

Chapter 2

Frontal Types

Abstract Fronts are a dynamic phenomenon separating water masses of different properties. They are narrow three-dimensional structures caused by diverse forcing mechanisms; and are characterized by distinct physical, chemical, and biological properties. Fronts occur throughout the world ocean at several spatial and temporal scales. Most stable fronts are steered by bottom topography. The most studied frontal types are tidal fronts, shelf-break fronts, upwelling fronts, estuarine fronts, plume fronts, fronts generated by convergence or divergence of water masses, frontal eddies and fronts associated with abrupt topographic features.

Keywords Classification of fronts • Physical forcing • Haline fronts • Thermal fronts • Spatio-temporal scales of fronts

Fronts are caused by diverse forcing such as tides, continental run-off, convergence of currents, wind, solar heating, bathymetry, etc. As a general rule, a front in one property (e.g. temperature) can be detected in other properties. The concurrent physical, chemical, and biological manifestations of the same front are typically collocated (Belkin et al. 2009). Long-term mean annual, seasonal, and monthly frontal frequency maps for the Atlantic, Indian, and Pacific Oceans reveal elevated concentrations of quasi-stationary fronts in coastal and marginal seas over the entire world ocean between 75°N and 75°S (Fig. 2.1). Most of stable fronts are steered by ocean bottom topography; the shelf break and upper continental slope play the most important role in stabilizing their respective fronts (Belkin et al. 2009).

There is no a definitive classification of fronts, but a partial listing of them would include tidal fronts, shelf-break fronts, upwelling fronts, estuarine fronts, plume fronts, fronts associated with the convergence or divergence of water masses in the open ocean, frontal eddies and fronts associated with geomorphic features such as headlands, islands, and canyons (Mann and Lazier 2006).

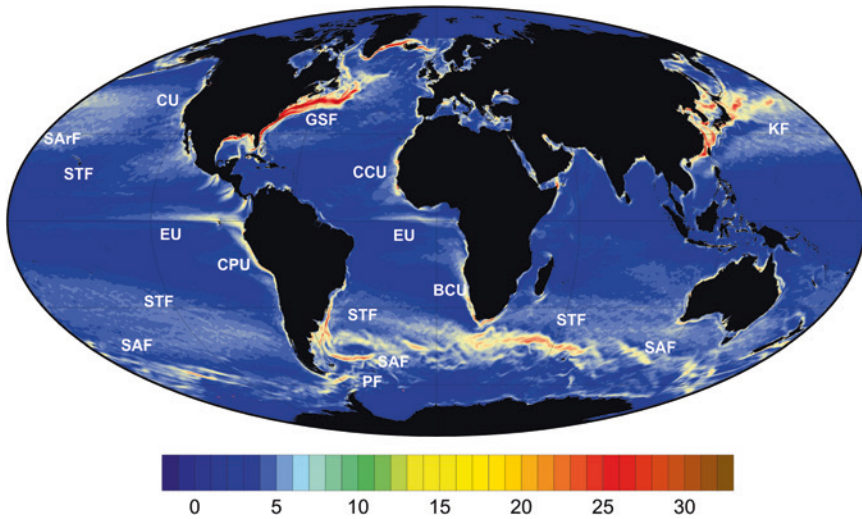


Fig. 2.1 Global distribution of maximum sea surface temperature gradient based on monthly mean 0.25×0.25 degree resolution data from Reynolds et al. (2007). The map shows the largest thermal fronts of the world ocean. *BCU* Benguela Current upwelling; *CCU* Canary Current upwelling; *CPU* Chilean-Peruvian upwelling; *CU* California Current upwelling; *EU* Equatorial upwelling; *GSF* Gulf Stream front; *KF* Kuroshio front; *PF* Polar front; *SAF* SubAntarctic front; *SARf* SubArctic front; *STF* SubTropical front

2.1 Tidal Fronts

In temperate climates, seasonal thermoclines develop near the surface during late spring and summer. Unless some forcing provides enough mechanical energy to mix the water column, thermoclines stabilize the water column, becoming stronger as the warm season progresses. Tides are one of the main forcing processes in the ocean (Munk and Wunsch 1998), whose energy distributes heterogeneously over the global ocean. In continental shelves where a seasonal thermocline develops and a high rate of tidal energy dissipation occur; there are regions in which the intensity of turbulent mixing is able to continuously overcome the barrier to mixing presented by stratification (Simpson and Hunter 1974; Pingree et al. 1975; Le Fèvre 1986). As the tidal wave approaches the coast, the tidal amplitude and its horizontal velocity gradually increase. At some critical depth, vertical turbulence produced by friction between the tidal stream and the sea bed is sufficiently enhanced (when added to turbulence produced by wind stress at the sea surface) as to overcome the seasonal thermal stratification of the water column, giving rise to tidally mixed regions near shore. Thus, the tidally mixed and the stratified regions of the shelf are separated by a frontal region (Longhurst 1998). In contrast with the more frequently observed situation described above there are some tidal fronts where changes in mixing efficiency lead to a more strongly stratified water column in the onshore region, such as in the southeast coast of Japan (Takeoka et al. 1997).

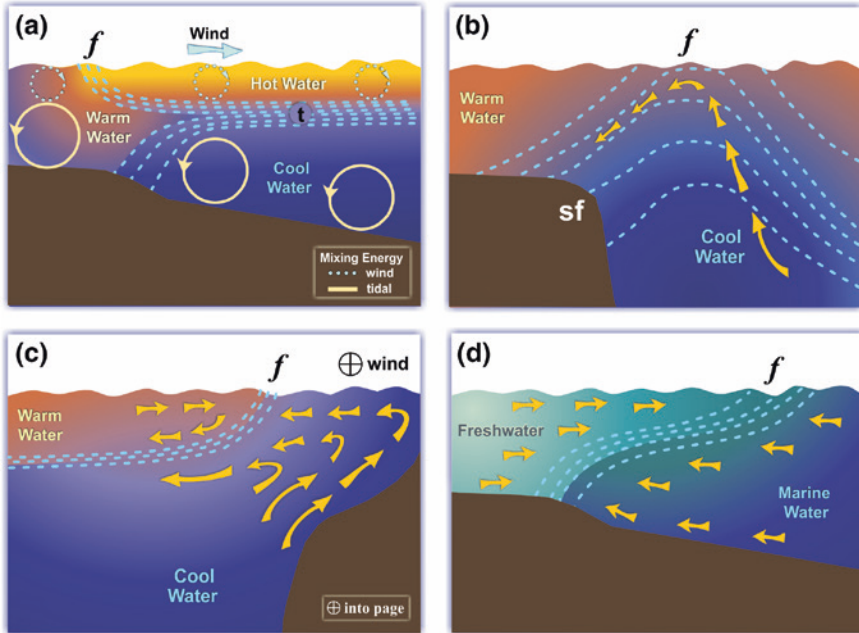


Fig. 2.2 Frontal types. **a** Tidal front; **b** Shelfbreak front; **c** upwelling front (southern hemisphere); **d** estuarine front. *f* Front; *sf* shelfbreak; *t* thermocline; *w* wind; *arrows* are currents; *dashed lines* are lines of equal density

More research efforts have focused on tidal fronts than on any other frontal types (Mann and Lazier 2006). Typical tidal fronts are seasonal and they establish each year at the same approximate time and location; and are characterized by strong thermal gradients (Fig. 2.2a).

2.2 Shelf-Break Fronts

A linear zone of cool surface waters, supporting a plankton bloom, frequently overlies the upper slope and shelf edge over continental shelves and other banks elsewhere around the world ocean. Not all these fronts are forced by the same mechanisms but the band of cold waters generally indicate entrainment of deeper, cooler, and nutrient-rich waters towards the surface. A widely accepted explanation of this observation involves the generation of internal standing waves on the thermocline at the shelf edge where the tidal stream encounters rough topography on the seabed (Longhurst 1998), but various alternative explanations involving small-scale eddies (coupled with episodic wind stress) have also been proposed. Additionally, the interleaving of water masses at the front could enhance vertical stability, retaining phytoplankton

cells in the euphotic zone (Podestá 1990; Brandini et al. 2000). Numerical simulations indicate that offshore flow in the bottom Ekman layer promotes overturning over the continental shelf and detaches from the bottom at the shelf break, where it mixes upward along sloping isopycnals, thus promoting upwelling (Gawarkiewicz and Chapman 1992). High resolution hydrographic observations across the Middle Atlantic Bight south of New England corroborate the model results (Barth et al. 1998; Houghton and Visbeck 1998). More recently Matano and Palma (2008) proposed a mechanism by which as a downwelling current flows along the continental slope in the direction of continental trapped waves (e.g. with the coast on the left (right) in the Southern (Northern) Hemisphere), bottom friction and lateral diffusion spread the flow onto the neighboring shelf, thus generating along-shelf pressure gradients and a cross-shelf divergence that is compensated by shelf-break upwelling. Though shelf break fronts are topographically trapped and generally reorganize in a few days after being disrupted (Gawarkiewicz and Chapman 1992), there are strong indications of frontal instability that by enhancing cross-shelf exchange might further promote nutrient enrichment. Despite of their ubiquitous occurrence, the fertilization mechanisms of shelf-break fronts seem to be diverse (Fig. 2.2b).

2.3 Upwelling Fronts

Wind driven currents that flow towards the Equator along the western coasts of continents (e.g. Peru; California; Benguela; Canaries Currents) are driven away from the coasts due to the Earth's rotation, leading to coastal upwelling of nutrient rich waters. Upwelling fronts frequently present strong seasonality derived from the seasonal variability of prevailing upwelling-favorable winds. For instance along the coast of California the onset of upwelling occurs during the "spring transition" when southerly winds reverse to upwelling-favorable, and last until late fall (Huyer 1983). The sloping isopycnals sustain an along-shore baroclinic jet. As the upwelling fronts are located a few tens of km from shore, the interaction between the frontal jet and coastal indentations promote frontal instabilities and vertical motions. These eastern boundary upwelling ecosystems are among the most productive regions in the oceans (Pauly and Christensen 2005). The upwelled waters move away from the coast by Ekman transport and converge at certain distance offshore, so the upwelled water sinks. Upwelling fronts form at this interface between shelf water and the cool, nutrient-rich water brought to the surface during wind-driven coastal upwelling. This frontal region is highly productive and planktonic organisms aggregate on the coastal side of the front and large numbers of fish concentrate at that location (Mann and Lazier 2006) (Fig. 2.2c).

2.4 Estuarine Fronts

Estuarine fronts are produced by the meeting of continental freshwaters and salty marine waters. The latter frequently form a salt-wedge below the former, leading to the most frequently observed structure (Fig. 2.2d). These fronts develop usually in bays, part of a bay, or inlets in which freshwater flows from land. These fronts are controlled by salinity variations, and are frequently the most contrasting in terms of water density. Estuarine fronts differ in stratification and dynamics mostly due to diverse patterns in river discharge, and to the variable importance of external forcing such as tides or wind. These frontal mechanisms lead to the formation of plume, tidal intrusion and shear fronts at estuaries, some of which might develop along-channel fronts, particularly during flood tide (O'Donnell 1993). Except for a few very large estuaries (e.g. Río de la Plata; St. Lawrence) most estuarine fronts have much smaller spatial scales than other types of marine fronts.

In some estuarine systems, a well-developed turbidity front characterizes the innermost part of the estuary. This maximum gradient in turbidity is due to the flocculation of suspended matter at the edge of the salt intrusion, and re-suspension of sediment due to tidal stirring. Turbidity fronts are clearly visible in satellite images and frequently from the deck of ships (Fig. 2.2d).

2.5 Plume Fronts

In some situations, waters from either a river or an estuary pouring onto a continental shelf predominate over any tidal effects and flow into the neighboring ocean creating a river plume, which may have a strong impact on the distribution of water properties, sediments and biota. When the surface outflow onto the continental shelf is mainly of freshwater from the river itself, these plumes are referred to as river plumes (e.g. those of the Mississippi or Amazon rivers); if the outflow is of river waters mixed with salt water the flow constitutes an estuarine plume (e.g. the Chesapeake; Río de la Plata or St. Lawrence estuaries). The Coriolis force affects plumes turning them to the left (Southern Hemisphere) or right (Northern Hemisphere), and the buoyant plume continues on its way as a coastal current parallel to the coast. Under favorable (downwelling) wind conditions buoyant river plumes can extend hundreds of km away from the river mouth. Recent numerical simulations have shown that in the absence of wind bottom-trapped plumes can also propagate in the opposite direction (e.g. upstream). This is associated with a baroclinic adjustment of the river discharge, while the downstream spreading is generated by the cross-shelf barotropic pressure gradient (Matano and Palma 2010). Coastal currents; tidal currents and winds can modify plume dynamics in a complex manner (Garvine 1975). At the boundary between the plume and the marine coastal waters, the low salinity buoyant waters ride on the top of denser saline waters, forming plume fronts where surface convergence and downwelling occur (Mann and Lazier 2006) (Fig. 2.3a).

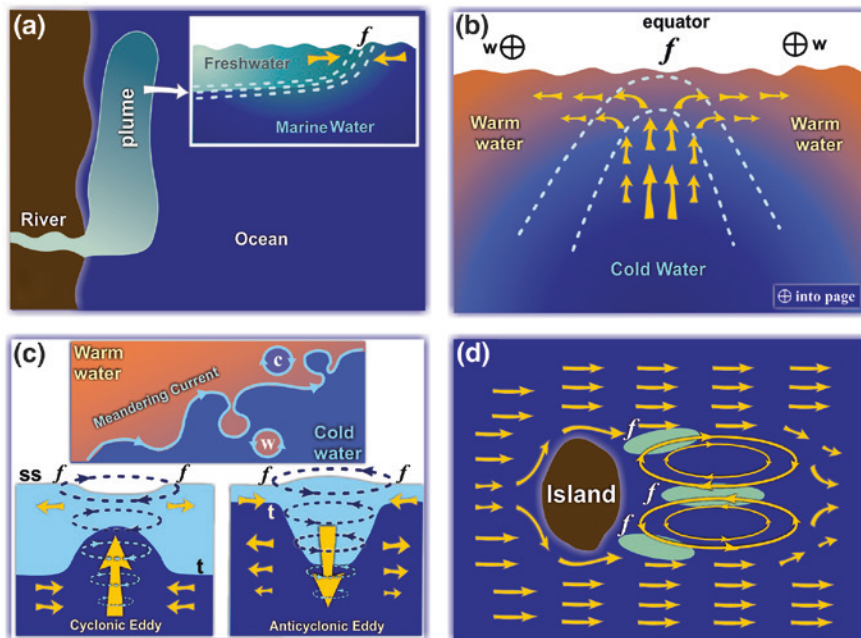


Fig. 2.3 Frontal types. **a** Plume front (southern hemisphere); **b** divergence front; **c** frontal eddies (*top panel*) show eddies formation from a meandering current, *w* warm core eddy; *c* cold core eddy. *Lower panels* show fronts (*f*) at convergences created in cyclonic or anticyclonic (southern hemisphere) eddies, modified from Mann and Lazier (2006) and Bakun (2006a); **d** topographically controlled front (*greenish* areas indicate convergence frontal zones), modified from Wolanski and Hamner (1988). *f* front; *ss* sea surface; *t* thermocline; *w* wind; *arrows* are currents; *dashed lines* in **a** and **b** are lines of equal density

2.6 Fronts Associated with the Convergence or Divergence of Water Masses at High Seas

In the Pacific, a westward current driven by the Trade winds is located roughly between 5°S and 5°N. The Earth rotation leads to divergence of the Ekman layer away from the equator, which is compensated by upwelling from subsurface layers (Fig. 2.3b). The upwelling in turn is compensated by equatorward flows below the mixed layers in both hemispheres (Wyrтки and Kilonsky 1984; Johnson et al. 2001). Upwelling of cool subsurface water forms a cold tongue along the equator: the equatorial upwelling and creates an extended thermal front of moderate intensity. This thermal front shows some degree of seasonality in response to the seasonal pattern of the trade winds (Mann and Lazier 2006). A relatively strong upwelling system referred to as the Antarctic Divergence is observed in the Southern Ocean. This system is caused by opposing southern hemisphere mid-latitude westerlies and high-latitude easterlies. Here the winds and the Earth rotation drive a flow divergence in the upper layers. Along the line of strongest wind stress curl separating

the two wind systems the upper layer divergence is compensated by upwelling (the Antarctic Divergence). A major flow of this upwelled water extends northward as far as the Antarctic Convergence or Polar Front (Mann and Lazier 2006). The Antarctic Convergence, which encircles Antarctica roughly 1,500 km off the coast, divides the colder and fresher southern water masses and the warmer and saltier northern waters; creating the largest pelagic boundary of the world ocean (Sournia 1994). Based on water mass properties within the Antarctic Circumpolar Current (ACC) three major transitions are apparent, referred to as the Subantarctic Front, the Polar Front, and the Southern ACC Boundary (Orsi et al. 1995). Changes in sea surface height determined from satellite altimeter indicate each of these fronts is in fact formed by three coherent fronts (Sokolov and Rintoul 2009). The most conspicuous open ocean fronts are those formed at the transitions between the poleward extensions of warm-salty western boundary currents (e.g. the Gulf Stream; Kuroshio; Agulhas and Brazil currents) and cold-less saline subpolar waters. As the ACC deflects northward downstream of Drake Passage the Subantarctic Front penetrates northward in the South Atlantic and nearly merges with the Subtropical Front creating even more intense surface gradients. These fronts are characterized by strong frontal jets and strong surface temperature, salinity and nutrient gradients, and are frequently associated with intense eddies and meanders that developed by instabilities of the mean flow (Fig. 1.1).

2.7 Frontal Eddies

Eddies and large-scale meanders are ubiquitous features of the ocean circulation and naturally emerge from instabilities of the mean flow. There are several classes of rings or eddies in the ocean, originated by different forcing and covering a range of spatial and temporal scales; we consider here just one type: the frontal eddies. They contain pockets of moving water that break off from the main body of a front and can travel independently, covering long distances before dissipating. Eddies are commonly found in the vicinity of faster flowing currents that form intense fronts with the surroundings waters, such as the Gulf Stream, the Kuroshio Current, the Brazil Current, the Agulhas Current and the Antarctic Circumpolar Current. Strong currents meander in a wave-like fashion and become unstable; these flow instabilities lead to pinching off of relatively warm or cold waters that act as a seed for frontal eddies. The water within such eddies has temperature and salinity characteristics different from the surrounding waters. Frontal eddies can take the shape of warm-core (masses of warm water turning within colder ocean waters) or cold-core (masses of cold water within warmer waters) eddies (Fig. 2.3c). Eddies nearly always contain embedded frontal interfaces, and like other frontal types, embody mechanisms by which the physical energy of the ocean system can be converted to trophic energy to support biological processes. Recent high resolution observations and numerical models also indicate that relatively short lived (~ 1 day) submesoscale structures (1–10 km) may significantly

contribute to pumping nutrients to the upper layer, subsequently increasing the ocean primary productivity (Lévy et al. 2001, 2012; Klein and Lapeyre 2009; D’Asaro et al. 2011). Fronts are therefore “hot spots” of intense biological and physical activity (Olson and Backus 1985; Olson et al. 1994; McGillicuddy et al. 1988; Bakun 2006a).

2.8 Fronts Associated to Geomorphic Features

Some fronts are topographically controlled. When tidal or other currents interact with irregularities in the sea bed, or coastline, it is usual to find consistent patterns of eddies and associated fronts. These obstacles to the flow create accelerations in the direction perpendicular to the upstream flow direction as well as frictional boundary layers close to the obstacle. These forces, together with vertical stratification and the Earth’s rotation determine the path of flow particles around the obstacle. Thus, the presence of a headland, an island, a bank, a reef or an undersea mountain cause a disturbance in the flow generating complex three-dimensional secondary flows of various scales (Aristegui et al. 1994; Dong et al. 2007) that result in a physical front (Fig. 2.3d) (Wolanski and Hamner 1988). Direct observations and numerical simulations indicate that these structures display enhanced phytoplankton growth (Dong et al. 2009).

Ecological Processes at Marine Fronts

Oases in the ocean

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