Collaborative Research: Vortex Dynamics and Interannual Variability in the Labrador Sea

PI: Annalisa Bracco, Georgia Institute of Technology

Note: this is a collaborative research proposal, linked to proposals by
Jonathan M. Lilly, Earth and Space Research,
and
Joseph Pedlosky, Woods Hole Oceanographic Institute

Funded by: National Science Foundation, 2008

Directorate: Geosciences
Division: Ocean Sciences (OCE)
Program: Physical Oceanography

PROJECT SUMMARY

Accumulating evidence suggests that deep convective ventilation in the Labrador Sea is partly controlled by mechanisms other than local surface forcing and local density gradients. It now appears that there exists an active eddy-driven restratification which is modulated by variations in boundary current dynamics. Large interannual variations in both eddy shedding and buoyancy transport from the boundary current have been observed but not explained.

We propose to investigate the processes controlling eddy generation and associated buoyancy transport by combining realistic and idealized numerical modeling, data analysis, and theory. Ensembles of numerical experiments with a high-resolution regional model will explore the sensitivity of eddy generation and property transport to variations in local and external forcing parameters. Extended analysis of eddy and boundary current properties in data, centrally the now fifteen-year TOPEX/Poseidon and Jason altimeter records, will allow comparison of modeled and actual vortex characteristics over a wide range of oceanic conditions. Theory, supported by idealized experiments, will provide criteria to test candidate hypotheses as to the nature of the instability, and will suggest possibilities for its parameterization.

The net result will be an understanding of the links between local and nonlocal forcing variability, and the eddy-driven buoyancy fluxes which limit deep convection. This process-oriented study should form an important step toward the larger goal of understanding and accurately modeling variability of the Atlantic Meridional Overturning Circulation in general.

Intellectual Merit

This work has a direct benefit to the representation of the Labrador Sea branch of the Atlantic Meridional Overturning Circulation (AMOC) in large-scale climate models, in which details of the narrow boundary current instability are not possible to resolve. In the face of dramatically increasing freshwater discharge from the Arctic, it is critical to understand the transport of buoyancy from boundary current to the convection region, and in particular, to identify the factors underlying its variability. Furthermore, this collaborative project will contribute to the broader effort of realistically representing the effects of mesoscale features on the large-scale circulation in coarse-resolution numerical models.

Broader Impacts

The primary societal benefit of this work is its relevance to understanding and possibly predicting variations of the AMOC. Results will be presented in graduate classes by two of the PIs, A. Bracco at Georgia Tech and J. Pedlosky at WHOI-MIT. Funds are included to support two graduate students, who will benefit from exposure to modeling, analytical investigation and data analysis techniques. Analysis algorithms developed in this work will be freely distributed to the greater scientific community, by inclusion in JLAB, J. M. Lilly's open-source software package for Matlab. The proposed research will also be incorporated into teaching material for high school teachers in the Atlanta area, with the support of the Center for Education Integrating Science, Mathematics and Consulting (CEISMC).

PROJECT DESCRIPTION

Collaborative Research: Vortex Dynamics and Interannual Variability in the Labrador Sea

Annalisa Bracco, Jonathan M. Lilly, and Joseph Pedlosky, Co-Principal Investigators

1 Introduction

Understanding the interannual variability of deepwater formation in the Labrador Sea is central to monitoring and possibly predicting the Atlantic Meridional Overturning Circulation (AMOC). Wintertime deep convection there forms a dense water mass, Labrador Sea Water (LSW), which spreads across the northwest Atlantic (Talley and McCartney, 1982) at mid-depths. The Labrador Sea appears to be particularly important owing to its sensitivity to advected freshwater perturbations. A large number of numerical studies have predicted that increased freshwater discharge from the Arctic could lead to a shutdown of deep convection, reducing the strength of the AMOC and associated northward heat transport (e.g. Cheng and Rhines, 2004). This possibility takes on new significance with reports of the dramatic accelerating freshening of Arctic surface waters (Peterson et al., 2006).

While deep convection is often idealized as being predominantly driven by variations in local surface buoyancy loss, with the role of ocean dynamics limited to gyre-scale “preconditioning,” recent work in the Labrador Sea has focused on the influence of active boundary current dynamics. Observations from current meter moorings and satellite altimetry have shown the importance of long-lived coherent eddies of boundary current origin to the heat balance of the gyre interior (Lilly et al., 2003). These eddies, termed “Irminger Rings” for the warm-water boundary current they originate from, have been identified by subsequent modeling (Katsman et al., 2004; Chanut et al., 2007) and observational (Straneo, 2006b; Hátún et al., 2007) studies as a major mechanism of heat and possibly also of freshwater flux from the boundary current to the interior. But the nature of the generation mechanism itself is a matter of debate, in particular whether the instability is controlled by surface forcing or by vertical shear at depth (Eden and Böning, 2002; Katsman et al., 2004; Bracco et al., 2007). The Irminger Rings and their associated heat transport exhibit interannual variability (Lilly et al., 2003) which have to date not been explained.

The other main restratification mechanism is baroclinic instability of the boundary current that occurs all around the periphery of the Labrador Sea (Spall, 2004; Straneo, 2006b). This instability mechanism also generates eddies (Eden and Böning, 2002; Chanut et al., 2007), of somewhat different properties and shorter lifespan than the Irminger Rings. Although the distribution of fluxes between these two pathways is a subject of ongoing research (Lilly et al., 2003; Katsman et al., 2004; Straneo, 2006b; Chanut et al., 2007), there is general agreement that both mechanisms are important. It has been argued that the baroclinic fluxes may be simply parameterized in terms of the isopycnal gradient between the interior and the boundary current (Straneo, 2006a,b). On the other hand, the topographic instability appears sensitive to the speed of the boundary current (Eden and Böning, 2002; Lilly et al., 2003; Bracco et al., 2007), and has been seen to undergo large interannual variations independent of changes in local forcing (Lilly et al., 2003; Brandt et al., 2004). Fluxes associated with the latter mechanism are particularly important because they represent a non-locally controlled source of variability which is likely to be poorly represented in coarse-grid general circulation models.

Labrador Sea ventilation varies substantially on interannual to decadal timescales (Lazier, 1980; Lazier et al., 2002; Yashayaev, 2007). Such variability is largely modulated by changes in the local atmospheric conditions associated with the North Atlantic Oscillation (NAO) (Curry et al., 1998; Esselborn and Eden, 2001; Eden and Willebrand, 2001), which strongly impact heat fluxes and deep convection in the Labrador Sea (Dickson et al., 1996). Yet in addition to variability associated with the NAO, it is clear that oceanic flux anomalies – the Great Salinity Anomaly of the late 1960s (Dickson et al., 1988) as well as subsequent episodes (Sundby and Drinkwater, 2007) – contribute substantially to interannual variability of deep convection, as a number of recent studies have also emphasized (Lilly et al., 2003; Straneo, 2006a; Avsic et al., 2006). Variations in Labrador Sea deep convection eventually propagate throughout the North Atlantic (Talley and McCartney, 1982; Curry et al., 1998). In particular, the vigorous convection of early 1990s appears to have contributed substantially to an accelerated freshening of the deep subpolar gyre during that decade (Dickson et al., 2002; Curry and Mauritzen, 2005).

Missing from the present picture of the Labrador Sea branch of the AMOC is a dynamical understanding of the processes contributing to interannual variability of restratifying fluxes. This calls into question our ability to accurately predict perturbations of the AMOC in climate change scenarios. Since these fluxes appear intimately linked to the underlying eddy field, one should begin by first identifying the factors controlling variability of eddy generation and characteristics in the Labrador Sea. We therefore propose a combined modeling/observational/theoretical study to attain this goal. In particular, we aim to understand the relation between the baroclinic instability and the localized topographic instability, on the one hand, and between local and non-local forcing mechanisms on the other.

Analysis of satellite altimetry and a variety of in situ measurements over a fifteen-year time period will characterize variability of the eddy field and the boundary current dynamics. Experiments with a high-resolution regional numerical model, together with powerful adjoint and parallel tangent model techniques, will investigate the sensitivity of eddy generation and properties to external and internal forcing, while ensembles of integrations will quantify the natural levels of variability. At the same time, a theoretical approach will provide predictions which permit testing hypotheses about the nature of the eddy generation. The three-way comparison between model, theory, and observations is expected to lead to a significant step forwards in understanding the processes controlling ventilation of the subpolar North Atlantic.

2 Background

2.1 Variability of Labrador Sea Water formation

Spreading of LSW across the subpolar North Atlantic at mid-depths is shown in Fig. 1. This ventilation of the subpolar North Atlantic by LSW formation (Talley and McCartney, 1982) undergoes dramatic interannual variability (Lazier et al., 2002; Lazier, 1980; Yashayaev, 2007). For example, the convected water mass of the early 1990s was both remarkably deep, reaching two kilometers in depth, as well as anomalously fresh (Lilly et al., 2003); but since 1997 a warmer, shallower convected water mass has been produced (Yashayaev, 2007). The formation of a fresh Labrador Sea Water layer during the 1990s (apparent in Fig. 1) was a major contributor to the marked freshening of the deep North Atlantic observed over the past decade (Dickson et al., 2002; Curry and Mauritzen, 2005).

In considering what controls deep convective ventilation in the Labrador Sea, the most obvious mechanism is local surface heat fluxes. Wintertime sensible and latent heat losses, primarily controlled by the North Atlantic Oscillation (NAO), undergo strong interannual variability (Dickson et al., 1996) which directly impacts deep convection. However internal oceanic processes also contribute substantially. The classic example is the Great Salinity Anomaly (Dickson et al., 1988), which is widely attributed with having shut down Labrador Sea deep convection during 1968–1972. Similarly Lilly et al. (2003) found that the winter of 1997 saw nearly double the average oceanic heat flux – associated with an increase in eddy shedding from

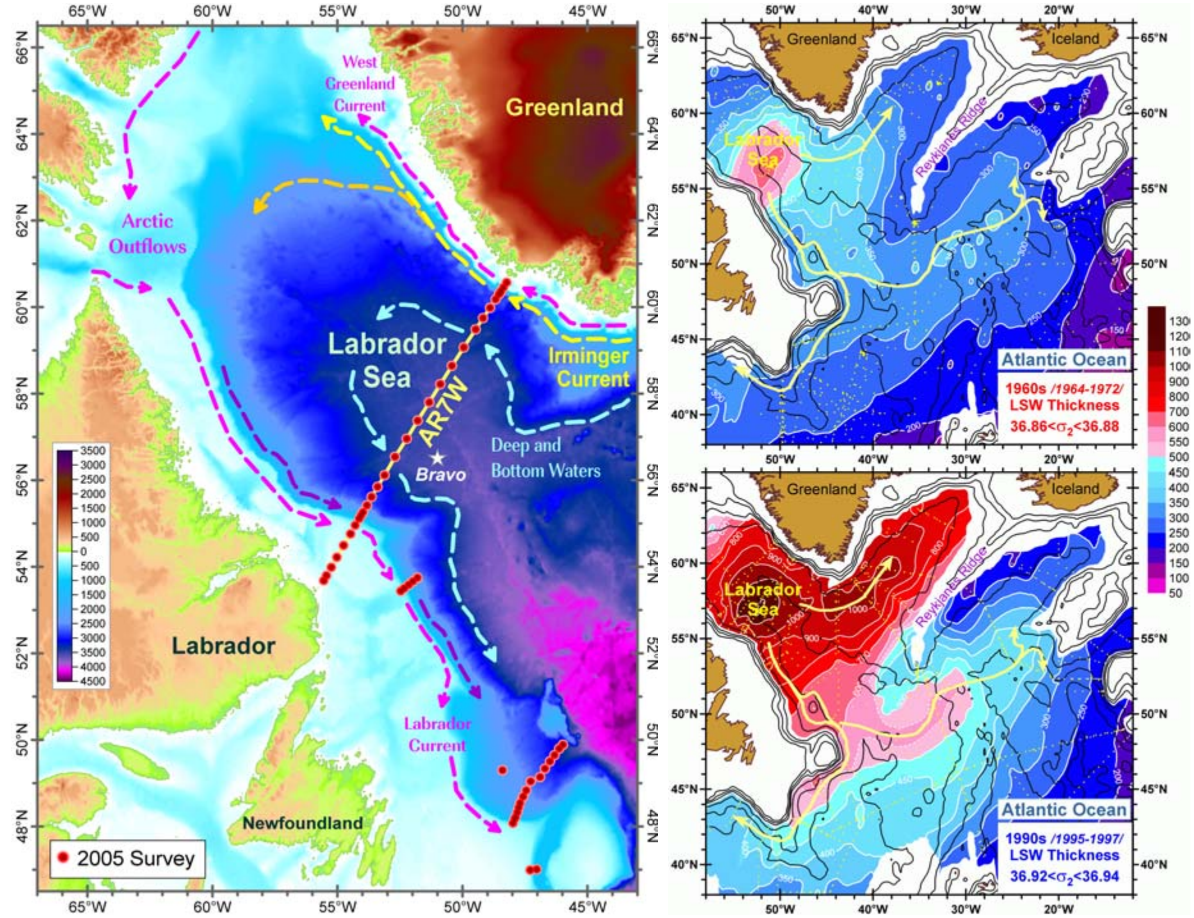

Figure 1: A schematic of the Labrador Sea (left panel) together with isopycnal thickness (right panels) during the 1960s and 1990s. Courtesy of Igor Yashayaev.

the West Greenland instability – and showed that this anomalous heat input reduced the depth of convection by hundreds of meters. This occurred even as the NAO index went from strongly negative back to positive. Thus internal oceanic processes appear able to episodically disrupt deep convection. The slow flushing timescale for the basin (Straneo, 2006a) implies that such events can limit ventilation for years following.

The state of the subpolar gyre itself is another important factor potentially impacting deep convection. Using sea-surface height data from satellite altimetry, Häkkinen and Rhines (2004) constructed a "gyre index" measuring the strength of the (cyclonic) circulation in the subpolar North Atlantic for the period 1992–2002, and documented a substantial decline in this index after 1994, a point which has however been contended (Schott et al., 2006). In any case the analysis of Häkkinen and Rhines (2004) suggested the weakening the subpolar gyre was linked to the weakening of Labrador Sea deep convection, rather than directly to NAO. The possibility of the feedback deep convection owing to reduction in preconditioning was suggested. A correlation between the gyre index and the strength of the AMOC has been also reproduced with an ocean general circulation model forced by atmospheric reanalysis by Hátún et al. (2005).

Thus we find that while interannual and decadal variations of Labrador Sea convection are well known to impact the entire the subpolar gyre, the reasons for this variability appear to involve several factors whose relative contributions are still under investigation.

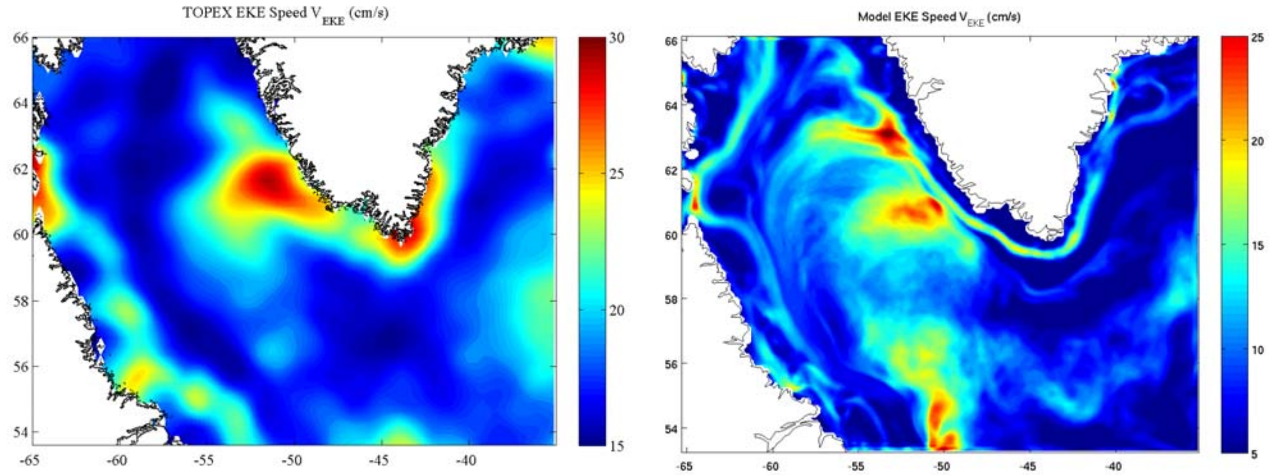

Figure 2: Eddy Kinetic Energy (EKE), cast as a speed $V_{EKE} \equiv \sqrt{2EKE}$, from satellite altimetry (left panel) and our regional Labrador Sea model (right panel). The eddy kinetic energy is constructed from despiked alongtrack data during the entirety of the TOPEX/Poseidon years 1992–2002. Gridding is performed by smoothing the alongtrack EKE with a 40 km radius Gaussian filter. The regional Labrador Sea model has been run at 8km resolution for 60 years, under the CLIM configuration described in the text.

2.2 Eddy-driven restratification

In a steady state, buoyancy from the boundary current system must be drawn inward to balance the extreme wintertime cooling and evaporation. Since the interior Labrador Sea is essentially a region of closed mean streamlines (Lavender et al., 2002), oceanic buoyancy transport is primarily accomplished by eddy fluxes extracting buoyancy from the boundary current system (Khatiwala and Visbeck, 2002).

The principle source of buoyancy is the warm, salty Irminger Current, which resides below and offshore of the fresh West Greenland / Labrador Current at the surface (see Fig. 1a). There exist two major sources of eddy activity, both generating strong mesoscale eddies which appear to be the primary medium for buoyancy fluxes (Chanut et al., 2007). These two sources may be seen in the eddy kinetic energy (EKE) map of Fig. 2. The EKE maximum near 61–62° N marks the generation point of the ∼25 km radius "Irminger Rings" (Fig. 3), long-lived warm eddies found by Lilly et al. (2003) to account for a substantial fraction of the heat extracted from the boundary current. This instability has been identified as being associated with the constriction of the isobaths along the West Greenland continental slope (Eden and Böning, 2002). A secondary maximum along the Labrador Coast appears to reflect baroclinic instability and subsequent eddy shedding (Eden and Böning, 2002; Chanut et al., 2007).

Although recent progress has been made on understanding both types of eddy fluxes, the relative contributions remain a matter of debate. The contribution to eddy fluxes from circum-basin baroclinic instability in the presence of stabilizing topography has been addressed using theory (Straneo, 2006b) as well as idealized numerical experiments (Spall, 2004). A quadratic relation between the lateral buoyancy gradient and inward buoyancy fluxes is expected, providing a reasonable match to observational estimates in the Labrador Sea (Straneo, 2006a). Katsman et al. (2004) used the MIT primitive equation model in an idealized configuration to concentrate on the heat flux associated with the Irminger Rings. Whereas the observational study of Lilly et al. (2003) estimated the lateral heat flux fraction associated with the Irminger

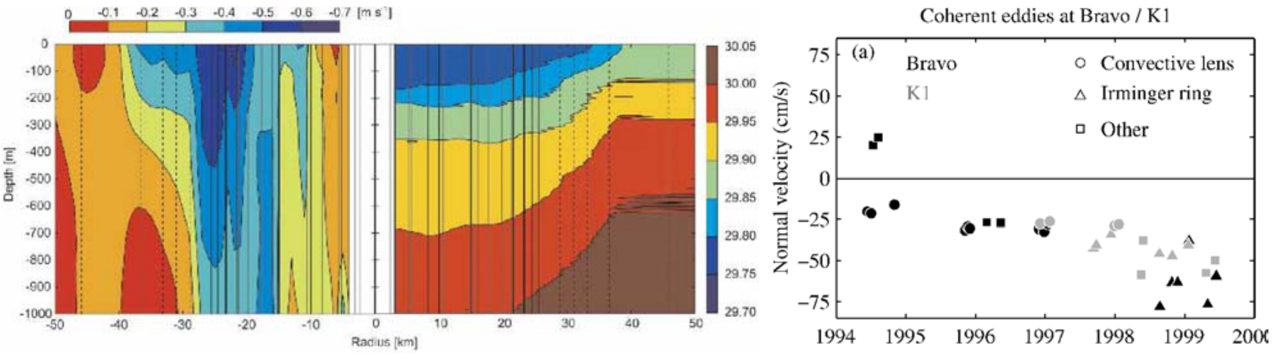

Figure 3: Left two panels: A buoyant "Irminger Ring" observed by a Seaglider (Hátún et al., 2007). The Seaglider was trapped inside the strong, propagating eddy due to a disadvantageous choice of swim direction. The left panel shows azimuthal velocity, negative velocities being into the page, while the center panel shows profile locations. Courtesy of H. Hátún. Right panel: Interannual variability of eddy type and structure observed at the Bravo / K1 mooring, from Lilly et al. (2003).

Rings as 28%-55% of the total needed to balance surface cooling, Katsman et al. (2004) found the number to be 55%-92%. Chanut et al. (2007) interpreted the boundary current eddies as being more important for a net heat transport, but found that the Irminger Rings shape the deep convection region by limiting its northern extent.

An outstanding mystery regarding the Irminger Rings is their sudden appearance in the Labrador Sea interior in 1997 (Fig. 3, right panel). Obvious comparisons with surface heat loss variation and EKE variations of the boundary current fail to explain the interannual variability in eddy populations (Lilly et al., 2003). Prior to that time period, smaller (5-10 km radius) "convective lenses" were seen which move heat only locally, and do not communicate with the boundary current system (Chanut et al., 2007). Such features are therefore not the focus of the present study.

Clarifying the extent to which restratification is accomplished by these two processes, and understanding the reasons behind their variability, is important if the eddy fluxes controlling convective ventilation are to be accurately parameterized.

2.3 Irminger Ring generation

The Irminger Rings require additional attention due to their importance for buoyancy fluxes together with the uncertainties surrounding their generation. Irminger Ring generation appears as a highly localized ejection of boundary current waters (Prater, 2002) associated with a steepening and subsequent flattening of the topographic slope. Upstream of the eddy formation region, energy fluxes indicative of barotropic instability coincide in realistic numerical models with the region of steep bathymetry (Eden and Böning, 2002; Czeschel, 2005). Eden and Böning (2002) suggested that seasonal variation in the barotropic strength of the West Greenland Current was the determining factor for the seasonal changes in eddy kinetic energy of the region. Katsman et al. (2004) instead found that the instability process is mixed, with barotropic energy conversion prevailing at the surface and baroclinic conversion dominating at depth. The annual cycle of heat loss in the upper water column was found in that study to be an important contributor to the seasonal signal in the eddy generation.

To examine the generation mechanism in more detail, Bracco et al. (2007), following earlier work (Bracco and Pedlosky, 2003), analyzed a three-layer quasigeostrophic channel model with

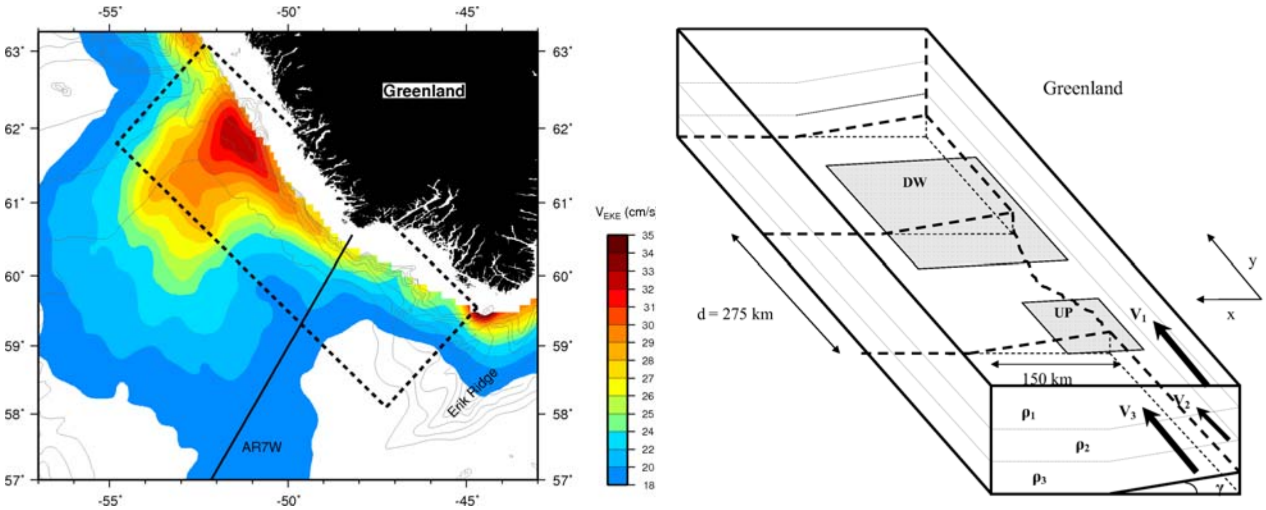

Figure 4: Idealization of the West Greenland Current instability proposed by Bracco et al. (2007). The left panel shows the distribution of surface eddy speed (color) in the eastern Labrador Sea. The right panel shows the geometry of the quasigeostrophic channel model, chosen to idealize the actual topography within the dashed box of the left-hand panel. For certain shear profiles the model flow becomes unstable in the interval denoted by d, with the shaded boxes UP and DW indicating the regions of vortex formation and detachment, respectively.

idealized topography as shown in Fig. 4. The generation of vortices was found to arise from a local baroclinic instability of the bottom flow at the upstream edge of the topographic flattening. Downstream energy fluxes reflect the barotropization of the initially baroclinic, bottom-trapped disturbances as they grow to finite amplitude until they reach the downstream step and are injected into the interior. The net result is an eddy-driven flux of water from the boundary current into the interior of the basin which involves the entire water column. With realistic choice of the current scales, the model of Bracco et al. (2007) is able to reproduce basic features of the observed vortex population, including vortex polarity, radius, rate of formation, and deep vertical extension. A similar scenario was described by the laboratory modeling of Wolfe and Cenedese (2006), who examined generation of vortices by a bottomed-trapped current flowing over a topographic gap. It has yet to be seen whether the same mechanism exists in models with more complete dynamics and more accurate representations of the complex topography.

Thus we find that the studies disagree as to the nature of the instability generating Irminger Rings. In particular, whether the instability is essentially a barotropic instability, or instead depends upon bottom-flowing Deep Western Boundary Current, is a major point of uncertainty.

3 Proposed work

3.1 Overview

The evidence presented in the preceding section supports the following hypothesis:

> *H1: Interannual variability in the Labrador Sea eddy populations and eddy-driven restratification are influenced by nonlocal forcing and ocean dynamics.*

This is to be contrasted with the null hypothesis:

> *H0: The Labrador Sea eddy populations and eddy-driven restratification are entirely controlled by local surface forcing together with interior/exterior gradients.*

Results from both dedicated observational studies as well as idealized numerical modeling weigh in favor of H1. However, the details — in particular, the nature of the controlling parameters — remain unclear. In order to proceed it is necessary to use an integrated approach which combines numerical modeling, theory, and data analysis.

The goal of testing the hypothesis H1 is to accomplished through the execution of the following three tasks:

Task 1: Identifying generation mechanisms and variability The focus of this task is to clarify the mechanisms of formation of the eddies that populate the Labrador Sea. At the same time, the intrinsic variability of eddy generation, characteristics, and property transport will be determined.

Task 2: Quantifying eddy-driven transport pathways In this task we will determine how mesoscale eddies and their variability shape the distribution of water masses by assessing the pathways and timescales of offshore transport of coastal waters from the boundary regions into the interior. The entire perimeter of the boundary current will be considered.

Task 3: Isolating effects of local and non-local forcing The goal of this research task is to investigate the role of transient external forcing in generating and modulating eddy and tracer variance. Specifically we plan to investigate the effects of positive vs negative NAO conditions (local forcing), and strong vs weak subpolar gyre circulation (remote forcing).

Completion of **Task 3** proves or disproves the organizing hypothesis that nonlocal forcing and oceanic processes impact the eddy-driven restratification of the Labrador Sea. The plan for execution of these tasks will be presented as the modeling and observational branches of the study are separately described.

The focus of this proposal, on the mechanisms of interannual variability, will invite active synergy with a number of ongoing observational projects documenting different aspects of this variability. Generally speaking, our goal is to assimilate individual process studies into a cohesive framework of the regional dynamics. The numerical experiments and data/model comparisons provide a tool to that end.

3.2 Theory and modeling

Advances in computing power and numerical tools enable us to propose the most comprehensive numerical study of Labrador Sea to date. Such a study is required by the fundamental uncertainties concerning the dynamics of the Labrador Sea eddy field which cannot be answered by observations alone.

3.2.1 The ocean model

Our primary modeling tool will be the Regional Ocean Modeling System (ROMS). ROMS is an incompressible, free-surface, hydrostatic, eddy-resolving primitive equation model that uses stretched, terrain-following coordinates (the "s-coordinate") in the vertical and orthogonal curvilinear coordinates in the horizontal (Shchepetkin and McWilliams, 2003, 2005). The s-coordinate allows for a better representation of the interactions between the flow and the bottom topography compared to the traditional height coordinate – a feature which is expected to be particularly important for dynamics along the west coast of Greenland. Both local and nonlocal closure schemes are implemented for the vertical mixing parameterization, with the former based on the level 2.5 turbulent kinetic energy equations, and the latter on the K-profile (KPP) boundary layer formulation (Large et al., 1994). A convective adjustment scheme for interior mixing is also activated (the LMD-KPP closure). In the horizontal, a third-order upstream biased advection scheme is used (Shchepetkin and McWilliams, 1998).

The terrain-following coordinates and closure schemes make ROMS an ideal tool for studying an unstable current system in the presence of topographic effects and vertical convection. Eddy kinetic energy from a preliminary 60-year run under climatological forcing conditions and 8km horizontal resolution is shown in Fig. 2, in comparison with EKE derived from satellite altimetry. The general patterns of highs and lows are quite similar. A high EKE region is seen the boundary current near 61° N (albeit somewhat further south than in the data) and elevated energy along the Labrador coast and surrounding Cape Desolation are also reproduced. Upon closer examination, one also finds a current bifurcation near 63° N which has been documented in surface drifter data (Cuny et al., 2002). The East and West Greenland Currents, blurred out by the altimetry, appear very narrow in the model as well as in surface drifter maps (see Fig. 5). This initial favorable comparison gives confidence that the model will be able to accurately represent salient features of the regional dynamics.

Model configuration The model bathymetry is obtained by a smooth interpolation of the Sandwell and Smith (1997) satellite-derived topography. At the open boundaries of the computational domain, we use nudging to the Simple Ocean Data Assimilation (SODA) reanalysis version 1.4.2 (Carton and Giese, 2007), which spans 46 years from January 1958 to December 2004 and is available at resolution of $0.5° \times 0.5°$. The ocean general circulation model used for the reanalysis, the Parallel Ocean Program (POP), has numerics which are close to those of ROMS. Observations assimilated in SODA include historical archives of hydrographic profiles and remotely sensed SST. Solutions from the North Atlantic Ocean Prediction System, obtained with the HYCOM 2.1 model running on a 1/12° grid and available from June 2003 to the present, will be used as boundary conditions to investigate the eddy variability in the Labrador Sea in the 5-year period 2003–2008, as discussed in more detail below. Most experiments will be run at 4km horizontal resolution. During the last year of the proposed work, selected integrations will repeated at 2km resolution.

Supplementary tools Recently two powerful tools for analyzing the sensitivity of the model solutions have been developed. The Tangent Linear Model (TLM) and adjoint model for ROMS (Moore et al., 2004; Di Lorenzo et al., 2007), created by the ROMS Data Assimilation Tools Development Team, will be made available to the PIs (see letter of support by E. Di Lorenzo). The TLM provides a first-order approximation to the non-linear evolution of perturbations for discrete dynamical systems, by identifying the Jacobian of the dynamical operators that are tangent linear to a solution trajectory of the full non-linear system. The adjoint model, on the other hand, produces a sensitivity gradient vector of the system, allowing direct evaluation of the solution response to variations in the model state and boundary conditions. The information provided by those tools can also be used to construct singular vectors (Barkemeijer et al., 1999), adjoint and tangent eigenmodes, and stochastic optimals (Kleeman and Moore, 1999).

3.2.2 Realistic numerical experiments

We will run four sets of numerical experiments with different forcing configurations to separate the intrinsic, locally forced, and remotely forced variability in the circulation and eddy activity of the Labrador Sea, with particular focus on the West Greenland boundary current system:

1. **CLIM** This experiment is designed to isolate the intrinsic variability of the eddy field under a fixed annual cycle.
2. **NAO** These experiments will allow for evaluating the forced variability in the boundary system and in the Labrador Sea induced by local atmospheric forcing alone.
3. **GYRE** The impact of low frequency changes of the Atlantic subpolar gyre circulation on the eddy variability in the Labrador Sea is the main focus of these integrations.

4. **FULL** These runs investigate how the full interplay between the state of the Atlantic subpolar gyre and the atmospheric forcing effects the circulation and eddy variability.

In forming these experiments, the NAO and the gyre index of Häkkinen and Rhines (2004) represent a convenient means with which to identify extremes of local and nonlocal forcing contributions, respectively. While these two are of course closely intertwined (e.g. Curry and McCartney, 2001; Czaja and Marshall, 2001; Bersch et al., 2007), the nature of their relationship appears irregular in time (Bellucci and Richards, 2006), which justifies their use as separate indices.

The full details of the numerical experiments are as follows.

CLIM Climatological forcing and boundary conditions will be used to integrate a 200 year run. The climatology for surface winds is calculated by using the six-hourly ECMWF winds (available at 1/12°) high-pass filtered to remove longer than seasonal time scales. The boundary conditions for temperature (T) and salinity (S) will be given as a relaxation to the SODA monthly means. A nudging to SODA will be applied to the surface values of T and S in order to avoid unphysical drift. The amount of nudging applied to CLIM will be saved into monthly climatologies and will be applied as climatological surface fluxes for the other runs. CLIM will also serve as the spinup for the other runs.

NAO Two runs $\mathrm{NAO}^{\pm}_{CLIM}$, each 100 years long, will be forced by ECMWF surface winds and heat flux anomalies constructed by averaging over the extremes (positive in NAO^{+}_{CLIM} , negative in NAO^{-}_{CLIM}) in the NAO probabilty distribution function (PDF) over the period 1958–2004. The boundary conditions for temperature T and salinity S will again be relaxed to the SODA monthly means. Two further runs, $\mathrm{NAO}^{\pm}_{FULL}$, analogous to $\mathrm{NAO}^{\pm}_{CLIM}$ in the surface forcing but with the boundary conditions for T and S from SODA retaining the time variability, will also be performed.

GYRE Two runs, $\mathrm{GYRE}^{\pm}_{CLIM}$, each 100 years long, will include a relaxation to the profiles of T and S constructed by averaging over the extremes in the gyre index PDF. Winds and surface fluxes will be as in CLIM. Two further runs, $\mathrm{GYRE}^{\pm}_{FULL}$, will retain all variability in the winds and surface fluxes over the 1958–2004 interval.

FULL An ensemble of 4 members forced with time-dependent winds and surface fluxes everywhere for the period 1958–2004, with a nudging to SODA time-dependent boundary conditions. Two members will be run at 2km resolution. A ten-member ensemble will also be run for the period June 2003–June 2008 using the HYCOM 1.2 North and Equatorial Atlantic Ocean Prediction System data as boundary conditions, which will allow a direct comparison with a new field campaign focused on the Irminger Rings (A. Bower, PI).

3.2.3 Tracer integrations and sensitivity analysis

We give some additional details as to the application of the adjoint model to the question at hand. To quantify the eddy-driven transport pathways, the adjoint model will be used to create ensembles of passive tracer trajectories both at the surface and at 1500m depth. Tracer evolution results from the advection and mixing properties of the flow, and the adjoint model can be used to follow particles backwards in time to quantify the origin of water masses (Fukomori et al., 2004; Chhak and Di Lorenzo, 2007; Brandt et al., 2007). We plan to deploy the tracers in the center of the convection region in the Labrador Sea and track their evolution backwards in order to determine the origin and pathways of restratifying water masses.

The adjoint sensitivity analysis will be performed to further isolate specific oceanic conditions and forcing patterns that lead to enhanced eddy activity (Chhak and Di Lorenzo, 2007). By calculating the singular vectors we will be able to track the dynamical signature of the various processes at play, discriminating among barotropic and baroclinic instabilities and topographic effects. In particular, analyzing the sensitivity of the eddy dynamics to atmospheric forcing and boundary conditions in the FULL ensemble will reveal the time-evolving response of the Labrador Sea circulation to variations in the entire suite of external forcing parameters.

3.2.4 Idealized Experiments

An additional set of idealized experiments will provide a bridge between the realistic numerical modeling and the quasigeostrophic channel model of Bracco et al. (2007). Here ROMS will be set in two north-south channel configurations, the first designed as in that study to mimic the west Greenland boundary current system, and the second chosen to be representative of the current system along the Labrador coast.

These idealized runs will address: (i) the role played by the horizontal and vertical shear in boundary current system on the formation and intensity of the coherent eddies, particularly the Irminger Rings; (ii) the impact of the width and strength of the current system on the flow instability; and, likewise, (iii) the role played by local atmospheric heat fluxes. The Tangent Linear Model will be used extensively to identify the source of instabilities by computing the singular vectors – the patterns of maximum growth over a specified period of time – and their associated growth rates. It is expected that the number and intensity of eddies can be related to these unstable growth patterns. The simple set-up will also be used as a framework for developing and testing a parameterization for the heat and fresh-water fluxes associated with eddy generation in boundary currents by baroclinic instability, as a function of the surface forcing and of the supercriticality of the flow.

3.2.5 Numerical timeline and relation to tasks

We now explain how these different aspects of the numerical study fit into the three tasks identified in the research plan.

Year 1 This year focuses on the execution and analysis of the CLIM run experiment and the idealized simulations. Analysis of the CLIM run and comparison with the idealized simulations will help identifying the physical processes responsible for the vortex generation and will quantify the intrinsic variations of the eddy field (**Task 1**).

Year 2 The NAO and GYRE runs will be conducted and analyzed as analysis of CLIM continues. Tracer release experiments in the adjoint model of the CLIM will contribute to the identification of transport pathways (**Task 2**). We will quantify the contributions of the eddy field to the advection of heat and freshwater into the interior of the domain, establish the long- and cross-shore contribution of the coherent vortices to the circulation, and determine the underlying dynamics (**Task 1**). Calculations of vorticity, momentum, heat and salinity budgets will assess the role of mesoscale dynamics on the transport of heat and freshwater anomalies from the boundaries into the Labrador Sea interior (**Task 2**). Differences between the CLIM, NAO, and GYRE runs will be assessed.

Year 3 With the insight gained from the previous years, the FULL experiment will be conducted and analyzed with heavy use of Tangent Linear Model and the adjoint model. The interannual variability associated with locally and non-locally forced low frequency changes in the eddy field (**Task 3**) will be characterized by the principal components of the leading EOFs and by evaluation of the standard deviation in eddy kinetic energy and heat and momentum fluxes during the last year of the project. A more detailed description of the techniques we envision is available in Bracco et al. (2004).

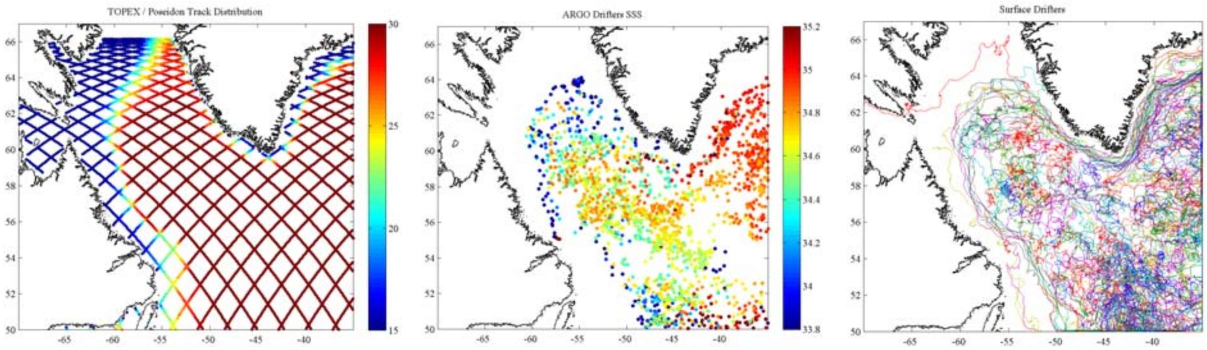

Figure 5: Distribution of three types of data. Locations of the altimeter tracks from the TOPEX/Poseidon and Jason missions are shown in the left panel, with color showing the average number of good cycles per year at each location. Argo floats are shown in the center panel along with sea surface salinity, and surface drifters are shown in the right panel.

3.3 Analysis of data

Understanding the variability of the Labrador Sea eddy field requires documenting the properties of the eddies and of their environment over a broad range of conditions. The observational branch of our study will accomplish this through a careful analysis of satellite altimeter data together with a variety of in situ data sources. This will enable us to ensure that the model accurately represents the ocean dynamics, as well as to apply the insights gained from the modeling study to our understanding of the recent history of the system.

3.3.1 General approach

In our opinion the best strategy will be to use the long satellite altimeter records to unite sparsely distributed in situ measurements into a coherent picture of long-term variability. We will build on and substantially extend earlier works to create fifteen-year records of eddy characteristics (radius, velocity, and population) and boundary current conditions (speed, vertical shear, and EKE) over the period 1992–2007. This time span encompasses both the heavily convected years of the early 1990s, and more weakly convected conditions since 1997. More practically, it coincides with the availability of high-quality satellite altimetry, beginning with the TOPEX/Poseidon satellite and continuing with the Jason instrument since 2002, covering the Labrador Sea as shown in the left panel of Fig. 5. Detailed comparison of the altimeter data with publicly available in situ data, as well as with dedicated observational studies being carried out by other researchers, will then enable reliable estimation of eddy and boundary current properties over the entire time period.

This altimeter data set, which forms the basis for the EKE map presented in Fig. 2, must be utilized in its alongtrack (ungridded) form on account of the small scales of the eddies and the boundary current with respect to the track spacing. A typical eddy radius is about 25 km, whereas the grid spacing is roughly 100 km. Careful statistical analysis and interpretation are therefore required.

3.3.2 In situ data sources

Annual hydrographic surveys conducted by the Bedford Institute of Oceanography extending back to 1992, and high-resolution XBT surveys extending back to 2000 resolving fine details of the thermal structure, will be analyzed to determine relevant gyre, boundary current, and eddy properties in collaboration with I. Yashayaev (see attached letter of support). Argo floats

(Fig. 5, center panel) will aid in the characterization of the hydrographic background, in particular, adding resolution to the annual cycle. The Argo floats began substantially sampling the Labrador Sea in in the mid-1990s. The data shown here are from the quality-controlled, archived distribution available from the United States Global Ocean Data Assimilation Experiment (USGODAE) server. Finally drogued surface drifters (Fig. 5, right panel) provide important details on the spatial structure and temporal variability of the boundary current. These sample the Labrador Sea with a somewhat uniform distribution over year and season also beginning in the 1990s. This is the interpolated, quality controlled dataset distributed by the Global Drifter Program Drifter Data Assembly Center of the Atlantic Oceanographic and Meteorological Laboratory (AOML).

Our fifteen-year record of interannual variability will be further aided by comparison with various ongoing observational studies, described in Section 3.4 below.

3.3.3 Upstream boundary current variability

Eddy generation in the Labrador Sea is intimately related to the strength of the boundary current. It is therefore critical to characterize both barotropic and baroclinic variability of the West Greenland Current upstream from the eddy generation regions. Remarkably, there have been few observational studies of the West and East Greenland currents. Aspects of the mean current structure were examined by Cuny et al. (2002) using available surface drifters, as was variability of extreme water mass properties during 1992–1999. Kieke et al. (2006) used hydrographic sections assuming a level of no motion to examine interannual variability in deep baroclinic currents during the 1990s. More work has been done on the Labrador side. In addition to the combined altimetric/ hydrographic work of Han and Tang (1999), extending to the latter part of the 1990s, a mooring array at the exit to the Labrador Sea (Dengler et al., 2006) monitored boundary current conditions. However, the extent to which the current strength on the Labrador side reflects fluctuations on the Greenland side is unclear. It is reasonable to expect much of the variability to be "filtered out" by the instability.

A promising approach is to combine the long altimetric record with surface drifters and other available "ground truth" observations to create virtual current meters at a number of cross-stream transects along the west coast of Greenland. Altimeter tracks there intersect the current nearly perpendicular to the axis, and data coverage is high (see Fig. 5, left panel). We have carried out a preliminary analysis along these lines, with encouraging results. A proxy speed record constructed on the west coast of Greenland gives a realistic annual cycle, and also shows a large speed increase just prior to the intense EKE event of 1997– possibly confirming the origin of the large anomalous heat flux observed that year as originating in a change in the boundary current structure.

3.3.4 An extended eddy census

The main observational study of Labrador Sea coherent eddies was that of Lilly et al. (2003). Details of coherent eddy structure during 1992–1999 were examined by using current meter mooring records and satellite altimetry. The altimetric portion of that study introduced an automated statistical method for eddy property and population estimation, which we aim here to use and improve. This census will be extended to the entire time period 1992–2007, quantifying the variability of eddy properties over a long time interval for a wide variety of forcing and gyre conditions using a uniform methodology.

The focus here is on eddies of boundary current origin, such as the Irminger Rings. These eddies began to dominate the data record only after 1997 (Fig. 3, right panel), thus only two years in which these were prevalent were included in Lilly et al. (2003). Intense eddies of boundary current origin have been consistently observed in hydrographic sections over the past decade (I. Yashayaev, pers. comm.), a marked change from the conditions of the early 1990s. Therefore the extended eddy census is expected to dramatically increase the number of realizations in our characterization of boundary current eddies.

3.3.5 Analysis method validation and refinement

The problem of characterizing vortices from altimeter sea surface height records was formalized by Lilly et al. (2003), who introduced a maximum likelihood method for inferring eddy populations and properties directly from alongtrack data. This method leads to estimates of eddy radius R_o, sea surface height magnitude δ_o, and population density N_o by classifying observed extrema in the alongtrack data according to their apparent radius and magnitude, and interpreting the resulting distributions in light of an assumed form for an eddy radial velocity profile. Here we will explore the biases and sensitivities of the method, and suggest potential improvements, by applying it to assess the eddy field in the numerical model for which the "correct answers" can be determined.

The maximum likelihood method will be applied to a synthetic "altimeter" dataset from the CLIM experiment, sampled in such a way as to mimic the TOPEX/ Poseidon sampling. Particular sources of uncertainty which we will address are the sensitivity to the assumed velocity profile, as well as the possibility of systematic biases. In the numerical model, vortices can also be identified as connected regions where the Okubo-Weiss parameter $Q = S^2 - \zeta^2$ is such that $Q < -\sigma_Q$, where S^2 is squared strain, ζ is vorticity, and σ_Q is the standard deviation of Q (Weiss, 1981). Although Q is defined for 2D incompressible flows, whenever divergence is small this parameter still provides a clear-cut separation between vorticity-dominated regions where $Q \ll 0$ and strain-dominated regions where $Q \gg 0$. The refined version of the maximum likelihood method should give comparable results to those obtained by identifying extrema of the Okubo-Weiss parameter.

3.3.6 Observational timeline and relation to tasks

We now explain how these different aspects of the observational study fit into the three tasks identified in the research plan.

Year 1 Methodological improvement and validation will be completed by analysis of the CLIM run. Analysis software will be written which can then be applied later in an automated fashion to the other experiments. An initial intercomparison of modeled and observed eddy properties will be performed for the period 1992–1999 (**Task 1**).

Year 2 The extended eddy census will be constructed (**Task 3**). Hydrographic and XBT data will also be analyzed during this year, which will lead to new insights as to the transport pathways (**Task 2**) for a range of forcing conditions (**Task 3**).

Year 3 The transport and shear time series from the boundary current will be constructed. This determines the important parameters controlling eddy generation (**Task 1**) and their variability with the NAO and the gyre index (**Task 3**).

3.4 Synergistic studies

Synergy with a number of ongoing or future studies is expected. The NSF project "Impact of Irminger Rings on Deep Convection in the Labrador Sea" (A.S. Bower, PI) is deploying a float-park mooring near the generation site of these eddies. This will lead to new insights on the internal structure of the Irminger Rings, permitting improved estimates of their contribution to the heat budget. The NSF project "Annual Absolute Velocity Structure Along AR7W in the Labrador Sea Since 1995" (M. Hall, PI) will quantify the interannual variability in the springtime boundary current system by analyzing over a decade's worth of lowered ADCP velocity transects. A group at Institut für Meereskunde in Kiel, Germany is working on constructing an interannual heat balance for the interior Labrador Sea using in situ data stretching back to the mid-1990's (P. Brandt, pers. comm.). The French OVIDE group deployed a mooring array sampling the East Greenland current system, just upstream from Cape Desolation, for two years beginning in June 2004 (P. Lherminier, pers. comm.). The NSF project "The Interaction of Anticyclonic Eddies with Deep Convection" (F. Straneo and J. M. Lilly, co-PIs), involving one of us, is examining the smaller-scale physics of convective mixing interacting with pre-existing anticyclonic eddies, with a focus on Greenland Sea and Gulf of Lion convection.

Results from these studies will be incorporated into this project as they become available, providing valuable comparison points for the numerical modeling and the data analysis. Conversely, our methods and results will be shared with other groups working in this region.

4 Work plan

The execution of all tasks will be achieved in close collaboration according to the timelines given earlier. Bracco, together with her student, Yuley Cardona, will take responsibility for implementing the realistic numerical modeling, and will contribute her experience in the analysis of variability for both the realistic and the idealized configurations. She will also be in charge of the analysis involving the Tangent Linear Model and adjoint model. Lilly will be responsible for the analysis of data and will collaborate with Bracco on the analysis of the model output. Additionally he will write, test, and distribute all necessary analysis algorithms as Matlab (or other) code. Pedlosky will lead the task of identifying the physical processes responsible for the variability of the eddy field, will supervise a graduate student in charge of integrating the experiments in idealized set-ups, and will lead the effort of developing a parameterization for the impact of eddies originating by different mechanisms. The two graduate students in the team, one at Georgia Tech and one at WHOI/MIT, will greatly benefit from the exposure to modeling, data analysis, and theoretical development, and will be educated on a fundamental and exciting topic in physical oceanography.

Most numerical integrations will be performed on Bracco's 192 CPU Opteron cluster at Georgia Tech. This system is owned by the PI and is used exclusively by the PI and her students. Preliminary tests indicate that each 100 year run will require 1.5 months occupying 32 CPUs (multiple integrations will be run at the same time). The idealized configurations, which require limited CPU time due to the small domain size, will be performed at WHOI.

5 Summary

The proposed research aims to substantially advance our understanding of the eddy processes contributing to interannual variability of Labrador Sea deep convective ventilation. Owing to the importance of the Labrador Sea for the Atlantic Meridional Overturning Circulation, it is critical to establish what processes control the fluxes of heat and freshwater from the boundary current into the deep convection region. Available evidence suggests that nonlocal forcing and internal oceanic processes may substantially impact deep convection, though the details are unclear. Taking this as our organizing hypothesis, we specifically accomplish the following: (i) the identification of the generation mechanisms of Labrador Sea eddies and their natural variability; (ii) the quantification of the eddy-driven transport pathways; and (iii) the isolation of the roles of local and nonlocal forcing effects on the eddy field and associated transport. The net result will be an important step for understanding the dynamics of the AMOC and for monitoring, evaluating, and possibly predicting its behavior in connection with climate variability.

References

Avsic, T., Karstensen, J., Send, U., and Fischer, J.: Interannual variability of newly formed Labrador Sea Water from 1994 to 2005, Geophys. Res. Lett., 33, L21S02, 2006.

Barkemeijer, J., Buizza, R., and Palmer, T.: 3D-Var Hessian singular vectors and their potential use in the ECMWF Ensemble Prediction System, Quart. J. Roy. Meteor. Soc., 125, 2333–2351, 1999.

Bellucci, A. and Richards, K. J.: Effects of NAO variability on the North Atlantic Ocean circulation, Geophys. Res. Lett., 33, L02 612, 2006.

Bersch, M., Yashayaev, I., and Koltermann, K. P.: Recent changes of the thermohaline circulation in the subpolar North Atlantic, Ocean Dynamics, 57, 223–235, 2007.

Bracco, A. and Pedlosky, J.: Vortex generation by topography in locally unstable baroclinic flows, J. Phys. Oceanogr., 33, 207–219, 2003.

Bracco, A., Kucharski, F., Kallummal, R., and Molteni, F.: Internal variability, external forcing and climate trends in multi-decadal AGCM ensembles, Clim. Dyn., 23, 659–678, 2004.

Bracco, A., Pedlosky, J., and Pickart, R. S.: Eddy formation near the west coast of Greenland, J. Phys. Oceanogr., in revision. Available at www.o3d.org/abracco/jpo07.pdf, 2007.

Brandt, P., Schott, F. A., Funk, A., and Martins, C. S.: Seasonal to interannual variability of the eddy field in the Labrador Sea from satellite altimetry, J. Geophys. Res., 109, C02 028, 2004.

Brandt, P., Funk, A., Czeschel, L., Eden, C., and Böning, C. W.: Ventilation and transformation of Labrador Sea Water and its rapid export in the deep Labrador current, J. Phys. Oceanogr., 34, 946–961, 2007.

Carton, J. A. and Giese, B. S.: A reanalysis of ocean climate using SODA, Mon. Wea. Rev., submitted., 2007.

Chanut, J., Barnier, B., Large, W., Debreu, L., Penduff, T., Molines, J.-M., and Mathiot, P.: Mesoscale eddies in the Labrador Sea and their contribution to convection and re-stratification, J. Phys. Oceanogr., accepted., 2007.

Cheng, W. and Rhines, P. B.: Response of the overturning circulation to high-latitude fresh-water perturbations in the North Atlantic, Clim. Dyn., 22, 359–372, 2004.

Chhak, K. and Di Lorenzo, E.: Decadal variation in the California Current upwelling cells, Geophys. Res. Lett., 34, in press, 2007.

Cuny, J., Rhines, P. B., Niiler, P. P., and Bacon, S.: Labrador Sea boundary currents and the fate of the Irminger Sea Water, J. Phys. Oceanogr., 32, 627–647, 2002.

Curry, R. and Mauritzen, C.: Dilution of the Northern North Atlantic Ocean in Recent Decades, Science, 308, 1772–1774, 2005.

Curry, R. G. and McCartney, M. S.: Ocean gyre circulation changes associated with the North Atlantic Oscillation, J. Phys. Oceanogr., 31, 3374–3400, 2001.

Curry, R. G., McCartney, M. S., and Joyce, T. M.: Oceanic transport of subpolar climate signals to mid-depth subtropical waters, Nature, 391, 575–577, 1998.

Czaja, A. and Marshall, J.: Observations of atmosphere-ocean coupling in the North Atlantic, Quart. J. Roy. Meteor. Soc., 127, 1893–1916, 2001.

Czeschel, L.: The role of eddies for the deep water formation in the Labrador Sea, Ph.D. thesis, Christian-Albrechts-Universität, Kiel, 2005.

Dengler, M., Fischer, J., Schott, F. A., and Zantopp, R.: Deep Labrador Current and its variability in 1996–2005, Geophys. Res. Lett., 33, L21S08, 2006.

Di Lorenzo, E., Moore, E., Arango, G., Chua, B., Cornuelle, B., Miller, A., Powell, B., and Bennet, A.: Weak and strong constraint data assimilation in the inverse Regional Ocean Modeling System (ROMS): development and application for a baroclinic coastal upwelling system, Ocean Modell., 16, 160–187, 2007.

Dickson, B., Yashayaev, I., Meincke, J., Turrell, B., Dye, S., and Holfort, J.: Rapid freshening of the deep North Atlantic Ocean over the past four decades, Nature, 416, 832–837, 2002.

Dickson, R., Meincke, J., Malmberg, S.-A., and Lee, A. J.: The "Great Salinity Anomaly" in northern North Atlantic 1968–1982, Prog. Oceanogr., 20, 103–151, 1988.

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

Eden, C. and Böning, C.: Sources of eddy kinetic energy in the Labrador Sea, J. Phys. Oceanogr., 32, 3346–3363, 2002.

Eden, C. and Willebrand, J.: Mechanism of interannual to decadal variability of the North Atlantic circulation, J. Climate, 14, 2266–2280, 2001.

Esselborn, S. and Eden, C.: Sea surface height changes in the North Atlantic ocean related to the North Atlantic Oscillation, Geophys. Res. Lett., 28, 3473–3476, 2001.

Fukomori, I., Lee, T., Cheng, B., and Menemenlis, D.: The origin, pathway and destination of Nino-3 water estimated by a simulated passive tracer and its adjoint, J. Phys. Oceanogr., 34, 582–604, 2004.

Häkkinen, S. and Rhines, P.: Decline of subpolar North Atlantic circulation during 1990s, Science, 304, 555–559, 2004.

Han, G. and Tang, C.: Velocity and transport of the Labrador Current determined from altimetric, hydrographic, and wind data, J. Geophys. Res., 104, 18 047–18 057, 1999.

Hátún, H., Sandø, A., Drange, H., Hansen, B., and Valdimarsson, H.: Influence of the Atlantic subpolar gyre on the thermocline circulation, Science, 309, 1841–1844, 2005.

Hátún, H., Eriksen, C. C., and Rhines, P. B.: Buoyant eddies entering the Labrador Sea observed with gliders and altimetry, J. Phys. Oceanogr., in press., 2007.

Katsman, C., Spall, M., and Pickart, R. S.: Boundary current eddies and their role in the restratification of the Labrador Sea, J. Phys. Oceanogr., 34, 1967–1983, 2004.

Khatiwala, S. and Visbeck, M.: An estimate of the eddy-induced circulation in the Labrador Sea, Geophys. Res. Lett., 27, 2277–2280, 2002.

Kieke, D., Rhein, M., Stramma, L., Smethie, W., LeBel, D., and Zenk, W.: Changes in the CFC inventories and formation rates of Upper Labrador Sea Water, J. Phys. Oceanogr., 36, 64–86, 2006.

Kleeman, R. and Moore, A. M.: A new method for determining the reliability of dynamical ENSO predictions, Mon. Wea. Rev., 127, 694–705, 1999.

Large, W. G., McWilliams, J. C., and Doney, S.: Oceanic vertical mixing: a review and a model with a non-local K-profile boundary layer parameterization, Rev. Geophys., 32(4), 363–403, 1994.

Lavender, K. L., Davis, R. E., and Owens, W. B.: Observations of open-ocean deep convection in the Labrador Sea from subsurface floats, J. Phys. Oceanogr., 32, 511–526, 2002.

Lazier, J., Hendry, R., Clarke, A., Yashayaev, I., and Rhines, P.: Convection and restratification in the Labrador Sea, 1990–2000, Deep-Sea Res. Pt. I, 49, 1819–1835, 2002.

Lazier, J. R. N.: Oceanographic conditions at Ocean Weather Ship Bravo, 1964–1974, Atmos. Ocean, 18, 227–238, 1980.

Lilly, J. M., Rhines, P. B., Schott, F., Lavender, K., Lazier, J., Send, U., and D'Asaro, E.: Observations of the Labrador Sea eddy field, Prog. Oceanogr., 59, 75–176, 2003.

Moore, A., Arango, H., Lorenzo, E. D., Cornuelle, B. D., Miller, A. J., and Neilson, D. J.: A comprehensive ocean prediction and analysis system based on the tangent linear and adjoint of a regional ocean model, Ocean Modell., 7, 227–258, 2004.

Peterson, B. J., McClelland, J., Curry, R., Holmes, R. M., Walsh, J. E., and Aagaard, K.: Trajectory shifts in the Arctic and subarctic freshwater cycle, Science, 313, 1061–1066, 2006.

Prater, M. D.: Eddies in the Labrador Sea as observed by profiling RAFOS floats and remote sensing, J. Phys. Oceanogr., 32, 411–427, 2002.

Sandwell, D. T. and Smith, W.: Marine gravity anomaly from Geosat and ERS-1 satellite altimetry, J. Geophys. Res., 102, 10 039–10 054, 1997.

Schott, F. A., Fischer, J., Dengler, M., and Zantopp, R.: Variability of the Deep Western Boundary Current east of the Grand Banks, Geophys. Res. Lett., 33, doi:10.1029/2006GL02656, 2006.

Shchepetkin, A. and McWilliams, J. C.: Quasi-monotone advection schemes based on explicit locally adaptive dissipation, Mon. Wea. Rev., 126, 1541–1580, 1998.

Shchepetkin, A. and McWilliams, J. C.: A method for computing horizontal pressure-gradient force in an oceanic model with a nonaligned vertical coordinate, J. Geophys. Res., 108, 35.1–35.34, 2003.

Shchepetkin, A. and McWilliams, J. C.: The regional oceanic modelling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model, Ocean Modell., 9, 347–3404, 2005.

Spall, M.: Buoyancy-forced circulations in shallow marginal seas, J. Phys. Oceanogr., 34, 1197–1213, 2004.

Straneo, F.: Heat and freshwater transport through the central Labrador Sea, J. Phys. Oceanogr., 36, 606–628, 2006a.

Straneo, F.: On the connection between dense water formation, overturning, and poleward heat transport in a convective basin, J. Phys. Oceanogr., 36, 1822–1840, 2006b.

Sundby, S. and Drinkwater, K.: On the mechanisms behind salinity anomaly signals of the northern North Atlantic, Prog. Oceanogr., 73, 190–202, 2007.

Talley, L. D. and McCartney, M. S.: The distribution and circulation of Labrador Sea Water, J. Phys. Oceanogr., 12, 1189–1205, 1982.

Weiss, J.: The dynamics of enstrophy transfer in two-dimensional turbulence, Physica D, 48, 273–294, 1981.

Wolfe, C. L. and Cenedese, C.: Laboratory experiments on eddy generation by a buoyant coastal current flowing over variable bathymetry, J. Phys. Oceanogr., 36, 395–411, 2006.

Yashayaev, I.: Hydrographic changes in the Labrador Sea, 1960–2005, Prog. Oceanogr., 73, 242–276, 2007.