benthic juvenile phase and settle on the bottom. The clues used by settling larvae to select the appropriate substratum are poorly known but there is some evidence to suggest that individuals can discriminate between substratum types and settle on their preferred type.

See also

Fish Ecophysiology. Fish Larvae. Mangroves. Rocky Shores. Salt Marshes and Mud Flats. Sandy Beaches, Biology of.

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INTRA-AMERICAS SEA

G. A. Maul, Florida Institute of Technology, Melbourne, FL, USA

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Introduction

The Intra-Americas Sea (IAS) is a semi-enclosed salt-water body of the tropical and subtropical western Atlantic Ocean that comprises the Caribbean Sea, the Gulf of Mexico, the Straits of Florida, the Bahamas, the Guianas, and the adjacent waters. Biogeographically, the IAS includes the estuarine, coastal, shelf, and pelagic waters from the mouth of the Amazon River at the equator off Brazil, to Bermuda and westward to the shores of North, Central, and South America. Geographically, the boundaries may be set approximately as $\phi = 0^\circ$ to 32°N latitude, and $\lambda = 50$–98°W longitude. **Figure 1** summarizes the geographical setting.

Early oceanographic explorations of the region were by European scientists who chose to name the IAS (the Caribbean Sea in particular) the 'American Mediterranean'. While superficially this terminology describes the IAS as a similar semi-enclosed sea where evaporation (E) exceeds precipitation (P) plus river runoff (R), $E > P + R$, the Mediterranean Sea is markedly different in character from its western Atlantic counterpart. Also, the IAS was broken into smaller components, and little attention was paid to the Caribbean Sea and by Gulf of Mexico oceanographers and vice versa. Conversely, the Straits of Florida and the water currents of the Gulf Stream system are perhaps the most widely studied oceanographic features on Earth.

With the coming of significant international cooperation between scientists from throughout all the Americas, the IAS began to be appreciated as a unified body of water distinctly different from the early and mid-twentieth century European perspective. An inclusive term was needed to integrate not only the oceanography of the region, but its meteorology and maritime socioeconomic connectivity as well. Thus the term Intra-Americas Sea was developed from the multilingual and multicultural heritage shared by its people.

Regional Overview

Pre-Columbian indigenous peoples of the Intra-Americas Sea certainly knew of the oceanic currents and atmospheric winds. Caribes from the south, Tainos in the middle Antilles, Arawaks from the north, Mayas and Olmecs to the west, all moved freely from island to island to continent, presumably with some knowledge of the currents and winds we have named Caribbean Current, Trade Winds, Gulf Stream, Hurricane, and Guianas Current. European explorers and conquistadors relearned this information, not from the IAS's inhabitants, but from hardship after experiencing what was so well known already. James A. Mitchner's 1989 novel *Caribbean* imagines so well what science could have learned directly.

As regards the geological setting, the IAS encompasses three tectonic plates: the North American Plate, the Caribbean Plate, and the South American Plate (the Cocos and Nazca Plates mark Pacific tectonic boundaries but are not significantly involved in the air–sea regime discussed herein). About 3 Ma the Caribbean Plate drifting from west to east closed the gap between North and South America, creating Panama and deflecting oceanic flow northward. Central America and the eastern Caribbean margin are volcanically active today.

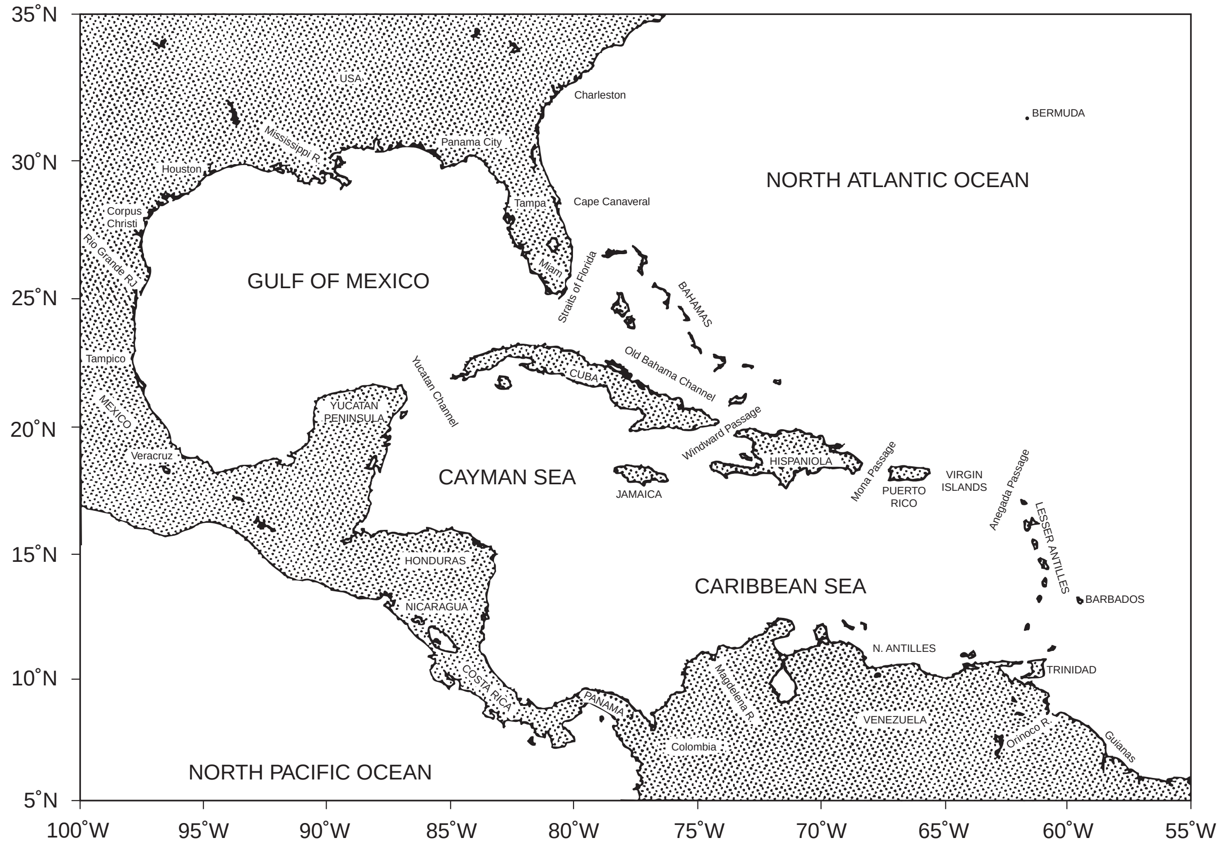

Figure 1 The Intra-Americas Sea, a semi-enclosed water body of the subtropical and tropical western North Atlantic Ocean. Place names in accord with the US Board on Geographic Names.

Associated with tectonics are earthquakes and seismic sea waves (tsunami) that are part of the circulation regime, as well as the complex bottom topography that channels water movement and perturbs the atmospheric circulation.

Geological forces then not only form the coasts and islands of the IAS; they are a central element in appreciating the flow of air and water. Geophysical fluids obey Newton's laws of motion, specifically $\sum F = \sum m \cdot a$ (where F is force, m is mass, and a is acceleration), the laws of thermodynamics, and continuity of mass. The air and water of the IAS are accordingly connected to all of Earth's ocean–atmosphere continuum, and have special complexities as they flow around and through the passages, channels, and straits within the region. Thus detailed knowledge of the water depths and land heights, and their attendant frictional characteristics, is essential to appreciating the flow patterns discussed below.

Sill depths control much of the oceanic flow patterns in the IAS. It has been reported that the deepest sill is in the Yucatan Channel (2040 m) between Mexico and Cuba, that the average sill-depth of the Antillean Arc is 1200 m, but that the Jungfern-Anegada Passage is 1815 m deep (between the Virgin Islands and the Lesser Antilles), and that the Windward Passage separating Cuba and Hispaniola is 1690 m deep. Within the IAS are many much deeper basins than these controlling sills, leading to the notion that the waters deeper than the sill depths are moved by convection rather than advection. This infers that the IAS has a two-flow regime: an upper layer mostly influenced by wind-driven advection, and a deep layer controlled by overflows. The controlling sill depth of the Straits of Florida is about 800 m, which means that the outflow of the IAS is topographically accelerated. **Figure 2** summarizes the IAS water depth information.

Lastly, to appreciate the ocean currents of the Intra-Americas Sea, the structure of atmospheric forcing needs to be mentioned. The southern portion of the IAS is under the influence of the Inter-Tropical Convergence Zone, the ITCZ. In the Northern Hemisphere summer, the ITCZ migrates northward and the easterly Trade Winds at the southern boundary of the Bermuda meteorological high-pressure zone dominate the IAS to its northern

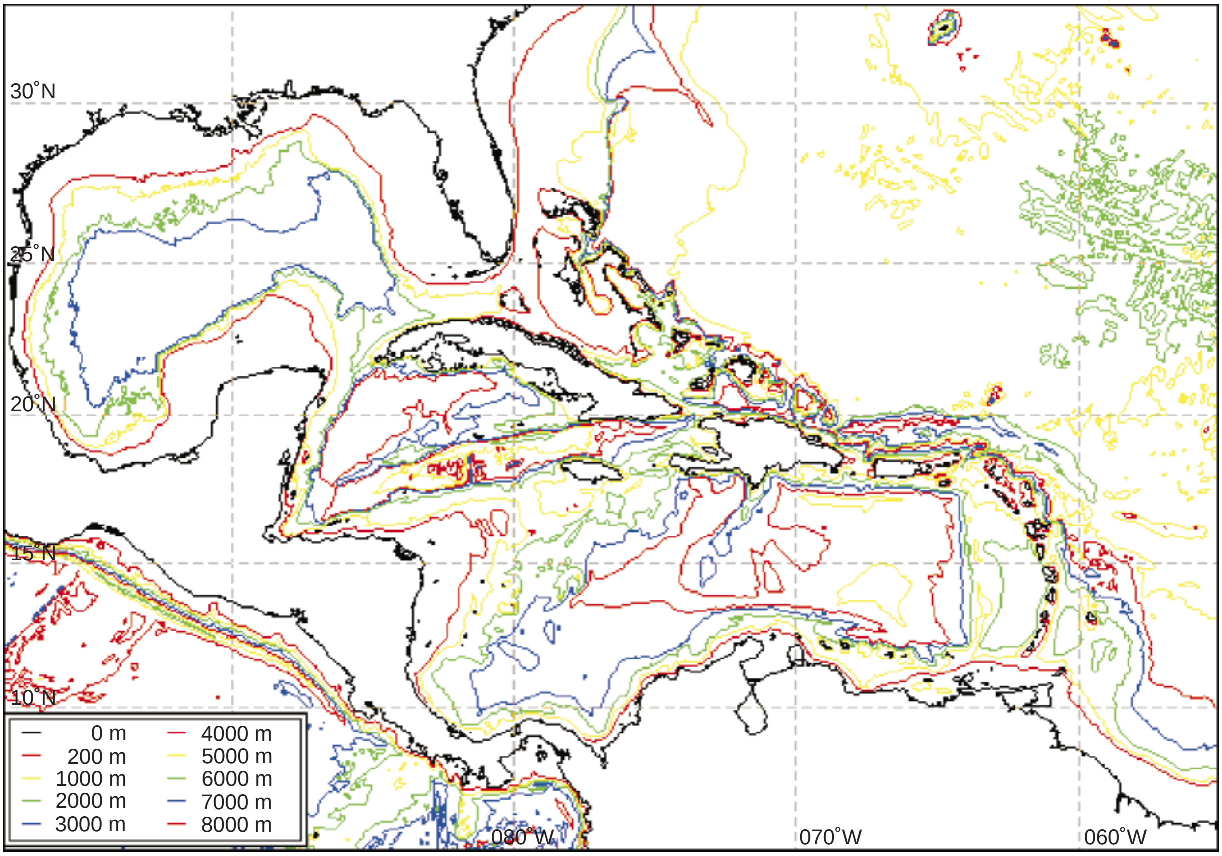

Figure 2 Bottom topography of the Intra-Americas Sea; water depths in meters.

extent. As boreal winter approaches, the ITCZ migrates southward and the midlatitude frontal passages sweep across the IAS to south of Cuba and sometimes almost to South America. During early autumn, the atmosphere is characterized by a series of tropical cyclones, that from time to time reach intensities known as the West Indian Hurricane. These severe atmospheric disturbances are cyclonic circulation features that bring not only strong winds, storm surge, and the associated damage, but also much needed precipitation and flushing of shallow bays and estuaries.

Climatologically, the Köppen classification system would place the northern IAS in a *Cfa* (humid subtropical) category; coastal Central America, the Greater Antilles and the Bahamas as *Aw* (tropical wet and dry) with sections as *Af* (tropical rain forest) including the Lesser Antilles. The southern and south-eastern coastal IAS is classified as *BSh* and *BW* (semi-arid or steppe, and arid desert, respectively), with *Am* (tropical monsoon) along the coasts of the Guianas and Brazil. These classifications are perturbed by interannual and decadal climate oscillations, in particular by El Niño–Southern Oscillation (ENSO) events, which tend to cause cold wet winters in the northern IAS (particularly Florida and Cuba) and warm dry autumn conditions in Panama, coastal Colombia and Venezuela, the Guianas, and northern Brazil.

Surface Throughflow Regime

Perhaps the best way to envision IAS surface currents is to take a Lagrangian perspective, and imagine floating on a northbound satellite-tracked buoy passing the equator off Brazil as part of the 'oceanic conveyor belt'. As the water parcel travels northward, perhaps entraining some Amazon River water, the dominant physics is conservation of potential vorticity, $\mathrm{d}/\mathrm{d}t[\varsigma + f/H] = 0$, where relative vorticity $\varsigma = \partial v/\partial x - \partial u/\partial y$, the Coriolis parameter $f = 2\Omega \sin \phi$ with latitude ϕ, and water depth H. For a given H, as the parcel flows northward, f increases and ζ must decrease, forcing an anticyclonic (clockwise) turning. The region where this occurs is called the North Brazil Current 'retroflection' and can be seen in satellite images as a distinct offshore turning of the current. Some of this water continues toward the east in the North Atlantic Equatorial Counter-Current, but some advects up the South American coast in the Guianas Current to the Lesser Antilles Arc, sometimes as an anticyclonic eddy. Much of this is evident in **Figure 3**.

The northward-flowing water parcel usually passes Barbados and often flows through the passages of the Lesser Antilles, carrying anticyclonic vorticity and perhaps Amazon riverine particles and biota into the Caribbean Sea. Under the influence of the North-east Trade Winds, the Caribbean Current moves westward at a leisurely pace of perhaps $0.2\,\mathrm{m\,s^{-1}}$, but with notable meandering and eddying along the path. Sometimes under this same wind regime, water from the Orinoco River is seen to be carried completely across the eastern Caribbean Sea to Puerto Rico and Hispaniola, particularly in late summer.

Similarly, in the Panama-Colombia Bight, the wind-stress (τ) curl, $\partial\tau_y/\partial x - \partial\tau_x/\partial y$, causes an $r \approx 150\,\mathrm{km}$ radius eddy to spin-up and spin-down annually, the so-called Panama-Colombia Gyre (PCG). In the vicinity of the PCG a major South American river, Colombia's Magdalena, flows into the ocean where its waters and its flotsam mix with the sea, and are carried to distant shores by ocean currents. The PCG is but one feature of the IAS surface current variability now being simulated in numerical models, and being observed by systems such as satellite altimeters and radiometers.

As the meandering, eddying, Caribbean Current approaches the Central America coast, it is forced anticyclonically northward into the Yucatan Channel. In the area off Belize and Yucatan Mexico, this IAS current takes on the characteristics of the Gulf Stream: a deep ($z \approx 1200\,\mathrm{m}$) western boundary current with swift surface flows of more than $\vec{v} = 1\,\mathrm{m\,s^{-1}}$ and a distinct cyclonic horizontal velocity shear boundary, $\partial\vec{v}/\partial x$, along the western edge. Here the stream is known as the Yucatan Current, and it is a northward flow connecting the Caribbean Sea with the eastern Gulf of Mexico.

Gallegos (1996) has shown that the Yucatan Current is highly geostrophic, the balance of forces (per unit mass) being $f\vec{v} = 1/\rho\,\partial p/\partial\vec{n}$, where ρ is the density of sea water, and $\vec{v}$ is the current speed at right angles to the horizontal pressure gradient, $\partial p/\partial\vec{n}$. Gallegos also studied the temperature–salinity (T–S) structure of the Yucatan Current and has concluded that it has T–S properties similar to those

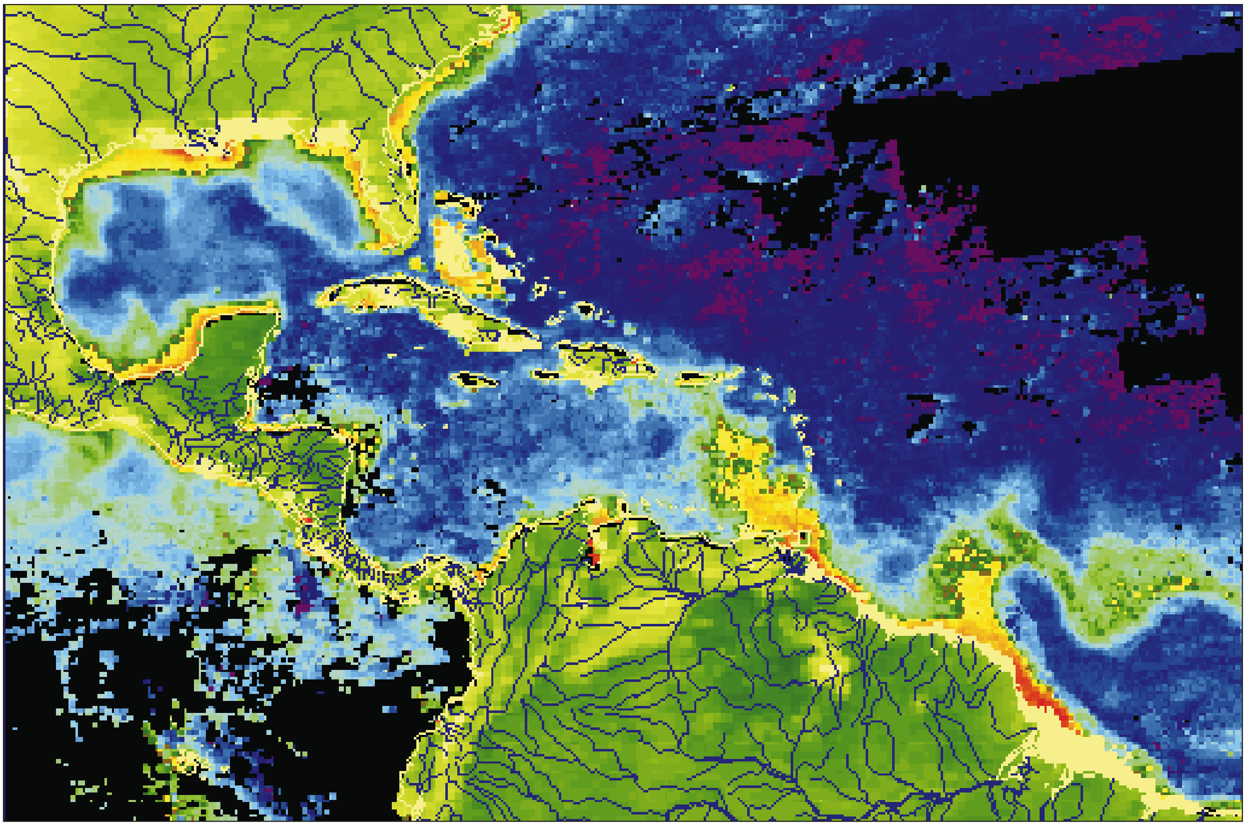

Figure 3 Ocean color composite of the Intra-Americas Sea showing concentration of chlorophyll + phaeophytins and suspended sediments. Image from observations of the Coastal Zone Color Scanner (NASA) compiled by Frank Muller-Karger for October 1979.

in the offing of Cape Hatteras. As this branch of the Gulf Stream system flows northward, it forces a vigorous upwelling regime along the eastern Campeche Bank that supports one of the IAS's greatest fisheries.

Once in the Gulf of Mexico, the Yucatan Current is known as the Gulf Loop Current because of its characteristic anticyclonic looping from northward to eastward to southward to eastward again as it exits the Gulf of Mexico through the Straits of Florida. This clockwise turning of the Gulf Loop Current is part of a cycle of growth (penetrating into the Gulf of Mexico almost to the latitude of the Mississippi River Delta, $\phi \approx 30°\mathrm{N}$), then turning eastward and southward to run along the west Florida escarpment. Near the latitude of Key West ($\phi \approx 24°\mathrm{N}$), the current turns sharply cyclonically and begins to run eastward in the Straits of Florida, where it is now called the Florida Current. Once the Gulf Loop Current has reached its maximum latitudinal extent, a large anticyclonic current ring, 100–150 km radius, separates from the flow, and the main current reforms farther south near the latitude of the Florida Keys. In its southernmost position, the Gulf Loop Current flows into the Gulf of Mexico, and turns rather sharply in an anticyclonic turn to exit almost directly into the Straits of Florida (**Figure 4**).

Anticyclonic Gulf Loop Current rings have all the T–S and flow features of the Gulf Stream system, just as in the Yucatan Channel and in the Straits of Florida. The ageostrophic dynamic balance is $\pm\vec{v}^2/r + f\vec{v} - 1/\rho\,\partial p/\partial\vec{n} = 0$, where r is the radius of curvature, and where $\pm\vec{v}^2/r$ is positive in cyclonic curvature and negative in anticyclonic. Accordingly, flow is super-geostrophic in anticyclonic turns, and sub-geostrophic in cyclonic turns. Identical dynamics describe midlatitude upper tropospheric flows in Earth's atmosphere, notably in the Jet Stream.

A separated Gulf Loop Current ring travels westward into the western Gulf of Mexico, most probably by a self-propulsion mechanism associated with the beta effect, $\beta = \partial f/\partial y$, of differing Coriolis parameter between the southern and northern ring edges. Using the hydrostatic equation, $\partial p = \rho g \partial z$, the horizontal pressure gradient term $1/\rho\ \partial p/\partial\vec{n}$ may be written as $g\partial h/\partial\vec{n}$, and for an anticyclonic Gulf Loop Current ring with a diameter of 300 km and $\partial h = 0.75\,\mathrm{m}$, it is calculated using $-\vec{v}^2/r + f\vec{v} - g\partial h/\partial\vec{n} = 0$ that eddies self-propagate at speeds of 5–10 cm s^{-1} ($\approx$ 5–10 km d^{-1}).

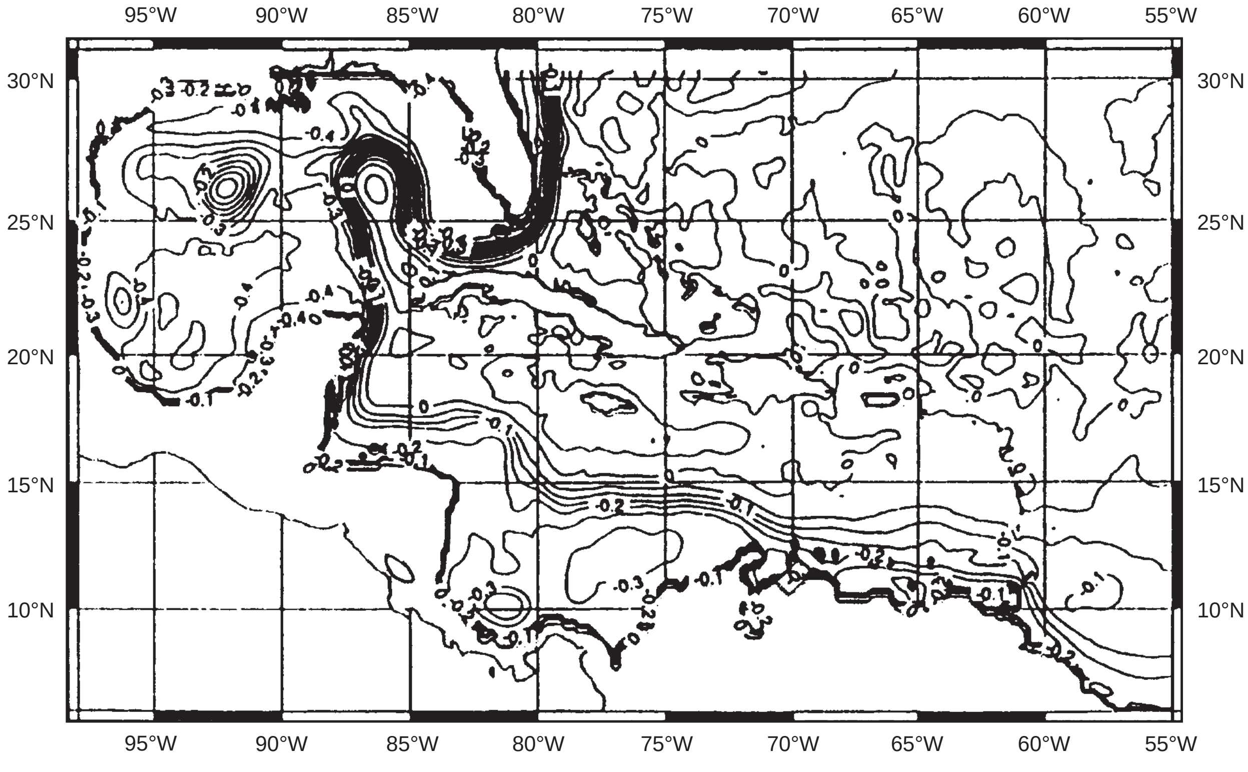

Figure 4 Sea surface height (h) in meters from numerical model calculations as reported in Mooers and Maul (1998). Geostrophic surface currents are calculated from $f\vec{v} = 1/\rho\partial p/\partial\vec{n} = g\partial h/\partial\vec{n}$. Anticyclonic eddies are isolated concentric height maxima, the largest of which is shown in the western Gulf of Mexico; cyclonic eddies have the opposite surface height field.

Direct observations from satellite-tracked buoys and from satellite altimeter measurements of sea surface height (h) substantially agree with such calculations.

As these Gulf Loop Current rings travel to the west, they begin to spin down, losing their momentum per unit volume, $\rho\vec{v}$, to horizontal friction and eventually mixing in with the ambient Gulf of Mexico Common Water. The lifetime of the current rings is typically 6 months, and they carry with them the temperature, salinity, and other characteristics of their source region, the Caribbean Sea. Approximately $3 \times 10^{13}\,\mathrm{kg\,y^{-1}}$ of salt is injected into the western Gulf of Mexico by an average Gulf Loop Current ring. Thus the salt balance of the western Gulf of Mexico is decidedly nonMediterranean, $E + \delta = P + R$, because in the IAS the classical evaporation/precipitation/runoff equation requires an additional term δ to account for the infusion of high salinity water from the rings. Typical values for these terms are $E\text{–}P \approx 35\,\mathrm{cm\,y^{-1}}$, $R \approx 75\,\mathrm{cm\,y^{-1}}$, and the volume of fresh water to maintain the salt balance $\delta \approx 40\,\mathrm{cm\,y^{-1}}$.

The Gulf Loop Current interacts with the fourth great riverine system of the IAS, the Mississippi River. As the Gulf Loop Current nears the Mississippi Delta, it is observed to entrain or advect the river water to the east. Mississippi River water has been observed by its low surface salinity all along the eastern edge of the Current, into the Straits of Florida, and up the east coast of the USA at least to Georgia ($\phi \approx 32^\circ$N), the northern boundary of the IAS. Thus the four great rivers of the IAS, the Amazon, the Orinoco, the Magdalena, and the Mississippi, and the many smaller tributaries, are all known to interact with the oceanic flows and to be carried great distances by them. This is an important transport mechanism in the IAS whereby riverine flotsam and jetsam is found on distant shores. This same flow-through regime is also responsible for the considerable impact of tars from maritime commerce and from oil drilling on the highly valuable tourist beaches of the area (cf. **Figure 3**).

Gulf Loop Current ring shedding seems to have a cycle of 10–11 months on average, with some rings being shed in as few as 6 months and others taking 17 months. This is a surprising frequency since it is not at the annual harmonic where many other oceanic features have a spectral peak. Gulf Loop Current ring shedding has been simulated by IAS numerical models, and super-annual periods are often calculated. The cycle of ring formation does not seem to be forced by the unmistakable annual cycle of volume transport, $\iint v(x,z)\,\mathrm{d}x\,\mathrm{d}z$, in the Gulf Stream system, with its maximum in June and minimum in October, nor by variability in the Caribbean Current along 15°N, which has a spectral peak at about 75 days. Connectivity between flow variability in the Caribbean Sea and the Gulf of Mexico seems remarkably weak.

In the Straits of Florida, the Florida Current turns cyclonically as it passes between Cuba, Florida, and the Bahamas. The lesser passages of the Straits of Florida contribute small amounts to the total volume transport, which by now is at the level of $30\,\mathrm{G\,s^{-1}}$ ($30 \times 10^6\,\mathrm{m^3\,s^{-1}}$) or about 30 Sv. At the latitude of Palm Beach, Florida ($\phi \approx 27^\circ$N), the meridional oceanic heat transport, $\iint \rho Cp\,Tv(x,z)\,\mathrm{d}x\,\mathrm{d}z$, is about 1.5 petawatts ($1.5 \times 10^{15}\,\mathrm{W}$), an amount comparable with the atmosphere at the same latitude. Transport is known to vary on timescales ranging from days to years. Fortnightly volume transport changes are observed to range from 20 Sv to 40 Sv, a value much larger than that of the annual cycle, which is more likely less than $\pm 5\,\mathrm{Sv}$.

In the narrow confines of the northern Straits of Florida, lateral friction is significantly larger than in the open sea. Here, from extensive *in situ* studies, the Guldberg-Mohn friction coefficient J in quasi-geostrophic flow $fv = g\partial h/\partial x + Jv$ has been estimated at approximately $4 \times 10^{-5}\,\mathrm{s^{-1}}$, one to two orders of magnitude larger than away from continental boundaries. In addition, the Florida Current axis meanders to the west when transport is high and to the east when it is less. Such detailed transport variations in other regions of the IAS are not as well documented as in the Straits of Florida between Palm Beach and the Bahamas.

North of the Straits of Florida the current is called the Gulf Stream, a name it retains to the offing of Nova Scotia. The flow northward to Cape Hatteras, North Carolina ($\phi \approx 35^\circ$N), seems to be topographically controlled, whereby H in the potential vorticity equation (above) directs onshore and offshore meandering. Near Charleston, South Carolina ($\phi \approx 32^\circ$N), a notably shallow area decreases H significantly, and the current responds by turning anticyclonically ($\varsigma < 0$) into deeper water. Once offshore, the larger value of H causes the flow to turn cyclonically again ($\varsigma > 0$) in a series of meanders as it progresses downstream (cf. **Figure 3**).

Along the outer boundary of the IAS, a surface flow with a great deal of changeability is observed, called the Antilles Current. This intermittent current, carrying on average about 15 Sv, progresses northward up the margin of the Caribbean Sea, along the eastern outer banks of the Bahamas, and eventually joins the Gulf Stream north of Cape Canaveral, Florida ($\phi \approx 29^\circ$N). Satellite-tracked buoys and subsurface floats both show the latitude of the Bahamas to be an area of great temporal and spatial variability, with many eddies of various sizes, and with inflows to the Straits of Florida through the Old Bahama Channel and the Northwest Providence Channel. The general sense is that of converging surface flows all feeding the Gulf Stream system.

Subsurface Flow Regime

The strong surface currents of the Gulf Stream system decrease with depth. Mathematically, this can be explored by applying Leibnitz' rule to the integral form of the hydrostatic equation $p = \int_h^z \rho g dz$. The geostrophic equation (above) can then be expressed as:

$$\rho f \vec{v} = \rho g \partial h / \partial \vec{n} + \int_h^z g \partial \rho / \partial \vec{n} dz$$

where the first term on the right-hand side is the barotropic term, and the integral term on the right-hand side is the baroclinic term. Facing downstream $\partial \rho / \partial \vec{n}$ is negative, and the surface current (at $z = h$) decreases with depth until the two terms on the right-hand side become equal and opposite. This depth is called the level-of-no-motion and $\vec{v} = 0$. In the Yucatan Channel, the level-of-no-motion is approximately 1200 m, but in the northern Straits of Florida ($\phi \approx 27°\mathrm{N}$) northward-flowing currents as much as $0.3\,\mathrm{m\,s^{-1}}$ reach to the seafloor at 800 m.

Details of the flows into and out of the Intra-Americas Sea at depth in other passages are less well known than the surface flows. Numerical models and observations suggest a general inflow though the passages of the Lesser and Greater Antilles into the Caribbean Sea, an outflow through the Yucatan Channel into the Gulf of Mexico, and continuing flow into the North Atlantic Ocean north of the Bahamas. Near the sill of the Yucatan Channel, approximately 100 m above the ocean floor, the flow is decidedly from the Gulf of Mexico into the Caribbean Sea. In the Windward Passage, there is also evidence of north-eastward outflow at depth, but it seems not to be as persistent as that in the Yucatan Channel.

A major characteristic of the deep waters of the IAS is their nearly isothermal and isohaline profiles below the depth of the major sills. The ocean, being a stratified fluid, tends to inhibit vertical mixing. Thus the sub-sill depth waters are characterized by near-zero vertical density gradients, $\partial \rho / \partial z \approx 0$, and are neutrally stable. Deep IAS waters have the T–S characteristics of the offshore waters of the juxtaposed North Atlantic Ocean, which seem to spill over the sills from time to time to replenish and ventilate the water interior to the IAS. Thus there must be a surging of sorts to bring into the Caribbean basin in particular, renewing mid-depth North Atlantic Common Water.

Along the eastern margin of the IAS at about 2000–3000 m water depth is a southward-flowing mid-level current called the Deep Western Boundary Current (DWBC). The DWBC has its genesis in the thermohaline circulation of the North Atlantic Ocean, north of the Denmark Strait, and is part of the global conveyor belt. The DWBC flows along the entire outer boundary of the IAS, and has a volume transport of approximately 15 Sv. This extremely important flow is climatically linked to the role of the ocean in Earth's heat budget and may participate in the complexities of the IAS's deeper flow patterns.

Other Currents in the IAS

Tidal currents in the IAS are generally weaker than in other semi-enclosed seas. The tides are typically semi-diurnal on the Atlantic Ocean margin of the IAS (M_2 and S_2 constituents usually), and progressively become diurnal in the Gulf of Mexico where the K_1 and O_1 constituents dominate. Estuaries such as the Mississippi Delta are of the salt-wedge category, mostly because the tidal currents and ranges are small and the river flows very large (average for the Mississippi River is about $10^3\,\mathrm{km^3\,y^{-1}} \approx 0.03\,\mathrm{Sv}$). Tidal currents around many IAS islands are similarly weak, with extremes rarely exceeding $\vec{v} = 1\,\mathrm{m\,s^{-1}}$ even in passes through the many bar-built barrier island lagoons.

Inertial currents are a ubiquitous feature of the ocean, and are characterized by periods $= 12^h/\sin \phi$. In the northern IAS, inertial currents often have periods equal to the dominant diurnal tidal currents, such as the K_1 or the O_1 because $\sin\phi \approx 0.5$. At these critical latitudes, the inertial currents are not separable from the diurnal currents in the tidal spectrum. Inertial currents, when they occur, are intermittent and have velocities typically below $\vec{v} = 0.2\,\mathrm{m\,s^{-1}}$.

Current flows past islands can induce complex patterns in their lee. Numerical models and observations suggest von Karman vortex streets downstream of many island land masses (**Figure 5**). Such complex currents can cause engineering design complexities, particularly regarding waste disposal and spills. Similarly, with the normally low wave heights so characteristic of the IAS, the longshore and littoral currents are also weak, although in certain

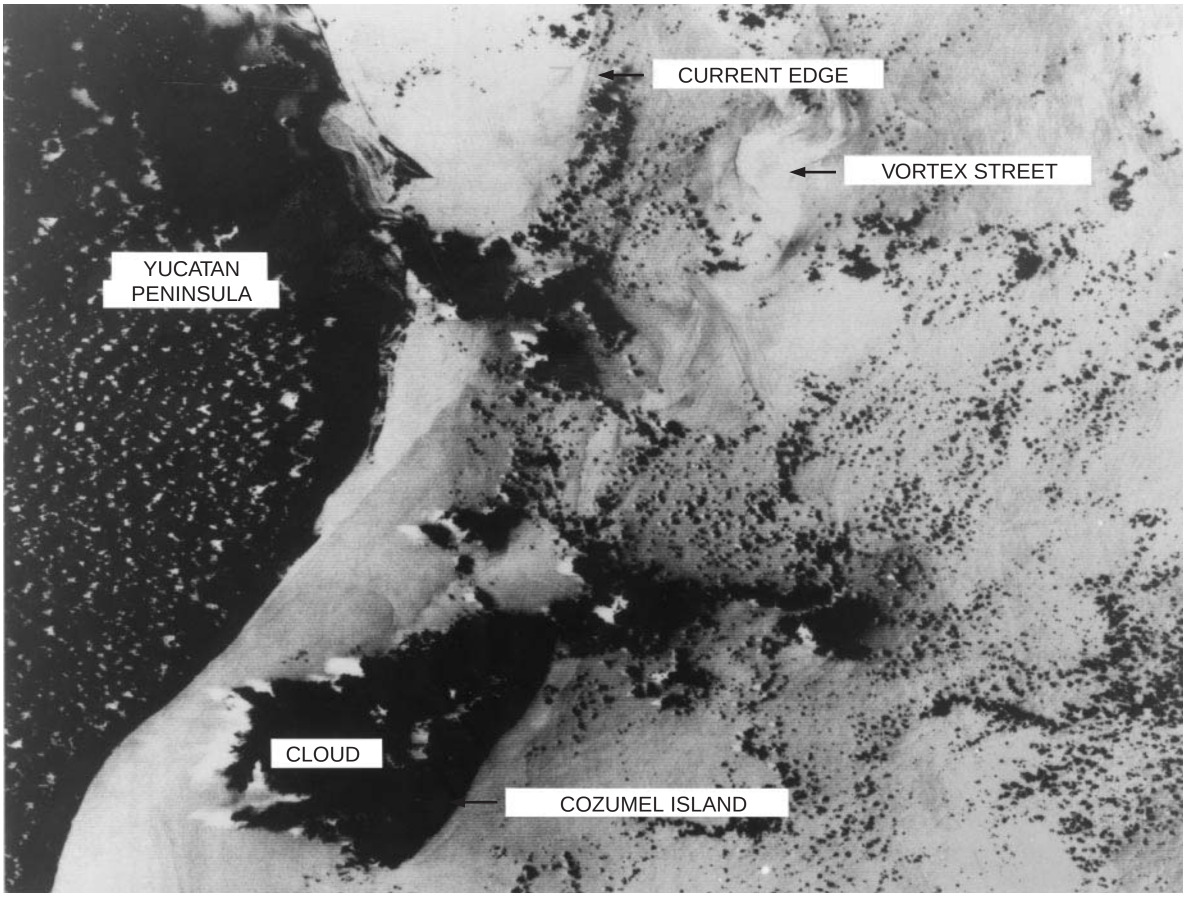

Figure 5 LANDSAT negative image of surface-wave glitter patterns showing von Karman vortices downstream of Cozumel Island in the Yucatan Channel. For scaling, Cozumel Island is approximately 50 km long.

areas, especially the east coast of Florida, dangerous wave-induced rip currents are very common.

Perhaps the most significant physical marine hazard in the Intra-Americas Sea is the combined storm surge and inverted barometer effect associated with hurricanes. Along linear coasts, the water level elevation from a major storm can exceed 7 m, on top of which may be 3 m or greater wind waves. Little is directly known of the currents associated with storm surges, but indirect evidence suggests that they can exceed $\vec{v} = 1\text{–}2\,\mathrm{m\,s^{-1}}$, especially in the vicinity of harbor entrances and inlets. Small islands are less at risk from large storm surge-driven currents than are long, low coasts with shallow offshore bottom topography. While storm surge currents are transient features of the IAS with timescales of approximately half a day, they can be costly to infrastructure, and very dangerous to human life.

Upwelling is a vertical current of note in the IAS, especially along the long east–west tending north coast of South America. Here the zonal wind stress τ_x can force an Ekman upwelling with mass transport per unit width $M_y = \int \rho v dz$ given by $M_y = \tau_x/f$. Accordingly, the easterly Trade Winds force a northward mass transport along the coast, and the ocean responds with classical coastal upwelling as seen in the $\approx 3°\mathrm{C}$ cooler sea surface temperatures along Venezuela. The same physical circumstances cause open-ocean Ekman pumping in the wake of hurricanes. The hurricane's large cyclonic wind stress, $\tau = \rho_{air} C_d v_{air}^2$, forces mass transport $M_{x,y}$ in all directions away from the storm center with attendant lifting of the thermocline and upwelling. Lower sea surface temperatures are often observed as a cool streak in the wake of these intense air–sea storm systems.

While the danger from seismic sea waves (tsunami) is recognized as another although largely unappreciated natural hazard of the IAS, it is the waves and wave particle motions that create currents of such great danger. Caribbean tsunami waves have been observed to exceed 9 m in height. Since a tsunami is a progressive shallow-water wave

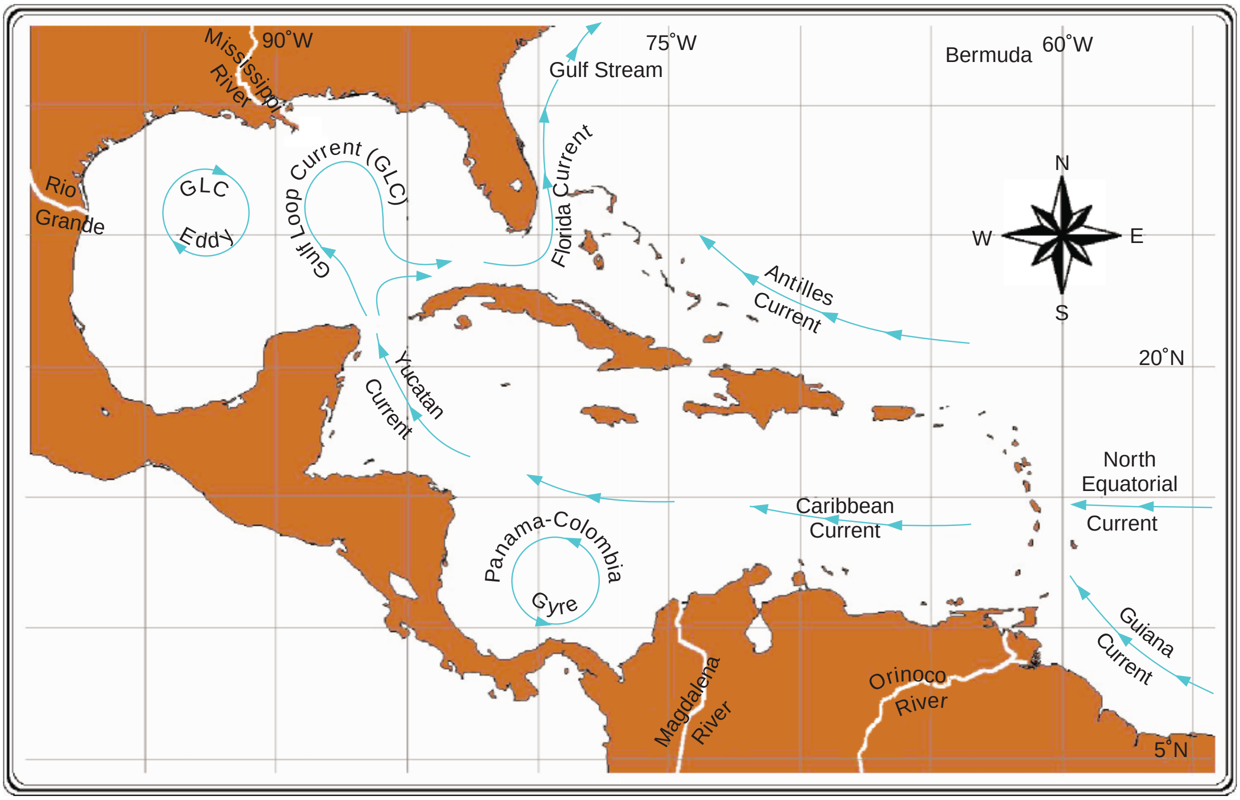

Figure 6 Summary of surface currents in the Intra-Americas Sea. Maximum IAS sea surface height variability $h = \pm 24$ cm is centered in the Gulf Loop Current (GLC) at $\phi = 26°$N, $\lambda = 88°$W; a second maximum in the Caribbean Current of $h = \pm 12$ cm is centered at $\phi = 15°$N, $\lambda = 77°$W.

with celerity $c = \sqrt{gH}$, the maximum currents come at the wave crest and at the wave trough. These currents probably exceed $\vec{v} = 10\,\mathrm{m\,s^{-1}}$, and have timescales of several minutes. In that short amount of time however, even more danger exists than with storm surge currents, and the small islands are equally as vulnerable as are the continental coasts.

Conclusions

Intra-Americas Sea surface currents (**Figure 6**) are dominated by a single fact: the IAS is the formation region of the Gulf stream system. Except along the northern coast of the Gulf of Mexico, the volume transport of the interior thermohaline component of IAS currents is minuscule compared with the wind-driven component. While there are important external and peripheral currents associated with the global thermohaline flow such as the Deep Western Boundary Current, it is the North Brazil Current–Guianas Current–Caribbean Current–Yucatan Current–Gulf Loop Current–Florida Current–Gulf Stream family of atmospheric wind stress-forced advective movements that characterizes the region (cf. **Figure 4**). All these 'currents' are in reality one current that, coupled with air–sea heat and moisture fluxes and winds, integrate into a single continuum that connect the Intra-Americas Sea and its peoples.

List of Symbols

c	wave celerity
f	Coriolis parameter
g	gravity
h	sea surface height
$\vec{n}$	direction vector parallel to pressure gradient
p	pressure
r	radius of curvature
t	time
u, v, w	eastward, northward, upward speed
$\vec{v}$	velocity vector orthogonal to $\vec{n}$
x, y, z	east, north, vertical Cartesian coordinates
C_d	air-sea drag coefficient
C_p	specific heat
E	evaporation
Gl	gigaliters
H	water depth
M	mass transport

P	precipitation
R	river runoff
S	salinity
Sv	Sverdrups
T	temperature
W	watts
δ	salinity anomaly from eddies
ϕ	latitude
λ	longitude
ρ	density
ς	vorticity
τ	wind stress
Ω	Earth's rate of angular rotation

See also

Spheniscіformes. Tides.

Further Reading

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INTRUSIONS

D. L. Hebert, University of Rhode Island,
Rhode Island, USA

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Introduction

In most frontal regions, where waters of different salinities and temperatures meet laterally, an interleaving of the different waters is observed. These features are commonly referred to as intrusions. Sometimes a single layer of water from one region is advected into the other region, such as the Mediterranean salt tongue in the North Atlantic, by either a mean flow or eddy motion. Multiple layers of the two different water masses are also seen quite often. The driving mechanism for these multiple intrusions is related to horizontal gradients in salinity and temperature and the small-scale (e.g., smaller than the thickness of the intrusions) mixing occurring between the interleaving layers. In this article, only intrusions produced by this latter process are discussed. Both observational and theoretical studies are presented.

Frontal regions are locations where waters of different temperature and salinity meet and interact. They are usually characterized by relatively large horizontal gradients in these two properties. Fronts have been found in the coastal ocean, at the shelf-break and at the boundaries of major currents, such as the Gulf Stream and Antarctic Circumpolar Current. An example of a front (**Figure 1**) is shown by the azimuthally averaged salinity structure of a Mediterranean eddy. A Mediterranean eddy (Meddy) is a coherent eddy of Mediterranean Sea water found in the eastern North Atlantic Ocean. The front with its larger horizontal gradients in salinity is located at a depth range of 700–1300 m and with a radius of 15–30 km. The temperature field has a similar structure to the salinity structure shown in **Figure 1**. With the horizontal change in salinity, it would be expected that there would be a horizontal change in the density of the sea water. However, the effect of the horizontal change of temperature on the density nearly completely compensates the density change due to the salinity change across the front. Thus, the density surfaces are nearly horizontal. However, there is a slight upward (downward) tilt of density surfaces in the lower (upper) half of the Meddy. The resulting pressure gradient balances the geostrophic flow of the eddy. Along-front geostrophic flows are found at most fronts.

A closer look at the structure of temperature and salinity in the frontal region shows an interleaving of water with the characteristics of the temperature and salinity on the two sides of the front. The temperature and salinity of the water in these interleaving layers show evidence that mixing of the two water types has also occurred. **Figure 2** shows a section of closely spaced (e.g., 1–2 km) vertical profiles of salinity starting from the center of the Meddy (**Figure 1**) and moving towards the outside edge. In