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LABORATORY AND THEORETICAL MODELS OF
PLANETARY-SCALE INSTABILITIES AND WAVES

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Meteorologists and planetary astronomers interested in large-scale planetary and solar circulations recognize the importance of rotation and stratification in determining the character of these flows. In the past it has been impossible to accurately model the effects of **sphericity** on these motions in the laboratory because of the invariant relationship between the uni-directional terrestrial gravity and the rotation axis of an experiment. We have studied motions of rotating convecting liquids in **spherical shells** using electrohydrodynamic polarization forces to generate **radial** gravity, and hence centrally directed buoyancy forces, in the laboratory.

The GFFC (Geophysical Fluid Flow Cell) experiments performed on Spacelab 3 in 1985 have been analysed. Recent efforts at interpretation have led to numerical models of rotating convection with an aim to understand the possible generation of zonal banding on Jupiter and the fate of banana cells in rapidly rotating convection as the heating is made strongly supercritical. In addition, efforts to pose baroclinic wave experiments for future space missions using a modified version of the 1985 instrument have led to theoretical and numerical models of baroclinic instability. Rather surprising properties were discovered, which may be useful in generating rational (rather than artificially truncated) models for nonlinear baroclinic instability and baroclinic chaos.

RESEARCH HIGHLIGHTS: June 1989 - June 1990

COLUMNAR CONVECTION

Under conditions of rapid rotation and relatively low differential heating, convection in a spherical shell takes place as columnar "banana cells" wrapped around the annular gap, but with axes oriented along the axis of rotation. These were clearly evident in the GFFC experiments. Because the cells are aligned with the rotation axis, the simplest models for understanding their dynamics can be two-dimensional. There has been much recent effort to understand this type of 2-D convection. For example, Lin Busse and Ghil (GAFD, 45, 1989) use a spectral truncated low-order model to map out speculations about the transition to chaos. Lin (GAFD, 1990, to appear) produced a low order model that generates *strong zonal banding* through the Reynolds stress associated with thermal convection in the presence of shear. This claim, which is offered as a mechanism for the banding on the giant planets, is in much dispute. Such bands were not seen in GFFC, although the parameters were different from those used by Lin. In an effort to resolve this dispute, a very accurate 2-D numerical model with resolution approaching 1024^2 , was constructed. This model reproduces the GFFC results qualitatively. When extended to the cases studied by Lin no "double column instability" was found. The zonal flows were relatively weak. Interestingly, the convective cells grouped together in the form of envelope solitons (Brummel et. al, 1990). Additions to the 2-D physics which will possibly lead to a strong zonal acceleration are under study.

Other numerical studies were completed which demonstrate the effects of compressibility and relatively high heat diffusion (typical of planetary and stellar atmospheres) on thermal convection, and on processes that may lead to different classes of turbulence in Boussinesq laboratory convection.

BAROCLINIC FLOWS AND BAROCLINIC CHAOS

Linear instability calculations by Dr. T. Miller at MSFC indicate that the GFFC should exhibit classic baroclinic instability at accessible parameter settings. Of interest are the mechanisms of transition to temporal chaos and the evolution of spatio-temporal chaos. In order to understand more about such transitions we have conducted high resolution numerical experiments for the physically simplest model of two layer baroclinic instability. This model has the advantage that the numerical code is exponentially convergent and can be efficiently run for very long times, enabling the study of chaotic attractors without the often devastating effects of low-order truncation found in many previous studies.

The principal results are:

- 1) There are a countable infinity of invariant manifolds in spectral space. This means that for a given set of external parameters

that there are potentially an infinity of possible distinct statistical equilibria. In practice most of these are unstable, but numerical studies have shown that for parameters relevant to the atmosphere, at least two and more typically three or four states can be attained a large times depending on the initial conditions.

2) The transition to chaos computed with high resolution (typically 64^2 spectral modes) is abrupt. Low order models predict exotic transition sequences (period doubling sequences, tori fragmentation). The fully resolved model behaves differently, with an imperceptibly small transition layer.

3) The transition to chaos and the nature of turbulent flow is strongly affected by the addition of a small amount of time-dependent seasonal forcing. The dynamic origins of these effects are associated with the periodic forcing causing the system to locally approach homoclinic trajectories of the various invariant spectral manifolds in the system. A theory based on this idea may lead to a better understanding of chaotic baroclinic wave systems.

RESEARCH PLANS

We wish to pursue a better understanding of nonlinear baroclinic flows, which are important in internal climate variability. Baroclinic instability in channels annuli with both rigid (a la GFFC) and slippery meridional walls at fixed latitudes (a la the classical meteorological theories) will be studied using both low-order and high-resolution numerical models. The emphasis will be on the following questions. What is the nature of the chaotic dynamics? How does it depend on boundary conditions? What is its fractal properties? Can it be represented by a robust low-order description?

For some ranges of external parameters, high resolution models indicate large-scale chaotic baroclinic waves with fractal dimensions of less than 10. The real atmosphere has a higher dimensional attractor, but this includes motions on smaller scales which may be less important for global climate modelling. Two methods of obtaining a robust low-order description will be tried. First, we shall try to obtain the inertial manifold for quasi-geostrophic baroclinic chaos. This manifold represents the inertial component of motion where the dissipative scales are projected or slaved to the low-order motion. The motion on the inertial manifold is much easier to compute than solving the full PDE's using spectral methods that include high enough wavenumbers that the dissipative modes are explicitly calculated.

If there is not a strong dissipative range of scales, or if such scales are very far removed from the energy containing eddies, then the inertial manifold approach may not be effective. Variants on the Proper Orthogonal Decomposition method will be tried. Empirical Orthogonal Functions that capture an optimum amount of energy are one example. Others may be better. Ideally it is not clear that energy optimization will track the flow on a strange attractor. For example, high energy modes may be slaved together. Other possibilities, like

the invariant wavenumber sets found by Cattaneo and Hart (1990) may be useful.

We shall also consider numerically the role of viscous sidewall layers (and possible flow separation) on the transition to chaos. In addition to providing new theories for the transition to chaos in baroclinic instability which will be of major interest in atmospheric and ocean sciences, this work will offer guidelines for scientifically important GFFC experiments with a stable stratification.

Other numerical work will continue study of the narrow annulus columnar convection models, including attempts to construct an analytical theory for the envelope convective solitons observed in our recent computational experiments. Laboratory work will focus on baroclinic annulus waves with non-zonally-symmetric heating (to verify theories about storm tracks), and on baroclinic waves with seasonal forcing (to verify ideas about the pivotal role seasonality can play in baroclinic chaos).

PUBLICATIONS WITH NASA SUPPORT

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