ON THE DECADAL MODES OF OSCILLATION OF AN IDEALIZED OCEAN-ATMOSPHERE SYSTEM

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ABSTRACT

Axially-symmetric, linear, free modes of global, primitive equation, ocean-atmosphere models are examined to see if they contain decadal (10-30 years) oscillation time scale modes. A two-layer ocean model and a two-level atmospheric model are linearized around axially-symmetric basic states containing mean meridional circulations in the ocean and the atmosphere. Uncoupled and coupled, axially-symmetric modes of oscillation of the ocean-atmosphere system are calculated. The main conclusion of this study is that linearized, uncoupled and coupled, ocean-atmosphere systems can contain axially-symmetric, free modes of variability on decadal time scales. These results have important implications for externally-forced decadal climate variability.

INTRODUCTION

There are numerous observational studies of decadal (10-30 years) time scale climate oscillations (see, for example, Pittock (1983), Currie and O'Brien (1988), Labitzke and van Loon (1989), and references therein). Most of these studies have tried to correlate decadal climate variations with solar and lunar influences. Although the existence (or otherwise) of these correlations and the mechanisms by which variability of solar and lunar influences might affect terrestrial climate are not yet clear, *the observational studies show that decadal climate variations do exist.* These variations may be due to internal variability of the climate system, they may be forced externally or a combination of internal variability and external forcing may give rise to these modes. Some results from a research effort to study the natural variability of an idealized ocean-atmosphere system, especially on decadal time scales, are reported here. In addition to the above-mentioned observations, more specific motivation for the work reported here was provided by two observational studies dealing with long-period (years to decades) fluctuations of the axially-symmetric (symmetric around the rotation axis of the earth) components of some climatic variables. Krishnamurti et al. (1986)'s analysis of global sea level pressures (SLP) and Semazzi et al. (1988)'s analysis of global sea surface temperatures (SST) showed that axially-symmetric components of SLP and SST fluctuate with a variety of time scales, including the years to decades time scales. In view of the above observations, the emphasis in the modelling

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work reported here is on axially-symmetric modes of the ocean-atmosphere system oscillating at decadal time scales.

Anderson and Stevens (1987) (hereafter referred to as AS) found that a multi-level model of the tropical atmosphere linearized about a Hadley cell basic state contains wavelike, axially-symmetric modes in thermal wind balance. The oscillation time scales of these modes range from a few weeks to a few months. Advection of perturbation zonal wind and temperature fields by the basic state meridional velocity was suggested as the mechanism giving rise to these modes.

In the ocean, there appears to be a similar but opposite mean meridional circulation (MMC) than in the atmosphere. This can be seen clearly in studies of model ocean circulations by Bryan and Lewis (1979, fig. 10a) and Meehl et al. (1982, fig. 2). This similarity of atmospheric and oceanic MMC raises some interesting questions in light of AS's results. If advection of perturbation fields by the basic state meridional velocity is indeed the mechanism giving rise to the axially-symmetric atmospheric intra-seasonal modes found by AS, then the same mechanism may give rise to axially-symmetric oceanic modes with time scales of several years and longer. This is because basic state meridional velocities in the ocean are at least 2 orders of magnitude smaller than in the atmosphere. If such long-period, axially-symmetric modes do exist in an idealized ocean model, then within the framework of a coupled ocean-atmosphere system, such oceanic variability might also result in atmospheric variability on long time scales. Moreover, since MMC exist not only in the tropics but also in higher latitudes, such axially-symmetric modes might exist in association with higher latitude MMC also. Therefore, a modelling study was carried out to test the hypotheses outlined above.

MODEL DESCRIPTION AND METHOD OF SOLUTION

The governing equations of the two-level model of the atmosphere formulated for this study are primitive equations in spherical co-ordinates with sigma (pressure at any level divided by surface pressure) as the vertical co-ordinate. The model atmosphere extends around the earth in longitudinal direction and from the South Pole to the North Pole in latitudinal direction. The governing equations of the two-layer model of the ocean are primitive equations with height as the vertical co-ordinate. The model ocean has the same horizontal domain as the model atmosphere. Vertically, the ocean is divided into two homogeneous layers separated by a thermocline. The model ocean has a uniform depth of 4000 meters. The model ocean and the model atmosphere interact via heat and momentum exchange. Other physical processes included in the models are entrainment of mass, momentum, and heat between the oceanic layers, thermal infrared radiation, and vertical diffusion within the atmosphere and the ocean. The two models and parameterizations of physical processes are described with details in Mehta (1990a, 1990b).

The two models and parameterizations of physical processes are linearized around an axially-symmetric basic climatic state containing mean meridional circulations in the atmosphere and the ocean. The resulting linearized perturbation climate system is solved as an eigenvalue problem. The eigenvalues are complex-valued, where the real parts are the oscillation frequencies and the imaginary parts are the growth rates of individual modes. The eigenvectors contain vertical and horizontal structures of individual modes. Details of linearization and numerical solution procedure are given in Mehta (1990a, 1990b).

RESULTS AND DISCUSSION

In the case of a motionless basic state, the oscillation frequencies of axially-symmetric modes in a model of the ocean or the atmosphere can be anticipated based on analytical calculations (see, for example, Matsuno (1966) and Lindzen (1967), among others). The two types of axially-symmetric modes which can exist for motionless basic state are fast (oscillation periods of a few hours), inertia-gravity modes and steady Rossby and Kelvin modes at zero frequency. Also, in the absence of a reservoir of energy in the basic state, these two types of axially-symmetric modes are neutrally stable. The two types of modes described above exist (not shown) in uncoupled two-layer ocean model and uncoupled two-level atmospheric model in the absence of basic state motion. In the next step, basic states containing mean meridional circulations were specified based on Meehl et al. (1982) for the ocean and Peixoto and Oort (1984) for the atmosphere. Figures 1a and 1b show eigenvalue spectra of the uncoupled ocean and the uncoupled atmospheric models, respectively. Comparing the oceanic spectrum (fig. 1a) in the presence of mean meridional circulations with the two types of modes described above for the motionless basic state case, it is clear that a new family of free, axially-symmetric ocean modes with oscillation periods ranging from about two years to several centuries appear when the basic oceanic state contains mean meridional circulations. These modes have practically neutral growth rates. A similar comparison of uncoupled, axially-symmetric atmospheric modes shows that specification of a basic atmospheric state containing MMC gives rise to atmospheric modes (fig. 1b) with oscillation periods ranging from about a week to several years. There are a few atmospheric modes with decadal and longer oscillation periods also. Unlike the decadal oceanic modes (fig. 1a), however, the low-frequency atmospheric modes have substantially large growth rates.

To see if these modes of individual systems (ocean and atmosphere) are modified due to interaction between the ocean and the atmosphere, the two models were coupled by wind stress and heating parameterizations. Coupled, axially-symmetric, ocean-atmosphere modes were then calculated for the same oceanic and atmospheric basic states as used for the uncoupled calculations. A representative value of the coupling coefficients was used. The eigenvalue spectrum resulting from this coupled calculation is shown in figure 1c. Comparison with figures 1a and 1b shows that eigenvalues, especially growth rates, change dramatically due to ocean-atmosphere coupling. This growth rate enhancement is maximum in the decadal time scale range. Ocean modes with periods of about 2 years to several hundred years grow much more quickly because of ocean-atmosphere coupling. Spatial structures of atmospheric and oceanic components of a coupled mode oscillating with 14.6 years period and growing with 3.19 years e-folding time are shown in figure 2a and 2b, respectively.

A number of sensitivity experiments were carried out to test the robustness of results by varying parameter values. Figure 3 shows coupled eigenvalue spectra from three experiments in which coupling coefficients were varied over a factor of four. As the coupling coefficients are increased, the modes in 1-20 years oscillation period range are slowed down and their growth rates are increased. This can be seen as general displacement of eigenvalues of decadal periods towards higher growth rates and lower oscillation frequencies as the coupling coefficients are increased. Modes with oscillation periods of weeks to months and periods longer than twenty years are also affected significantly by increasing coupling coefficients. Results from other sensitivity experiments are described and discussed in Mehta (1990b). The most important result of the sensitivity studies is that decadal modes exist in the coupled models over a wide range of parameter values and even in the presence of dissipative processes.

Like any model, the ocean-atmosphere models formulated for this study also have their limitations. The most important ones are absence of continents, absence of fully interactive hydrological cycle in the atmosphere, and absence of salinity, ice-snow, and high-latitude convection in the ocean. In spite of these limitations, it is felt that the results are reliable enough, computationally and physically, to proceed to experimentation with models of higher complexity. There are two main implications of the results presented here for the Sun-climate relationship. One implication is that if there is external forcing on decadal time scales, there is a possibility of resonant response of the climate system since the system appears to have natural variability on decadal time scales. The other implication is that it will be necessary to separate internal climate variability from externally-forced climate variability, if any. It can be speculated that transient correlations between solar activity and climate, such as solar cycle-level of Lake Victoria and solar magnetic field sector boundary-atmospheric vorticity area index, may be due to internal variability. It is suggested that climate data analysis studies be carried out with an aim of separating internal variability from externally-forced variability.

ACKNOWLEDGEMENTS

This work was supported partially by a Supercomputer Computations Research Institute Fellowship and partially by NSF grant ATM-8714674 to the Florida State University. The Florida State University Supercomputer Computations Research Institute is partially funded by the U.S. Department of Energy through contract no. DE-FC05-85ER250000.

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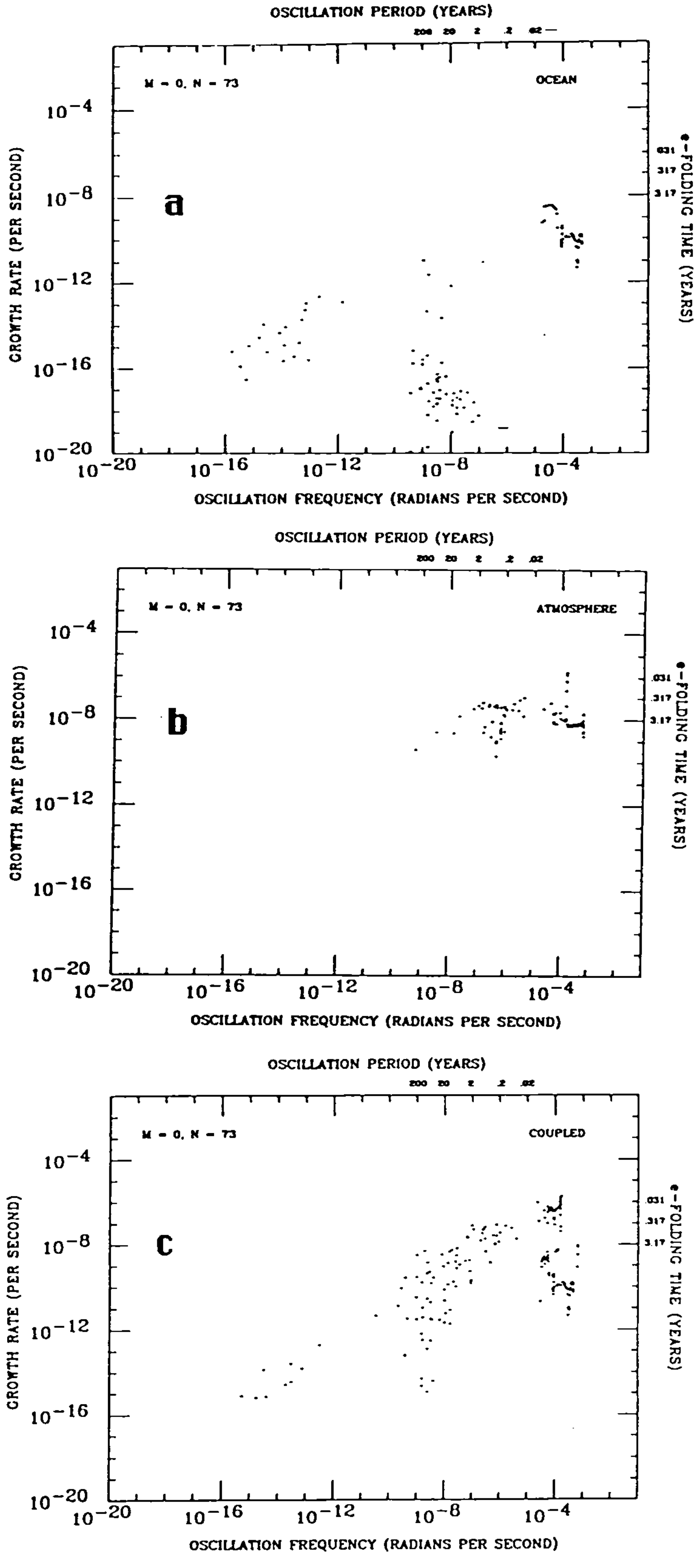

Figure 1. Oscillation frequency (rad/sec) versus growth rate (/sec) of free axially-symmetric modes in the presence of basic state with motion. Only positive values are plotted. M is the zonal wavenumber and N is the number of north-south grid points including the poles. 2.5 degree north-south resolution. (a) Uncoupled ocean (b) Uncoupled atmosphere (c) Coupled ocean-atmosphere with nominal values of coupling coefficients.

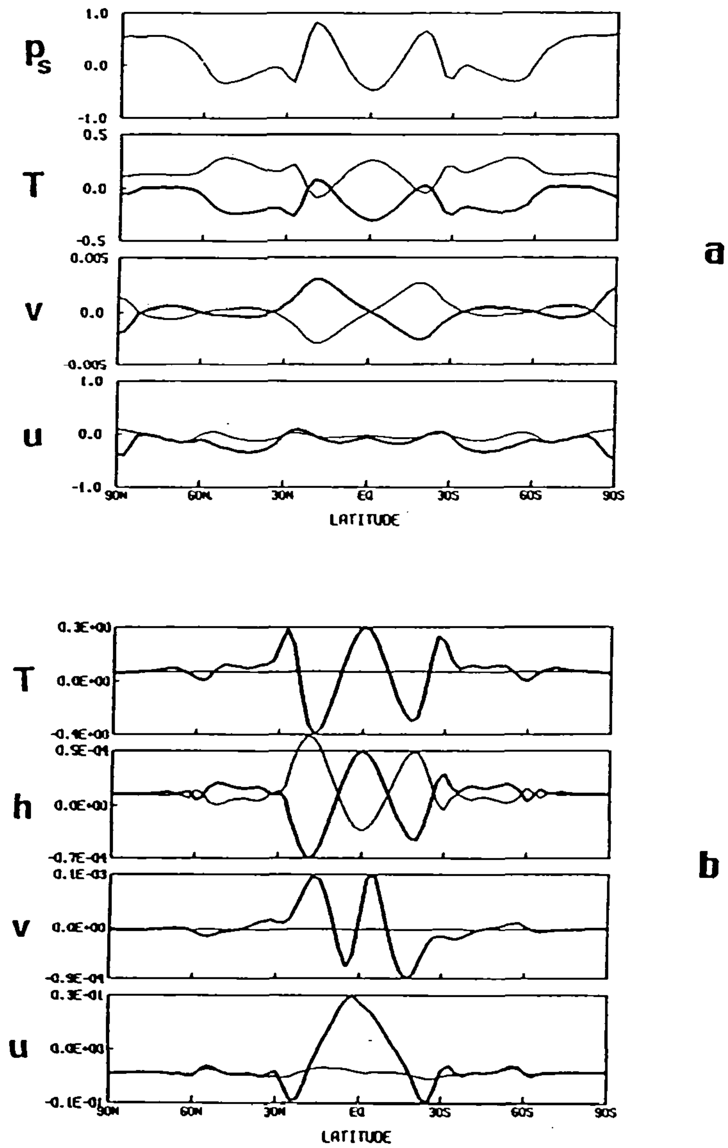

Figure 2. Latitudinal structure of an axially-symmetric coupled ocean-atmosphere mode oscillating at 14.6 years period with amplitude e-folding time of 3.19 years. All variables are non-dimensional. Upper (lower) level variables are plotted with heavy (light) solid lines. u and v are zonal and meridional velocities, respectively. T is temperature. (a) Coupled atmospheric component. p is surface pressure. (b) Coupled oceanic component. h is layer thickness.

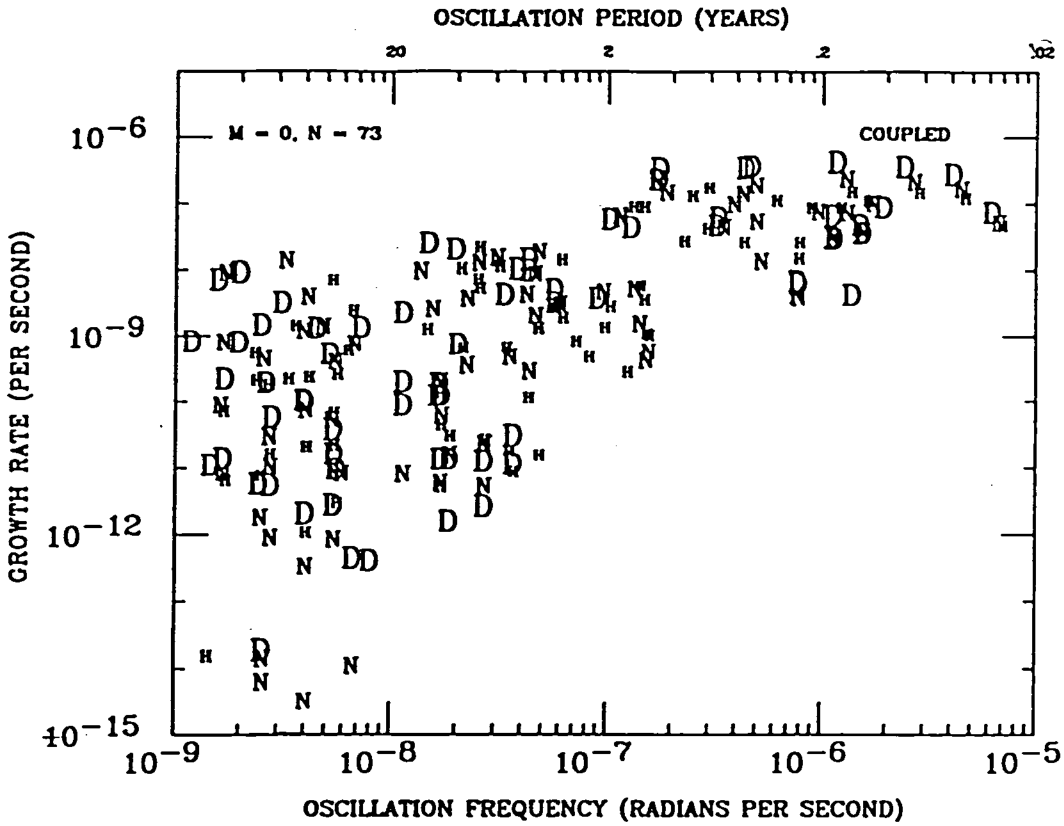

Figure 3. Oscillation frequency (rad/sec) versus growth rate (/sec) of axially-symmetric coupled ocean-atmosphere modes in the presence of basic states with motion. Only positive values are plotted. M is the zonal wavenumber and N is the number of north-south grid points including the poles. 2.5 degree north-south resolution. H, N, and D denote eigenvalues for half, nominal, and double values of coupling coefficients.