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LABORATORY AND THEORETICAL MODELS OF PLANETARY-SCALE INSTABILITIES AND WAVES

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RECENT PROGRESS

Research work is proceeding in theoretical, numerical, and experimental geophysical fluid dynamics leading up to a reflight of the GFFC (Geophysical Fluid Flow Cell Experiment) on USML - 2. The work is intended not only to generate ideas for future space experiments, but to provide fundamental results concerned with nonlinear and chaotic properties of thermal convection and baroclinic waves in terrestrial and planetary atmospheres. The major efforts are focussed on thermal convection in a rapidly rotating annulus relevant to Jovian atmospheric dynamics, and on the chaotic behavior of baroclinic waves relevant to the Earth's atmosphere. The approach, in preparation for USML - 2, is primarily theoretical and numerical.

Mechanistic process models are solved numerically in order to identify physical mechanisms that may be observed in the GFFC, and which are important in real geophysical applications. The results from numerical simulations of geophysical fluid flow (subject to rotation and stratification) are compared with previous GFFC experiments on Spacelab-III and with existing and proposed terrestrial laboratory experiments of various types. Pattern recognition algorithms have been employed to generate low-dimensional descriptions of the the highly nonlinear and turbulent numerical simulations. Such empirically truncated descriptions provide for simplified but robust physical interpretations of the dynamics, as well as yielding highly efficient computations of these chaotic flows.

Our most important new results are:

1) The completion and exploration of a fully nonlinear computational model of thermal convection in the presence of strong basic rotation which varies with latitude. The model assumes the thermal convection takes place on cylinders parallel to the axis of planetary rotation, but is influenced by the spherical topography (the β effect). The resulting thermal convection is composed of banana cells, as observed on Spacelab III flight of the GFFC, but the computation is simplified by using an equatorial annulus geometry. Thus very high Rayleigh and Taylor numbers can be studied on workstations.

The results are most interesting. The turbulence at high Rayleigh numbers is associated with extremely strong, even dominating, mean zonal jets. A scaling of the model results with the observed heat flux of Jupiter, for example, leads to zonal jets with velocities of order 100 meter per second. This number is similar to Voyager observations. The turbulence can have isolated spots imbedded in the self-induced zonal jets. At very high Rayleigh number and large β the whole system pulsates. The differential rotation and the turbulent convection patches oscillate almost-periodically. If an effective eddy viscosity appropriate to solar convection is used, the pulsation period is about 11 years - the observed period of the solar cycle. All our work so far has been with unit Prandtl number, and one consequence of this is that the associated solar convective heat flux is much too small. We propose to correct this deficiency and to study further properties of this system at low Prandtl number in the second year.

2) Accurate simulations of the way in which baroclinic atmospheric instabilities become chaotic were completed. It was discovered that almost all previous numerical simulations intending to look at the transition to baroclinic chaos were in error, or at least very slowly convergent. Pseudo-spectral models must employ some lateral viscosity to arrest the enstrophy cascade to small scales. However, with small lateral viscosity present the standard Phillips' condition on the zonal flow at the sidewalls is slightly inconsistent. This small inconsistency has a strong effect on the bifurcation sequence, even when the lateral viscosity is small.

The new model has a different spectral representation that avoids these problems. The baroclinic waves become weakly chaotic for Froude numbers about a factor of 2 smaller than in previous models. However, the degree of chaos is small, when compared with terrestrial laboratory experiments. It is thought that this may be due to the presence of rigid walls in terrestrial and GFFC space experiments, and we propose to rewrite our codes to look at this important problem. For example, the lateral shears induced by the walls will allow for critical layers that will have a significant effect on the baroclinic waves. Although walls are not relevant to atmospheres (though they are to oceans), the transition to chaos with meridional mean shear is a key unsolved problem in atmospheric dynamics.

3) Algorithms to do pattern recognition on both the β - convection and baroclinic wave simulations were competed and tested. Pattern recognition extracts empirical orthogonal functions (nonlinear eigenfunctions) which can be used as basis functions for constructing low order models of the highly nonlinear and fully resolved simulations. In some circumstances modest (e.g. 10 mode) sets of ordinary differential equations can mimic numerical solutions requiring over 10^4 degrees of freedom.

PROPOSED RESEARCH

Our successful numerical model of banana cell convection subject to the β effect will be expanded. The goals are to understand the heat flux and the 11 year cycle on the Sun, and the reason for prograde equatorial jets on Jupiter and Saturn, but retrograde jets on Uranus and Neptune. The hypothesis for the latter difference is that the distance to the inner core (which is significantly larger on Jupiter and Saturn) plays a key dynamical role. We shall:

a) Determine the effect of small ($\simeq$0.01, as in the Sun) and modest ($\simeq$8, as in GFFC) Prandtl number on β - convection.

b) Compare full numerical simulations of β - convection with asymptotically derived nonlinear amplitude equations. These comparisons will allow us to understand the conditions under which multiple zonal jets may arise, as in Jupiter, vs. the single jet on Uranus and Neptune.

c) Determine the effect of deep anelastic compressibility on the liquid GFFC type models. The convection and zonal jets must extend some distance into the giant planets and the effect of penetration through many scale heights must be addressed before truly quantitative comparisons with the Voyager data will be possible. Our code will be for a rectilinear geometry (retaining β effects) and will run much faster than full spherical shell models. Thus we will be able to pursue questions about scaling and banana cell breakup at very high Rayleigh and Taylor numbers.

d) Determine the effect of core depth on zonal jets. Simulations with β increasing or decreasing with latitude, or with a singularity at subtropical latitudes, will be run to investigate the effect of variable β on zonal jet sign (prograde vs. retrograde) and structure.

e) Complete a rigid sidewall boundary model of baroclinic instability. Investigate the transition to chaos and compare with the previous free slip models. The results are of fundamental interest and important for generating baroclinic wave experiments on GFFC - USML2.

f) Perform pattern recognition and EOF analyses on the above simulation results. Analyse the resulting projected low order models as predictive and interpretive tools in nonlinear geophysical fluid dynamics.

g) Construct a simple rapidly rotating - convection experiment using centrifugal buoyancy. Compare with anaytical and numerical results. Verify the existence of pulsating turbulent states.

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