T6.1 OCEAN CURRENTS

The ocean is a major component in the hydrological cycle which exchanges water between land, sea and air (see Figure T8.1.1). In Nova Scotia the marine influence is apparent in the character of the physical landscapes and biotic communities inland, at the coast and offshore.

The ocean imposes a set of conditions on biological organisms that is different from those they encounter on land and in most cases significantly different from those occurring in freshwater environments. On land, the atmosphere plays a role in transferring heat, in providing essential gases and moisture, and for moving and dispersing species. Soil acts as a foundation for plant and animal life, and the groundwater brings nutrients. In the ocean, water is the principal medium for doing all these things. Although the sea bottom is important in supporting marine plants and various forms of animal life, most biological activity takes place near the top of the water column. Over millions of years, biological life in the ocean has adapted to the physical processes and features — tides, currents, waves, upwellings, etc. — of the ocean, much as biological communities have adapted to the physical and biological landscape of terrestrial environments.

The sea is constantly in motion. Much of the motion seems at first chaotic—the turbulence of waves on a rocky shore and the changing pattern and intensity of waves on the sea surface. Underneath this exterior, there is an order that begins to become apparent only in special instances to the shore-based observer. These include the rhythmic vertical and horizontal movements of the tides, such as the strong nearshore tidal currents observed off Cape Split in the Bay of Fundy (Unit 912).

The sea has a range of orderly movements known collectively as currents. Tidal currents are a feature of every coastal area and consist of a regular in-and-out flow strong enough to influence the movements of boats and the activities of marine operations. Several hundred kilometres from shore, the Gulf Stream flows at up to 2.5 m/s. Less striking but equally significant currents are present in, and influence, Nova Scotian waters. These range from the steady flow of water originating in the Gulf of St. Lawrence and flowing southwestward along the Nova Scotia Atlantic coast (the Nova Scotia Current), to subtle currents circling some of the fishing banks, which are caused when the back-and-forth tidal movements do not completely erase each other, giving a residual flow in one direction.

Ocean currents benefit marine organisms by dispersing eggs and larvae, and they serve as road maps and routes for migratory species. Under special circumstances, currents lead to transfers of nutrients between water masses, which can enhance productivity.

Ocean currents are important precursors to the ocean environment (or climate) and biological productivity. The forces which produce ocean currents are introduced first. These forces reappear in various combinations in estuarine, continental-shelf and open-ocean settings.

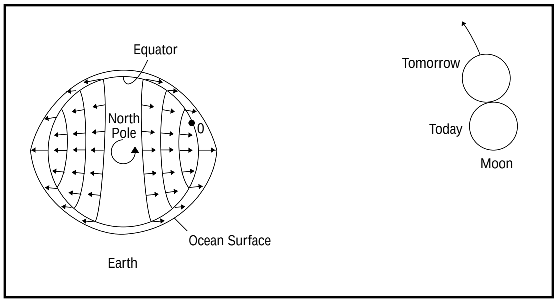


Figure T6.1.1[5]: The small arrows on the earth represent the net force due to the imbalance between the gravitational pull of the moon and the centripetal force which leads to “tidal bulges” on two sides of the earth. The moon is shown at two positions one day apart, to illustrate the delay of the tides by ± 50 minutes each day as seen by the observer at 0.

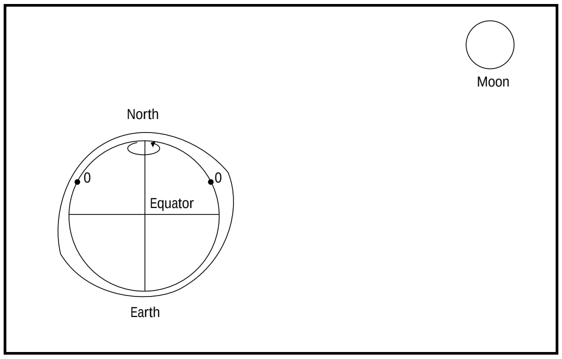


Figure T6.1.2[5]: Viewed from the side (north up) and with the moon north of the equator, the tidal bulges are asymmetric about the equator, resulting in the diurnal inequality in the heights of the high and low tides.

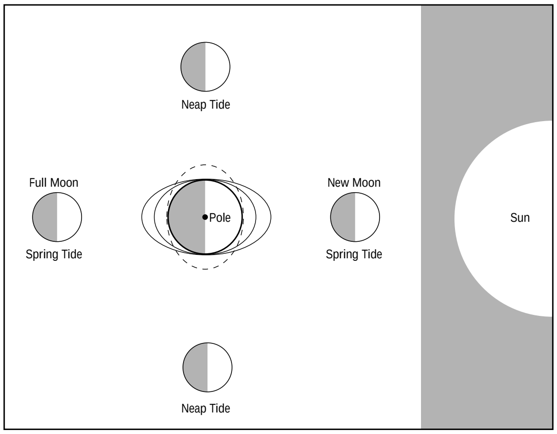


Figure T6.1.3[5]**:** Positions of the sun and moon at spring and neap tides.

DRIVING FORCES

Tides, winds, buoyancy (density differences), waves and remote forcing (factors that act at a distance) supply the forces that drive ocean currents. Each driving force is introduced here and described again in particular settings where it dominates.

Tides

In Atlantic Canada there are two tides per day and they are usually unequal. The rise (flood) and fall (ebb) of tides are a consequence of a combination of forces: the separate gravitational forces of the moon and sun on the earth, and the centripetal forces resulting from the revolution of the moon about the earth and the revolution of the earth about the sun[1] (see Figure T6.1.1).

The gravitational attraction between the moon and earth is directly proportional to their masses and inversely proportional to the squared distance apart. Centripetal force is the force required to hold a rotating mass in orbit, e.g., the force on the rope if you were spinning a bucket of water around in a circle. On the side of the earth nearest the moon, the gravitational force of the moon exceeds the centripetal force and pulls ocean water into a tidal bulge. On the side of the earth farthest from the moon, centripetal force exceeds gravitational force and pulls the water into a tidal bulge (see Figure T6.1.2).

Two tides per day arise because the solid earth revolves under these two bulges once in approximately twenty-five hours. The extra hour is required for the earth to regain its original position with respect to the moon, which itself revolves around the earth. Unequal tides arise when the moon is, for example, north of the earth's equator.

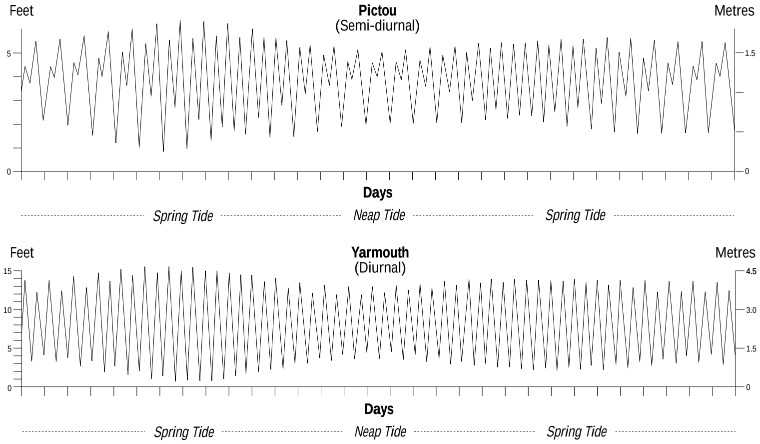
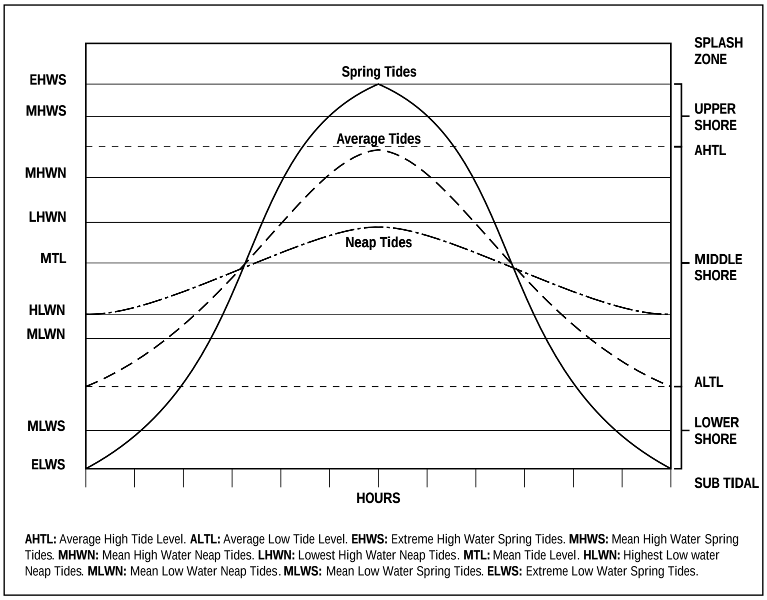


Figure T6.1.4a: Typical tidal curves showing tidal patterns in Pictou and Yarmouth.



AHTL: Average High Tide Level. **ALTL:** Average Low Tide Level. **EHWS:** Extreme High Water Spring Tides. **MHWS:** Mean High Water Spring Tides. **MHWN:** Mean High Water Neap Tides. **LHWN:** Lowest High Water Neap Tides. **MTL:** Mean Tide Level. **HLWN:** Highest Low water Neap Tides. **MLWN:** Mean Low Water Neap Tides. **MLWS:** Mean Low Water Spring Tides. **ELWS:** Extreme Low Water Spring Tides.

Figure T6.1.4b: Another tidal chart for spring, average and neap tides, showing relationship to zones on the shore.

The interaction of the earth and sun sets up a pattern of forces similar to that of the earth and moon, but the influence of the moon is about twice that of the sun (due to its distance away), and the moon and sun patterns are not synchronized. When the sun, earth and moon are aligned (in a straight line)—which occurs at new moon and full moon—the tides are larger and are called spring tides. When the sun, earth and moon make a right angle—which occurs at the moon's first and last quarters—the tides are reduced and are called neap tides. This is illustrated in Figure T6.1.3.[2]

The configuration of ocean bottom topography and coastlines provides another layer of complexity. Thus the tides may exhibit quite complicated responses. For example, Figure T6.1.4a shows exam-

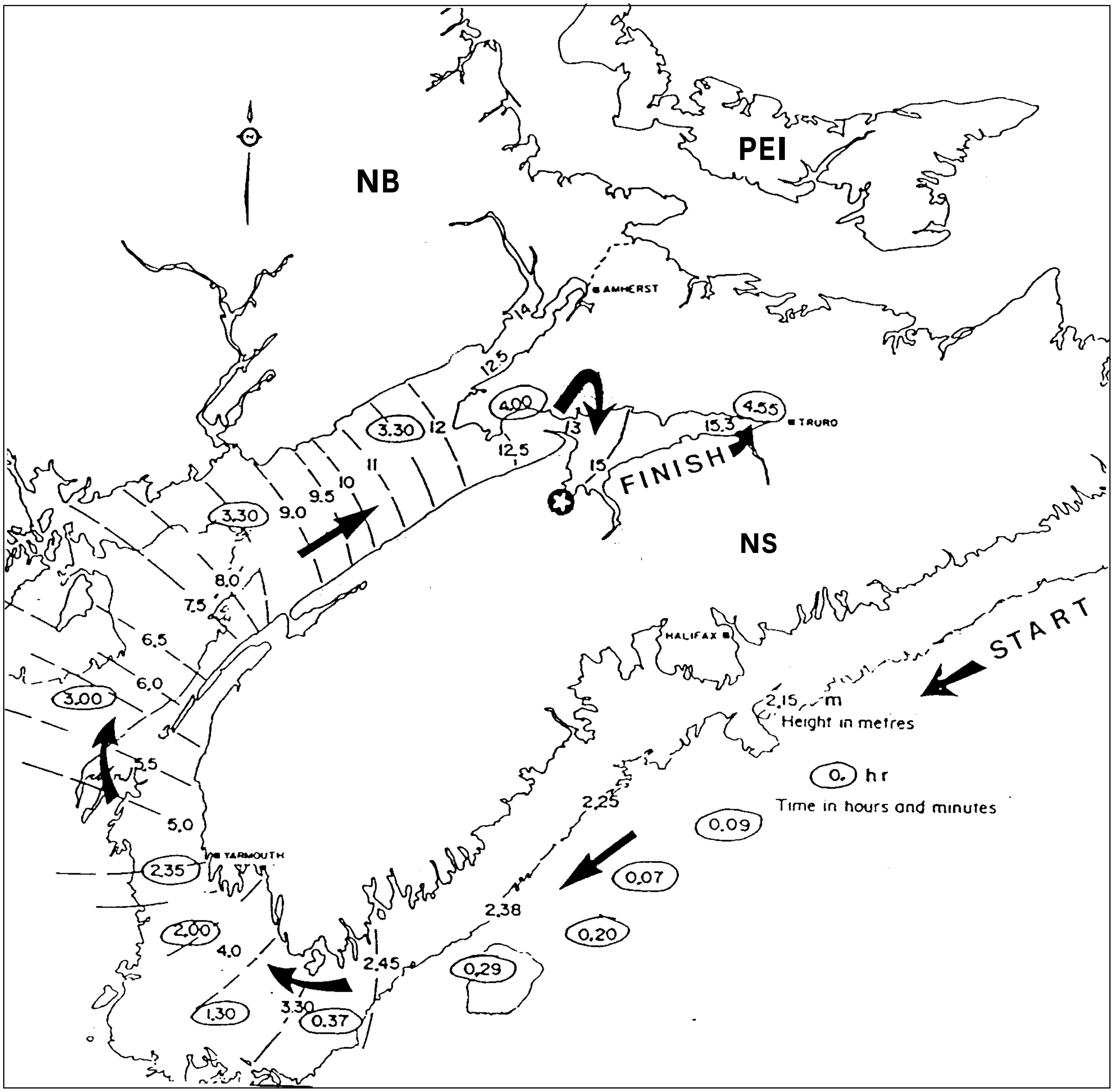


Figure T6.1.5: Sequence of tidal heights and times for South Shore of Nova Scotia and Bay of Fundy.

ples of tidal patterns experienced in Nova Scotia. Tidal ranges vary from extremely large in the inner Bay of Fundy (Unit 913) to rather small in the Northumberland Strait (Unit 914).[3]

The observed tidal response can be analysed into components. The largest of these is the principal lunar semi-diurnal component: high water occurs twice daily, with intervals averaging 12.4 hours. There are also solar semi-diurnal components, and lunar and solar diurnal components. Diurnal tides are those where high water occurs but once daily, at intervals from 24 to 27 hours. Superimposed upon the astronomical tides are meteorological tides resulting from winds and atmospheric pressures. Thus, when storms are forecast, warnings of higher-than-usual tides may be issued.

The tide is really a long wave that travels at a speed proportional to the square root of the depth, i.e., faster in deeper water. Figure T6.1.5 shows the progression of tides around the Atlantic coast of Nova Scotia, with the time of high water shifting up the Bay of Fundy at equivalent speeds of 200 kilometres per

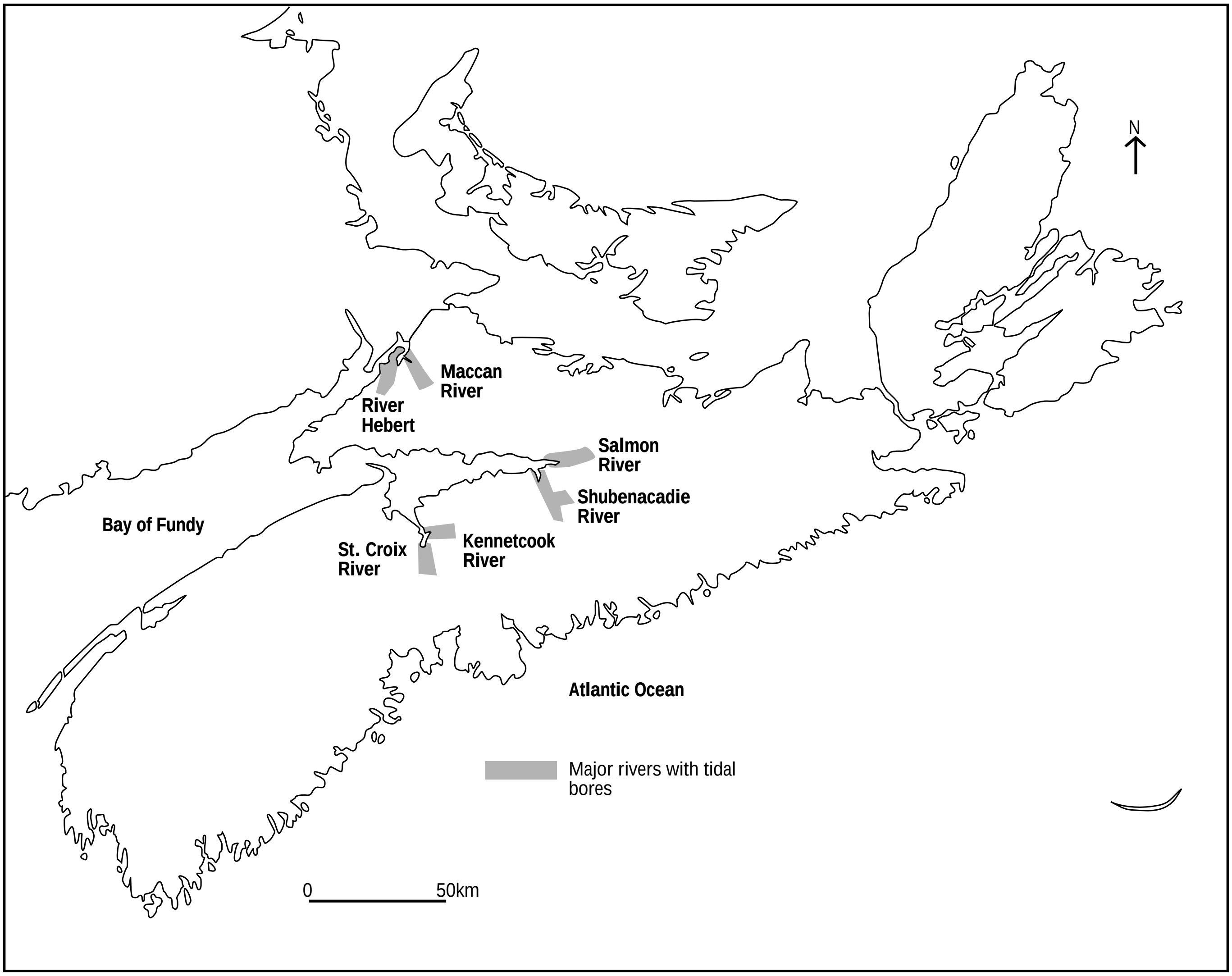


Figure T6.1.6: Major rivers with tidal bores in Nova Scotia.

hour. Where strong tidal currents enter a shallow, constricting estuary, the speed of the advancing wave is limited by the depth relationship. Water accumulates and deepens faster than the wave speed increases. This leads to a steep-fronted surge called a tidal bore.

Tides have a significant effect on biological processes in the ocean. The conspicuous vertical movements create a distinctive zone of shore exposed to both seawater and the air twice a day. Tidal currents carry nutrients and sediments, and erode and change the shape of the seabed. Life cycles of many organisms are keyed to the seasonal occurrence of highest tides. The mudflats at the head of the Bay of Fundy have the largest tides in Nova Scotia. This habitat is an important feeding area for migratory shorebirds and other birds and for small mammals along the coast.

Strong tidal currents concentrate dissolved nutrients and create conditions which favour the development of dense growths of algae or of animals, such as mussels, which feed on particles in suspension. In offshore waters, the hidden or internal tides lead to mixing of nutrient-rich water below into the surface waters, where it can be used by phytoplankton.

Winds

Wind-driven circulation in the oceans occurs only in the upper few hundred metres[4]. In open areas the total transport of water is to the right of the wind direction. This is because the rotation of the earth creates a force on moving bodies called the Coriolis force.

When the wind, blowing over the surface, drags water along, the Coriolis force acts to the right of the direction of motion, and the water-drag force acts in the direction opposite to the direction of motion (Figure T6.1.7A). These forces are not in balance; this imbalance causes a change in velocity (Figure T6.1.7B). When the water velocity has rotated to the right, these forces do approach a state of balance. Then (Figure T6.1.7C) the Coriolis force and the water drag together balance the wind stress. Thus, wind-driven currents move at an angle rotated to the right of the direction of the wind and are associated with the name of Walfrid V. Ekman (1905), a famous Norwegian oceanographer; hence, Ekman drift (see Figure T6.1.9).

The interaction of winds with the ocean create conditions which impact on biological organisms. Offshore or alongshore winds push surface waters away from the coast, leading to an inflow into coastal areas of nutrient-rich water from deeper layers, and enhancing productivity in near coastal waters. This process of upwelling is the same one, though on a reduced scale, that drives the famous upwellings off Peru and off the west coast of Africa (El Niño is a change in surface-water mass patterns off Peru that stifles and temporarily curtails the high productivity of the upwelling).

Further at sea, patterns of winds in the equatorial zone lead to a massive northward-moving ocean current—the Gulf Stream—which transfers many warm-water organisms to waters off Nova Scotia.

On a smaller scale, windrows and lines of smooth sea surface (slicks) result from steady wind which causes the water to circulate in a cylindrical pattern, converging along a line and bringing floating mate-

The Coriolis Effect

In the Northern Hemisphere, the Coriolis force causes the average motion of the water to be turned to the right.

The Coriolis force is an apparent force which is used to bring our senses into correspondence with reality. While our senses suggest that an observer standing at one point on the surface of the earth is stationary, actually this observer is rotating with the earth. Ocean waters tend to flow in the direction of the forces causing them to move, but this direction changes from an earth observer's point of view, since the earth is rotating. The Coriolis force accounts for this change and brings our rotating frame of reference into correspondence with an absolute frame of reference. For example, imagine an elf standing in a groove on a long-play record as it spins counter-clockwise on a turntable. Suppose, when she is just at the north point of her circle she bends down and rolls a tiny ball toward the needle, which is at the west side of the circle (i.e., 90 degrees rotated). The ball rolls straight toward the needle, but to the elf, moving on her curved path to the left, the ball appears to deviate to the right. This deviation is attributed to the apparent force—the Coriolis force—and is an artifact of the elf's rotating frame of reference.

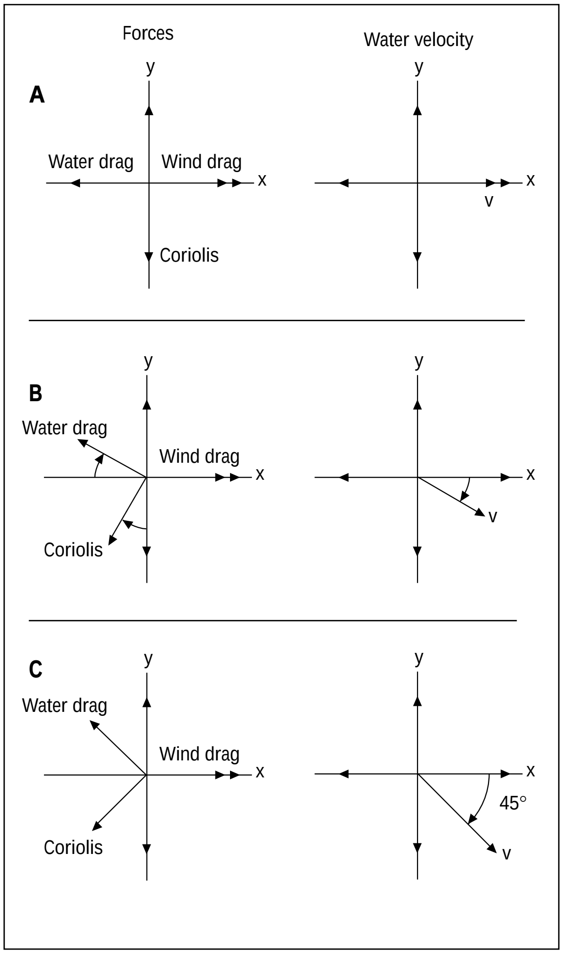


Figure T6.1.7[5]**:** The beginning of a wind-driven surface current in three stages, showing the forces on the left and the water velocity on the right. In stage **A** the wind drag creates a flow of water which gives rise to the water drag and the Coriolis force. In stage **B** the Coriolis force causes the current in the water to rotate around to the right (in the northern hemisphere). The force due to the water drag and the Coriolis force rotate with the current in the water. In the final stage (**C**), the current has rotated the amount required to have the force due to the wind drag balanced by the combined effects of the Coriolis force and the drag of the water.

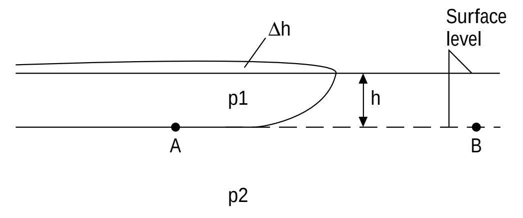


Figure T6.1.8[5]**:** A pool of light water, p1, lies on top of and beside water of greater density, p2. If the pressure at A and B are the same, the height of the sea surface above A must be higher than above B.

Waves

Why are there sometimes huge waves breaking on the rocks at Peggy's Cove on a day when winds are light ?

Wind waves travel at different speeds depending on their wavelength; the longer waves travel faster. A storm will generate waves over a range of wavelengths. Thus, if a storm is hundreds of kilometres away (e.g., off the Carolina coast), the longer waves can arrive here before the storm does, if it does.

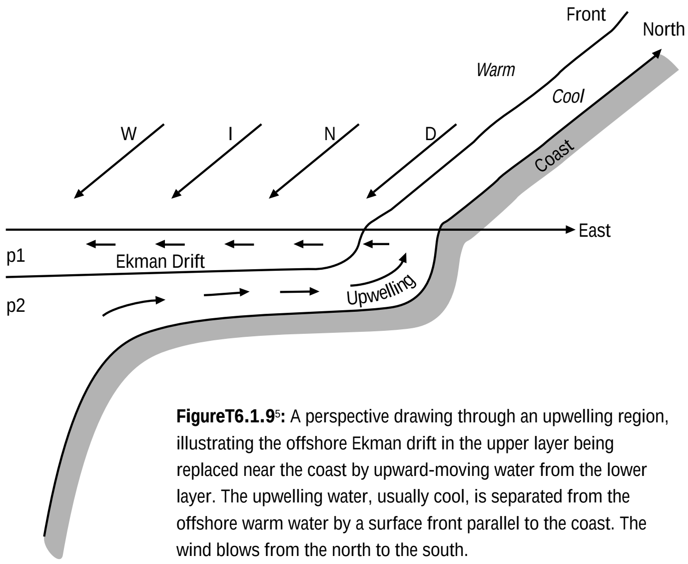
rial and organisms to pile up there. Windrows are the focus of fish and seabird feeding and, in rare cases, can lead to accumulations of poisonous algae sufficient to cause a health risk.

Storms often blow unusual species of seabirds into Nova Scotia waters, and terrestrial birds are frequently found great distances at sea after major storms.

Buoyancy

Some ocean currents arise where the density of the water is changed in a significant portion of its bulk. For example, convection is driven by buoyancy. If a long tank of water is cooled at the surface at one end, the water there will contract, become more dense and start to sink. Warmer water will flow horizontally towards the cool end, to fill the void left by the sinking, colder water.

If this is seawater, and if ice is formed, the density is increased further. This is because the salt is largely excluded from the ice and adds to the density of the remaining water. As this dense water sinks, water at the other end of the tank will rise—a consequence of the continuity of volume—and flow toward the cool side of the tank (see Figure T6.1.8).



FigureT6.1.9[5]**:** A perspective drawing through an upwelling region, illustrating the offshore Ekman drift in the upper layer being replaced near the coast by upward-moving water from the lower layer. The upwelling water, usually cool, is separated from the offshore warm water by a surface front parallel to the coast. The wind blows from the north to the south.

Since, in general, fresh water is less dense than seawater, freshwater runoff at the coasts or precipitation will reduce the density. Where fresh water runs off the land and overlies a denser layer of seawater, it likewise sets up a horizontal pressure gradient.

In this case, the fresh water, being less dense, causes the surface at the coast to be slightly elevated; the flow is down the gradient toward the sea. Thus, density changes in the ocean occur by heating or cooling, by ice formation and by the addition of fresh water.

Waves

Waves can drive currents in two ways: either through their particle motions, which is how tide waves lead to tidal currents, or through actually pumping energy into currents, which appears to occur on the continental shelf off Nova Scotia (Scotian Shelf).

The tremendous energy of waves influences biological organisms. The high speeds combined with the density of seawater expose some species in the subtidal area to forces equivalent to 1500-kph winds on land. Plants have evolved firm anchor systems to attach them to the substrate, and many animals have streamlined shapes to resist being lifted off surfaces. Wave energy also influences the form seaweeds take during growth, and members of species in exposed environments are more elongate and blade-like than representatives in sheltered environments.[5] The washing of the waves also brings nutrients and carbon dioxide and takes away waste products.

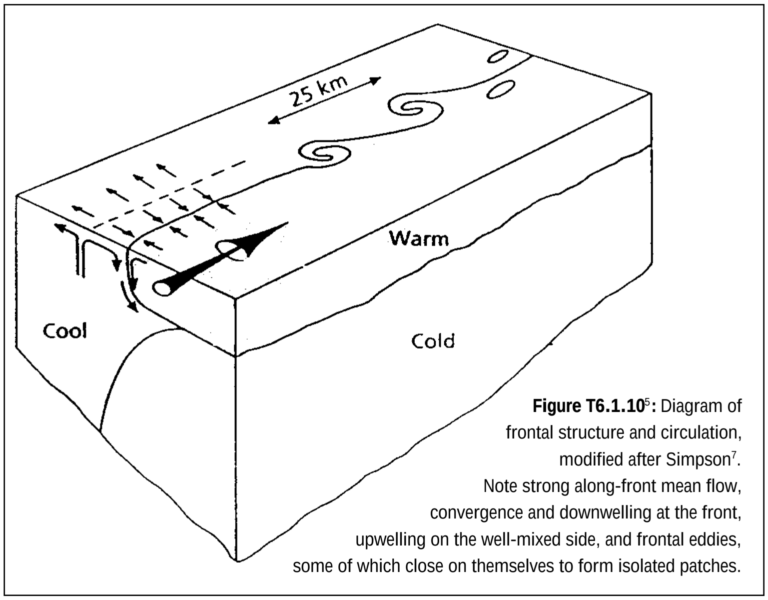


Figure T6.1.10[5]: Diagram of frontal structure and circulation, modified after Simpson[7]. Note strong along-front mean flow, convergence and downwelling at the front, upwelling on the well-mixed side, and frontal eddies, some of which close on themselves to form isolated patches.

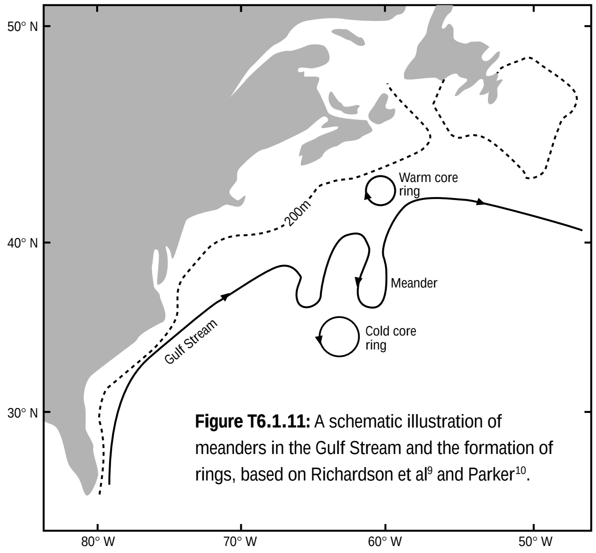


Figure T6.1.11: A schematic illustration of meanders in the Gulf Stream and the formation of rings, based on Richardson et al[9] and Parker[10].

Remote forcing

Remote (non-local) forcing means that currents at a particular place arise because of a force that has acted in another, remote area. For example, the Gulf Stream out beyond the edge of the Scotian Shelf is forced indirectly by the northeast equatorial trade winds.

Weather and ocean patterns off Nova Scotia are influenced by events taking place in far-removed locations, and these effects influence the biological organisms found here. Nova Scotia is particularly prone to remote effects, because it is positioned in mid-latitudes, that is, it lies between the influences of cold-water masses originating in the Arctic and warm-water masses from the south, and near a major freshwater flow of the St. Lawrence River entering the Atlantic Ocean. The complex patterns that result are large in scale but vary significantly in size and pattern.

As a result of these patterns, Nova Scotia's marine organisms include species which can be found in northern areas, such as Greenland, as well as species typically found in warmer waters to the south. Occasionally, exotic species such as the Portuguese Man-of-war and Leatherback Sea Turtle "hitchhike" to Nova Scotian shores.

The interaction of water masses leads to an enhanced mixing and productivity. (The North Atlantic, of which Nova Scotian waters are a part, is one of the most productive zones in the world's oceans.) As a result, many species of organisms (seabirds, migratory fishes, marine mammals) feed here during periods of high productivity. Global warming and cooling trends, however, can have significant and unpredictable effects on marine ecosystems, because of the links to areas far away.

SPECIAL FEATURES

Estuarine Circulation (see T6.4)

In estuaries, the addition of fresh water sets up a differential movement of water. As the upper, less-saline layer flows seaward, it mixes with the lower layer. This modifies the distribution of buoyancy forces in the estuary, so that the lower, more-salty layer flows landward, wells up near the head of the estuary and provides a portion of the upper water. This ongoing sequence of upwelling and stratification provides nutrients to the surface waters.[5]

Coastal Upwelling

Coastal upwelling is driven by winds blowing principally alongshore (as well as offshore). The surface water velocity is at an angle to the right of the wind direction and therefore has an on-offshore component. If the wind is alongshore in the direction such that a rotation of 90 degrees to the right is offshore (i.e., southwest winds along the Atlantic coast of Nova Scotia, Region 800 and Unit 911), then the surface water velocity—the Ekman drift—is directed offshore. The water drifting offshore is replaced by upwelling from lower layers, hence coastal upwelling (see Figure T6.1.9).

Coastal upwelling occurring along the Atlantic coast of Nova Scotia is conducive to the growth of phytoplankton and is a key factor in the productivity of the coastal zone. Other factors include closeness to a supply of nutrients from the seabed, estuarine circulation in bays and inlets and the availability of plant material in the form of detritus.

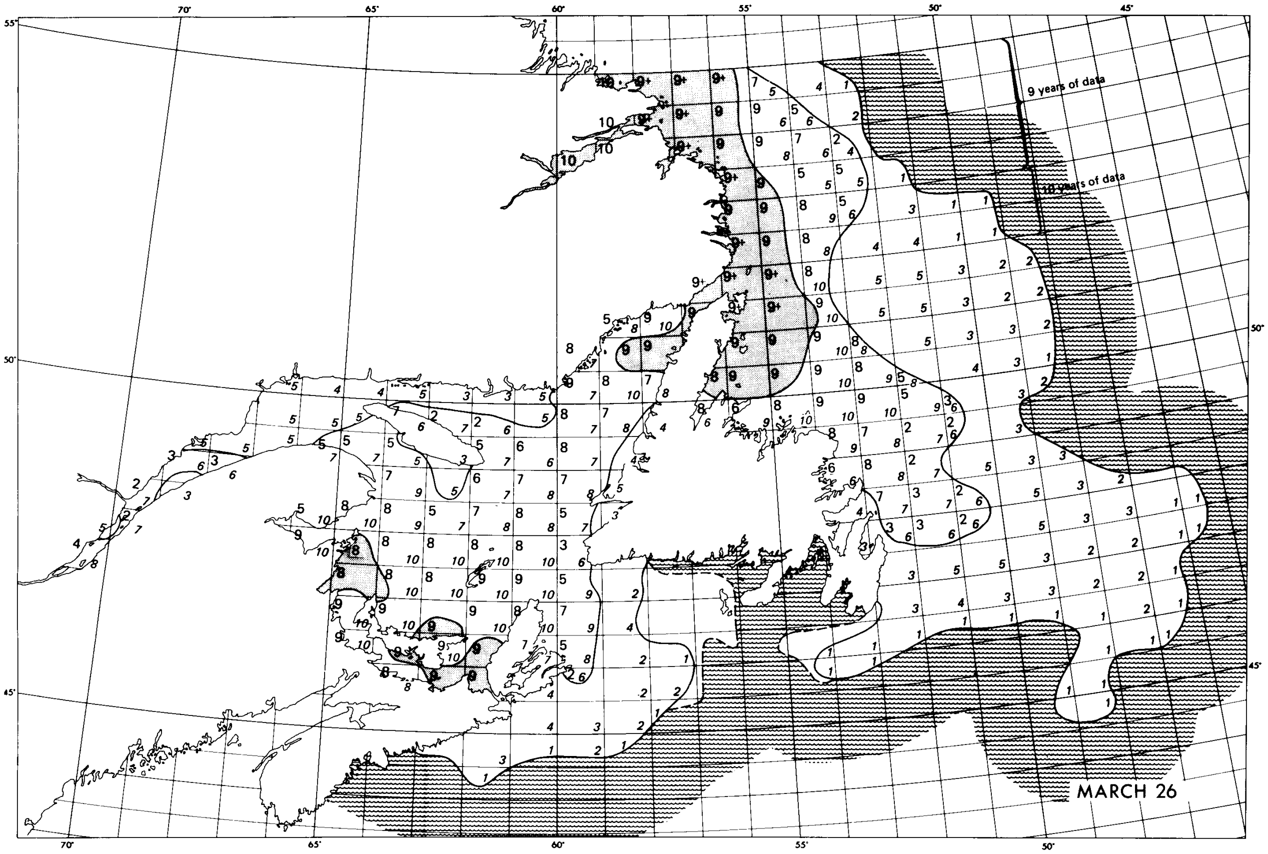


Figure T6.1.12: Chart showing minimum, median and maximum position of ice edge in the Gulf of St. Lawrence and on the Atlantic Coast for the years 1963–73; late March

Extreme Maximum Limit — defined by outer edge of ripple
Median Limit — black line
Extreme Minimum Limit — defined by grey stipple

Between the maximum and median positions, the number of years ice was present (out of 11) is shown by digits in lower right of each square. Between the median and minimum lines, the median total concentration is by digits in the upper left of each square, and the number of years that ice was present is shown by a smaller digit in the lower right. For example, 6_8 = a median concentration, 6 tenths for ice present 8 years out of 11. Within the minimum line, the years that ice was present is always equal to the number of years of data.[11]

Tidal Fronts

A front is a sharp boundary between water masses of different properties. Simpson and Hunter[6] theorized that a front would be found where the intensity of turbulent mixing was just sufficient to continuously overcome the barrier to mixing presented by the stratification[7] (see Figure T6.1.10). They derive a tidal mixing index which reflects this balance at a front and which is mapped for the whole Gulf of Maine.[8,9,10]

Energy from the tides can result in significant mixing of nutrient-rich water to the surface, where it can contribute to water-column productivity under certain conditions. In cases where the tidally mixed water lies adjacent to a more stable surface layer (a front), the nutrients can feed into marine-plant populations in the surface layer and develop high plant concentrations. A major tidal front occurs off southwest Nova Scotia, and herring spawn in the area. Young herring use the production in the water column as they grow. The resulting elevated populations of juvenile herring at the mouth of the Bay of Fundy form the basis for a herring fishery on the New Brunswick side of the Bay.

Shelf-break Fronts

The shelf break is the region where the continental shelf ends and the continental slope down to the abyss begins (see T3.5). The present understanding of shelf-break fronts is that as the tide impinges on the shelf at the shelf break, tidally generated internal waves radiate away and add energy to the mixed layer. (Internal waves occur on the interface between the upper and lower layers of the water column.) The mixed layer is deepened and incorporates nutrient-rich water from below. This process varies in intensity with the semi-diurnal tide, so that

Ice

Sometimes ferries, even though they have icebreaking capability, become stuck in the ice for hours or even days. Before this happens, there would have been a period of noisy, bumpy crashing into the ice. There could also have been a period when the ferry repeatedly backed up and steamed hard into the ice to try to force its way through. Then, once stuck, the ship becomes more quiet. One might see ice ridges where pieces of ice are forced by pressure (windstress) up into mounds of broken ice, higher than the normal level of the pack ice. Finally, a large Coast Guard icebreaker appears, to free the ferry.

it produces a twice-daily augmentation of nutrients, resulting in a fairly constant elevation of rates of growth of marine plants.

Tidal Gyres

Banks are broad, raised plateaus on the continental shelf which, in some cases (e.g., Georges Bank, Unit 931), can reach to within 30 m of the surface. Oscillating tidal currents washing back and forth over the banks sometimes generate mean (steady) currents at the edge of the bank where the depth is increasing rapidly. These mean currents form a gyre around the bank and can provide a “larval retention” area where, except in extreme conditions, fish eggs and larvae are kept in place over the bank. The process is a factor in the distribution of species and in maintaining the integrity of stocks for fishing, but its importance in relation to other factors has not been determined.

Warm-core Rings

North of Cape Hatteras, North Carolina, the Gulf Stream moves away from the coast, and warm-core rings form on the shoreward side of the current. After the Gulf Stream leaves the coast, it continues eastward as a strong, narrow stream, but at about 65 degrees west longitude it becomes unstable and begins to develop large north-south oscillations, or meanders. These meanders cause the cooler water found to the north of the Gulf Stream to be brought further south than usual and the warmer southern water to be transported further north. Some of these meanders grow too large, and the ends separate into isolated rings of water, as illustrated in Figure T6.1.11.[9,10]

The clockwise-rotating rings to the north of the Stream are known as warm-core rings, because they contain warmer water surrounded by the cooler waters found northwest of the Stream. An

Plate T6.1.1: Gulf of St. Lawrence ice fills Halifax Harbour in early 1987. Photo: L. Morris.

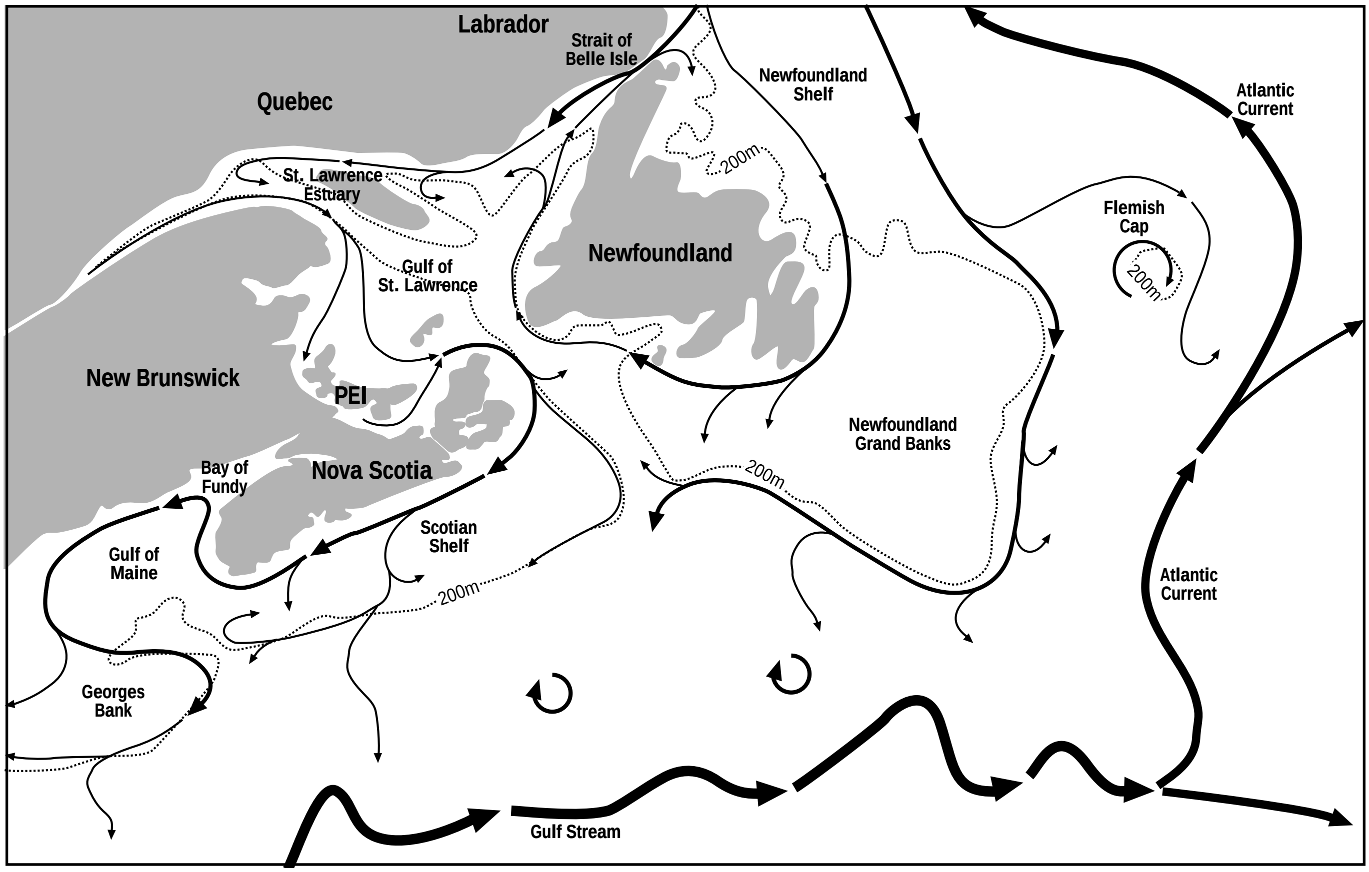


Figure T6.1.13: Major currents offshore Nova Scotia.

average of five warm-core rings is formed each year, but the production rate is quite variable. The diameter of a warm-core ring is approximately 100 km. A ring lasts for about a year before being re-absorbed into the Stream or dispersed.[5]

Geostrophic Balance

The initial tendency of water is to flow down a pressure gradient. For large-scale flows, the Coriolis force exerts its influence and turns the flow to the right. At equilibrium, the pressure gradient to the left is just balanced by the Coriolis force to the right. This geostrophic balance—between pressure gradient and the Coriolis force—is an everyday occurrence in the atmosphere and in the ocean. In the atmosphere, it is evident in the daily weather charts which display the distribution of isobars. The flow of air around the high- and low-pressure systems is parallel to the isobars, not across them, because the air is close to being in geostrophic balance. In the ocean, the flow of water is often parallel to the ocean isobars for the same reason. On the Scotian Shelf, the Nova Scotia Current flowing southwestward along the coast is in approximate geostrophic equilibrium.

Ice

Seawater freezes at between –1 and –2°C, depending on the salinity. Mean winter temperatures at the Nova Scotian coastline do not fall very far below the freezing point, and as a result, cold and mild winters have a very significant effect on the extent and severity of the ice cover. Some coastal areas experience ice annually; in other areas ice is unusual. Sea ice regularly covers large areas of water in the Gulf of St. Lawrence.

Winter winds from the west to north are typically cold and dry, whereas those from the west through south to northeast are typically mild and moist. The winds have a decided effect on the location of areas of ice dispersal and congestion once it has formed. Prevailing winds, currents and Coriolis force all contribute to a residual west-to-east flow pattern. For example, northwest winds with accompanying cold temperatures tend to move ice floes from west to

Why does the tide sometimes stay high all day on the beach near Pugwash?

In the western Northumberland Strait, tides are mixed but mainly diurnal, i.e., with a period of approximately 25 hours, as distinct from the more usual situation in Nova Scotia, where the semi-diurnal tides are predominant. Thus, you can experience days when the tide stays high (within a relatively narrow range) continuously for 12 hours!

east along the Northumberland Strait. Winds blowing onshore produce thick, congested ice fields against windward shores.

Figure T6.1.12 shows the median, minimum and maximum limits of ice occurrence in late March for the years 1963–73.[11] Shore ice begins to form in December and by late January covers much of the Northumberland Strait. This ice breaks up and melts as early as late March or as late as late May. By February, ice may be present along the eastern shore of mainland Nova Scotia, depending on the severity of the winter.

Sea ice can extend into the Sydney Bight (Unit 915) and in rare cases has been carried down the coast of Nova Scotia, even entering Halifax Harbour and Bedford Basin (see Plate T6.1.1).

Ice is more often a barrier to the establishment of marine organisms; however, some species do take advantage of its features. Harp and Hooded seals in the Gulf of St. Lawrence use the ice for giving birth (whelping). Microscopic algae can develop as film-like coatings under ice floes and live in crevices where they cannot be washed off. Sea ice can enable the migration of land animals; e.g., the introduction of the eastern coyote into Prince Edward Island and Newfoundland across the ice of the Gulf of St. Lawrence.

CIRCULATION IN NORTHWEST ATLANTIC

The dominant driving forces for North Atlantic circulation are winds and buoyancy (density differences). The ocean moves both horizontally and vertically under these influences. Density differences are generated by heating and cooling, evaporation, precipitation and runoff.

The principal feature is a great clockwise gyre or circular current pattern driven by the trade winds, westward in the tropical Atlantic and eastward in the North Atlantic, first as the Gulf Stream and then as the North Atlantic Current (Figure T6.1.13).[12]

East of the Grand Banks of Newfoundland, the North Atlantic Current divides, part flowing northeastward between Scotland and Iceland and contributing to the circulation of the Norwegian, Greenland and Arctic seas. The remainder turns south, past Spain and North Africa, to complete the North Atlantic gyre and to feed into the North Equatorial Current.[4]

In the tropical Atlantic, solar heating and evaporation in excess of precipitation and runoff create an upper layer of relatively warm, saline water.[13] As this water flows north it gives up heat to the atmosphere, particularly in winter. Because winds in the higher mid-latitudes are generally eastward, this heat is carried over Europe, producing its relatively mild winters. So much heat is withdrawn by the time it reaches the Greenland Sea that the water temperature drops close to the freezing point. This water remains relatively saline, and the combination of low temperature and high salinity makes the water more dense than deeper water below it. The water sinks to deeper levels, occasionally right to the bottom. There it slides under and mixes with other near-bottom, dense water. It spreads out and flows southward, deep and cold. This pattern, known as thermo-haline circulation (surface warm water flowing north, cooling, sinking and then flowing south), provides an enormous northward movement or flux of heat, fully comparable with that transported northward by the atmosphere.

LABRADOR CURRENT

The most important “drivers” for the Labrador Current appear to be the large-scale current gyres of the northern ocean and buoyancy fluxes (addition of low-salinity water) associated with outflow from Hudson Strait.

The Labrador Current is formed by the confluence of the West Greenland and Baffin Island currents, supplemented by flows out through Hudson Strait. It flows southeastward along the coasts of Labrador and Newfoundland. Off Newfoundland, the Labrador Current branches, the main portion flowing around the Grand Banks along the slope of the continental shelf and the weaker part flowing inshore over the shelf. This inshore part divides to provide some flow through the Strait of Belle Isle; the remainder flows along the eastern and southern coasts of Newfoundland.

Losing some flow to the North Atlantic Current, the stronger branch, consisting of relatively more temperate waters derived from the West Greenland Current, continues southwestward, even to the slope of the Scotian Shelf.

The weaker, inshore branch, consisting mostly of cold, low-salinity water, continues along the southern coast of Newfoundland and through Cabot Strait to join the Gulf of St. Lawrence circulation.

CIRCULATION IN THE GULF OF ST. LAWRENCE

The Gulf of St. Lawrence is a highly stratified, “marginal” (semi-enclosed) sea. (“Highly stratified” means that there are distinct layers which differ in temperature and density.) Its circulation is driven mainly by freshwater runoff originating from the St. Lawrence River and North Shore rivers, winds, tides, and changes in temperature and salinity at the edge of the continental shelf.[14]

The surface circulation in the Gulf of St. Lawrence is essentially counterclockwise (see Figure T6.1.13). The Gaspé Current, driven by the St. Lawrence River outflow, results in an eastward flow of water which extends to the Magdalen Shallows and Northumberland Strait. Over most of the Gulf, the mean drift is eastward. In Jacques Cartier Passage, north of Anticosti Island, the mean flow is westward, completing the counterclockwise pattern. The North Shore rivers contribute “new” water to the westward flow. Of course, a particular parcel of water is not likely to flow completely around this circuit.

Most of the southeastward flow at the surface leaves the Gulf via Cabot Strait between Cape Breton and Newfoundland, and is balanced mainly by the deeper flow of more-saline water entering from the continental shelf. This surface flow, eastward through Cabot Strait then turning southwestward along the Scotian Shelf, has a mean annual flow of water estimated at 340 000 m^3/s, peaking at approximately 700 000 m^3/s in August, apparently in response to peak freshwater runoff of approximately 31 000 m^3/s in May. The peak outflow from Cabot Strait amounts to 20 times peak freshwater runoff. Although not driven entirely by runoff buoyancy, it does show how the river flow in an estuary can be amplified by the estuarine processes.

The outward flow of surface waters through Cabot Strait forms the Nova Scotia Current, which flows southwesterly along the Nova Scotian Atlantic coast (see Circulation on the Scotian Shelf).

In addition to the horizontal currents, vertical currents, such as upwelling flows, are important biologically because they bring nutrient-rich water into the surface, euphotic or lighted, zone. In the St. Lawrence, wind-driven upwelling occurs along the Gaspé Coast and buoyancy-driven and tidally driven upwelling occurs in the estuary.

Several Nova Scotia estuaries connect with the Northumberland Strait and the Gulf of St. Lawrence. Currents in these estuaries are driven mainly by freshwater runoff and tides. The tides are a mixture of semi-diurnal and diurnal constituents (Figure T6.1.4a), with ranges from 1.1 to 2.9 metres. The freshwater runoff and relatively low tidal ranges in many of these Nova Scotian estuaries leads to buoyancy effects (pressure distributions) which cause lower-layer water to flow in from the mouth of the estuary, to upwell into the surface layer and then to flow seaward in a residual current which transports on the order of ten times the flow of the freshwater itself—the two-layer estuarine circulation.

For swimmers on Atlantic Coast beaches, warmest water temperatures will occur after a period of easterly to southeasterly winds. These winds, also associated with rain, drag warm surface water shoreward. Winds from the northwest to southwest sector drag surface water offshore, causing deeper cold water to upwell along the coast.

CIRCULATION ON THE SCOTIAN SHELF

The continental shelf under the sea on the Atlantic coast of Nova Scotia from Misaine Bank to Northeast Channel is known as the Scotian Shelf. Important driving forces for the circulation on the Scotian Shelf include buoyancy fluxes, wind stress, tidal forces, and the large-scale circulation associated with adjacent deep-ocean gyres.[15]

The general circulation on the Scotian Shelf is southwestward, with a predominant southwesterly drift along the coast (the Nova Scotian Current) and a minor southwesterly drift along the outer edge of the Shelf (see Figure T6.1.13). The mean and seasonal strength of the Nova Scotia Current appears to be related to buoyancy fluxes associated with runoff from the St. Lawrence River. Figure T6.1.15 summarizes actual current measurements in three depth ranges, averaged over all months.[16]

The Nova Scotia Current flows at an annual mean transport of 340 000 m^3/s, with a speed of 0.05–0.10 m/s. The maximum transport of the Nova Scotia Current is approximately 700 000 m^3/s. This transport can be compared to the Gulf Stream, which transports up to 150 million m^3/s, and the Labrador Current, at 5.6 million m^3/s [17].

The Nova Scotia Current is dominant over the nearshore region of the Scotian Shelf. The large-scale current response on the Scotian Shelf is geostrophic. That is, the pressure gradient is sloped downward to the southeast and the flow is relatively steady to the southwest, even though prevailing winds are to the northeast.

Computer model studies of the Bay of Fundy tides suggest that if a tidal barrage (i.e., a dam for tidal power) were placed across Minas Basin at Economy Point, the tidal amplitude would be increased by about 15 cm from Saint John to Boston. The barrage would shorten the Bay and bring the natural period of the Bay of Fundy/Gulf of Maine system closer to the forcing tidal period. In simpler terms, consider the Bay of Fundy as a bathtub, with its natural period of sloshing, end-to-end. Suppose your child is making waves at a frequency slightly too rapid to cause the maximum waves. If you were to insert a barrier and shorten the tub, your child's waves would then slosh perfectly—onto the floor.

Recent studies suggest that, although the mean wind stress opposes the mean current, the energy in the fluctuations of the wind is transformed into a driving force for mean current—southwestward, against the mean wind.[15]

Satellite images demonstrate that persistent southwesterly summer winds produce a band of cold, upwelled water near the coast that subsequently forms eddies through instability of the upwelling front.[17] Periods of upwelling alternating with periods of light winds and stratification can provide the conditions for phytoplankton blooms. Upwelling also occurs off Cape Sable (Unit 911), driven not by winds but apparently by alongshore density variations maintained by tidal mixing.[18] Upwelling off Louisbourg (Unit 911) may be similarly driven.

At the shelf "break" and slope, there are shelf-break processes and dynamic interactions with Gulf Stream derivatives. In the deeper layers of the slope water, there is a Labrador component from the Grand Banks. There are responses at the shelf break to a) the tide, b) the wind field and c) the fluctuating offshore currents associated with the Gulf Stream. The semi-diurnal internal tide over the shelf edge at times develops into an internal undular bore, or at other times into internal solitary waves. These waves can bring nutrient-rich lower-layer waters into the euphotic zone and provide good conditions for the growth of phytoplankton.

Offshore eddies and rings have an important influence on the circulation over the slope, although not, it appears, over the shelf itself. When a Gulf Stream ring suddenly encounters a sloping bottom, it radiates low-frequency energy in the form of "continental shelf waves" with characteristic periods of 10 to 30 days. On approaching the shelf, however, the energy is strongly refracted by the continental slope and scattered into waves trapped to the shelf edge so that little energy penetrates onto the shelf. Nevertheless, eddies do affect near-bottom currents, stress and sediment transport near the shelf break.[15]

CIRCULATION IN THE BAY OF FUNDY AND THE GULF OF MAINE

At the head of the Bay of Fundy, the tidal driving force is predominant and establishes a macro-tidal environment. Tide ranges here are among the highest experienced anywhere in the world. (The tide gauge at Saint John Harbour has functioned almost continuously since 1894, forming an excellent tide record.) Toward the mouth of the Bay, freshwater runoff (buoyancy) from the Saint John River also plays a major role. In the Gulf of Maine, the circulation is driven by wind stress and non-local forcing, as well as the tides.

The general residual circulation is counterclockwise in the Bay of Fundy and the Gulf of Maine (see Figure T6.1.13). In the inner Bay of Fundy, gyres on either side of Minas Channel (one clockwise and one counterclockwise) occur due to the bathymetry which induces tidal rectification. For example, the very strong flood-tidal stream enters Minas Basin at the northern edge as a "jet," while the ebb-tidal stream is more widespread and slower. Thus, the tidal currents do not average to zero; the pattern of average currents shows a gyre, reflecting the strong influence of the flood jet.

In the Bay of Fundy, especially in Chignecto Bay and Minas Basin, tidal amplitudes and currents are extremely high. The reason for this is that the 12.5-hour period of the lunar semi-diurnal tidal driving force coincides fairly closely with the travel time of a long wave into the Gulf of Maine/Bay of Fundy system, which is determined by the depth and length of the system. The large tides give rise to unusual effects, such as tidal bores and reversing falls. At the mouth of the Bay of Fundy, there is a counterclockwise gyre which seems to be driven by the density gradients arising from the freshwater input of the Saint John River[19] (see Figure T6.1.13).

The seasonal circulation in the Gulf of Maine is partly determined by the distribution of dense slope water that enters intermittently from the continental slope and spreads over sills into the deep basins of the Gulf. Warm core rings from the Gulf Stream occasionally approach the mouth of the Northeast Channel; at times, ring water modifies the slope water.[20] Slope water accumulates in Georges Basin. There is a counterclockwise surface circulation, which brings Scotian Shelf water westward into the Gulf and contributes to the eastward jet (speeds of 30 cm/s) along the inner edge of Georges Bank. The circulation around Georges Bank is clockwise, driven in large part by the tides. The slope water also crosses a sill and enters Jordan Basin, where it may enhance a counterclockwise gyre partly driven by nearshore buoyancy sources and the wind (see Figure T6.1.13).

Clockwise tidal gyres over Georges Bank and Browns Bank are permanent features. The tidal front on the northern and northwestern side of Georges Bank makes a twice-daily excursion of 10 to 15 km as a result of changes in tidal-current velocity. Its position is in rough agreement with the prediction made by Loder and Greenberg.[6] Along the southern flank of Georges Bank, the alongshelf current is associated with the alongshelf wind.

Vertical currents can be inferred from water properties. The Gulf of Maine bottom water originates from slope water that enters the Gulf through the Northeast Channel; it is modified within the Gulf by vertical mixing with the near-surface waters of Scotian Shelf origin. Wind-driven coastal upwelling is also observed, associated at times with dense plankton blooms.

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Associated Topics

T2.7 Offshore Geology, T3.5 Offshore Bottom Characteristics, T5.1 The Dynamics of Nova Scotia's Climate, T5.2 Nova Scotia's Climate, T6.2 Oceanic Environments, T6.3 Coastal Aquatic Environments, T6.4 Estuaries, T7.1 Modifying Forces, T8.1 Freshwater Hydrology

Associated Habitats

H1 Offshore

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