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.

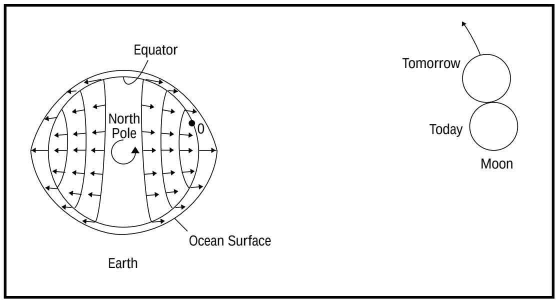


Figure T6.1.1[5]: The small arrows on the earth represent the net force due to the imbalance between the gravitational pull of the moon and the centripetal force which leads to "tidal bulges" on two sides of the earth. The moon is shown at two positions one day apart, to illustrate the delay of the tides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

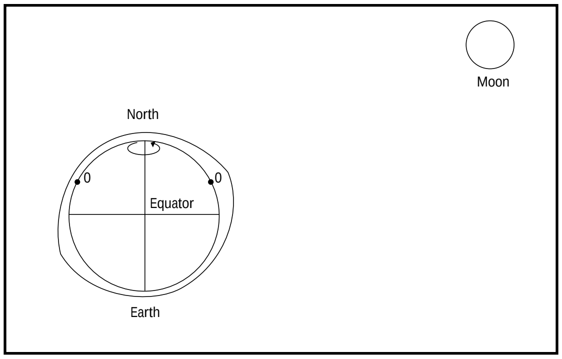


Figure T6.1.2[5]: Viewed from the side (north up) and with the moon north of the equator, the tidal bulges are asymmetric about the equator, resulting in the diurnal inequality in the heights of the high and low tides.

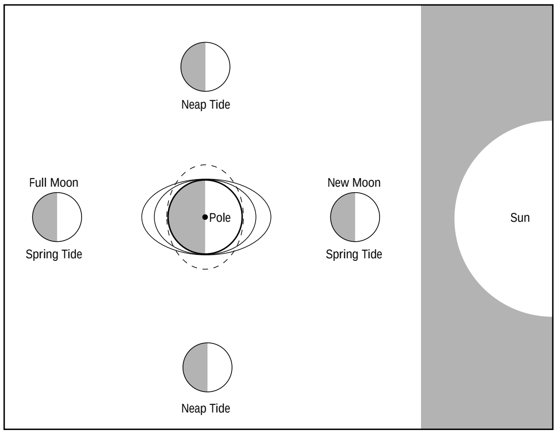


Figure T6.1.3[5]: Positions of the sun and moon at spring and neap tides.

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.

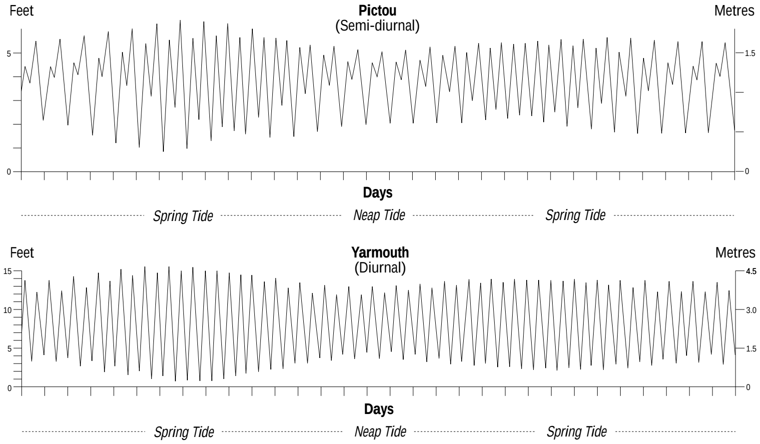
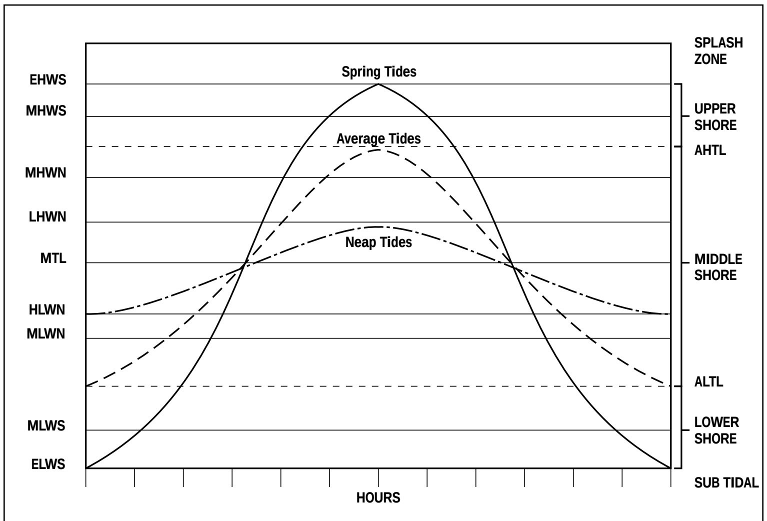


Figure T6.1.4a: Typical tidal curves showing tidal patterns in Pictou and Yarmouth.



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-

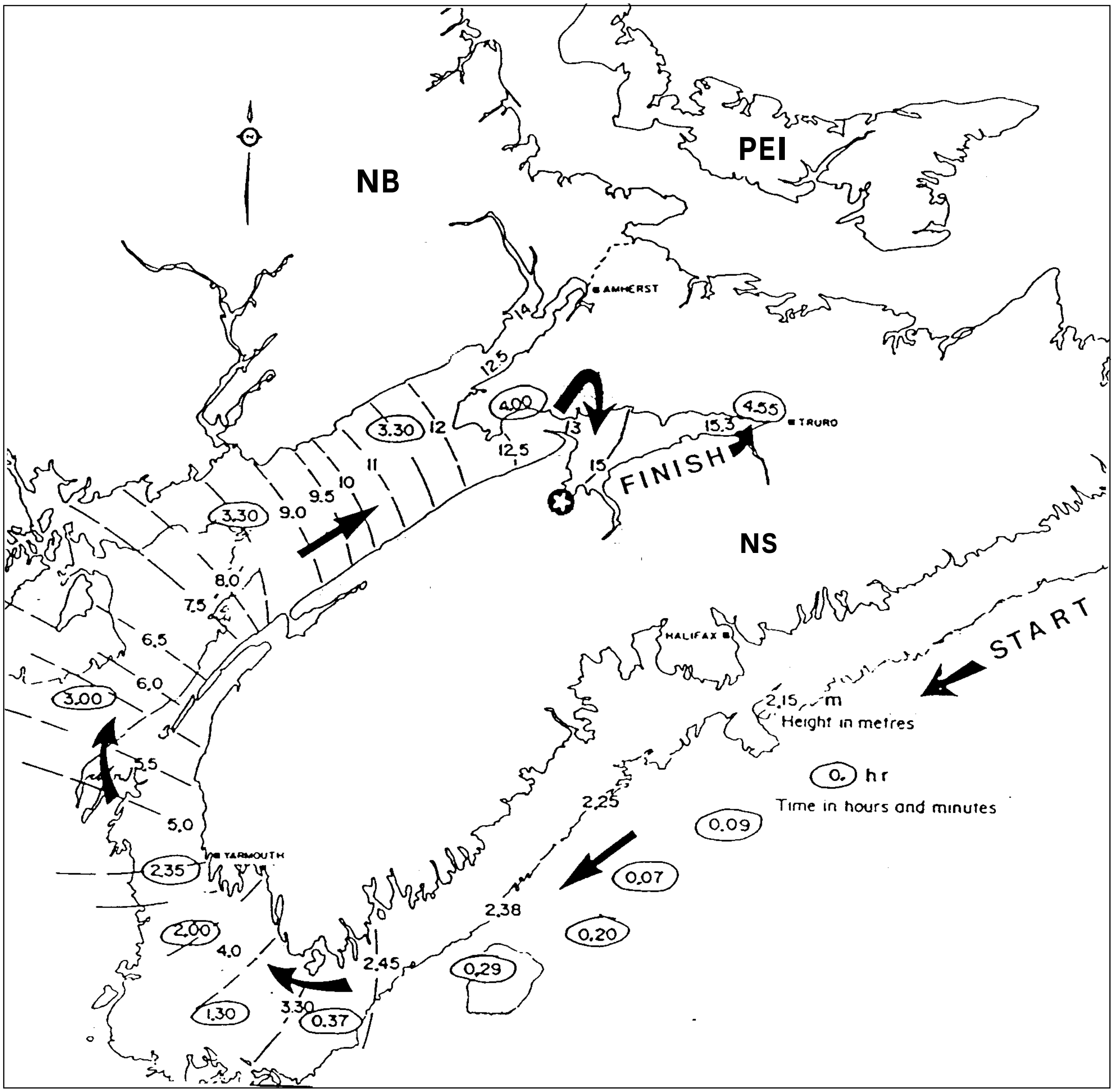


Figure T6.1.5: Sequence of tidal heights and times for South Shore of Nova Scotia and Bay of Fundy.

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

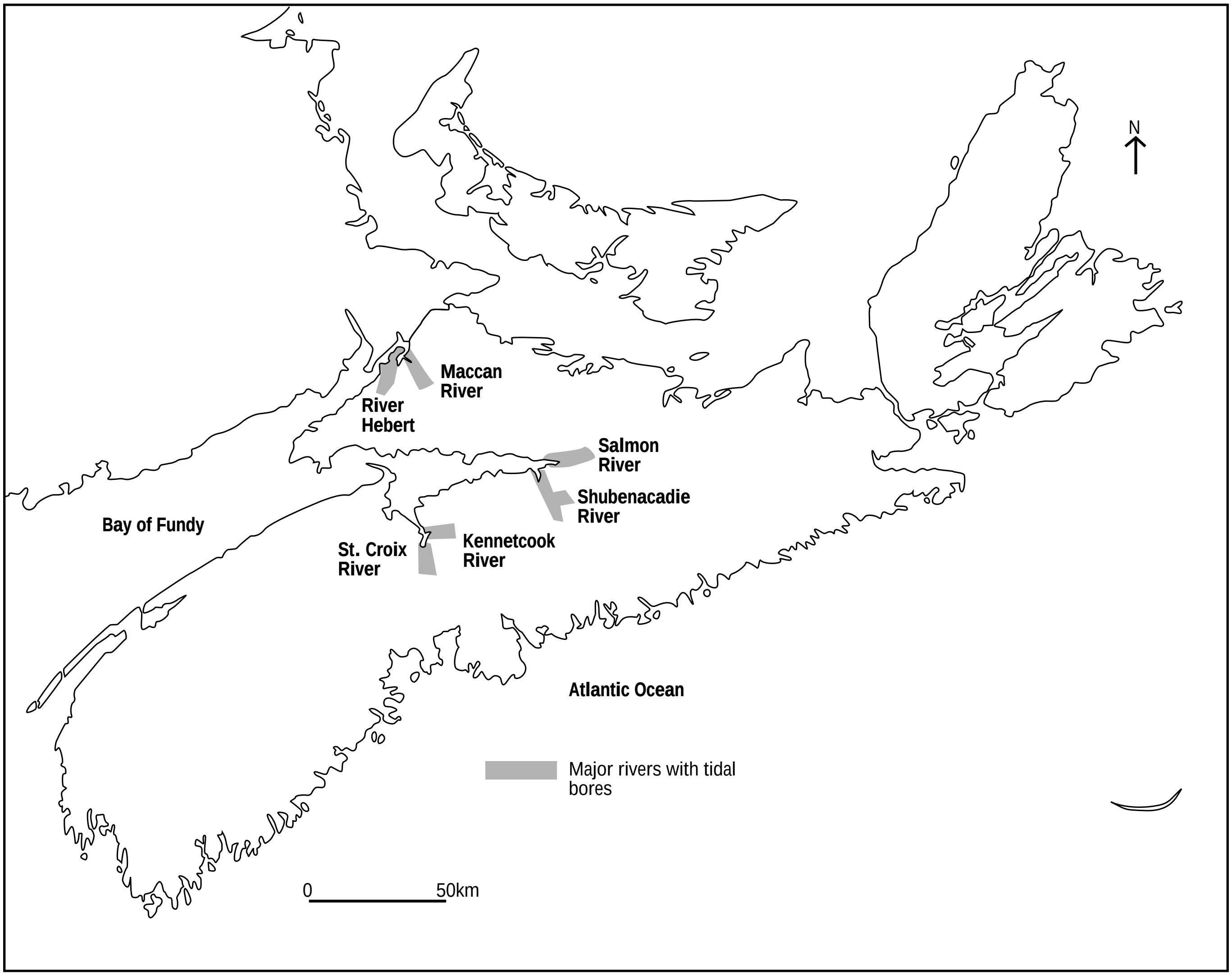


Figure T6.1.6: Major rivers with tidal bores in Nova Scotia.

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.

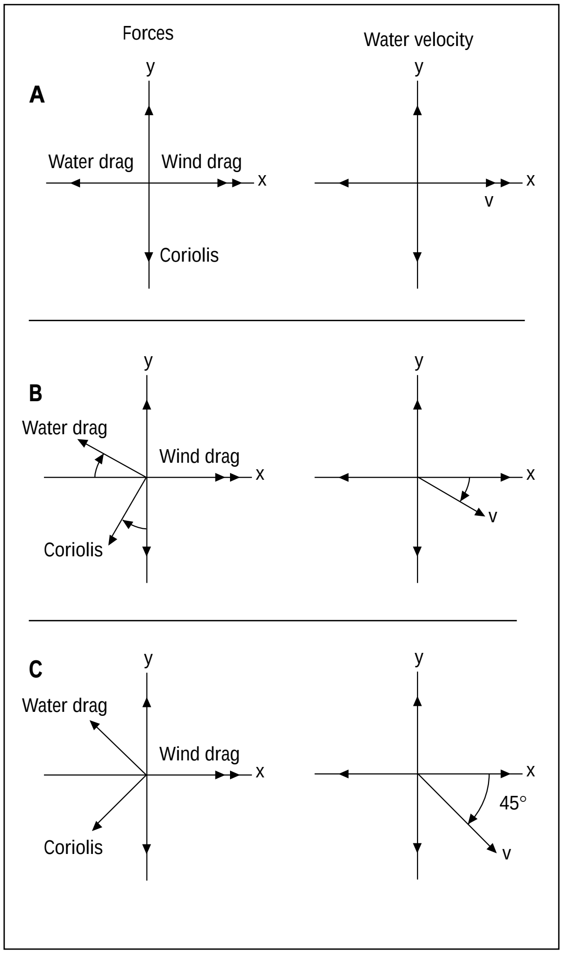


Figure T6.1.7[5]: The beginning of a wind-driven surface current in three stages, showing the forces on the left and the water velocity on the right. In stage **A** the wind drag creates a flow of water which gives rise to the water drag and the Coriolis force. In stage **B** the Coriolis force causes 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.

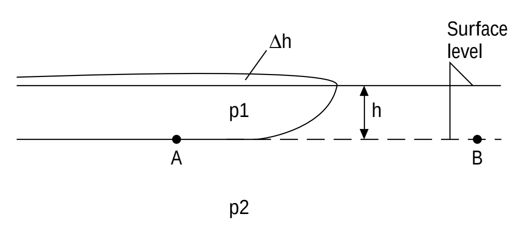


Figure T6.1.8[6]**:** A pool of light water, p1, lies on top of and beside water of greater density, p2. If the pressure at A and B are the same, the height of the sea surface above A must be higher than above B.

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.

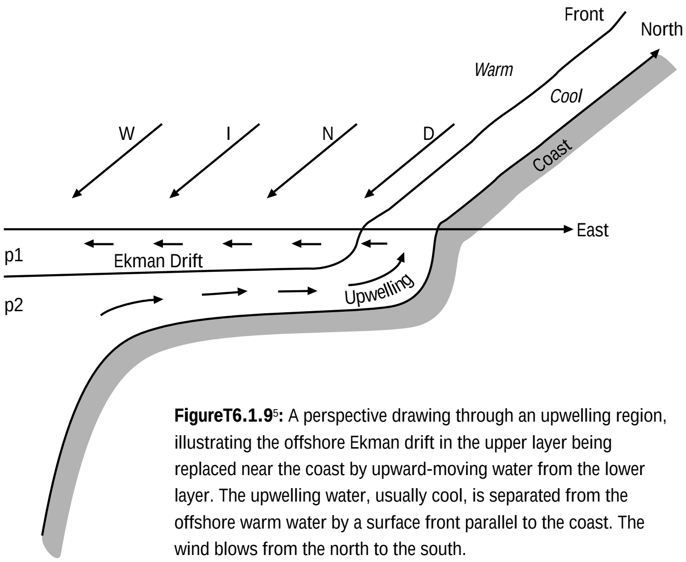
rial and organisms to pile up there. Windrows are the focus of fish and seabird feeding and, in rare cases, can lead to accumulations of poisonous algae sufficient to cause a health risk.

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[6]**:** 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.

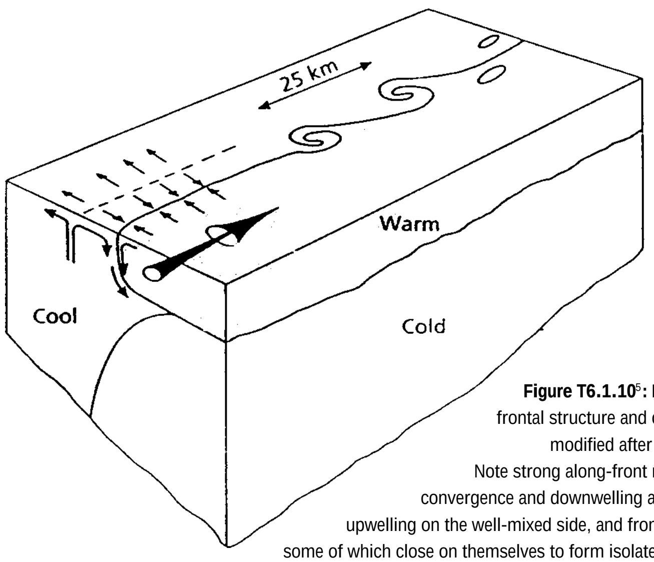


Figure T6.1.10[5]**:** Diagram of frontal structure and circulation, modified after Simpson[7]. Note strong along-front mean flow, convergence and downwelling at the front, upwelling on the well-mixed side, and frontal eddies, some of which close on themselves to form isolated patches.

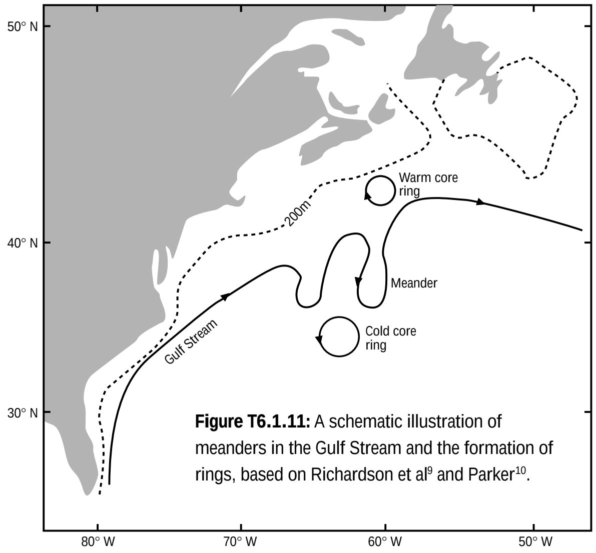


Figure T6.1.11: A schematic illustration of meanders in the Gulf Stream and the formation of rings, based on Richardson et al[9] and Parker[10].

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.

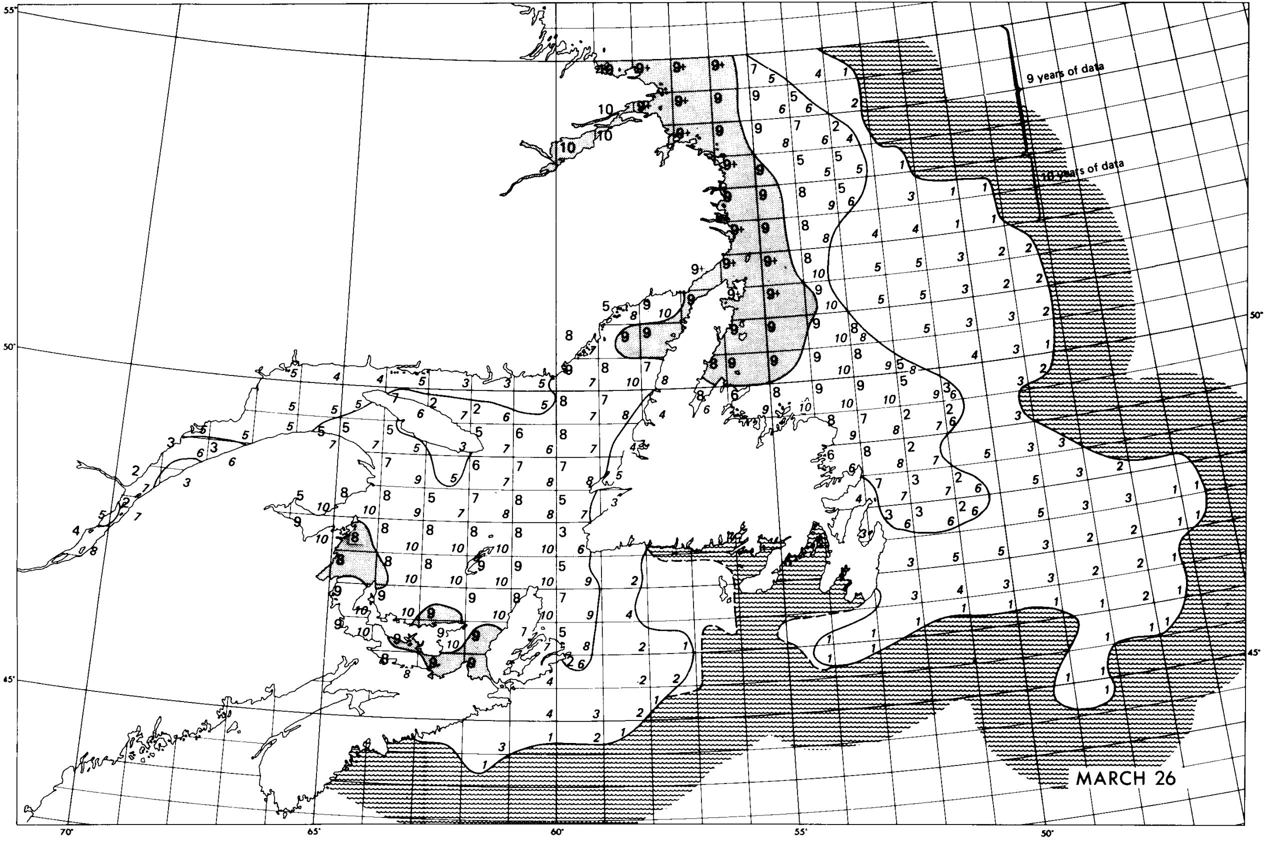


Figure T6.1.12: Chart showing minimum, median and maximum position of ice edge in the Gulf of St. Lawrence and on the Atlantic Coast for the years 1963–73; late March

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.

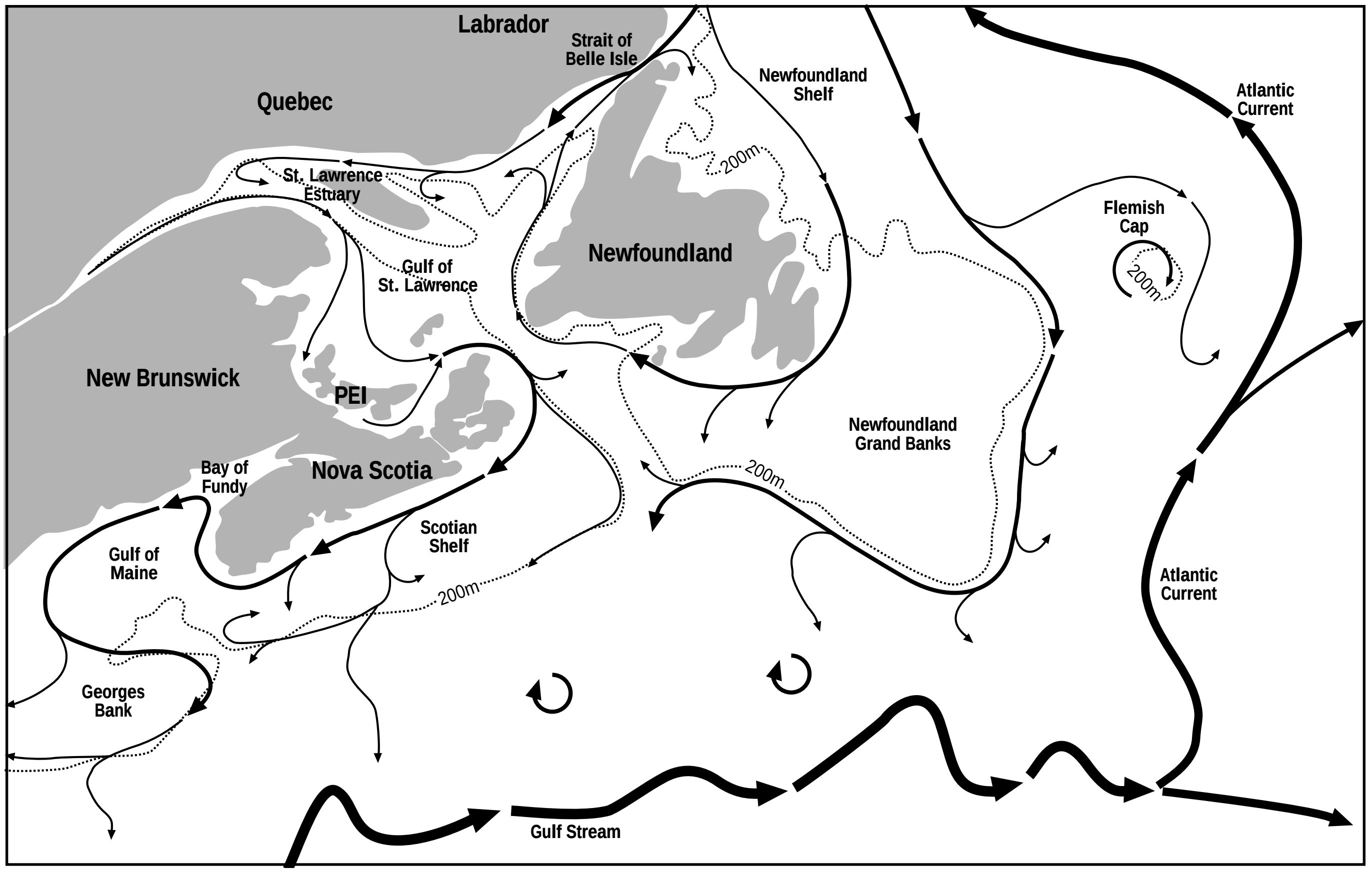


Figure T6.1.13: Major currents offshore Nova Scotia.

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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Additional Reading

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T6.2 OCEANIC ENVIRONMENTS

Temperature and salinity are important components of the oceanic environment influencing biological productivity. Figures T6.2.1a to T6.2.1d[1] show charts of February and August temperatures and salinities in the shallow nearshore waters of Nova Scotia. The February upper-layer temperatures are at or close to freezing; the south shore of Nova Scotia and Bay of Fundy show the highest values in the region. August temperatures are highest in Northumberland Strait and become cooler southwestward from Cape Breton along the Atlantic Coast.

Traditionally there are three distinct oceanic environments that influence Nova Scotia: the Gulf of St. Lawrence, the Scotian Shelf and the Bay of Fundy–Gulf of Maine. The Nova Scotian portions of these larger areas are described in Theme Regions (Vol-

Name	District /Unit	Temperature (°C)						Salinity (%)					
		0 m		30 m		100 m		0 m		30 m		100 m	
		Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug
Canso	911	-0.8	17.4	-0.6	6.7	0.9	1.0	31.2	29.7	31.2	31.2	32.1	32.7
Eastern Shore	911	0.7	15.4	1.0	4.8	3.8	3.6	31.2	30.7	31.3	32.0	32.9	33.1
South Shore	911	0.6	14.8	0.5	4.1	2.8	3.8	31.3	31.0	31.4	32.0	32.5	33.2
Shelburne	911	1.6	10.6	1.6	6.2	N/A	4.6	31.2	31.9	31.2	32.1	N/A	33.1
Lurcher Shoal	911	2.9	9.7	3.2	8.8	N/A	7.2	31.5	32.1	31.6	32.5	N/A	33.2
Sydney Bight	915	-1.5	17.1	-1.1	7.8	1.2	1.2	30.4	29.4	31.2	30.7	32.4	32.7

Table T6.2.1a: Average February and August temperatures and salinities at 0-, 30- and 100-m depths for Inner Scotian Shelf (District 910).[1]
N/A = not available

Name	District /Unit	Temperature (°C)						Salinity (%)					
		0 m		30 m		100 m		0 m		30 m		100 m	
		Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug
Roseway Bank	921b	2.0	15.6	2.1	5.8	3.0	4.6	31.6	31.3	31.6	31.9	32.2	33.1
Middle Bank	921e	-0.1	17.3	-0.4	6.8	2.1	1.1	31.4	30.6	31.4	31.7	32.5	32.6
Misaine Bank	921g	0.8	16.7	1.1	5.6	2.5	1.0	31.7	30.3	31.8	31.4	32.4	32.6
Banquareau	921h	2.2	16.1	2.1	6.9	2.2	4.5	32.2	31.1	32.2	32.0	33.0	33.7
Georges Basin	922b	4.3	17.7	4.7	12.4	6.3	6.5	33.0	32.1	33.1	32.5	33.8	33.6
LaHave Basin	922c	1.1	15.7	1.5	4.9	3.8	4.6	31.2	31.0	31.4	32.3	33.1	33.5
Emerald Basin	922d	2.4	17.7	2.9	5.3	7.1	5.3	32.1	30.9	32.3	32.4	34.2	33.7
East Gulf of Maine	923	3.5	12.6	3.6	9.4	4.9	7.1	31.8	32.4	31.7	32.8	32.7	33.6
Roseway Channel	923	N/A	N/A	N/A	7.3	N/A	N/A	N/A	N/A	N/A	32.6	N/A	N/A
Roseway Basin	923	1.9	10.9	1.8	4.7	3.8	3.1	31.2	31.8	31.2	32.3	32.6	32.8

Table T6.2.1b: Average February and August temperatures and salinities at 0-, 30- and 100-m depths for Middle Scotian Shelf (District 920).[1]
N/A = not available

Name	District /Unit	Temperature (°C)						Salinity (%)					
		0 m		30 m		100 m		0 m		30 m		100 m	
		Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug
E Georges Bank	931a	3.9	15.1	4.5	10.7	5.7	7.2	32.7	32.3	33.0	32.6	33.1	33.4
Georges Shoal	931a	4.4	13.9	4.9	12.4	N/A	N/A	33.1	N/A	33.4	32.5	N/A	N/A
Browns Bank	931b	3.5	14.3	3.5	7.3	8.0	8.3	32.0	31.8	32.1	32.5	34.1	34.2
Baccaro Bank	931b	2.3	14.4	3.1	7.8	4.5	4.1	31.9	31.6	32.2	32.1	32.5	33.1
LaHave Bank	931c	2.5	16.6	2.3	6.5	5.1	5.6	31.6	31.3	31.7	32.1	33.3	33.6
Emerald Bank	931d	3.4	19.1	3.7	8.1	8.1	8.9	32.4	31.2	32.5	32.9	34.4	34.7
Western Bank	931e	3.4	18.9	3.5	8.6	7.5	7.0	32.3	31.7	32.4	32.6	34.0	34.2
Sable Island Bank	931e	2.5	17.1	2.4	12.1	N/A	7.3	31.1	31.2	31.4	31.8	N/A	34.0
Banquereau	931f	2.2	16.1	2.1	6.9	2.2	4.5	32.2	31.1	32.2	32.0	33.0	33.7
NE Channel	932	3.2	15.8	1.7	12.0	6.6	8.7	32.1	32.4	32.8	32.9	33.7	34.2
Saddle	932	N/A	18.1	N/A	6.9	N/A	7.1	N/A	31.1	N/A	32.8	N/A	34.0
The Gully	932	N/A	16.8	2.3	7.0	3.6	3.6	N/A	30.8	32.1	31.7	33.0	33.3

Table T6.2.1c: Average February and August temperatures and salinities at 0-, 30- and 100-m depths in the Outer Scotian Shelf Region (District 930).[1]
N/A = not available

Name	District / Unit	Temperature (°C)						Salinity (%)					
		0 m		30 m		100 m		0 m		30 m		100 m	
		Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug
Southern Slope	940	5.8	17.7	9.3	11.5	4.1	4.2	33.2	32.3	34.4	35.0	34.9	34.9
Central Slope	940	4.8	19.2	8.8	9.4	N/A	4.1	32.9	31.8	34.4	34.7	N/A	35.0
Northern Slope	940	4.0	18.2	6.9	7.7	3.4	4.1	32.7	31.9	34.1	34.3	35.0	35.0

Table T6.2.1d: Average February and August temperatures and salinities at 0-, 30- and 100-m depths for the Continental Slope (District 940).[1]
N/A = not available

ume 2) and the corresponding Districts and Units are indicated below.

ENVIRONMENT OF THE GULF OF ST. LAWRENCE

The Gulf of St. Lawrence (Unit 914) is an inland sea as well as a large estuary. It has been compared to the Baltic Sea in northern Europe because both hold similar quantities of water, both drain fresh water from comparable watersheds, and both have similar biological productivity. However, the Gulf of St. Lawrence exchanges ten times more ocean water than the Baltic Sea,[2] for reasons related to the larger runoff in the Gulf of St. Lawrence. Thus, while the residence time for water in the Baltic is approximately twenty years (7000 days), in the Gulf of St. Lawrence it is 200 to 500 days.

The environment in the Gulf of St. Lawrence is influenced by freshwater flow from the St. Lawrence River, by winds and air temperatures, and by flows in and out of the Strait of Belle Isle and the Cabot Strait. In the winter a two-layer water column structure exists, with a thick, cold, relatively fresh layer overlying deep, warmer water from Cabot Strait (Figure T6.2.2). The cold, upper layer, formed by cooling rather than by influxes of polar water, has temperatures of –1 to 2°C and associated salinities of 32 to 33

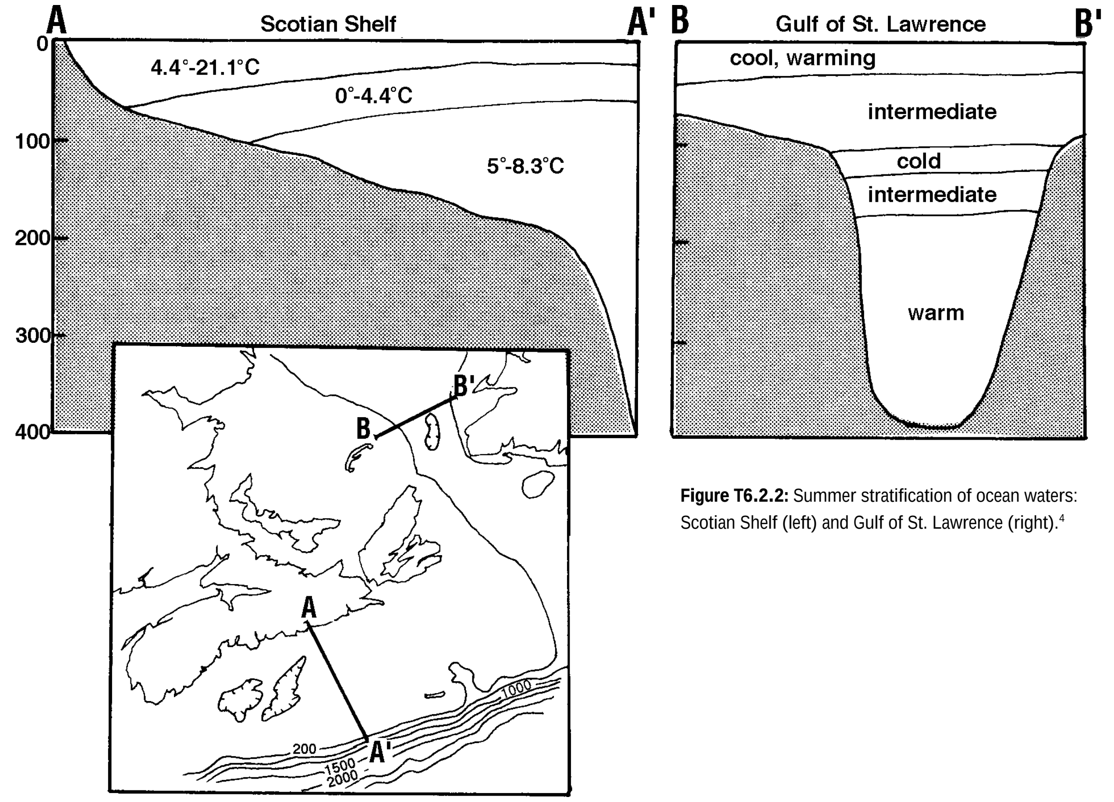

Figure T6.2.2: Summer stratification of ocean waters: Scotian Shelf (left) and Gulf of St. Lawrence (right).[4]

particle salinity units (psu), or parts per thousand. The deep "warm" layer has temperatures as high as 6°C and salinities over 34 psu. The temperature of this deep, warm layer has increased by up to 2°C between the mid-1960s and the late 1970s. Analysis indicates that the primary factor determining the variation of the deep-water properties is the variation of the oceanic waters at the mouth of the Laurentian Channel, rather than variation of freshwater runoff, as previously suggested.[3]

In the spring, a third layer—a warm, surface layer—develops on top of the cold layer. The cold layer persists at middle depths. The surface layer is approximately 20 m thick, with temperature typically around 15°C and salinity, 30 per cent.

In the Magdalen shallows and the Northumberland Strait, the difference between summer and winter temperatures is even more pronounced, due to summer heating of the relatively shallow water column. Summer temperatures in the Northumberland Strait are higher than on the Atlantic Coast (see Figure T6.2.2). These warm temperatures result from the combination of shallow water, stratification and relatively weak currents. The tidal range is 2 m in the Northumberland Strait, and at certain times, only one tide occurs (see Figure T6.1.4a).

In summer, the low tides that occur during the day, expose beaches and sandbars to the sun. The incoming water is warmed as it moves over these sand flats, retaining the high water temperature.

In the open Gulf, surface salinities range from 26 to 32 psu, but may be lower in bays and estuaries. As the summer progresses, the surface layer in the southwestern area of the Gulf becomes thinner and less salty, due to the arrival and influence of the spring peak of the St. Lawrence River freshwater runoff, which has been two to three months in transit. Of course, changes in wind direction and strength may alter the relative positions of the water layers, resulting in changes in temperature and salinity.

Environmental variations linked with river flow may be an important determinant of commercial fish production, especially in the spring. There is an upwelling effect of fresh water; nutrients are brought to the surface.[5] The arrival of the spring discharge from the St. Lawrence estuary significantly affects the hydrology of the area and, through the formation of fronts, may result in increased aggregation of food organisms and fish larvae.[6]

In addition to natural effects, there are significant changes in seasonal flow patterns resulting from the control of the freshwater supply by hydroelectric

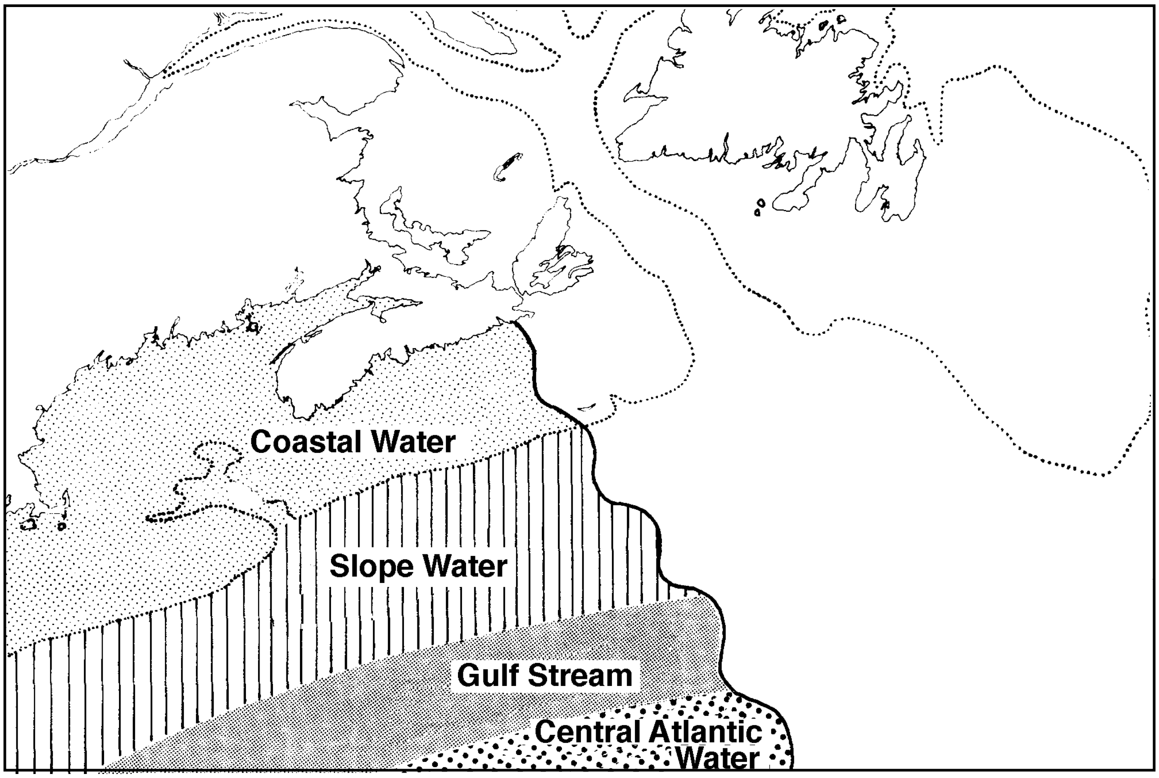

Figure T6.2.3: Classification of ocean water off the Atlantic Coast.[7]

development, principally in Quebec. The effect is to reduce greatly the biologically important spring discharge. Total productivity of the Gulf system has probably already been seriously reduced, and further hydroelectric development could further reduce productivity.[6]

ENVIRONMENT OF THE SCOTIAN SHELF

The environment of the Scotian Shelf (Units 911, 915 and Districts 920, 930) is determined largely by the circulation. Moving outward from the Atlantic Coast of Nova Scotia, four distinct bands of water are crossed, as shown in Figure T6.2.3[7]. The Scotian Shelf is normally covered by a surface layer of relatively fresh and low-density coastal water, the Nova Scotia Current. Beyond this, in the vicinity of the edge of the continental shelf and separated by a sharp front, is a band of slope water consisting of Gulf Stream water diluted approximately 20 per cent by coastal water. Beyond the slope water lies the Gulf Stream and beyond that is central Atlantic water.

On the Scotian Shelf in summer, three vertical layers of water are evident:

1. an upper, warm, “fresh” layer, typically 30 m thick, with temperatures of 5 to 20°C and salinities of less than 32 psu
2. an intermediate, cold layer, typically 100 m in thickness, with temperatures of 0 to 4°C and with salinities from 32 to 34 psu
3. a warm, saline, bottom layer, located at depths between 90 and 200 m, with temperatures between 5 and 8°C, and salinities up to 35 psu. Temperatures in the warm bottom layer may rise as high as 12°C due to incursions of slope water.

A long-term, large-scale overview of shelf sea-surface temperatures from Newfoundland to Maryland shows coherent trends for the Grand Banks, Scotian Shelf, Gulf of Maine, and the Sydney Bight. Annual averages vary coherently over a range of approximately four Celsius degrees. Increased sea-surface temperature is related to increased onshore winds.[8]

Against this background, there are many areas on the Scotian Shelf where the mixing/stratification sequence (and consequent high productivity) occurs. There are coastal upwelling areas, estuarine upwelling, banks with tidal gyres, and shelf-break fronts.

ENVIRONMENT OF BAY OF FUNDY AND GULF OF MAINE

The dominant influence on the marine environment of the Bay of Fundy (Units 912, 913) is that exerted by the phenomenally large tides. The waters of the Bay of Fundy come from the Scotian Shelf as well as from the Gulf of Maine. The tidal mixing of waters with different characteristics tends to modify seasonal temperature variations and to create a water column that is fairly uniform in temperature and salinity. Ice occurs in the upper reaches of the Bay of Fundy from December to April, and ice conditions are influenced by the macro-tidal characteristics of the area. Tides influence patterns of erosion and sediment deposition in coastal areas. Tidal mixing, coupled with ample sediment sources, makes the water quite opaque, an important factor in limiting phytoplankton productivity.

The mud-flat habitat at the head of the Bay of Fundy is influenced by the large tidal extreme and seasonal occurrence of highest tides (see T6.1).

The Gulf of Maine ocean environment (parts of Unit 911 and Districts 920, 930) is determined by the environmental condition of Scotian Shelf waters and by tidal and mean currents, slope-water incursions, and atmospheric influences. In contrast to the Bay of Fundy, the tides are not so very dominant.

The intermittent incursions of relatively warm, saline slope water occurs in surface and bottom layers. 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.

Analyses suggest that as much as 44 per cent of the new nitrate which enters the Gulf of Maine at depth through the Northeast Channel upwells in the eastern Gulf. This feature appears to be very important to the general biological productivity of the inner Gulf of Maine.

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Associated Topics

T3.5 Offshore Bottom Characteristics, T5.2 Nova Scotia's Climate, T6.1 Ocean Currents, T6.3 Coastal Aquatic Environments, T6.4 Estuaries, T7.1 Modifying Forces, T10.9 Algae, T11.7 Seabirds and Birds of Marine Habitats, T11.12 Marine Mammals, T11.14 Marine Fishes, T11.17 Marine Invertebrates

Associated Habitats

H1 Offshore, H2.4 Mud Flat

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T6.3 COASTAL AQUATIC ENVIRONMENTS

The coastline of Nova Scotia encompasses numerous bays, inlets and lagoons. The largest include St. Georges Bay (Units 521b/914), separating Antigonish and Inverness counties, and St. Margarets Bay (District 460b, Unit 911); the smallest, coastal inlets, such as Herring Cove (Unit 851), near Halifax. Bras d'Or Lake (District 560/Unit 916) in Cape Breton Island is a unique inland waterbody.

The majority of inlets and harbours were formed as the result of submergence of river valleys. Physical conditions in coastal waterbodies tend to be warmer, more estuarine (see T6.4), and more sheltered than exposed sections of the ocean coastline. Consequently, they have animal and plant communities that differ from those found on the open coast.

TOPOGRAPHY

Coastal aquatic environments are largely determined by the type of underlying rock. Rivers on less-resistant bedrock in northern Nova Scotia erode wide lowlands and result in shallow bays and branching estuaries (e.g., Pictou Harbour and East, West and Middle rivers in Unit 521a).[1]

Rivers and glacial meltwaters have eroded narrow valleys in more-resistant bedrock in southern Nova Scotia and, consequently, formed deeper estuaries and excellent harbours. The larger bays and features such as St. Georges Bay reflect their position between major geological formations. Fjords, which are common in Newfoundland and along the Labrador coast, are uncommon on the Nova Scotia coastline. They are typically deep, have a U-shaped cross section and become shallower at the outward end. (This is called a "sill.") Examples can be found on Cape Breton Island at Ingonish Harbour (Unit 552c) and parts of Bras d'Or Lake.

PROCESSES

Land obstructions prevent tidal currents moving freely around the earth. Instead, the water moves backwards and forwards in semi-enclosed basins. Every bay or basin has a natural period of oscillation depending on its length, depth and shoreline. If this period coincides with the period of the tides, the two will augment each other, resulting in tides with high amplitude. When the two periods differ substantially, tides will tend to be low. The Bay of Fundy is tuned to semi-diurnal tidal frequencies, resulting in ever-increasing amplitudes towards the upper reaches.

The water column is not mixed significantly by tidal action in areas of southern Nova Scotia, and the water may be stratified (density increasing with depth). These areas typically receive waters which are high in organic material, or "brown water," which can block the penetration of light to the seawater below and reduce productivity during periods of high freshwater flow.

Wave exposure is generally lower in inlets and bays, resulting in sediment accumulation and lower seaweed populations. Coastal oceanographic processes often pile up more sediments along the coast than can be carried laterally by currents, leading to the formation of bars or barriers, which block the mouths of some river systems (see T8.3).

LAGOONS AND BARACHOIS

The entrance to harbours can be blocked by the development of coastal spits, barrier islands and barrier beaches, depending on local conditions. These protected areas develop an estuarine character. In the Northumberland Strait, coastal lagoons are protected from ice scour. Species of seaweed preferring warm water may develop there.

BRAS D'OR LAKE

The two channels—the Great and Little Bras d'Or Channels—leading into the Bras d'Or Lake system are very narrow, restricting the volume of water entering and leaving with each tide. For this reason, the tidal range is small, approximately 0.08 m near Baddeck, compared to 0.9 m in the Cabot Strait. In smaller basins, such as Whycocomagh Bay, the tidal range is almost nonexistent. Tidal currents in the two channels can nevertheless be strong, with great variations in strength and direction at different depths. Barometric pressures can cause water levels in the confined lake to rise or fall by up to 0.3 m while the adjacent ocean is, of course, unaffected. The ocean water brought in through this process maintains the relatively high salt content in the system. Therefore, although they occur less frequently, the barometric tides have much greater impact on the Bras d'Or Lake than do the normal tides. Strong tidal currents of 3 m/s in the Great Bras d'Or Channel and 1.5 m/s in the Barra Strait combine with the barometric tides to mix the fresh and salt waters in the lakes.

LARGE BAYS

St. Georges Bay (Units 521b/914), Mahone Bay (District 460a/Unit 911) and St. Margarets Bay (District 460b/Unit 911) have marine environments similar to the conditions typical of the open ocean offshore. Oceanic organisms, including jellyfish and pelagic fish (such as tuna), often enter the bays, and seaweed populations can be extensive. The size of the bays permits significant wind fetch and moderate wave exposure. These areas may be affected by influxes of fresh water from coastal streams, but the bays as a whole are not estuarine. Events such as storms and tides in offshore waters have a greater impact on these bodies than local factors.[2]

CULTURAL FACTORS

Coastal bays and inlets are used increasingly for culture of fish and molluscs, principally mussels. Human development tends to cluster in areas affording suitable harbours and availability of water for disposal of wastes. As a result, some of these areas have been extensively polluted (see T12.12).

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Associated Topics

T2.7 Offshore Geology, T3.5 Offshore Bottom Characteristics, T5.2 Nova Scotia's Climate, T6.1 Ocean Currents, T6.2 Oceanic Environments, T6.4 Estuaries, T8.1 Freshwater Hydrology, T7.1 Modifying Forces, T8.2 Freshwater Environments, T7.2 Coastline Environments, T7.3 Coastal Landforms, T10.6 Trees, T11.6 Shorebirds and Other Birds of Coastal Wetlands, T11.7 Seabirds and Birds of Marine Habitats, T11.12 Marine Mammals, T11.14 Marine Fishes, T11.17 Marine Invertebrates, T12.7 The Coast and Resources

Associated Habitats

H1 Offshore, H2.5 Tidal Marsh, H3.1 Open Water Lotic (Rivers and Streams), H3.3 Bottom Lotic (Rivers and Streams)

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T6.4 ESTUARIES

Estuaries occur at the mouths of rivers where seawater becomes diluted by fresh water draining from the land. They are among the most productive ecosystems—comparable to rainforests and coral reefs—partly because they tend to be shallow, receive a continuing supply of nutrients from the river and are mixed by the tidal movements of the sea.[1] They are not easy environments for organisms to inhabit, due to variations in salinity and temperature, periodic exposure to the atmosphere and the great influences exerted by human beings (see T12).

Nova Scotia has many estuaries (almost as many as there are rivers) and they vary regionally.

PHYSICAL FEATURES

Important physical features which determine estuarine conditions include the morphology of the river mouth and availability of soft sediments (both related to the geology of the area), and the relative strengths of tidal movements and river outflow.

Tides vary over several different time scales (see T6.1). The sea level is also influenced by wind and changes in barometric pressure; these may either increase or decrease the natural tidal movement near a coastline. River flow, in turn, tends to be seasonal—higher following major storms or snow melt in spring, and lower during mid-winter and in dry periods such as commonly occur in summer.

The relative rate of sea-level rise can also contribute to estuarine conditions. Studies in Chezzetcook Inlet indicate that rapid sea-level rise (3.8 mm per year between 1920 and 1970) has resulted in widespread coastal erosion and subsequent infilling of the estuary.[2]

FRESHWATER INFLUENCE

When river flow is much greater than tidal movements, the fresh water tends to remain on top of the seawater because it is less dense, forming a freshwater layer above a distinct salt wedge. Such an estuary is said to be stratified (see Figure T6.4.1). Under these circumstances, many of the dissolved and particulate materials brought by the river move seaward in the estuary and may in fact be flushed right through it if the flow is very high. As the water travels further into the estuary, its velocity usually decreases, allowing heavier particles to settle toward the bottom and resulting in an accumulation of sediments and other detritus in deeper water. The outward flow of the river also mixes with and carries along some of the underlying seawater. This phenomenon has the effect of causing water in the deeper seawater layer to move upstream as a reaction current or countercurrent (see T6.1). The reaction current can carry free-floating objects in the water just above the bottom (suspended sediments, planktonic larvae, fragments of detritus, etc.), bringing them upstream toward the head of tidal influence. Because of a relative lack of mixing in the salt wedge, water remains at about the same salinity as that of the nearby sea. It can be inhabited by marine plants and animals that in some cases move from the ocean all the way to the head of the salt wedge. The surface layer, being fresh, may be inhabited by plankton and fish originating in fresh water.

Few of Nova Scotia's rivers have such a dominating flow all year, but during periods of snow melt or following heavy rainstorms, many estuaries may become temporarily stratified. Where the

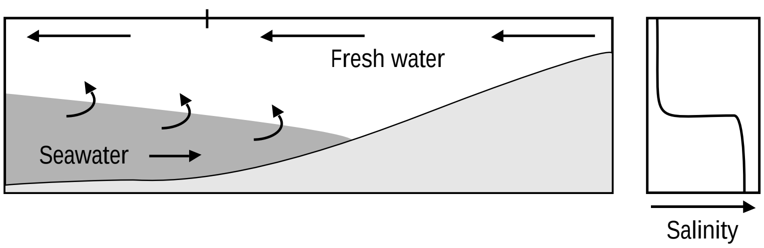

Figure T6.4.1: Diagramatic longitudinal section and profile of a stratified estuary.

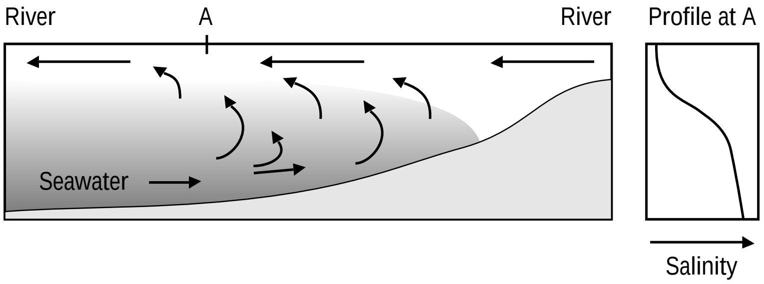

Figure T6.4.2: Diagramatic longitudinal section and profile of a vertically mixed estuary.

influence of the tide has been reduced by building of dams or causeways (e.g., the Annapolis River at Annapolis Royal, District 610), such stratification may become a permanent feature.

TIDAL INFLUENCE

Many Nova Scotia estuaries are more strongly influenced by tidal and wind-generated movements of the sea than by the river flow. The strong bottom currents tend to mix the fresh water and seawater together, so that the salinity at any point in the estuary is approximately the same from the surface to the bottom of the water column. Such an estuary is said to be vertically mixed (see Figure T6.4.2).

In these estuaries, salinity declines progressively as one moves upstream. In vertically mixed estuaries, materials brought down the river from the watershed are also mixed from top to bottom. They may accumulate in the upper part of the estuary, forming a zone of distinctly turbid water, known as the turbidity maximum. Marine organisms, having little tolerance for reduced salinity, will be confined to the outer parts of the estuary. Freshwater species will be restricted to the end where the river enters. Most parts of such estuaries are inhabited by species that have relatively wide tolerance of salinity and temperature. Furthermore, animals living attached to the bottom or in bottom sediments may be subjected to widely varying salinity as the tide ebbs and floods.

Most of the estuaries along Nova Scotia's coast (Atlantic Coast and Gulf of St. Lawrence) have tidal ranges of about 1 to 2 metres. The smallest tidal range (less than 20 cm) is found in Bras d'Or Lake (Unit 916). In the Bay of Fundy (Units 912, 913), on the other hand, average tidal range increases from about 4 m near Yarmouth to almost 12 m in Minas Basin. Estuaries with tidal ranges smaller than 2 m are classed as microtidal, those from 2 to 4 m as mesotidal and those above 4 m as macrotidal.

Estuaries with large tidal ranges naturally have extensive areas of tidal flats that are successively covered and exposed as the tide floods and ebbs (see H2.4 and H2.5). This is a difficult environment for many organisms to inhabit, owing to the interaction of physical and chemical factors: salinity and temperature variations, the nature of the substrate, alternations in wetting and drying, and so on. Consequently, the diversity of species is often rather limited, certainly by comparison with rivers, streams and rocky shores. Where there are few species, however, those present may be extremely abundant.

SEDIMENTS

Many estuaries have extensive areas of soft sediments, such as deposits of sand, silt or clay, which are exposed at low tide. Their distribution is determined by the strength of tidal and river currents, or exposure to waves, but they each represent significantly different habitats for organisms.

Sands occur where water movements are quite strong. They are coarse in texture and drain quickly as the tide ebbs. The larger clams, polychaetes that construct tubes from sand grains, burrowing isopods and other crustaceans are common inhabitants of this zone. In nutrient-rich sand flats, common in estuaries, the sand may also be colonized by benthic diatoms, which provide the base of the sand-flat food chain. This food source is often augmented with detritus from surrounding salt marshes and submerged Eel Grass beds, or by organic matter brought down the river. Silts tend to be richer in organic matter, do not drain as readily at low tide and are more likely to become anaerobic. These are also inhabited by polychaetes, species of clams, mud snails and small crustaceans. Clay-dominated "mud flats" occur in relatively calm water, appear "sticky," tend to retain the water at low tide and are often anaerobic just below the surface because of the high content of plant-derived material. The surface of a mud flat may sometimes be held together by carbohydrates exuded by microscopic diatoms living in the upper millimetre of sediments and migrating to the surface to photosynthesize as the tide ebbs. Each type of deposit has its characteristic fauna and flora and exhibits very strong interactions between the physical and biological world.[3]

PRODUCTIVITY

Estuaries and other coastal environments are important for biological organisms in a variety of ways. They tend to act as traps for sediment and nutrients brought down the river. The nutrients support phytoplankton growth and extensive development of tidal marshes and frequently Eelgrass beds, which are important to the Brant and Canada Goose. The stems and leaves of Eelgrass decay in coastal waters and form detritus. Several estuarine species, including crustaceans, molluscs and worms, consume detritus either for its inherent food value or for the rich microflora of bacteria and fungi that may be decomposing it. Many Nova Scotia estuaries, particularly in the inner Bay of Fundy (Unit 913a), support ecosystems which are almost entirely based on detritus.

The estuary is open to the sea, allowing mobile species, such as fish and crustaceans, to migrate into the estuary for feeding, as well as to find appropriate spawning grounds. Estuarine circulation, and the nutrients it provides, offers an added benefit to marine organisms over the already-important coastal regimes where upwelling, light and temperature are favourable to growth. Estuaries have high productivity by organisms in the water column and in suspension-feeding marine organisms (such as mussels) that feed on them, because of the physical interaction of the fresh and salt water and the nutrient supply it provides. In estuaries in which the surface freshwater layer is well defined, a tongue of salt water can extend significant distances upriver and provide habitat for marine organisms.

The warm temperatures, rich food supply and relative absence of predators make estuaries important nursery grounds (areas where young stages are able to feed, find shelter and grow rapidly). A number of fish species (e.g., salmon, flounder, herring, shad and Striped Bass) are linked closely to estuarine environments at important stages in their life cycle. The fertile estuarine regions of the Bay of Fundy also attract migratory fish (e.g., pollock, dogfish), seabirds, shorebirds and marine mammals, which sometimes come from great distances. These estuaries are therefore important for Nova Scotia and much of the Northern Hemisphere.

CULTURAL FACTORS

There is a long tradition of use related to estuaries in Nova Scotia. Most recently, aquaculture has focused attention on maintaining the quality of estuarine environments (see T12.7 and T12.11).

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Associated Topics
T6.1 Ocean Currents, T6.2 Oceanic Environments, T6.3 Coastal Aquatic Environments, T8.2 Freshwater Environments, T10.5 Seed-bearing Plants, T10.6 Trees, T11.6 Shorebirds and Other Birds of Coastal Wetlands, T11.7 Seabirds and Birds of Marine Habitats, T11.12 Marine Mammals, T11.13 Freshwater Fishes, T11.14 Marine Fishes, T11.17 Marine Invertebrates, T12.7 The Coast and Resources, T12.11 Animals and Resources

Associated Habitats
H2 Coastal

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