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Circulation, Hydrographic Structure and Mixing at Tidal Fronts: The View from Georges Bank [and Discussion]

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Circulation, hydrographic structure and mixing at tidal fronts: the view from Georges Bank

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The steep slope on the northern side of Georges Bank and its location in the Fundy–Maine tidal system result in a persistent summertime frontal system comprising a tidal-mixing front and a stratified tide-topography interaction at the Bank edge. Recent field studies have provided a high-resolution description of the circulation, hydrographic structure and mixing in the region. Frontal features include an along-front residual jet, a surface convergence zone, regular variations in frontal structure and position over the tidal period and tidal modulation cycle, large-amplitude internal waves, and strong spatial and temporal variations in small-scale turbulence. The observations suggest that the magnitude of cross-front and vertical exchange in frontal regions can be site-specific depending on the relative importance of the underlying physical processes.

1. Introduction

Tidal-mixing fronts – the transition zones from mixed to seasonally stratified waters – are prominent and persistent hydrographic features of tidally-energetic shallow seas in summer (see, for example, Simpson 1981). The circulation and mixing at these fronts are important to both local processes (e.g. biological productivity) and the larger-scale distribution of materials and water properties. Although substantial progress has been made in recent decades towards understanding frontal physics and its implications, many fundamental questions remain (see, for example, Hill *et al.* 1993). These include the rates of vertical transfer in the vicinity of frontal zones, and the dominant mechanisms and rates of cross-front (horizontal) exchange. Indeed, it is not clear whether the presence of tidal-mixing fronts results in enhanced or reduced horizontal exchange in shallow seas.

While much of our understanding of tidal-mixing fronts has come from pioneering studies on the northwest European shelf, valuable insight into the basic processes can be gained from fronts elsewhere. The pronounced frontal system around Georges Bank on the northwestern Atlantic shelf is such an example, in that the Bank's abrupt bathymetry results in physical phenomena with strong signals (as well as considerable nonlinearity). Here we present an overview of results from the 1988–1989 Georges Bank Frontal Study in which high-resolution observations of hydrography, currents and microstructure were obtained in the vicinity of four mooring sites across the Bank's northern side (figure 1*a*) during June–October. For further detail on the observations, the reader is referred to the component papers from the study (see references throughout).

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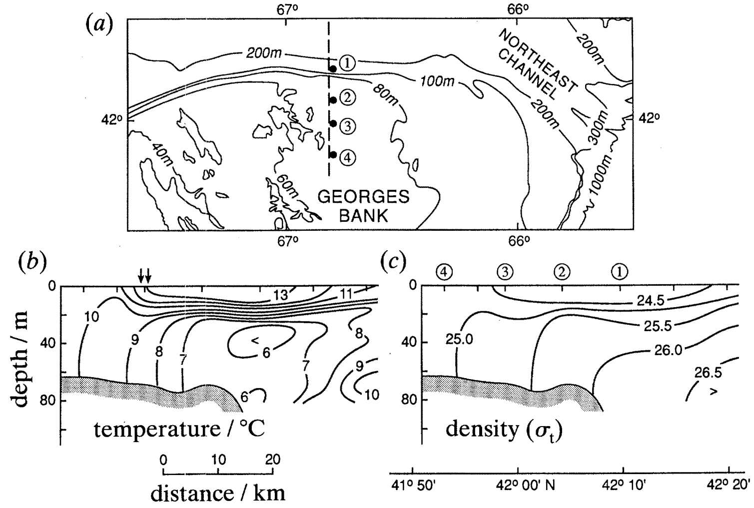

Figure 1. (*a*) Study area showing the principal study line (dashed) and mooring sites (circled numbers). (*b*) Temperature and (*c*) density distributions from a CTD section on 3 July 1988. The original profiles (fig. 3 of Loder *et al.* 1992) have been computationally adjusted to the time when two surface drifters (positions indicated by arrows in (*b*)) were crossing the line.

In §2 the hydrographic structure of the frontal system is described, including the occurrence of large-amplitude internal waves. The circulation in the frontal region is summarized in §3, with particular attention to surface convergence detected with lagrangian drifters. In §4 the spatial and temporal structure of small-scale turbulence is presented from repeated drops of the profiler EPSONDE (Oakey 1988), while conclusions and implications are summarized in §5.

2. Hydrographic setting

(*a*) *Frontal structure and position*

The structure of the frontal system on northern Georges Bank in early summer is illustrated in figure 1 derived from CTD stations along the principal study line. A classic tidal-mixing front, with temperature making the dominant contribution to density structure, is apparent on the Bank plateau. Over the side of the Bank below the surface layer, salinity differences between Bank and Gulf of Maine waters are the primary contributors to density structure (Loder *et al.* 1992), so that the system is a hybrid of tidal-mixing and shelf-break (bank-edge) fronts.

The position of the tidal-mixing front on northern Georges Bank in early summer lies between the 60 and 80 m isobaths, within a tidal excursion of that expected from the Simpson & Hunter (1974) depth/dissipation criterion (Loder & Greenberg 1986). The moored measurements on the study line reveal that stratification in the frontal zone on the Bank plateau increases through the summer, with a distinct monthly variation which is closely related to the dominant monthly modulation of the tidal currents (figure 2). These observations imply that particular isolines of vertical temperature difference undergo monthly and seasonal displacements of 10–20 km along the mooring line (Loder *et al.* 1993). This is clear evidence for the elusive tidal-modulation variation in frontal position hypothesized in European shelf studies (see, for example, Pingree *et al.* 1977; Simpson & Bowers 1979).

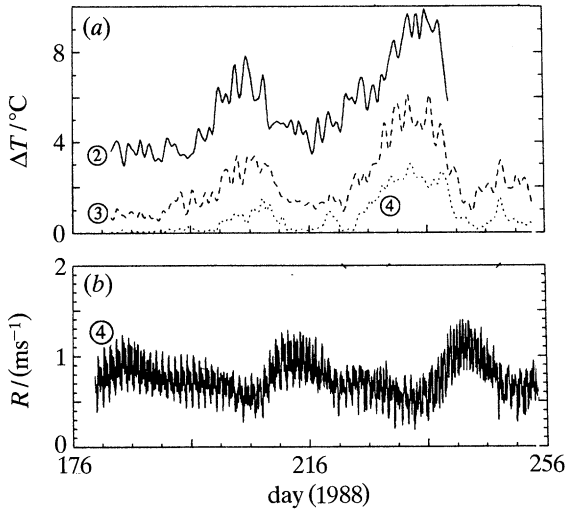

Figure 2. (*a*) Vertical difference (11–64 m) in de-tided temperature (ΔT) at the three mooring sites (circled numbers) on the Bank plateau during June–September 1988. (*b*) Current speed (R) measured at 11 m below surface at site 4.

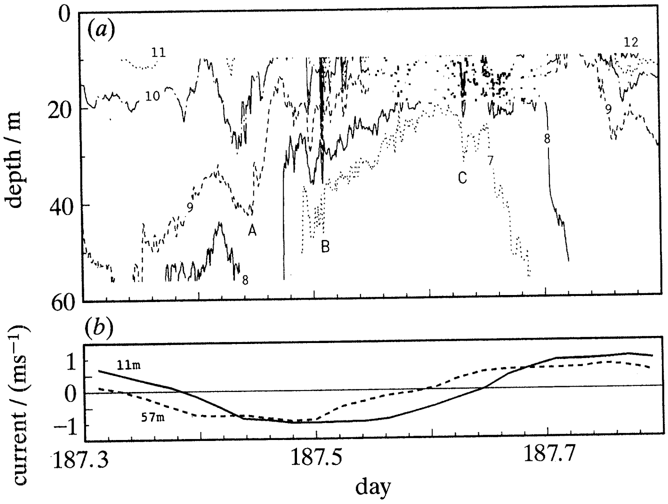

Figure 3. (*a*) Depth of isotherms (7–12 °C) from thermistor chain observations at site 2 on 5 July 1988. The internal-wave depressions (A, B) which propagate onto the Bank during on-bank flow and the internal waves (C) which contributed to the large dissipation rates in the pycnocline (figures 7 and 8) are labelled. (*b*) Cross-bank currents (positive northward) at 11 m and 57 m at site 2.

A major contributor to instantaneous frontal position is advection by the barotropic tidal current. On northern Georges Bank the semidiurnal current amplitude is near 1 m s^{-1}, with major axis approximately normal to the front, so that the cross-front tidal excursion is 10–15 km. This advection results in large scalar variations in the eulerian reference frame (see, for example, Loder & Horne 1991), and continual deformation of the frontal structure over the tidal period, particularly over the Bank's side. For example, to obtain an approximate picture of instantaneous frontal structure, the hydrographic section in figure 1 has been obtained by

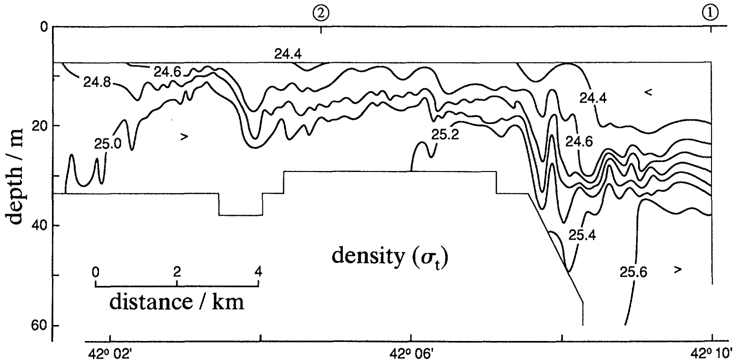

Figure 4. Density distribution from a Batfish section along the study line near the end of off-bank flow on 28 June 1988.

computationally advecting and stretching CTD profiles to a common time using (vertically averaged) measured currents. Tidal advection also provides a coupling mechanism between the tidal-mixing front and the Bank edge, resulting in the periodic movement of water parcels into different physical (e.g. mixing) régimes (Brickman & Loder 1993). The strength of this coupling varies with the monthly modulation and season, as the tidal excursion and position of the tidal-mixing front vary.

Barotropic tidal advection also causes a periodic variation in frontal structure over the tidal period (even on the Bank plateau), through tidal straining (Simpson *et al.* 1990) associated with the frictionally induced vertical structure in the phase of the cross-front flow. The tidal current's phase lead at depth results in isopycnal steepening (flattening) in the lower water column during the transition to flow towards the stratified (mixed) side, and hence steeper isopycnals during the peak flow towards the stratified side. In the eulerian view provided by a moored thermistor chain in the frontal zone (figure 3), this appears as an asymmetry in the tidal evolution of isotherm depth, with slower isotherm ascent during on-bank flow than descent during off-bank flow. This variability over the tidal period has potential implications for overall frontal structure (Allen *et al.* 1980) and the temporal variability of vertical mixing in the frontal zone.

(*b*) *Role of internal waves*

Another important feature of the frontal zone on northern Georges Bank (figure 3) is the occurrence of two soliton-like depressions propagating onto the Bank during most tidal periods (Brickman & Loder 1993). The depressions are generated when tidal flow off the Bank plateau is supercritical to internal gravity wave propagation and a pronounced internal hydraulic jump (height $\approx$ 30 m) develops near the Bank edge (Loder *et al.* 1992). As the flow reverses to on-bank, the jump evolves into the two on-bank propagating depressions and an internal wave packet propagating away from the Bank (see Lamb (1993) for a numerical model interpretation). Brickman & Loder (1993) computed a depth-integrated on-bank energy flux of 190 W m^{-1} for the two depressions, which is comparable to the on-shelf flux estimated for internal waves originating at shelf breaks elsewhere (Huthnance 1989). The internal waves on northern Georges Bank are illustrated (figure 4) in an undulating CTD (Batfish) section taken near the end of off-bank flow, which shows a mature depression from the preceding off-bank flow approaching the mixed-water boundary and two newly formed depressions near the Bank edge. It appears that these depressions dissipate either prior to (see §4), or upon, arrival at the mixed-water boundary.

The northern Georges Bank frontal system thus includes a stratified tide-topography interaction at the Bank edge which is further coupled to the tidal-mixing front via internal wave propagation. The hydraulic jump is a potential mechanism for vertical mixing at the Bank edge during off-bank flow, while the on-bank propagating depressions provide a regular energy source for mixing in the frontal zone (Brickman & Loder 1993). In both cases and in contrast to the expected vertical distribution of barotropic tidal dissipation, the mixing should be concentrated in the pycnocline where the potential energy demands are greatest and, for example, the vertical nutrient supply is most limited (Horne *et al.* 1989).

3. Frontal circulation

(*a*) *Eulerian residual currents*

The dominant feature of the low-frequency residual circulation on northern Georges Bank is a strong seasonally varying 'jet' along the Bank edge (Butman *et al.* 1987). Previous studies (see, for example, Loder & Wright 1985) have suggested that, in summer, this jet has major contributions from both topographic rectification of the barotropic tidal currents and baroclinic pressure gradients. Acoustic Doppler current profiler observations together with moored current measurements indicate a peak flow speed exceeding 0.5 m s^{-1} (at the Bank edge) with a total transport of 0.9 Sv† in early summer (Loder *et al.* 1992). The moored current and hydrographic measurements indicate that about half of the vertical shear in the low-frequency current near the Bank edge in July–August can be accounted for by 'thermal wind' associated with the frontal density field (Loder *et al.* 1993), consistent with the previous studies.

The residual current on northern Georges Bank is a major factor in the large-scale movement of water parcels and materials in the Gulf of Maine region, but an important question there and in other shallow seas is the extent of 'cross-front' exchange. Theoretical models (see, for example, James 1978) have suggested a two-celled circulation pattern and associated surface convergence in the cross-front vertical plane, which Garrett & Loder (1981) concluded was the leading cross-front exchange mechanism. The observational determination of the cross-front residual circulation in the study area on Georges Bank is confounded by two factors: the $O(1)$ ratios of the tidal excursion to the horizontal scales of the topography and frontal structure, resulting in significant Stokes velocities (see, for example, Loder & Wright 1985); and the diverging isobaths which make the appropriate choice of along- and cross-front coordinates difficult.

One approach to the latter difficulty is to use the semidiurnal eddy temperature fluxes from the moored current meters and the recent finding that, in the lower water column on the Bank plateau, such fluxes arise primarily from the advection of scalar gradients by the rotary (horizontal) tidal currents (Loder & Horne 1991). This results in 'skew eddy fluxes' which have the useful property of being directed along mean isolines of the corresponding scalar field (Middleton & Loder 1989). Using the eddy temperature fluxes at 10 m above bottom during the two-day period investigated in

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† 1 Sv = 10^6 m^3 s^{-1}.

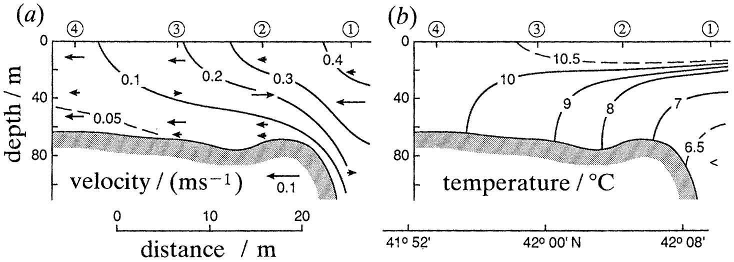

Figure 5. (*a*) Along-front (isotachs) and cross-front (vectors) mean currents, and (*b*) mean temperature from moored measurements over a 49.5 h period on 2–4 July 1988.

detail by Loder *et al.* (1992), the along-front direction at mooring sites 2, 3 and 4 (figure 1*a*) is found to be rotated clockwise by 26°, 28° and 36°, respectively, from the eastward 'along-isobath' direction at the Bank edge. When the mean currents from this period are presented in their local 'frontal' coordinate system (figure 5), features consistent with theoretical expectations are apparent on the Bank plateau. In addition to the along-front residual current extending across the frontal zone, the cross-front flow near the surface and bottom is towards the mixed side with a return flow towards the stratified side at mid-depth at sites 2 and 3, qualitatively consistent with a two-celled pattern. There are also suggestions of another process (perhaps tidal rectification) dominating the cross-bank flow over the Bank's side, and of a vertically averaged cross-front current of a few centimetres per second towards the mixed side in the frontal zone, but, like the entire cross-front flow pattern, this is sensitive to the coordinate system.

(*b*) *Near-surface lagrangian circulation*

The eulerian residual currents (with 10 km cross-front resolution) do not indicate near-surface convergence, but numerous cases of convergence were detected during the study using lagrangian drifters (Drinkwater & Loder 1993). In an example from early July during light winds, two satellite-tracked surface drifters released 3 km apart in the frontal zone upstream of the study line moved eastward at about 0.15 m s^{-1} and were recovered three days later less than 0.5 km apart in a visible convergence line (Loder *et al.* 1992). The CTD section in figure 1, which has been adjusted to a time when the drifters were crossing the study line, indicates that they were located in the high surface-gradient portion of the frontal zone where the surface-to-bottom density difference ($\Delta\rho$) was approximately 1 σ_t unit. Contemporaneous Batfish sections also indicate that the drifters were in positions of similar stratification, and that the on-bank propagating internal depressions may have played a role in the convergence.

A proper quantitative evaluation of convergence and other kinematic properties of the lagrangian flow requires resolution of the dominant tidal variation and hence temporal sampling at intervals of an hour or less. Later in the Georges Bank Frontal Study, this was obtained using LORAN-C drifters with a sampling interval of 0.5 h. An example of lagrangian drift and convergence obtained with these drifters in late July is shown in figure 6, where two drifters drogued at 10 m were released about 3 km apart across the mixed-water boundary (Drinkwater & Loder 1993). As the drifters spiralled eastward with highly harmonic trajectories, they quickly 'converged' after about two tidal periods and remained close together until their recovery a day later. The northern drifter was released and recovered near the

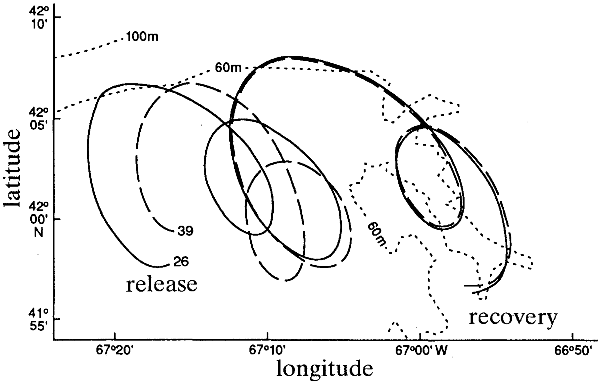

Figure 6. Trajectories of two LORAN-C drifters released west of the study area on 27 July 1989 and recovered together on 29 July 1989.

mixed-water boundary ($\Delta\rho \approx 0.2\ \sigma_t$), whereas the southern drifter moved from the mixed area ($\Delta\rho = 0.01\ \sigma_t$) into the boundary zone. A third drifter (not shown), deployed 4 km further north in more stratified water ($\Delta\rho = 0.95\ \sigma_t$), also moved into this zone.

The drifter studies have indicated that a number of mechanisms contribute to near-surface convergence on Georges Bank. In the examples above, it appears that the convergence was related to baroclinicity near the mixed-water boundary but, unlike the weak convergence predicted by steady diagnostic models (James 1978; Garrett & Loder 1981), it was highly time-dependent over the tidal period. Internal waves and horizontal (cross-front) shear in the along-front current may also have contributed to this convergence. Over the side of the Bank, there was a periodic current convergence/divergence associated with the stretching/collapsing of water columns during off/on-bank tidal flow. In addition, when strong winds disrupted the residual jet in fall and displaced drifter clusters onto the central Bank where there is complex small-scale bathymetry (figure 1*a*), drifters were often found in groups in spite of the expected dispersive effects from wind and tides. Clearly, when there are strong spatial gradients in the current field, as in frontal zones, the Euler–Lagrange transformation can be complex in spite of smooth temporal forcing.

4. Turbulence variability in the frontal zone

(*a*) *Temporal and spatial structure*

Tidal-mixing fronts exist because of horizontal differences in vertical mixing rates, so the magnitude and variability of these rates can be expected to be of critical importance to frontal processes in general. Observational and theoretical studies of bottom boundary layer structure in shelf seas have advanced our understanding of small-scale turbulence structure in regions of weak horizontal gradients (see, for example, Soulsby 1983; Dewey & Crawford 1988; Davies 1991), but the combination of strong spatial and temporal variability can result in considerable complexity at tidal-mixing fronts.

Initial velocity microstructure measurements in the upper water column on Georges Bank in 1985 revealed a strong temporal variation over the tidal period and increasing turbulent kinetic energy (TKE) dissipation rates with depth in the mixed area, as expected (Horne *et al.* 1993). In the frontal zone, dissipation rates were

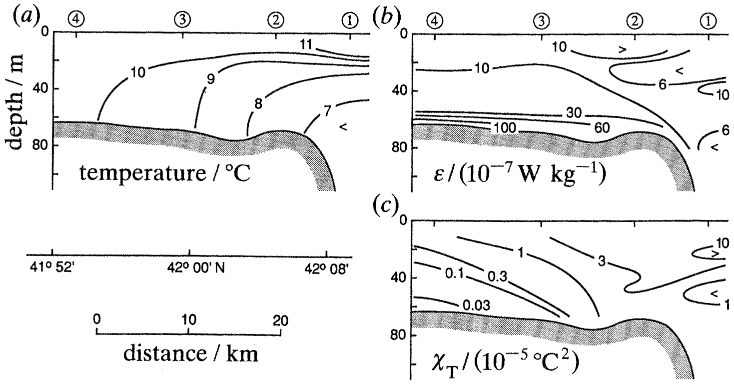

Figure 7. Cross-bank distributions of the mean value (over the 92 microstructure stations) of (*a*) temperature, (*b*) TKE dissipation rate, and (*c*) temperature variance.

about an order of magnitude lower than in the mixed area, with a less regular temporal and vertical structure.

A more extensive set of temperature and velocity microstructure profiles that extended to the seafloor was obtained during anchor stations over the tidal period near the four 1988 mooring sites (Oakey & Pettipas 1992). Here we consider the set of 98 approximately hourly stations (each comprising 5–8 profiles) obtained during light winds and moderate tides in late June and early July. The mean distributions (over all stations) of TKE dissipation rate (ϵ) and small-scale temperature variance (χ_T) show the expected features (figure 7): large values of ϵ near the seafloor and a general decrease towards the Bank edge, and general increases in χ_T towards the sea surface and stratified side. In addition, there are maxima in ϵ in the upper water column near the Bank edge (site 2) and at mid-depth over the Bank's side.

Further information on the local ϵ maxima and on the spatial and temporal structure of the microstructure was obtained by sorting the 98 microstructure stations into four tidal stages: peak on-bank and off-bank flows, and the intervening transitions (figure 8). On the Bank plateau, the average ϵ value changes by nearly an order of magnitude over the tidal period with largest values during on-bank flow (this variation is partly smeared in figure 8*a* by the sorting and averaging procedure). Over the Bank edge, the mid-depth ϵ values are about an order of magnitude larger during off-bank flow than during the other stages. Detailed examination of individual dissipation and concurrent CTD profiles (Oakey 1990) has confirmed that this enhanced dissipation was associated with the internal hydraulic jump (figure 4).

Furthermore, it can be seen that the ϵ maximum in the upper water column at site 2 (figure 7) resulted from a local maximum during the transition from on- to off-bank flow (figure 8*a*). Examination of individual ϵ profiles and the thermistor chain observations (figure 3) indicates that this maximum was associated with the dissipation of large-amplitude internal waves as the tide turned. In one case, the measured dissipation rates over 28 min and a 5 m vertical interval in the pycnocline accounted for about 2% of the total on-bank propagating (internal-wave) energy estimated by Brickman & Loder (1993). The apparently enhanced dissipation of the internal wave energy during the transition from on-bank to off-bank flow raises the possibility of an important influence of the barotropic tidal current's vertical shear (§2*a*) on the wave evolution, either directly or indirectly through reduced stratification.

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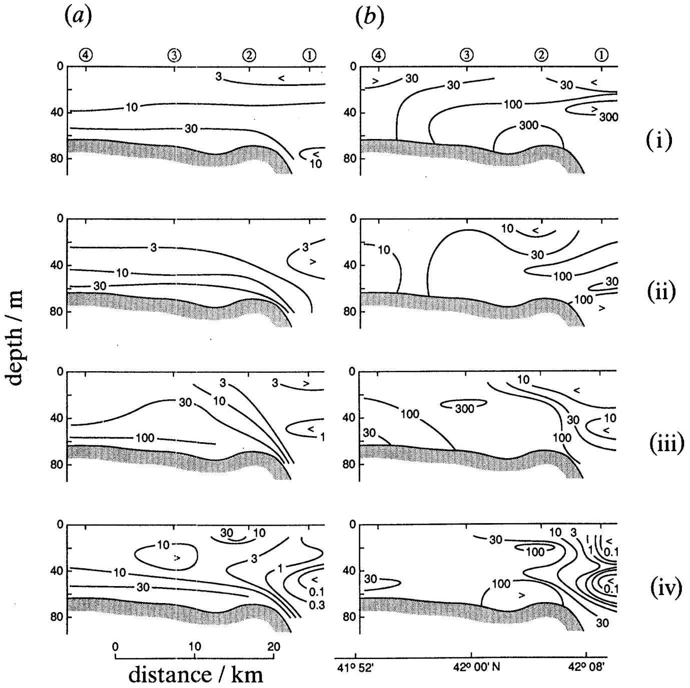

Figure 8. Temporal evolution over the tidal period of the cross-bank distributions of (*a*) TKE dissipation rate (ϵ (10^{-7} W kg^{-1})) and (*b*) the vertical eddy diffusivity (for heat) (κ_T (10^{-4} m^2 s^{-1})) computed from the temperature microstructure observations. The stations have been sorted into four tidal phases, using the cross-bank component of the vertically-averaged current at site 3 as an index. (i) Peak off-bank flow, (ii) off-bank to on-bank transition, (iii) peak on-bank flow, (iv) on-bank to off-bank transition.

This glimpse at the structure of TKE dissipation on northern Georges Bank suggests that internal waves can be of comparable (and perhaps greater) importance with small-scale mixing in the upper frontal zone as the barotropic tidal dissipation, in spite of the latter being much greater in a depth-integrated sense (Brickman & Loder 1993).

(*b*) *Vertical fluxes*

Direct measurement of turbulent fluxes (e.g. heat, nutrients) in the frontal zone is difficult. Indirect estimates can be obtained from the microstructure and ancillary measurements with assumptions about the dominant balances in the TKE and temperature variance equations.

The vertical diffusivities (for heat) can be estimated directly from the ratio of χ_T to the square of the mean temperature gradient (Osborn & Cox 1972). The variation over the tidal period of this diffusivity's structure in the cross-front vertical plane is illustrated in figure 8*b*. Values are generally in the range of $10\text{–}200 \times 10^{-4}$ m^2 s^{-1}, except for lower values over the Bank's side during the transition from on-bank to off-bank flow when the residual and tidal currents cancel (Loder *et al.* 1992). The diffusivity's spatial structure varies with tidal phase, with large values associated with the high ϵ in the hydraulic jump at the Bank edge (off-bank flow) and the breaking internal waves at site 2 (on-bank to off-bank transition), as well as in other parts of the frontal zone. Vertical diffusivities for density, estimated from ϵ and CTD profiles (Weinstock 1978), are generally within a factor of 2 of the thermal diffusivities at sites 1–3, but greater at site 4 (Oakey & Pettipas 1992). These differences and the considerable variability in both diffusivities presumably reflect the frontal zone's complexity and approximations in the diffusivity computations.

The estimation of vertical fluxes from such diffusivities requires knowledge of the appropriate scalar gradient which, in the frontal zone, can also have strong spatial and temporal variability. In the case of heat, flux estimates are implicit in the diffusivity computation. For the 10–34 m vertical interval, the average (downward) fluxes corresponding to the χ_T distribution in figure 7 are 430, 390, 180 and 50 W m^{-2} respectively for sites 1–4. These estimates bracket the climatological surface values for early summer (Bunker 1976), with the larger values at the more stratified sites (1, 2) being qualitatively consistent with a possible cross-front advection of buoyancy into the frontal zone (Brickman & Loder 1993).

An important biological implication of vertical mixing (and cross-front exchange) in the Georges Bank frontal zone is the supply of external nutrients to support the Bank's high biological production (Loder & Platt 1985). Horne *et al.* (1993) have used density diffusivities and concurrent concentration profiles of the limiting nutrient, nitrate, from 1985 to show that the vertical nitrate fluxes in the frontal zone are comparable to those required by primary production as inferred from carbon assimilation and nitrate uptake measurements. Collectively, the measurements indicate that vertical exchange of various properties in the frontal zone is substantial, with the internal waves making an important contribution.

5. Discussion

The description of the northern Georges Bank frontal system illustrates the physical processes which occur at tidal-mixing fronts and over shelf breaks, as well as the interactions which can occur between them.

Features of the frontal system that are consistent with expectations for tidal-mixing fronts in general include:

(*a*) the variation in frontal position with season and tidal modulation;

(*b*) the generation of skew scalar fluxes and straining of the frontal structure over the tidal period by barotropic tidal advection;

(*c*) the along-front residual current jet and the possibility of a two-celled circulation pattern in the cross-front plane;

(*d*) time-dependent near-surface convergence; and

(*e*) strong spatial (cross-front, vertical) and temporal (over the tidal period) structure in small-scale turbulence.

Potentially generic features of bank-edge (shelf-break) régimes include:

(*a*) the water mass boundary and associated geostrophic residual circulation;

(*b*) the stratified tide-topography interaction including both barotropic tidal rectification and internal wave generation; and

(*c*) enhanced vertical mixing in the pycnocline associated with the various internal-wave structures.

On northern Georges Bank, the strong tidal currents and (abrupt) topography result in a hybrid system with temporally varying coupling of the tidal-mixing front and Bank-edge régime via internal-wave propagation, tidal advection, variations in position of the tidal-mixing front and, more tentatively, a net cross-front (on-bank) drift. Although the last three mechanisms are probably of limited significance in the more general setting, in which there is greater separation of the component régimes, the internal-wave coupling may be of general importance resulting in tidal-mixing fronts being preferential sites for internal-wave dissipation in shallow seas. This would have the biological implication of providing an important mechanism for vertical nutrient supply across the frontal-zone pycnocline.

The implications of the northern Georges Bank observations for cross-front exchange and vertical mixing in general are less clear. During the summer period of weak wind forcing, water parcel movement over the 200 km extent of the frontal system is dominantly ‘along-front’, particularly in the upper water column. This is largely dependent on the abrupt topography resulting in a strong residual current jet and, apparently, limited baroclinic eddy formation. Nevertheless, for limited-source materials, the frontal system can be interpreted as restricting cross-bank exchange because of the rapid transit of water parcels through the region (Perry *et al.* 1993). On the other hand, for materials with a continuous upstream source, the persistently strong jet may enhance their supply to Georges Bank. The determination of cross-front exchange rates requires improved models of the complex cross-front circulation and of the spatial and temporal evolution of the properties of interest. These models must also consider the vertical exchange associated with various processes in the frontal zone which, in the Georges Bank case, occurs at a substantial rate. In general, the myriad of physical phenomena identified at the Georges Bank frontal system suggests that the basic questions of cross-front exchange and vertical mixing rates at tidal-mixing fronts require knowledge of the underlying processes as a conceptual framework for the interpretation of observations from particular régimes.

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Discussion

J. M. Huthnance (*Proudman Oceanographic Laboratory, Birkenhead, U.K.*). It was shown that the area over Georges Bank which remains mixed decreases during the summer. This appears to contrast with the rather stable location of North Sea tidal mixing fronts. Is it possible to indicate differences in the context or processes which may cause such contrast?

J. W. LODER. The 1988 moored measurements and historical hydrographic data both indicate that the size of the Georges Bank mixed area continues to decrease after peak surface heating (June). This and the tidal-modulation (monthly) variation on Georges Bank in summer (figure 2) are in contrast to the northwest European shelf where the seasonal 'advance' of the thermocline appears limited to April–June (Pingree 1975; Simpson & Bowers 1979) and limited tidal-modulation variability is predicted (and observed) after peak heating (Simpson & Bowers 1981). Several factors may be contributing. The leading possibility is the cross-front residual flow on Georges Bank. The depth-averaged cross-front flow towards the mixed side apparent in the study area is an additional buoyancy source, particularly under stratified summer conditions (Brickman & Loder 1993). More generally, there can be a cross-front buoyancy flux associated with the cross-front residual circulation, even when the latter's vertical average is zero (Garrett & Loder 1981). If the strength of this circulation varies with the tidal modulation, as expected for tidal rectification, then it can contribute to both the greater seasonal advance and monthly variation on Georges Bank where tidal rectification is a major factor. There may also be different wind influences on Georges Bank, either a different seasonal mean or asymmetries associated with the fluctuating winds (Wang *et al.* 1990). Models of both the circulation and stratification evolution, and further data analysis, are required to investigate these possibilities properly.

B. S. MCCARTNEY (*Proudman Oceanographic Laboratory, Birkenhead, U.K.*). In this study of the front on Georges Bank and in the study of the North Sea front, described in the previous paper of this volume by Hill *et al.*, it was not possible to detect evidence of cross-frontal mixing. Does this suggest that cross frontal mixing is therefore small enough to ignore in water quality models? This would imply that model resolution is needed to resolve the front and its along front circulation, but that the front behaves as a barrier, with different diffusion properties either side.

J. W. LODER. Although firm estimates of cross-front exchange rates have been elusive, there are indications of significant exchange in many cases. In the study area on northern Georges Bank, the observations indicate cross-front residual currents of a few centimetres per second which are important in supplying nutrients to support the Bank's high biological production (see Horne *et al.* 1989). Elsewhere on Georges Bank, and also on the northwest European shelf (see Pingree 1979), satellite imagery has revealed frequent eddy activity at tidal-mixing fronts. While the North Sea study results indicate relatively weak cross-front exchange in the absence of strong eddy activity, they do not rule out significant episodic exchange due to eddies or storms, nor that the rates are significant to some water quality problems.

D. PRANDLE (*Proudman Oceanographic Laboratory, Birkenhead, U.K.*). Could sequential remote sensing of surface temperature (by aircraft sensors) or of surface currents (by high-frequency radar) be used in conjunction with drifting buoys to determine horizontal dispersion rates?

J. W. LODER. In principle, dispersion rates for the near-surface region can be obtained from sequential snapshots of the surface current field with appropriate spatial and temporal resolution. Because of practical constraints on data resolution, synopticity and quality, multiple measurement types such as those which you mentioned will generally be valuable and sometimes necessary for reliable estimates. For a particular frontal system, the required mix of measurement types will depend on both the complexity of the flow field and logistical factors such as weather and proximity to the coast.

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