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The eddy radiation field of the Gulf Stream as measured by ocean acoustic tomography

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Abstract. The Gulf Stream System is one of the most important components of the North Atlantic Circulation. Reciprocal acoustic transmissions have been analyzed to determine the structure and variability of temperature, current velocity, and relative vorticity in a region just south of the Gulf Stream. Observational evidence is presented that the Gulf Stream is the source of the energetic eddy variability found in the Atlantic interior. Through highly nonlinear processes, eddy activity (energy) radiates away from the Stream southward via Rossby wave packets.

Introduction

Experimental evidence accumulated in the northwestern Atlantic shows that eddy potential and kinetic energy densities increase by orders of magnitude when proceeding from the basin interior towards the Gulf Stream [Schmitz et al., 1983]. This large increase of eddy variability, coupled with difficulties in finding other adequate sources of eddy energy, leaves the Stream as the most likely source of eddy activity through radiation into the far field [Schmitz et al., 1983]. Recent theoretical studies have capitalized on the transient behavior of Gulf Stream meanders, whose life cycles are characterized by growths and decays, often abrupt, and amplitude pulsations. The stochastic meander motions excite transient pulses of Rossby waves, and the transient part of the response is capable of radiating energy away from the source and assumed to be responsible for the observed high eddy energy in the far field [Malanotte-Rizzoli et al., 1987; Hogg, 1988].

Strongly inertial, tight recirculation cells exist both to the south and to the north of the Stream [Hogg, 1992]. Can the eddy Reynolds stresses, i.e., the divergence of the eddy potential vorticity fluxes, induce a mean recirculation south or north of the Stream? Observational studies and numerical simulations provide well-known examples of eddy-driven recirculation cells [Hogg, 1988; Holland and Rhines, 1980]. The observational evidence and theoretical endeavors illustrate the importance of obtaining accurate estimates of eddy potential vorticity fluxes, i.e., of second-order statistics, as well as of average properties, that are dynamically linked to the inertial nature of the recirculation regions. Diagnostic tools capitalizing upon estimates of eddy fluxes can then be used to prove that the source of the eddy energy found in the far field is the Gulf Stream itself.

In this paper we wish to report some scientific results obtained from a tomographic experiment, specifically:

1. Temperature, current velocity, and relative vorticity are estimated in the upper 4000 m of the water column in a region just south of the Gulf Stream at 55°W. The measurement of relative vorticity is a unique capability of tomography, being very difficult to measure with any traditional instrumentation. Relative vorticity can be used to identify cyclonic (cold core) rings passing through the area.

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2. Tomographic estimates of eddy potential vorticity fluxes are used to diagnose properties of eddy-mean flow interactions. Specifically, we use diagnostic tools taken from meteorology, i.e., the generalization of the Eliassen-Palm flux to three dimensions [Plumb, 1986]. Under assumptions that are well founded for the present situation, including the quasi-geostrophic assumption, this approach leads to the construction of a three-dimensional flux that can be thought of as a propagation, by Rossby wave packets, of wave activity from one region to another [Plumb, 1986]. Mapping of this flux suggests the Gulf Stream as the source of the eddy activity in the region just south of the Stream at 55°W.
3. Tomographic measurements are capable of providing accurate and reliable estimates of mean temperature and velocity as well as of eddy statistics.

The SYNOP Tomography Experiment

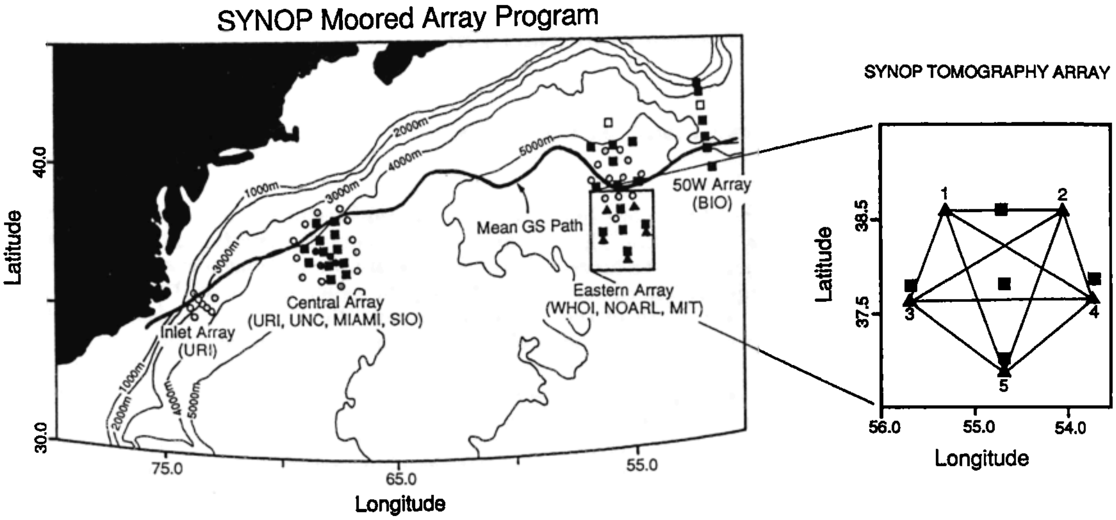
In 1986–1990 an intensive observational program was carried out in the Gulf Stream System under the auspices of the Office of Naval Research, the SYNOP (Synoptic Ocean Prediction) Experiment (Figure 1). The SYNOP tomographic experiment consisted of a pentagonal array of acoustic transceivers centered near 37°N, 55°W in the northern portion of the Gulf Stream southern recirculation gyre. The location of the five moorings, along with concurrent current meter moorings, is displayed in Figure 1. The tomographic moorings were deployed in October 1988 and retrieved in August 1989. All five transceivers were moored at about 1200-m depth, within 200 m of the sound channel axis. Transmission distances varied from 100 km along the periphery of the array to 200 km across the array. The sampling scheme consisted of six transmissions per day, every four hours, every other day.

The basic datum in tomography is the travel time of acoustic multipaths [Munk and Wunsch, 1979]. Each multipath has an associated arrival time. By matching the measured acoustic arrivals with the arrivals calculated using an acoustic ray tracing model, one infers the paths of propagation leading to the observed arrival times. Typically, two to six acoustic arrivals were stable, resolvable, and identifiable for each source/receiver pair for this experiment.

A full discussion of the errors in the tomographic measurements is given elsewhere [Chester, 1993]. Here we summarize the pertinent results. The accuracy of the daily-averaged travel time estimate is ~1 ms, which corresponds to a daily-averaged temperature accuracy of roughly 0.1°C at thermocline levels and a daily-averaged velocity accuracy of roughly 3 cm/sec over most of the water column. The tomographic measurement errors are thus of the same order as errors in field estimates obtained with conventional instrumentation.

Results and Discussion

Range-averaged temperature, velocity, and relative vorticity time series have been estimated throughout the tomographic array. The multipath travel time data for each reciprocal source/receiver pair have been used to infer the structure of the oceanic medium, both temperature and current velocity. The tomographic inverse estimation problem consists of estimating the sound speed (or equivalently temperature) field, and velocity, in a vertical slice using the observed multipath arrival times [Munk and Wunsch, 1979]. A



URI.........University of Rhode Island
BIO.........Bedford Institute of Oceanography
MIT.........Massachusetts Institute of Technology
NOARL...Naval Oceanographic and Atmospheric Research Laboratory
UNC.....University of North Carolina
SIO.......Scripps Institute of Oceanography
WHOI...Woods Hole Oceanographic Institute

Fig. 1. Observational plan of the Synoptic Ocean Prediction (SYNOP) Experiment, (adapted from T. Shay and J. Bane, unpublished work, 1992). To the right of the full plan is a blow-up of the southern portion of the eastern array. Solid triangles (squares) indicate the location of tomographic transceivers (current meters).

linear inverse least-square formalism based upon the singular value decomposition has been used. A full discussion of the assumptions and analysis is given elsewhere [Chester, 1993].

A model ocean of 12 layers has been assumed with closer spacing in the surface layers than at depth. Vertical resolution in the upper 1000 m ranges from 100 m to 300 m with depth. Beneath 1000 m the resolution decreases from 400 m to 800 m at 4000 m depth. Depths greater than 4000 m are not insonified by the acoustic energy. Ocean eddy variability is typically confined in the surface and thermocline layer. A convenient measure of such variability is the Brünt-Väisälä frequency, N^2, which is proportional to $\partial\bar{\rho}/\partial z$, where $\bar{\rho}(z)$ is the average vertical density profile. The ocean model is made more realistic by scaling the vertical structure of the expected noise covariance for temperature by $N^{3/2}$ and velocity by $N^{1/2}$ [Richman et al., 1977]. This is equivalent to having a vertical scale that is not simply the geometric scale z but rather a dynamic scale determined by ocean eddy motions.

A representative example of the estimated temperature perturbation from the reference field is displayed in Figure 2a. The plot shows 300 days of daily-averaged temperature anomaly along leg 2-5, which is situated in the north/south direction (see Figure 1). The temperature anomaly field has a fairly simple structure, with much of the variability in periods of the order of one month. Most of the anomalous events are coherent with depth. Note the presence of strong cooling events, particularly those occurring in November 1988 and April 1989. These intense events coincide with the passage of cold core rings which have been shed from the Gulf Stream and have migrated through the array, as evidenced by satellite infrared imagery for these periods (Figure 2c).

The estimated relative vorticity at 1000 m depth for part of the array (the quadrilateral formed with moorings 2-3-4-5 (see Figure 1)) is shown in Figure 2b. Relative vorticity is

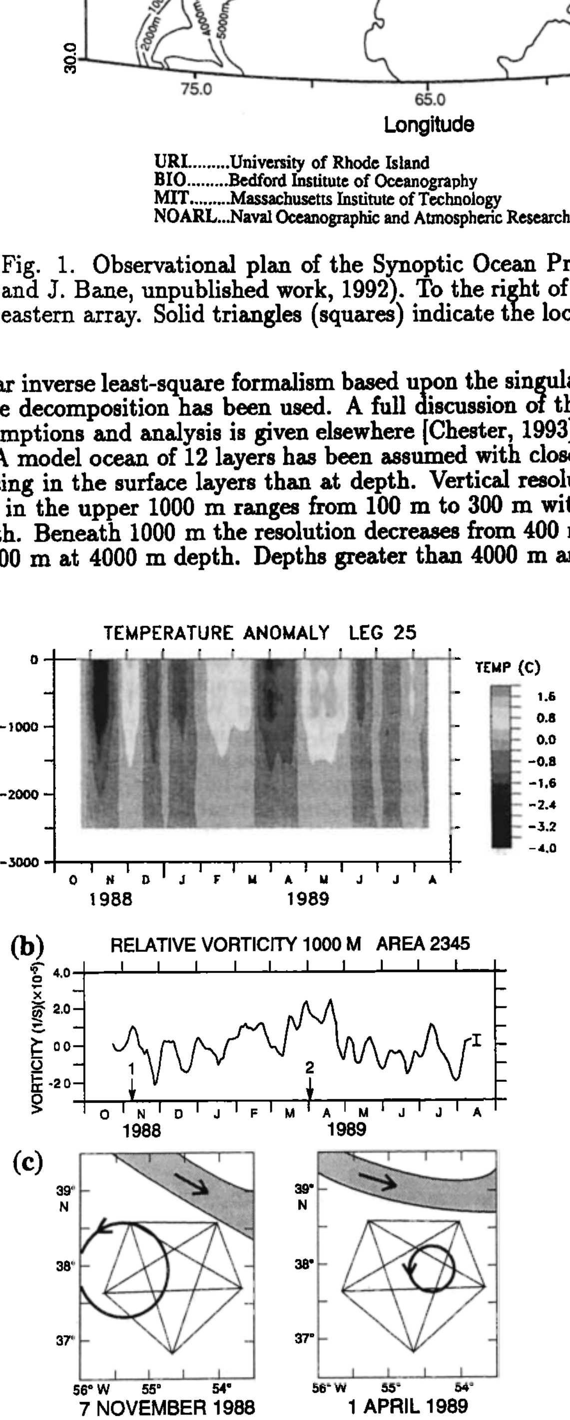


Fig. 2. Temperature time series (2a). The range-averaged temperature anomaly from the background (reference) temperature field is shown for leg 2-5 (roughly in N/S direction and 200-km range). Note the anomalous cold events (occurring in November 1988 and April 1989), indicative of cold core rings in the area. The relative vorticity at 1000 m depth evaluated over the quadrilateral 2-3-4-5 (an area of 20,000 km^2) is plotted in (2b). The error bar is for the tomographic estimate of vorticity. Note the positive values of relative vorticity (cyclonic) for events labeled 1 and 2, also consistent with cold core rings in the region. For comparison, NOAA sea surface infrared (temperature) maps for November 7 (event 1) and April 1 (event 2) are provided in (2c).

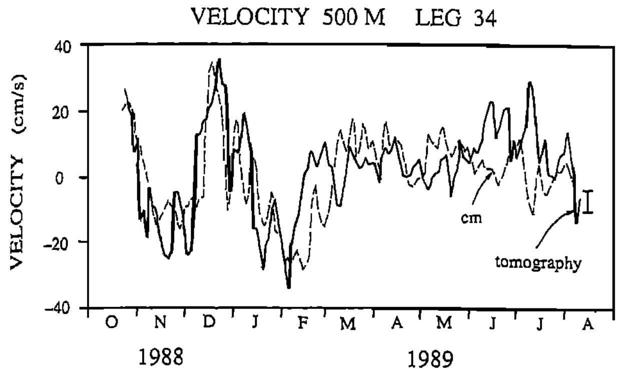


Fig. 3. Current velocity time series at 500 m. The range-averaged absolute velocity along leg 3-4 (situated almost in W-E direction, and 170 km range) is given by the solid line. For comparison, the u-component of velocity averaged over three current meters aligned with this leg is given by the dashed line (see Figure 1 for current meter locations). The error bar is for the tomographic estimate of current.

obtained as the line integral of velocity along the periphery of the quadrilateral 2-3-4-5. Through the circulation theorem, this measurement provides an estimate of the relative vorticity averaged over the area of the quadrilateral. The relative vorticity record has a near-zero mean ($-1.1 \times 10^{-6}\ s^{-1}$), with fluctuations ten times as large. The ambient planetary vorticity is an order of magnitude larger, with a value of $9 \times 10^{-5}\ s^{-1}$. Note the two events labeled 1 and 2 in Figure 2b. These events correspond to anomalously cold temperatures in November 1988 and April 1989 (Figure 2a), and illustrate the presence of cold core, cyclonic rings, as depicted in Figure 2c. During event 1 the ring is exiting the array (migrating westward) and is only partially covered by quadrilateral 2-3-4-5. During event 2 the ring is imbedded in the quadrilateral, hence the stronger positive relative vorticity peak.

The estimated daily-averaged velocity is shown in Figure 3 for leg 3-4, situated in the east/west direction, at a depth of 500 m. Leg 3-4 was chosen as three current meter moorings are positioned along this path (see Figure 1). The velocity estimated from the average of the u-component of velocity of three current meters aligned with this leg is plotted for comparison (Figure 3). The two independent estimates compare favorably over the entire record. Estimated rms uncertainties are 3 cm/sec for both records. The close agreement is a function of both the small errors in the two measurements and a horizontal correlation length scale of 0(100 km). As with the temperature field, the velocity variability is dominated by motions with mesoscale periodicities [Richman et al., 1977].

Tomographic estimates of second-order statistics are now used to diagnose properties of eddy-mean flow interactions. We adopt diagnostic tools developed in the meteorological literature, specifically the generalization to three dimensions of the Eliassen-Palm flux [Plumb, 1986]. The usefulness of the normal Eliassen-Palm flux vector as a diagnostic tool has been limited by its restriction to waves on zonally-averaged flows. Plumb [1986] has developed a quasi-geostrophic theory for small-amplitude transient eddies on a slowly time-varying mean flow leading to the definition of a flux $\mathbf{M}_T$ which is a conservable measure of the flux of eddy activity and is parallel to the group velocity for an almost-plane wave train. This total wave activity flux $\mathbf{M}_T$, the generalization of the Eliassen-Palm flux, is given by

$$\mathbf{M}_T = \mathbf{M}_R + \overline{u} M , \qquad (1)$$

where $\mathbf{M}_R$ is the radiative activity flux and $\overline{u}M$ is the wave activity flux due to advection by the mean flow. In the almost-plane wave limit

$$\mathbf{M}_T = \mathbf{c}_g M , \qquad (2)$$

where $\mathbf{c}_g$ is the group velocity of the transient waves. Under the assumption that the mean potential vorticity gradient is slowly varying, Plumb [1986] uses this flux as a diagnostic of transient eddy propagation to infer sources and sinks of wave activity. In the quasi-geostrophic limit, Plumb's approximation, the energy flux vector is equal to the wave energy multiplied by the group velocity [Pedlosky, 1979]. As the group velocity is parallel to energy flux vector, the wave activity flux is thus parallel to the energy flux.

Several assumptions have been made prior to reaching this conclusion. The mean potential vorticity gradient is assumed to be meridional. This is valid since the potential vorticity is dominated by the planetary vorticity in the area. At thermocline levels, however, the vortex stretching is of comparable magnitude to the planetary vorticity. McDowell et al., [1982] find that contours of vortex stretching are mostly parallel to planetary vorticity contours throughout the region. The basic assumption for Plumb's approximation to hold is that the total vorticity contours be mostly zonal. This assumption is therefore appropriate. In the experimental region the mean zonal velocity is negligible compared to the eddy-component of the velocity, so $\mathbf{M}_T \approx \mathbf{M}_R$, i.e., the total wave activity flux is approximately equal to the radiative component of the wave activity flux. In the coordinate system where the y-component of the flux is in the direction of the potential vorticity gradient, i.e., the actual north in our case as $\nabla_H \overline{q} = \nabla_H \overline{f}$, the wave activity flux has components

$$\mathbf{M}_R = \left(\overline{v'^2} - \epsilon \ , \ -\overline{u'v'} \ , \ \frac{f\,\overline{v'\theta'}}{d\overline{\theta}/dz} \right) \qquad (3)$$

in the quasi-geostrophic approximation, where $\epsilon = (1/2)[\overline{u'^2} + \overline{v'^2} + (\overline{N^2\,\theta'^2})/((d\overline{\theta}/dz)^2)]$ is the eddy kinetic plus potential energy, $\overline{\theta}(z)$ is the background temperature profile, and $N^2(z)$ is the background Brunt–Väisälä frequency profile. The components of the radiative flux $\mathbf{M}_R$ are thus related to the second moments of the eddy field, specifically the eddy variances and the eddy heat flux.

The evaluation of second-order statistics from tomographic (slice) measurements differs from the approach used with point observations. Second-order statistics have been calculated from the estimated range-averaged temperature and along-path velocities. The heat flux estimate is for the flux of heat in the plane connecting the source/receiver pair. Since the estimate of velocity is solely for the component in the plane connecting the instruments, the covariance of velocities from two crossing slices (i.e., one leg oriented north/south, the other east/west) is used to calculate the momentum flux.

Errors for the estimated statistics were typically the same order as the estimated quantities due to the short (300 day) time series. Thus, one must be cautious when considering statistical significance of quantities derived from the flux estimates. A comparison of second-order statistics derived from both tomographic and current-meter measurements indicates that the statistics are consistent [Chester, 1993].

The flux $\mathbf{M}_R$ can be physically interpreted as showing the propagation by Rossby wave packets of wave activity (energy) from one region to another. It is therefore a powerful diagnostic to identify and locate the sources and sinks of eddy activity. A schematic of the wave radiation process is presented in Figure 4. Three planar sections have been extracted from the fluid cube in which the tomographic array is embedded. The wave activity flux is directed southward in the plan views at 500 m and 1000 m and downward in a vertical section through 55°W. The source of the wave activity flux as diagnosed from the flux vector $\mathbf{M}_R$ is located to the north of the tomographic array, in the region of the Gulf Stream jet path. This diagnosis provides a strong foundation

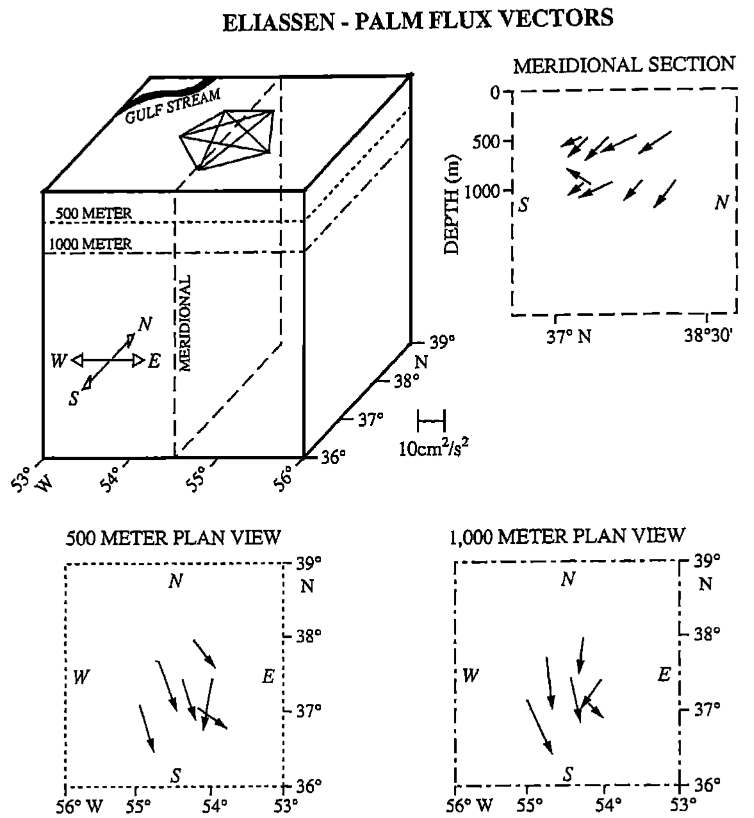


Fig. 4. A schematic of the Eliassen-Palm Flux vectors. The flux vector $\mathbf{M}_R$ is projected onto horizontal sections at 500 m and 1000 m depth, and a vertical slice that cuts the array through the middle in the north/south direction at 55°W.

to the hypothesis that the Gulf Stream itself is the source of wave energy radiation into the far field and found in the interior of the Northwestern Atlantic.

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