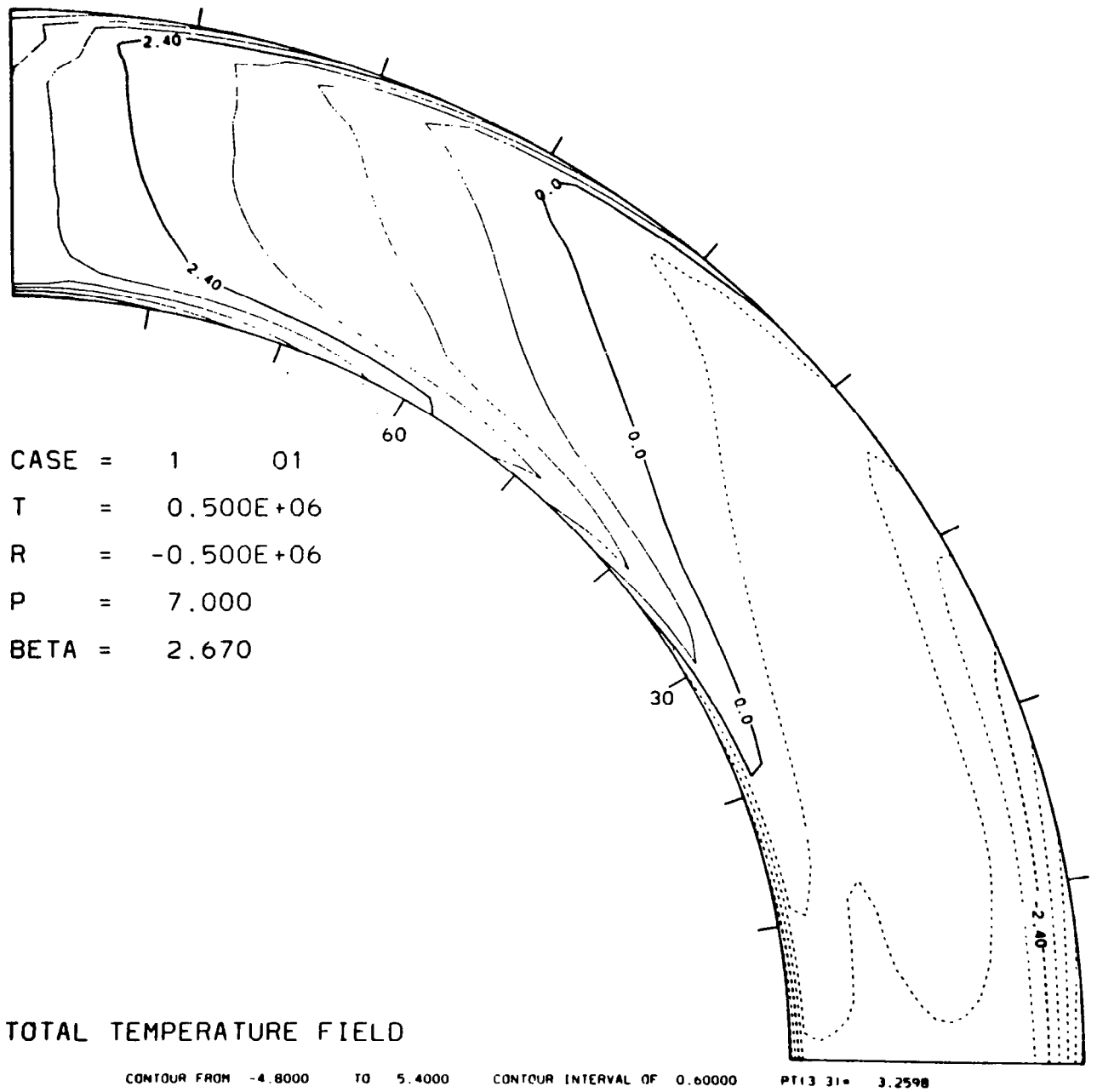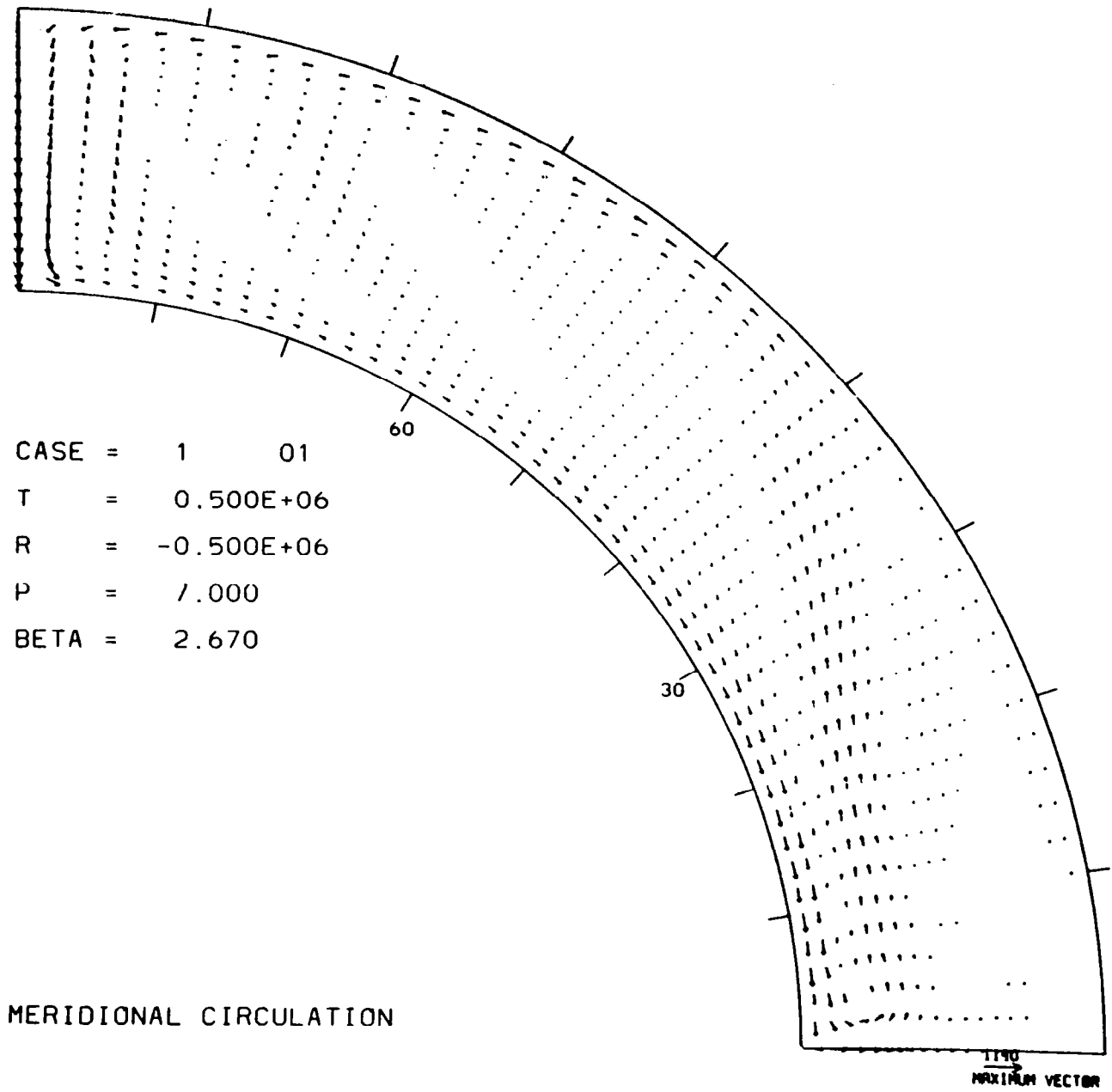al interest, but in addition, any GFFC experiment studying unstable waves must be able to observe them using the current visualization system. This latter point means that they must have sufficient amplitude. In particular, if the driving is done with boundary differences of order 10^0, as seems to be the a priori case, then the wave radially-averaged temperature fluctuations should be at least $.5^0$, or more conservatively 1^0. That is, they should have amplitudes of 10% of $\nabla T_{hor.}$. Without doing a full numerical model, we can only approximate the amount of super-criticality needed to bring about these amplitudes. However, a good estimate of the required super-criticality can be obtained by estimating the predicted unstable baroclinic wave amplitudes using the weakly non-linear theory of Drazin (1970, 1972). He derives an amplitude equation for unstable quasi-geostrophic disturbances on a thermal wind. For steady equilibrated waves, the pressure disturbance, relative to the basic state, has amplitude

$$A_e = (c_1/c_2)^{.5} \cdot (R-R_c)^{.5}/\sqrt{R_c} \qquad (7)$$

where R_c is the critical thermal Rossby number required for linear instability. The Landau constants c_i are functions of E and the aspect ratio. When these are evaluated for typical GFFC numbers, the coefficient of the supercriticality varies between .13 and .22 depending on the wavenumber. Now the temperature, within the hydro-

static approximation is of form $T = p_z$. Thus the radial averaged
temperature is just the difference in pressures at the top and bottom
of the gap, and the equilibrium amplitude gives the size of the thermal
disturbance. We see that the supercricality needs to be about .5 or so
for the waves to be observable. To be strongly non-linear the
supercriticality should be order 1. This should be kept in mind when
evaluating the meaning of regime diagrams based on linear stability
theory.

In considering the linear stability problem it is first useful to
attempt a qualitative answer to the question of the effect of the hot
pole in the GFFC. If one looks at the integral conditions on
quasi-geostrophic instability (Charney and Stern, 1962, Pedlosky, 1964)
one finds that a necessary condition for instability is that

$$\int_o^1 \int_c^2 dydz[\psi^2 q_y/(u_o-c)^2] +$$

$$\int_\nu^2 dy[\psi^2 u_{oz}/(u_o-c)^2]_1 - \int_c^2 dy[\psi^2 u_{oz}/(u_o-c)^2]_0 = 0 \qquad (8)$$

where ψ is the perturbation streamfunction, u_o the zonal flow (a
function of y and z), and q_y the basic state potential vorticity
gradient

$$q_y = \beta L^2/U - u_{oyy} - \partial/\partial z \cdot F \cdot \partial u_o/\partial z \qquad (9)$$

in which F is the rotational Froude number. Now if g is much larger
near the lower boundary, the lower boundary integral will dominate the
boundary terms (the single integrals) of (8). Since for a hot pole
u_{oz} is negative the boundary integrals will be positive in sum. Then
the necessary condition requires that the potential vorticity gradient
q_y must be negative in the flow interior for instability to be
possible at all! Looking at (9) is can be seen that for q_y to be

negative, that the β-effect must be over-ridden by either the second or
third terms. The second is the barotropic instability term and can, in
some flows like Jupiter's cloud bands, exceed β. However we are
interested in the baroclinic instability. The third term rarely
exceeds β in the atmosphere of the Earth, and does not come close in
the GFFC. Thus the suggestion is that the hot pole may stabilize the
GFFC to baroclinic waves. To make the equator hot and the pole cold,
allowing for a 20^0 latitudinal difference in temperature, would require
a massive re-design and re-construction of the instrument. Nonetheless
it might be that the GFFC flows are so unstable even with a hot
polethat experiments with non-linear baroclinic waves might be
possible.

To look at this aspect of the problem we consider the
mid-latitude channel problem for quasi-geostrophic instability of the
zonal flow $u_0(z)$ with $T_0(y,z)=T_0$. We use the Barcilon (1964)
model where damping occurs in Ekman layers at the top and bottom of the
domain. The boundary value problem for the stability of waves of form

$$\psi = \sin\pi y \cdot \exp(i\alpha(x-ct) \cdot \Psi(z)$$

is

$$(u_0-c)(\partial/\partial z \cdot F(z)\partial/\partial z \cdot \Psi - (\alpha^2+\pi^2)\Psi) + \Psi q_y = 0 \qquad (10)$$

where $q_y = \beta L^2/U - \partial/\partial z \cdot F(z)\partial u_0/\partial z$ and $F(z) = 1/R \cdot \partial T_0/\partial z$. This
interior problem must be solved subject to the top and bottom boundary
conditions that $w = w_{Ekman}$, where this latter velocity is given by the
version of (1) that includes the total wave vertical vorticity instead
of just $\partial u/\partial y$. In the equation for $F(z)$, we incorporate the variable
gravity into the basic state stratification as a factor $(1+z/\beta)^5$. The
upper and lower boundary conditions are

$$(u_0-c) \cdot \partial \Psi/\partial z - \Psi \partial u_0/\partial z \mp \sqrt{E}(\alpha^2+\pi^2)\Psi/RF(z)i\alpha/2 = 0 \qquad (11)$$

at $z=0$ and 1 respectively.

These equations are solved numerically by a shooting method. The computation was checked by using the same basic state as Barcilon (1964) and comparing with his analytical results. We actually use a basic state u_0 and $\partial T_0 / \partial z$ from the numerical simulation on the full hemisphere, taking a y-average in mid-latitudes to get u_0. The resulting stability diagram for wavenumber 3, which was the most unstable as a function of E, is shown in figure 15. We have taken $\beta = 0$ here because the calculation is simpler. Note that $c_i = .05$ is close enough to $c_i = 0$ to be considered a fair approximation to the neutral curve. The region of linear instability, where one might expect to find growing baroclinic waves in the GFFC is to the left of the curve at small values of friction. From our previous discussion concerning amplitudes and supercriticality we see that one would need to have an Ekman number of less than .02 to observe the waves, and probably around .01 to get near the strongly non-linear regime. This is a factor of three smaller than is possible in the GFFC. The required low values of the Ekman number means one would need a spherical annulus of three times the GFFC depth to observe strongly non-linear baroclinic waves at the highest rotation rates used by GFFC.

Thus we conclude that no GFFC experiments using the current cell are likely to exhibit strong baroclinic waves. There are many approximations in the analyses presented above (quasi-geostrophic, y independent basic states, etc.) that might change the quantitative details a little bit. But on the basis of this and other studies (Fowlis, private communication), it would be un-rewarding to try and use the GFFC for science problems for which baroclinic instability is the central issue.
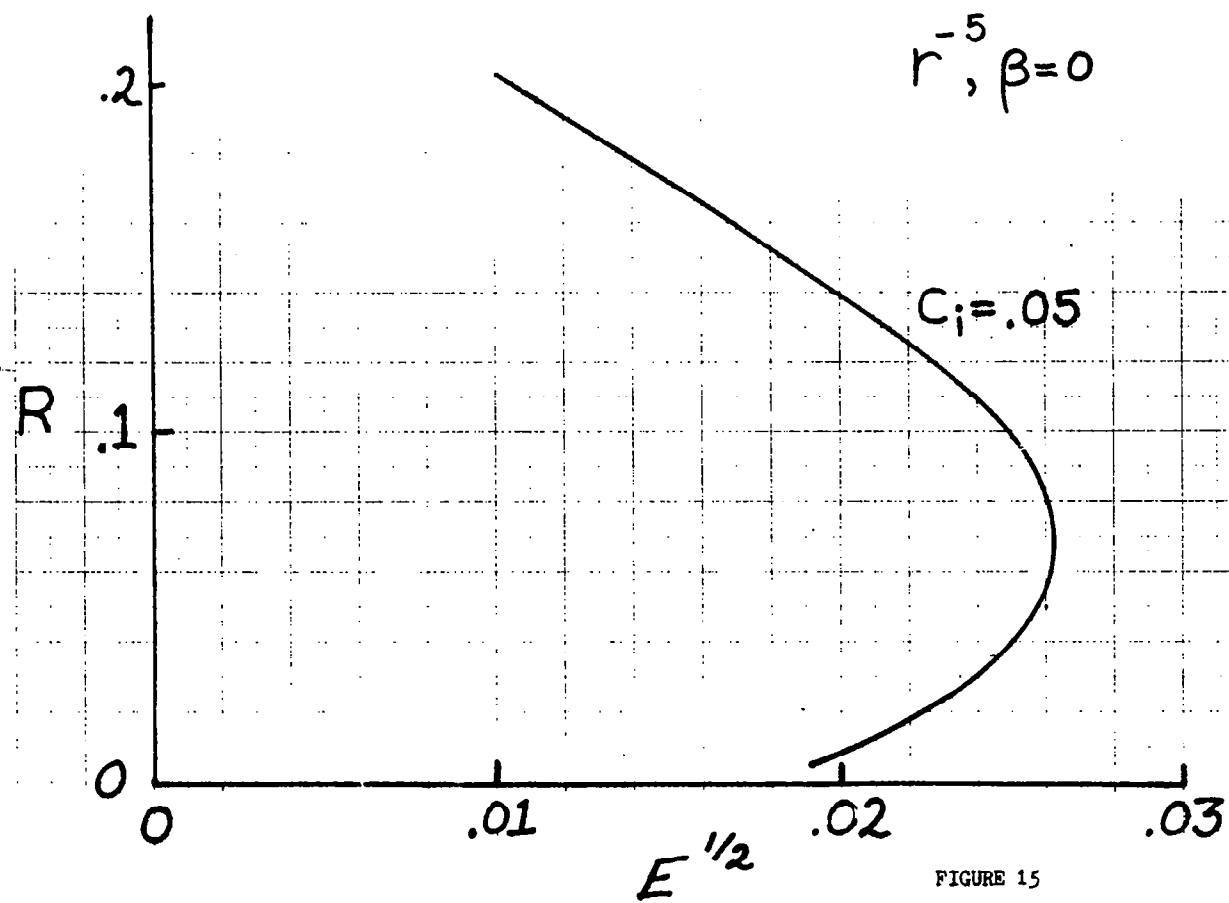
FIGURE 15

5. OCEANOGRAPHIC EXPERIMENTS

Given that eddy generation in a stably stratified flow in the GFFC is weak, are there any other kinds of fundamental experiments that might be done? There has been much recent progress in understanding the wind driven ocean circulation (Rhines and Young 1982) and in certain problems associated with forced buoyancy driven motions in the wind gyre (Luyten, Stommel, and Pedlosky 1983). However most of the theoretical understanding of the wind-driven circulation comes from models that contain a predetermined and usually fixed vertical stratification. How is this stratification set up and how is it maintained? The history of physical oceanography has followed a course of studying the wind-driven, or mechanically forced, circulation separately from the thermohaline, or buoyancy forced, circulation. This separation is loosely based on a scale separation for the two circulations, the buoyancy one being much deeper and of much longer time-scale. The long term goal is to understand the two separately, and then attack the coupled problem. Compared with the wind-driven circulation, the thermohaline circulation has received little attention until recently. A review by Killworth (1979) points to the many areas of buoyancy driven flows of critical importance to oceanography that sorely lack understanding. In the last couple of years, however, interest in the thermohaline circulation has blossomed and now the subject has become one of the really hot topics in ocean science.

Can the GFFC contribute anything to this problem? We have already seen that modelling a strong eddying ocean is probably unrealistic. Indeed it would be hard for the GFFC to compete with eddy resolving ocean circulation models, partly because of the

low Reynold's numbers and lack of strong baroclinic instability in the GFFC, but also because the measurements of the flows are made at rather low resolution (dealing with radial averages of temperature, for example).

There are, as Killworth points out, few, if any, prototypical large-scale rotating and thermally driven flows that are well understood. Even the theory for the f-plane zonally symmetric thermally forced circulations discussed in section 3 is in a pretty primitive state. The nature of the end-wall boundary layers and their stability has not been addressed except superficially. Of course f-plane convection can be studied in the terrestrial laboratory (Hignett et. al.). So it is anticipated that at least one aspect of the thermohaline circulation might be approached terrestrially. But terrestrial experiments can never address any questions having to do with the global or even large-basin thermohaline circulations because in the oceans the β-effect (sphericity) plays a crucial role that can never be simulated on Earth. And in fact the meridionally bounded β-gyre circulations are probably so different from the f-plane ones that the insights gained by completing the f-plane convection studies will probably be of little use to large-scale oceanographers.

Consider for example the simple problem of a box gyre forced thermally from above (or below) by a latitudinal temperature gradient. That is, take the box of figure 7, add two meridonal walls at x=0,L, and let Ω be a linear function of y (the β-plane). What will the circulation look like? Certainly some of the processes discussed in section 4 will still be present, There will be Ekman suction and associated thermal advection tending to produce a thermocline. However there are some fundamental and perplexing differences.

One might first attempt to describe the thermally driven gyre flow as follows. Since the forcing is y-independent, the interior should be as well. This then requires complicated eastern and western boundary layers, whose structure is not known and even hard to contemplate. Nonetheless if one knows where the boundary layers are, at least one could perhaps make a stretched grid numerical model to study the problem. However the situation is probably worse still.

The continuity equation

$$w_z + v_y + u_x = 0$$

gives an estimate for v. If zonality is assumed in the interior, and the gyre has scale L in y and x, and D in z, then we find

$$v \approx wL/D \approx w_{Ekman}L/D$$

since Ekman suction is presumed to be the dominant vertical velocity generator outside strong convective sinking regions. On the other hand the interior dynamics are dominated by the vertical vorticity equation, that for ocean scales reduces to Sverdrup balance

$$fw_z = \beta v$$

Letting v_E be the first estimate of v, and v_S be the second, it is clear that

$$v_S/v_E \approx fL/\beta = f/\delta f$$

where δf is the variation of the Coriolis parameter across the gyre. This is Rhines' recirculation index, and for typical gyres varies from 2 to 5. Thus continuity and Sverdrup are incompatible with the Sverdrup velocity v_S being bigger. This requires an adjustment to the continuity equation, namely that u_x be included to make up the difference. Thus one suspects that the buoyancy driven flow in this very simple gyre model will not be zonal at all.

There is a real need for fundamental insights into the qualitative nature of buoyancy circulations on the β-plane. What are the shapes of the circulations for various degrees of forcing? Where are the boundary layers and what are their functions? Where are the sinking (or rising) regions? What is the extent of small scale sinking in these regions and how is it coupled to the more or less laminar large scale circulation? These are just some of the problems that could benefit from experimental guidance.

Can a computer do the job? State of the art now is a perhaps 10 layer model with relatively course (20X20 or so) horizontal resolution. However the buoyancy circulation spin up time is so long (800 years) that few runs can be carried out. These models are not eddy resolving in any sense of the word. In studying smooth circulations, numerical computations probably exceed the science potential of the GFFC because of their much greater information gathering. However, it should perhaps be mentioned again that the laboratory experiment is well-defined in terms of its small-scale truncation, and this may be a significant advantage. There is something more thought provoking, too, in trying to understand observations of a real fluid motion. Where the GFFC exceeds foreseeable computational efforts is in problems that have small scale convective sinking regions. It is unlikely that such narrow plumes as expected on the basis of rotating direct-convection models can be modelled numerically along with a large laminar but stratified ocean.

It is clear that the present configuration of the GFFC is adequate for such studies. One would need to place a set of meridional barriers into the gap, but this is a relatively inexpensive task.

As opposed to the baroclinic instability case, the fact that the pole is hot makes no fundamental difference here. One would impose a latitudinal thermal gradient on the inner sphere and think of it as the ocean surface. The outer sphere would be constant in T such that the polar region of each gyre would be statically unstable. A key issue, however, is the data acquisition instrumentation. While it certainly can see.convective cells and thermal side-wall boundary layers, it only measures the radially-averaged temperature field. Many of the major issues in thermocline theory revolve around the generation of the basic stratificition in the oceans, so one would really like for this aspect of the problem to have detailed thermal sections. Unfortunately, given the presence of the 10kv electric fields in the GFFC, it is hard to see how in-situ temperature sampling would be possible. Constructing additional remote sensing is also impractical. On the other hand, the dye lines would give some information on radial structure, and certainly would give the sense of the flow in the gyre, the position of asymmetries, internal boundary layers, etc.

Thus the main conclusion of this paper is that the most promising class of geophysical flow studies with the GFFC involving stably stratified rotating fluids is that concerned with large scale buoyancy-driven circulations. The fundamental science issues are largely qualitative and don't depend on precise measurements of detailed quantities like turbulent fluxes or laminar vorticity fluxes. The main question is whether or not the GFFC flow visualization instrumentation is adequate to resolve the key science issues. This problem can be addressed by further study of prototype problems like the one posed in this section. With a little probing

it should be possible to focus in on some more specific questions so that one can more precisely determine whether the optical instrumentation and data gathering capability of the GFFC is up to the tasks. It is felt that the current interest in this class of problem in the physical oceanographic community is a sign of their importance, and suggests that further study of possible GFFC contributions is warranted.

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1. REPORT NO. NASA CR-3766	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Alternative Experiments Using the Geophysical Fluid Flow Cell		5. REPORT DATE January 1984
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) John E. Hart		8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Astrogeophysics University of Colorado Boulder, Colorado 80309		10. WORK UNIT NO. M-436
		11. CONTRACT OR GRANT NO. NAS8-31958
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D. C. 20546		13. TYPE OF REPORT & PERIOD COVERED Contractor Report (Final)
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES Technical Monitor: Charlie T. Jones
Alternate: Dr. George H. Fichtl
George C. Marshall Space Flight Center, Alabama 35812

16. ABSTRACT

This study addresses the possibility of doing large scale dynamics experiments using the Geophysical Fluid Flow Cell. In particular, cases where the forcing generates a statically stable stratification almost everywhere in the spherical shell are evaluated. This situation is typical of the Earth's atmosphere and oceans. By calculating the strongest meridional circulation expected in the spacelab experiments, and testing its stability using quasi-geostrophic stability theory, it is shown that strongly nonlinear baroclinic waves on a zonally symmetric modified thermal wind will not occur. The Geophysical Fluid Flow Cell does not have a deep enough fluid layer to permit useful studies of large scale planetary wave processes arising from instability. It is argued, however, that by introducing suitable meridional barriers, a significant contribution to the understanding of the oceanic thermocline problem could be made.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Stability theory Atmospheric circulation Baroclinic waves Fluid-flow processes Large-scale hydrodynamic flows	Unclassified-Unlimited STAR Category: 46

19. SECURITY CLASSIF. (of this report) Unclassified	20. SECURITY CLASSIF. (of this page) Unclassified	21. NO. OF PAGES 46	22. PRICE A02