Predictability and Dynamics of Geophysical Fluid Flows

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LONG-TERM GOALS

The long-term goal of my research in this project is to improve our ability to predict environmental conditions using dynamical models.

OBJECTIVES

The central objective of my research in this project is to understand the mathematical and physical connections between the bred-growing-mode and singular vector techniques recently developed for numerical weather prediction, the Lyapunov vectors and exponents of dynamical systems theory, and instability theories of geophysical fluid dynamics. My intent is to gain insight into fundamental mathematical and physical aspects of predictability in unstable (irregular, chaotic) continuous systems.

APPROACH

I am using a combination of analytical and numerical methods to study a variety of mathematical models of geophysical fluid flows.

WORK COMPLETED

In collaboration with graduate student Christopher Wolfe, who is supported by this grant, I have completed a study of a strongly nonlinear baroclinic wave-mean oscillation and its time-dependent normal-mode instabilities in a high-dimensional geophysical fluid model (Samelson and Wolfe, 2002). This model is a two-layer, quasi-geostrophic, numerical channel model with 48 along-channel and 40 cross-channel modes in each layer, for a total of 3,840 degrees of freedom. This study included a novel application of the efficient Newton-Picard solver PDECONT developed by Lust et al. (1998). We have completed preliminary studies of related nonlinear wave-mean cycles, for which we have computed all of the unstable and stable linear disturbance eigenvalues and eigenmodes (Fig. 2).

Research on weakly nonlinear baroclinic waves and on predictability in a coupled tropical ocean-atmosphere model, undertaken in earlier years of this project, has been published (Samelson, 2001; Samelson and Tziperman, 2001). This project has also provided partial support for several other efforts, including research on ocean model formulation (de Szoeke and Samelson, 2002) and on Lagrangian motion in coastal ocean circulation (Kuebel et al., 2002), and studies of the coastal lower atmosphere and comparisons of model and scatterometer wind stress fields (Samelson et al., 2001; http://www-hce.coas.oregonstate.edu/~cmet/index.html; see also Bielli et al., 2001).

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RESULTS

The quasi-geostrophic channel model was studied in a strongly nonlinear regime, in which small disturbances to an unstable, steady, zonal, baroclinic shear flow grow to finite amplitude and continue to vacillate irregularly for arbitrarily long times. We identified and computed an unstable periodic solution in this regime (Samelson and Wolfe, 2002), using a manual Newton-Picard iteration and an implementation of the efficient Newton-Picard solver PDECONT, developed by Lust et al. (1998). The PDECONT iteration converged rapidly (Fig. 1). This oscillation is an example of a strongly nonlinear, baroclinic wave-mean cycle with multiple time-dependent normal-mode instabilities (Floquet vectors). The complete Floquet spectrum computed for another cycle in the strongly nonlinear regime (Fig. 2) shows structure similar to that found in the weakly nonlinear case (Samelson, 2001): several weakly damped or unstable modes, several rapidly damped modes, and many modes that are damped at a rate roughly equal to the Ekman friction timescale.

IMPACT/APPLICATIONS

The primary potential future impact of these results is on the design and use of ensemble forecasting techniques for the prediction of oceanic and atmospheric conditions.

TRANSITIONS

George Haller (Brown University) is using dynamical systems techniques to analyze Lagrangian motion in the unstable, periodic solution of the quasi-geostrophic model discussed above.

RELATED PROJECTS

This work is part of the ONR Predictability DRI. The coastal meteorological research is partially supported by the ONR project “COAMPS Simulations of the Coastal Atmosphere” and the NSF project “COAST: Coastal Ocean Advances in Shelf Transport.”

SUMMARY

The results described above open a new perspective on the analysis of the evolution and predictability of oceanic and atmospheric flows, by showing that techniques previously restricted to highly simplified models can be extended and adapted for models that are sufficiently complex that they can be expected to provide substantial insight into geophysical fluid motion. This perspective is yielding new results relevant to instability theory and to ensemble forecasting methods for environmental prediction. Participation in this ONR-sponsored work has enhanced my institution by increasing its visibility in the research community, stimulating interaction among institutional colleagues, and supporting a graduate student specifically interested in the problems addressed in this work.

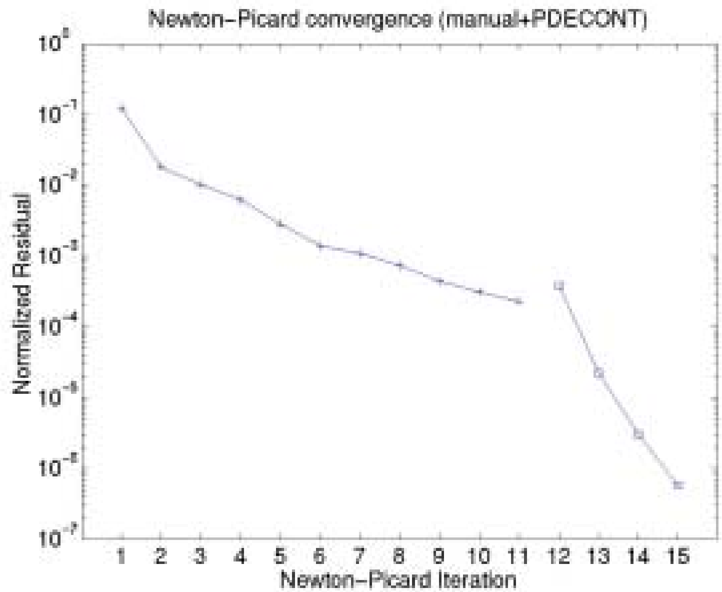

Figure 1. Relative difference in initial and final states vs. Newton-Picard iteration step, showing convergence to the unstable nonlinear baroclinic wave-mean cycle, for 11 steps of the manual iteration followed by 4 steps of the PDECONT iteration.

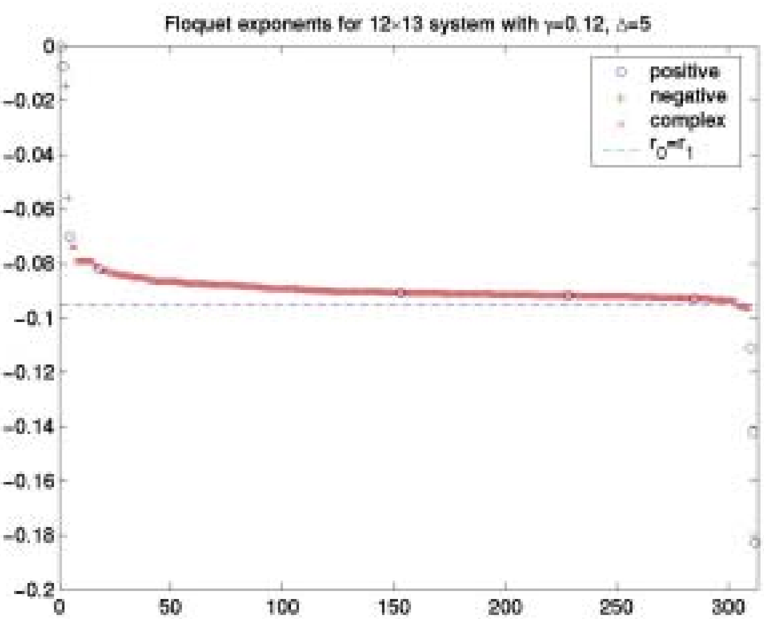

Figure 2. Floquet exponents (ordinate) vs. mode number (abscissa) for the 312 linear normal modes of a stable, nonlinear cycle in a 12x13 spectral truncation of the 2-layer quasigeostrophic channel model. The linear normal modes for disturbances to oscillatory flows are Floquet vectors. The Floquet exponents $\lambda = \ln|\Lambda|/T$, where Λ is a Floquet multiplier and T is the oscillation period. Modes with positive, negative, and complex Λ are indicated. The frictional timescale is also shown (dashed line).

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