JOURNAL OF MARINE RESEARCH

The Journal of Marine Research, one of the oldest journals in American marine science, published important peer-reviewed original research on a broad array of topics in physical, biological, and chemical oceanography vital to the academic oceanographic community in the long and rich tradition of the Sears Foundation for Marine Research at Yale University.

An archive of all issues from 1937 to 2021 (Volume 1–79) are available through EliScholar, a digital platform for scholarly publishing provided by Yale University Library at https://elischolar.library.yale.edu/.

Requests for permission to clear rights for use of this content should be directed to the authors, their estates, or other representatives. The Journal of Marine Research has no contact information beyond the affiliations listed in the published articles. We ask that you provide attribution to the Journal of Marine Research.

Yale University provides access to these materials for educational and research purposes only. Copyright or other proprietary rights to content contained in this document may be held by individuals or entities other than, or in addition to, Yale University. You are solely responsible for determining the ownership of the copyright, and for obtaining permission for your intended use. Yale University makes no warranty that your distribution, reproduction, or other use of these materials will not infringe the rights of third parties.

This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. https://creativecommons.org/licenses/by-nc-sa/4.0/
Meddy, spiral arms, and mixing mechanisms viewed by seismic imaging in the Tagus Abyssal Plain (SW Iberia)

by Haibin Song¹, Luis Menezes Pinheiro², Barry Ruddick³,⁴, and Francisco Curado Teixeira²

ABSTRACT

Seismic imaging of the water column is used to investigate the relative roles of thermohaline intrusive mixing and stirring (straining and shearing) by mesoscale eddies in the NE Atlantic, in and around a Meddy, and in waters between the Meddy and the coast of Portugal. The images show that mixing is virtually absent within the core but anomalously high in the top, bottom, and surrounding frontal region, as previously found by conventional means. In the immediate periphery of the Meddy, bands of water with numerous reflectors consistent with thermohaline intrusions, and with anomalously high mixing rate can be seen. We suggest these may be “spiral arms” of water that was removed from the Meddy periphery by instability or external stirring.

The region between the Meddy and the Portuguese continental slope was also imaged, and shows numerous reflectors with relatively small slope and strength similar to the reflectors found in the Meddy periphery. This is in contrast to the predictions of individual thin filaments of slope $O(f/N)$ by Smith and Ferrari (2009), and we suggest that eddy stirring in this region produces thermohaline fronts that are acted upon by thermohaline intrusions. Therefore, the cascade of thermal variance to microscale dissipation could involve a partnership between eddy stirring and thermohaline intrusions.

1. Introduction

Stern (1975a) derived equations expressing the variance budget of thermal and haline fluctuations and deduced “power integrals” that related the surface flux of freshwater to the global volume integral of microscale salinity dissipation. Joyce (1980) made some simplifying assumptions to Stern’s approach and obtained a similar result for heat:

$$\frac{1}{\rho C_p} \iiint \bar{T} \mathbf{F} \cdot d\mathbf{A} = - \iiint \mathbf{F} \cdot \nabla \bar{T} dV = \frac{1}{2} \iiint \chi dV$$

(1)
where $F = u'T'$ is the eddy flux of temperature on all scales, and $\chi = 2\kappa_T (\nabla T')^2$ the microscale dissipation of thermal fluctuations by molecular diffusion. The overbar indicates a long-time average, the primes a deviation, and the integrals are taken over the global ocean.

This remarkable relationship states that global-scale surface thermal forcing results in down-gradient eddy stirring that cascades thermal variance from global scales through a range of intermediate scales to the Batchelor scale (typically cm), where dissipation occurs. Joyce (1980) used zonal averages of surface heat flux and temperature to estimate the average microscale dissipation to be approximately $10^{-7}$ K$^2$ s$^{-1}$. Schneider and Bhatt (2000) used more detailed surface flux estimates and integrated over water classes bounded by isotherms to obtain estimates of dissipation and diathermal eddy diffusivity as a function of temperature, yielding diffusivities of $1-3 \times 10^{-5}$ m$^2$ s$^{-1}$ for all but the warmest waters, and dissipations ranging from $1-20 \times 10^{-8}$ K$^2$ s$^{-1}$, in accord with modern microstructure observations. Stern’s power integrals constrained interior mixing in terms of surface forcing, but say nothing about the cascade of variance from global scale to microscale.

Many physical mechanisms, isopycnal and diapycnal, may be involved in this cascade, and a quantitative picture is still evolving. Large-scale thermal contrasts produced by global-scale forcing are stirred isopycnally by ocean currents and mesoscale eddies, producing thermohaline fronts and features with lateral scales of a few km and vertical scales of a few hundred m (Arhan and King, 1995; Klein et al., 1998). Fine-scale processes (several to hundreds of meters vertical scale) such as internal waves (Garrett and Munk, 1979), vortical modes (Sundermeyer et al., 2005), thermohaline intrusions (Stern, 1967), and single thermohaline inversions or “filaments” produced by isopycnal stirring (Woods et al., 1986), may act as intermediate steps in the cascade to molecular dissipation. Although the individual processes have been studied, their relative roles have not been explored.

### a. Eddy stirring

Woods et al. (1986) show high-resolution towed CTD observations of a single ~10 m × 6 km intrusion (we prefer “filament”) in the North Atlantic Polar Front, apparently produced by isopycnal stirring during frontal meandering. They simulated this feature in a frontogenetic model that created a thermohaline front, followed by instability that folded the isothermal surface in a three-dimensional fashion. They showed that such stirring can produce (individual) features that slope relative to isopycnals, a characteristic that had been claimed for thermohaline intrusions.

Isopycnal stirring of large-scale thermohaline gradients causes downgradient heat transport and cascades thermal variance from large scales through submesoscales, producing thermohaline fronts with weak density signature (Klein et al., 1998; Smith and Ferrari, 2009). Eigenvalue analysis of the velocity gradient tensor (Okubo, 1970; Klein et al., 1998) shows that fronts tend to develop at the periphery of eddies and near the saddle points between them (also demonstrated in the laboratory and numerical experiments discussed in Section 3a, in which strong vortex interactions can create “spiral arm” features with azimuthally-wrapped features). Their width, observed to be a few km (Arhan and King,
1995; Ledwell et al., 1998), reflects a “Batchelor-like” balance between strain rate and the effective rate of lateral mixing (Smith and Ferrari, 2009; Ledwell et al., 1998). Vertical shear tilts the fronts, producing laminae (“filaments”) that might then be mixed diapycnally. The three-dimensional stirring described by Klein et al. (1998) and Smith and Ferrari (2009) could then cascade lateral thermal variance through vertical mixing to the dissipation scale, although the limited vertical resolution in their model did not allow this possibility to be directly assessed. Density features produced by this isopycnal stirring were extremely weak because the thermal and haline filaments were almost completely compensating. Smith and Ferrari’s (2009) simulation of the isopycnal production of thermal variance in the NATRE region (Ledwell et al., 1998) produced thermohaline anomalies similar to those observed, and showed that the rate of production equals or exceeds the observed microscale dissipation.

b. Eddy instabilities

Otheguy et al. (2006) investigate the zigzag instability of a pair of vortices from the strongly stratified to the strongly rotating limit. They find (their Fig. 2) that for $Ro = \omega_c/f \leq 1$, where $\omega_c$ is the core vorticity of the vortex and $f$ the Coriolis parameter, the wavenumber of the fastest growing zigzag instability $k_{zm} = 2\pi/D$, scales as (Dritschel and de la Torre Juarez, 1996) $k_{zm} = 1.74b(f/N)$, where $b$ is the vortex pair horizontal spacing, and $N$ the buoyancy frequency. The approximation is valid for Meddies which have $Ro \sim 0.35$ (Hebert et al., 1990). Taking $f/N \sim 1/100$ and the minimum $b$ to be 20 km, smaller than the core radius of a Meddy, we find the vertical wavelength $D = 3.6b(f/N) = 700$ m, comparable to a Meddy core thickness. It would thus, therefore, appear that zigzag instability is not the primary cause of the $\sim 25$ m thermohaline intrusive features found at the edge of Meddies (Ruddick and Hebert, 1988), but the possibility of a combined thermohaline-zigzag instability cannot be ruled out.

Baroclinic and barotropic instabilities can act to produce mesoscale structures, but have only been suggested as a cause of mesoscale fine structure in combination with double-diffusive diapycnal mixing, as described in the next subsection.

c. Thermohaline intrusions

Almost any oceanic temperature and salinity profile contains multiple coincident temperature and salinity inversions typically 2–200 m in thickness (Ruddick and Richards, 2003), indicative of lateral thermohaline intrusions that transform lateral temperature gradients to vertical. Stern (1967) developed an instability theory that showed how lateral intrusions could be driven by salt finger flux convergences. The theory was groundbreaking because, in addition to discovering a new mechanism to drive lateral fluxes, Stern’s vertical diffusivity parameterization (linking the heat flux to the salt flux via a flux ratio) incisively captured the major effect of salt fingers, allowing more complex and complete instability analyses (reviewed in Ruddick and Kerr, 2003) and could be extended to diffusive stratification. Stern also clearly showed that turbulent mixing alone, with equal turbulent diffusivities for salt and heat, cannot drive intrusions. The clarity of Stern’s (1967) paper, along with laboratory
experiments demonstrating the mechanism (Turner, 1978; Ruddick et al., 1999), created focus on double-diffusive mixing as a likely cause of thermohaline intrusions, potentially linking lateral thermohaline gradients to microscale dissipation. Intrusion instability theories predict multiple inversions with a clearly definable scale and a slope nearly parallel to isopycnals that can be related to the fluxes of heat and salt driving them. Observations of intrusions generally exhibit the predicted structure; for example Ruddick and Hebert (1988) found a definite 25-m spectral peak in the Meddy “Sharon” intrusions, and Ruddick (1992) found intrusions to have small slopes that could only be identified with careful T-S analysis in closely-spaced stations.

Other work finds that thermohaline intrusions may be much more complex than Stern’s original model. McIntyre (1970) found an intrusion-like instability of a baroclinic vortex involving differential diffusion of mass and angular momentum. Ruddick (1992) tracked thermohaline features from a detailed tow-yo in Meddy Sharon and concluded that the observed intrusion slopes were outside those allowed by the pure McIntyre mechanism. While potential energy release associated with baroclinicity (McIntyre, 1970; Ruddick, 1992; May and Kelley, 1997; Kuzmina and Rodionov, 1972) was found to affect intrusion properties, steeply sloping double-diffusive/baroclinic intrusions were not found. Intrusion properties can be affected by the combination of turbulence and double-diffusion (Smyth and Ruddick, 2010; Kuzmina and Zhurbas, 2000), and equatorial intrusions that were tracked over large lateral distances (Richards and Pollard, 1991; Richards, 1991), may be affected by kinetic energy release via a combined double-diffusive-inertial instability (Edwards and Richards, 1999; Richards and Banks, 2002). Without definitive parameterizations of turbulent and double-diffusive diffusivities for heat, salt, and momentum, and without an understanding of finite-amplitude thermohaline intrusions, predictions of intrusive properties and fluxes will be difficult, even with numerical models offering fine-scale resolution (Ruddick and Kerr, 2003).

Although some of the above instabilities can produce steeply-sloping features, most instability modes have small slopes. Virtually all observed intrusions that have been tracked by connecting their thermohaline properties have slopes relative to isopycnals that are significantly smaller than $f/N$ (Ruddick, 1992; Edwards and Richards, 1999; and Arctic Ocean intrusions discussed by Carmack and others, reviewed in Ruddick and Richards, 2003). Furthermore, previous seismic images of Meddies (Pinheiro et al., 2009; Biescas et al., 2008) exhibit multiple reflectors with small slope and vertical scale of several 10’s of m, features consistent with observations of Meddy intrusions (Ruddick 1992; Ruddick and Hebert, 1988). We thus classify “thermohaline intrusions” as multiple inversions expected to have slopes smaller than $f/N$, and “filaments” as individual inversion features. Thus thermohaline intrusions result from instabilities similar to those reviewed in Ruddick and Kerr (2003) while filaments are dynamically generated by eddy stirring and instabilities in the presence of lateral thermohaline property gradients.

The kinematic model of thermohaline intrusive mixing by Joyce (1977) argues that lateral intrusive fluxes $\overline{F} = (\overline{u} \overline{T})$ convert large scale lateral gradients ($\nabla \overline{T}$) to intrusion-scale
vertical gradients $\left( \frac{\partial \tilde{T}}{\partial z} \right)$ that are mixed with diapycnal eddy diffusivity $\tilde{K}_{VT}$. Here the overbar is taken to be an average over scales larger than intrusive, and the tilde represents intrusion-scale structure. This model makes no assumptions about the type of vertical mixing, which might be turbulent, double-diffusive, convective, or any combination. Joyce (1977) showed that lateral intrusive production of variance creates vertical production, resulting in molecular dissipation, $\chi$ (defined below Eq.1):

$$\tilde{F} \cdot \nabla \tilde{T} = \tilde{K}_{VT} \left( \frac{\partial \tilde{T}}{\partial z} \right)^2 = \chi.$$  

Joyce’s model allows lateral intrusive fluxes to be estimated by assuming a diapycnal eddy diffusivity (Joyce et al., 1978) or by use of microstructure observations (Gregg, 1975; Alford et al., 2005; Ruddick et al., 2010). Although not explicitly stated, lateral fluxes due to filaments are included in Joyce’s model.

d. Meddies

Anticyclonic eddies, with a near-homogeneous core of Mediterranean Undercurrent water (Ambar et al., 2002) called “Meddies,” are commonly found in the eastern North Atlantic and can retain their anomalous properties for years, altering dispersal characteristics from traditional eddy stirring (Richardson et al., 2000). Armi et al. (1989) followed Meddy “Sharon” for two years and found that the core properties remained constant while the Meddy became smaller due to lateral erosion. This erosion occurred in the thermohaline front at the Meddy periphery, a region dominated by thermohaline intrusions with vertical scale of $O(25 \text{ m})$. Ruddick et al. (2010) analyzed microstructure observations from Meddy “Sharon,” comparing the radial/depth distribution and integrals of microscale thermal dissipation with the observed Meddy erosion rate. They concluded that the Meddy mixed via thermohaline intrusions near the Meddy front, and that the lateral intrusive production (leftmost term in Eq. 2) was dissipated locally (rightmost term) in a manner consistent with the Joyce (1977) model, giving a model that allowed lateral intrusive flux to be estimated from microstructure observations. Thus, lateral intrusions were a key link in the variance cascade involving Meddy “Sharon.” They note, however, that since the heat and salt content of the Meddy decreased over time, a nonintrusive mechanism such as mesoscale stirring must transport the heat and salt beyond the intrusive zone. Their Figure 4b shows a “burst” of high thermal dissipation as well as significant temperature finestructure at 53 km radius, features that they suggested could be part of the Meddy’s “salty trail.”

e. Other finescale processes

The possible roles played by internal waves (diapycnal mixing, internal wave-driven shear dispersion, and generation of vortical modes from collapse and adjustment of mixed regions) were discussed by Smith and Ferrari (2009). While these pathways may be important in
the variance cascade, only diapycnal mixing, intrusions, and filaments will be considered in this paper.

f. New tools to study the variance cascade

Questions arise as to how much mixing occurs beyond the frontal zone of Meddies, what causes it, and the relative roles of frontal intrusions and mesoscale stirring. These cannot currently be answered with microstructure observations because they are sparse and highly variable, and their locations tend to be biased because microstructure surveys are usually part of a focused experiment. CTD observations can be used to quantitatively map thermohaline fine structure, but the nonsynoptic nature and relatively wide spacing of CTD casts requires careful statistical analysis (e.g., Ferrari and Polzin, 2005).

The discovery by Holbrook (2003) that multichannel seismic techniques (MCS) can synoptically visualize water column reflectors with O(10 m) vertical and horizontal resolution gives a flow visualization tool analogous to the Schleiren technique that shows refractive index gradient in laboratory fluid experiments. Water column MCS gives detailed images of fine structure temperature gradients smoothed on the O(10 m) scale of the seismic source wavelet (Ruddick et al., 2009) and these features may be coherently tracked over large horizontal distances. Features like fronts, eddies, currents, and Meddies are outlined by the impedance contrasts of their associated thermohaline fine structure, allowing us to visualize the relationship of fronts, tendrils, filaments and intrusions to these features, thus giving highly resolved information on the relative roles of stirring and intrusive mixing.

In this note, we use seismic imaging as a form of flow visualization to “see” where the mixing tends to occur in a newly discovered Meddy, the relationship of this mixing to mesoscale features, and to use spatial characteristics of the visualized reflectors in an attempt to determine mixing mechanisms. We conclude that Meddy mixing proceeds as has been found by conventional means (Armi et al., 1989; Ruddick et al., 2010), but that tendrils of Meddy water containing thermohaline intrusions can be seen for 10s of km beyond the edge of a Meddy. We further conclude that, far from the Meddy, intrusive mixing may partner with eddy stirring (Smith and Ferrari, 2009) such that significant thermal variance may pass through thermohaline intrusions enroute to thermal dissipation.

2. Data acquisition and methods

A series of deep (25.6s Two-Way Travel Time - TWT), high quality, multichannel seismic reflection profiles, combined with refraction and wide-angle data, were acquired off west and south Iberia in the scope of the Iberian Atlantic Margins (IAM) Project, under the JOULE programme funded by the European Commission, in 1993 (EEC Contract #JOU2-CT92.O177; Pinheiro et al., 2009). A total of 20 multichannel seismic reflection profiles, covering a total distance of 3585 km, were acquired under contract by Geco-Prakla, using the RV Geco Sigma, between August and October 1993. A 4.8 km long analog streamer, with 192 channels and a group interval of 25 meters was used, towed at an average depth of
15 m. The shot interval was 75 m and the recording sampling rate was 4 ms. The near offset was 254 m. The seismic source used consisted of a 36 airgun array with a total volume of 7524 ci. The navigation system included DGPS (SKYFIX) and TRANSIT (MAGNAVOX) and the average acquisition speed was 4.6 knots. The data were recorded using a DFS V/GDR 1000 acquisition system and the field data were recorded in SEG-D Demultiplexed format.

The seismic line GB3 (Fig. 1) extends from 36° 56’ 10.77”N; 12° 22’ 14.69”W, in its southwestern end, to 37° 16’ 36.67”N; 9° 22’ 27.97”W, in the northeast. It crosses a majority of the Tagus Abyssal Plain and the lower continental slope of W. Iberia Margin. It was acquired from southwest to northeast, from the 9th till the 10th of September. Line GB3 was a 226.5 km long seismic line with a total of 3021 shots generated with an interval of 75 m.

The seismic processing flow, similar to Pinheiro et al. (2009), includes geometry definition, direct-wave suppression, common mid-point (CMP) sort to 12.5 m CMP spacing, velocity analysis, normal moveout (NMO) correction, stacking and migration. Divergence corrections are made and complex trace analysis used as for studies of gas hydrate bottom simulating reflections (Song et al., 2001, 2007). Principles, limitations and technical terms of multichannel seismic water column imaging are described in Ruddick et al. (2009).

3. A previously undiscovered Meddy

In the stacked seismic image of Figure 2, a large, well-defined lens-like structure is observed in the southwestern part of Line GB3, extending from the southwestern end to
Figure 2. Stacked seismic section showing detail of suspected Meddy and multiple features to the east of the Meddy. Horizontal scale: 2000 CMP = 25 km. Vertical scale: 3000 ms TWT = 2250 m depth.

CMP 7000, a distance of about 75 km. It is about 1200 m thick, and centered near 1000 m depth.

This feature has the size, thickness, depth, shape and general appearance characteristic of Meddies that have been conventionally observed (Armi and Zenk, 1984, Richardson et al., 2000) and seismically imaged (Biescas et al., 2008; Pinheiro et al., 2010). One of the features imaged by Pinheiro et al. (2010) was confirmed to be a Meddy by float tracks and sea-surface height and temperature imagery. There is a near-complete lack of reflectors in the center of the feature, similar to the observations of Armi et al., (1989) except for some near-horizontal reflectors near 950-m depth, likely the boundary between the upper and lower Mediterranean Water cores known to form Meddies (Ambar and Howe, 1979a,b). The reflectors near top and bottom of the feature are consistent with double-diffusive layering, with slope parallel to isopycnals, which follow the core as can be seen in Figure 4a of Armi et al. (1989), and those near the edge consistent with thermohaline intrusions, having relatively weak slope and vertical separation of a few tens of m (Armi et al., 1989).

In Figure 3 the decrease in acoustic wave amplitude due to spherical spreading is compensated for (divergence correction) and the squared amplitude of return is plotted, along with individual “wiggle” traces to allow some details to be observed. Although seismic data acquisition and processing are known to distort amplitudes, the image in Figure 3 is a rough approximation to \( (\frac{dI}{dz})^2 \) which, according to the central term of Eq. 2 is an indicator of intrusive mixing intensity. This mixing “proxy” is strongest near the sides and top of the feature, weaker and more diffuse near the bottom, and virtually absent in the core, similar to the pattern found by Ruddick et al. (2010, their Fig. 4b).
Figure 3. Divergence-corrected stacked seismic section, with computed mean square return amplitude, argued in the text to be related to mixing rate. Color bar indicates mean square reflector amplitude; selected individual stacked traces show detail of the square of reflector amplitude. The aspect ratio is slightly different from Figure 2.

a. Spiral Arms or “salty trail”

The zone to the northeast of the Meddy in Figure 2 (75–110 km) shows an “onion-like” structure in which regions of more intense reflections alternate with regions of weaker reflections. The reflectors are nearly horizontal, with thickness consistent with thermohaline intrusions, in bands of width of about 10 km and vertical extent similar to that of the Meddy. We suggest that these bands of reflectors may be tendrils of intrusion-laden water removed from the periphery of the Meddy and wrapped around it – we may be seeing spiral arms of incompletely mixed Meddy water made visible by thermohaline intrusions.

Spiral arms are commonly observed in laboratory (e.g., van Heijst et al., 1991) and numerical (e.g., Brandt and Nomura, 2010) experiments on vortex instability and merging, and can in particular (Fig. 4a) be seen in laboratory simulations of a Meddy (a homogeneous intrusion of low vorticity water into rotating stratified fluid) by Hedstrom and Armi (1988, their Fig. 17). Figure 4b, from the a video of the experiments of Brickman and Ruddick (1990), shows an anticyclonic baroclinic eddy in an external strain field, in which tendrils of frictionally influenced fluid are being drained from the lens. Figure 4c from van Heijst et al. (1991) shows a cyclonic vortex that has undergone instability and formed a vortex tripole, wrapping the vortex material that was originally in
Figure 4. (a) Anticyclonically rotating non-double-diffusive Meddy observed 406 rotation periods after formation, showing multiple spirals of material shed from the equator of the Meddy (Hedstrom and Armi, 1988). (b) Anticyclonic vortex in a barotropic strain field generated by two sources and two sinks located just beyond the corners of the figure (Brickman and Ruddick, 1990). Frictionally influenced fluid is drained from the vortex by the strain field, stabilizing the lens. (c) Cyclonic vortex that has spread due to friction, undergone instability, and formed a vortex tripole. Anticyclonic vortices behave similarly. (Figure from van Heijst et al., 1991.) (d) Spiral arms formed by merger of two cyclonic vortices (figure courtesy of Gert-Jan van Heijst).

the outer fringe into a pair of spirals. Figure 4d, from the beautiful web-site of Gert-Jan van Heijst (http://web.phys.tue.nl/nl/de_faculteit/capaciteitsgroepen/transportfysica/ fluid_dynamics_lab/research/vortex_dynamics/interact/merging/), shows the result of the merger of two cyclonic vortices (Trieling et al., 2005), in which the material from one vortex becomes wrapped around the other. Anticyclonic lenses undergo the same processes shown in Figure 4c and 4d, but the visualization in these images is exceptionally clear. The common thread in all of these experiments is that material removed from the eddy periphery is wrapped around the eddy by the circulation external to the core.

Shapiro et al. (1995) document a “salty trail” apparently removed from Meddy “Irving” during passage through a narrow channel between seamounts; despite the loss of 20–27% of the heat and salt in the collision, the Meddy retained its structure. Ruddick et al. (2010) noted a burst of thermal dissipation and an excess of thermal fine structure in the region beyond the intrusive frontal zone of Meddy “Sharon” and suggested that salt and heat are likely removed from this region by eddy strain. Hence, both laboratory and observational evidence suggests that salty tendrils of Meddy water could be found near a Meddy.

4. Stirring and mixing: Intrusions, tendrils, or both?

The full stacked and divergence-corrected MCS section is shown in Figure 5, allowing the structure and relative intensity of reflectors in the Meddy core and edge to be compared with reflectors from the main thermocline outside the Meddy. Ruddick et al. (2009) created synthetic seismogram traces from CTD casts taken near Meddy “Sharon” and analyzed the relative contributions of thermal, haline, and density fine structure. They found that 99% of the reflectivity was from thermohaline fine structure (about 82% from thermal and 17% from haline fine structure almost perfectly correlated with temperature), with only 1%
contribution from density variations. Sallares et al. (2009) and Biescas et al. (2008) similarly found that density fluctuations were negligible compared with thermohaline fluctuations in their contribution to reflectivity. Comparison of the reflectors in the depth range 500 m – 1800 m from Figure 5a (outside the Meddy core) and 5b (where eddy stirring is thought to occur) shows reflectors of similar intensity, indicating that the reflectors in Figure 5b are thermohaline in origin. Smith and Ferrari (2009, their Fig. 6) show that density fine structure produced by eddy stirring in a thermohaline gradient is one or more orders of magnitude weaker than thermohaline fine structure. Combining this result with the analysis of Ruddick et al. (2009) suggests that the reflectors in Figure 5b are almost completely associated with thermohaline fine structure.

Because thermohaline reflectors tend to have small slopes relative to isopycnals, it is sometimes possible to estimate the slope spectrum of isopycnals by tracking seismic reflectors and computing reflector slope spectra (Sheen et al., 2009). However, as noted in Pinheiro et al. (2010), a few “steeply dipping” reflectors with slopes of order $f/N$, steeper
than allowed for thermohaline intrusions, can be seen in the vicinity of mesoscale features, so this connection is not unequivocal.

Smith and Ferrari (2009) suggest that eddy strain acts on lateral thermohaline gradients to produce sharp fronts that are tilted by mesoscale vertical shear. They predict sharp features from this stirring with slope of $O(f/N) \sim 0.01$ where $f = 8.8 \times 10^{-5}$ s$^{-1}$ is the Coriolis frequency, and $N = 7.4 \times 10^{-3}$ s$^{-1}$ is the buoyancy frequency estimated from CTD casts in the region. An example of the predicted salinity structure from numerical simulations is shown in their Figure 10b, which shows a two-dimensional cut through their model domain, analogous to the seismic section. Seismic reflectivity structure is expected to look like the vertical derivative of salinity because fine scale salinity gradient is closely proportional (correlation coefficient 0.997) to fine scale temperature gradient, which combine to create sound impedance variations with less than 1% contribution from density variations (Ruddick et al., 2009).

Figure 5a shows that the Meddy has aspect ratio approximately $f/N$, consistent with the model of Gill (1981) and experiments by Hedstrom and Armi (1988), who find that a homogeneous low vorticity intrusion into a stratified fluid has an aspect ratio proportional to $f/N$ at any Rossby number. Figure 5b images reflectors in the region between the Meddy and the Portuguese continental slope. Instead of individual sharp, tilted reflectors as predicted by Smith and Ferrari, Figure 5b shows multiple parallel reflectors with slope significantly less than $f/N$, with vertical periodicity of about 50 m, and with undulations that are likely due to internal wave motions. The only reflectors with slopes near $f/N$ are those near the top and bottom of the Meddy (following the core), in the tendrils, and a set of reflectors in the northeast, near 190 km. This latter set of reflectors is at the correct depth ($\sim 1500$ m) and approximate location to be consistent with the Mediterranean Undercurrent, as was discussed in the IAM-5 section by Pinheiro et al. (2010). The remaining reflectors are more consistent with thermohaline intrusions than sloping tendrils created by stirring and shear.

It is possible that both eddy stirring and thermohaline intrusions take part in the variance cascade, with lateral stirring producing fronts with width $\sim 10$ km and thermohaline intrusions acting upon those fronts to convert strong lateral gradients to strong vertical gradients, which are then acted upon by double-diffusion and turbulent mixing before finally being dissipated. This scenario is closely related to the possibility discussed in Smith and Ferrari (2009, particularly scenario 1 in their Section 7) that vertical mixing may not be passive.

In seismic surveys that are augmented by temperature or temperature/salinity profiles, it is possible to combine the seismic and profile observations to obtain accurate high resolution sections of temperature and salinity (Papenberg et al., 2010; Kormann et al., 2011). Such techniques could extend the points made here to more detailed comparison with model predictions by giving simultaneous high-resolution images equivalent to salinity, temperature, and seismic reflectivity. This would allow detailed comparisons between model and seismically-observed sections, with statistical and spectral comparison of intensities and slopes (Cole and Rudnick, 2012).
5. Summary and discussion

The high resolution and strong lateral coherence of the multichannel seismic images of a Meddy and the waters of the Iberian Basin allow several conclusions to be made that relate to Stern’s cascade of thermal variance:

1. The Meddy core has relative absence of fine structure, but has strong fine structure at the surrounding front.
2. The Meddy has spiral arms beyond the Meddy front that is rich in thermohaline intrusions, consistent with a “salty trail” of water that is still mixing into the background.
3. Reflectors outside the Meddy and spiral arms, with the exception of those near what we interpret as the Mediterranean Undercurrent, appear more like thermohaline intrusions than sloping tendrils associated with stirring.

Thus, Stern’s variance cascade is blocked in the Meddy interior, with relatively little mixing. The surrounding front and nearby tendrils, however, compensate for this, with strong mixing via thermohaline intrusions, and the likelihood of long-distance transport of Meddy core water with the Meddy (Armi et al., 1989). In regions away from Meddies, where the Smith-Ferrari cascade is expected to operate, we see near-horizontal, vertically periodic, intrusion-like structures rather than individual, sloping, sharp features. It is a testament to Melvin Stern’s brilliance and overview just how many of the phenomena involved here were illuminated by his work: solitary vortices (Stern, 1975), eddy stirring (Stern, 1987), thermohaline intrusions (Stern 1967), double-diffusion and salt fingers (Stern 1960, 1975a), and of course the variance cascade (Stern 1975a). Melvin Stern knew all along just how closely the scales and phenomena of the ocean are intertwined.

Acknowledgments. BRR has long been in awe of Melvin Stern’s insightful way of stripping all that isn’t necessary from a model. His brilliant “power integral” equations caused many nights of lost sleep, and will hopefully cause many more. The authors gratefully acknowledge the European funded GO Project (Geophysical Oceanography—FP6-2003-NEST15603), which enabled the authors to undertake this and other collaborations. HB Song’s research was co-financially supported by the National Major Fundamental Research and Development Project of China (No. 2011CB403503) and China NSF(No. 41076024). BR acknowledges support from Canada’s Natural Sciences and Engineering Research Council, and specifically wishes to thank Larry Armi for fun and fruitful collaborations investigating Meddy “Sharon,” and for many honest, helpful and encouraging suggestions over many years. We thank Rudolf Kloosterziel and GertJan Van Heijst for permission to reproduce some of their stunning experimental images of vortices and for their helpful comments. We thank Michael Waite for valuable comments relating to vortex instabilities. And finally, the comments of two reviewers helped immensely to improve this manuscript.

REFERENCES


Received: 6 May, 2011; revised: 22 December, 2011.