SHELF-SEA AND SLOPE FRONTS

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Introduction

Horizontal gradients in temperature and salinity in the ocean are generally very weak. Regions of enhanced horizontal gradient are referred to as fronts. The scalar gradients across a front indicate concomitant changes in the physical processes that determine water column structure. Fronts are important oceanographic features because, corresponding to the physical gradients, they are also sites of rapid chemical and biological changes. In particular, fronts are often sites of enhanced standing stock of primary producers and primary production, with related increases in zooplankton biomass, fish, and foraging seabirds. These frontal aggregations of fish are also an important marine resource, targeted specifically by fishing vessels.

This article discusses three types of fronts. In shelf seas fronts can be generated by the influence of freshwater runoff, or by surface heat fluxes interacting with horizontal variations of tidal mixing. At the edge of the continental shelves, fronts are often seen separating the inherently contrasting temperature–salinity characteristics of shelf and open ocean water. These three types are illustrated schematically in **Figure 1**.

Fresh Water Fronts in Shelf Seas

The lateral input of fresh water from rivers results in coastal waters having a lower salinity than the ambient shelf water. In the absence of any vertical mixing, this low-salinity water would spread out above the saltier shelf water as a density-driven current, eventually turning anticyclonically (i.e., to the right in the Northern Hemisphere, to the left in the Southern Hemisphere) to form a buoyancy current. Parallel to the coastline there will be a thermohaline front separating the low-salinity water from the shelf water. If there is stronger vertical mixing, supplied by tidal currents or wind stress, or if the fresh water input is very strong, then the front can extend from the surface to the seabed.

Determining the Position of a Fresh Water Front

The distance offshore at which this front lies depends on whether or not the buoyancy current ‘feels’ the seabed. If the buoyancy flow is confined to the surface, then the coast-parallel region containing the low-salinity surface layer will be approximately one internal Rossby radius thick (i.e. the distance traveled seaward by the surface buoyancy current before the effect of the Earth’s rotation drives it parallel to the coastline). Typically, in temperate regions, this distance will be a few tens of kilometers.

When the buoyancy current is in contact with the seabed, the situation is altered by the breakdown of geostrophy within the bottom Ekman layer of the flow. Within this Ekman layer there is a component of transport perpendicular to the front, pushing the bottom front offshore and driving low-density water beneath the higher-density shelf water. Thus the frontal region becomes convectively unstable, and overturns rapidly. The effect of this is to shift the position of the front further offshore. Numerical modeling studies have suggested that this continual offshore movement of the front is halted as a result of the vertical shear in the alongshore buoyancy current. As the water deepens, this vertical shear results in a reduction of the offshore bottom flow. Eventually the offshore flow is reversed, so that low-density water is no longer transported underneath the shelf water, and the front becomes fixed at that particular isobath.

Mixing and Frontogenesis in ROFIs

Fronts associated with the lateral buoyancy flux from rivers are affected by the amount of vertical mixing. In regions of fresh water influence (ROFIs) the modulation of tidal mixing over the spring–neap cycle has a dramatic effect on frontal dynamics. Strong vertical mixing at spring tides results in a vertically mixed water column, with salinity increasing offshore and often only a weak horizontal front. As the mixing then decreases toward neap tides, a point is reached when the vertical homogeneity of the water column cannot be maintained against the tendency for the low-density coastal water to flow offshore above the denser shelf water. This surface density-driven offshore current then rapidly establishes vertical stratification, with the offshore progression eventually being halted by the earth’s rotation.

Fluid dynamics experiments have shown that such a relaxation of the initially vertically mixed density structure will produce a strong front within any nonlinear region of the initial horizontal density gradient. Furthermore, a periodic modulation of the mixing about the level required to prevent this frontogenesis will result in a similar periodic variation in the density-driven mass flux. Spring–neap control of frontogenesis has been observed in a number of shelf seas; for instance, Liverpool Bay (eastern Irish Sea), the Rhine outflow (southern North Sea), and Spencer Gulf (South Australia). The physical switching between vertically mixed and stratified conditions is well established (**Figure 2**), though the biological responses within these dynamic environments have yet to be determined.

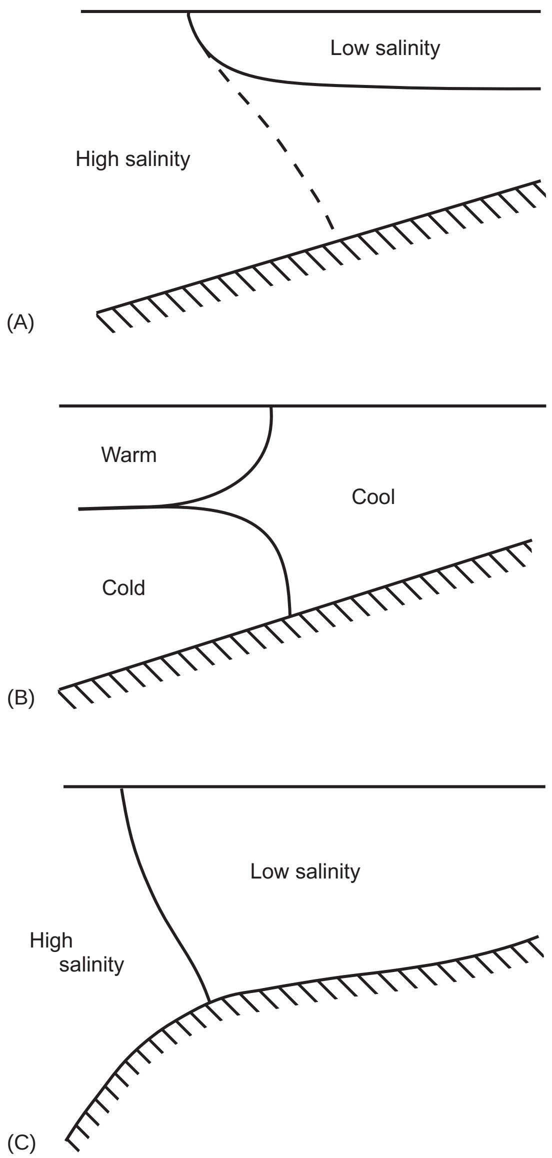

Figure 1 Schematic illustration of the main types of fronts found in shelf seas. (A) A fresh water front, caused by the input of fresher estuarine water into the coastal zone. The front can either be confined to the surface (weak vertical mixing) or extend from the surface to the seabed (strong vertical mixing). (B) A shelf sea tidal mixing front, caused by competition between surface heating and tidal mixing. The stratified water on the left occurs because of weak tidal mixing being unable to counter the stratification generated by surface heating. The mixed water on the right is the result of strong tidal mixing being able to prevent thermal stratification. (C) A shelf break front. The low-salinity water on the shelf results from the combination of all the estuarine inputs from the coast. There can also be a cross-shelf edge contrast in temperature.

Tidal Mixing Fronts in Shelf Seas

In summer, away from sources of fresh water, temperate shelf seas are partitioned into thermally stratified and vertically well-mixed regions. Such partitioning is clearly visible in satellite remote sensing images of sea surface temperature (SST, **Figure 3**).

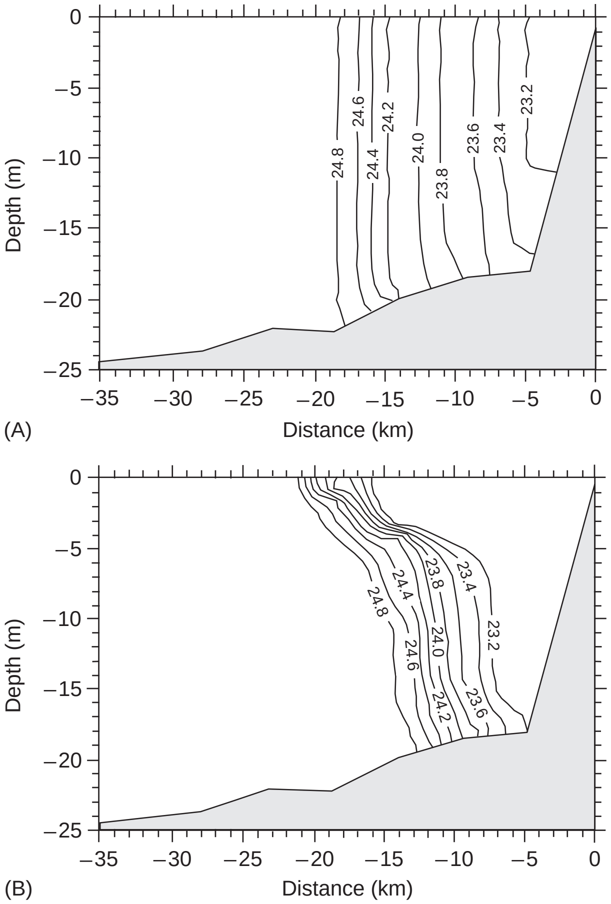

Figure 2 Density sections (σ_t, kg m^{-3}), normal to the coastline through the Rhine outflow. (A) Spring tide section, showing vertically mixed water with a fresh water-induced horizontal density gradient. (B) Neap tide section, showing the relaxation of the horizontal gradient and stratification caused by the reduction in mixing. (After Souza and Simpson (1997) *Journal of Marine Systems* 12: 311–323. Courtesy of Elsevier Science.)

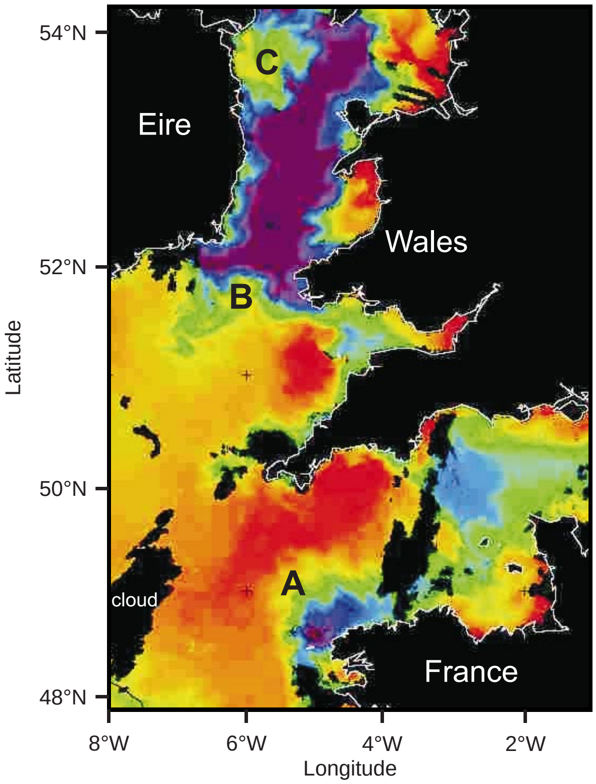

Figure 3 Sea surface temperature image from the Advanced Very High Resolution Radiometer (AVHRR). The image was taken at 0419 GMT on 12 July 1999. Violet/blue represents a temperature of 13–14°C, and shows regions of shelf sea that are vertically mixed. Red represents 18–19°C, indicating the surface temperature of strongly stratified water. Green/yellow represents 16–17°C, and shows the regions of weak stratification at the tidal mixing fronts. The regions of strong horizontal temperature gradient separating the mixed and stratified areas are the tidal mixing fronts (A, Ushant front; B, Celtic Sea front; C, Western Irish Sea front). (Image courtesy of the Dundee Satellite Receiving Station, and the Remote Sensing Group, Plymouth Marine Laboratory.)

Warm SST indicates the temperature of the surface mixed layer of a stratified water column, while cool SST shows the temperature of the entire, vertically homogeneous water column. The transition region between these stratified and well-mixed regions, with horizontal temperature gradients of typically $1^\circ\mathrm{C\,km^{-1}}$, are the shelf sea tidal mixing fronts.

Physical Control of Fronts and h/u^3

The suggestion that the intensity of tidal mixing was responsible for controlling the vertical structure of shelf seas was first made by Bigelow in the late 1920s, with reference to the variations in vertical temperature structure on and off Georges Bank. The first quantitative link between shelf sea fronts and tidal mixing was made by Simpson and Hunter in 1974. Surface heating, which is absorbed rapidly within the upper few meters of the ocean, acts to stabilize the water column by expanding the near-surface water and thus reducing its density. Friction between tidal currents and the seabed generates turbulence. Most of this turbulence is dissipated as heat (although the heating produced is insignificant) but a small fraction of it (typically 0.3%) is available for working against the thermal stratification near the sea surface. This seemingly low conversion rate of turbulence to mixing arises because turbulence is dissipated very close to where it is generated (the 'equilibrium hypothesis'). Most of the vertical current shear (and hence turbulence production and dissipation) in a tidal flow is close to the seabed. Current shear higher in the water column near the thermocline (where turbulence can work against stratification) is much weaker, leading to a low overall efficiency.

Thus, there is a competition between the rate at which the water column is being stratified by the surface heating and the ability of the tidal turbulence to erode and prevent stratification. If the magnitude of the heating component exceeds that of the tidal mixing term, then the water column will stratify. Alternatively, a stronger tidal current, and therefore more mixing, results in a situation where the heat input is continuously being well distributed through the entire depth and the water column is kept vertically mixed. A shelf sea front marks the narrow transition between these two conditions, with equal contributions from the heating and tidal mixing. This simple analysis led Simpson and Hunter to predict that tidal mixing fronts should follow lines of a critical value of h/u^3, with h (m) the total water depth and u ($\mathrm{m\,s^{-1}}$) a measure of the amplitude of the tidal currents. Subsequent analysis of satellite SST images in comparison with maps of h/u^3 confirmed the remarkable power of this simple theory: shelf sea front positions are controlled by a local balance between the vertical physical processes of tidal mixing and sea surface heating (**Figure 4**).

Modifications to h/u^3

A prediction of the Simpson–Hunter h/u^3 hypothesis is that a shelf sea front should change position periodically with the spring–neap tidal cycle, owing to the fortnightly variation in tidal currents (**Figure 5**). In NW European shelf seas, spring tidal current amplitudes are typically twice those at neap tides. However, predicting the horizontal displacement of a shelf sea front using h/u^3_{Springs} and h/u^3_{Neaps} leads to a substantial overestimate, typically suggesting a transition distance of 40–50 km compared to satellite-derived observations of only 2–4 km. Two

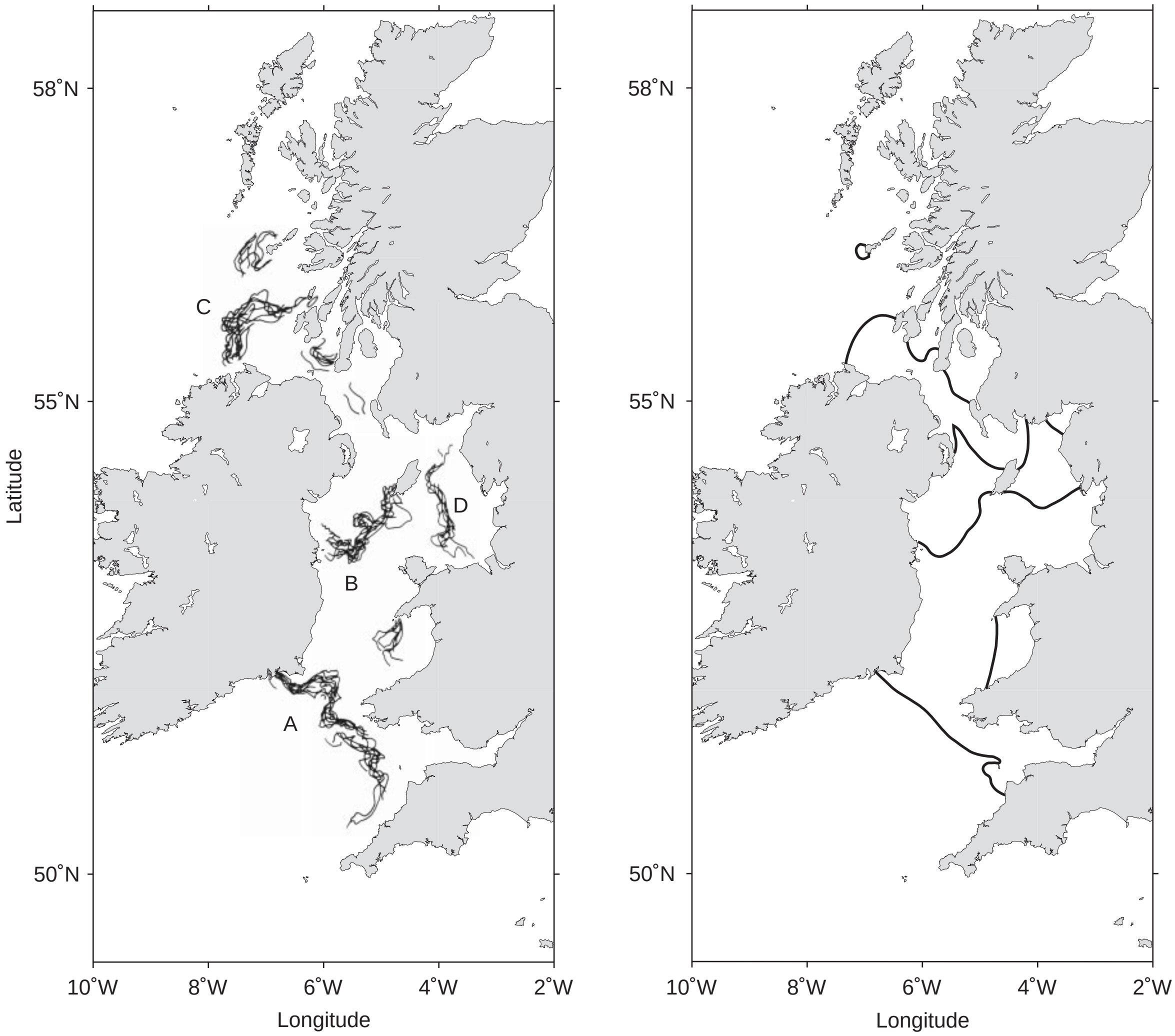

Figure 4 Left, mean positions of tidal mixing fronts observed in SST images, May 1978. A, Celtic Sea front; B, Western Irish Sea front; C, Islay front. Right, contours of $\log_{10}(h/u^3) = 2.7$. Note the correspondence between fronts A, B, and C, and the contours of constant h/u^3. Front D is caused by fresh water inputs from the estuaries of NW England, and so does not conform to the h/u^3 hypothesis. (After Simpson and James (1986) *Coastal and Estuarine Sciences*, 3: 63–93. Courtesy of the American Geophysical Union.)

modifications to the theory were subsequently made. First, as tidal turbulence increases from neap to spring tides, the mixing not only has to counteract the instantaneous heat supply but it must also break down the existing stratification that has developed as a result of the previous neap tide. Incorporating this behavior into the theory reduced the amplitude of the adjustment region to 10–20 km. Second, stratification inhibits vertical mixing, so the mixing efficiency would be expected to be lower as the existing stratification was being eroded. Simpson and Bowers used a simple parametrization linking mixing efficiency to the strength of the stratification, and showed that the predicted spring–neap adjustment was then similar to that observed. More recently the use of a turbulence closure model, providing a less arbitrary link between stability and mixing, has provided further confirmation of the need to include variable mixing efficiency.

The only source of mixing accounted for in the h/u^3 theory is tidal friction with the seabed, and the success of the theory in NW European shelf seas is arguably a result of the dominance of the tides in these regions. A better prediction of frontal position could be made by incorporating wind-driven mixing, so that the competition becomes one of surface heating versus the sum of tidal + wind mixing. Again, only a small fraction of the wind-driven turbulence is available to work against the stratification, about 2–3%. This is significantly larger than the tidal mixing efficiency because the thermocline is generally nearer to the sea surface than the

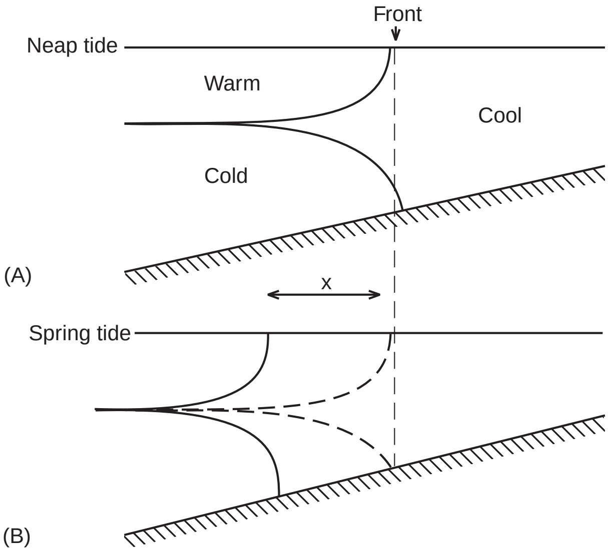

Figure 5 Schematic illustration of the adjustment of a tidal mixing front as a consequence of the spring–neap variation of tidal currents. At neap tides (A) the weaker tidal mixing allows stratification to develop in shallower water. At spring tides (B) the stronger tidal currents re-mix the shallow stratification. The adjustment distance, x, is typically 2–4 km.

seabed, and hence in a region of wind-driven current shear.

A debate arose in the late 1980s concerning the validity of the h/u^3 theory. Loder and Greenberg, and subsequently Stigebrandt, put forward an alternative hypothesis based on a more realistic description of tidal turbulence that includes the effect of the bottom rotational boundary layer as a control on the vertical extent of tidal turbulence away from the seabed. The position of the shelf sea front would, in this theory, simply reflect the position at which the tidal boundary layer was thick enough to reach over the entire depth, and fronts should follow a critical value of h/u. Moreover, in temperate latitudes the similar values of Coriolis and tidal frequencies suggests that there should be a very significant rotational constraint on frontal position as the tidal currents become cyclonically polarized.

Observations of frontal positions were not precise enough to determine which of the two theories was correct. However, use of a numerical model showed that both mechanisms contributed. For anticyclonically polarized tidal currents, boundary layer limitation is not a significant factor, and the frontal position is well described by the h/u^3 theory. As currents become more cyclonic, the vertical limitation of turbulence due to the reducing thickness of the boundary layer does alter the frontal position away from that predicted using h/u^3, but by less than predicted using the boundary layer theory alone.

Circulation at Shelf Sea Fronts

The density gradients associated with shelf sea fronts drive a weak residual circulation, superimposed on the dominant tidal flows (**Figure 6**). A surface convergence of flow at the front often leads to an accumulation of buoyant debris. This can form a clear visual indicator of a front. The convergence is associated with a downwelling, predicted by models to be around $4\,\mathrm{cm\,s^{-1}}$. On the stratified side of the front a surface, geostrophic jet is predicted to flow parallel to the front. Models have predicted this flow to be of the order of $10\,\mathrm{cm\,s^{-1}}$. Direct observations of such flows against the background of strong tidal currents is difficult, but both drogued buoys and high frequency radar have been used successfully to observe along-front speeds of $10\text{–}15\,\mathrm{cm\,s^{-1}}$. These frontal jets are prone to baroclinic instability, with meanders forming along the front, growing, and eventually producing baroclinic eddies that transfer water between the two sides of the front.

Biological Implications

The physical structure of a shelf sea front controls associated biochemical gradients. From the mid-1970s, alongside the physical oceanographic studies

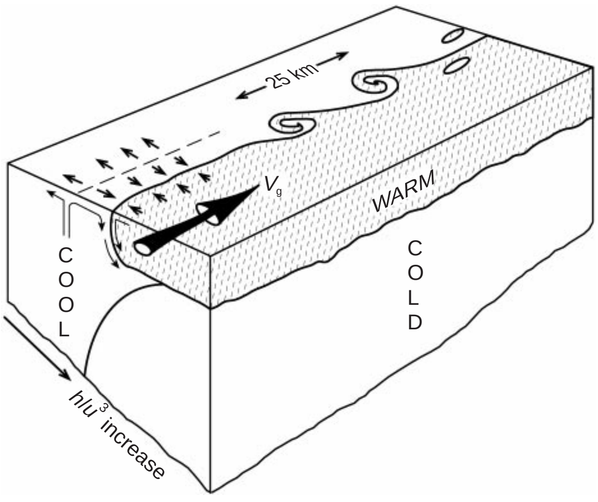

Figure 6 Pattern of circulation at a tidal mixing front. V_g is an along-front surface geostrophic jet, typically about $10\,\mathrm{cm\,s^{-1}}$. There is a surface current convergence at the front, followed by downwelling, with a compensatory upwelling and surface divergence in the mixed region. Baroclinic eddies develop along the front, with typical wavelengths of around 25 km. (After Simpson and James (1986) *Coastal and Estuarine Sciences*, 3: 63–93. Courtesy of the American Geophysical Union.)

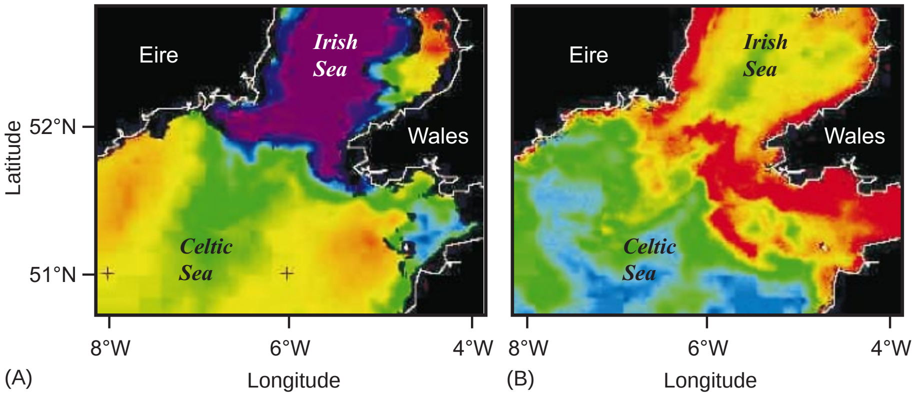

Figure 7 (A) SST image of the Celtic Sea front, 12 July 1999. (B) Sea surface chlorophyll concentration on 12 July in the same region, derived from the SeaWIFS sensor on NASA's SeaStar satellite. The mixed water of the Irish Sea is associated with chlorophyll concentrations of 1–2 mg m^{-3}. The strongly stratified water in the Celtic Sea has surface chlorophyll concentrations of less than 0.5 mg m^{-3}. At the front there is a clear signature of enhanced chlorophyll concentration, reaching about 5 mg m^{-3}. (Image courtesy of the Dundee Satellite Receiving Station, and the Remote Sensing Group, Plymouth Marine Laboratory.)

of fronts, it was recognized that enhanced levels of chlorophyll (phytoplankton biomass) were often seen in the frontal surface water. The availability of satellite remote sensing of surface chlorophyll (in particular the SeaWIFS sensor) now allows dramatic evidence of these frontal accumulations of phytoplankton (**Figure** 7). It is conceivable that the convergence of flow at a front could lead to enhancement of surface chlorophyll, by concentrating the biomass from the mixed and stratified water on either side. However, the spatial extent of the observed frontal chlorophyll ($\sim$ 1–10 km) is typically at least an order of magnitude greater than the horizontal extent of the convergence region (of order 100 m). More recently, at the Georges Bank frontal system, the enhanced frontal chlorophyll has been observed directly associated with an increase in rates of primary production compared to the waters on either side of the front. Thus, it appears that locally enhanced concentrations of frontal phytoplankton biomass are a result of locally increased production, and so require some source of nitrate to be mixed into the region.

For primary production the shelf sea front marks the transition between a nutrient-replete but light-limited, environment and a stratified water column with a well-lit but nutrient-deficient surface layer (**Figure** 8). Highest nutrient levels are usually found in the bottom mixed layer on the stratified side of the front, owing to negligible utilization and the contribution from detritus sinking down from the surface layer. Enhanced primary production in the frontal surface waters requires a mechanism to transport nutrients into the region, from the deep, high-nutrient water (vertical nutrient flux) and/or from the moderate nutrient-containing waters on the mixed side of the front (horizontal nutrient flux).

Four supply mechanisms have been suggested (**Figure** 8). First, the surface outcropping of the front is a region of gradually reducing vertical stratification, and thus a region where the inhibition of vertical mixing is reduced. The increased turbulent flux of nutrients will be available for surface primary production, as long as the residence time of the phytoplankton cells in the photic zone is still sufficient to allow net growth. Second, the spring–neap adjustment of a front's position results in the 2–4 km adjustment region undergoing a fortnightly mixing–stratification cycle. Thus, toward spring tides the region becomes vertically mixed and replenished with nutrients throughout the water column, and as the water restratifies toward neap tides the new surface nutrients become available for primary production. The predicted fortnightly pulses in surface frontal biomass have been reported at the Ushant shelf sea front, in the Western English Channel. A third nutrient supply mechanism is weak diapycnal flux, transferring water from the mixed side of the front into the surface frontal water. Finally, baroclinic eddies will transfer pools of water from the mixed side into the stratified side, though at the cost of a similar flux of water containing phytoplankton in the opposite direction.

Shelf Slope Fronts

Typical seabed slopes in shelf seas are about 0.5°–0.8°. At the edge of the shelf seas this slope increases to 1.3°–3.2°, a transition that occurs at a depth typically between 100 and 200 m. This region of steeper bathymetry, just seaward of the shelf edge, is the shelf slope, and is often associated with sharp horizontal gradients in temperature and/or salinity (for example, see **Figure 9**). The difference in the water characteristics of shelf seas and the open ocean arises as the result of several mechanisms. Coastal and shelf waters tend to have lower salinity than the open ocean, owing to the input of fresh water from land runoff. The fresh water input also alters the temperature of the shelf water, as does the seasonal heating/cooling cycle, which will generate more pronounced temperature fluctuations within the shallow water. Offshore, the open ocean is part of a larger, basin-scale circulation that, for instance, brings much warmer water from equatorial regions past the shelf edge (e.g., consider the along-slope circulation of the world's western boundary currents). There is often a marked seasonality in the form of the shelf break front. Shelf waters can be more buoyant than oceanic waters during summer, but surface cooling in winter can reverse this to leave a denser water mass on the shelf that has the potential for cascading off the shelf and down the shelf slope.

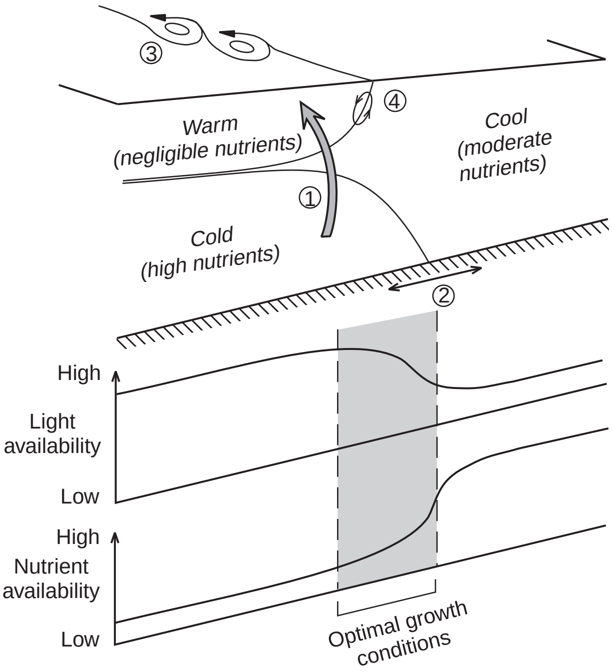

Figure 8 Nutrient supply mechanisms that are thought to fuel primary production at a tidal mixing front. (1) Vertical turbulent nutrient flux through the weaker stratification at the front. (2) The spring–neap adjustment of the front, causing a fortnightly replenishment of surface nutrients within the adjustment region. (3) Baroclinic eddy shedding along the front, transferring nutrient-rich water from the mixed side of the front into the stratified side. (4) A weak cross-frontal circulation caused by friction between the residual flows within the front (see **Figure 6**). In the surface layer on the stratified side of the front, the algae receive plenty of light but are prevented from growing because new nutrients cannot be supplied through the strong thermocline. On the mixed side of the front, nutrients are plentiful but growth is limited by a lack of light as the algae are mixed throughout the entire depth of the water column. The problem of lack of light on the mixed side is compounded by tidal resuspension of bed sediments, acting to increase the opacity of the water. As the transition zone between these two extremes, the front provides optimal conditions for algal growth. Processes (1) and (2) are thought to be capable of supplying about 80% of the nutrient requirements at a typical front.

The Position of a Shelf Slope Front

While the reasons for the contrast in water characteristics are straightforward, an explanation is required of why these differences between shelf and oceanic waters are maintained across such sharp fronts at the shelf slope. This is not as straightforward as for the case of the tidal mixing front. The limited number of processes governing the vertical structure of shelf seas resulted in a testable prediction for the position of a tidal mixing front in terms of water depth and tidal current amplitude. At the shelf break there are a number of potential controlling factors on a front's position, and a corresponding difficulty in producing an unambiguous, testable hypothesis. Numerical modeling provides the best technique for investigating frontal dynamics, allowing simultaneous consideration of several physical processes. However, a major problem with the assessment of any description of controls on shelf slope fronts is that there are considerable logistic difficulties in collecting current and scalar observations of sufficient quality and resolution to compare with the model outputs. The following arguments are based on both analytical and numerical models of shelf slope fronts.

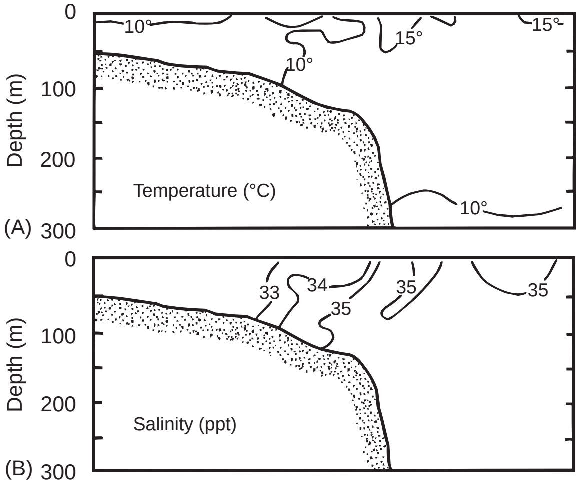

Figure 9 (A) Temperature and (B) salinity structure across the shelf break south of Cape Cod, eastern North America. (After Wright (1976) *J Marine Research* 34: 1–14. Courtesy of the Sears Foundation for Marine Research.)

A fundamental dynamic constraint on the exchange of water masses across the shelf slope lies with the geostrophic behavior of the oceanic flows. Geostrophic currents cannot cross steep bathymetry. Instead, they are forced to flow along isobaths, parallel to the topography of the shelf slope and shelf edge. Both the oceanic flow seaward of the shelf edge, and the buoyancy-driven flows of shelf water close to the shelf edge, behave geostrophically. This basic topographic constraint on these geostrophic flows often forms the basis of descriptions of shelf slope fronts (e.g., work by Csanady, Ou, and Hsueh). This topographic constraint on offshore movement of shelf water has been shown to be more important when the shelf water is denser than the oceanic water, with the shelf edge controlling the cascading of the denser water down the shelf slope. When shelf water is less dense, the internal Rossby deformation radius appears to have the dominant influence.

Such gravitational relaxation of the horizontal density structure across the shelf slope only explains the formation of the front. The resulting strong along-slope flows and current shear suggest that the frontal signature should be rapidly mixed and dissipated, and yet observations clearly show that the fronts exist for prolonged periods. This implies that the dynamics of the fronts must also act to maintain frontal structure, in addition to causing its initial formation. One suggestion by Ou is that the front can be maintained, paradoxically, by the action of wind stress at the sea surface. This wind mixing generates a surface mixed layer, which still contains a cross-shelf horizontal density gradient and so continues to relax under gravity and feed the along-slope current.

The above mechanisms for frontal formation and maintenance explicitly use a cross-shore density gradient as the pivotal dynamical process. However, it has been noted (e.g., by Chapman), that in the Middle Atlantic Bight in summer the combined frontal structures of temperature and salinity compensate to produce no horizontal density gradient. In other words, a shelf slope front can exist in the scalar fields without any apparent horizontal density structure to maintain them. Chapman, again utilizing a numerical model, showed that such a situation could be supported if there is a strong along-shore flow on the shelf and a distinct shelf break. Friction with the seabed in the shallower shelf water causes a cross-shelf component of the flow. Above the shelf slope, in deeper water, the effect of friction is reduced, and so there is a convergence of the cross-shelf flow close to the shelf break. The existence of the temperature and/or salinity front is then dependent on the relative contributions of advection and diffusion. Seaward of the shelf edge, diffusion is the dominant process, smoothing out any horizontal gradients. The convergence at the shelf edge concentrates the cross-shelf scalar gradients into a front, and the dominance of advection moves this structure along the shelf edge faster than diffusive processes can erode it. Thus, the front can be visible along several hundred kilometers of the Middle Atlantic Bight.

Implications of Shelf Slope Fronts

As with the tidal mixing fronts, shelf slope fronts in summer are often associated with concentrations of relatively high chlorophyll biomass, compared to the oceanic and shelf surface waters on either side. Fundamentally, this is again likely to be due to the diffusion of bottom water nutrients through the weaker stratification just at the surface front. Evidence from some shelf edge regions indicate the areas to be influenced by energetic internal waves on the thermocline, driven by the dissipation of the internal tidal wave (which is itself generated on the steep slope bathymetry seaward of the shelf edge). There has been some suggestion that secondary production can be more clearly linked to the primary production at shelf slope fronts than at shelf sea tidal mixing fronts, due to the temporal variability of the tidal fronts (e.g., spring–neap adjustment). Certainly many shelf slope regions are places of intense fishing activity.

The shelf slope is recognized as a region key to the global cycling of carbon. The shelf seas and slope areas are highly productive, and thus have a high capacity for uptake of atmospheric carbon. Atmospheric carbon is drawn into the ocean as the result of algal growth extracting carbon from the sea water. The fate of some of this carbon uptake is to sink when the algae die, and become buried in the shelf and slope sediments. This flux of carbon to the seabed is an important carbon removal process, with shelf sea and slope regions currently thought to be responsible for about 90% of the global oceanic removal of carbon. Thus, one of the important questions in oceanography concerns the transfer of water across the shelf edge, between the slope and shelf seas. This transfer controls both the rate at which carbon is transferred to the shelf slope from the shelf seas and the rate at which new nutrients from the slope waters are supplied to the shelf waters ready to fuel new carbon uptake.

Summary

Locally enhanced regions of horizontal salinity, temperature, and density gradient occur across the coastal and shelf seas, driven by a variety of mechanisms. The dynamics controlling the structure and position of fresh water fronts and shelf sea tidal mixing fronts are relatively well understood. Fresh water fronts result from the relaxation of a horizontal density gradient, arrested either by the diversion of flow caused by the Earth's rotation or by the interaction between nearbed cross-frontal flows and a sloping seabed. Tidal mixing fronts are controlled by the competition between the rate of supply of mixing energy (supplied either by tidal current stress against the seabed or by wind stress against the sea surface) and the rate of stratification (produced by surface heating). For fronts at the shelf edge/slope region, the change in the slope of the seabed must play a pivotal role, but the full dynamics controlling the fronts are less clear. Partially this is due to the difficulty in collecting observations of sufficient resolution, in both time and space, against which to test hypotheses. Also, in particular contrast with the tidal mixing fronts, there appears to be no dominant process controlling these fronts.

All fronts are observed to be regions of enhanced surface primary production. The common feature causing this production is likely to be the reduced stability close to surface fronts allowing increased vertical turbulent mixing of nutrients into the well-lit surface water. Fronts close to the shelf edge, or other regions of steep bathymetry, have the additional feature of locally generated internal waves providing enhanced mixing across the shallowing pycnocline. This increased primary production is often seen to be associated with increases in zooplankton and larger fish, ultimately supporting populations of sea birds and providing an important fisheries resource for people.

There are still important questions that remain to be answered concerning the physics of fronts. For instance, direct measurements of turbulent mixing have only recently become possible, so the potential for horizontal gradients in rates of vertical turbulent exchange still needs to be addressed. Shelf slope fronts are perhaps the most lacking in terms of a coherent theory of their dynamics (assuming such a general approach is possible), and have particular questions related to cross-frontal transfers that still require attention. The link between the physics of fronts and the closely coupled biology and chemistry is perhaps the area of greatest research potential. Oceanographic instrumentation is developing rapidly to allow the biological and chemical environment to be observed at the same spatial and temporal scales as the controlling physics.

See also

Carbon Cycle. Dispersion in Shallow Seas. Ekman Transport and Pumping. Primary Production Distribution. Primary Production Methods. Primary Production Processes. Tides. Turbulence in the Benthic Boundary Layer.

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SHELF-SEA MODELS

See **REGIONAL AND SHELF SEA MODELS**

SHIPPING AND PORTS

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Introduction

Ships and ports have been an important medium for trade and commerce for thousands of years. Today's maritime shipping industry carries 90% of the