

## SUMMARY

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### **Collaborative Research: Barotropic Radiation Experiment (BARX)**

The question of how energy flows through the oceans, especially how energy is lost from the currents comprising the general circulation, is receiving much theoretical and modeling attention. This issue is important for understanding not only the structure and transport of the general circulation, but also how water masses and tracers are stirred horizontally and mixed vertically throughout the water column. On theoretical grounds, an important process contributing to the damping of strong currents is radiation of barotropic Rossby waves. The mechanism of Rossby wave excitation by strong meandering currents has been studied extensively by theoreticians in the last two decades. There is some evidence of the existence of this phenomenon between the Gulf Stream and the continental shelf of North America. How much energy this radiation carries away from strong meandering currents, and how fast that energy flux is released to other processes such as diapycnal mixing are issues about which very little is understood. An organized field program specifically aimed at observing radiation toward the open ocean has never been undertaken due to the difficulty of isolating barotropic currents (here meaning simply depth-independent currents).

We will deploy an array of instruments especially sensitive to barotropic variability in order to detect and quantify barotropic Rossby wave radiation that escapes the Gulf Stream's recirculation region. The existence of other kinds of mesoscale variability (e.g., wind-forced barotropic motions; baroclinic eddies) is explicitly acknowledged and accounted for in both the design of the array and the hierarchy of methodologies to be employed to analyze the observations, including a sequence of numerical modeling activities. Discrimination of the radiated, wind-forced, and baroclinic components of variability can be achieved to a good degree by taking advantage of their different frequency-wavenumber characteristics, and their different signatures in current, pressure, temperature and vorticity.

**Intellectual Merit.** A fundamental process by which ocean currents lose the energy acquired from the wind will be explored with a two-year field program and numerical modeling activities. The results will lead to new understanding of the importance of this process not only to the damping of the general circulation, but also to the maintenance of the overall level of "background" barotropic variability in the oceans. Such ubiquitous barotropic variability may play a role in stirring water masses and tracers, both horizontally and vertically, in the deep oceans.

**Broader Impacts.** The results from this work will provide a benchmark on a phenomenon that is important to the dynamics of ocean currents but is difficult to isolate. This benchmark will likely be valuable for testing models of the ocean circulation that are used in studies of climate variability, ecosystem evolution, and CO<sub>2</sub> sequestration, to name just a few broader applications. In addition, this project will provide excellent opportunities for training the next generation of sea-going oceanographers, and for expanding the horizons of new postgraduates, especially in the arenas of data analysis, data assimilation and numerical modeling.

# PROJECT DESCRIPTION

## Collaborative Research: Barotropic Radiation Experiment (BARX): Observing and Modeling Radiated Barotropic Variability in the Central North Atlantic Ocean

### 1. Motivations and Objectives

The paths along which energy flows through the ocean fundamentally influence the structure and strength of the general circulation. As observational knowledge of the general circulation has increased, and as ocean general circulation models (OGCMs) have become more sophisticated and now produce detailed simulations of the general circulation, the need for more information about the energy pathways has become compelling (e.g., Willebrand 2002; Wunsch 1998). Modeling the general circulation and its variability will remain inaccurate unless the pathways for the energy flux from the atmosphere to the general circulation and on to dissipation are parameterized correctly. How does the general circulation lose energy? Does it occur because of friction in surface and bottom boundary layers? Is it simply via the production of interior balanced mesoscale eddies (e.g., Gent and McWilliams 1984) that slowly feed turbulent cascades, or even via potentially faster un-balanced sub-mesoscale cascades<sup>1</sup>? Or, is energy radiated away from the stronger currents by internal gravity waves generated

by flow over topography, or by barotropic Rossby waves forced by meandering jets?

All of the processes mentioned above (and others) have been or are being studied to varying degrees, although mostly via modeling efforts. *We propose to address experimentally the issue of radiation of energy via barotropic Rossby waves as a pathway for energy loss from the stronger components of the general circulation.*

There has been a steady stream of theoretical refinements on the nature of radiation of barotropic Rossby wave energy by meandering non-zonal (especially, boundary) currents, from Talley (1983a,

<sup>1</sup>Molemaker and McWilliams (2002), acknowledging that balanced baroclinic eddies are not efficient at moving energy toward the small scales that are ultimately dissipated (e.g., quasi-geostrophic turbulence cascades move energy to larger scales away from the dissipation scales), are employing numerical models to examine the impact of un-balanced instabilities and turbulent cascades, including interior internal wave radiation, as a pathway for energy loss from the general circulation.

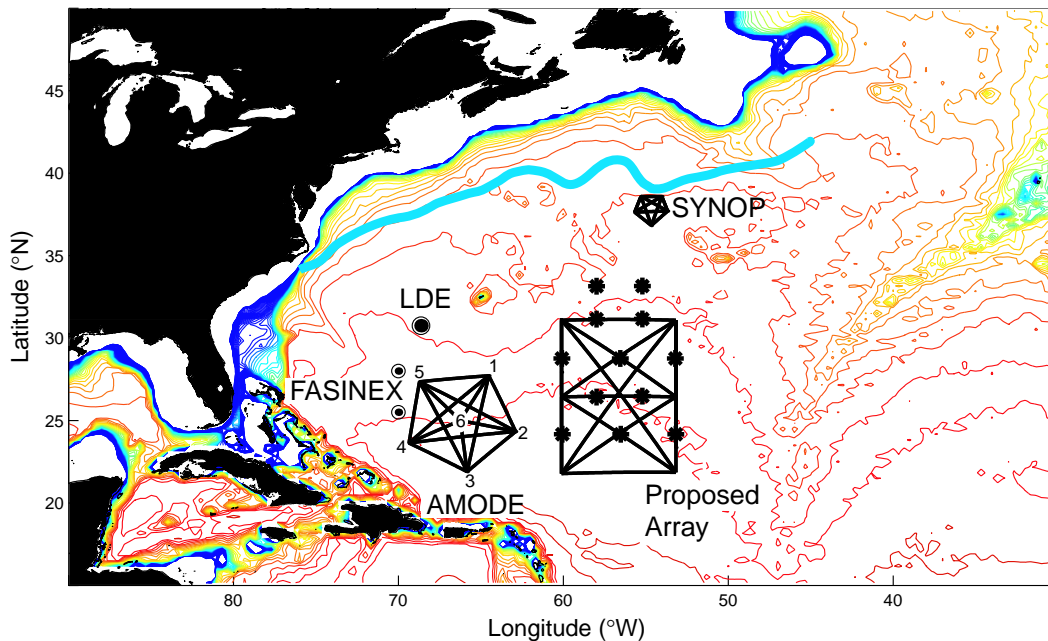


Figure 1. A map showing the proposed array along with the locations of the FASINEX and LDE moorings, the AMODE experiment, and the SYNOP tomography experiment. The stars scattered over the proposed tomography array show nominal locations of 12 pressure and HEF gauges. The contour lines show potential vorticity ( $f/H$ ) (e.g., Koblinsky 1990). The heavy shaded line north of SYNOP is the nominal location of the Gulf Stream.

1983b) through Kamenkovich and Pedlosky (1996, 1998a, 1998b). The implication of this work is that radiation is a viable pathway for the loss of energy from the stronger components of the general circulation, such as the Gulf Stream. One of us (Miller et al. 1987) demonstrated 15 years ago with a numerical model that a boundary current forced by only mean winds can readily fill a simple model basin with barotropic energy radiated from the meandering current after it separates from the boundary. Yet, no experiment to date has explicitly sought to observe this process in the real oceans due to the difficulty and expense of observing barotropic motions with traditional instrumentation such as moored current meters<sup>2</sup>. There are, however, tantalizing bits of evidence, reviewed in Section 2, suggesting that such radiation does exist (e.g., Price and Rossby 1982; Bower and Hogg 1992; Chester et al. 1994).

Three technologies have been well proven in the last two decades to be eminently appropriate for mounting a study exploring the magnitude of radiated barotropic energy from a meandering jet. These technologies are bottom pressure recorders, acoustic tomography (e.g., Munk et al. 1995; Dushaw et al. 2001), and horizontal electric field recorders (e.g., Chave and Luther 1990; Luther et al. 1991). The latter two directly yield the vertically-averaged water velocity. *We propose to deploy an array of tomography moorings, horizontal electric field recorders, and bottom pressure gauges on the south side of the Gulf Stream, but outside of the Gulf Stream recirculation (Fig. 1), to achieve the following:*

- (i) observe the magnitude and kinematic characteristics (frequencies, wavenumbers, etc.) of radiated barotropic Rossby waves forced by Gulf Stream meanders, and*
- (ii) measure the magnitude and convergence (in latitude) of the wave energy flux associated with these radiated waves.*

While the question of the magnitude and characteristics of radiated barotropic waves is the principal motivation for this work, it must be acknowledged that the consequences of this radiation impact other important processes in the ocean and thus motivate the work further. Wunsch (1997) has estimated that up to 50% of the eddy horizontal kinetic energy in the global oceans is due to barotropic motions. It is probable that these barotropic motions have many sources, such as the aforementioned radiation, direct atmospheric forcing, and in situ baroclinic instability of the broad gyres of the general circulation followed by a geostrophic turbulence

cascade to barotropic motions (e.g., Charney 1971; McWilliams et al. 1994). But it is unlikely that any one source mechanism dominates all over the globe.

Perhaps the most clearly observed source is direct atmospheric forcing. Solid evidence now exists for the dominance of this mechanism in generating large-scale barotropic variability observed by bottom pressure records away from strong boundary currents (e.g., BEMPEX in the northeast Pacific; Luther et al. 1991). Simple OGCMs predict well the observed barotropic bottom pressure variability (e.g., Fig. 2) even when the models are forced solely by atmospheric variability (that is, with the mean fields excluded). However, these models significantly underestimate the observed barotropic currents at the same frequencies (Fig. 2). Observationally, there are certainly links, at least in some frequency bands, between barotropic currents and direct atmospheric forcing (e.g., Niiler and Kobalinsky 1985; Samelson 1990; Chave et al. 1992), but the observed magnitudes of the barotropic currents are much greater than expected from simple models of direct atmospheric forcing (e.g., Brink 1989; Samelson 1990; and, Dushaw et al. 1994, who employed tomography data overlapping BEMPEX in space and time to examine vorticity as well as currents). The evidence to date, therefore, implies that direct atmospheric forcing is an important source of barotropic potential energy at very large scales (thousands of km), but is not an important source of barotropic kinetic energy.

Due to the probable existence of a direct atmospherically-forced signal in at least some of our measurements (especially the bottom pressure which will ultimately be employed to calculate energy flux) we have designed an analysis protocol, described in Section 5, which will separate radiated variability from atmospherically-forced variability.

But how important is it to understand the ocean's barotropic variability, aside from the fact that it accounts for up to 50% of the eddy kinetic energy in the ocean? After all, the vertical structure of baroclinic motions ensures that baroclinic variability will dominate near the air-sea boundary (e.g., Wunsch 1997) where the important climate-affecting interactions with the atmosphere occur. The answer lies in the dominance of barotropic variability beneath the thermocline.

At sub-inertial frequencies, barotropic motions are expected to dominate over baroclinic variability in the deep ocean, that is, well below the thermocline. The dominance of barotropic currents at depth has been assumed frequently in the analysis of current meter records, e.g., Bower and Hogg (1992) in their study of energy flux using moored current meter data from the western North Atlantic, and Luyten and Stommel (1991) in their study of tidal

<sup>2</sup>Decomposition of moored current meter data into vertical modes is notoriously unreliable (e.g., Wunsch 1997, Appendix A).

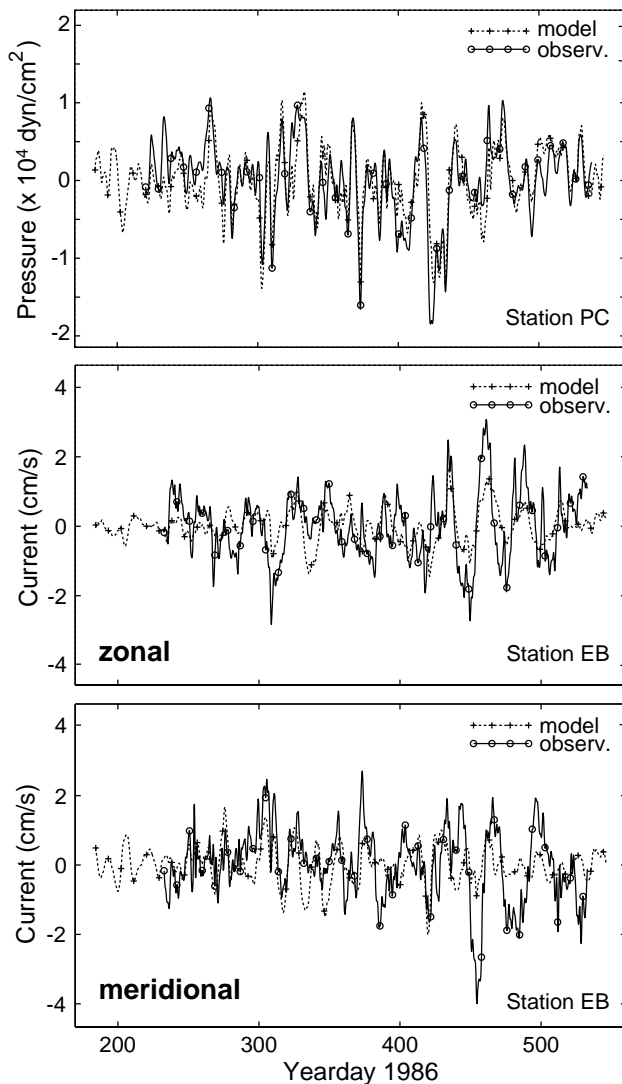


Figure 2. Pressure and currents measured during BEMPEX (Chave et al. 1992) compared to equivalent variables derived from a wind-forced, stratified (32 levels), but non-eddy-resolving (5/3 degree resolution) POP model with a free surface (courtesy F. Bryan and D. Wang, personal communication, 1998). The model was forced with ECMWF 6-hrly wind and air pressure for a time period including the '86-'87 BEMPEX. While the model can accurately simulate the bottom pressure variations caused by the winds (top panel), it significantly underestimates the amplitudes of zonal and meridional barotropic currents.

currents. Combine this fact with the renewed interest in topography-catalyzed diapycnal mixing as the means for maintaining the abyssal stratification (Munk and Wunsch 1998), and the nature and origin of barotropic variability takes on a new significance as both a means to stir boundary-mixed products into the deep interior ocean and as one of many potential energy sources for the near-boundary diapycnal mixing itself. How the abyssal stratification is maintained is expected to have an important impact on vertical motion in the deep ocean and on convection at high latitudes, and thus on the nature and strength

of the thermohaline circulation (e.g., Munk and Wunsch 1998; Huang and Jin 2002).

The rate of dissipation of radiated barotropic energy, that is, whether the waves lose their energy rather quickly through interaction with bottom topography near their source or whether they propagate long distances before dissipating, has implications for not only how far from the source the energy may propagate (and thus how much of the ocean basins will be affected by this source) but also for the rate of dissipation of the general circulation (e.g., Wunsch 1998) and for the spatial distribution of topography-catalyzed abyssal diapycnal mixing. ***This is why our proposed experiment will attempt to measure the rate of convergence of the radiated energy as well as its flux.***

In summary, studying the radiation of barotropic energy from the Gulf Stream is relevant to understanding the following:

- (i) how energy is lost from strong meandering currents,
- (ii) how the "background" level of barotropic variability is maintained in the ocean, and
- (iii) the impact such radiation may have on the horizontal variation of abyssal diapycnal mixing and on the horizontal stirring and transport of water masses and tracers.

The existence of radiation of barotropic energy is not in doubt; here we are asking, how strong is it, and how fast do the radiated waves decay?

## 2. Radiation of barotropic waves from current jets (e.g., western boundary currents)

The forcing of barotropic Rossby waves by meandering current jets has been studied extensively with analytical and numerical models over the past 25 years (Pedlosky 1977, Harrison and Robinson 1979, Talley 1983a, 1983b, Malanotte-Rizzoli 1984, Malanotte-Rizzoli et al. 1987, Miller et al. 1987, Yun et al. 1995, Malanotte-Rizzoli et al. 1995, Kamenkovich and Pedlosky 1996, 1998a, 1998b). The phenomenon is anticipated to be an unavoidable and ubiquitous product of meandering current jets, particularly those with a meridional component of flow. Miller et al. (1987) found that an ocean general circulation model, forced only with mean winds, rapidly filled up an idealized ocean basin with barotropic motions from radiated barotropic modes. The phenomenon is a fundamental element of the theory of the general circulation, but it has yet to be observed to the south of the Gulf Stream. Compared to other kinds of variability, such as baroclinic mesoscale variability in the upper ocean, this radiation is of lesser magnitude, but theoretically it ought to be ubiquitous, emanating from the strong non-

zonal components of the general circulation, including western boundary currents and the Antarctic Circumpolar Current. Further, this radiation should be a significant source of sub-thermocline variability.

Gulf Stream meanders are not steadily-advecting frozen features, but, rather, they are characterized by often abrupt growth and decay periods and by amplitude pulsations (Hogg 1988, Malanotte-Rizzoli et al. 1995). Free barotropic waves can be excited by these highly non-linear motions when the frequency-wavenumber characteristics of these motions overlap the dispersion relation for free Rossby waves (Hogg 1988). "Off resonant" barotropic variability can also be excited by the meanders, but it will have trapped wave or evanescent properties, so its energy will not escape the immediate vicinity of the Gulf Stream.

Topographic-Rossby waves have been identified radiating from the Gulf Stream onto the continental slope to the north of the Gulf Stream (Hogg 1981, Welsh et al. 1991, Bower and Hogg 1992, Pickart 1995). Pickart (1995) suggested that the generating mechanism for these waves was likely the interaction of the meanders with topographic features to the north of the Gulf Stream. This interaction, also discussed by Malanotte-Rizzoli et al. (1995), couples the meanders directly to topographic waves. (Thus, if this generating mechanism has been correctly identified, these particular waves may not be typical of the free Rossby waves expected to originate from the meandering of open-ocean current jets, as described by the many authors cited at the beginning of this section.) On the other hand, Hogg (2000) examined data collected from an array of current meter moorings deployed in the hypothesized meander-topography-wave coupling region on the western flanks of the Grand Banks and found little evidence for topographic wave activity, so the precise mechanism for the generation of the observed topographic-Rossby waves propagating from the Gulf Stream to the north is enigmatic.

In an effort to find evidence for barotropic wave radiation from the Gulf Stream, Bower and Hogg (1992) examined 607 historical time series from deep current meters spanning 30°N–42°N, 77°W–37°W. Only current meter records from deeper than 2000 m and with record lengths greater than 128 days were considered (as mentioned before, the deep variability was assumed to be dominated by the barotropic mode). The approach was to calculate statistics such as eddy kinetic energies and Reynolds stresses, paying close attention to statistical reliability. The sign and magnitude of the Reynolds stress at a point, for instance, is an indicator of the magnitude and direction of wave radiation. The results confirmed the existence of barotropic radiation

northward from the Gulf Stream in the form of topographic Rossby waves, although with varying degrees of statistical reliability in each frequency band examined.

However, even though southward radiation was expected to have a comparable magnitude as that to the north, Bower and Hogg (1992) found only ambiguous evidence for southward radiation. Focusing just on their three measurement sites nominally south of the Gulf Stream recirculation (i.e., south of 32°N between 73°W and 53°W), the two sites with the most data suggest southward radiation of energy in the 51–256 day period band, while the third site does not. The two sites that suggest southward radiation are also the most energetic of the three, and have Reynolds stress magnitudes as large as all but one of the sites within or to the north of the Gulf Stream and its recirculation. (The westernmost site, at 31°N, 69.5°W, corresponds to the central mooring of the Local Dynamics Experiment (LDE - see Fig. 1). The deep currents from the LDE mooring were shown by Price and Rossby (1982) to exhibit strong transient fluctuations with characteristics consistent with barotropic topographic-Rossby wave propagation; current amplitudes exceeded  $10 \text{ cm s}^{-1}$  and the energy flux was southward.) Due to the ambiguity of their mean statistics, Bower and Hogg (1992) concluded that "we suspect that energy does radiate outward to the south. However, the associated velocity fluctuations may be difficult to detect due to the scattering of Rossby waves by small-scale bathymetric features, and/or due to the overwhelming presence of other eddy generating processes such as baroclinic instability."

*The experiment proposed here is designed to overcome the observational difficulties that thwarted Bower and Hogg's (1992) investigation.* That is, we employ both horizontal electric field recorders (HEFRs) and tomography arrays in order to isolate the barotropic variability from the baroclinic variability (such as that generated by the baroclinic instability of the recirculating currents mentioned by Bower and Hogg, 1992); and, our analysis and modeling protocols (described in Section 5) are specifically designed to further discriminate barotropic waves from baroclinic motions (something which Bower and Hogg, 1992, could not do with just deep current meters). Furthermore, by employing both HEFRs (which provide point measurements of the barotropic currents) and tomography arrays (which provide horizontal averages of the barotropic currents) we will be able to separate the variability by wavenumbers and thus isolate the radiated waves (expected at wavelengths of 150 to 1400 km) from the smaller scale variability. Smaller scale variability is due to both baroclinic variability and

the scattering of some of the barotropic Rossby wave energy by the small-scale sea-floor bumps.

We must emphasize here, as was noted by Bower and Hogg (1992), that the lack of strong, statistically-significant mean Reynolds stresses in their data is not at all an indicator that radiating waves do not exist. Even without any other extant phenomena in the data, if the scattering of the radiated waves is strong enough, the coherence between  $u'$  and  $v'$  will decrease (i.e., the Reynolds stress will be small) due to the multiplicity of wavenumbers and propagation directions. Furthermore, their mean statistics don't take advantage of the fact that the radiated waves are probably episodic, as suggested by Price and Rossby's (1982) work and the theoretical analyses previously mentioned.

During the Synoptic Ocean Prediction Experiment (SYNOP; see our Fig. 1), a tomography array was used to measure energy flux (and thus detect wave radiation among other things). The data from that array were used to calculate the Eliason-Palm fluxes which showed that energy is flowing southward from the Gulf Stream at 37°N, 55°W, on the southern edge of the Gulf Stream's meander envelope (Chester et al. 1994). The analyses did not separate barotropic and baroclinic components. However, the fluxes do corroborate a maximum in the southward radiation of energy found by Bower and Hogg (1992).

In the Pacific south of the Kuroshio Extension, Tai and White (1990) have observed significant positive Reynolds stresses of surface currents using satellite altimeter data. Unfortunately, these data cannot separate barotropic and baroclinic processes, so this only represents a possible suggestion for the existence of radiated barotropic wave energy.

*Given the theoretical work pointing to the importance of wave radiation and, most importantly, given the observational evidence to date, we believe that wave radiation from the Gulf Stream does occur and is a significant contributor to the energy in the deep ocean south of the Gulf Stream recirculation. This phenomenon needs to be studied with a field program specifically designed to elucidate its characteristics.*

### 3. Observing Barotropic Currents (Why It's Difficult)

The barotropic mode (here implying the mode with depth-independent currents) is difficult, if not impossible, to accurately isolate with traditional instruments such as moored current meters. This section discusses the various obstacles to the extraction of a barotropic signal from data.

Current meters typically measure velocity at a single depth (or over a small range of depths in the

case of ADCPs), and even with six or more current meters on a mooring, the barotropic variability cannot be unambiguously extracted. Wunsch (1997) showed (consistent with the extensive meteorological literature on this subject) that application of empirical orthogonal function analysis (EOF) to moored current meters will not yield an accurate representation of the barotropic mode unless the dynamical modes have very different energy levels. For example, the 1st EOF mode obtained may be in-phase with depth like a barotropic mode, but have a near-surface amplification like a baroclinic mode. This result might be erroneously interpreted as the result of phase-locking between the barotropic and first-baroclinic dynamical modes. The problem is exacerbated by other factors, as well, such as the lack of orthogonality of the dynamical modes over a finite number of instruments, while the EOF analysis imposes orthogonality (see Wunsch 1997, Appendix A for details).

The alternative to EOF analysis is to simply assume the existence of independent modal variability and project the data onto the linear dynamical modes derived from a numerical solution of the vertical structure equation (e.g., Wunsch 1997), possibly allowing suitable weightings for data noise and *a priori* notions of the partitioning of variance among the modes. This, too, generally yields inaccurate results (but is often considered to be the best, among bad, options). For instance, if the data contain variability with relatively small vertical scales compared to the distance between current meters, the projection will allow some of the high wavenumber "noise" to contaminate the lower modes. With such lack of vertical resolution, the solution becomes sensitive to the choices of data noise and mode amplitude weighting assumed for the projection.

For the case when the variable currents are actually surface-intensified, perhaps extending through only a fraction of the water column (a common occurrence in the western North Atlantic, e.g., Brink's, 1989, FASINEX currents - see our Figs. 1 and 3), a modal decomposition will yield significant amplitudes for at least the barotropic and 1st-baroclinic dynamical modes, and these modes will be phase-locked, somewhat obviating the value of a modal decomposition in the first place. A common alternative to modal decomposition for extracting the barotropic variability in this case is to simply employ the deep current meter records as a proxy for the barotropic mode (e.g., Bower and Hogg 1992). The assumption is that if the barotropic and 1st baroclinic modes have approximately equal total energy, then the structures of the modes dictate that the barotropic mode will dominate in the deep ocean. While this may be a reasonable assumption for much

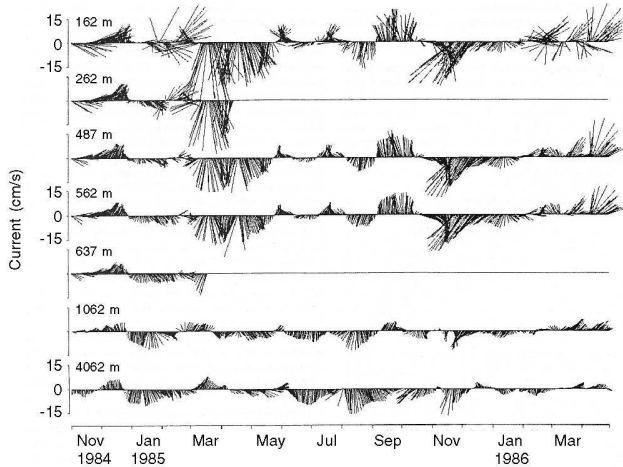


Figure 3. FASINEX mooring (see Fig. 1) currents show that the current variability can be surface intensified, bottom intensified or nearly depth independent. The latter may be associated with the radiation of barotropic waves from the western boundary currents.

of the world's oceans (e.g., recall Wunsch's, 1997, estimation that up to 50% of the eddy horizontal kinetic energy in the global oceans is due to barotropic motions), the ratio of energies is certainly time and space variable, implying that this proxy for the barotropic mode will have varying amounts of baroclinic "noise" in it.

*Currents measured by tomography and HEFRs provide better measures of the barotropic mode because they inherently observe the depth-averaged currents.* But, even these data types include the effects of baroclinic currents that have to be carefully separated. Depth-averaged currents measured during the AMODE tomography experiment in the western North Atlantic (Fig. 1) are qualitatively compared in Fig. 4 to those obtained from a wind-forced barotropic model by Stammer et al. (2000) (N.B., the two time series are plotted on the same scales, but actually are not coincident; the comparison is simply intended to indicate the much greater amplitude of observed depth-averaged currents compared to model barotropic currents that are directly generated by wind variability). Stammer et al. (2000) have shown that their model has considerable skill in modeling the directly atmospherically-forced, high-frequency barotropic sea height variability in TOPEX/POSEIDON altimeter data (which variability is an aliased "noise" for the T/P data). That the observed currents have considerably larger amplitude than the predicted atmospherically-forced barotropic currents is consistent with the observations and modeling by Brink (1989) in FASINEX, just west of AMODE (Fig. 1). In AMODE, both surface-intensified baroclinic eddies and jet-like

features (some of which may originate from the nearby boundary currents to the west and southwest) were present at times. Both of these phenomena produced depth-averaged signatures. Separation of this baroclinic variability from barotropic variability is naturally accomplished with the well-tested procedures discussed in Section 5.

The HEFR measurements of the horizontal electric field also provide estimates of the depth-averaged currents (e.g., Chave and Luther 1990; Luther et al. 1991). In past experiments, combining the HEFRs with data from an overlapping array of inverted echo sounders has enabled the separation of barotropic (depth-independent) and baroclinic (vertically sheared) contributions to the depth-averaged

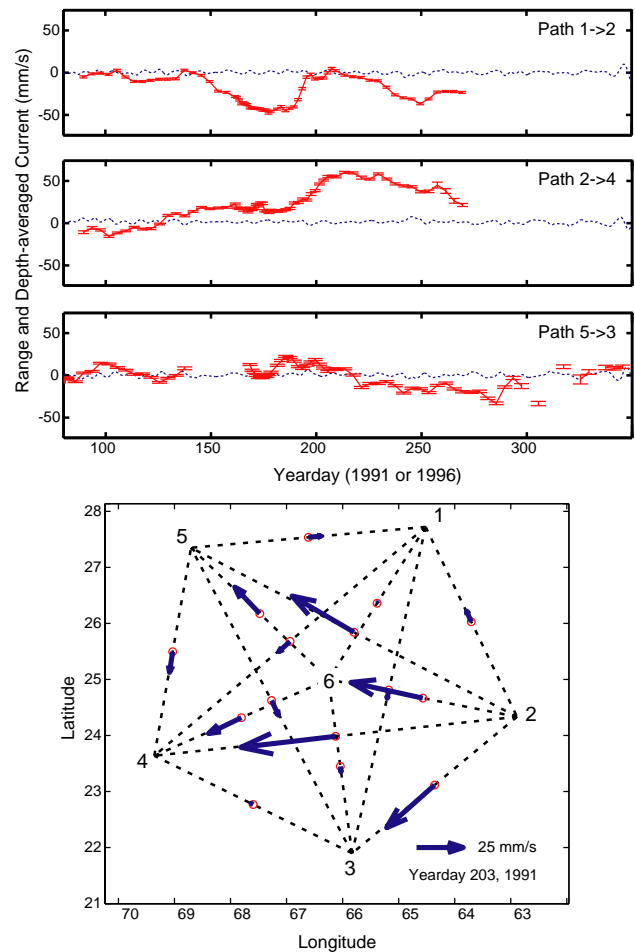


Figure 4. Top 3 panels: AMODE currents in 1991 (solid, with error bars) and the Stammer barotropic model currents in 1996 (dotted) along three acoustic paths of the AMODE array (see Fig. 1 for the location of the array). There is little similarity between the amplitudes and frequency content of the measured depth-averaged currents and the wind-forced model currents; the model currents are an order of magnitude smaller than the observed depth-averaged currents. As shown by the current vectors measured on each of the acoustic paths on yearday 203 (bottom panel), the main feature of the depth-averaged current was a westward flowing jet through the center of the array.

currents (e.g., Meinen et al. 2002a). In the experiment proposed here, the tomography array will provide the necessary vertical structure of the baroclinic currents, and it will also provide vertical profiles of seawater electrical conductivity (calculated from the tomography-derived temperature profiles) to remove a slight bias toward surface currents, such as may arise from a surface-trapped eddy, from the electric field measurements (e.g., Luther et al. 1991).

The AMODE experiment did not include any pressure data, nor was TOPEX/POSEIDON altimeter data or accurate wind data available during the experiment. The lack of these data, and the brevity of the experiment, make AMODE's acoustic data alone much less useful for a search for barotropic Rossby waves than the experiment proposed here. In spite of these difficulties, a part of the proposed work is to analyze the AMODE data from the point of view of the radiation phenomenon, employing the tools described in Section 5. This work may provide a useful extension in space of the results expected from the proposed project.

#### **4. Proposed Field Work: A Multi-scale Array of Tomography, Electric Field Recorders and Bottom Pressure Gauges**

The phenomenon we propose to observe, radiation of barotropic Rossby waves from the Gulf Stream, necessarily requires that we use tools that are capable of observing well the barotropic component of variability, which also means distinguishing barotropic from baroclinic variability. Unlike traditional instrumentation such as moored current meters, both tomography and horizontal electric fields (HEFs) have a proven ability to accurately measure the depth-averaged horizontal currents which are usually dominated by the barotropic mode of variability. Tomography will also provide the means to distinguish barotropic from baroclinic variability.

The observing array will combine point (i.e., horizontal electric field recorders - HEFRs) and line integral (i.e., tomography) observations of current and temperature in an array that will be sensitive to phenomena with scales of 10–1500 km (Fig. 1). The array may be viewed as an antenna for detecting the radiation of free Rossby waves. The HEFR measurements will observe depth-averaged currents produced by phenomena with horizontal scales as short as 10 km (specifically, twice the ocean depth; Chave and Luther, 1990). Single tomography paths (i.e., between two moorings only) will yield currents and temperature averaged over the distance of the mooring separation, so that the smaller horizontal scale variability is filtered out. The path lengths in Fig. 1 range from 500 to 1200 km. Of course, inverting all

the tomography data at once yields a smaller scale resolution of currents and temperature within the array, as required for the "correction" of the HEF measurements for baroclinic variability. This resolution is particularly enhanced when the inversion includes dynamical constraints through data assimilation.

The ability of our combined tomography/HEFR array to provide information on both the full-wavenumber spectrum of barotropic variability (from the HEFRs) and a low-passed version of that variability (from tomography) is highly advantageous for this experiment. Possible "noises" that must be discerned will tend to have  $O(100 \text{ km})$  or smaller scales, e.g., surface-trapped baroclinic variability, or the scattering of the radiated barotropic waves by bottom roughness, as suggested by Bower and Hogg (1992). Having both point measurements and horizontal integrals of the depth-averaged currents will allow us to ascertain the strengths and wavenumber characteristics of the "noises." The analysis methods to be used to extract this information from the data will be described in the next section.

Both tomography (Howe et al. 1987, Dushaw et al. 1994) and HEFRs (Luther et al. 1991) have been shown to be sensitive to depth-averaged currents weaker than a few mm/s, with accuracies of the same order of magnitude or better. In this experiment, the tomography currents are expected to have as good or better accuracy, because the sound speed profile is ideal for tomography (Munk et al. 1995; actual predictions may be viewed at

<http://faculty.washington.edu/dushaw/barotropic/>), permitting the identification of many more acoustic rays than was possible by Dushaw et al. (1994) in the North Pacific. The smallest Reynolds stresses observed by Bower and Hogg (1992) in the deep ocean at a location that corresponds to the northern edge of our proposed array were of the order  $1 \text{ cm}^2 \text{ s}^{-2}$ . Bower and Hogg's (1992) moored current meter observations were likely "contaminated" by baroclinic variability and small-scale barotropic variability so that the correlation between horizontal current components was reduced (because of the increased wavenumber bandwidth). Since Reynolds stresses depend on the correlation of the horizontal currents, we consider Bower and Hogg's Reynolds stresses to be somewhat smaller than we expect to observe. Even if they aren't biased low, our measurement tools are more than sufficient to observe correlations much smaller than  $1 \text{ cm}^2 \text{ s}^{-2}$ .

The last elements of the array in Fig. 1 are bottom pressure gauges collocated with the HEFRs. The pressure instruments employ a Bourdon tube design that has high sensitivity and accuracy, except



that the DC component is not obtained (Filloux et al. 1991). The sensitivity is better than 0.5 mm of water head.

Except directly under strong boundary currents or strong high-latitude currents, bottom pressure in the deep ocean is dominated by variability that is coherent over many hundreds of kilometers, as discovered first in the Mid-Ocean Dynamics Experiment (MODE; Brown et al. 1975) in the western N. Atlantic (around the FASINEX location in Fig. 1). Similar large scales in pressure records were found, for example, in the central North Pacific (Luther et al. 1990). The large scales and high horizontal coherences are the result of the dominance of barotropic fluctuations that have narrow wavenumber bandwidth. The fact that barotropic variability dominates bottom pressure can be understood as a consequence of the geostrophic balance and the vertical structure of the dynamical modes, as discussed previously.

Measurements of bottom pressure are required in order to directly estimate energy flux via  $\langle u'p' \rangle$  and  $\langle v'p' \rangle$ , where the angle brackets denote time average. The next section describes other methods of estimating energy flux, as well as the use of the bottom pressure to enhance the discrimination of barotropic and baroclinic variability through incorporation into a data inversion with the other data types.

The array of instruments will be deployed for nearly two years. The radiated barotropic waves are expected to occur at the time and space scales of the originating meanders. Such meanders have periods as short as 10 days and as long as 90 days, with wavelengths as short as 150 km (long periods) and as long as to 1400 km (short periods) (Bower and Hogg 1992; Pickart 1995; Watts 1983; Price and Rossby 1982). (N.B., these wavelengths imply "length scales" of 40–225 km.) The nearly two-year record length offers up to 18 realizations at the dominant period of 40 days.

**Array Location and Design.** The largest meanders of the Gulf Stream occur at longitudes around 55°W, and, thus, this region is likely to be the source of the most intense radiation. In fact, Bower and Hogg (1992) found their largest Reynolds stresses near the Gulf Stream's mean latitude at this longitude. The array is situated in a region to the southwest of these intense meanders, because (i) that is the expected direction of the strongest energy flux (Hogg 1988; Bower and Hogg 1992; Hogg, personal communication, 2002), and (ii) we want to avoid the rough topography to the east. We have not moved the array farther west because we want to avoid Gulf Stream rings as much as possible.

The array starts at the southern edge of the Gulf Stream recirculation and extends southward, because we want to observe the energy that escapes the recirculation. That is, much of the flux away from the Gulf Stream (such as observed by Bower and Hogg 1992, and Chester et al. 1994, just outside the Gulf Stream's meander envelope at about 37°N) is expected to be convergent in the recirculation region, helping drive that recirculation. This would seem to be born out by Bower and Hogg's (1992) observation of much weaker stresses at 32°N compared to 37°N along 55°W (but keep in mind all the caveats about the potential noises in those stresses, as discussed by those authors and earlier in this proposal).

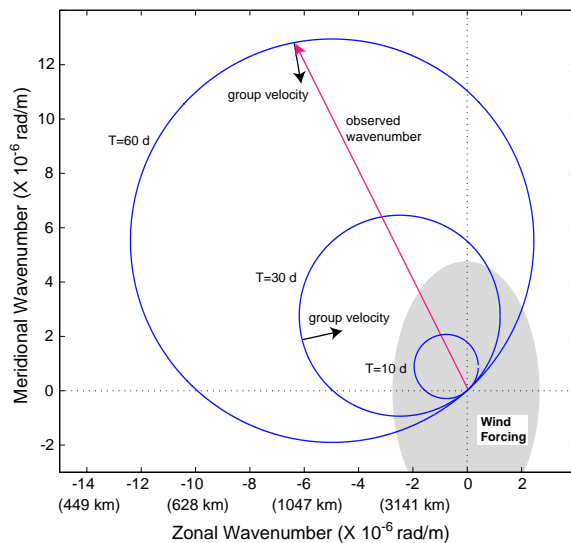


Figure 5. The dispersion relation for free barotropic topographic-Rossby waves is plotted for three periods; the mean planar slope through the proposed array in Fig. 1 is used in the computation. The figure schematically indicates the likely wavenumber separation between atmospherically-forced variability (the shaded region denotes the principal wavenumber content of the atmospheric forcing) and a wave with larger wavenumber and southward group velocity forced by Gulf Stream meandering. The different spectral characteristics of radiated and wind-forced variability can be used to separate the two.

The proposed tomography array consists of two approximately square sub-arrays at different meridional distances from the Gulf Stream, with the HEFR/Pressure instruments distributed within and slightly north of these arrays. The intent of this elongation in latitude is to obtain estimates of energy flux as a function of latitude, so that flux decay (or, rather, convergence) can be calculated.

The region of the proposed array has acoustic properties for tomography that offer excellent resolution of depth-averaged current and baroclinic temperature variations. Initial simulations, with reasonable assumptions for barotropic and baroclinic

variability, indicate that reciprocal transmissions over the short (840 km) diagonal paths in the array will recover 99% of the variance of the barotropic mode current averaged along the paths

(<http://faculty.washington.edu/dushaw/barotropic/>).

One of the tasks of the first year of this project will be to refine the design of the antenna, i.e., to maximize the multi-scale sensitivity and directionality of the array and to adjust the locations of the array elements for optimal observation.

## 5. Combined Analysis and Modeling Plan

In order to clearly discriminate the significant phenomena (e.g., radiated barotropic waves, atmospherically-forced barotropic motions, baroclinic mesoscale eddies) that produce variability at periods of a few days to many months, we have designed an analysis hierarchy that begins with few assumptions about the existing phenomena, then progresses through a series of refinements that take advantage of what is known about these phenomena. In particular, successively more complex models will be employed to isolate the different phenomena and test the analysis procedures.

Before describing the planned analysis and modeling hierarchy, it is useful to note that discrimination of the radiated waves from the wind-forced and baroclinic "noises" can be achieved to a good degree by taking advantage of their different frequency-wavenumber characteristics and their distinct signatures in current, pressure, vorticity and temperature. For instance, barotropic oscillations directly forced by atmospheric winds and pressure are strongest at long wavelengths ( $O(1000 \text{ km})$ ) and shortest periods (3–20 days). As mentioned above, radiated barotropic waves will be strongest at the wavelengths and periods associated with Gulf Stream meandering, i.e., 150–1400 km and periods of 10–90 days (Watts 1983; Bower and Hogg 1992; Pickart 1995). Barotropic energy scattered by bottom roughness, as well as baroclinic variability, will likely be strongest at wavelengths shorter than 200 km, with the baroclinic variability being at relatively long periods.

We anticipate that radiated barotropic waves will occur by bursts of southward energy propagation (and northward phase propagation) during discrete time intervals because they will be generated by discrete meander events of the Gulf Stream (e.g., Bower and Hogg 1992). Atmospherically-forced variability may also be episodic, but it should have a seasonal cycle, which is not expected for baroclinic mesoscale eddies or for radiated waves. The transport of the Gulf Stream has only a very weak seasonal cycle. The baroclinic eddies will also tend to have a more strongly westward phase propagation.

Figure 5 displays several dispersion circles from the barotropic topographic-Rossby wave dispersion relation calculated for the location of the proposed experiment; just the broad scale slope of the bottom is employed in the calculation. The figure is intended as a cartoon showing the scale separation that is expected between atmospherically-forced barotropic oscillations and the radiated waves with southward energy flux.

Within southward packets of radiated barotropic Rossby waves, the current variations should be polarized in the northeast-southwest direction (a diagnostic employed by Bower and Hogg (1992), the phase propagation should be northwestward with wavenumbers consistent with the barotropic topographic-Rossby wave dispersion, the group velocity should be southward (likely with a westward component; Hogg 1988), and there should be oscillatory relative vorticity, concomitant bottom pressure variations, and negligible temperature fluctuations. The array described in the previous section has the ability to measure all of these variables.

**"First Look" Analysis.** A natural first step is to make statistical calculations to determine if the observed variability is consistent with radiation, as described in the previous paragraph. These analyses make no assumptions about dynamics, other than the expectation of plane waves and appropriateness of linear dynamical vertical modes as a basis set for decomposing vertical structure.

The tomography data will be inverted to yield time series of depth-averaged currents, as well as temperature, on a coarse grid within the tomography domain (e.g., Fig. 4). HEFR's will be processed to yield time series of depth-averaged current, employing "corrections" for the tomography-derived, surface-trapped baroclinic currents, and for the vertical profile of conductivity that causes a small bias toward surface currents (e.g., Luther et al., 1991). Bottom pressure records will be processed to remove a well understood drift caused by the strain of deep ocean pressures (Filloux et al. 1991; the drift is not dependent upon temperature). With these depth-averaged current and bottom pressure records, the following properties will be estimated:

- (i) the magnitude and direction of horizontal phase propagation within groups of records of currents and pressure; ultimately, wavenumber spectrum analysis will be performed; consistency of the dominant wavenumbers with topo-Rossby dispersion will be checked, and group velocity will be calculated, if appropriate;
- (ii) horizontal Reynolds stress,  $\langle u'v' \rangle$ , and the phase lag between  $u'$  and  $v'$ , to compare with the expected polarization of radiated topo-

- Rossby waves;
- (iii) energy flux via direct calculation from the data:  $\langle p'v' \rangle$  and  $\langle p'u' \rangle$ ;
- (iv) energy flux via  $\langle E \rangle C_g$ , where  $\langle E \rangle$  is the total potential and kinetic energy as a function of frequency, and  $C_g$  is the group velocity from (i) above;
- (v) coherence between oceanic variables and surface winds and air pressure to ascertain the presence of directly atmospherically forced variability (e.g., Luther et al. 1990; Chave et al. 1992), although we are acutely aware of the fact that lack of coherence does not necessarily preclude atmospheric forcing if the wavenumber bandwidth of the forcing and/or oceanic response is broad; and,
- (vi) relative vorticity directly from the tomography data.

**Analysis Enhancement #1: Employing a Model of Atmospherically-Forced Variability to Remove this "Noise".** In this stage of the analysis, the objective is to 'improve' the bottom pressure observations by subtracting whatever atmospherically-forced, bottom pressure variability exists. We have already discussed why it is probable that bottom pressure will display a significant "contamination" from barotropic motions directly forced by atmospheric variables.

The existence of this kind of barotropic variability is important to the analysis of altimetric sea height observations, because short-time-scale (e.g., 2–10 days) barotropic variability can be aliased to lower frequencies by the altimeter sampling scheme. There has been much recent work to assess the dimensions of this problem and to develop wind-forced models to remove as much barotropic "noise" as possible from the altimeter data (e.g., Stammer et al. 2000; Tierney et al. 2000; Gille and Hughes 2001). The wind-forced models are effective for this purpose because this type of variability is large scale and the dynamics are quite simple (e.g., Muller and Frankignoul, 1981). These models are therefore also able to predict accurately the wind-forced variations observed by bottom pressure sensors (bottom pressure and sea height are essentially equivalent for these atmospherically-forced barotropic motions). This fact will be used here to predict the direct atmospherically-forced bottom pressure variations.

Predictions of atmospherically-forced variability are now performed on a routine basis (e.g., Stammer et al. 2000, makes one of several available predictions) for "correction" of altimeter sea heights. We will acquire these model predictions and subtract the predicted bottom pressure from our observed bottom pressure. Coherences between the residual bottom pressure and surface winds and air pressure

will be computed to check that atmospherically-forced "noise" has been completely removed.

While the modeling of atmospherically-forced bottom pressure is now quite accurate, the same cannot be said for modeling of the atmospherically-forced currents, as discussed in Section 1 (recall Fig. 2). The currents tend to be dominated by smaller scales than the bottom pressure (although still with >1500 km dominant wavelengths, e.g., Chave et al. 1992, Figs. 21–23), and so are probably more sensitive than bottom pressure to the details in the models of the bottom topography, the accuracy of the wavenumber spectrum in the wind forcing, and the parameterization of dissipation (e.g., if lateral friction is the dominant friction parameterization in the model, shorter scales are discriminated against). Despite our pessimism about the ability of existing models to accurately predict atmospherically-forced barotropic currents, we will also acquire these predicted currents from one of these models and investigate whether subtracting these "noises" from our observations produces a residual less coherent with the atmosphere and thus more useful for looking for radiated waves.

Once we are satisfied with the "correction" for atmospheric forcing, the residual currents and bottom pressures will be re-analyzed per steps (i) - (vi) above. Even if the atmospherically-forced currents are not well-removed from the observations, the removal of this phenomenon from the bottom pressure will ensure that the wavenumber estimation in (i) and the energy flux calculation in (iii) will be improved.

The output of the model will also be used to test the simple analysis methodologies above. For example, by employing these methodologies, what frequency-wavenumber spectrum and energy fluxes are obtained from just the modeled atmospherically-forced currents and bottom pressures, and how do these results compare with the full analyses of the model data?

**Analysis Enhancement #2: Assimilation of All Data in a Regional QG Model.** In order to more completely distinguish baroclinic "noises" from the barotropic signals we seek, we will employ a model that assumes a particular dynamical balance (quasi-geostrophy; QG) among the variables. All our observations (tomography, HEFR, bottom pressure, thermistor data from the tomography moorings, etc.) will be assimilated into a regional QG model. This modeling/assimilation capability has been developed by Cornuelle and Worcester (1996; see also Yaremchuk and Nechaev 2001), and it can be readily applied for this purpose. The QG data assimilation simultaneously solves for a truncated grid of wavenumbers of both baroclinic and

barotropic variability, obtaining a dynamically consistent partitioning between the two. The tomography measurements of both currents and temperatures are available as dynamical constraints on this partitioning. The frequency-wavenumber characteristics of the dominant barotropic energies will be compared with a simple topo-Rossby dispersion relation to confirm the free radiating wave hypothesis; the energy flux will then be calculated. This decomposition will also permit a fuller comprehension of the "noises" inhabiting this region of ocean.

The modeling/assimilation computation will be applied with differing dynamical assumptions and with differing datasets to ascertain the robustness of the results to these changes. For instance, the assimilation will first assume linear, then later non-linear, dynamics. The data to be assimilated will first include the "correction" for atmospherically-forced variability discussed above, then later the "un-corrected" data will be used. Also, altimeter sea-height data will be explored in the assimilation to determine the value of its information content. It may be that the substantial information on temperature, current and bottom pressure variability to be collected during this experiment precludes any substantive value of the relatively noisy altimetric sea heights.

**Analysis Enhancement #3: Simulation of the Inter-play Between Signal and "Noises".** We propose to study the large-scale context of the forced atmospheric response and its inter-play with the radiated energy from the western boundary currents, using a primitive equation model, in order to (i) improve our understanding of the nature of the variability produced by episodic forcing by the Gulf Stream and by the atmosphere; (ii) explore the strength of the interactions among these phenomena; and, (iii) get a sense for how well our analysis methodologies will distinguish these two primarily barotropic phenomena from each other and from the model's baroclinic variability; e.g., in comparison with the full analyses of the model data, we would want to know how well our analysis procedures on sub-samples of the model data (corresponding to the planned experiment) extract the correct energy levels for the radiated waves, the correct frequency-wavenumber spectra, the correct Reynolds stresses, the correct energy fluxes, etc.

We will use the Regional Ocean Modeling System (ROMS) which is a generalized sigma-coordinate primitive equation ocean model that is a descendent of SCRUM (Song and Haidvogel 1994). The model has been developed jointly between Rutgers and UCLA and it includes new mixing parameterizations and multi-processor capabilities. We have previously used the model to study the California Current System (Miller et al. 2000) and we are

presently involved in developing the adjoint for it (under ONR funding).

The model grid will have enhanced resolution in the western boundary current region and the Gulf Stream region to better simulate the instability processes there. Away from those regions, where the energy is organized into larger-scale flows, the grid will be coarser. The details of how finely resolved the grid will be are to be determined once the model domain is built. We expect to use at least 10–20 km resolution in the most highly resolved areas and at least 50–100 km resolution in the distant regions. The domain will likely be confined to the region between 20°N and 60°N (sponge layers or radiation/relaxation conditions will be employed at these boundaries), and will include the coastal shallow seas around North America. Realistic topography from Smith and Sandwell (1997) will be used.

Forcing will be obtained from the best available sources, probably the NCEP re-analysis 2 (RA2; Kalnay et al. 1996) which is available at 6-hourly sampling. Although we expect to employ the forcing at 1-day resolution (i.e., 1-day averages), we will explore the effects of including the 6-hr versus daily forcing. Wind stress curl variations are the most important forcing for the time scales of the Rossby waves to be studied and these are fairly well represented in the RA2 (e.g., Miller et al. 1996; Auad et al. 2001). Hence, we are not too concerned about the problems associated with specifying or determining surface heat flux and fresh-water flux forcing that are most important at the very long periods (e.g., Miller et al. 1994). However, we will test the sensitivity of the flows to including these time-dependent effects as represented in the RA2.

The model will be used in two ways to explore the generation, propagation and exchange of energy of the barotropic and baroclinic mesoscale fields: (1) statistical equilibrium; and, (2) actual winds. For the former, the model will be run in seasonal-cycle mode, with only climatological atmospheric forcing, allowing it to reach a statistical equilibrium and archiving 10–20 years of simulated flows. The distribution of mesoscale energy in the barotropic and baroclinic flows will be assessed. The model rms fields will be compared with TOPEX sea level rms distributions and with available current meter (and other data) records to quantify the model's verisimilitude, especially at the source of the radiated waves in the Gulf Stream. This will be the baseline "model" radiated energy field that will be compared with the next case.

The model will next be run with actual wind stress variations over a chosen time interval, nominally 10–20 years (the actual dates will depend on the computer time availability and the duration of

the field experiment). The distribution of mesoscale energy in the barotropic and baroclinic flows will be assessed and compared to the results with only climatological winds. This will provide a baseline "model" of the combined wind-forced-radiated energy field for comparison with observations.

Should it be considered worthwhile, after evaluating the runs above, a simulation with only atmospheric fluctuation forcing (i.e., no seasonal climatological winds), and no mesoscale eddies, will be run with a model resolution of 100–200 km. This run would be for comparison with the combined forcing run to determine the large-scale forced atmospheric flows without non-linear interaction with the radiated mesoscale fields.

One product of this modeling project will be a model tuned such that the generation of currents by wind forcing is accurate.

## 6. Timeline

Sept. 1, 2003	Start model development, array design & ancillary data acquisition.
2003/2004	Preparation of tomography, HEF/Pressure and T/C instruments.
Sept./Oct. 2004	Deploy all instruments.
2004–2006	Additional ancillary data acquisition (currents, altimeter, wind, etc.) and analysis; model development and testing; test analysis methodologies.
July–Aug. 2006	Recover all instruments
2006–2008	Data analysis, preparation of publications
Fall 2008	End of project

## 7. Satellite Measurements of Sea Height & Pressure: A Two-Way Street

A natural question to ask is whether part or all of the scientific goals of this proposal can be accomplished more inexpensively by employing data about the oceans being obtained by satellites. While satellite-derived data may help our work, we do not believe that satellite data can replace any of the observations we propose.

Sea level heights measured by satellite altimeters (e.g., TOPEX/POSEIDON, JASON) contain information about the surface currents of the oceans. From geostrophy, one might expect that barotropic currents, with their generally smaller wavenumbers, would have a disproportionate impact on sea surface height, thus permitting altimetry data to be used quite successfully for the study of barotropic variability, hence mitigating the need for our bottom

pressure sensors (essentially, the assumption would be that sea height equals bottom pressure). However, the scale advantage of barotropic variability is overwhelmed by the vertical structure of the baroclinic variability which yields much higher surface currents (and, usually, sea heights) for baroclinic variability than for barotropic variability with the same total energy (Wunsch 1997). Partitioning the altimeter sea surface height measurements into barotropic and baroclinic components usually requires a variety of modeling assumptions (e.g., Wunsch and Stammer 1995; Wunsch 1997). Despite these limitations, we hope that incorporating the satellite altimeter data in the data inversions discussed in section 5 will be advantageous.

The Gravity Recovery And Climate Experiment (<http://www.csr.utexas.edu/grace/>) (GRACE) mission was launched in March 2002 to estimate global models for the mean and time variable gravity field. The instrument will measure gravity variations at space scales greater than 500 km and time scales longer than 30 days over the 5 year lifetime of the mission. The data returned by GRACE are expected to provide the precise, high resolution geoid measurements required to measure dynamic topography effects at the seafloor, i.e., yielding bottom pressure variations due to ocean currents. These data are to be used to better describe the general circulation of the oceans and its large-scale variability. With accurate global maps of sea surface height from the altimeters and bottom pressure from GRACE one can imagine obtaining the gravest vertical structure (essentially, the barotropic and first baroclinic modes) of the largest horizontal scales of the general circulation. The large spatial and temporal sampling intervals of the GRACE data, plus the uncertainty in the ultimate accuracy of the derived bottom pressure after extensive corrections are applied (the gravity field measured at any point by GRACE is ultimately dependent on all mass fluctuations in the atmosphere and hydrosphere around the earth), suggest that we should not rely on the GRACE-derived bottom pressures for achieving any of our scientific goals. More likely, the bottom pressure measurements we make will provide useful validation points for GRACE, especially since the high temporal resolution of our measurements will permit the evaluation of aliasing of high-frequency variability into the low-frequencies measured by GRACE.

## 8. Broader Impacts

The field of physical oceanography has a fundamental impact on the studies of climate variability, ecosystem evolution, and gaseous sequestration (e.g., CO<sub>2</sub>), just to name a few linkages. Enormous effort is being expended on modeling how the ocean

currents and temperature fields behave and how they affect these other phenomena. The models are only as good as the physics that are programmed into them. If they have fundamental flaws in how energy flows through the ocean, and not just heat energy but kinetic and potential energy, then the variability they produce for studies of climate, biogeochemical processes, etc., will be incorrect.

The work proposed here is intended to address one of the longstanding questions about the nature of barotropic variability in the oceans, which variability contributes to the stirring, both horizontally and vertically, of water properties, and is likely related to energy loss by the ocean's strongest currents. What is learned from this work will provide important benchmarks for validation of ocean numerical models, and thus has the potential to improve understanding of those phenomena dependent upon accurate oceanic models.

The proposed work will provide excellent opportunities for training the next generation of sea-going oceanographers, so we are requesting funds to support several graduate students. In addition, the work is a fertile ground for expanding the horizons of new postgraduates, especially in the arenas of data analysis, data assimilation and numerical modeling, so we have included funds for postdoctoral investigators.

## 9. Results from Prior NSF Support

### A. PI: B. Dushaw (U.W.)

#### **A Study of Baroclinic and Barotropic Tides in the Western North Atlantic Using Long-Range Reciprocal Acoustic Transmissions**

Grant No. OCE-9415650

Amount: \$144,000 Period: 11/94–10/97

Grant No. OCE-9720680

Amount: \$252,465 Period: 11/97–10/01

B. Dushaw has been partially supported by this project. The Acoustic Mid-Ocean Dynamics Experiment (AMODE) (Fig. 1) (Dushaw et al. 1996) provided highly accurate, spatially filtered observations of the barotropic and baroclinic fields. A comparison of the estimated barotropic tidal currents with Egbert's TPXO.2 model currents (Dushaw et al. 1997) found generally good agreement; the slight disagreement observed is consistent with spatially coherent errors in the model resulting from the nearby Caribbean island arc and with the model uncertainties. Barotropic tidal vorticity ( $O(10^{-9}) \text{ s}^{-1}$ ), resulting from the stretching of vortex lines by tidal elevation, was measured as well. The directly measured vorticity was generally consistent with the TPXO model, but inconsistent with the simple

shallow water equations, perhaps because of slight horizontal shear in the tidal currents. Not surprisingly, a comparison of the accurate TPXO model currents to estimates from historical open-ocean current meters found that the point measurements were not particularly accurate.

The internal tide observed by the AMODE array was highly spatially and temporally coherent, similar to earlier results in the Pacific by Dushaw et al. (1995). Dushaw (2003) described the antenna properties of acoustic tomography arrays in detecting internal tides. The ratio of diurnal to semidiurnal internal-tide amplitudes observed during AMODE was an order of magnitude larger than that which would be expected from the ratio of barotropic tide amplitudes. The diurnal internal tides apparently reflect at the turning latitude ( $27\text{--}30^\circ$ , depending on frequency), so the acoustic array detects a standing wave in the meridional direction, i.e., the internal wave is in resonance (Dushaw and Worcester 1998). Additional work on these issues is in progress.

Part of this grant supported preparation of the review paper on acoustic tomography by Dushaw et al. (2001) for the OceanObs'99 conference and conference proceedings book.

### B. PI: A. Miller (S.I.O.)

#### **Analysis of Decadal Variability in the North Pacific**

Grant No. OCE-9711265

Amount: \$335,000 Period: 10/97–9/00

Grant No. OCE-0082543

Amount: \$497,813 Period: 11/00–10/02

A. Miller (co-PI N. Schneider) commits three mos./year to this project. Results that include Miller as a co-author can be grouped into three categories below: subduction, decadal ocean physics, and Latif-Barnett mode studies. This grant also supported the Second Surfside Climate Workshop on "Climate Forcing of Oceanic Ecosystems: Are Significant Biological Feedbacks Possible on Interdecadal Timescales?" held April 2001 which resulted in the publication by Miller et al. (2002).

**Subduction studies:** Schneider et al. (1999a) analyzed observations of oceanic temperature in the upper 400 m of the North Pacific over the last 25 years. They found decadal signals that move in the thermocline along lines of constant potential vorticity from the subduction region in the central North Pacific to approximately  $18^\circ\text{N}$  in the western Pacific with a transit time of eight years. The propagation path and speed are consistent with advection by the observed geostrophic mean circulation and with a model of the ventilated thermocline. The thermal anomalies are driven at the ocean surface by the

atmosphere (via surface heat fluxes, mixing and Ekman advection). South of 18°N, simple models and ocean GCM hindcasts (Schneider et al. 1999a,b) support the interpretation that tropical Ekman pumping, rather than equatorward movement of the mid-latitude signal, drives the tropical thermocline variability. These results indicate no significant coupling between the Northern Hemisphere midlatitudes and the equatorial region via advection of thermal anomalies along the oceanic thermocline (i.e., no support for the Gu-Philander decadal oscillation mechanism). Although the limited data in the Pacific Southern Hemisphere revealed no coherent subducting anomalies, the subduction path there is shorter and straighter and hence warrants further research (Schneider 1999a, Schneider et al. 1999b.)

**Decadal ocean physics studies:** Miller et al. (1998) showed that the main thermocline of the North Pacific subpolar gyre shoaled from the 1970's to the 1980's with temperatures at 200–400 m depth cooling by 1–4°C. Using an ocean model hindcast forced by observed wind stress and heat flux anomalies from 1970-1988, they interpreted the strengthening of the subpolar gyre as a response to decadal-scale changes in basin-scale wind stress curl. This oceanic response is quasi-stationary, representing a time-dependent quasi-Sverdrup balance. Although this wind-stress curl driven response is quasi-stationary, it occurs in conjunction with the subducted temperature anomaly (discussed above) that propagates from the central North Pacific to the subtropical gyre which also exhibits a stationary wind-stress curl forced thermocline response. These two distinct physical processes acting together give the appearance of coherent circumbasin propagation, but different physics evidently controls the decadal subsurface temperature signal in different parts of the extratropical North Pacific. Auad et al. (1998) further analyzed the the complicated processes of the decadal upper ocean heat balance in that hindcast in terms of the diabatic (from the model temperature equation) and the adiabatic (from the model mass conservation equation) parts of the heat content for several regions in the North Pacific. Miller and Schneider (1998, 2000) describe our current understanding of the processes of oceanic decadal variability in the Pacific and underscore its possible effects on ecosystem variations. Determining how these ocean variations feed back to atmosphere is the crucial issue needing further research. (Miller et al. 1998, Auad et al. 1998, Miller et al. 2000.)

**Latif-Barnett mode studies:** Schneider et al. (2001) analyzed the 130-year coupled model run that contains the celebrated Latif-Barnett mid-latitude 20–30 year period climate mode. They found that the enhanced variance in the oceanic streamfunction

and SST that is centered on the Kuroshio-Oyashio Extension (KOE) region is not due to a closed feedback loop that had been hypothesized by the original authors and had been modeled in many other simplified and conceptual model frameworks. Instead, the departure from a purely red spectrum is likely due to the short record length of the simulation or to remote forcing (e.g., from the tropics). There is, however, a predictable component to the KOE SST due to Rossby wave dynamics. Schneider and Miller (2001) show that 10-25% of the variance of observed wintertime KOE SST can be predicted up to 3 years in advance by this effect, which may be exploitable by fisheries managers. (Schneider et al. 2001, Schneider and Miller 2001.)

### **C. PIs: D. Luther (U.H.), A. Chave (W.H.O.I.)**

#### **U.S. - Australia Cooperative Study of the Northern Branch of the Antarctic Circumpolar Current**

Grant Nos. OCE-9204113(DL); OCE-9204063(AC)  
Amounts: \$375,000(DL); \$820,000(AC)  
Period: 6/1/94 - 5/31/99

#### **The Sub-Antarctic Flux and Dynamics experiment (SAFDE): Renewal Proposal for Data Analysis and Model Comparisons**

Grant Nos. OCE-9911974(DL); OCE-9912110(AC)  
Amounts: \$238,000(DL); \$177,000(AC)  
Period: 5/1/00 - 4/30/03

The first project, in conjunction with grants to D.R. Watts (URI), J.G. Richman (OSU), and J.H. Filloux (SIO), funded the Sub-Antarctic Flux and Dynamics Experiment (SAFDE; Luther et al. 1997), which included a 2-year deployment of 17 seafloor horizontal electric field recorders (HEFRs), 18 inverted echo sounders (IESs) and 9 full-water-column current meter moorings in the Sub-Antarctic Front (SAF) southwest of Tasmania. The SAF at these longitudes is the strongest branch of the Antarctic Circumpolar Current.

To date, we have completed papers on (i) the efficacies of several definitions of stream coordinates (Meinen and Luther, 2002a); (ii) the method and accuracy of combining HEFR and IES data to yield time series of full-water-column, vector horizontal currents (Meinen et al., 2002a); (iii) the barotropic and baroclinic structure, transport and divergence of SAF currents (Meinen et al., 2002b); (iv) galvanic distortion effects on the horizontal electric fields, and how to mitigate their effect (Chave et al., 2002); and, (v) a new method of correcting moored current and temperature data for mooring motion biases (Meinen and Luther, 2002b)

Manuscripts are in preparation discussing the nature of the vertical velocity of the SAF in Eulerian

and stream coordinates, the total transport variability across the SAFDE array, and the momentum budget of the SAF. The projects supported 9 presentations at national and international meetings authored or co-authored by A. Chave and D. Luther. The first project provided support for a graduate student at U. Hawaii, Reka Domokos, who will defend her Ph.D. dissertation in Spring, 2003; and the second project provided support for a Postdoctoral Fellow at U. Hawaii, Dr. Chris Meinen, now at CIMAS.

**D. PIs: P. Worcester (S.I.O.), B. Cornuelle (S.I.O.), B. Dushaw (A.P.L.-U.W.)**

**The Farfield Component of the Hawaii Ocean Mixing Experiment (HOME)**

Grant No. OCE-9819525 (Worcester/Cornuelle)

Amount: \$2,414,746      Period: 1/00–12/04

Grant No. OCE-9819527 (Dushaw)

Amount: \$429,079      Period: 11/00–10/04

[Although OCE-9819525 is only in the early stages of its data analysis phase, so that there are just a few published results to date, it is the only NSF grant obtained by Worcester or Cornuelle during the past 5 years, and is therefore required to be mentioned in this section.] Dushaw, Worcester, and Cornuelle are part of the HOME collaboration (Luther et al. 1999, Pinkel et al. 2000). This grant has supported the deployment of an array of acoustic tomography moorings (Dushaw, 2003) and electromagnetic and pressure sensors on both sides of the Hawaiian Ridge; the instruments were recovered in Spring 2002. The tomographic array on the northern side of the Ridge suffered two instrument failures, but still acquired sufficient data for estimating internal-tide energy flux; the southern tomography array acquired full 200-day time series for all acoustic paths. Analyses of these data are underway, and preliminary results were presented at the 2002 Ocean Sciences meeting in Honolulu (Dushaw et al., 2002). It appears that in the farfield of the Hawaiian Ridge, the low-mode internal tides have a surprisingly weak  $O(1 \text{ kW/m})$  energy flux on either side of the Ridge, so that most of the available tidal energy is dissipated in the "nearfield", i.e., within 500 km, of the Ridge. This preliminary energy flux estimate is consistent with values of internal-tide energy determined by TOPEX/POSEIDON altimetry data (Dushaw, 2002). Analysis of the HOME data has just begun.



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