DEEP CONVECTION IN THE LABRADOR SEA: MOORINGS, HYDROGRAPHY AND LABORATORY SIMULATIONS

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LONG-TERM GOALS

Observing and modeling the wintertime breakdown of the upper-ocean thermocline/halocline, including deep convection in the high-latitude ocean, and developing an understanding of its effect on the circulation: particularly at the rim of the ocean, and in semi-enclosed seas; forming a comprehensive view of air/sea interaction both above and below the sea-surface; understanding the interplay of geophysical fluid dynamics and heat/salt/freshwater/ice thermodynamics, particularly involving
involving coastal runoff and sea-ice.

OBJECTIVES

Convection is a key process in the world ocean. It occurs everywhere, but only in extreme circumstances does it penetrate deeper than about 150m. Where this occurs the potential energy generated by cooling is amplified, and atmospheric forcing of all kinds--momentum, potential vorticity, trace gases--is communicated to the deep ocean. The convective process is also very poorly represented in computer models of the ocean. This has motivated the ONR-ARI on Deep Convection which is now in progress. A broad attack on the problem has formed, with a remarkable population of ocean modellers, seagoing oceanographers and meteorologists.

The direct objective is to develop through new observations and modelling a simple picture of the mesoscale and basin-scale response to convective forcing.

APPROACH

The Labrador Sea was selected as the observational site, for many reasons. It has some of the severest wintertime weather on felt by oceans anywhere, with cold-air outbreaks from the Arctic Canada that cause net cooling in excess of 300 watts m^{-2}, averaged over the entire winter. Labrador Sea Water, the product of deep convection, permeates the world ocean at about 1500m depth, as an important low-salinity water mass. The climatic profile of the region has gone through a remarkable range of conditions over the past 90 years, and this is demonstrably important to deep convection.

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Field Work. We deployed a site mooring near the former location of Weather Station Bravo, with 15 instruments, which provided the start-up information for the intensive observational program during winters 1996/7 and 1997/8. This mooring is now in its 4th year; initially funded by NOAA, the mooring is now jointly supported with ONR.

The PI and his students have joined hydrographic cruises of the CSS Hudson in 1992, 93, 94, 95, and a 5 week cruise in Oct/Nov. 1996. These represent an ongoing collaboration with Drs. John Lazier and Allyn Clarke of Bedford Institute of Oceanography (BIO).

For the present intensive period of observations we proposed to ONR an array of current meter moorings spanning the boundary current off the Labrador Coast, reaching to the central Labrador Sea. In combination with other moorings of the Kiel, Germany group this provides an extensive ‘fence’ along which to view convection and its circulation product. In January 1998 we will join in hydrographic sampling on the 31-day Knorr cruise being organized by Dr. Eric d’Asaro. This work, together with sections carried out this year by other investigators, has given the first 3-dimensional picture of the Labrador Sea; the only prior 3-dimensional work was the 1966 survey of John Lazier and the 1976/78 winter cruises of Clarke and Gascaard.

Modelling. In the Geophysical Fluid Dynamics Laboratory we have developed a large suite of simulations of convectively driven ocean basins. These began with Ph.D. research projects of David Pierce (Pierce and Rhines, 1995, 1996) and Robert Hallberg (Hallberg and Rhines, 1996) and are continuing with current student Leif Thomas. Senior collaborators Scott Condie (Condie and Rhines 1994 and, this year, Boris Boubnov have augmented the effort (Boubnov is supported by NSF).
In each case there have been accompanying numerical models configured to reproduce the experiments. In one such case (Hallberg’s thesis project) an entirely new isopycnal model was built, which successfully handles the interaction of bottom topography with the stratified ocean. We are also using large ocean general circulation models to encompass more of the geography and physics of the North Atlantic.

WORK COMPLETED

This year’s Hudson 5-week Hudson cruise was very productive, giving us the first three-dimensional survey of the Sea since 1966. The size and shape of the Labrador Sea Water following the cold winters of 1990-95 and the exceedingly warm winter of 1996 was striking. We deployed 3 new ONR-funded moorings for the intensive period of the experiment.

In the GFD laboratory we have investigated a wide parameter space for the cooled, rotating basin (varying rotation and cooling rate over wide ranges). This puts the experiments in the context of the classic annulus experiment which was the first extensive study of convectively forced circulation, waves and instability of a geophysical fluid.

A major paper on the early results of our Bravo mooring has been submitted (Lilly, Rhines, Visbeck, Davis, Lazier, Schott and Farmer, 1997). A paper discussing the climate aspects of the Labrador and Greenland Seas and North Atlantic Oscillation has appeared (Dickson, Lazier, Meincke, Rhines and Swift, 1996). The Bravo paper, and numerous images of laboratory experiments are available at our Web site, http://www.ocean.washington.edu/people/staff/lindahl/gfd.html.

RESULTS

The 3 years' data now in hand from the Bravo mooring and associated hydrographic cruises show the deep convection process across a remarkable range of winters: 1994/5 was severely cold, with average wintertime heat flux above 300 watts m^{-2} . 1995/6 the North Atlantic Oscillation reversed dramatically, the Icelandic Low weakened and the winter was exceptionally mild. Convection reached about 500m depth at most. 1996/7 was again a respectably cold and windy winter, and the mooring showed convection to about 1500m. The mooring samples a wide region of the Labrador gyre, due to strong eddy stirring, and in this way gives a good statistical view of the deep convection process (see the attached figure, showing the temperature history for one year, June 1994 to June 1995). Intense fine-structure of temperature and salinity occurs during deep convection, as low-salinity surface waters mix with high-salinity deep and boundary waters. The generation and decay of this fine structure over the year is documented well by mooring. Both mooring and hydrography show convection to be both incomplete and inhomgeneous. That is, only in the most intense events does the water column become well-mixed in potential temperature and salinity (even though it may have homogenized potential density); the inhomogeneity of the process reflects convection to different depths in different (nearby) locations. As a result the salinity profiles show a quasi-diffusive appearance, with increase in salinity downwards. We believe this is the solution to the puzzle of apparently rapid restratification of the sea. The velocity field accompanying convection is remarkable, with strong mesoscale eddies energized in late winter. As yet we do not know whether the boundary currents are involved in this process, or if it is instead a cascade of energy from finescale (200-500m wide) convective plumes. The horizontal velocities, typically 20 cm sec^{-1}, far exceed the typical convective vertical velocity (unlike simple convection simulations or experiments using spatially uniform cooling).

We have compared the Eulerian mooring picture of convection with the Lagrangian picture from the PALACE floats, in collaboration with Dr. Russ Davis (reported in Lilly *et al.* 1997). The mooring sees the intense fine-structure and variability of convection in one region, and the floats sample its variability over larger distances. Generally the comparison was successful.

IMPACT/APPLICATIONS

Convection is found world-wide, at all latitudes, and represents a fundamental part of the upper ocean's communication with the atmosphere. By studying it here in its most extreme form we hope to spur new interest in the process for more temperate regions. The primary direct application, however, is to the upper- and mid-depth ocean at high latitude. There, fresh water spilling off the continent, and flowing out of the Arctic, and produced through sea-ice cycling, provides buoyancy which must be removed by cooling and mixing with more saline water masses. The shelf-waters and warm, saline currents from the subtropics carry out this interaction with strong seasonal and interannual variation. Biological productivity of the region is extremely high in spring, and the physical oceanography impacts it through control of nutrient supplies and deep mixing.

TRANSITIONS

Some of our Geophysical Fluid Dynamics laboratory studies using ferrofluid are being exploited by other research groups (for example, at University of Colorado). This ONR-sponsored work produced the first laboratory experiments of fluid on a truly spherical 'Earth', using magnetic fields to simulate gravity (Ohlsen and Rhines, 1996).

An unusual transition concerns our long-term interest in geostrophic turbulence, of which deep convection is a subset. The PI participated in an extended workshop, *Two-dimensional turbulence in Plasmas and Fluids*, (R.E.Dewar, organizer) at Australian National University in July 1997 (see Rhines, 1997b). This brought together plasma physicists working on both basic problems and controlled fusion; remarkably, the problem of drift waves in plasmas turns out to be structurally similar to geostrophic turbulence with Rossby waves, a subject we have contributed to extensively. The kind of turbulence studied in physical oceanography involves extensive use of tracers and Lagrangian 'particle-following' techniques, and these are widely applicable outside of our field.

RELATED PROJECTS

Our group is involved in projects on general ocean circulation funded by National Science Foundation, in which the subpolar North Atlantic is prominent. This work specifically involves the incorporation of deep overflows into numerical models (which heretofore have done a poor job of simulating the sinking of dense waters at high latitude), and also the dynamics of high-latitude circumpolar oceans. NOAA has funded the Bravo mooring hardware and deployment, joined recently by a contribution from ONR. We have proposed to NOAA a scientific study of the decade-to-century climate variability of the subpolar Atlantic, which has shown such prominent cooling in the face of global warming elsewhere.

REFERENCES

Condie, S. and P.B.Rhines, 1994: Topographic Hadley cells, *J.Fluid Mech.*, **280**, 349-366.

Dickson, R.R., J.R.N.Lazier, J.Meincke,, P.B.Rhines and J.Swift, 1996, Long-term coordinated changes in the convective activity of the North Atlantic, Prog. in Oceanogr.,38, 241-295.

Lilly, J.M., P.B.Rhines, M.Visbeck, R.Davis, J.R.N.Lazier, F.Schott and D.Farmer, 1997: Observing deep convection in the Labrador Sea during winter 1994-1995, *J.Phys.Oceanogr.*, submitted.

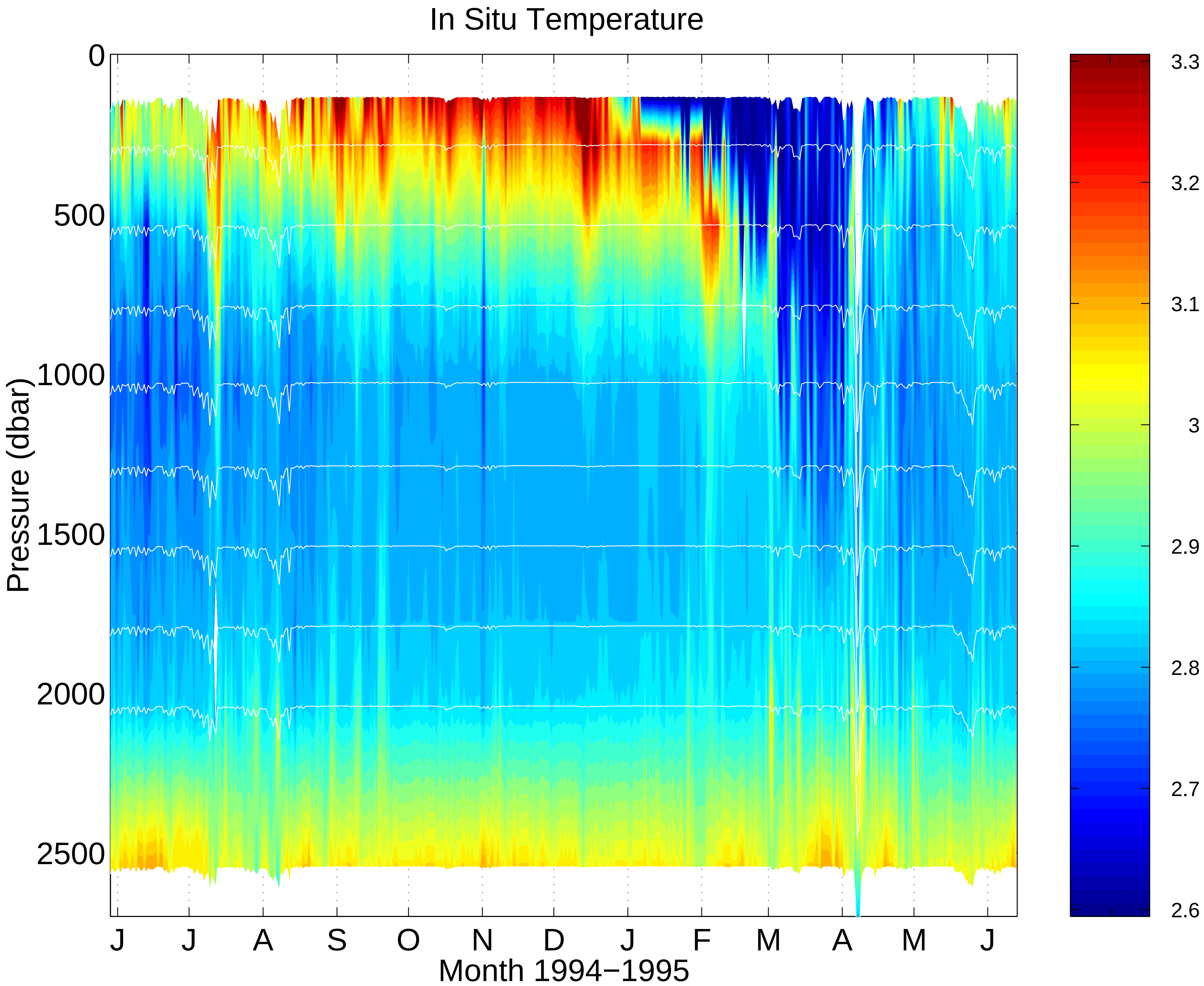
Ohlsen, D. and P.B. Rhines, 1996: Laboratory experiments on equatorially trapped waves using ferrofluid, *J.Fluid Mech.* **338**, 35-58.

Pierce, D.W. and P.B.Rhines, 1996: Convective building of a pycnocline: part A: laboratory experiments, *J.Phys. Oceanogr*. **26**, 176-190.

Pierce, D.W. and P.B.Rhines, 1997: Convective building of a pycnocline: part B: a two-dimensional non-hydrostatic numerical model, *J.Phys. Oceanogr.* **27**, 909-925.

Rhines, P.B., 1997a: Dynamics of small rotating, stratified basins with sloping topography, *in* Physical Limnology, J. Imberger *Ed.*, in press

Rhines, P.B., 1997b: Geostrophic turbulence and geophysical circulations, in *Two-dimensional turbulence in Plasmas and Fluids*, R.E.Dewar *Ed.* American Physical Soc.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2500
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Month 1994−1995
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