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A STUDY OF THE EXPECTED EFFECTS OF LATITUDE-DEPENDENT ROTATION RATE ON LABORATORY GEOPHYSICAL FLOW EXPERIMENTS

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ABSTRACT

This paper reports results of a theoretical model study of some of the expected effects of spherical geometry on laboratory simulations of the type of geophysical flow that dominates the general circulation of the earth's troposphere.

INTRODUCTION

The traditional device for laboratory simulation of the general circulation of the atmosphere is an annular container of liquid situated on a rotating turntable (Hide, 1958; Fowlis and Hide, 1965). Fluid motion is driven by heating the outer wall of the annulus and cooling the inner wall, a crude analog of the observed fact that the earth's troposphere is heated in the tropics and is cooled in high latitudes. In the real atmosphere and in the laboratory annulus, the function of the motion field is to transport heat laterally from the heat source to the heat sink.

The annulus suffers from the defect that its geometry is far different from that of our spherical-shell atmosphere. Attempts to design a rotating spherical laboratory device have been frustrated by the presence of gravity, which acts vertically downward in the laboratory. This influence would be absent in a satellite. Atmospheric general circulation simulations in a spherical container with an electrostatic radial force field acting as "gravity" on a fluid with radially dependent dielectric constant have been proposed for Spacelab by Fowlis and Fichtl (1977). In this paper we report some results of a simple mathematical model study which isolates some of the expected differences between annulus flows and spherical shell flows.

THE MODEL

Consider a spherical shell of fluid rotating with constant angular velocity around a polar axis. The local vertical component of this rotation vector varies as the sine of the latitude, being zero for an equatorial observer and a maximum for a polar observer. As is generally well known, this latitudinal variation of the local vertical component of rotation plays a significant role in the dynamics of the class of motions constituting the general circulation of the atmosphere (and laboratory simulations thereof). The simplest mathematical model which incorporates this effect is one in which the relevant equations are written in a Cartesian (rectangular) coordinate system rotating with respect to the vertical axis. This rotation rate is taken to be constant in the equations, except when it is differentiated with respect to the north-south coordinate. This local tangent-plane formulation of fluid motion on a sphere is generally known as the β-plane. If rigid walls are erected at two arbitrary latitudes in this model, we have a β-plane channel.

In its treatment of the dynamical effects of rotation, the β-plane channel is sort of midway between an annulus and a sphere. In our mathematical model study, we have subjected the β-plane channel to different degrees of cross-channel heating and different rotation rates, and noted the character of the resulting motion field. In particular, following the traditional description of the analogous flow patterns in the annulus, we distinguish between axially-symmetric motions and wave motions.

RESULTS

Figure 1, shows a so-called regime diagram (after Fowlis and Hide, 1965) showing the types of motion occuring in a typical annulus experiment.

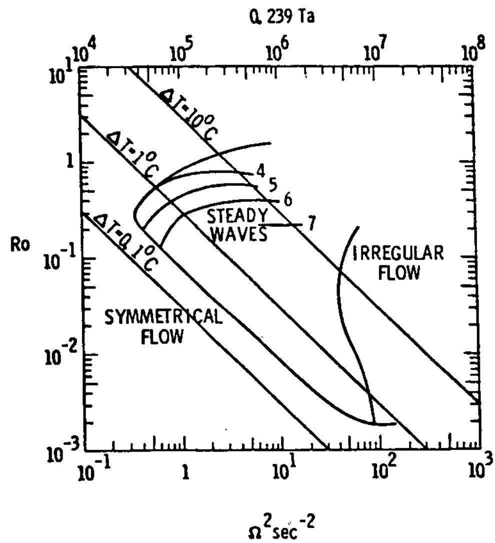

Figure 1
Experimentally determined regime diagram for annulus flow

The horizontal axis in the figure is the rotation rate squared; the vertical axis in the figure is a "thermal Rossby number", which varies directly with the imposed thermal contrast across the annulus and inversely as the square of rotation rate. We wish only to call attention to the fact that in this parameter space the region occupied by waves is bounded on the left by a convex, "knee-shaped" curve which we refer to as the stability boundary.

Figure 2 shows results of a simple mathematical model simulation of annulus flow (after Barcilon, 1964).

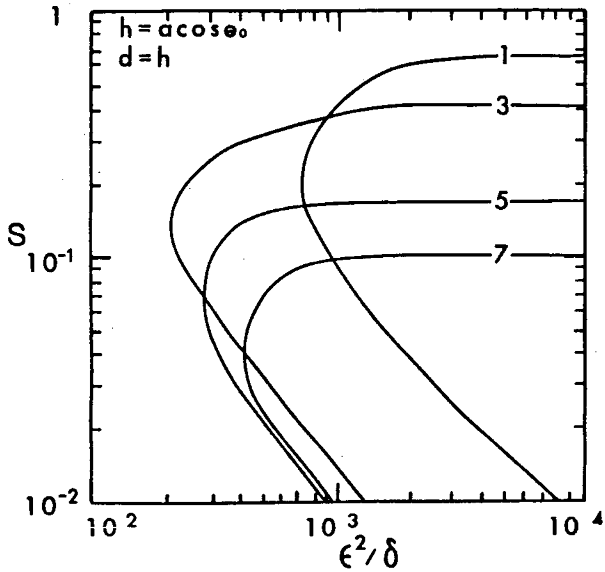

Figure 2
Theoretically determined regime diagram for annulus flow

The parameter space in this figure can be shown to be essentially identical to the parameter space in Figure 1. Each curve is the stability boundary for the zonal wavenumber shown. (Zonal wavenumber is formally equivalent to quantum number; that is, zonal wavenumber 1 means that the horizontal wavelength of the wave is exactly equal to the circumference of the annulus). The stability boundary for the system is the envelope of these curves. It is seen that this theoretically-obtained stability boundary has essentially the same shape as the experimentally determined one (Figure 1).

Figure 3 shows results from our β-plane channel model when the dimensions of the channel are the same as the annulus in Figure 2.

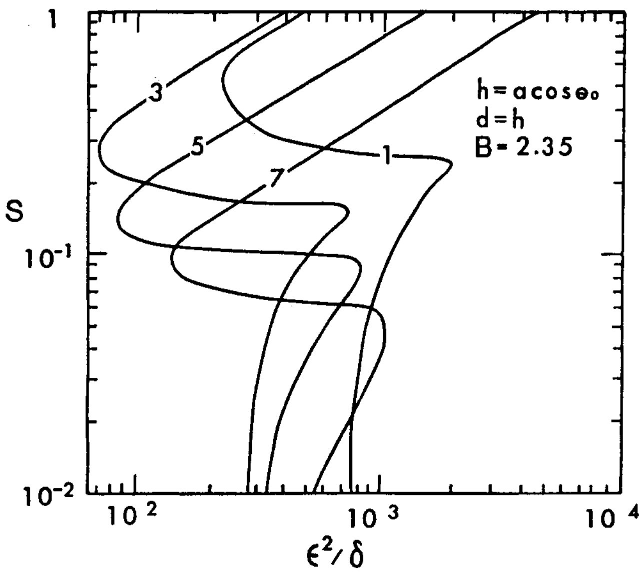

Figure 3
Theoretically determined regime diagram for β-plane channel flow

Again, the envelope of all these curves is by definition the stability boundary. In comparing this with Figure 2, it can be seen that the stability boundary has a considerably different shape and that it extends somewhat farther to the left. The conclusion here is that the β-effect (that is, the variation of local vertical rotation rate with latitude) results in more of parameter space being occupied by waves. Another interesting result, not discussed here, is that the β-effect produces a marked change in the vertical structure of the waves present and it also greatly changes the dependence of the results on the presence of a rigid lid upper boundary condition.

We have repeated these model simulations for a wide range of channel dimensions and compared these results with simulations in annular geometry. These simulations support the general conclusion that the β-effect drives the stability boundary to the left in the parameter space diagram.

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