Final report for DOE-FG03-93ER61690:

A Hierarchy of Thermohaline Circulation Models

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The objectives of this effort were:

- 1: to understand the variability caused by the competitive roles of salt and heat in the ocean circulation;
- 2: to understand the effect of differential advection of active tracers, such as temperature, salinity and angular momentum;
- 3: to improve the parametrization of convection in models of the ocean circulation.

Thermohaline oscillations and convective adjustment

One result of our project is the discovery that the characteristics of the quasi-periodic centennial and millennial oscillations found in OGCM's, associated with alternating suppression and activation of high latitude convection, are extremely sensitive to the salinity flux and specific choice of convective adjustment scheme. In particular, the period of the oscillation depends crucially on the salinity fluxes (whether deterministic or with a stochastic component) and can be arbitrarily long. This result has clarified that these long-period oscillations (termed "flushes") are **not** the result of the excitation of an intrinsic linear "eigenmode" of the system, but rather are relaxation-oscillations towards one of the several equilibria available to the system. This implies that it is the *amplitude*, rather than the *period*, of the oscillation which is almost independent of the salinity flux.

At the same time we documented that the convective adjustment schemes currently used in OGCMs lead to grid-scale instabilities which affect the large scale distribution of properties. The grid-scale instability is not a "computational mode", and convective adjustment algorithms achieve the desired parametrization (i.e., suppress the grid-scale instability) only when coupled with poor numerical accuracy; this is a step in the wrong direction given the ongoing progress in computational technology.

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Density compensated thermohaline gradients in the mixed layer

Oceanographers and meteorologists use nonlinear diffusion equations (with a diffusivity which increases as the horizontal buoyancy gradient increases) to parametrize tracer transport by baroclinic eddies. We have shown that this type of parametrization leads to a systematic correlation between the strength of a front (i.e., the buoyancy jump across a front) and the thickness of the front. A statistical consequence of this relation between frontal strength and frontal thickness is that temperature and salinity gradients are correlated in the sense of buoyancy compensation. We offer this as an explanation of the widely observed phenomenon of buoyancy gradient compensation in the ocean mixed layer.

The Hadley circulation

By examining the classical problem of the axially symmetric Hadley circulation in the atmosphere, we showed that, in general, the meridional transport of the Hadley cell diffuses angular momentum and potential temperature laterally with a "diffusivity" proportional to the square of the latitudinal temperature gradient. Contrary to the common belief, we have shown that for values of the parameters appropriate for the earth, the homogenization of angular momentum is negligible, and the main role of the meridional circulation is to homogenize temperature laterally in an equatorial region a few equatorial baroclinic radii wide.

Geostrophic nonadjustment

When the classical problem of geostrophic adjustment of an initially unbalanced buoyancy anomaly is approached as an initial value problem, ageostrophic, near-inertial standing modes and critical points occur. These structures prevent a fraction of near-inertial energy from escaping away from the region of the initial buoyancy disturbance and a geostrophically adjusted state is never reached. The time-dependent, ageostrophic standing modes and critical points focus near-inertial energy and cascade it to small spatial scales. Because the shear becomes very large, near-inertial energy must be either dissipated or absorbed by the geostrophic flow. The trapping of near-inertial energy implies that, in convective regions, more potential energy is available for baroclinic instability than in the geostrophically adjusted state. This is an important result because baroclinic

instability is responsible for the formation and export of deep and abyssal water-masses, and the more near-inertial energy is trapped the more effective is water-mass formation.

Publications:

Chen, L. and W.R. Young, 1995: Density compensated thermohaline gradients and diapycnal fluxes in the mixed layer. *J. Phys. Oceanogr.*, **25**, 3064-3075.

Young W.R. and L. Chen, 1995: Baroclinic instability and thermohaline gradient alignment in the mixed layer. *J. Phys. Oceanogr.*, **25**, 3172-3185.

Cessi P., 1996: Convective adjustment and thermohaline excitability. *J. Phys. Oceanogr.*, **26**, 481-491.

Cessi P., 1996: Grid-scale instability of convective adjustment schemes. *J. Mar. Res.*, **54**, 407-420.

Cessi P. and W.R. Young, 1996: Some unexpected consequences of the interaction between convective adjustment and horizontal diffusion, *Physica D*, **98**, 287-300.

Cessi P., 1997: Angular momentum and temperature homogenization in the symmetric circulation of the atmosphere. Accepted by the *J. Atmos. Sci.*.

Cessi P. and J.T. Noyes, 1997: Geostrophic nonadjustment. To be submitted to the *J. Mar. Res.*.

Graduate students supported

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Meetings and talks related to CHAMMP

Invited speaker, UCAR Climated System Modeling Program, Thermohaline Workshop, UCLA, October, 1993.

Invited speaker, International Conference on Nonlinear Dynamics and Pattern Formation in Natural Environment, Noordwijkerout, Netherlands, July, 1994.

Invited speaker, Center for Nonlinear Studies, LANL, "Nonlinear Phenomena in Ocean Dynamics", May 1995.

Speaker, CHAMMP Science Meeting, Rockville, MD, Oct. 1995.

Speaker, ASLO Ocean Science Meeting, San Diego, CA, Feb. 1996.

Speaker, DOE ARM/CHAMMP Joint Meeting, San Antonio, TX, Mar. 1997.

Speaker, American Meteorological Society, Atmosphere and Ocean Fluid Dynamics meeting, Tacoma, WA, June 1997.