BULLETIN No. 134

Oceanography and Canadian Atlantic Waters

By H. B. HACHEY
Fisheries Research Board of Canada

PUBLISHED BY THE FISHERIES RESEARCH BOARD OF CANADA UNDER THE CONTROL OF THE HONOURABLE THE MINISTER OF FISHERIES
OTTAWA, 1961

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AN OCEAN AT SUNRISE

"And I stood serene and peaceful
In the quiet morning hush
Gazing eastward o'er the ocean
As the Master plied his brush."

(Apologies to Boutilier)

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PREFACE

Hast thou entered into the depths of the sea,
And walked in the lowest parts of the deep?
Hast thou considered the breadth of the earth?
Tell me if thou knowest all things?

The Book of Job
Chapter 38, verses 16 and 18.

One can enter into the depths of the sea, walk in the lowest parts, and attempt to perceive the breadth of the earth. This in the fullness of its allegory is oceanography. In its immensity and its diversity, the ocean has a humbling influence on the oceanographer, who rather than making the claim "knowest all things" appreciates how little he knows.

Over the years, the few Canadian oceanographers have made noteworthy contributions to the science of the sea. The expansion of activities in oceanography in recent years has attracted a number of young scientists to this most interesting of subjects. What follows is a summary, albeit incomplete, of the developments in the study of Canadian Atlantic waters over the years. This, with an outline of some basic physical principles and a bibliography, is presented as a background for the new generation of Canadian oceanographers.

INTRODUCTION

The ocean area of the Atlantic to the north of Lat. 40°N and west of Long. 40°W, and encompassing waters of the eastern Canadian Arctic, is best defined as the northwestern North Atlantic. As the ocean waters of this area are of particular interest to Canada, they are referred to herein as Canadian Atlantic waters. The area so delimited embraces waters associated with the drift of arctic ice, the drainage waters of the St. Lawrence River, and the confluent waters of two great ocean systems, the Gulf Stream and the Labrador Current.

SUBMARINE TOPOGRAPHY

The foundations of knowledge of the floor of the North Atlantic were laid during the latter half of the nineteenth century. The greatest impetus was given to the exploration of the sea floor by the need for information on the character of the sea bottom for the laying of transatlantic cables. The large-scale features were thus brought to light. The echo sounder came into use about 1925 and over the years this equipment has become standard on most vessels, and much detailed information has become available.

In the North Atlantic Ocean, one of the major features of the submarine topography is the North Atlantic Ridge submerged to 1000 and 2000 fathoms, extending from the south of Greenland to the equatorial regions, thence into the South Atlantic, where it is known as the South Atlantic Ridge. In the North Atlantic, this ridge separates the North Atlantic Basin from the Cape Verde Basin. This ridge discovered nearly a century ago during the laying of the transatlantic cable is now known to be the mightiest single mountain system on earth, at least 10,000 miles long and 500 miles wide, more than twice the length and width of the Andes, and with many peaks loftier than most continental mountains. Although for most of its length its summits lie a mile or more below the surface, here and there a peak emerges. These are the scattered islands of the Atlantic, among which are Ascension Island, the Rocks of St. Paul, and the Azores. The highest of all, Mount Pico of the Azores, towers 7613 feet above the surface of the sea and plunges 20,000 feet below the surface. A second feature of the submarine topography of the North Atlantic is the extended nature of the continental shelf. Within the general area of this shelf which extends all the way across the North Atlantic, are shallow inland seas such as Hudson Bay and the Baltic, and deep inland seas such as the Caribbean, the Gulf of Mexico, and the Mediterranean. A third feature is the expansion of the North Atlantic Ridge to the north into what is known as the Telegraph Plateau, which in turn merges into the continental shelf to the north.

Extending into the area defined as the northwestern North Atlantic, the bottom of the North Atlantic rises gradually to form, between Greenland and

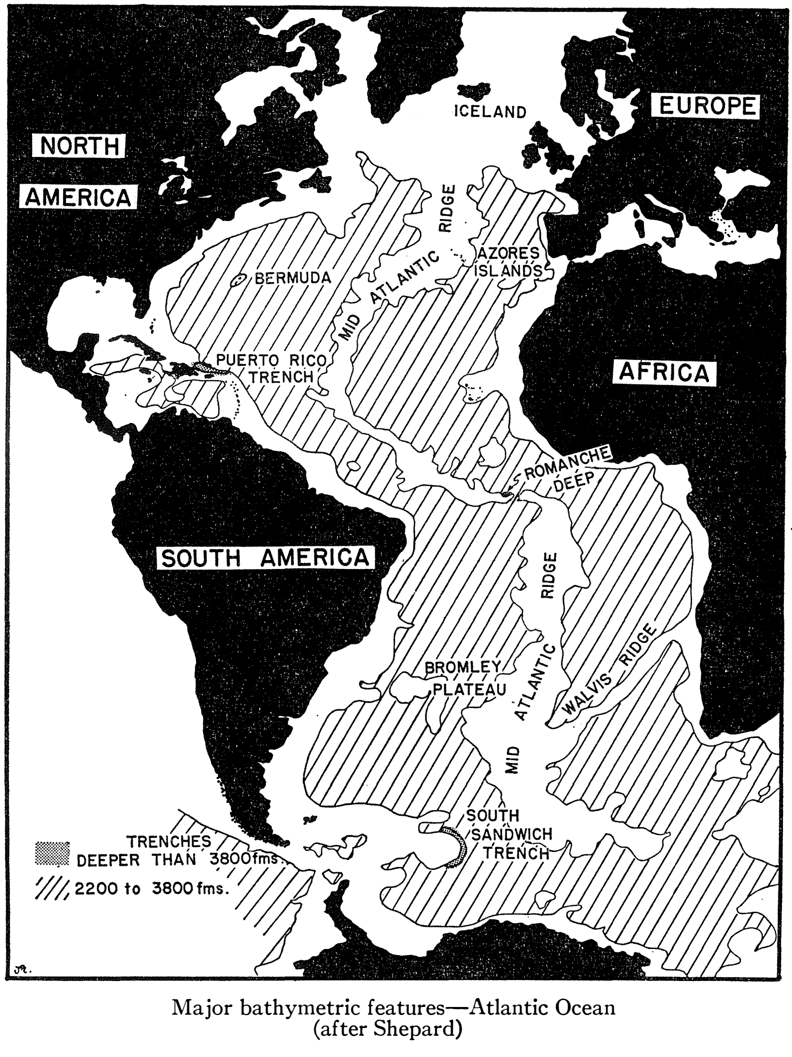
Labrador, the Labrador Basin, with depths extending to greater than 2200 fathoms. In the region of Davis Strait, there is an area with depths less than 400 fathoms.

A ridge separates the Labrador Basin from the Baffin Bay Basin, where depths are greater than 1000 fathoms. The Labrador side of the Labrador Sea with its well defined continental shelf is in contrast with the narrow continental shelf on the Greenland side. The basins are readily outlined by the 600-fathom isobath while the continental shelves are at less than 200 fathoms. The intervening areas between the two contours, the continental slopes, may be steep as along the west coast of Greenland, or broad as along the Labrador coast, particularly in its southern limits. To the north, however, the Greenland shelf broadens, and the 200-fathom contour is found to extend 80 miles off the coast. This broader shelf is divided into three principal shoals, Fylla, Little Hellefiske and Great Hellefiske Banks. Off northern Labrador, the shelf has a width of 70 miles which broadens to a width of 180 miles off Newfoundland, and in the vicinity of the Grand Banks becomes one of the broadest of continental shelves.

The northeasterly extension of the 600-fathom isobath between the Greenland slope and Reykjanes Ridge creates an eastern appendage and a heart-shape form to the Labrador Basin. The waters in this northeasterly extension of the Labrador Basin are generally referred to as the Irminger Sea. The islands of the Canadian Arctic Archipelago form the emerged part of the continental shelf that extends poleward from the North American mainland and joins it to Greenland. Except for Baffin Bay and Davis Strait, all the channels lie on this shelf, which is deeper than most continental platforms, especially in the eastern part of the archipelago. In the eastern waters of the Canadian Arctic the greatest depths are found in the southern part of Davis Strait with over 1700 fathoms, and in the southwestern part of Baffin Bay where the greatest charted depth is 1305 fathoms. In Hudson Strait, charted depths are in general from 100 to 200 fathoms with a maximum of 500 fathoms near its eastern entrance. Depths of 100 to 200 fathoms are also found in Foxe Channel. Foxe Basin however is relatively shallow, with depths up to 50 fathoms in the western part and much less elsewhere. West of the Grand Banks, the continental shelf is broad, forming the Scotian Shelf and Georges Bank. Features of the submarine physiography of the American Continent are the channels which cut deeply into the continental shelf and into the continent itself. These are, from north to south respectively, Hudson Strait, the Laurentian Channel and, on a lesser scale, the Scotian Channel and the Fundian Channel. These channels have a very significant influence on the oceanography of the shelf waters in that they bring waters of deep oceanic origin close to the shores of the continent.

It is a general fact that soundings from the shore of the continents towards the sea show that the depth increases slowly to about 100 fathoms, after which the increase in depth is more rapid. The location of this more rapid increase in depth is defined by oceanographers as the "edge" of the continental shelf, leading to the specific definition of the "continental shelf" as that part of the sea bottom between the shore and this "edge". The edge of the continental shelf from Labrador to Cape Cod has been traditionally outlined by the location of the 100-fathom isobath. The details of this continental shelf, thus outlined, may be closely followed by plotting the isobaths of 25, 50, 75 and 100 fathoms.

It should be appreciated that the delimitation of the continental shelf is not as simple as indicated above, and particularly where matters of international



Major bathymetric features—Atlantic Ocean
(after Shepard)

law or rights are concerned. The general subject has been dealt with by various writers. Detailed mapping has shown that the more rapid increase in depth, which might be used to locate the edge of the continental shelf, occurs roughly between 60 and 80 fathoms. On a world-wide basis, the average depth at which the greatest change in slope occurs is 72 fathoms.

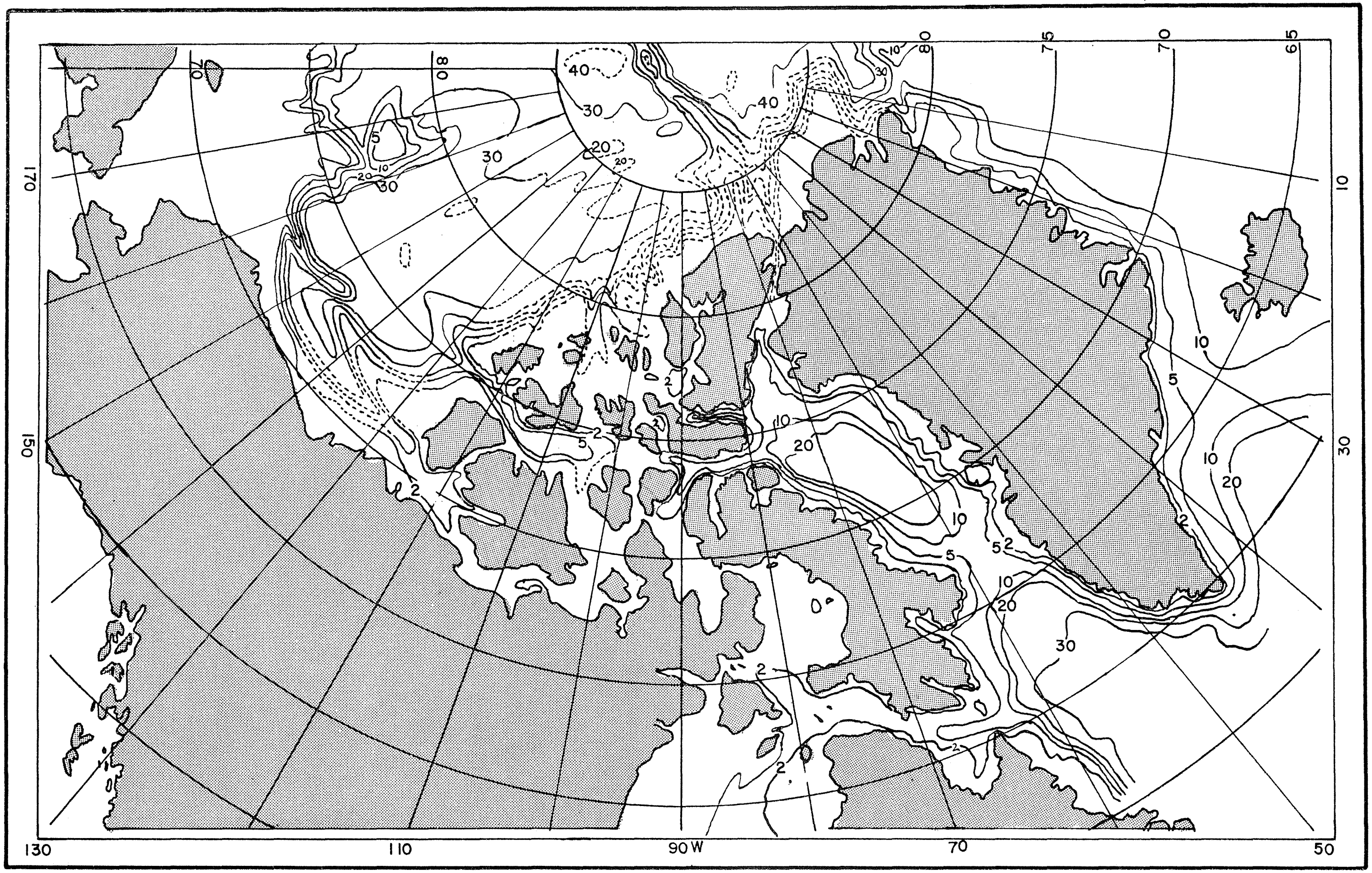
To the southeast of Newfoundland, the outer shelf consists of a mass of irregular banks which constitute the well known Grand Banks, chief of which are Grand Bank and St. Pierre Bank. Although the depths on these banks average about 30 fathoms, there are many places nearer the land with depths greater than 100 fathoms.

Separating the Grand Banks from the Scotian Shelf is the submerged Laurentian Channel with depths from 100 to 300 fathoms, and extending from the St. Lawrence river outwards into the Gulf of St. Lawrence and thence completely across the continental shelf. The Esquiman and Mingan Channels within the Gulf of St. Lawrence are branches of this Laurentian Channel extending respectively northeastward toward the Strait of Belle Isle and northwestward above Anticosti Island.

The Scotian Shelf is an irregular-shaped submarine plateau of irregular topography extending outwards from the coast to a distance of 100 to 150 miles. The more important elevations on this shelf are Sable Island, and Middle, Western, Roseway, La Have, Emerald, and Sambro Banks, as well as the banks known as Banquereau, Canso, and Misaine. With the exception of several basins of limited extent whose depths are greater, the Scotian Shelf as a whole is less than 100 fathoms below the sea surface. A large western area of the Scotian Shelf has depths greater than 50 fathoms and less than 100 fathoms. Bounded as it is on the north by the mainland of Nova Scotia, on the east by Canso Bank, Middle Ground, and Sable Island Bank, and on the west by Brown's Bank, and with its greater depths extending to the edge of the continental shelf to the southward, this submarine area has been termed the Scotian Gulf. Roseway, LaHave, Sambro, and Emerald Banks form elevations over this portion of the sea floor.

The Fundian Channel with depths greater than 100 fathoms separates the Scotian Shelf from Georges Bank and provides a comparatively deep submerged channel into the Gulf of Maine. Georges Bank is about 140 miles in length by 80 miles in width when based on the location of the 50-fathom contour, and hence occupies an area of approximately 11,000 square miles. In the Gulf of Maine area the same type of bottom topography is found as farther north. On the inside is the Gulf of Maine with its troughs, basins and rises which resemble the Gulf of St. Lawrence. The complexity of the relief of the floor of the Gulf of Maine has been outlined by hydrographic mappings. On the outer shelf, Georges Bank with its shoals is comparable with the Grand Banks, but not as wide. The shelf beyond the shoals of Georges Bank is comparatively smooth except for its irregular margin.

In this zone of irregular topography extending from Newfoundland to the Gulf of Maine, the bottom character follows a definite pattern. On the banks, sand bottom predominates, although gravel and stones are found in many localities. The inner deeps and the troughs are mud-covered but samples reveal a considerable number of stones mixed with mud. The inner zones along the shore have a rock or boulder bottom, and ridges rising above the inner deeps are also reported as being rocky.



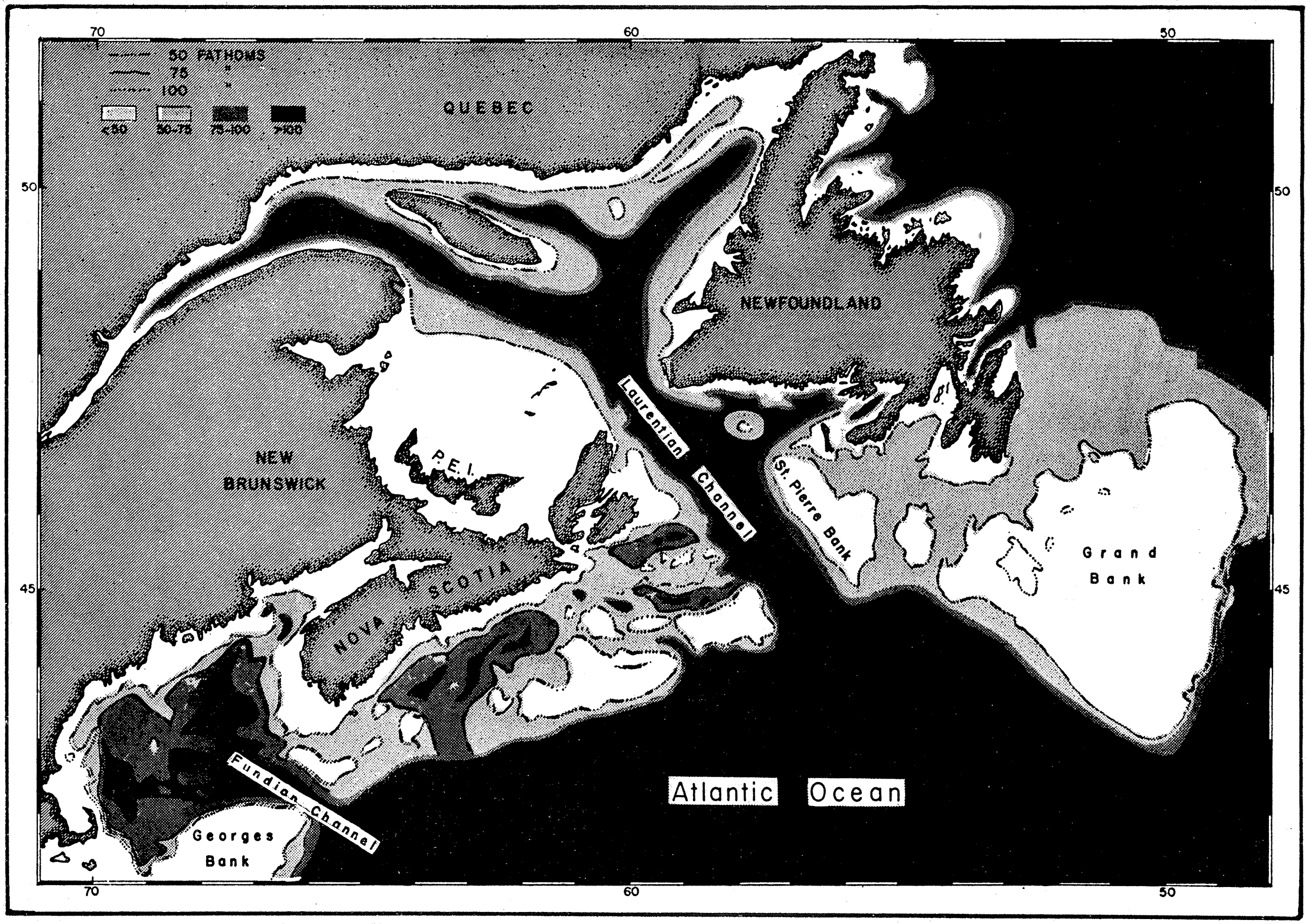
The bathymetry of the Arctic and sub-Arctic areas

Geologists tell us that in preglacial times eastern Canada extended to the edge of the continental shelf, 140 miles beyond the present southeastern coast of Nova Scotia, and Newfoundland was a part of the mainland. The old St. Lawrence River channel can be followed by soundings to the edge of the submerged continent, where the shallow water ends and the bottom descends towards the depths of the sea. The fishing banks extending from Newfoundland to Cape Cod are said to represent "a submerged upland of the Atlantic coastal plan", and the Gulf of Maine is the "drowned inner lowland" between the Banks and the lowlands of New England. The broad and shallow submerged platform bordering the Gaspé Peninsula and the shores of the St. Lawrence embayment "...appear to be normal subaerial features formed above sea level, then submerged and very slightly modified by marine agencies". Students of continental faulting have been attempting to trace the faults of Cape Breton across Cabot Strait to Newfoundland, and have suggested that the Laurentian Channel is, in part, of the nature of a "fault graben". It has been suggested that the St. Lawrence trough probably was started by river erosion, possibly, in part, along the fault lines. Later during the glacial period, tongues of ice moved down the valley causing great deepening and widening. The present form of the trough is believed to be due principally to this glaciation, which makes it a submarine glacial trough. In any event, this deep submerged Laurentian Channel, reaching well into the estuary of the St. Lawrence, not only permits the continental penetration by the deeper waters of oceanic origin, but furthers the phenomenon of the Gaspé Current.

The many furrows cutting across the continental shelf, some areas of which have received considerable attention in recent years, are generally referred to as canyons. Some of these canyons can be traced across the shelf, and even into the estuaries of rivers. Various theories have been put forward to explain the formation of such submarine canyons, but no single hypothesis has yet been advanced to account for their characteristic features. A submarine escarpment, sometimes divided into two or more branches and bordering one of the major fault fractures of North America, has been discovered under the waters of the Gulf of Maine and traced to its connection with topographic features bordering the northwestern side of the Bay of Fundy.

The North Polar Basin and the Norwegian Basin are separated from the open Atlantic by a ridge extending from Greenland to Scotland upon which Iceland and the Faeroe Islands rise above sea level. The maximum depths in Denmark Strait, between Greenland and Iceland, and over the Wyville Thomson Ridge between the Faeroes and Scotland, are only about 250 fathoms. A lowering of sea level of about 250 fathoms would impose a land bridge from North America to Europe and completely isolate the waters of the Polar Basin from the Atlantic and the Pacific Oceans.

The general features of the submarine physiography of the Canadian Arctic and neighbouring seas are the basins of the Arctic Ocean and of Baffin Bay, the relative shallows of the Canadian Archipelago and Davis Strait, and the



Submarine topography to show the main fishing banks off the Atlantic coast

Lomonosov Ridge which north of Greenland divides the Arctic Basin into the eastern and western parts.

The western Arctic Basin has, for the most part, depths greater than 1500 fathoms, with one depression near the Pole exceeding 2000 fathoms in depth. Separating the Arctic Ocean from the Atlantic Ocean, its archipelago is interlaced with many relatively deep channels. However, it forms a barrier with an effective sill depth of 100 fathoms or less between the two oceans. The principal channels which connect Baffin Bay to the Arctic Ocean are Smith Sound–Kennedy Channel on the north, and Lancaster Sound and Barrow Strait on the west. The sill depths in these channels are approximately 100 fathoms.

On the eastern side of the archipelago, the channels are deep and lead directly into the basin of Baffin Bay which has depths in excess of 1000 fathoms. Baffin Bay is in turn separated from the Atlantic Ocean by a sill in Davis Strait with a depth of 350 fathoms. To the south of Davis Strait, depths gradually increase to those of the Labrador Basin.

It was in 1924, when echo soundings were first taken across an ocean basin by the German ship *Meteor*, that it was found the irregularities of the ocean bottom might be as great as those of the continents. Formerly it was supposed that sedimentation over the years had smoothed the basins and buried most of the hills. Since 1924, countless soundings with fathometers have been made across the oceans of the world. Hundreds of high submarine mountains have been discovered, many of them forming parts of great mountain chains. Among the most perplexing and interesting features of the sea bottom are the submarine canyons. The extension of some of these deep valleys down the great marginal slopes of the continents have been known for some time. As a result of modern methods of sounding, it has been found that submarine canyons are widespread, being found in part virtually along all the coasts of the world. The Hudson Canyon running from the Hudson River out to the deep floor of the Atlantic has received considerable attention in recent years.

The various areas of ocean waters delineated by the general submarine topography have their own specific oceanographic features which are receiving increasing attention from students of deep-sea oceanography. The great contrasts in water conditions between the open Atlantic and the Norwegian Sea, due to the existence of the Wyville Thomson Ridge, is the classic example of the effect of a submarine ridge in preventing full interchange of ocean waters. In the northwestern North Atlantic, the northwest extension of the North American Basin between Greenland and Labrador, and the persistence of depths greater than 500 fathoms towards Davis Strait, have a profound influence on the water exchanges between the Arctic and the Atlantic. Submarine barriers, whether large or small, form boundaries of submarine basins in which horizontal communication with adjacent seas is restricted by sill depth. Renewals of the water in the deep basins can take place only through processes of vertical circulation. It is therefore characteristic of all basins that, below sill depth, the water is nearly uniform in temperature and salinity, and approximately of the same character as the water at sill depth.

OCEANOGRAPHIC HISTORY

Early Exploration

It was said of the Vikings that, from their point of view, nothing was discovered until they discovered it. Yet Norse accounts tend to admit that the Irish were in Iceland when the Vikings "discovered" it about 850 A.D. Greenland was visited about 982 A.D. by Eric the Red, and his son Leif Ericsson is given credit for the first discovery of the land of the North American continent in the summer of 1000 A.D. The details of Leif's voyages are recorded in the Saga of Eric the Red. It is generally thought that he landed on the shores of the New England States, and that he sailed along the coasts of Nova Scotia and Newfoundland on his return journey via Greenland.

Various other voyages by Norsemen followed in search of the Vinland described by Leif Ericsson. This was the beginning of a new age of discovery. It marks the beginning of the white man's recording of features of the waters of the northwestern North Atlantic as the early voyagers contended with wind, wave, current and tide, and explored for food on the shallower areas of the continental shelf. The study of the sea was thus ushered into the areas of the western world spurred on by the urge for discovery. The history of this period records the voyages of Columbus, Cartier, the Cabots, De Monts and Champlain and a host of others, and extends into the nineteenth century. The added incentive was the search for the riches of the new world.

To the north, Davis Strait was visited in the year 1500 by an expedition under the joint leadership of the Scandinavians and the Portuguese. Before this, the Portuguese had been fishing on the Grand Banks of Newfoundland, an industry which they have continued to foster for more than 500 years. Martin Frobisher recorded crossings of the Labrador Sea in 1576, 1577 and 1578. These were followed by various voyages of exploration by Davis, Hudson, Button, Bylot, Baffin, Foxe, James, Middleton, Moor, Smith and others, in search of a northwest passage for a short route to China. On the basis of the adverse findings of these expeditions, interest in the search for the northwest passage waned, but ships of the Hudson Bay Company, as well as those of their French and English rivals, plied the waters of Hudson Strait and Hudson Bay to further a lucrative fur trade. Whaling activities were initiated by the Dutch in Baffin Bay in the early years of the seventeenth century, to be followed by the British and others, and continued to the end of the nineteenth century. All this resulted in the accumulation of knowledge of these ice-infested waters. Several scientific expeditions followed in later years, the first under Sir John Ross.

The study of the waters of the Canadian Arctic began with Parry in the early years of the nineteenth century, climaxed by the ill-fated expedition of Sir John Franklin. The organized expeditions that followed in search of the lost

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Franklin expedition made invaluable contributions to the geography of the Canadian Arctic. The names of Parry, Sir John and Sir James Ross, Back, Franklin, Beechey, Kellett, M'Clintock, M'Clure, Collinson, Austin, Penny, Kennedy, Bellot, Belcher, Hall, Young and others are recorded in the history and geography of the land and waters of the Canadian Archipelago. Not so well known is that of Lt. E. J. De Haven who headed the first United States expedition to the Canadian Arctic in 1858, an expedition that was privately financed to assist in the Franklin search. Although the expedition accomplished but little, the event marks the beginning of Canadian–United States interest and co-operation in the exploration of the Canadian Arctic.

In more southerly latitudes, the French, British and the Spanish, in the early days of exploration, vied with one another in opening up the treasures of the new world. In the process of colonizing, trading, and carrying on the feuds of the old world, harbours and coast lines were charted, and current and tidal features of the waters were recorded. The early settlers became aware of the bountiful supplies of food in the surrounding seas. The growth of the knowledge of the extent and shape of the eastern and arctic coasts of North America is well recorded in maps and charts, among which might be mentioned those of Behaim (1492), Ptolemy (1548), Desceliers (1550), Zaltieri (1566), Mercator (1595), Velasco (1610), Foxe (1635), and Admiralty (1835).

Age of Commerce and Communication

By the end of the eighteenth century, the oceans were known as to their size and shape, and the winds that blew across them attracted the interest and attention of the men who sailed the ships. Benjamin Franklin gathered data on the Gulf Stream and by 1769 had prepared a chart to show how ships bound for New York could avoid the stream on their westward passage and take advantage of the stream on their eastward passage. Although the information put together by Franklin was generally ignored, the competition for world trade was keen and called for faster ships. This, in part, meant taking every advantage of wind and current, and sailing masters became the oceanographers of the time. The information gathered was analyzed under the direction of Lt. M. F. Maury of the U.S. Navy and his publication "Physical Geography of the Sea" in 1855 introduced a new era in the science of oceanography. This book is described as the first ever to review the oceans of the world as a whole, and one that is now accepted as having established Maury as the founder of one phase of the science of oceanography. His book directed attention to the wind and current systems of the oceans, and it was estimated that his sailing charts were responsible for annual savings to United States commerce of more than $2,000,000 on the outward voyages from New York alone. These were the days of the clipper ships and Maury's efforts here no doubt were highly appreciated by the sailing masters of that time.

Another era was fast approaching, brought about by the first submarine cable across the English Channel in 1845 which directed thought to the ocean floor, and the possibility of laying ocean cables across the Atlantic. Although valuable work has been carried on in the open oceans by scientific organizations by far the greater proportion of our knowledge of submarine topography is based on soundings taken by national agencies for the preparation of charts. In any event, before the nineteenth century ended enough was known about specific areas of the ocean floor to allow the laying of hundreds of thousands of miles of ocean cable, connecting every continent. Never before had there been any practical reason for determining what conditions existed in the deep sea. Public interest was now aroused to the new field of research. A widespread curiosity was directed towards the results of the deep-sea investigations of Professor Wyville Thomson in the Norwegian Sea during the period 1868–70. Thomson in the *Lightning* carried out his initial investigations between Scotland and the Faeroes, finding animal life at 600 fathoms. Further work was carried out with the *Porcupine*. It was aboard these two ships, and for the very first time on any consequential scale, that the study of life in the deep sea began.

The *Challenger* Era

These efforts eventually led to the organizing of the *Challenger* Expedition, which during the period 1872–1876 made a voyage over the oceans of the world to study their physical, chemical, and biological conditions. So important had the study of the sea become that survey ships, cable ships, and specially built craft were soon at work in all the seven seas. The Zoological Station at Naples was established in 1872, the Marine Laboratory at Plymouth in 1879, and the International Council for the Exploration of the Sea was organized in 1899. It is of interest to record that rock samples from the *Challenger* expedition by Sir John Murray led to the exploitation of the phosphate deposits of Christmas Island, and returned in royalties to the British Treasury much more than the whole cost of the *Challenger* Expedition.

Towards the end of the nineteenth century we now find that the ocean waters have a new interest. In northern waters in 1872, Bessels in the *Polaris* of the U.S. Polar Expedition was recording sub-surface temperatures in Kane Basin, while in 1875, Moss in H.M.S. *Alert* of the British North Polar Expedition carried out observations in Smith Sound. In the same year, from H.M.S. *Valarous*, serial temperatures from top to bottom were recorded in the Labrador Sea. In 1884, Dr. Alex Hamberg of the *Sofia* took a series of oceanographic stations along the west coast of Greenland. Hydrographic surveys were carried out in this area in 1884, 1886, and 1889 by the *Fyla* of the Royal Danish Navy, which proved to be the beginning of a continuing interest of the Danes in the waters of the Labrador Sea, Davis Strait, and Baffin Bay. Martin Knudsen occupied fifteen oceanographic stations in Davis Strait in 1895. Oceanographic literature relative to the Grand Banks seems to date from the publications of Schott in 1897 based on data extracted from ships' logs.

Enough readings of surface temperatures of the Gulf of Maine and the Bay of Fundy had accumulated during the first half of the nineteenth century to permit Maury between 1885 and 1858 to indicate the general seasonal temperature distributions out to the edge of the continental shelf. In 1878, the first subsurface temperatures in the Gulf of Maine were recorded by Verrill. Such observa-

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tions were supplemented by those taken from the *Blue Light*, the *Bache* and the *Speedwell*. It was in this period, in the year 1873, that the *Challenger* Expedition had made oceanographic sections across the Atlantic from Teneriffe in the Canary Islands to the West Indies, and from the West Indies to Halifax and thence to Bermuda and the Azores. Modern oceanographic research in the Gulf of Maine dates from the *Speedwell* observations in 1878 and 1879, and from those of the *Blake* and *Fish Hawk* in 1880. Here also occurred an event that directed attention to the problems of the sea. This was the disaster to the tilefish, which first came to light in March 1882, presumably caused by a temporary flooding of the upper part of the continental slope by abnormally cold water. For the later years of the nineteenth century, the study of the oceanographic conditions in the Gulf of Maine and Georges Bank took on added fervour, involving such ships as the *Albatross* and the *Grampus*. It was during this period that the name of Alexander Emanuel Agassiz was established in the field of biological oceanography.

It was in 1687 that Isaac Newton put forward the first rational explanation of the connection of the moon with the tides of the ocean. Although we do not know how early in man's history this connection between moon and tide was recognized, Pytheas of Massilia, who lived about 325 B.C. and who had sailed the ocean from the Strait of Gibraltar to the British Isles, had noted a relation existing between moon and tide. Newton, in his "Principia", which appeared in 1687, proved that the tides were a necessary consequence of the law of gravitation. The sun and the moon in their varying positions relative to the earth bring about attractive forces which, with regard to the solid earth and the overlying waters, are unequal. These differences of attraction give rise to the tides. Newton's simplification of the problem consisted in considering the whole earth covered with water. The practical problem resolved itself into deriving a formula that would express the relation between the rise and fall of the sea and the tide-producing forces. Newton's static theory did not accomplish this, and it was not until the end of the eighteenth century that the great French mathematician Laplace developed his dynamic theory of tides. Further developments of tidal theory were made by outstanding mathematicians such as Airy, Ferrel, Harris, Stokes, Kelvin, Darwin, Rayleigh, Lamb, Hough, Levy, Poincaré and Börgen. William Whewell and Sir John Lubbock, dealing largely with observational results during the early half of the nineteenth century, made great contributions to the practical aspects of tidal forecasting. From their analyses there developed the progressive wave theory which considers that a forced tide wave in the southern ocean dominates the tides of the world. From this primary forced tide wave, progressive waves move through the various oceans at rates which are dependent on the depths. Lord Rayleigh showed how the progressive waves could be studied by supposing that the observer travelled with the waves, thus reducing the motion to a steady one to which Bernoulli's equation could be applied. Harris' stationary wave theory which was developed at the beginning of the present century does away with the conception of a single world phenomenon and substitutes regional oscillating areas as the origin of the dominant tides of the various oceans. Modern theories of the tides are indebted to him for the stress he laid on the importance of stationary oscillations, but in his own theory of tides he leaves out of account the important effects of the earth's rotation.

In the early part of the nineteenth century, the Royal Navy began the first systematic surveys of Canada's ocean approaches. Admiral H. W. Bayfield was probably the outstanding surveyor of this period and "Bayfield" charts were known to every sailor from the Great Lakes to the sea. Tidal recordings were made in Halifax by the Admiralty in 1860 and 1861 and the Tide Tables were published in 1891 based on these data. The Canadian Tidal Survey was set up in 1893 with Dr. W. Bell Dawson as Engineer-in-Charge. This action by the Canadian Government followed on recommendations put forward by the Royal Society of Canada and the British Association for the Advancement of Science. Survey and tidal work were consolidated into the Canadian Hydrographic Service with Wm. J. Stewart as Chief Hydrographer. The first tidal stations were set up in 1890 at Father Point, P.Q.; Southwest Point, Anticosti; Saint John, N.B.; Magdalen Islands and St. Paul's Island. One was later set up at Quebec. The first current measurements on main sailing routes were made in the Strait of Belle Isle and Cabot Strait in 1894, using electrical recording devices. Dawson's brilliant career in the field of tides and currents extended over a period of 30 years, and his extensive studies form the basis of our knowledge of the tidal and current phenomena in Canadian waters.

The *Challenger* Expedition, as was forecast by Sir Wm. Herdman, ranks in importance today with the voyages of Vasco de Gama, Columbus, Magellan, and Cook. Its practical results were far-reaching, as indicated by the greater activity in investigation of the seas in the latter half of the nineteenth century, by the establishment of various marine biological laboratories, great and small, and by the employment of methods of scientific investigations at sea, relative to fisheries. It is then not surprising that developments in oceanography were in the offing in Canada during this period of activity on the oceans.

Lt. Millen Owen R.N., residing at Campobello, N.B., recorded that on October 15th, 1770, he made two hauls of the trawl near Indian Island but took nothing except a few curious shells and other submarine productions. He mentions earlier dredgings off the coast of Massachusetts, when he brought up scallops, sea-eggs, starfish, coral, weeds and other curious submarine productions. While this is an early record, the study of the waters of the Atlantic Coast and their fauna had been initiated early in the seventeenth century, and went on apace as French, English, Spanish, Portuguese and Jersey fishermen and settlers took part in the fisheries of this new-found land.

The Province of Canada was founded in 1841. Scientific societies with interests in natural history were being established. The Natural History Society of Montreal had been formed in 1827 and had furthered scientific exploration at depth in the St. Lawrence estuary. Zoological collections had been made in the St. Lawrence as early as 1858.

In 1862 the Natural History Society of New Brunswick was formed, and men like L. W. Bailey, Philip Cox, Moses H. Perley and W. F. Ganong directed attention to things of the sea. Dredging in Passamaquoddy Bay was carried out in 1884, the interest no doubt stimulated by the work of Sir Wyville Thomson and the *Challenger* Expedition. In 1862, the Nova Scotia Institute of Science was formed and among the investigators of matters of interest to fisheries were H. R. Storer, T. F. Knight, J. B. Gilpin, A. Gesner, and Rev. John Ambrose. The Dominion of Canada was formed in 1867. The first scientific dredging operations in connection with the Canadian Department of Fisheries was carried out on board the *La Canadienne* and the *Stella Maris* during the summer of 1871. Previous to this, in 1867 and 1869, Dr. J. F. Whiteaves made dredgings in Gaspe Bay to depths of 50 fathoms. In 1884, Professor McMurrich of the Ontario Agricultural College at Guelph published a paper "Science in Canada" and made possibly the first concrete suggestions for the establishment of biological stations in Canada. Rev. Moses Harvey of the Colony of Newfoundland, in a paper before the Royal Society of Canada in 1892, pleading for a scientific foundation for our fisheries, suggested a biological station for the East Coast. The Royal Society was instrumental in placing this matter before the government. In 1892 Professor E. E. Prince of the St. Andrews Marine Laboratory, Scotland, was appointed Commissioner and General Inspector of Fisheries of Canada. In 1884 Professor Prince put forward a formal report to the Department urging the establishment of a laboratory to further marine biological work. He was supported in this by action of the Royal Society of Canada, which in 1896 urged upon the Government the desirability of taking steps at an early date to bring Professor Prince's recommendations into force. Further action was taken at the Toronto meeting of the British Association for the Advancement of Science in 1896, resulting in a report which was placed before the Government in 1898. Action by the Government followed and funds were made available to establish a floating station in the Gulf of St. Lawrence in the summer of 1899. Active field work on the waters of the Canadian Atlantic coast were thus inaugurated. Out of these activities came the establishment of two marine biological stations, one at St. Andrews, N.B., and one at Nanaimo, B.C., with initial operations at both during the summer of 1908. In 1910 the systematic taking of temperatures and salinities was begun in Passamaquoddy Bay, and this has been a regular feature of the St. Andrews Station's work ever since.

Developments Following the *Titanic* Disaster

In 1913 the Grand Banks and the Atlantic waters adjacent to Newfoundland received their first systematic study when D. J. Mathews in the *Scotia* initiated a service designed to provide protection to transatlantic shipping from ice and icebergs.

This marks a new era in the history of oceanography in the Northwest Atlantic. It was ushered in with tragic loss of the *Titanic* on April 14th, 1912, the result of a collision with an iceberg in the region of the Grand Banks. A patrol of the iceberg zone was set up and carried out during the seasons of 1913 and 1914. The International Convention for the Safety of Life at Sea then organized the International Ice Patrol which has been operated ever since by the U.S. Coast Guard. Over the years, it has developed from an iceberg scouting and patrol effort to a project of oceanographic research, unsurpassed on any ocean for its continuity of interest on such a scale for nearly half a century.

The studies of Dr. Johan Hjort and Sir John Murray, carried out in the Northern Atlantic on the cruise of the *Michael Sars* in 1910, and Dr. Hjort's researches which had proven so beneficial to the fisheries of Norway, had attracted world-wide attention. In particular, the *Michael Sars* had made two oceanographical sections over the Grand Banks on its crossing from the Azores to Newfoundland and twice to Norway. These two sections provided the rough introductory survey of these waters, and outlined the remarkable transitions between warmer and colder water layers, and the associated plant and animal communities. This survey was to serve as the foundation for the introduction of modern oceanographic methods to studies of Canadian Atlantic waters. In spite of the fact that the great cod and other fisheries off our Atlantic coast had been carried on for centuries, it was felt that there were possibilities of development and expansion that awaited accurate knowledge to turn them to account. There were as well certain urgent problems affecting the herring resources of the Gulf of St. Lawrence and the adjacent Atlantic coast which called for scientific investigation. Funds were made available by the Department of the Naval Service, and Dr. Hjort was employed to carry out what became known as the Canadian Fisheries Expedition of 1914–15. It can be truly said that the methods of investigation employed by Dr. Hjort, and the results, provided the basis for Canadian investigations in oceanography in the years that followed. The report published under the title of the Canadian Fisheries Expedition, 1914–15, provided a text book on theory and methods that is much prized by investigators of today.

In 1912 the United States Bureau of Fisheries and the Museum of Comparative Zoölogy of Harvard University jointly undertook the general oceanographic exploration of the Gulf of Maine, which began and continued for many years under Dr. H. B. Bigelow. For this area, his reports on the fishes, plankton, and physical oceanography are the "classics" and serve today as basic references for all students of oceanography.

The years of World War I curtailed peacetime activities at sea. However, in July to November, 1916, Dr. Wulff in charge of the Second Thule Expedition occupied 27 oceanographic stations along the West Greenland slope from Disko Island to Smith Sound.

The decade following World War I saw considerable activity in the waters of the northwestern North Atlantic. Captain L. Beaugé in command of the French Hospital ships *Jeanne d'Arc* and *Ville d'Ys* carried out investigations over the Grand Banks and West Greenland Banks. On these he was associated with Dr. Le Danois who introduced the theory of transgressions, which suggested a periodicity to the variations in water conditions from one year to another. The *Michael Sars* in Davis Strait in 1924, the *Dana* on the west coast of Greenland in 1925, the *Chance* on the Labrador shelf in 1926, the *Godthaab* in Baffin Bay and the Labrador Sea in 1928, the *Carnegie* in the North Atlantic, and the *Meteor* in 1928, 1929, 1930 and 1933 in areas to the east and south of Greenland, all contributed to the study of the waters of the area. The *Dana* Expedition of 1928–30 circumnavigated the globe, and though confining its interest to the tropical oceans and to biological problems, contributed to an appreciation of the scope of oceanography. In 1932, the new British *Challenger* worked the three following sections:

(*a*) tail of the Grand Banks to St. John's, Nfld.,

(*b*) St. John's eastward along Lat. 50°N, and

(*c*) near Cape Harrigan and normal to the Labrador coast.

It was in 1928 that the U.S. Coast Guard, in broadening the scope of the International Ice Patrol, dispatched the *Marion* to carry out an oceanographic survey of the waters between Greenland and the North American Continent. The work of the *Marion* was amplified by the cruises of the *General Greene* to the Labrador Sea in 1931, 1933, 1934 and 1935. The report entitled "The *Marion* and *General Greene* Expeditions 1928–1935" furnishes the third "classic" for the waters of the northwestern North Atlantic, and summarizes the researches of the International Ice Patrol over more than 20 years. Subsequently ships of the Ice Patrol made other post-season cruises in the Labrador Sea and Davis Strait in 1938, 1939, 1940, and in the post-war years.

Following the Canadian Fisheries Expedition of 1914–15, although all activities were somewhat curtailed by World War I, oceanography relative to fisheries was carried on. In 1916 hydrographic investigations were conducted in Passamaquoddy Bay, St. Mary's Bay, Annapolis Basin, Yarmouth Harbour, the Kennebecasis, and the lower Saint John River. The Cheticamp Expedition in 1917, and the Miramichi Expedition in 1918, relative to underdeveloped fisheries in the Gulf of St. Lawrence, were carried out. In 1919 and 1920 Mavor carried out an organized survey of the Bay of Fundy, supplemented by drift bottle experiments, to determine the circulation of Bay of Fundy waters. In 1920 and 1921 the waters off the outer coast of Nova Scotia were given attention. It was in 1922 that a plan of drift bottle experiments between Newfoundland and New York was formulated by the International Committee on Deep Sea Fisheries. The experiments which were continued over a period of years were carried out chiefly by Canada and the United States with some assistance from France. In 1923, the Belle Isle Strait Expedition with the *Prince* and the *Arleux* operated in the Strait of Belle Isle in a general oceanographic study of that region.

In 1920 representatives of Canada, the United States, and Newfoundland met to form the International Committee on Marine Fisheries Investigations. This eventually became the North American Council on Fishery Investigations, on which France was subsequently represented. This Committee, which was to function up to World War II, proved most effective in furthering international aspects of oceanography and fisheries.

The Biological Board of Canada initiated special studies in 1923 and 1924 of the biological environments of the bays and harbours of the Atlantic Coast. From 1925 to 1930, special attention was given to the waters of the Bay of Fundy and Passamaquoddy Bay as considerable interest was being directed to the Cooper Power Project for developing electrical power from the tides. In 1928, the Board made its first appointment of a full-time hydrographer. The first detailed study of the waters of Hudson Bay and Hudson Strait was carried out in 1930 by the Hudson Bay Fisheries Expedition. In 1931 the International Passamaquoddy Fisheries Commission was established, and for a two-year period gave attention to the possible effects of the Cooper Power Project on the fisheries of the Passamaquoddy area.

In 1931 the appointment of Dr. H. Thompson to the position of Director of the Newfoundland Fishery Research Laboratory ushered in a five-year period of active investigation of the waters of Newfoundland, with particular attention being paid to the variations in the contributions of Labrador waters to the various fishing areas surrounding Newfoundland. In particular, two oceanographic cruises were made annually to monitor the coastal waters from Hamilton Inlet southward to the Grand Banks and the Laurentian Channel. This pioneer work of Dr. Thompson was to be continued with some interruptions and modifications and eventual expansion in the years that followed. In 1932 the general study of the waters of the Scotian Shelf was inaugurated which expanded and continued until the advent of World War II.

The late twenties saw great developments in oceanography in the United States, which in part brought about the establishment of the Woods Hole Oceanographic Institution, and the initiation of a detailed study of the Gulf Stream and adjoining waters of the western North Atlantic. The developments within this Institution would probably have had a greater effect on developments in oceanography in Canada were it not for the financial depression of the thirties which was followed by World War II. Eventually however, the influence of these developments in the United States was to spread world-wide. The *Atlantis* which has now been in service at the Woods Hole Oceanographic Institution for nearly 30 years has sectioned the Gulf Stream and neighbouring waters from the Gulf of Mexico to Long. 40°W.

For a period of 10 years between 1929 and 1939, the Biological Board of Canada (now the Fisheries Research Board of Canada), associated with the Meteorological Service of Canada, supervised the operation of thermographs on vessels of the Canadian National Steamships making regular crossings of the Gulf Stream. These thermometric units, installed on the water intake to the condenser, furnished a surface-water temperature–time record of Gulf Stream crossings. Supplementing these Canadian operations were those conducted by United States agencies on ships making other crossings from New York. Combined, these records provided unique information on the meanderings of the Gulf Stream, monthly, seasonally, and annually. In 1929 and 1930, the Biological Board of Canada organized a system of recording surface sea water temperatures at selected representative points on the Atlantic coast. This recording has continued uninterruptedly to the present time with some modifications and later expansions. The analyzed data have proved to be valuable means of following temperature trends, both in a short-term and long-term basis.

In 1938 the Biological Station of Laval University, which had been located for several years at Trois Pistoles, P.Q., was moved to Grande-Rivière, P.Q., to initiate studies in the marine biology of the northern part of the Gulf of St. Lawrence. The activities of this Biological Station continued over a period of years, finally being incorporated into the Marine Biological Station which is now operated at Grande-Rivière by the Department of Fisheries of the Province of Quebec.

The outbreak of World War II temporarily brought the developing Canadian oceanographic activities on the Atlantic coast almost to a standstill.

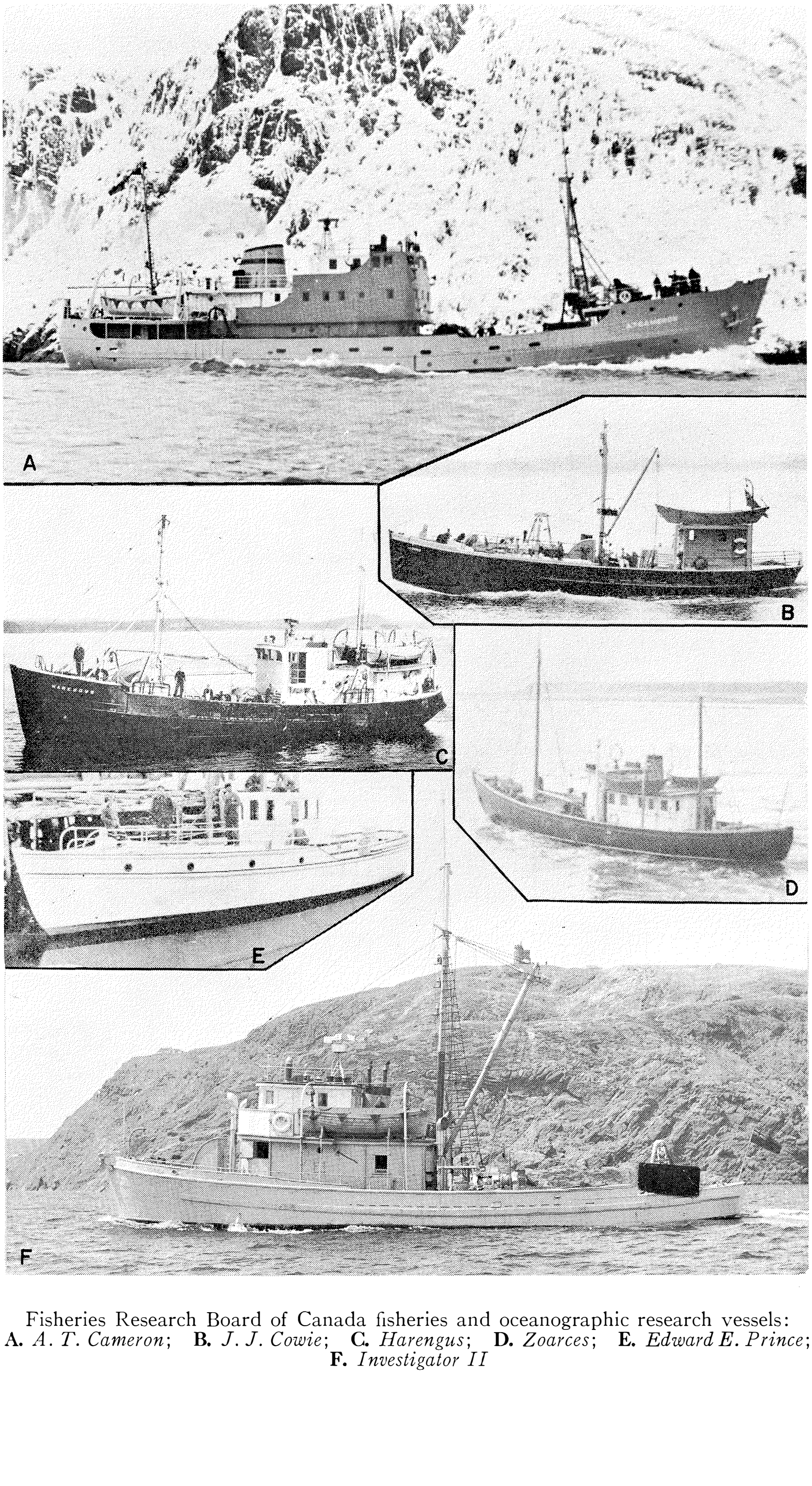
World War II and After

Oceanographic research became of particular significance to defence in Canada during World War II, when ASDIC was brought into use in Canadian naval vessels for the detection of submarines. As is well known now, the efficiency of ASDIC in the waters of the western North Atlantic was seriously limited at times by the physical characteristics of the waters. With the development of throwing weapons for anti-submarine warfare, whose efficient operation demanded a knowledge of the depth of the attacked submarine, the Depth Recorder was introduced. Here the vertical distribution of water temperatures became of increasing significance, as large refraction errors were involved at certain times in certain areas. These and other problems thus indicated that a detailed knowledge of our Canadian waters was essential for the efficient operation of a Navy geared almost wholly to anti-submarine warfare. Thus, with the exigencies of World War II, began a new era in Canadian oceanography which was to extend into the post-war years and eventually give emphasis to the need for expansion of the national oceanographic effort.

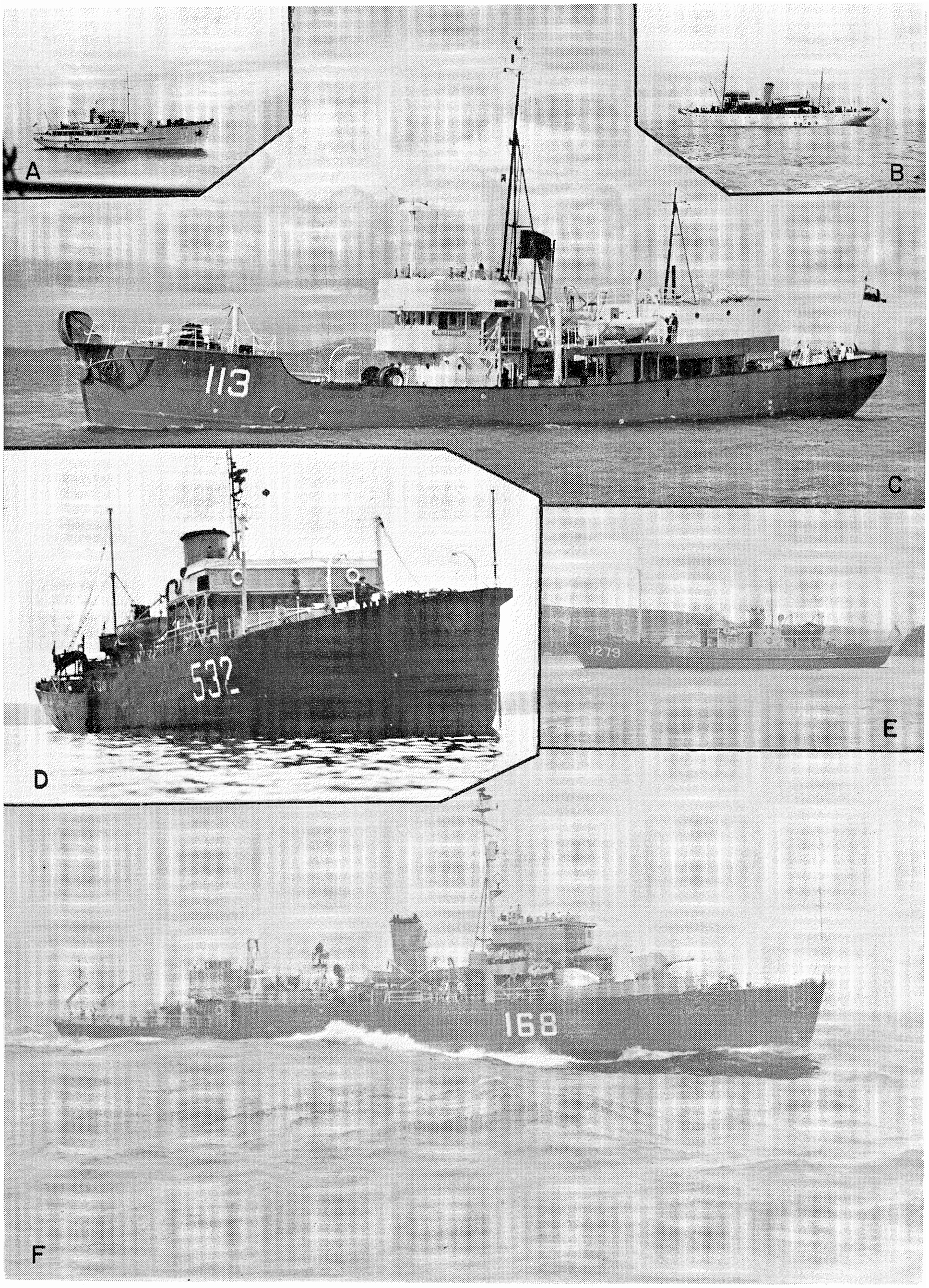
In 1944, under co-operative arrangements between the Royal Canadian Navy, the National Research Council and the Fisheries Research Board of Canada, the Board's Atlantic Oceanographic Group and Pacific Oceanographic Group were set up to give attention to oceanographic problems of first importance to the Royal Canadian Navy. In this they did yeoman service, with the results having particular application in the anti-submarine war carried out by the Royal Canadian Navy off the Atlantic coast.

Before hostilities were ended, discussions were held to consider the possibilities of carrying oceanography forward on a co-operative basis. As a result, the Joint Committee on Oceanography came into being on April 1st, 1946, the Committee originally comprising representatives of the Fisheries Research Board, the Royal Canadian Navy, and the National Research Council. Subsequently, the Canadian Hydrographic Service, the Meteorological Service and the Defence Research Board took membership on the Committee. Mr. R. O. King, representing the Royal Canadian Navy, was the first Chairman. The chief function of the Committee was to further co-operative research in Candnda, and over a period of more than 13 years it was eminently successful in this. A re-organization of the Committee, with the name changed to the Canadian Committee on Oceanography, came into effect on December 14th, 1959.

In the post-war years, developments which furthered oceanography went forward at a relatively rapid rate. The Fisheries Research Board expanded as



Fisheries Research Board of Canada fisheries and oceanographic research vessels:
A. *A. T. Cameron*; **B.** *J. J. Cowie*; **C.** *Harengus*; **D.** *Zoarces*; **E.** *Edward E. Prince*; **F.** *Investigator II*



Royal Canadian naval and oceanographic research vessels: **A.** *Cartier*; **B.** *Acadia*; **C.** *Whitethroat*; **D.** *Sackville*; **E.** *Lloyd George*; **F.** *New Liskeard* policy decisions directed increased attention to problems of pelagic and ground fisheries. The Atlantic Herring Investigation Committee was set up in 1944, and over a 5-year period gave particular attention to the oceanography of the Gulf of St. Lawrence in relation to herring concentration and dispersal. This was followed by the organization of the International Commission for the Northwest Atlantic Fisheries which eventually was to draw twelve nations into co-operative investigations of problems of the fisheries for cod, haddock and redfish over the fishing areas extending from Georges Bank to Baffin Bay. In 1949 Newfoundland became the tenth province of Canada, and in the re-organization of departments that ensued, the Biological Station at St. John's was brought under the Fisheries Research Board, and its activities were considerably expanded. Extensive cruises were made annually over the waters of the Labrador Current and the Grand Banks by the Board's research vessel *Investigator II*, and in more recent years by its larger research ship *A. T. Cameron.*

The Atlantic Oceanographic Group of the Fisheries Research Board was gradually enlarged in an attempt to keep pace with national requirements in oceanography. The Naval Research Establishment at Dartmouth, N.S., emerged as an integral part of the Defence Research Board, with military programs which required oceanographic support. The Royal Canadian Navy and the Naval Research Establishment co-operated generously with the Fisheries Research Board in many oceanographic projects over the years. In particular, the H.M.C.S. *New Liskeard* took part in many oceanographic cruises. In 1960 the Naval Research Establishment announced the perfection of the Variable-Depth Sonar, a project which took more than 10 years to complete, and which overcomes many of the detection problems in anti-submarine warfare.

The activities of the Canadian Hydrographic Service on the Atlantic coast gradually expanded after World War II, its specialized activities in charting and tidal and current studies extending eventually from the Bay of Fundy to the Polar Basin. A program for the collection of oceanographic data was set up for all hydrographic ships, and the tidal and current service expanded into fundamental studies on the relation between wind and surface drift, on silting in harbours, on effects of causeways, and on tidal power projects.

The *Blue Dolphin* expeditions, conducted under the auspices of the Arctic Institute of North America, operated in Labrador coastal waters for several seasons, starting in 1949. In 1948 the Royal Canadian Navy sent three ships, the *Magnificent* and the destroyers *Haida* and *Nootka*, on a cruise of Labrador waters, Hudson Bay and Hudson Strait, and a series of oceanographic observations were taken.

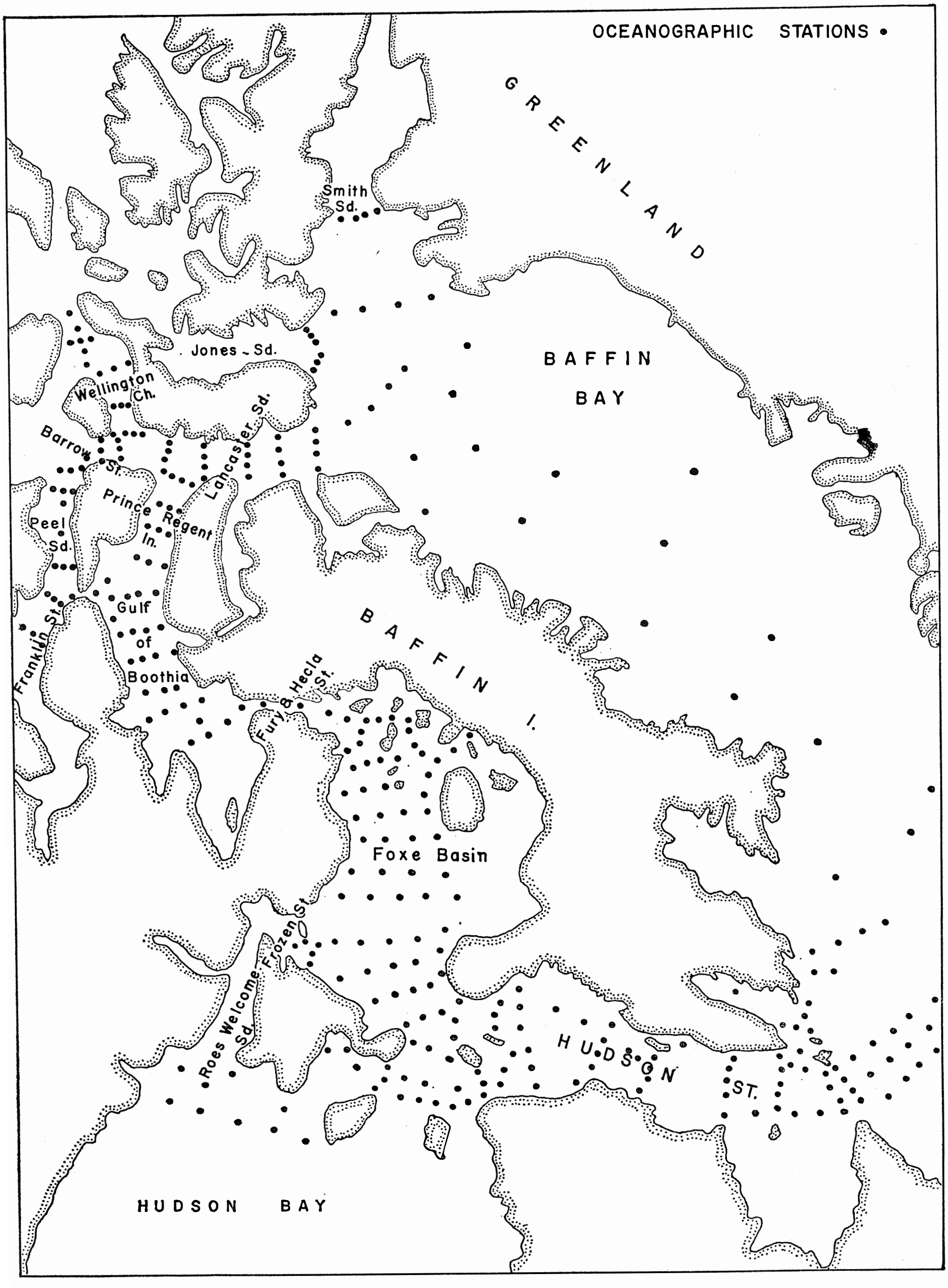
Post-war arctic investigations were initiated by the Fisheries Research Board in 1949, with the *Calanus* in Ungava Bay. These investigations were gradually expanded into the program of the Board's Arctic Unit organized in 1955, and the *Calanus* carried out successive operations in Ungava Bay, Hudson Strait, Hudson Bay, James Bay and Foxe Basin. During a complete 12-month period in 1955–56, the *Calanus* was frozen in near Igloolik in Foxe Basin, and the annual cycle of water conditions was recorded for the water column in this area.

Arctic oceanographic investigations generally received considerable impetus from the Canadian–United States activities relative to the construction of the DEW Line. Some oceanographic activities by United States ships between 1939 and 1945, and again following the cessation of hostilities, were carried out in association first with supply missions, and later in connection with the DEW Line. As early as 1948 a United States Task Force, with the icebreakers *Edisto* and *Eastwind*, entered Smith Sound, Lancaster Sound, and Prince Regent Inlet, eventually making the first passage into Foxe Basin. In 1954 the primary responsibilities in physical oceanography in the Arctic were undertaken by the Atlantic Oceanographic Group of the Fisheries Research Board. In that year the first of four teams of scientists took part in the northern cruises of the *Labrador*. The cruise of the *Labrador* in 1954 carried oceanography around the North American continent, through the "Northwest Passage". In the Arctic, particular emphasis was placed on the oceanography of Lancaster, Smith, and James Sounds, while further west the ship joined up with the United States–Canadian Expedition in the Beaufort Sea. In 1955 and 1956 the *Labrador* occupied hundreds of oceanographic stations in Baffin Bay, Hudson Strait and Foxe Basin. Towards the end of the season the ship made the first south-to-north passage through Fury and Hecla Strait and carried out an oceanographic reconnaissance in the Gulf of Boothia and Prince Regent Inlet. Series of stations were also occupied in Barrow Strait, Lancaster Sound, Baffin Bay, Davis Strait and the Labrador Sea. In 1957 the work of the *Labrador* was largely in Lancaster Sound, Prince Regent Inlet, Gulf of Boothia and Barrow Strait. Stations were also occupied in Bellot Strait, Franklin Strait, Peel Sound, Wellington Channel, Baffin Bay and Davis Strait. In 1958 the now C.G.S. *Labrador* carried out a detailed oceanographic survey of the eastern area of Hudson Strait. The ship also did oceanographic work in 1959 and 1960.

The activities of the Biological Station of Laval University at Grande-Rivière were gradually expanded in the post-war period, but eventually the Quebec Department of Game and Fisheries took it over and established a Marine Biological Station to direct attention to fisheries problems of the northern Gulf of St. Lawrence and the Bay of Chaleur.

In 1951 the Nova Scotia Centre for Geological Sciences, the Nova Scotia Department of Mines, the Nova Scotia Research Foundation, and the University of St. Francis Xavier, in association with the Atlantic Oceanographic Group of the Fisheries Research Board, initiated a preliminary geological investigation of the sea floor of the lower Gulf of St. Lawrence. In 1955 the Dominion Observatory became interested in some seismic studies in the Gulf of St. Lawrence and the Sable Island region. These events mark the beginning of a developing interest in phases of submarine geology which is now furthered under the expanding program of the Department of Mines and Technical Surveys.

In 1950 operation CABOT, a detailed investigation of the northern edge of the Gulf Stream, was carried out as a co-operative United States–Canadian project involving the Woods Hole Oceanographic Institution, the U.S. Navy Hydrographic Office, the Naval Research Establishment of the Defence Research



Oceanographic stations occupied by the *Labrador* in the eastern Arctic

Board, and the Atlantic Oceanographic Group of the Fisheries Research Board. Using several ships, these investigations made a great contribution to a clearer understanding of the dynamics associated with large eddies which form on the northern edge of the Gulf Stream. The investigations also elucidated the complexities in relation to the "cold wall", the boundary between the Gulf Stream and the slope water.

Background of Some Recent Projects

The Passamaquoddy power project, originally put forward in the early twenties by Dexter P. Cooper, is a United States–Canadian proposal to develop power from the tides in the Passamaquoddy Bay region of the Bay of Fundy. As mentioned earlier, to investigate the possible effects of such a project on the fisheries, an international study was initiated first in 1931–33 under the International Passamaquoddy Fisheries Commission. Further studies were conducted in 1957–59 under a second International Passamaquoddy Fisheries Commission. The oceanographic studies under this project involved the Fisheries Research Board, the Canadian Hydrographic Service of the Department of Mines and Technical Surveys, the U.S. Fish and Wildlife Service, and the Woods Hole Oceanographic Institution. By means of current measurements, drift bottle releases, drift pole tracking, electromagnetic measurements of flow, and dynamical calculations, considerable detailed knowledge has been obtained on the water movements involving Passamaquoddy Bay, the Bay of Fundy and the Gulf of Maine. The associated studies in oceanography and fisheries were directed towards determining the effects, beneficial or otherwise, which such a power project might have on the local and national economies in the United States and Canada. To this end it was necessary to study specifically the effects which the construction, maintenance, and operation of tidal power structures might have upon the fisheries in the area.

In 1959 the Polar Continental Shelf Project was organized by the Department of Mines and Technical Surveys to conduct integrated investigations in the general area of the Canadian portion of the polar continental shelf and the Arctic Ocean, and within the Canadian Archipelago. The study of the oceanic waters of arctic Canada and of the adjacent regions of the Arctic forms a major and essential part of this program. The program as at present in operation comprises the following activities in oceanography:

(*a*) A systematic, relatively detailed study of the waters over a representative section of the polar continental shelf, and of the straits opening onto the shelf.

(*b*) A reconnaissance, in the form of stations at intervals on judiciously placed cross-sections, of the channels and sounds of the Arctic Archipelago away from, and in advance of, the area of detailed study.

(*c*) A systematic study of sub-arctic and arctic waters, which is carried out whenever facilities are available.

(*d*) Studies in marine biology with specific attention to marine mammals and the productivity of the waters.

(*e*) Other related studies such as hydrography, marine geology and sea ice studies.

The development of oceanography in Canada was aided in many ways and by many organizations. In 1949 the Royal Society of Canada organized a "Symposium on Oceanography" which created considerable interest, and the Society later set up a Committee on Oceanography which had for its main purpose the development of interest in the science. The Nova Scotia Research Foundation and the Nova Scotia Department of Mines jointly sponsored a symposium given over solely to oceanography. The Royal Society of Canada has continued to sponsor oceanographic sessions within its annual program. The Associate Committee on Geodesy and Geophysics of the National Research Council was re-organized after the war with a section on oceanography, and gives much encouragement to all stages of development.

Oceanographic research by Denmark in West Greenland waters was expanded after the war, and since 1946 extensive coverage has been made of the fishing areas in those waters. The waters of the Grand Banks, Labrador Sea and Baffin Bay in the post-war years have been given considerable attention by ships of several nations. Of these, the observations of ships of the United States have been concerned chiefly with forecasting ice conditions.

The organization of the International Geophysical Year, 1957–58, resulted in a study of the world-wide oceans in which nearly every maritime nation was involved. The idea developed from what were formerly known as Polar Years. In 1882–83 Austria, Denmark, Finland, Germany, Great Britain, Holland, Norway, Russia, Sweden, and the United States joined in a great international scientific enterprise known as the International Polar Year. During the period of this Polar Year the geophysics of the Arctic was intensively studied, expeditions were set up, and meteorological, magnetic, and auroral stations were operated. In the polar area to the north of North America, the United States sent expeditions to Point Barrow, Alaska, and to Lady Franklin Bay, north of Lat. 80°40′ between Ellesmere Island and Greenland. The British established an observation station on Great Slave Lake, while the Germans sent an expedition to Cumberland Sound. Failure to get a relief ship to Lt. Greeley, who headed the American expeditions to Lady Franklin Bay in 1881, brought disaster. Of a party of twenty-four, only Lt. Greeley and six companions were found alive when a relief party finally reached them in 1884. The Arctic-wide project was, however, successfully carried out. Even the records of Greeley's party were found intact.

In 1932–33 the jubilee of this first Polar Year was celebrated by a repetition and extension of the enterprise as the Second International Polar Year. The observations carried out concerned meteorology, terrestrial magnetism and electricity. Valuable pioneer contributions were made also in the field of radio. During this period the scientific work of the Byrd Expedition in the Antarctic gained world-wide recognition.

The International Polar Years of 1882–1883 and 1932–33 produced such valuable results that experts in various branches of science were encouraged to plan for an International Geophysical Year to extend from July 1957 to December 1958, and to involve simultaneous observations over the whole globe, including especially the arctic and the antarctic regions. The oceanographic program was organized on a world-wide basis and nearly one hundred ships assisted in furthering projects in deepwater circulation, polar front surveys, multiple-ship surveys and sea-level recording. The international co-operation thus established carried on through 1959, and will no doubt be fostered in oceanography in the years that follow by the Scientific Committee for Oceanographic Research set up by the International Council of Scientific Unions, and by the Intergovernmental Oceanographic Commission organized under UNESCO.

SOME BASIC PRINCIPLES

Diurnal Motion of the Earth

Jean Bernard Leon Foucault demonstrated in 1851 the diurnal motion of the earth by the rotation of the plane of oscillation of a freely suspended long heavy pendulum. It occurred to him that a pendulum undisturbed by external forces must persist in its original direction of oscillation if one were swung at the North Pole by some suspension which could not transmit torsion. Its direction of oscillation would remain constant while the earth turned around under it, so that to an observer moving with the earth the pendulum would seem to change its direction of vibration at the rate of 15° per hour. If such a pendulum were swung along a meridian at the equator, the plane of oscillation would remain unchanged, as the meridian remains parallel to itself as the earth rotates. At any intermediate latitude the apparent angle of rotation of the oscillation plane of the pendulum can be calculated as follows: Suppose a parallel of latitude is drawn around the earth (see Fig. 1). From this parallel of latitude let tangents

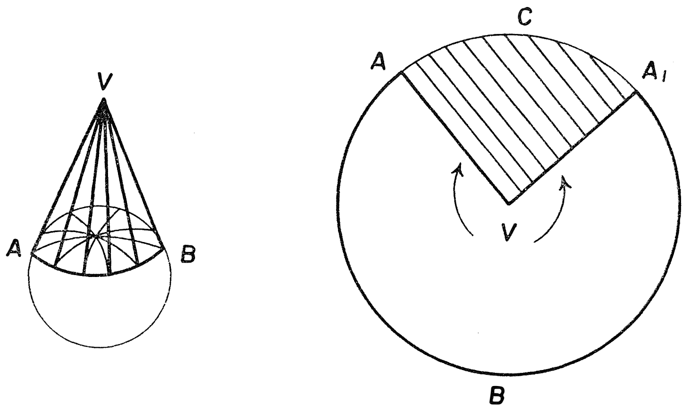


Figure 1.

be drawn at intervals of 15° of longitude, directed towards the north. All of these tangents would meet at some point V which is located on the earth's axis as produced. Taken together, these tangents would outline a cone with its apex at V and its base the section of the earth encompassed by the parallel of latitude. Consider this cone cut down upon one side and opened up. It would present us with a sector of a circle, and the angle subtended at the center would be the sum total of all the angles between all the adjacent meridians tangent to the earth at the chosen parallel of latitude. The angle of this sector would be equal to 360° sin φ, where φ is the latitude.

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The proof is as follows:

Circumference of the parallel of latitude $= 2\pi R \cos\varphi$ where R = radius of the earth, and φ = latitude. The side of the cone $AV = R \cot\varphi$. Hence the circumference of the circle outlined by the opened cone $= 2\pi R \cot\varphi$.

$$\angle AVA' : 360° = \text{arc } ABA' : \text{arc } ABA'C$$

$$= 2\pi R \cos\varphi : 2\pi R \cot\varphi$$

$$\angle AVA' = 360° \times \frac{\cos\varphi}{\cot\varphi} = 360° \sin\varphi.$$

Hence under the pendulum, at Lat. φ, the plane of oscillation would apparently turn through an angle $360° \sin\varphi$ in one day. Hence the angular velocity of this plane in degrees per hour is

$$\frac{360° \sin\varphi}{24} = \omega.$$

But the angular velocity of the earth in degrees per hour $= 360°/24 = \omega_0$;

$$\therefore\ \omega = \omega_0 \sin\varphi.$$

In the northern hemisphere then, an area at Lat. φ is rotating in a counterclockwise direction with an angular velocity ω. As an example, Cape Breton Island, whose center is approximately at Lat. 46°N, makes a complete anticlockwise revolution in approximately 33 hours.

The Coriolis Parameter

Consider a smooth straight tube, fixed in a horizontal plane at the North Pole N and consequently rotating with the earth about its axis with the angular velocity ω = 0.00007292 radian per second (Fig. 2). Suppose a ball M in the tube to move away from the center N with a constant velocity v. The acceleration of the ball is the resultant of two components, one due to the change in direction of v, and the other due to the change in r (distance of M from N) with respect to time. In a short interval of time Δt, the particle will have travelled a distance Δr along the tube. In the same interval Δt, the velocity will have changed direction by an angular amount of $\omega\Delta t$ radians. When the particle was at M, the linear velocity in the direction B_1B was ωr. When the particle was beyond M after an interval Δt, the linear velocity in the direction B_1B was $\omega(r+v\Delta t)$;

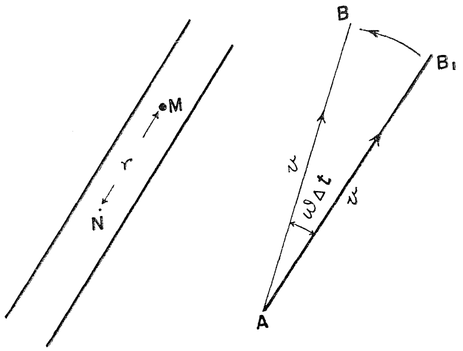

Figure 2.

$$\therefore\ \frac{\Delta v}{\Delta t} = \omega v \qquad \text{.....(I)}$$

and this acceleration is in the direction B_1B.

But $B_1B = \omega v \Delta t$, and this represents the change in velocity due to change in direction;

$$\therefore \frac{\Delta v}{\Delta t} = \omega v \qquad \ldots\ldots (II)$$

and this acceleration is in the direction B_1B.

The resultant acceleration directed to the left of the velocity direction is equal to (I) + (II) $= 2\omega v$. The force required to keep the mass moving in the tube is equal to $F = ma = 2m\omega v$ and is supplied by the pressure of the wall of the tube, as the tube rotates with the earth.

Relative to the earth, the particle moves in a straight line with velocity v and the force $F = 2m\omega v$, supplied by the pressure of the wall of the tube, is directed to the left and balances the deflecting force directed to the right owing to the earth's rotation. It is necessary to compute the deflecting force at any latitude φ.

Let the moving particle under consideration be at some point P_1, whose latitude is φ (Fig. 3). Let ω be the angular velocity of the earth about the axis of the earth NC. The angular velocity at P_1 can be resolved into two components, one about the axis ZP_1, and one about the axis CP_1. When the great circle NP_1D_1 rotates to the position NP_2D_2 through a small angle $\omega\Delta t$ in the time Δt, $P_1OP_2 = \omega\Delta t$, and $P_1ZP_2 = \omega_\varphi \Delta t$ where ω_φ is the angular velocity about ZX or CP_1. The direction and velocity of horizontally moving particles at P_1 are affected only by this component angular velocity ω_φ.

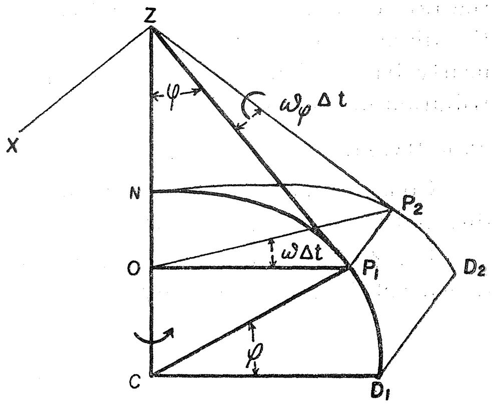

FIGURE 3.

$P_1P_2 = OP_1 \times \omega\Delta t$. But $OP_1 = r \cos \varphi$ where r is the radius of the earth;

$$\therefore P_1P_2 = r\omega \cos \varphi \Delta t. \qquad \ldots\ldots (III)$$

But P_1P_2 also equals $ZP_1 \times \omega_\varphi \Delta t$ and $\tan \varphi = r/ZP_1$;

$$\therefore P_1P_2 = \frac{r}{\tan \varphi} \times \omega_\varphi \Delta t = \frac{r \cos \varphi}{\sin \varphi} \omega_\varphi \Delta t. \qquad \ldots\ldots (IV)$$

From (III) and (IV) we get $\omega_\varphi = \omega \sin \varphi$. The deflecting force on a particle of mass m travelling with velocity v in latitude φ in the northern hemisphere is therefore

$$F = 2m\omega_\varphi v = 2m\omega v \sin \varphi \qquad \ldots\ldots (V)$$

and this equation is referred to as the Coriolis parameter, where:

F is the force in dynes acting on unit mass,

v is the velocity in centimetres per second,

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φ is the latitude, and
ω is the angular velocity of the earth's rotation in radians per second.

From this equation it follows that the deflective force due to the rotation of the earth acting on a quantity of moving water is:

(*a*) directly proportional to its mass,
(*b*) directly proportional to its horizontal velocity,
(*c*) directly proportional to the sine of the latitude of its location,
(*d*) exactly the same whatever the horizontal direction,
(*e*) always at right angles to its instantaneous direction,
(*f*) tending to produce clockwise rotation in the northern hemisphere and anti-clockwise in the southern.

The angular velocity of the earth's rotation is 0.00007292 radian/sec, where 86,164 seconds is the length of the siderial day. The value of F in mid-latitudes is approximately 10^{-4}. Hence a current in the northern hemisphere, flowing at the rate of 2 knots, would be acted upon by a force, acting on right angles to the direction of flow, of approximately 10^{-2} dyne/cm³.* This force would be nearly balanced by the horizontal pressure gradients due to the density distribution in the ocean.

The Balance of Forces

Consider a system of rectangular co-ordinates in the ocean with the x-axis directed to the east, the y-axis to the north, and the z-axis vertically upward.

Let p denote the pressure, g the acceleration due to gravity, and ρ the density of the water. For a hydrostatic balance of the forces in the ocean we have:

$$\frac{\partial p}{\partial z} = -g\rho. \qquad \text{.....(VI)}$$

The order of magnitude of the product of these two terms is approximately 10^3 dynes/cm³, and the balance of forces expressed by the equation is correct to a very high order of approximation. Surface waves, which are important in the upper 300 feet, may introduce terms up to the order of 10^2 dynes/cm³, while ocean tides introduce acceleration terms only of the order of magnitude of 10^{-6} dyne/cm³. The vertical component of the Coriolis force due to horizontal motions is of very minor practical importance.

Let u and v be the x and y components of velocity, and let F be the Coriolis parameter. For horizontal motion the geostrophic equations can be written:

$$\rho F v = \frac{\partial p}{\partial x} \qquad \text{...(VII)}$$

and

$$-\rho F u = \frac{\partial p}{\partial y}, \qquad \text{.....(VIII}$$

where $F = 2\omega \sin \varphi$, and φ is the latitude. These equations express an approximate balance between the Coriolis force and the horizontal pressure gradient.

* 1 dyne per cubic centimetre (1 dyne/cm³) = 0.06 pound per cubic foot (0.06 lb/ft³).

From (VI) and (VII) we get

$$\frac{\partial(vF\rho)}{\partial z} = -g\frac{\partial p}{\partial x}. \qquad \ldots\ldots (IX)$$

From (VI) and (VIII) we get

$$\frac{\partial(uF\rho)}{\partial z} = g\frac{\partial p}{\partial y}. \qquad \ldots\ldots (X)$$

Consider an ocean current flowing toward the north (positive y-direction) in the northern hemisphere. With $u = 0$, we have $\partial v/\partial z$ at each level z associated with a decrease of density towards the east (positive x-direction) at that level. Hence the density of sea water, as a function of depth and position, along a vertical section through the area provides us with a basis for computing the vertical gradient of horizontal velocity normal to the section.

If we knew the velocity for any one value of z we could determine the velocity at all depths by integrating Equation (X) with respect to z. To overcome our lack of knowledge we assume a "level of no motion" or at least a "level of reference". In some cases this procedure has some justification.

In practice, a formula has been derived for the computation of the geostrophic currents associated with the relative distribution of pressure as follows:

$$v_1 - v_2 = \frac{10\ (D_A - D_B)}{2\omega L \sin\varphi}, \qquad \ldots\ldots (XI)$$

where v_1 and v_2 are the velocities at two different depths, D_A and D_B are the dynamic heights at two oceanographic stations A and B, L is the distance between A and B, ω is the angular velocity of the earth, and φ is the latitude. Knowing the velocities, the volume transport can be calculated.

BJERKNES' FUNDAMENTAL HYDRODYNAMICAL CONCEPT

The foregoing formula (XI) was obtained from what is known as Bjerknes' circulation theorem. While it is derived in various text books, the present author's following method may be of interest to the mathematically inclined oceanographer:

Let Fig. 4 represent a vertical section in the sea. If no movement of the water is taking place, the various isobaric and isosteric surfaces would be represented by parallel and horizontal lines. If movement of the water is taking place, the isosteric and isobaric surfaces will be represented in the section as isobars and isosteres which intersect to form a number of parallelograms. Each such parallelogram endeavors to bring about a rotary movement of the

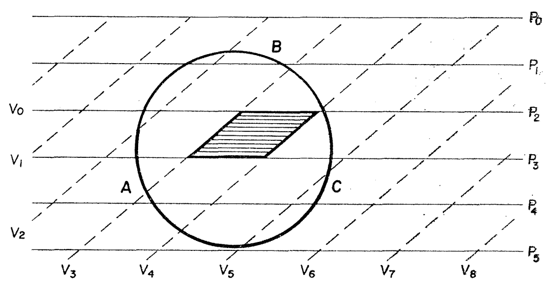

FIGURE 4.

water which would tend to bring the isosteric surfaces into a horizontal position. In three dimensions these parallelograms become tubes. Bjerknes calls these tubes solenoids when formed by the intersection of isosteric and isobaric surfaces which are unit distance apart. Let the isobaric surfaces be represented by the isobaric lines p_0, p_1, p_2, etc., and let the isosteric surfaces be represented by the isosteric lines v_0, v_1, v_2, etc. Let ABC represent a closed curve of molecules at any instant t.

The equations of motion of a compressible viscous fluid are of the type:

$$\rho \frac{\mathrm{D}u}{\mathrm{D}t} = \rho X - F_x \qquad \ldots\ldots \text{(XII)}$$

where u, v, w, denote the component velocities of the particle which happens to be at the point x, y, z at time t, where X, Y, Z are the components of the external force per unit mass, where F_x, F_y, F_z are the components of force per unit volume, and where $\frac{\mathrm{D}}{\mathrm{D}t}$ is equivalent to $\frac{\mathrm{d}}{\mathrm{d}t} + u\frac{\mathrm{d}}{\mathrm{d}x} + v\frac{\mathrm{d}}{\mathrm{d}y} + w\frac{\mathrm{d}}{\mathrm{d}z}$.

If we consider at any instant t a closed curve of molecules (such as ABC, Fig. 4), the integral of the velocity vector around this closed curve is known as the "circulation" around it. Denoting the "circulation" by C we have the equation of definition:

$$C = \int_{ABC} (u\mathrm{d}x + v\mathrm{d}y + w\mathrm{d}z). \qquad \ldots\ldots \text{(XIII)}$$

The "circulation acceleration" is the rate of change of circulation and is given by:

$$\frac{\mathrm{D}C}{\mathrm{D}t} = \int_{ABC} \left(\frac{\mathrm{D}u}{\mathrm{D}t}\mathrm{d}x + \frac{\mathrm{D}v}{\mathrm{D}t}\mathrm{d}y + \frac{\mathrm{D}w}{\mathrm{D}t}\mathrm{d}z \right) \qquad \ldots\ldots \text{(XIV)}$$

and from (XII) and (XIV) we obtain:

$$\frac{\mathrm{D}C}{\mathrm{D}t} = \int_{ABC} (X\mathrm{d}x + Y\mathrm{d}y + Z\mathrm{d}z) - R \qquad \ldots\ldots \text{(XV)}$$

where

$$R = \int_{ABC} \left(\frac{F_x}{\rho}\mathrm{d}x + \frac{F_y}{\rho}\mathrm{d}y + \frac{F_z}{\rho}\mathrm{d}z \right).$$

The external forces acting on the water masses in the sea are those of gravity (X_1, Y_1, Z_1), the deflecting force of the earth's rotation (X_2, Y_2, Z_2) and pressure (X_3, Y_3, Z_3). Equation (XV) may then be written:

$$\frac{\mathrm{D}C}{\mathrm{D}t} = \int_{ABC} (X_1\mathrm{d}x + Y_1\mathrm{d}y + Z_1\mathrm{d}z) + \int_{ABC} (X_2\mathrm{d}x + Y_2\mathrm{d}y + Z_2\mathrm{d}z)$$

$$+ \int_{ABC} (X_3\mathrm{d}x + Y_3\mathrm{d}y + Z_3\mathrm{d}z) - R. \qquad \ldots\ldots \text{(XVI)}$$

Let us now apply the above Equation (XVI) to the closed curve of molecules ABC (Fig. 4). The contribution of gravity to the "circulation acceleration" would be equal to zero (as it represents work done in moving unit mass around a closed path). Hence:

$$\int_{ABC} (X_1 dx + Y_1 dy + Z_1 dz) = 0. \qquad \ldots\ldots (XVII)$$

The contribution of the deflecting force due to the earth's rotation to the "circulation acceleration" is represented by:

$$\int_{ABC} (X_2 dx + Y_2 dy + Z_2 dz).$$

Due to the earth's rotation, the component of spin about the normal to a plane which is parallel to the earth's equatorial plane is equal to ω (the angular velocity of the earth). Consequently, the component of spin about the normal to a plane which makes an angle θ with the earth's equatorial plane is equal to $\omega \cos \theta$. Using Stokes' theorem which states that "the circulation around any closed curve drawn in the fluid is equal to twice the surface integral of the normal component of spin taken over any surface having the curve for a boundary, provided the surface lies wholly within the fluid", we have that the "circulation" due to the earth's rotation is equal to:

$$2 \iint^{(\text{area enclosed by curve } ABC)} \omega \cos \theta \, dS$$

or $2\omega S$, where S is the projection of the area enclosed by the curve ABC on the equatorial plane, and θ is the latitude in which the vertical section has been taken. Therefore we have for the "circulation acceleration" for the closed curve of molecules ABC:

$$\int_{ABC} (X_2 dx + Y_2 dy + Z_2 dz) = -2\omega \frac{DS}{Dt}. \qquad \ldots\ldots (XVIII)$$

The minus sign indicates that the "circulation acceleration" due to the earth's rotation increases as S decreases.

The contribution of pressure to the "circulation acceleration" is represented by:

$$\int_{ABC} (X_3 dx + Y_3 dy + Z_3 dz).$$

From the definition of pressure gradient we have for a fluid of density ρ:

$$dp = -\rho \, (X_3 dx + Y_3 dy + Z_3 dz),$$

where dp is an increment of pressure. Hence:

$$\int_{ABC} (X_3 dx + Y_3 dy + Z_3 dz) = -\int_{ABC} \frac{1}{\rho} dp = -\int_{ABC} v dp$$

as applied to the closed curve ABC, and where v is the specific volume.

Now the surface enclosed by any curve can be divided into a large number of small elements by a double series of intersecting lines which form a network over the surface. It is a fundamental theorem of hydrodynamics that the sum of the circulations around all of these elements, taken in the positive sense, is equal to the circulation around the boundary of the surface. In our problem the surface enclosed by the curve ABC is divided into a number of small elements by the isobaric and isosteric lines. Hence the "circulation" around the closed curve must be equal to the sum of the "circulations" around all the elements formed by the intersection of the various isobaric and isosteric lines. It would also follow that the "circulation acceleration" around the closed curve would be given by the sum of the "circulation acceleration" of the various elements.

The "circulation acceleration" around an element formed by the intersection of the isobaric lines p_2 and p_3 with the isosteric lines v_3 and v_4 (Fig. 4) is equal to:

$$-\int_{ABC} v dp = (v_4 - v_3)(p_3 - p_2).$$

If we choose suitable units so that $v_4 - v_3$ is equal to unity, and $p_3 - p_2$ is equal to unity, then the value for the "circulation acceleration" around the element will be equal to unity. Therefore the sum of the various "circulation accelerations" around the various elements will be equal to N, where N is the number of elements within the closed curve ABC. Hence, for the closed curve ABC we have:

$$\int_{ABC} (X_3 dx + Y_3 dy + Z_3 dz) = N. \qquad \text{.....(XIX)}$$

In order to make $v_4 - v_3$ and $p_3 - p_2$ both equal to unity, Bjerknes chose as his unit of specific volume one which had a value equal to 10^{-5} c.g.s. unit of specific volume, and for his unit of pressure he chose the decibar, which is equal to 10^5 c.g.s. units of pressure.

From (XVI), (XVII), (XVIII) and (XIX) we obtain our equation which expresses the value of the "circulation acceleration" for a closed curve in the sea:

$$\frac{DC}{Dt} = N - 2\omega \frac{DS}{Dt} - R. \qquad \text{.....(XX)}$$

Equation (XX) is the fundamental equation as derived by Bjerknes, which has played an important role in the investigations of the hydrodynamical problems of the sea. This formula contains all that influences the circulation of the water in the sea.

If we consider the closed curve moving with the current, Bjerknes' equation reduces to:

$$\frac{dC}{dt} = N - 2\omega \frac{dS}{dt} - R. \qquad \text{.....(XXI)}$$

In the practical investigation of currents, we are interested only in horizontal velocities, which are large in comparison with those in the vertical. Hence we need only to deal with the projection of the closed curve on the surface of the sea. In such a case:

$S = A \sin \varphi$, where A is the area of our closed curve.

If we consider only steady motion, there is no acceleration of circulation, and $dC/dt = 0$. If the closed curve is drawn across the steady current, then R reduces to zero.

We thus arrive at a simplified equation:

$$N = 2\omega \sin \varphi \frac{dA}{dt}. \qquad \text{.....(XXII)}$$

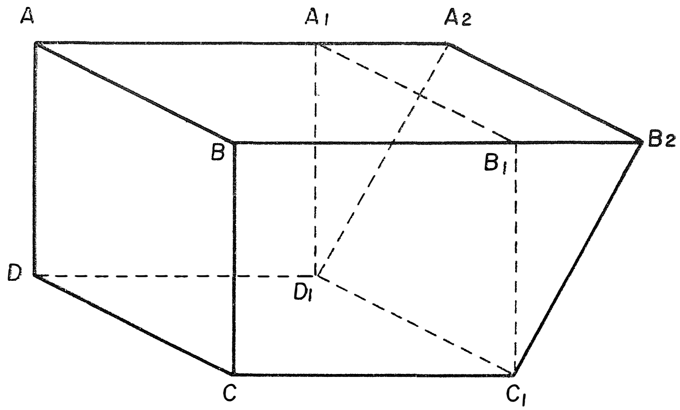

FIGURE 5.

In order to evaluate dA/dt, reference is made to Fig. 5.

Assume that the movement of water is normal to the plane $ABCD$.

Let AA_2 and BB_2 represent the velocity of the surface current, v_0.

Let CC_1 and DD_1 represent the velocity of the current v_1 at greater depth.

The area $A_1A_2B_2B_1$, the projection of $A_2B_2D_1C_1$ on the surface, represents the change of area in unit time. Therefore:

$$\frac{dA}{dt} = (v_0 - v_1)\ L,$$

where $L = AB$, and $N = 2\omega \sin \varphi\ (v_0 - v_1)\ L$; or:

$$v_0 - v_1 = \frac{N}{2\omega L \sin \varphi}. \qquad \text{.....(XXIII)}$$

Now N is the number of "elements" within the closed curve $ABCD$, and the number of "elements" can be counted by plotting pressures and specific volumes. Here Bjerknes introduced the term "solenoid", which is an "element" or an isobaric–isosteric tube. It is convenient to select as a unit tube one included by isosteric surfaces constructed for intervals of 10^{-5} of specific volume, and isobaric surfaces constructed for intervals of one centibar. Graphically the number of solenoids can be determined by counting the number of intersections. N can also be readily calculated and is given by:

$$N = 10\ (D_A - D_B)$$

where D_A and D_B are the dynamic heights at A and B respectively. Equation (XXIII) can therefore be reduced to:

$$v_0 - v_1 = \frac{D_A - D_B}{2\omega L \sin \varphi}$$

where v_0 and v_1 are expressed in cm/sec, L in kilometres, D_A and D_B in dynamic metres; and where φ is the latitude, and 2ω is 0.0001458 radian/sec (see also Equation XI).

The volume transport between A and B is given by:

$$T = 10^5 L \int_C^B (v_0 - v_1)\, dz = \frac{10^5}{2\omega \sin \varphi} \int_C^B (D_A - D_B)\, dz \qquad \text{(XXIV)}$$

where z is the depth in centimetres, and T is expressed in cm^3/sec.

Isentropic Analysis

While the currents and the volume transports can be determined according to the methods based on Bjerknes' circulation theorem, there are dangers inherent in the unrestricted use of these methods. Assumptions are made that a steady state exists, and therefore no acceleration of currents. When calculations of absolute values of currents and transports are made, a depth of no motion is assumed to exist. Practical applications have led to the use of dynamic topographies to outline the trajectories of water particles. In such cases, it must be remembered that dynamic topographies can only illustrate components of motion in horizontal flow, and do not present features of the third-dimensional component. This third-dimensional component can become of considerable significance in areas of upwelling, intense mixing or cabelling. For example the sinking of northern waters as they mix with those of the Gulf Stream in the region of the Grand Banks is an outstanding example of converging and submerging waters, pointing up the importance of the third-dimensional component of flow.

Probably a more realistic picture of actual particle trajectories is to be obtained by the methods of isentropic analysis, which methods are also based on the approximation of the steady state. Isentropic analysis consists in charting one of the properties of sea water, such as salinity, for surfaces of constant potential density. Where pressures do not exceed 1,000 decibars, a surface of constant potential density is practically equivalent to a surface of constant σ_t. Essentially the method is based on the fact that a free water particle is constrained to move within and with its proper isentropic surface (in practice a σ_t surface). If, for example, the distribution of salinity within a given σ_t surface is charted, the isohalines form a current pattern, illustrative of the paths of particles in motion within the given surface. To be of significance, the pattern must have some stability, in that it must represent more than a temporary situation. This stability must of course depend upon the rate of change in the physical nature of the water particles considered.

T–S Diagrams

A homogeneous water mass in the ocean can readily be described by its temperature T and salinity S. If temperatures were plotted against salinities, a homogeneous water mass would be represented graphically by a single T–S point. If we consider two such homogeneous water masses which differ from one another in temperature and salinity characteristics, then graphically we would have two points *A* and *B*, one representing *A*-water and the other *B*-water. Any mixture of the various proportions of *A*- and *B*-water would be represented graphically on a line joining the two points *A* and *B* and we would refer to the mixture as *A–B* water. This constitutes the simple basis of T–S diagrams. It will be obvious that T–S diagrams may become complicated where several types of water masses and various mixtures are concerned.

This graphical method can be combined in studying mixing processes by superimposing on the T–S plot lines of equal σ_t. While the T–S diagram can be used with confidence in studying mixing generally, its use in combination with the σ_t surface must be used with caution. Where ranges of temperature and salinity are small, no great error is involved in assuming mixing along σ_t lines; but when they are large, the change in entropy involved causes the mixed water to sink in the process which is later referred to in some detail as cabelling.

Wind and Drift Currents

The frictional force of the wind exerted directly on the surface of the sea plays an important role in maintaining the large-scale currents of the open ocean. This of course is particularly true where wind systems such as the "trades" are features of atmospheric circulation. Modern methods of analysis have led to treatments of the relations between mean wind distributions and transports of the resulting drift currents. The energy of the wind system is of course transmitted to the water through friction and the efficiency of this transport will depend to some extent on the roughness or smoothness of the water surface. In general, at moderate and strong winds, the stress of the wind on the water is proportional to the square of the wind velocity. At low wind velocities somewhat different conditions prevail. The frictional effect of winds and the associated wave action are important factors in the establishment of the homogeneous surface layer in the ocean.

The wind stress can be expressed in terms of the surface wind by:

$$\tau_0 = \rho y^2 w^2$$

where τ_0 is the wind stress,

ρ is the density of the air,

w is the wind velocity, and

y is a constant depending on the height at which the wind is measured, and the smoothness or roughness of the sea surface.

The resulting transport of water is given by:

$$\tau_0 = fT$$

where τ_0 is the wind stress,

T is the transport, and

f is the Coriolis force.

As the Coriolis force is a deflecting force acting at right angles to the mean motion, the water will be directed in the northern hemisphere to the right of the direction of the wind stress.

The depth of the homogeneous layer has been expressed by the formula:

$$h = (K \csc L) \times W_0 - K_1 W_0^2$$

where h is the depth of the homogeneous layer,

L is the latitude,

W_0 is the wind speed, and

K and K_1 are constants.

This formula has been applied successfully for latitudes greater than 20°N, its accuracy obviously limited to some degree by seasonal and latitude effects.

The general theory of drift currents produced by the wind was developed by Ekman. His theoretical results were derived from a study of a number of type problems which he solved by ordinary hydrodynamical methods. The Ekman spiral which illustrates the changing velocities and directions with depth is well known. A particular problem dealt with by Ekman was concerned with a steady and uniform wind blowing in a constant direction everywhere outside a straight and infinitely long coast, where the sea is considered to be of uniform depth. In such a case, a slope of the surface waters will arise, perpendicular to the coast, and gradually increase until the total flow perpendicular to the coast, due to wind and pressure gradient, is zero.

The equation for a steady current under such conditions (density differences neglected) has been derived by Ekman, and he has shown that the character of the motion will depend upon the depth d of the sea compared to the depth D of the wind current, and on the angle between the wind direction and the coast line. If the depth is sufficiently great ($d>2D$), three currents will be present as follows:

(*a*) a surface current which will be a pure drift current deflected to the right of the wind direction,

(*b*) a mid-water current parallel to the coast, and

(*c*) a bottom current moving more or less in a direction at right angles to the coast.

The bottom current is the lower part of the gradient current and in order to satisfy the condition of continuity, the flow towards or away from the coast in this layer must equal the flow away from or towards the coast in the surface layer. Thus in a cross-section normal to the coast, the components of flow normal to the coast in the surface and bottom layers are productive of circulation as illustrated in Fig. 6. In Fig. 6(*a*) a steady uniform wind (normal to the paper, towards the reader), blowing in a constant direction everywhere outside a straight and infinitely long coast, is causing a sinking of surface waters in the neighborhood of the coast, and thus a replacement of bottom waters by surface waters. In Fig. 6(*b*) the wind is represented as blowing in the opposite direction (normal to the paper and away from the reader). In such a case, the resultant vertical circulation is responsible for offshoreward movement of surface waters with consequent upwelling. Theoretically, a wind of given strength would have its greatest effect when directed a little more than 13° to the left of the coast line and when perpendicular to this direction would have its least effect.

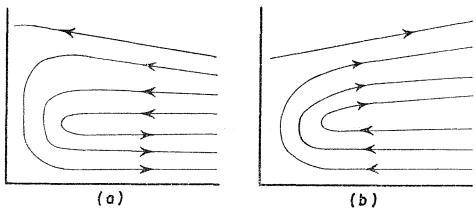

FIGURE 6.

The typical circulation is brought about under certain stated ideal conditions which are only approximated in the actual case. Prevailing winds at certain seasons of the year approximate these ideal conditions in some areas, and contribute to the well known phenomenon of upwelling, which is readily observed along the Atlantic Coast. At other times the accumulation of warmer surface waters along our Atlantic seaboard is a contrasting manifestation. On the southern coast of Nova Scotia for example, the predominating wind in summer is from a general southerly direction. Hence in summer, offshore movements of surface waters and onshore movements of bottom waters are favoured. In winter, the prevailing winds are from a westerly direction. During the fall months when easterly and northeasterly winds build up in association with tropical cyclones comparatively high surface water temperatures along the south coast of Nova Scotia have often been experienced. A water column in Halifax Harbour efficiently reflects the changing atmospheric pressure and wind systems over the open ocean, and some interesting observations have been made therein when tropical cyclones are in the making.

Waves

The wave equation from classical hydrodynamics can be written:

$$C = \sqrt{\frac{gL}{2\pi} \tanh \frac{2\pi h}{L}} \qquad \text{. . . . . (XXV)}$$

where C is the velocity,

h is the depth, and

L is the wave length.

If the depth is greater than half the wave length, tanh $2\pi/4$ approaches 1, and we get:

$$C = \sqrt{\frac{gL}{2\pi}} \qquad \text{. . . . . (XXVI)}$$

which is the equation for short or surface waves.

If the depth is small compared to the wave length, tanh $2\pi h/L$ can be replaced by $2\pi h/L$ and we get:

$$C = \sqrt{gh} \qquad \text{. . . . . (XXVII)}$$

which is the equation for long waves.

For short or surface waves, the velocities are therefore independent of the depth, but dependent on the wave length. For long waves, the velocities are dependent only on the depth and are independent of the wave length. The critical depth at which the transformation from short to long waves takes place is:

$$h = \frac{1}{4\pi} gT^2 \qquad \text{. . . . . (XXVIII)}$$

where T is the period.

The longest waves known in the ocean are those associated with the tides and their velocity of progress is given by Equation (XXVII).

Whenever stratified water or water in which the density varies with the depth exists, two different types of waves are possible: the ordinary waves as considered above, and the internal waves between two layers in contact. It can be shown that in the ocean, wherever there exists a comparatively thin top layer of water of low density, we can have the ordinary short surface waves that progress with velocity $\sqrt{gL/2\pi}$ and the short internal waves at the boundary between the light and heavy water that progress with velocity $\sqrt{gh_1 \left(\frac{\rho - \rho_1}{\rho}\right)}$, where h_1 and ρ_1 are the thickness and density of the upper layer, and ρ is the density of the lower layer. These short internal waves may be quite conspicuous in the areas of the ocean where suitable density variations exist. In the open ocean, long internal waves can be observed with a velocity of progress given by $\sqrt{\frac{ghh_1}{h + h_1}\left(\frac{\rho - \rho_1}{\rho}\right)}$ where h_1 and ρ_1 are the thickness and density of the upper layer and h and ρ are the thickness and density of the lower layer.

Attention is called to internal waves chiefly to direct attention to their bearing on oceanographic problems with respect to: (*a*) their importance to the process of mixing, and (*b*) their effect on dynamic computations.

The disturbance of a sea surface in a storm area advances into an area of calm with a velocity C_1 of a group of surface waves which is only half the velocity C of the individual waves. This can be shown by considering the combined effect of two trains of waves of equal wave height whose lengths differ by a small amount dL. The interference pattern will travel with a velocity equal to:

$$C_1 = C - L\,\frac{dC}{dL}. \qquad \text{..... (XXIX)}$$

Based on energy considerations, C^2 is proportional to L, and if we write $C^2 = KL$, we get:

$$C_1 = \frac{C}{2}.$$

These individual waves, which travel at twice the velocity of the disturbance of the sea surface, are the forerunners which provide storm warnings of practical value. A disturbance of the sea surface sets up waves of all lengths within a certain range. The first waves to arrive at an observation point distant from the disturbance are those of the longest period.

If a train of waves with group velocity C_1 is generated by a sudden disturbance, the distance travelled in time t is:

$$x = C_1 t = \frac{C}{2}\,t. \qquad \text{..... (XXX)}$$

But the velocity C for deep water waves is:

$$C = \frac{L}{T} = \sqrt{\frac{gL}{2\pi}} = \frac{gT}{2\pi},$$

where $T = \sqrt{2\pi L}.$

Substituting for C in (XXX), we get:

$$T = \frac{4\pi}{g} \times \frac{x}{t}. \qquad \text{..... (XXXI)}$$

For observations at a given fixed point,

$$\frac{\partial T}{\partial t} = -\frac{4\pi x}{gt^2} = -\frac{T}{t}. \qquad \text{..... (XXXII)}$$

Combining (XXXI) and (XXXII), we get:

$$x = \frac{gT^2}{4\pi\left(-\dfrac{\partial T}{\partial t}\right)}, \quad t = \frac{T}{\left(-\dfrac{\partial T}{\partial t}\right)}. \qquad \text{..... (XXXIII)}$$

The period, and the decrease of period with time, can both be determined from wave recordings. Hence x and t can both be determined. It is obvious that the position of the storm center can be readily fixed by observations from two or more shore stations x_1, x_2, etc., distant from the storm center.

If a system such as a body of water in a rectangular trough is set oscillating, it does so with its natural period determined by the length and depth of the trough according to the formula:

$$T = \frac{4L}{\sqrt{gh}}, \qquad \ldots\ldots \text{(XXXIV)}$$

where T is the period of the oscillation, L is the length of the trough, and h is the depth.

If there is now applied to the trough a periodic disturbance of period equal to the natural period of the system, the amplitude of the oscillation will be increased and will be prevented from becoming infinite by the various forces of resistance.

The oscillation of the body of water is of the nature of a standing or stationary wave. Such a wave is set up when two progressive waves proceeding in opposite directions are superimposed. In a lake, a bay, or an open sea, such waves are referred to as seiches. They are readily set up by wind or seismic disturbance. Where the natural period of oscillation conforms with a disturbance of a periodic nature, the amplitudes of the waves may reach considerable proportions.

When the body of water considered is of variable width and variable depth, modifications to the simple theory are necessary. In a closed or nearly closed body of water, the simplest form of a standing wave will be that where the node is at the center, and the antinodes are at the ends. In the case of a bay that opens to a larger body of water, the simplest form of a standing wave is that which has a nodal line across the opening, and an antinode at the closed end of the bay.

It has been shown that the comparatively large tides in the Bay of Fundy are due in part to its natural period of oscillation, which conforms to the tidal period. An examination of tidal curves recorded in various bays and estuaries will show at times the effects of an imposed standing wave.

Like a barometer in reverse, the sea responds to changes in barometric pressure. Along a coast, a rapidly falling barometer and associated wind systems can bring about a considerable rise in the level of the sea. When such phenomena occur simultaneously with spring tides, some exceptional water levels are experienced, and when the associated winds are strong, considerable damage is the result of the high waters and wave and wind action. This type of so-called tidal wave is experienced on the Atlantic coast associated with tropical cyclones.

Other types of so-called tidal waves are associated with seismic disturbances which might cause sudden movements of the sea floor thereby causing oscillations within the water body. When such waves originate in the open sea and progress over the shelving continental shelf, they increase in height and can be very destructive. While such phenomena are common enough in the Pacific Ocean, it is only on rare occasions in the North Atlantic such as during the Grand Banks disturbance in 1928, that seismic shocks have produced a destructive wave of this type. Since the waves set up by seismic disturbances are long waves and many times the depth of the water in which they travel, the velocities are according to the formula $C = \sqrt{gh}$. In the case of the Chilean disturbance of 1960, the speed of travel was as much as 500 m.p.h. The submarine earthquake in the Aleutian Islands in 1946 set up waves in the Pacific Ocean which reached Hawaii $4\frac{1}{2}$ hours later. Even at Valparaiso in South America these waves were as much as 5 feet high.

WATER REPLACEMENTS

The many problems of the pollution of harbours and coastal areas have directed considerable attention in recent years to the study of water replacements. The estimations of the rates of dilution of the pollutants and their seaward dispersion have introduced the terms "flushing time" and "exchange ratio".

The seaward dispersion of pollutants from an estuary, a harbour or a bay is furthered by the density distributions which favour:

(a) an outflow of lighter mixed waters in the surface layers, and

(b) an indraft of heavier ocean water in the sub-surface layers.

Wind, tides, and the Coriolis force are factors which introduce various modifications to the above simple mechanism.

The "flushing time" of an estuary, a harbour or a bay is defined as the average length of time required to remove one day's contribution of drainage water. It is equivalent to the ratio of the quantity of drainage water accumulated in the estuary, harbour or bay to the quantity introduced daily by the drainage system. The "flushing time" t is therefore given by:

$$t = \frac{Q_F}{Q_D}. \qquad \text{.....(XXXV)}$$

The "exchange ratio" r for an estuary, harbour or bay is given by:

$$r = \frac{Q_T}{Q_F}, \qquad \text{..... (XXXVI)}$$

where Q_F is the drainage water accumulated,

Q_D is the quantity introduced daily, and

Q_T is the quantity introduced during a tidal cycle.

From (XXXV) and (XXXVI), the relationship between "flushing time" and "exchange ratio" is given by:

$$t = \frac{1}{r} \times \frac{Q_T}{Q_D}. \qquad \text{..... (XXXVII)}$$

Knowing the salinity of the undiluted sea water carried to a given area in tidal flow, and observing the salinity distribution in the area, Q_F can be readily calculated.

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For a more precise computation of "exchange ratios", the estuary, harbour or bay is generally subdivided into segments which are horizontally defined by the width of the segment and the average excursion of a particle of water on the flooding tide. If the mixing is sufficiently vigorous so that all the water within the segment is diluted with drainage water, the "exchange ratio" for each segment is given by:

$$r_S = \frac{V_I}{V_I + V_L} \qquad \text{..... (XXXVIII)}$$

where V_I is the intertidal volume of the segment, and

V_L is the low-tide volume of the segment.

The total quantity of drainage water accumulated within each segment is given by:

$$Q_S = \frac{Q_T}{r_S}. \qquad \text{..... (XXXIX)}$$

The total drainage water Q_F accumulated within the area studied can therefore be obtained by a summarization of the accumulations within the segments. If below a given depth in a segment no dilution is evident, the segmentation excludes the waters at the greater depths.

It should be appreciated that the calculations are made on the basis of average distributions and average exchanges of water across complete cross-sections. Actual conditions in various parts of a cross-section, or in the separate cross-sections, may vary considerably from the average. For example, the mean "flushing time" of the Bay of Fundy has been calculated as 76 days. Actual observation has indicated that the waters of the Bay of Fundy were replaced in the fall of 1952 in a period of less than 46 days. Other calculations have furnished "flushing times" of 200 days for the Bay of Fundy.

The problem of the flushing of estuaries, etc. is only one interesting phase of the general replacement of one water mass by another. Studies on the replacement of Bay of Fundy waters have indicated the influence of land drainage, wind and tide. The effect of the Coriolis force is also strikingly demonstrated by the inward tendency of waters on the Nova Scotia side of the bay and the outward tendency on the New Brunswick side. Other things being equal, an excess of southwesterly winds favours the retention of surface waters within the bay, thus nullifying the normal dynamic tendency for surface outflow and renewal at greater depths. Under such wind conditions, and particularly during periods of minimum land drainage, a type of "closed circulation" is set up within the bay, as opposed to the "open circulation" when there is considerable interchange of waters with the Gulf of Maine. Features of this are indicated by the wide variation in "flushing times". Others have been demonstrated by large-scale drift bottle experiments. During the summer months if the "closed circulation" prevails the surface waters are comparatively warmer. Use has been made of the surface temperature data to show that successful year-classes of scallops are produced in those years when the "closed circulation" prevails. Not only do the warmer surface waters hasten development of the scallop larvae to the settling stage, but the closed "circulation" favours the retention of the larvae within the bay where they settle and grow on suitable scallop bottom.

Under the "open circulation" system, as indicated by comparatively lower surface temperatures, the larvae are carried out of the Bay of Fundy and are lost to the bay scallop fishery.

It might be emphasized that associated with these water replacements are the various plankton forms, as well as the free-swimming forms which are feeding at random. Under certain circumstances, the plankton concentrations in a water mass may be used as a criterion of the water replacements or exchange. The Gulf of Maine is the source of many of the plankton forms found in the Bay of Fundy and Passamaquoddy Bay. Due to the high tides of the region, and the physical nature of the passages, the waters passing in and out of Passamaquoddy Bay are thoroughly mixed. If the exchange of waters between Passamaquoddy Bay and the Bay of Fundy were at all times of comparable efficiency, the plankton distributions within and without Passamaquoddy Bay would be similar in both quality and quantity. One of the features of the area seems to be the very great differences in plankton concentrations that can persist at times as between a water mass inside Passamaquoddy Bay and a comparable water column outside. A study of these contrasts should indicate the pulsating nature of the interchange.

Up to this point, water replacements considered have been those associated with the flushing of an estuary, a harbour or a bay as a result of the normal influences of land drainage and the modifications introduced by tide, wind and the Coriolis force. Heavy freshets experienced in spring from the Saint John River area are effective in bringing about almost complete removal of Saint John Harbour water during a tidal cycle. Processes associated with the formation and subsequent movement of a tropical cyclone bring about complete replacement of Halifax Harbour waters within a few days. Water masses are removed from fishing banks under various transport systems, causing at times wholesale removal of larval forms with resultant failure in the production of a year-class of certain fishes. The replacing waters sometimes have sufficiently contrasting characteristics to deter, if not kill, the mature forms of the species from their normal habitat.

The replacements in the Gulf of St. Lawrence are in considerable contrast to those just mentioned. Based on calculated transports from observations in Cabot Strait in spring, summer and autumn, the net outward transport from the Gulf of St. Lawrence is approximately 15,000 km^3/year (53×10^{13} ft^3/year). Of this, about 3% is accounted for by the net contribution from land drainage, rainfall and evaporation. Accepting a rough figure of 35,000 km^3 for the volume of water contained in the Gulf of St. Lawrence, the replacement time of the waters of the Gulf of St. Lawrence is $2\frac{1}{3}$ years.

Cabelling

It can be shown that the mixing of two water masses of the same density but of different temperatures and salinities produces water of a greater density than either of its components. This phenomenon depends upon the non-linear relation between the temperature and density of sea water, and the practically linear relation between salinity and density. In nature, horizontally adjacent bodies of water will have nearly equal density when such adjacent bodies of water are of different temperatures and salinities; a mixture of the two will result in a sinking of the mixture to its own density level. This process of mixing and sinking is called "cabelling". It is obvious that the presence of two water masses of dissimilar characteristics in contact is indicative of horizontal flow. The mixing of two such water masses along their common border will be furthered by the frictional effects of the transporting currents, and enhanced by extraneous forces such as winds and waves.

In the open ocean this phenomenon is of considerable magnitude where two ocean waters of different origins come in contact. It is a common phenomenon along the northern edge of the Gulf Stream and particularly in the area of the Grand Banks where the Gulf Stream comes in direct contact with the Labrador Current.

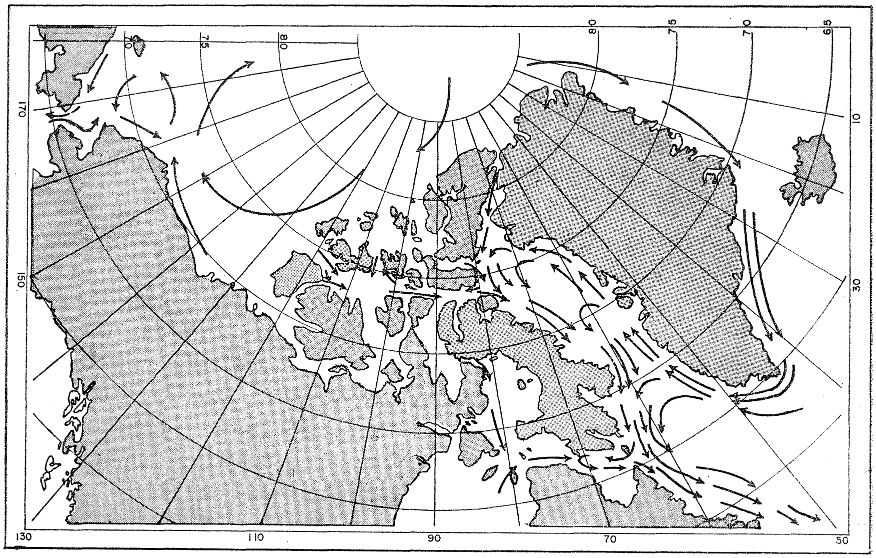
In the area of the Grand Banks the area of cabelling is normally offshore in deep water. With a deficiency of arctic water south of Newfoundland, the result of a subnormal Labrador Current, this area of cabelling is found on the banks. In this case cabelling is free to supply an abnormally large quantity of cold water directly from the surface to the bottom on the banks themselves. On the other hand, an intensified Labrador Current forces the area of cabelling offshore, and unusually warm water is then observed on the banks.

CIRCULATION IN THE WESTERN NORTH ATLANTIC

The General System

The circulation in the western North Atlantic is dominated by the Gulf Stream System and the Labrador Current. The main water body of particular Canadian concern is contained in the south within the confluences of these two great ocean systems. In the north the main water body is composed chiefly of the outflow from the Polar Sea.

In the north, the main features are the northward flow in the West Greenland Current along the West Greenland slope, and the southward movement along the Canadian coast in the Baffin Land and Labrador Currents. The West Green-



General scheme of circulation in the Arctic and northwestern Atlantic

land Current is composed of the East Greenland Current and the Irminger Current which became re-energized on rounding Cape Farewell. The Labrador Current is the summation of the flows of the Baffin Land and West Greenland Currents with added energy from the waters moving outwards from Hudson Bay and Foxe Channel through Hudson Strait.

In the northern latitudes of the northern hemisphere, the land masses offer considerable barriers to the exchange of waters as between the Polar Sea and the Atlantic and Pacific Oceans. The annual water balance of the Arctic Ocean has been calculated in which the inflow and outflow of waters through the Faeroes, the Shetland Islands, the Danish and Bering Straits, also the continental run-off, have been taken into account. One of the latest sets of data gives the annual balance of flow to and from the Arctic Basin as follows:

	km^3
Inflow:	
Faeroe–Shetland	128,500
Bering Strait	37,500
Rivers and glaciers	3,700
Precipitation	700
	170,400
Outflow:	
East Greenland	162,000
Canadian Archipelago	8,400
	170,400

$$(1 \text{ km}^3 = 35.3 \times 10^9 \text{ ft}^3).$$

In criticism of the above, it is considered that the values for the outflow through the Canadian Archipelago are much too small. The net contribution to Baffin Bay through Smith, Jones, and Lancaster Sounds has been estimated at 31,500 km^3 per year. The total contributed from the Canadian Archipelago is therefore in the neighbourhood of 45,000 km^3 per year. As calculations are based on observations made in the open-water season, it is possible that this latter value is somewhat high.

The waters of the West Greenland Current, made up by contributions from the East Greenland and Irminger Currents, are mixtures of waters of widely different origins and characteristics, and the oceanographic conditions along the west coast of Greenland at any given time are dependent on the relative strengths of the contributing currents. Off the southeast coast of Greenland, the East Greenland Current is mainly restricted to the shelf area, and the characteristics of the water are those of the Polar Sea. Off the shelf, and in part underneath the flow of the East Greenland Current, the comparatively warm Irminger Current of Atlantic origin is found. Intensive mixing of the waters of these two currents takes place, and continues as they round Cape Farewell and move northward along the west Greenland Coast. The mixing of these two water masses, and the northward flow of the mixture in the West Greenland Current, are responsible for the very pronounced differences in the water characteristics of the East Greenland, the West Greenland, and the currents along the Canadian coasts. While the East Greenland Current carries great masses of heavy polar ice, which block the Greenland coast for the greater part of the year, the West Greenland Current appears, in most years, as temperate and nearly ice-free, even as far north as Lat. 67°N. The Labrador Current that flows southward over the Canadian continental shelf is a cold water stream of comparatively low salinity, and corresponds in its characteristics to the waters of the East Greenland Current. As the West Greenland Current flows northward, part of it branches off westward, its northward transport rapidly decreasing beyond Lat. 65°N.

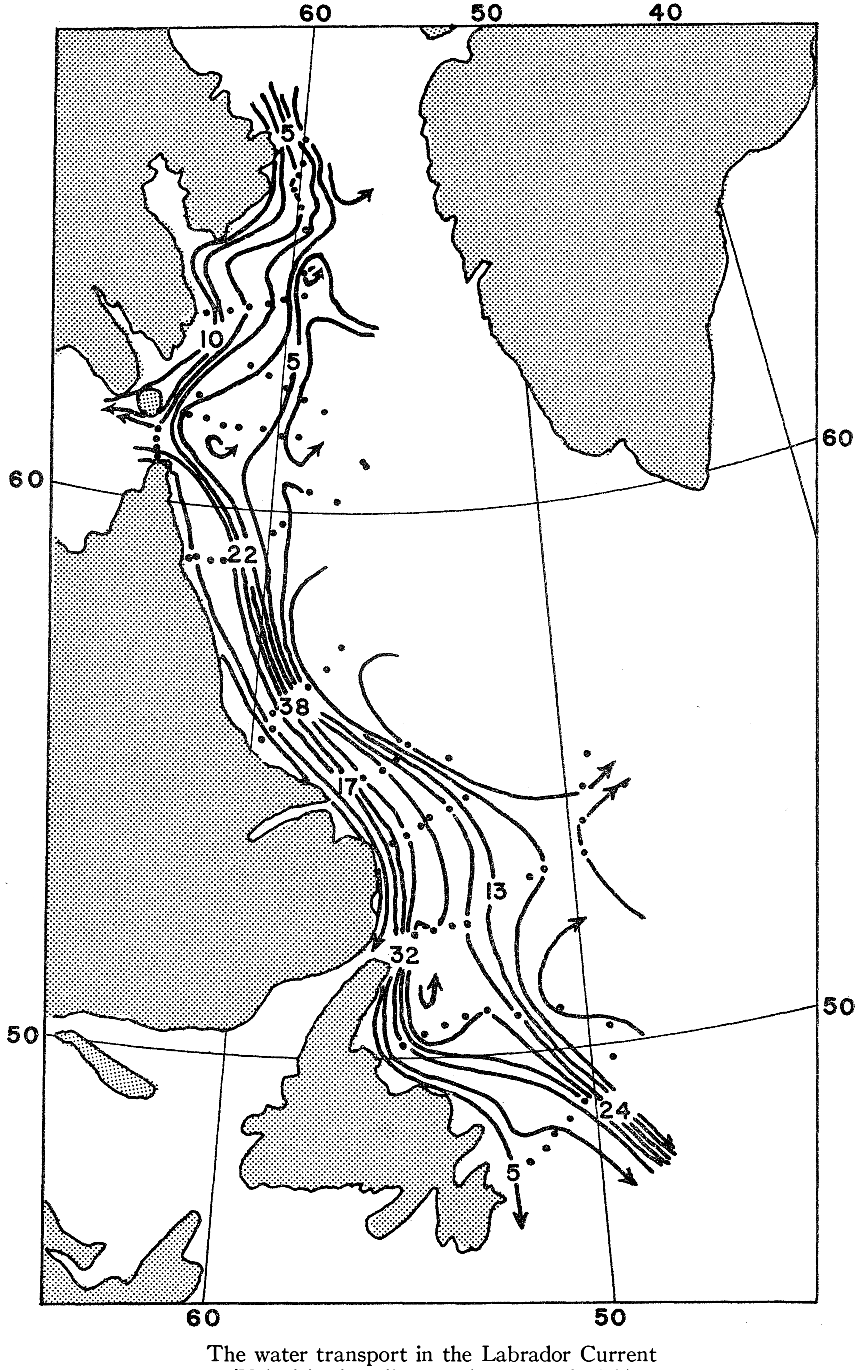
THE LABRADOR CURRENT

The Labrador Current, as has been noted, receives its energy from the Baffin Land and the West Greenland Current, supplemented by the flow from Hudson Bay and the Foxe Basin through Hudson Strait. It may be divided into two streams, an inshore and an offshore one. The inshore stream contains the greater volume of the cold polar water and is confined to the continental shelf. This stream penetrates some distance into Hudson Strait along the northern shore line. The offshore stream, which contains water characteristic of the West Greenland Current, tends shoreward in the vicinity of Hudson Strait and continues its southward flow over the Canadian continental slope. The characteristic low temperatures of the Labrador Current persist as the southward flow continues, the great stability of the water layers offering resistance to the penetration of solar heat by convection. On reaching the vicinity of the Strait of Belle Isle, water from the inshore stream is carried at times through the strait into the Gulf of St. Lawrence. Water moving outwards at times along the southern side of the strait enters into the southward flow of the Labrador Current. Continuing southward of the Strait of Belle Isle, the Labrador Current meets the northern face of the Grand Banks and is split, the slope branch continuing down the slope of the Grand Banks, while an inshore branch swings south and west to penetrate westward over the Grand Banks. In its southward progress, this water of the Labrador Current contributes directly to the Gulf of St. Lawrence through the Strait of Belle Isle, where the threshold is less than 50 fathoms, and with some modification through mixing, through Cabot Strait. It also spreads far and wide over the Grand Banks, finally coming into contact with the waters of the Gulf Stream system. It has been shown that these waters are of particular import in their contribution to what has been termed the "cold water layer" so characteristic of the Scotian Shelf at intermediate depths. Its distribution in late winter and early spring is well demonstrated by the drift of ice and icebergs.

As noted, the Labrador Current has its origin in the Labrador Sea. When attempts are made to calculate the annual inflow and outflow to and from the Labrador Sea a balance sheet is obtained as follows:

	km^3
Inflow:	
West Greenland Current	157,500
Outflow from Canadian Archipelago	45,000
	202,500
Outflow:	
West Greenland Current to Baffin Bay	31,000
Labrador Current	145,000
	176,000

The calculations are based on observations in the upper 500 fathoms, and the discrepancy in the above balance sheet, amounting to 26,500 km^3 per year, represents the water which sinks and moves out of the Labrador Sea to the Atlantic at



The water transport in the Labrador Current
(Velocities in miles per day, after Smith)

the greater depths. The variations in the strength of the Labrador Current are well known. Calculations have indicated great variations from one year to another. It is to be expected that the outflow at the greater depths would also be subject to great variations. This southward flow of the deeper waters of the Labrador Sea has an important bearing on the entire deep-sea circulation of the Atlantic Ocean.

The Ridges Between Greenland and Scotland

The submarine ridges between Greenland and Scotland act as a threshold offering resistance to the interchange of deep polar waters and those of the Norwegian Sea with the North Atlantic. There is however a surplus outflow from the Arctic, in the deeper layers over three ridges, which have different sill depths as follows:

(*a*) Greenland–Iceland Ridge which represents a broad rise in the ocean floor with a deep cross channel and with a sill depth of 300 fathoms,

(*b*) Iceland–Faroe Ridge representing a broad rise in the ocean floor, but without any channel, and with a sill depth of 240 fathoms,

(*c*) Faroe–Shetland Ridge with a deep cross channel and with a sill depth of 400 fathoms.

The greater part of the deep outflow from the Norwegian Seas takes place through the cross channel of the Greenland–Iceland Ridge. It has been estimated that the total outflow in the deeper layers over these ridges into the North Atlantic amounts to 0.0035 km^3/sec (1.2×10^3 ft^3/sec).

The Gulf Stream System

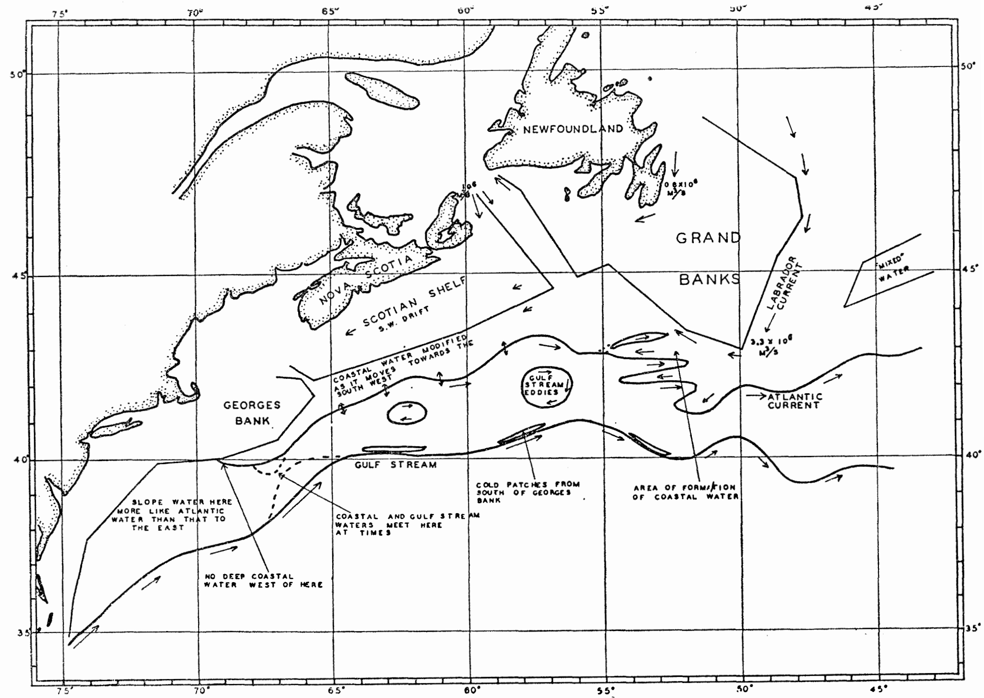
One of the early descriptions of the Gulf Stream referred to a "river in the sea" with the Gulf of Mexico its "fountain" and its "mouth" the Arctic Seas. While this may have sufficed as a description one hundred years ago, it will hardly pass muster today even though our present conception of the Gulf Stream is far from complete. The Gulf Stream has always been a feature of interest in the western North Atlantic and attracted the attention of the early oceanographic expeditions. It has certain features which make it easily recognized, such as a well-defined northern edge, and a readily measured velocity of considerable magnitude. It lends itself to some interesting studies as it can be readily crossed in a day. Its similarity in physical features of flow with those of the atmosphere has attracted the attention of students of dynamic meteorology. Oceanography and meteorology have both profited from the principles derived from the resultant studies. In discussing this feature of the circulation of the western North Atlantic the term "Gulf Stream" is reserved for that part of the Gulf Stream System between Cape Hatteras and the tail of the Grand Banks. The Gulf Stream System is the great clockwise circulatory system of the North Atlantic Ocean. The modern conception of the Gulf Stream is that of a narrow ribbon of comparatively high-salinity water acting as a boundary that prevents the warm water of the Sargasso Sea from overflowing the colder denser waters on the inshore side. A very precise definition relates the term "Gulf Stream" to a band of swift current extending to depths of 900 fathoms. The converging in the Caribbean of one phase of the westward drift caused by the Trade Winds is the main source of energy for the Gulf Stream System.

Proceeding outwards and southwards from Nova Scotia to the Central Atlantic, four distinctive bands of water are crossed, easily distinguished on the surface by their salinity and temperature characteristics. There is first the relatively fresh coastal water normally covering the continental shelf. Between the continental slope and the Gulf Stream lies a band of water having intermediate surface salinities and relatively low temperatures at mid depth. Beyond the stream, true Central Atlantic water of salinities higher than 36.0 ‰ are found. It has been amply demonstrated by various observers that waters of Gulf Stream origin can exist as a body, separate and distinct from the stream itself. Frictionally driven eddies develop from time to time along the northern edge of the Gulf Stream and are often as much as 80 miles in diameter. An intensive study of some of these eddies was carried out in 1950 under Operation CABOT.

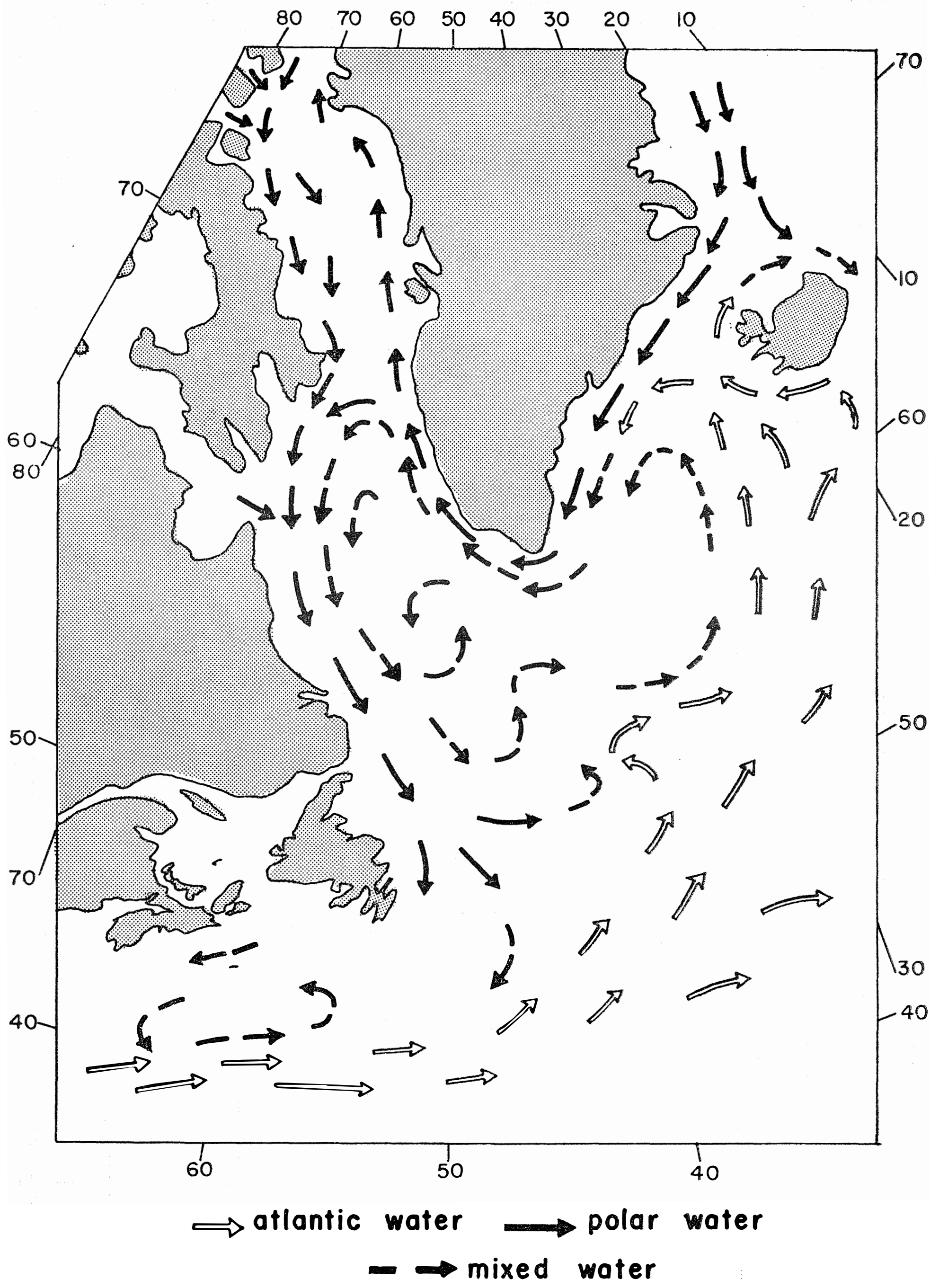
Over a period of 10 years or more the northern limit of Gulf Stream water was located by means of thermographs installed on ships making frequent crossings of the stream. The debouching of warm masses from the stream into the cooler slope water sub-area was noted as happening at any point between the longitudes of Cape Hatteras and Halifax. Fixing the temporary migrations of Gulf Stream water by means of these thermograph observations between Boston and Bermuda, it was indicated that the northern limit of the stream water varied between 60 and 300 miles from the coast. The more northerly positions were recorded in early winter and again in late summer, while the more southerly positions were noted in spring and again in the autumn. Calculated transports of the Gulf Stream, and tide-gauge records which indicate the slope of the surface waters across the current, have suggested that the stream is relatively strong during the early summer, falls off rapidly in strength to a minimum in October or November and then increases rapidly until January or later. A secondary minimum is called for in April or May. These results have been explained on the seasonal variation in the strength of the winds over the northern equatorial region, as well as the annual north–south migration of this wind system. In substance it is considered that the northern migration of Gulf Stream water results from a weakening of the stream. More recent and more critical analyses of these earlier data have raised the question as to whether there is any real relationship between the position and transport of the Gulf Stream and the seasonal fluctuation in the strength and position of the wind system.

The above, of course, is a very simplified consideration of what constitutes the Gulf Stream. Basically there is a more or less undisturbed current. The secondary phenomena are many. The multiple-ship survey in Operation CABOT in 1950 made detailed studies of some phases of the eddies associated with meanders of the stream. Some considerations of the immense amount of energy stored in the waters of the central North Atlantic emphasize the fact that current fluctuations in the Gulf Stream System need not respond completely to the

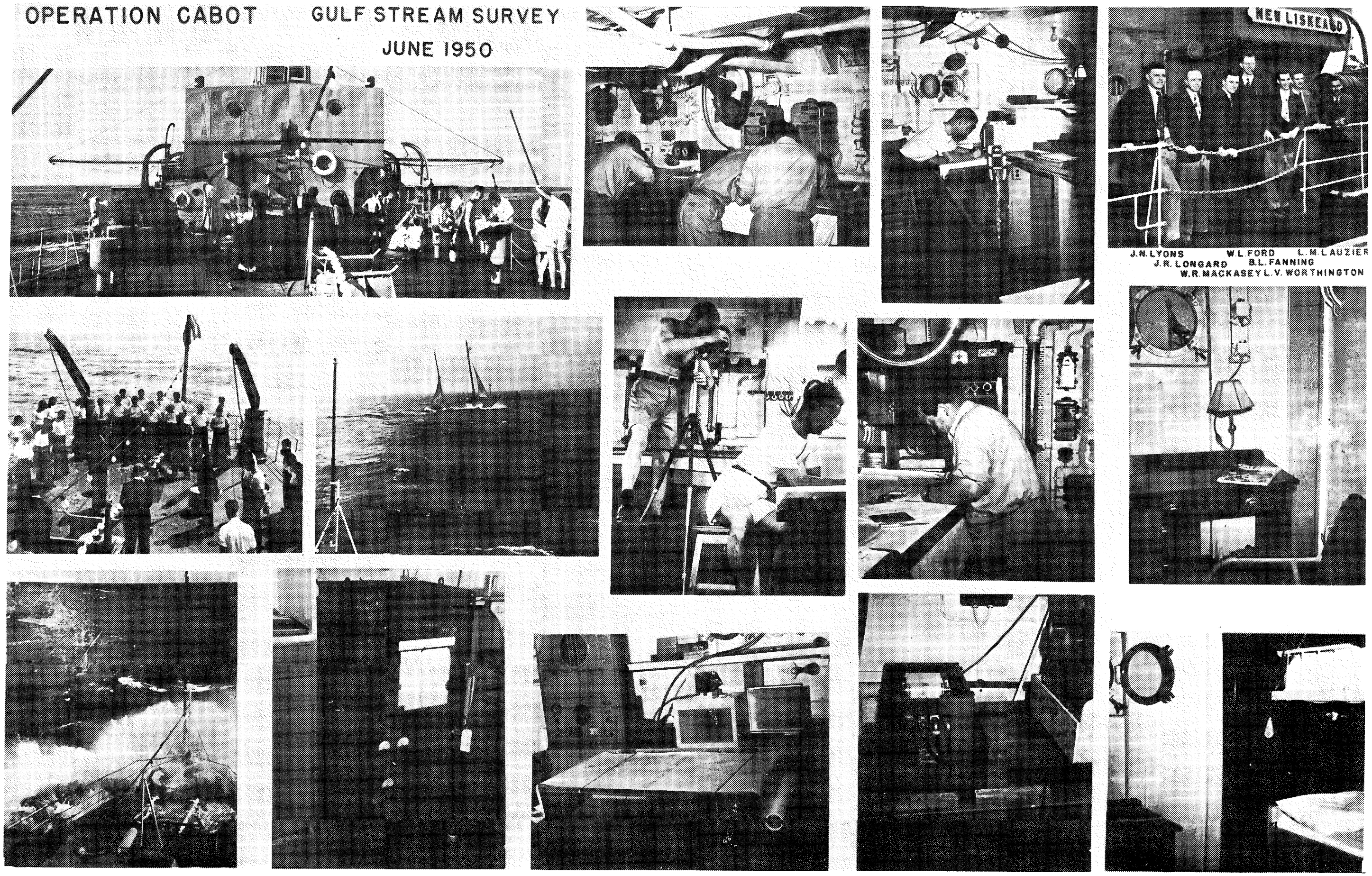
Franklin's chart of the Gulf Stream



The Gulf Stream and neighboring waters (after McLellan)

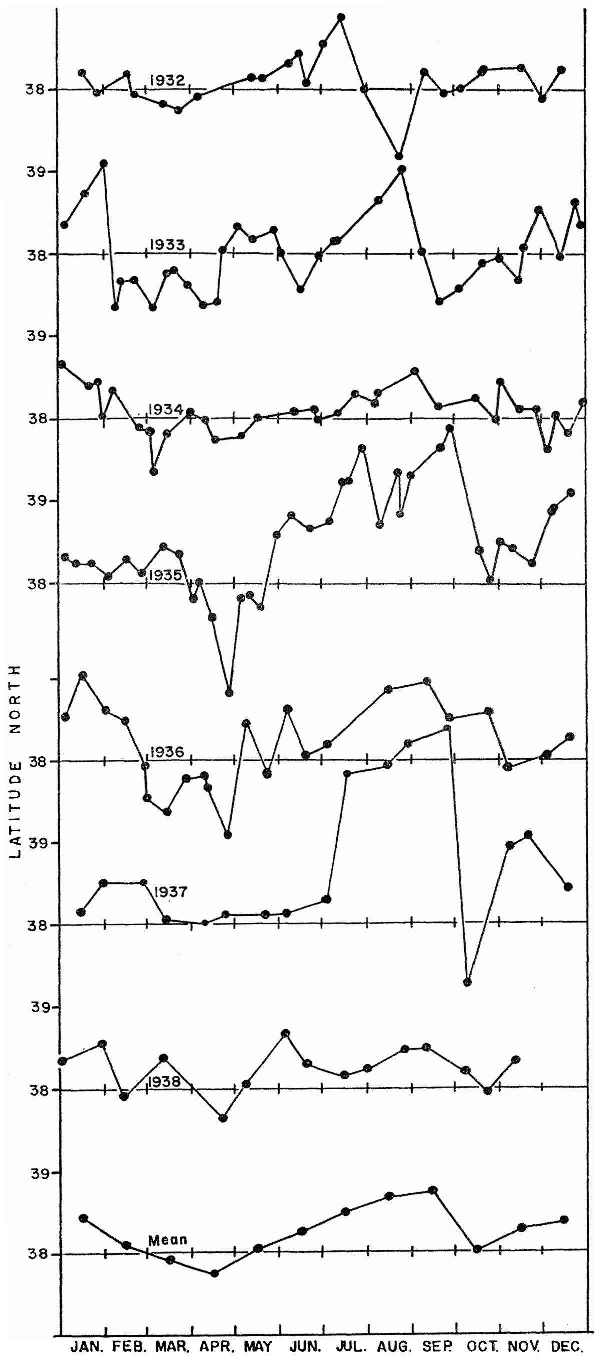


General scheme of circulation showing contributions to the water mass (after Deitrich)

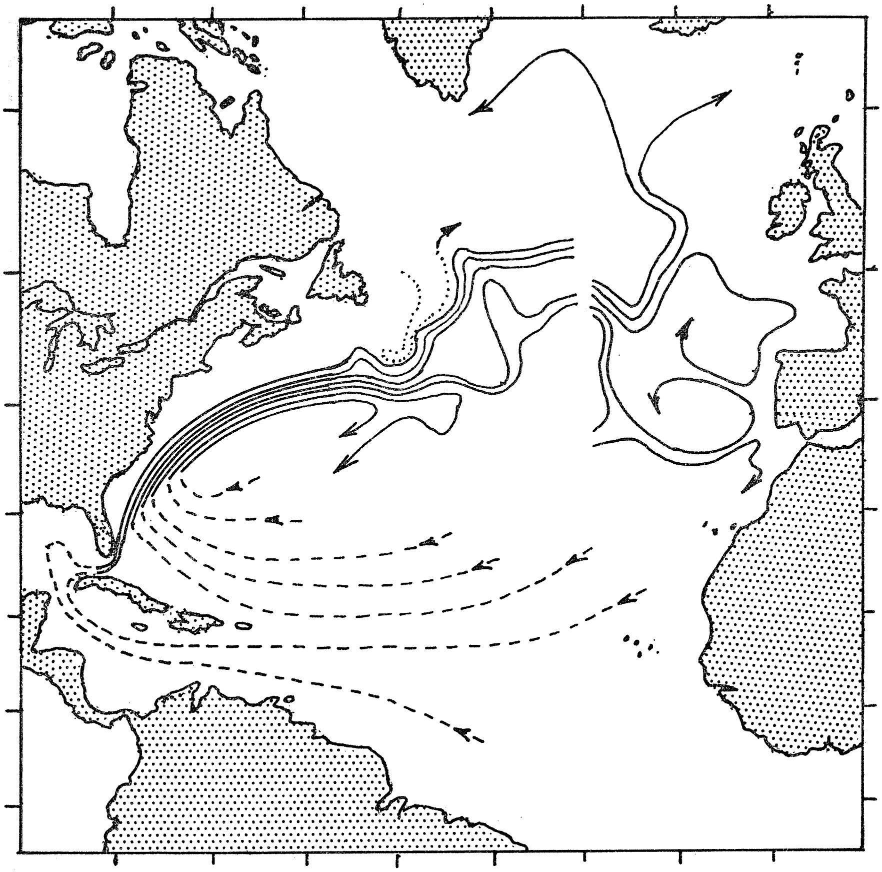


Some action pictures of the joint Canada—U.S. Survey of the Gulf Stream

(RCN photos)



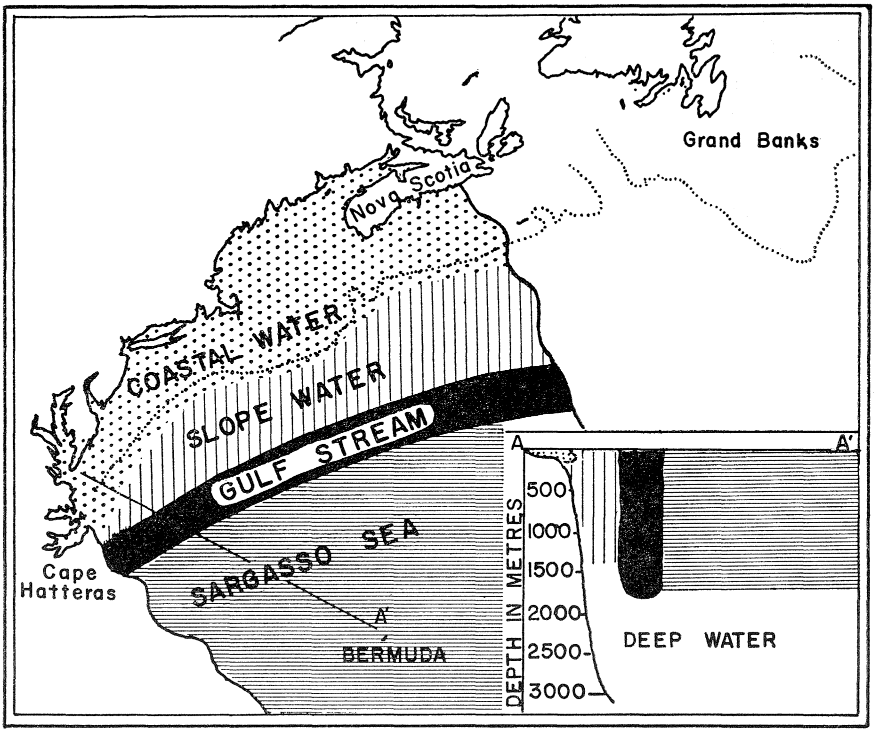
Varying positions of northern edge of the Gulf Stream as obtained from thermograph records confluence of the Labrador Current and the Gulf Stream in the southwestern area of the Grand Banks and to the westward, that large-scale mixing processes occur to provide a type of "slope water". This "slope water" contributes largely to the characteristic waters that are in contact with the continental shelf, and penetrate at greater depths even into the Gulf of St. Lawrence. These "slope waters" have a profound influence on the waters of the Scotian Shelf, indirectly through mixing with coastal water, and directly when mass incursions of these waters take place.



The Gulf Stream System (after Iselin)

The term "slope water" has been applied to the band of water between the edge of the continental shelf and the Gulf Stream. Off Nova Scotia, it averages about 170 miles in width. It is a continuous band of water from Cape Hatteras to the Grand Banks. It is characterized as mixed water involving coastal, Labrador Current and Gulf Stream contributions.

The relative contributions of the Labrador Current and the Gulf Stream to the water areas contiguous to the southerly portion of the Canadian coast



Waters off the Atlantic coast (after Iselin)

vary within considerable limits. Attempts have been made to show that when the Labrador Current is strong, the Gulf Stream is weak, and vice versa. A bit of a paradox is encountered here, for it is observed that when the Gulf Stream is weak, incursions of stream water are to be observed over the continental shelf. This is sufficient to indicate that our knowledge of the two main factors determining the water characteristics of Canadian coastal areas is rather meagre.

The Gulf of St. Lawrence

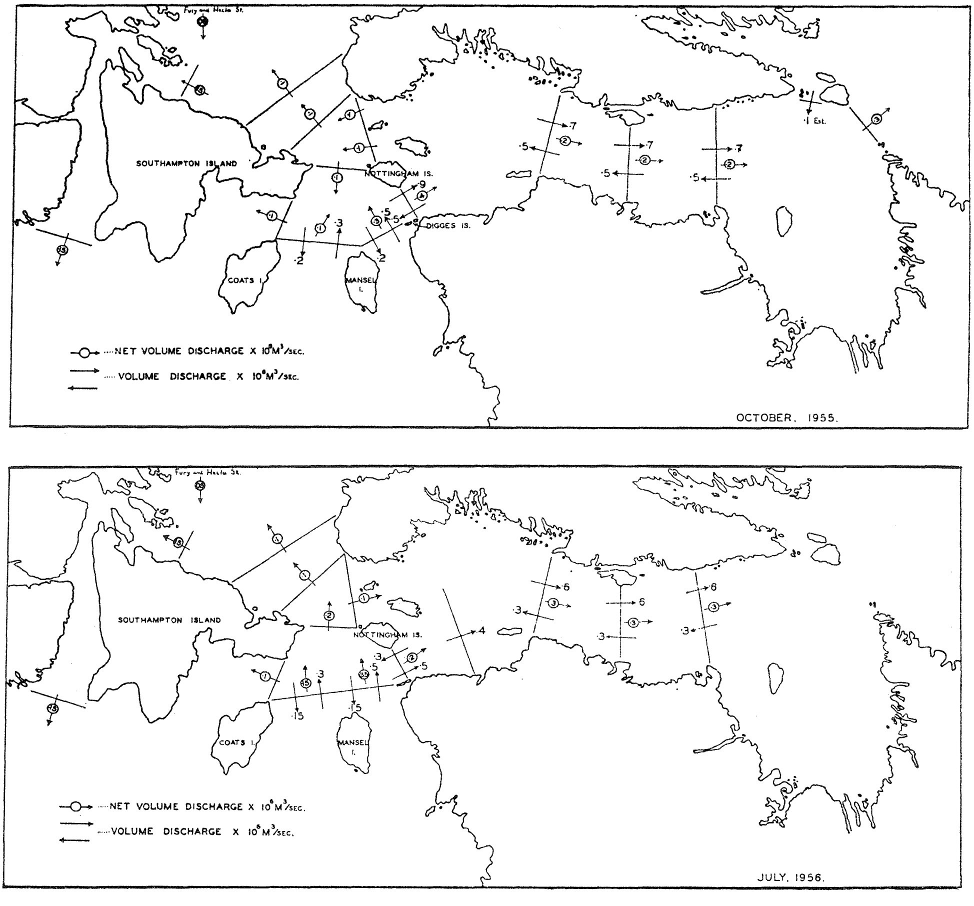
The circulation of the waters in the upper layers in the Gulf of St. Lawrence is in general anti-clockwise. Waters that enter the gulf past Cape Ray, Newfoundland, are deflected to the right and flow northeastward along the west coast of Newfoundland. Along the north shore of the gulf there is a westward drift of a water type that may have had its origin north of the Strait of Belle Isle, while part of the northeast flow is deflected by Mecatina Bank, lying across the head of the Esquiman Channel. Investigations have shown the circulation of the waters in the Strait of Belle Isle to consist of:

(*a*) a progressive inward movement of Labrador coastal water on the north side,

(*b*) a progressive outward movement of Gulf of St. Lawrence water on the south side, and

(*c*) a dominant flow which may be Labrador coastal water inwards at times, or gulf water outwards.

Along the north shore of the gulf there is a net westward movement part of which extends past the western end of Anticosti Island. In the Gaspe Passage between Anticosti Island and the Gaspe Peninsula, there is a preponderance of movement to the east in the form of the Gaspe Current.



Volume discharge in the region of Hudson Strait (after Campbell)

This current is very strong at times and its effects can be seen and felt several miles from the coast. While the Gaspe Current is constant in direction, outwards towards the Gulf of St. Lawrence it is subject to wide variations in strength. The current persists to depths of at least 90 fathoms. It keeps well to the Gaspe Peninsula, but after it passes Cape Gaspe and enters the open gulf, the Gaspe Current may spread out and become weaker, or it may narrow to a stream of considerable strength. When strong, it seems to have a greater tendency towards the southwest, due to the increased deflecting force of the earth's rotation. This greater tendency to the southwest no doubt accelerates the circulation of the waters of the Magdalen Shallows. The waters in the southern Gulf of St. Lawrence

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area form a general eastward flow which works towards Cabot Strait where the main efflux of the gulf takes place. This efflux is generally referred to as the Cape Breton Current or Cabot Stream. The waters borne by the Cabot Stream on passing through Cabot Strait round Cape Breton and flow over the Scotian Shelf.

The net transport from the Gulf of St. Lawrence through Cabot Strait has been calculated on the basis of observations made during the spring, summer and autumn months. A value of 5.3×10^{14} ft^3/year has been obtained. It might be emphasized that land drainage, rainfall and evaporation account for only 3% of this value, and that the outward-moving water is of a salinity which is generally higher than 28‰. A comparison of the annual transports of the Labrador Current, the Gulf Stream and those through Cabot Strait indicates that the contribution through Cabot Strait is only $\frac{1}{10}$ of that of the Labrador Current, and only $\frac{1}{35}$ of that of the Gulf Stream. Its particular relative importance is due to its comparatively lower density which maintains the identity of its waters in the surface layers of areas of the Scotian Shelf.

The Scotian Shelf and Bay of Fundy

The general circulation pattern on the Scotian Shelf is anti-clockwise, with a predominantly southwesterly drift along the coast of Nova Scotia and a northeasterly drift along the edge of the continental shelf. The average rate of drift is approximately 0.15 knot.

The general circulation of the waters of the Bay of Fundy is anti-clockwise, the resultant inward movement holding close to the Nova Scotia side of the bay. Both the bay and the Gulf of Maine derive their characteristic ocean waters through an influx of water past Cape Sable and also from the slope water at the edge of the continental shelf. The circulation of the waters of the Gulf of Maine is anti-clockwise and there is an interchange between that gulf and the Bay of Fundy which varies considerably with the season.

ATMOSPHERIC CIRCULATION OVER THE WESTERN NORTH ATLANTIC

The Wind System

The frictional force of the wind when exerted on the surface of the sea puts water in motion, and the elementary principles involved have been referred to earlier. The distributions of atmospheric pressure over the western North Atlantic determine the wind system. Mean sea level atmospheric pressure, and wind distribution, at the height of summer and winter respectively, bring into focus two features of the atmospheric pressure distribution which have been designated as the Icelandic Low and the Bermuda–Azores High. On the average there is a low-pressure area between Greenland and Iceland associated with an anti-clockwise wind circulation. These winds exert a frictional force on the surface waters in these northern latitudes. This Icelandic Low, or low-pressure area between Greenland and Iceland, is more pronounced during the winter months, and hence the winter atmospheric circulation is more intense. In the south, on the average, the high-pressure area extends between Bermuda and the Azores, and associated with it is a clockwise atmospheric circulation exerting a frictional force on the waters of the North Atlantic Ocean. This Bermuda–Azores High is more extensive and more highly developed in summer, and therefore the atmospheric circulation about this high is more intense at this time.

The annual average position of the center of this Bermuda–Azores High is about 600 miles southwest of the Azores, and the average positions of the center by months are within 700 miles of the annual average center. The steadiest winds in the atmospheric circulation, clockwise around the center, are those from Africa to the Caribbean, and are known as the Trade Winds. The strongest are those of the westerlies from north of Bermuda towards Spain and Portugal.

Another feature of the Bermuda–Azores High is its northward displacement in summer. Between March and July there is generally a northward shift by as much as 500 miles. There are also variations in the intensities of this Bermuda–Azores High as well as in the Icelandic Low, and the normal distributions vanish at times under the influence of more intense meteorological phenomena. The change from the summer type of atmospheric circulation to the winter type is not a gradual process but a very erratic one. As the winter season approaches, the winter circulation pattern is more frequently present, the summer pattern less frequently. The more intense meteorological phenomena that disturb the normal patterns are those of fronts, stagnant lows, linkage between highs, and cyclones.

While a normal or average seasonal weather pattern is seldom present, the normal mid-winter weather charts for the North Atlantic indicate that the winter atmospheric circulation is featured by strong westerlies in the middle latitudes.

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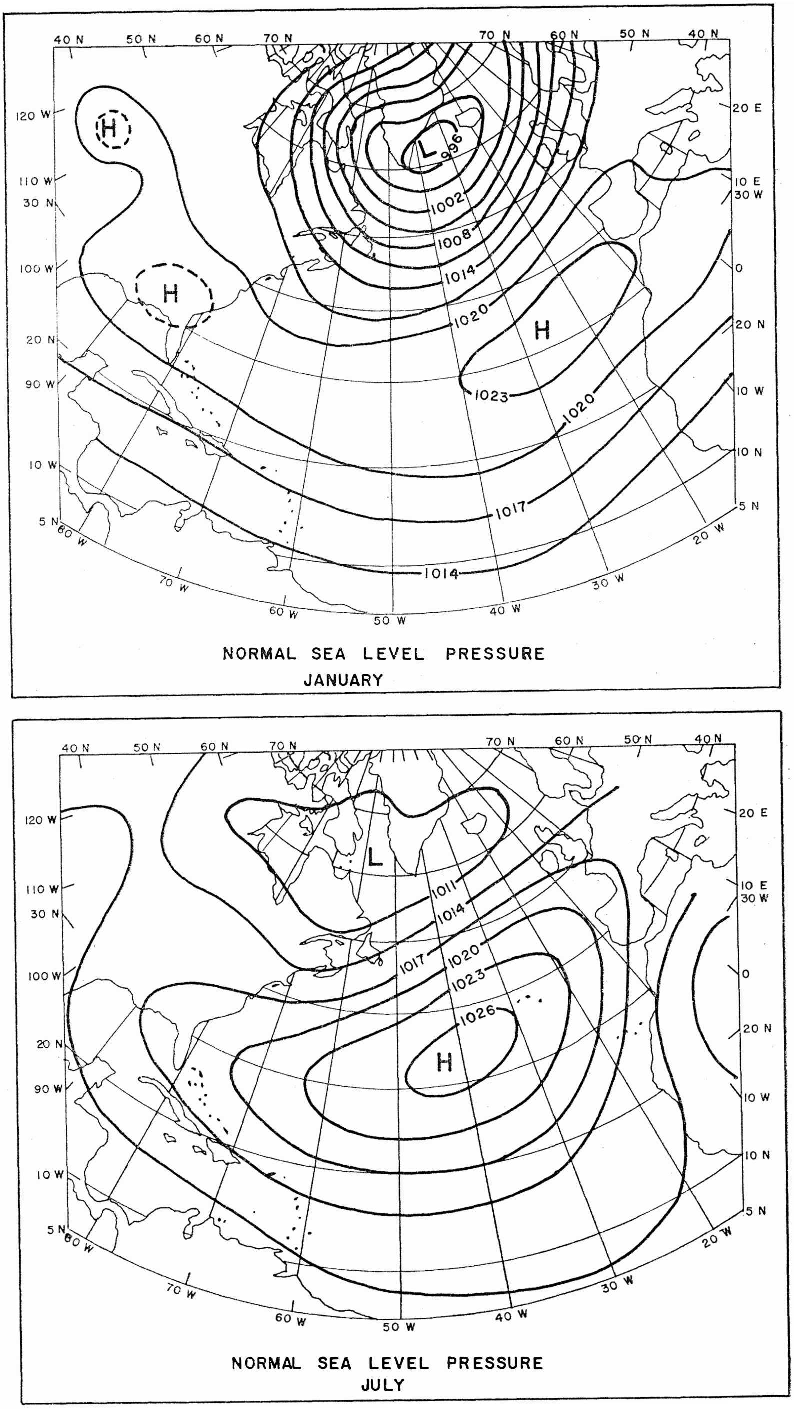
During this period, the Polar Front, representing the southerly extension of polar air, lies in mid-Atlantic, extending eastward and northeastward from Florida towards the northwest coast of Europe, and a well developed Bermuda–Azores High is centered south of Lat. 40°N in the vicinity of the Azores. Low-pressure areas which develop off the southwest coast of the United States move rapidly northeastward with increasing intensity. They tend to reach maximum intensity off Greenland and Iceland thus maintaining the Icelandic Low. The atmospheric circulation is of course strong when this mid-winter weather is well established. In August, the Icelandic Low is weaker, the westerlies are weaker, and the Bermuda–Azores High dominates the atmospheric circulation over much more of the western North Atlantic Ocean. The westerlies in summer are centered about 300 miles further north than in winter. This northerly shift of the wind system is a feature of the change in atmospheric circulation with change of seasons over the North Atlantic Ocean, affecting the northeasterly trade winds as well.

INTERRUPTIONS

The interruptions of the normal pattern of atmospheric circulation by tropical cyclones of hurricane force are, in late summer and early fall, not only spectacular but also, along the Atlantic coast of North America, most destructive at times. North Atlantic cyclones are classed according to zone of origin as tropical or extra-tropical. Many tropical cyclones fail to reach hurricane wind intensities, in which case they are referred to as tropical disturbances. At hurricane wind intensities, they are referred to as tropical hurricanes. A tropical hurricane may therefore be defined as an area of low atmospheric pressure, or a cyclonic storm having its origin and primary development in tropical or sub-tropical latitudes and attaining full hurricane wind velocity in the course of this development. Extra-tropical cyclones have their origin outside the tropics and are typical of winter storms of middle latitudes. They move, almost without exception, in an easterly direction. The tropical cyclones, and particularly the tropical hurricanes, are featured atmospheric disturbances most frequent over the North Atlantic in late summer. The destructive feature of the tropical hurricane is chiefly due to wind-driven currents and waves. While some rise in sea level over the open ocean is produced through reduction of atmospheric pressure, this factor is negligible compared with the wind-driven water and waves which cause flooding and destruction in coastal areas during tropical hurricanes.

As noted, the tropical hurricane has its genesis in the tropics. The storm then moves in a westerly to northwesterly direction generally developing greater intensity as it moves in low latitudes. When the hurricane attains full development it may continue westward and inland at low latitudes. It may re-curve at low latitudes to move eastward into the mid-Atlantic, or it may re-curve only in the vicinity of Florida. This latter type represents a large majority of hurricanes of the strongest and most persistent type, that form during the months of August and September and move eastward and northeastward off the Atlantic Coast. The characteristic track is U-shaped. One branch of the track has its extremity



Normal distribution of sea level pressure in the tropics, and the second branch, running to the east and north, has its extremity in the middle latitudes where the identity of the hurricane as a tropical one is lost.

Conforming Ocean Circulation

The general features of oceanic circulation in the North Atlantic conform closely with the prevailing wind systems associated with the patterns of atmospheric pressure distributions. The ocean currents in the North Atlantic maintained by the stresses of the wind and the density distribution in the sea are contained within the following:

(*a*) the North Equatorial Current which flows from east to west in the region of the Trade Winds,

(*b*) the Gulf Stream System, which includes the Florida Current, the Gulf Stream, and the North Atlantic Current,

(*c*) the East Greenland Current, which with the Iminger Current supplies the energy for the West Greenland Current, and

(*d*) the Labrador Current, which includes the waters received from the West Greenland and Baffin Land Currents.

As we have seen, a wind stress on a level ocean surface in the northern hemisphere produces a water displacement to the right of the wind direction. Consequently in a closed clockwise atmospheric circulation, such as that about the Bermuda–Azores High, the water displacements constitute a convergence towards the center. This convergence is offset by the slope of the ocean surface as the new mass and pressure distributions come to equilibrium. The change of mass distribution can therefore be related to wind stress, and the resulting circulation is therefore looked upon as a wind-driven one. A further adjustment to the final state results from the tendency of the clockwise vortex with its corresponding mass distribution system to move westward, resulting from the changing value of the Coriolis force with changing latitude of northward-moving water. As a result, the center of the clockwise water circulation would be expected to be located further west than the center of the clockwise atmospheric circulation. Since the whole ocean current system is ultimately wind driven, any change in the strength or positioning of the wind system will be accompanied by changes in the strength and positioning of the current. In a closed anti-clockwise atmospheric circulation, such as that about the Icelandic Low, the water displacements constitute a divergence from the center. This divergence is also offset by the slope of the ocean surface as the new mass and pressure distributions come to equilibrium. Any change in the strength will also be accompanied by changes in the current. The current system of the western North Atlantic is therefore closely allied with the wind system, which in turn is dependent upon the relative strengths and positions of the Bermuda–Azores High and the Icelandic Low. We might briefly summarize what might be expected from variations in these two centers of pressure as follows:

(*a*) Intensification of the Bermuda–Azores High would tend to increase the ocean circulation of the Gulf Stream System. The volume transport may or may not be higher, as increased flow may be confined to a contracted portion of the ocean. A contraction of the periphery of the body of circulating water should theoretically cause the northern edge of the Gulf Stream to move southwards. On the other hand a shifting of the position of the Bermuda–Azores High could also shift the whole circulating system north or south. A more active circulation, involving as it does the movement of tropical waters to higher latitudes, would be responsible for greater heat transfers to higher latitudes.

(*b*) An intensification of the Icelandic Low would presumably bring about an increase of the circulation with resultant increase in the flow of the Labrador Current. Increased circulation with the resultant divergence of surface waters would increase the upwelling of deeper waters which might be warmer or colder than the displaced waters, depending upon the time of the year.

INTERACTIONS BETWEEN SEA AND ATMOSPHERE

Climatic Changes

The interactions between sea and atmosphere provide a common field of interest to oceanographers and meteorologists. The passage of the seasons brings changes of water temperatures that in general differ only in amplitudes from those of the atmosphere. The rate of loss or gain of heat by a body of water is however a much slower process than that for air, and the conservative properties of the oceans cause interesting variations in temperature history. In general, the annual maximal and minimal temperatures for a body of water lag behind the corresponding maxima and minima for the atmosphere above, and the annual amplitudes in water are smaller. Continental climate can be a predominant factor in producing large annual variations in sea temperatures. Off the Atlantic coast of North America, the ocean waters, as a result of the prevailing winds, are subjected to the wide fluctuations in air temperatures which characterize the changes of seasons on the North American continent. This dominating effect is lessened by the water transports from more southerly latitudes in the Gulf Stream System, and from more northerly latitudes in the Labrador Current.

During recent years increased atmospheric circulation with rising air temperatures has been observed, and this has been accompanied by increases of water temperatures over vast areas of the oceans. The increase in ocean water temperatures was especially pronounced in the Arctic. In the years 1893–1896 Nansen in the *Fram* Expedition found in the Polar Seas a surface layer more than 650 feet thick and of temperatures between −1.0 and −1.9°C. Below this was a layer of water of Atlantic origin of temperatures greater than 1.0°C. These observations were later confirmed in 1901 by a Russian expedition. Other Russian expeditions between 1927 and 1935, in the same waters between Franz Josef Land and Novaya Zemlya, observed that the cold surface layer was now only 200 to 400 feet thick, and that below this layer the temperatures were between 0.2 and 2.6°C. Rising sea-surface temperatures have been noted along the edge of the Gulf Stream from Cape Hatteras to the tail of the Grand Banks, and this was becoming prominent in the later years of the 19th century. By 1930, the accumulated rise in Gulf Stream temperatures was as much as 2 Centigrade degrees (3.6 Fahrenheit degrees). The warming of the waters in the far northern Atlantic was a feature from 1920 to 1930 in Greenland waters, and from 1920 to 1940 in Iceland and northern British waters. Associated with the increasing water temperatures in the Greenland area was a very pronounced amelioration of climate in Greenland, Iceland and Scandinavia.

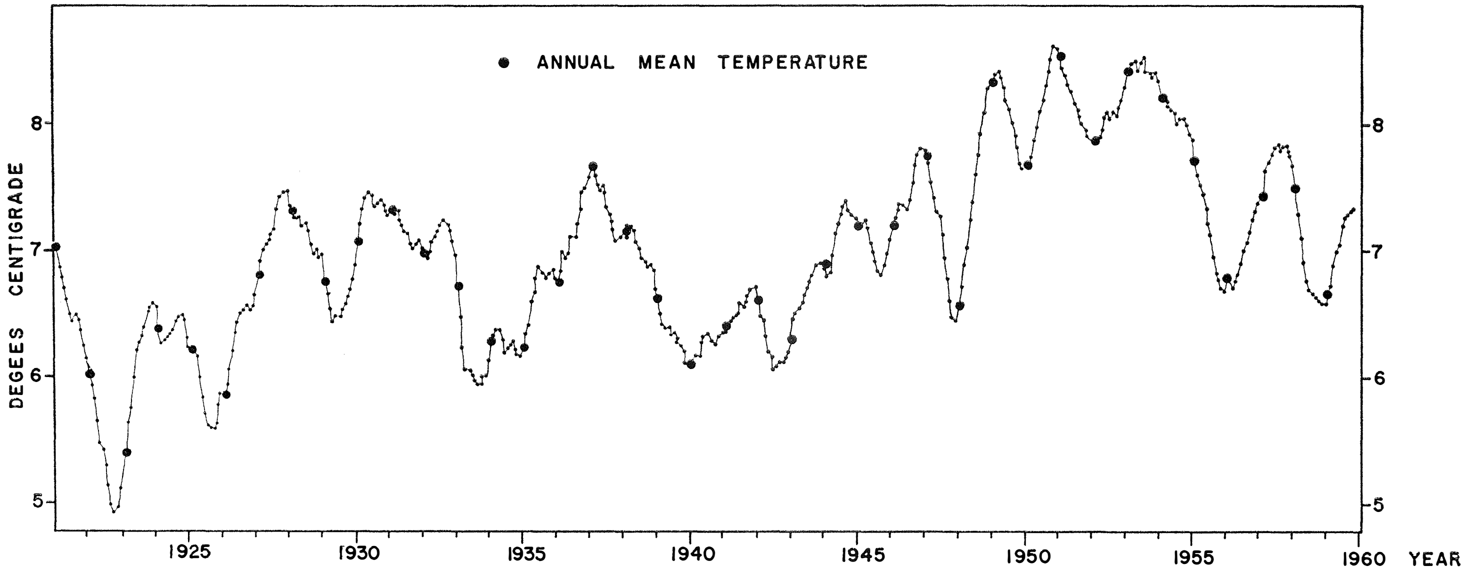
Trends in Water Temperatures

The climatic changes in the atmosphere are reflected in the oceans, and it has been shown that the trend of warming along the Gulf Stream was concurrent with an intensification of the Bermuda–Azores High and increasing westerly winds as far as Lat. 55°N. This logically points to a progressive strengthening of the Gulf Stream with increased transport of tropical waters to more northerly latitudes. During this same period of intensification of the Bermuda–Azores High, there has been a general weakening of the Icelandic Low. A weakening of the Icelandic Low means a lessening of the anti-clockwise wind stress in the eastern North Atlantic. This change in the atmospheric circulation was accompanied, as noted, by increasing surface water temperatures in the eastern North Atlantic. The trend toward increasing surface water temperatures in this area would be furthered by the strengthened Gulf Stream. It would also be aided by decreased upwelling of the colder waters in the eastern North Atlantic due to the decreasing anti-clockwise frictional winds.

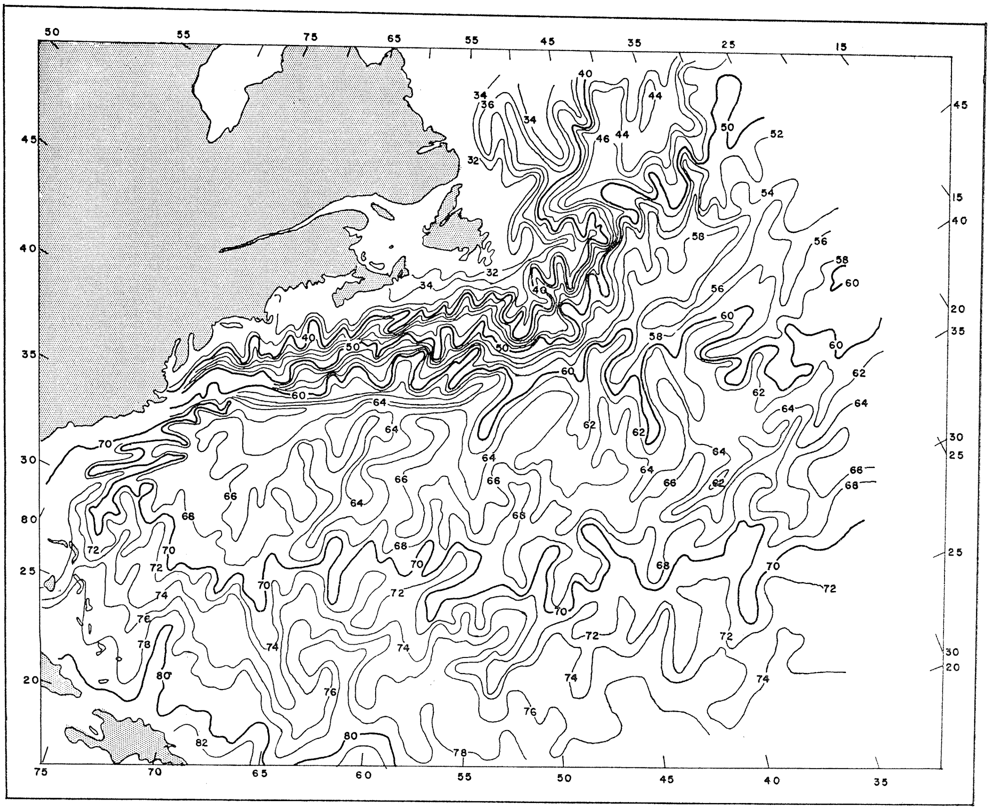
Over the last 40 years, the general trend of water temperatures along the Canadian Atlantic coast has been monitored from a number of coastal stations at which observations were made twice daily, as well as from hydrographic stations which were occupied at regular intervals. Due to strong tidal action in the Bay of Fundy area, the surface water temperatures at St. Andrews, N.B., were found not only to reflect the water conditions in the Bay of Fundy, but also to be indicative of the general surface water temperature trends over a goodly portion of the North American coast. On the basis of the analysis of the St. Andrews data, an upward trend in surface water temperatures was indicated from the twenties to the fifties, with a secondary maximum in the early thirties, and a minimum in the late thirties. The rate of the warming trend was greater in the forties than in the twenties and thirties. A reversal of this trend has been experienced in the last few years. A close correlation has been shown to exist between water and air temperatures, and in extrapolating on this basis, a warming period from 1870 to 1890 has been indicated, with a cooling period for the first two decades of the present century.

Theories of Climatic Changes

The conditions in the atmosphere have both a dynamical and a thermal effect upon the ocean. The essential direct dynamic effect is the creation of wind-driven currents, and convection currents due to variations of precipitation, evaporation, and vertical mixing produced by wind and swell. The direct thermal effect is the heating and cooling by the air in its contact with the water. Indirectly, variations in the transparency both of the atmosphere and of the ocean will evoke variations in the quantity of solar radiation absorbed by the ocean and in the quantity of radiation from the ocean. The direct thermal effect of the atmosphere upon the ocean, due to contact between the two elements, is but small when observed for a brief period. The cumulative effect, however, may be large, particularly in periods of cooling during the winter months in the higher latitudes of the northern hemisphere, when cooling of the surface waters produces downward convection currents to considerable depths.

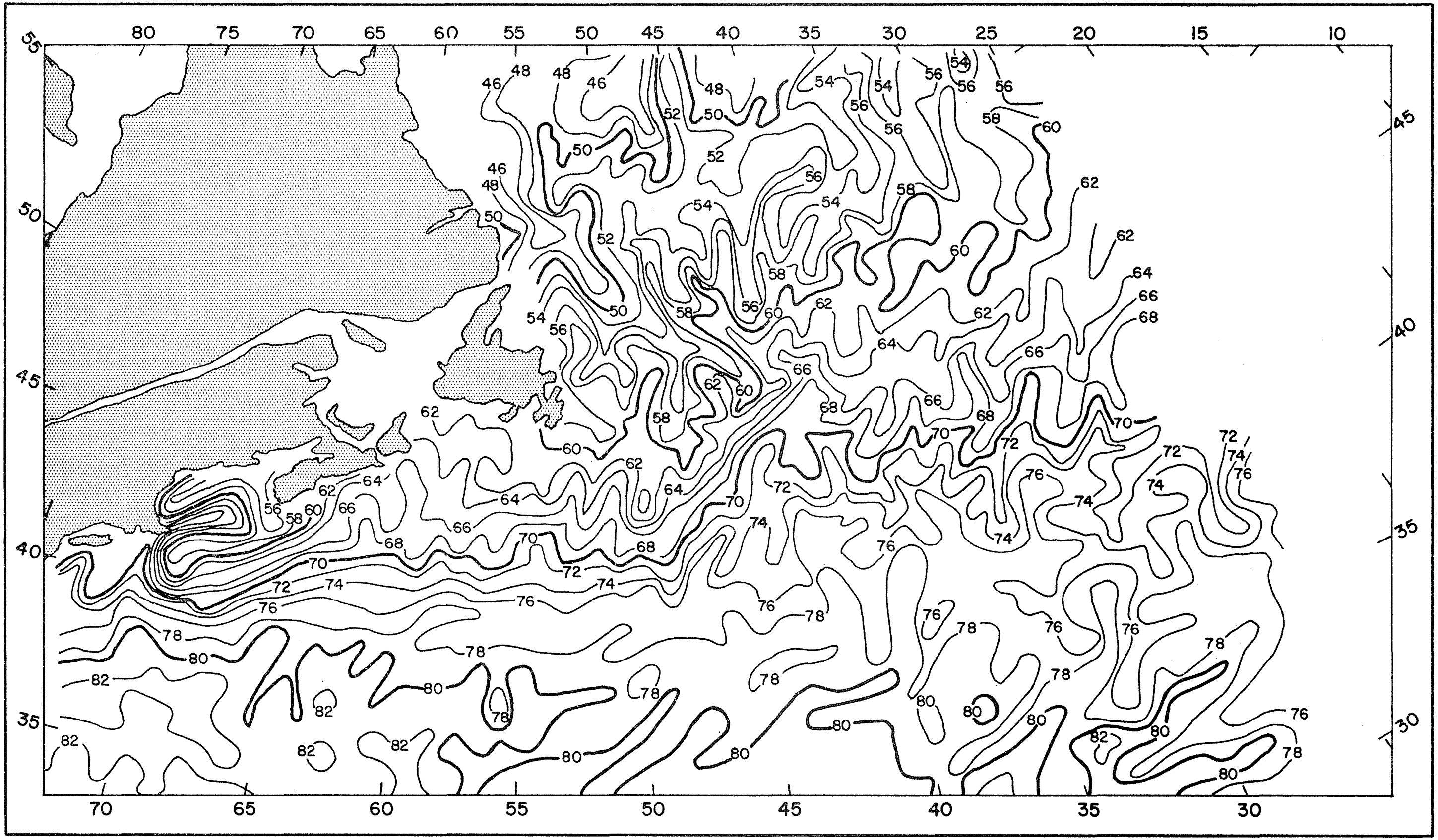


Twelve month running average of surface water temperatures at St. Andrews, N.B.— 1921–1960 (annual averages shown by large dots) (after Lauzier)



Mean sea surface temperature, March 11–20, 1960

Air temperatures immediately associated with the oceans have generally much the same distribution of average temperatures. This points up the direct influence of the ocean upon the atmosphere, as air at the ocean surface readily reacts to the ocean surface conditions. When the ocean surface water temperatures are higher than the overlying air temperatures, heat as well as moisture is transmitted upwards into the atmosphere, and its further transport is dependent then upon the atmospheric circulation. When the ocean surface water temperaatures are lower than the overlying air temperatures, evaporation decreases, and cooling of the air above the ocean surface will be limited to a thin stratum at the interface. In most regions, and over the greater part of the year, the ocean surface waters are warmer than the air, and therefore on the whole the resultant heat and water transfer is from the ocean to the air. Hence the ocean surface temperatures, the air temperatures, the ocean surface salinities, the humidity of the air, and even the amount of cloud, are inter-related. Modifications are introduced by variations in atmospheric circulation, in solar activity, and in the absorption conditions of the atmosphere. It is therefore obvious that the surface waters of the ocean, occupying 70% of the earth's surface, provide one of the fundamental controls of world meteorology.



Mean sea surface temperature distribution for mid-summer 1960

The variations of world climate have been a subject of extended study, and the theories to account for these are based chiefly on considerations of:

(*a*) variations of solar radiations indicated by the sun-spot cycle,

(*b*) changes in atmospheric transmission of solar radiation caused primarily by variable amounts of air-borne nuclear dust, and

(*c*) changes in transmission of longer-wavelength terrestrial and atmospheric radiation caused primarily by changes in the CO_2 content of the atmosphere.

ICE PROBLEMS OFF THE ATLANTIC COAST

Basic Knowledge

The ice encountered off the Atlantic coast of North America is in part drifting ice from arctic regions, and in part ice formed locally. In total it constitutes an item of considerable international and national interest as it presents hazards to transatlantic shipping, creates problems of supply in arctic and sub-arctic regions, and to a large extent decreases the otherwise great natural advantage of Canadian Atlantic ports in overseas and coastwise shipping.

The arctic ice has its origin in the great cap of heavy ice that lies over the north polar region of the earth. This great polar ice cap covers 1,800,000 sq. miles of the sea. Throughout the year, the East Greenland Current, the West Greenland Current, the Baffin Land Current, the various flows through the islands of the Canadian Archipelago, the outflow from Hudson Bay and Foxe Basin through Hudson Strait, the Labrador Current, and the outflow of the Gulf of St. Lawrence through Cabot Strait, carry the broken ice and icebergs to lower latitudes. Every year hundreds of square miles of ice travel as much as 1500 miles, reaching as far south as Lat. 40°N, and extending westward as far as the southwestern tip of Nova Scotia. The lowest position recorded for an iceberg in the North Atlantic was Lat. 39°18′N, Long. 48°30′W, on May 25th, 1923.

Of all the ice forms that originate in the polar pack, the iceberg is the most spectacular. Greenland produces somewhere between 10,000 and 15,000 bergs every year. Actual count through air reconnaissance in 1948 gave a total of more than 40,000 bergs in Davis Strait, Baffin Bay, and the Labrador Sea. In 1940, the count approximated 12,000. Due to their massive proportions these icebergs sometimes survive long journeys, and those reaching south of Lat. 48°N constitute the greater menace to transatlantic shipping lanes. The number of bergs that reach the sea area south of the above latitude varies considerably from year to year. The total count was more than 1300 in 1929, and practically zero in 1958. The number of bergs reaching the tail of the Grand Banks is determined by a variety of factors, among which the more important are:

(*a*) the number of bergs calved from the glaciers,

(*b*) the number of bergs stranding on the Labrador coast on their southward journey,

(*c*) the amount of melting during the southward journey, and

(*d*) the mortality of the bergs on their journey south.

The general average travel time of a berg from the time of calving until arrival at the tail of the Grand Banks is 3 years.

Pack ice is defined as any sea ice that has drifted from its original position under the influence of winds and currents. Ice of this nature streaming southward from the arctic regions is most voluminous and extends furthest southward during spring and early summer and shrinks towards its sources during late summer and early fall. Pack ice invades the North Atlantic along the eastern side of Greenland and the eastern side of North America. Much of the pack ice originates in the more southerly corner of Foxe Basin, Hudson Bay and Strait, the Labrador and Newfoundland coasts, and the Gulf of St. Lawrence.

Our knowledge relative to the regional distribution of the ice on our Atlantic coast, its state, its behaviour, its direction and rate of drift, has been accumulated over a long period of years. The ice that reaches the transatlantic shipping lanes has been a matter of intensive scientific study. Problems of particular Canadian concern, however, relating to the Gulf of St. Lawrence and the Canadian Arctic and sub-Arctic, are only in recent years receiving attention as national problems of considerable importance.

Current and wind systems in the western North Atlantic are the main factors determining the transportation of pack ice. In turn the distribution of pack ice is a factor that controls to some degree the southerly transportation of icebergs. When the pack ice is concentrated along the Labrador and Newfoundland coasts, it acts as a cushion, preventing the drifting icebergs from grounding in the shallower areas. It is thus not surprising to find that the number of icebergs that menace the shipping lanes south of Newfoundland is, in any year, closely related to the abundance of pack ice which blockades the Labrador and Newfoundland coasts.

The International Ice Patrol

As noted earlier, the tragic loss of the *Titanic* on April 14th, 1912, led to the establishment of the International Ice Patrol. The responsibility for the patrol was assigned to the U.S. Coast Guard in 1913, and except for some interruptions during World Wars I and II, the patrol has not only provided valuable service to shipping in the ice-infested waters of the western North Atlantic but has carried out over nearly half a century a scientific program designed to increase our knowledge of arctic ice.

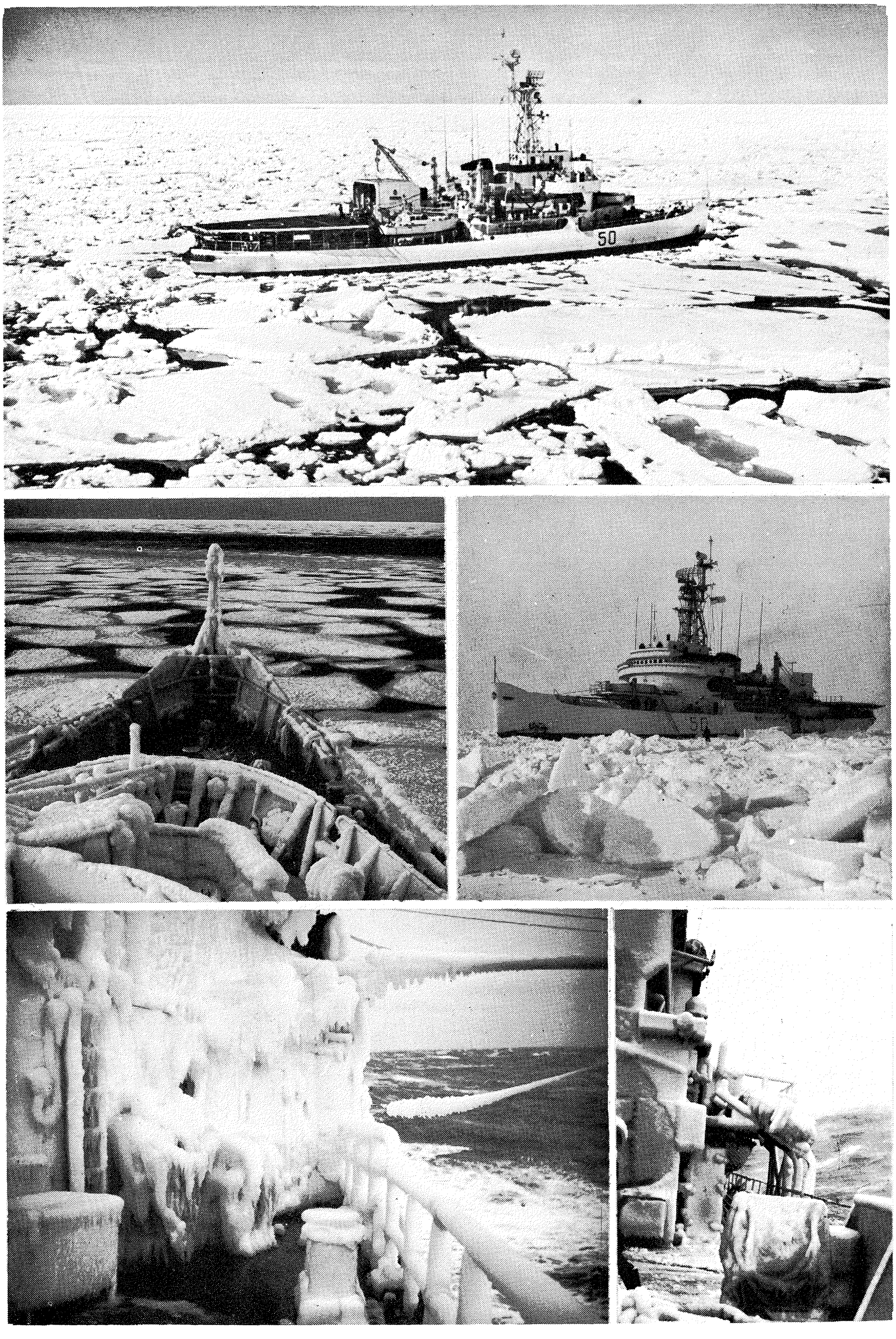
The International Ice Patrol was set up primarily to:

(*a*) assess the locations and the progressive movements of icebergs and field ice in the vicinity of the Grand Banks of Newfoundland,

(*b*) disseminate information on icebergs and field ice for the guidance and warning of navigators, and

(*c*) make such oceanographical and meteorological observations as will contribute towards our knowledge of ice and icebergs.

Over the years, it has been well established that water masses from the north, carried southward in the Labrador Current, flood the northern part of the Grand Banks. Here the current branches into two. A western branch contains those arctic waters which, flooding over the continental shelf, swing to the right, penetrating westward along the south coasts of Newfoundland and Nova Scotia. An eastern branch consists of the offshore waters which, following the bottom



Ice on the Atlantic coast

(RCN photos)

so that a cold water salient extends southeasterly as far as Lat. 41°N. An apparent weakening of the Labrador Current may cause a retreat of Labrador waters northward. An intrusion of Gulf Stream waters between the 44th and 45th parallels of latitude on the east side of the Grand Banks is a feature of the circulation during the early summer months. The system of circulation at the junction of the Labrador and Atlantic Currents is generally complex.

The volume of flow of arctic waters southward varies considerably from year to year. As measured in a section off Wolf Island, Labrador, it has been as low as 46×10^6 ft³/sec in 1931, and as high as 360×10^6 ft³/sec in 1957. The average value is 170×10^6 ft³/sec for mid-July. The mean temperatures of the waters of the Labrador Current, as measured in this same section, have varied from a low of 1.3°C in 1936 to a high of 3.4°C in 1933, with a mean value of 2.4°C for mid-July. It is therefore obvious that the amount of heat transport undergoes considerable annual variation. The "cold wall" is a term used to define the region where cold water—either that of the Labrador Current or that of the "slope water"—comes in contact with the waters of the Gulf Stream and its extension in the Atlantic Current. In the region of the tail of the Grand Banks, it has been found convenient to define the position of the "cold wall" as the horizontal projection of the line of intersection of the isothermal surface of 6°C and the isohaline of 34.95‰. This "cold wall" in the neighborhood of the tail of the Grand Banks is subject to considerable variation in position due to the varying relative strengths of the Labrador and Atlantic Currents.

The area encompassed by the 49th meridian between Lat. 42 and 45°N, the 45th parallel extended eastward to meet the "cold wall", the extension of a line to the "cold wall" through points 43°N 49°W and 42°N 47°W, and the cold wall itself, has proved to be an area of considerable value in a study of the relative importance of the two great currents which meet here in relation to ice and iceberg distributions. As has been indicated earlier, it may be assumed that a weakening of the circulation of North Atlantic waters as indicated in the Gulf Stream System is associated with a contraction of the northern boundary of the Gulf Stream System, this northern boundary being termed the "cold wall". Further, weakening circulation of the North Atlantic waters, and contraction of the boundary, would affect the peripheral currents that are fed by the main circulatory system. Among these is the Irminger Current, which is a re-curving of Atlantic waters to the westward in the vicinity of Iceland. This Irminger Current represents the contribution of Atlantic waters to the West Greenland Current. Observations of the West Greenland Current off Cape Farewell have been made during many summertime occupations of a section extending from Cape Farewell to the Labrador coast. These include six of the eight years 1934–1941, and each of the four years in the period 1948–1951. The Irminger Current component of the West Greenland Current was subnormal in 1948 and almost totally absent from this section in each of the three subsequent years. These results are in general agreement with indications of a contracted and weakened Gulf Stream System in this period.

In monitoring changes in the strength of the Gulf Stream System, it has been assumed on good theoretical grounds that these changes are proportioned to changes in the difference in sea level between Bermuda, and Charleston, South Carolina. To date, the attempts to correlate the fluctuations in sea level between Bermuda and Charleston with the shifting of the "cold wall" in the region of the tail of the Grand Banks has led to some anomalies which require further consideration. However, some promising suggestive results have been obtained.

FORECASTING ICE

Modern hydrodynamic methods of mapping currents were introduced into the oceanographic procedures adopted by the U.S. Coast Guard 35 years ago, and these methods have proved to be of value in forecasting the drift of icebergs after they reach the tail of the Grand Banks. The success attained in this field led to considerations of methods of forecasting the number of bergs expected to reach the tail of the Grand Banks in any one year. There followed a study of the possible relationships between pack ice, icebergs, currents and meteorological events.

With a given amount of pack ice in the north, the amount drifting south is, other things being equal, dependent upon the water transport and wind action. Offshore winds tend to broaden and scatter the floes, while onshore winds tend to narrow the ice field and pack it against a coast.

As noted, in the North Atlantic, and controlling the weather in the ice regions, we have three great centers of action, triangularly situated and with their relative conditions determining the consequent behaviour of the air:

(*a*) the Icelandic Low,

(*b*) the Bermuda–Azores High, and

(*c*) the continental effect of bordering land areas.

In summary, it was reasoned that the prevailing direction of the winds over the Labrador–Greenland region, when expressed in terms of departures from the normal, and considered in monthly periods, would be reflected some time later in the variation from normal in the amounts of ice. As a relation was indicated between the amount of ice and the number of icebergs reaching the tail of the Grand Banks, an initial formula of the following type was derived:

$$X = 4.8 - 0.08\ C - 0.12\ D,$$

where X is the number of icebergs reaching the area south of Lat. 48°N, expressed in values between 0 and 10,

C is the pressure difference in millibars between Belle Isle and Ivigtut, and

D is the pressure difference in millibars between Slykkisholm and Bergen.

It will be noted that this formula takes no account of the amount of ice or the number of icebergs available for transport. The results from the use of the formula have shown promise but there has been at least one outstanding anomaly. With the counts of icebergs now made annually through air reconnaissance, and with critical analysis of the theory, it will be interesting to see what results may be obtained through modification of existing methods.

Ice in the Gulf of St. Lawrence and on the Outer Coast

Newfoundland acts as a barrier separating the Gulf of St. Lawrence ice from the main pack of arctic ice moving southward in the Labrador Current. Some of this arctic pack ice and even small icebergs and growlers penetrate into the gulf at times through the Strait of Belle Isle. The amount getting in depends on the dominant flow through the strait, also on the pressure exerted by the main pack, and these factors vary. In general the greater part of the pack ice found in the gulf during the winter months is of local origin, the extent of the ice coverage depending upon the severity of the winter and the heat budget of the waters in the months preceding the winter. The heat budget in turn is dependent upon the meteorological condition that prevailed previous to freeze-up.

The climate of the Gulf of St. Lawrence region is influenced mainly by air that moves from land to sea. This continental air is modified to some extent as it moves towards and over the coastal area. During the winter months the air isotherms tend to run northeast–southwest across the gulf. With air so moderated by the open Atlantic, temperatures in the Cabot Strait area are generally about 5.6 Centigrade degrees (10 Fahrenheit degrees) higher than those at Quebec. This winter air temperature situation is of course reflected in the dates of freeze-up of various harbours and bays. Generally in the open Gulf of St. Lawrence, water temperatures have been lowered sufficiently by January to give rise to large-scale production of ice.

Prevailing winds in the Gulf of St. Lawrence in the winter are from the west and northwest. Such winds tend to move ice from the western gulf to the Cabot Strait area. Wind direction and velocity, and sustained wind mileage are important factors in determining movement and distribution of ice in the gulf. Winds from the west will tend to drive the gulf ice seaward through the strait. Northerly winds would have much the same effect. Winds from a southerly direction oppose movements of ice out of the gulf, while winds from the northeast and east pile the flows into the southwestern gulf.

As noted, the amount of ice that moves into the Gulf of St. Lawrence through the Strait of Belle Isle is controlled in part by the dominant flow in the strait, which can be inward or outward. Probably the pressure exerted by the ice pack of the Labrador Current is a more important factor at times. In any event, the ice that forms in the Strait of Belle Isle, together with the heavy ice entering it from the Labrador Current, moves into the gulf at times. That which works its way westward along the north shore of the gulf extends at times as far as Anticosti Island. Ice also tends to work its way down the west coast of Newfoundland. A few small icebergs and growlers may be contained within the pack ice from the Labrador Current. This ice is shifted about the gulf through the winter months.

Pack ice begins to move outwards through Cabot Strait in January. While generally light and scattered at this time of the year, in severe ice years it can be heavy and packed, and extend outwards a considerable distance. In February, a general steady outward movement of ice is under way through Cabot Strait. The Cabot Strait outflow of ice is compensated for, at least in part, by inflows from the St. Lawrence River estuary, from the Strait of Belle Isle, and from areas of local freezing. The real break-up season is in March and April. The progress of the pack ice as it leaves the Gulf of St. Lawrence is usually southwest and south towards Sable Island. It may also spread eastward along the coast of Newfoundland, and in conjunction with ice moving from the eastward can form an almost continuous mass. Westward it sometimes extends past Sable Island even to the southwestern tip of Nova Scotia.

In the lighter ice years, the western coast of Newfoundland is generally quite free of ice. The freeze-up of harbours and bays is always delayed in relation to the western side of the Gulf of St. Lawrence. Light ice years have at times offered considerable opportunity for early navigation in the open gulf, and to harbours on the west coast of Newfoundland, the north shore of the gulf, and even into certain ports in the Bay of Chaleur and the Port of Quebec. The heavy ice years offer challenging problems to winter navigation in the gulf. The industrial developments in the northern gulf areas in recent years have directed attention to the requirements for winter navigation and studies are now directed to methods of dealing with the problem.

OCEANOGRAPHIC ENVIRONMENTS

Hudson Bay and Strait

In extent, Hudson Bay is an inland sea. Its area is about 200,000 sq. miles with an average depth of about 50 fathoms and a maximum depth of about 125 fathoms. Characteristically, Hudson Bay is an estuary, as indicated by the intense salinity stratification in summer in the upper 12 fathoms of water. Surface salinities in the open bay may be as low as 23‰, and salinities at 12 fathoms less than 31‰, with this intensity of stratification decreasing from James Bay to open waters of Hudson Strait.

During the winter months, Hudson Bay is almost completely ice covered. In summer, surface water temperatures may reach 10°C in the open bay. Below 25 fathoms, water temperatures are lower than −1.0°C throughout the year. Salinities may exceed 33.0‰ at 100 fathoms. The general circulation is anti-clockwise. The bottom consists of mud, sand, stones and large boulders.

Labrador and Grand Banks

As has been noted earlier, the waters of the Labrador Current represent the outflow from the Arctic Basin, the greater part of which is carried to the Labrador Current through the West Greenland Current. The Labrador Current flows southward along the Labrador coast with its axis along the continental slope, the colder waters being on the coastal side of the axis. While some of this water enters the Gulf of St. Lawrence through the Strait of Belle Isle, the major portion continues southward and completely floods the northeastern part of the Grand Banks. One branch of the current sweeps southwestward around Avalon Peninsula, while another continues southward. The tail of the Grand Banks is an area of confluence of the two great current systems of the North Atlantic, and here are found great contrasts in oceanographic conditions.

The mass of irregular banks to the south of Newfoundland, which constitute the Grand Banks, are literally flooded with the cold water of northern origin. Although the depths on these banks average about 30 fathoms, there are many areas near the land with depths greater than 100 fathoms.

The temperature of the sub-surface waters of the colder inshore section of the Labrador Current is generally less than −1.0°C, and water of this temperature may occupy the greater portion of the Labrador Shelf. The temperature of the waters of the outer section of the Labrador Current is generally not much greater than 3.0°C. Salinities in the Labrador Current range from less than 30.0‰ to 34.8‰. Waters of the Labrador Current, flooding the shelf and slopes of the North American coast, extend as well over the Grand Banks of Newfoundland. On the south and western slopes of the Grand Banks, incursions of slope water introduce waters of temperatures as high as 10°C. The strength of the

Labrador Current varies between wide limits, and from the fisheries point of view, a weaker Labrador Current, supplying less than normal quantities of colder waters, provides temperature conditions more favourable to certain groundfish.

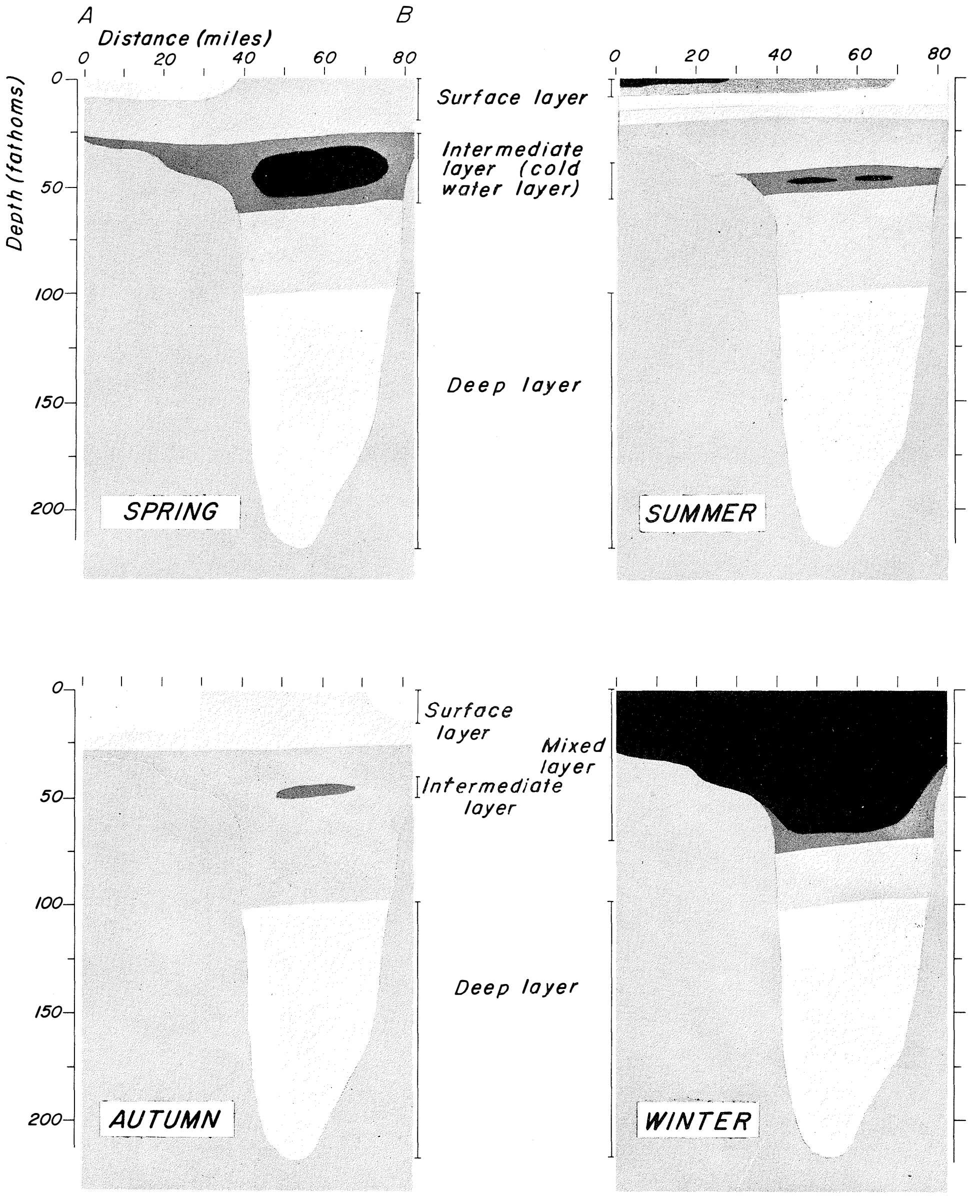
Gulf of St. Lawrence

The Gulf of St. Lawrence comprises an area of approximately 57,000 sq. miles with two main openings to the ocean, Cabot Strait and the Strait of Belle Isle. From the St. Lawrence River system, the gulf receives the drainage of approximately 500,000 sq. miles.

The main features of the submarine physiography are the Laurentian Channel, the Esquiman Channel and the Magdalen Shallows. The Laurentian Channel is a deep trench, with a maximum depth of 250 fathoms, extending from the edge of the continental shelf almost to the Saguenay River. The Esquiman Channel, branching off from the Laurentian Channel, extends from the central portion of the Gulf of St. Lawrence northeastward towards the Strait of Belle Isle. It is more than 100 fathoms deep except as it approaches the strait. To the west of the Laurentian Channel is the shallower area of the Magdalen Shallows. One-quarter of the gulf area is shallower than 25 fathoms while less than one-fifth is deeper than 150 fathoms. Cabot Strait connecting the gulf to the open ocean is 60 miles wide, and with the depths of the Laurentian Channel. The Strait of Belle Isle is only 10 miles wide at its narrowest point, and here the depth does not exceed 12 fathoms.

One of the most interesting oceanographic features of the Gulf of St. Lawrence is the surface layer. This layer is most readily delimited by the top of the thermocline which is fully developed by late summer. Thus outlined is a layer of water which is practically homogeneous as to temperature and salinity. The thickness of this surface layer can be as much as 30 fathoms, the depth at any one time and place depending upon factors such as radiation, precipitation, evaporation, distribution of atmospheric pressure, and winds. The water temperatures in this layer range from a minimum of −1.8°C to 20.0°C and higher. In the open gulf salinities range between 26.0 and 32.0‰. Lowered salinities are encountered in the various bays and estuaries.

In this surface layer, we find that the salinities in the southwestern portion of the Gulf of St. Lawrence decrease with progress of the summer season. Associated with these decreasing salinities is a thinning of the surface layer which occurs with the establishment of a stronger vertical temperature gradient in the thermocline. As the increasing vertical temperature gradient is accompanied by increasing stability, vertical mixing is to some extent confined to an ever-thinning surface layer with the progress from spring to summer. Hence, the waters of the continental drainage, even though lessening in volume, are seemingly more effective in lowering the salinity during the summer months. The physical processes involved in the growth and decay of this surface layer and the paradoxical decrease in salinity offer an interesting environmental study relating to plankton and fish larvae distributions.



Water layers — the Gulf of St. Lawrence (after Lauzier)

The "intermediate" or "cold water" layer, defined as the layer of water of temperatures less than 0.0°C during the warmer months of the year, is found throughout the Gulf of St. Lawrence under the thermocline. The associated salinities of the water are between 32.0 and 34.0‰. The thickness of this layer varies from 15 to more than 50 fathoms. Seasonal variations are quite prominent, a decrease in thickness occurring between spring and autumn.

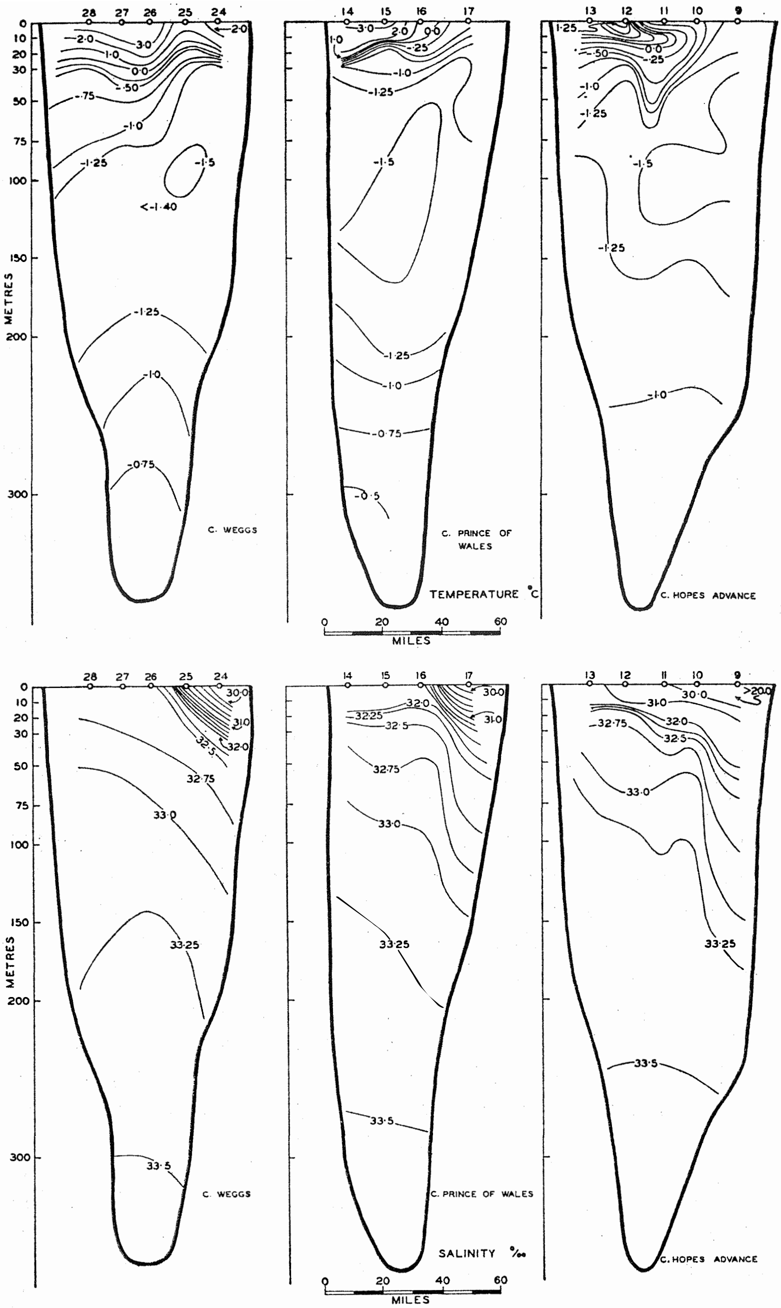
Underlying this "cold water" layer is a comparatively warm deep layer, with temperatures as high as 5.6°C and with salinities greater than 34.0‰. The volume of this water increases between spring and autumn and there are annual variations in volume as well. Long-term variations in the temperature and volume of this deep layer have been recorded. Increases in temperature were associated with the observed increases in volume. These deep waters in the Gulf of St. Lawrence, found chiefly in the Laurentian Channel, are a mixture of Labrador water and slope water. Fluctuations in the temperature of Labrador water are reflected by corresponding temperature fluctuations in the deep layer.

A persistent feature is the constancy of the proportion of Labrador water in the core of the deep layer. The general inward direction of flow in the deep layer in Cabot Strait indicates that there is an almost constant contribution to the Gulf of St. Lawrence at the greater depths.

The southwestern area of the Gulf of St. Lawrence, which is termed the Magdalen Shallows, constitutes an environment of considerable biological interest. Tidal amplitudes are comparatively small, and the fetch of southerly and westerly winds is minimized by the long coastlines of New Brunswick and Nova Scotia. Due to its shallowness, summer insolation produces water temperatures comparatively high for such latitudes on the North Atlantic coast. Winter water temperatures are extreme, and most of the area is closed in winter with fast or drifting ice. At depth a gradually sloping sea floor makes contact with the "intermediate" or "cold water" layer as well as with the surface layer. In summer therefore, temperatures along the sea floor range from less than 0.0°C to 20.0°C and higher. Depending on the slope of the sea floor, internal adjustments of water layers, associated with atmospheric disturbances, bring about sharp and intensive variations in temperature. It is obvious that organisms which cannot tolerate such sudden changes in temperatures will not form an important group in the populations in certain areas of the southwestern gulf.

While the prolific fisheries of the Gulf of St. Lawrence are known, the fundamentals of the primary productivity in this area have been little studied. It is considered that the primary productivity of the surface layer in spring is high, the potential being built up over the long winter with ice cover, and supplemented by the inflow of water and ice of northerly origin. There are many general observations to support such suggestions.

In summary, attention is drawn to the great variety of environments in this area, both in the horizontal plane as well as in the vertical.



Top: Temperatures in section—Hudson Strait
Bottom: Salinities in section—Hudson Strait

SCOTIAN SHELF

The Scotian Shelf is that area bounded on the north by the outer coast of Nova Scotia, on the east by the deep Laurentian Channel, on the south by the edge of the continental shelf, and on the west by the Fundian Channel which separates Georges Bank from the Nova Scotia banks. The depth of water on the Scotian Shelf is generally less than 100 fathoms. The Laurentian Channel is from 100 to 300 fathoms deep, the Fundian Channel is from 100 to 200 fathoms deep, and off the edge of the continental shelf the depths rapidly increase to over 1000 fathoms. The more important offshore elevations of this Scotian Shelf are Sable Island, and Sable Island Bank, as well as Browns, Roseway, La Have, Emerald, Sambro, Middle, Banquereau, Canso, and Missaine Banks. Inshore, numerous small banks and ledges form other irregularities of the sea floor. The nature of the bottom ranges from fine sand and gravel to rocks and mud, the softer mud bottom generally being confined to the greater depths.

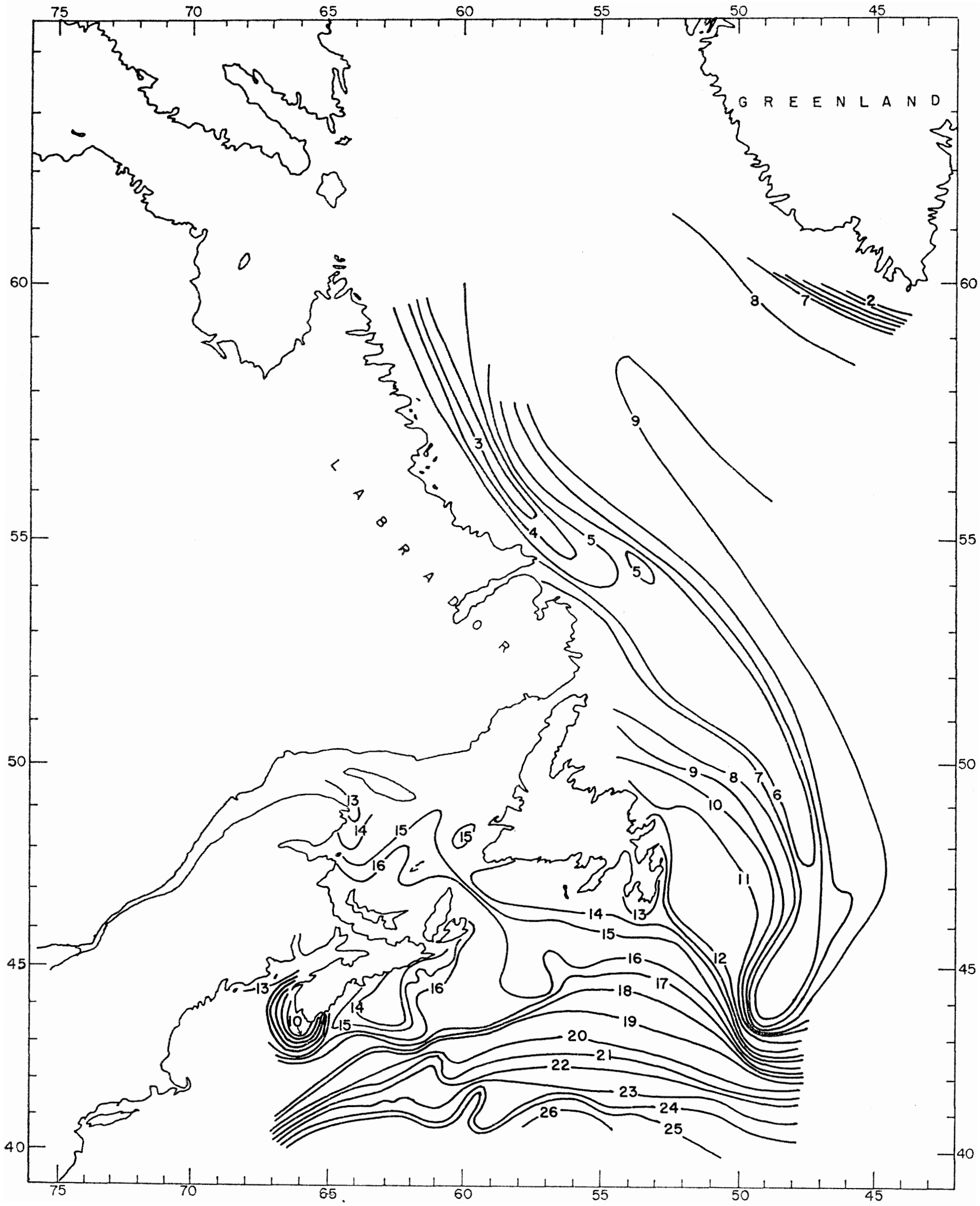
In summer the waters of the Scotian Shelf are strongly stratified as to temperature and salinity, and may readily be described according to layers. The upper layer, which may be as much as 40 fathoms thick, has temperatures greater than 5°C and as high as 20°C. The salinity is less than 32.0‰. At the height of summer the temperature stratification is particularly high. Inshore the waters consist wholly of this "upper layer" and as the inshore thickness varies considerably with atmospheric disturbances, there are extensive variations in bottom water temperatures.

The "intermediate layer", which varies between 17 and 80 fathoms in thickness, has temperatures less than 4°C and as low as 0.0°C. The salinity is between 32.0 and 33.5‰. This water layer determines the water characteristics on the majority of the offshore banks.

The "bottom layer", which is located at depths between 50 and 110 fathoms, has water temperatures higher than 5°C and normally as high as 8°C. At times, incursions of slope water over the Scotian Shelf may introduce bottom water temperatures as high as 12°C. The salinity of the waters of the "bottom layer" is greater than 33.5‰ and as high as 35.0‰.

Probably the most important feature of the waters of the Scotian Shelf is the cold "intermediate layer" of temperatures less than 5.0°C. The presence of this cold water on the shelf is due chiefly to volume transport of water from the east and northeast, and "winter chilling in situ" is a negligible factor in its production. It would appear that this layer is continuous, at least during part of the year, with the similar feature in the Gulf of St. Lawrence, and which has shown to be formed, at least in part, by "winter chilling in situ". The thickness of the "intermediate layer" on the Scotian Shelf has undergone considerable variation over the past 30 years. This layer was noticeably colder and thicker in the periods 1932–37 and 1955–59 than it was in the period 1949–51, probably reflecting to some extent anomalies in the climate of eastern Canada.

The slope water off the Scotian Shelf forms a well-defined band between the typical coastal waters on the shelf and the Gulf Stream. Its northern boundaries



Surface temperatures, August 1950 (after Bailey)

fluctuate widely with no apparent systematics, sometimes transgressing upon the shelf. The composition of slope water is Atlantic water diluted by approximately 20% of coastal water. It has a general eastward movement away from the areas of formation. Characteristic salinities of slope water fall between 33.0 and 33.5‰. Temperatures are generally greater than 5.0°C and as high as 20.0°C.

The general circulation pattern on the Scotian Shelf is anti-clockwise, with a southwesterly drift along the coast of Nova Scotia, and a northeasterly drift along the edge of the continental shelf. The average rate of drift is approximately 0.15 knot.

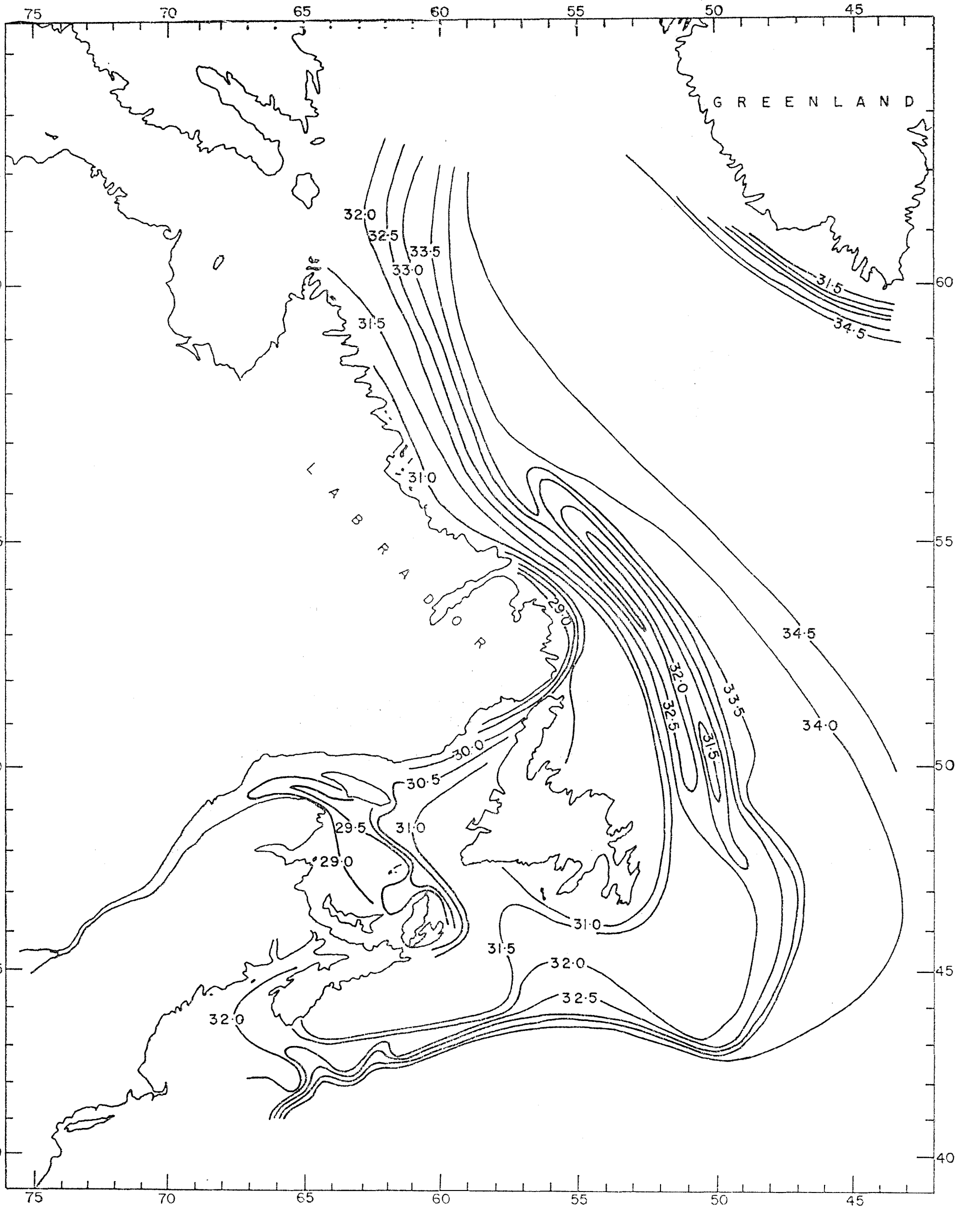
Gulf of Maine

Cape Sable on the southwestern tip of Nova Scotia, and Cape Cod jutting out from the eastern coast of the United States, are configurations of the coast line which delineate what has been termed the Gulf of Maine. The submarine topography of this area outlines a submarine gulf of depths greater than 50 fathoms, and whose boundaries are the Scotian banks on the east, Georges Bank on the south, and the shallower areas of the continental shelf on the north and west. The Fundian Channel, of depths greater than 100 fathoms, is the opening of the submarine gulf to the open ocean. The Gulf of Maine encloses typical coastwise water of the northwestern North Atlantic. Slope water of a salinity of approximately 35‰ and of temperatures between 6.0 and 8.0°C flow intermittently into the Gulf of Maine at the greater depths. A large volume of comparatively cold and low-salinity water penetrates into the Gulf of Maine from the eastward past Cape Sable chiefly in spring. A surface drift composed of varying proportions of intermediate water of the Scotian Shelf, slope water, and tropic water of the Gulf Stream also enters the Gulf of Maine. The tidal currents in this gulf are strong enough to cause active mixing of the waters, and this mixing is particularly enhanced in its northeastern part. In the southwestern part, the continental drainage and weaker tidal action allow for a progressive development of a temperature and salinity stratification.

Bay of Fundy

The outstanding oceanographic features of the Bay of Fundy are associated with the tidal phenomenon in the area. The tidal phenomenon is basically of the stationary-wave type. The combined action of a stationary wave and the progressive tidal wave, coupled with the funneling effect due to the physical features of the area, is responsible for the phenomenally large tides of the Bay of Fundy. Covering an area of some 6,000 sq. miles, the mouth of the bay is about 85 miles wide, gradually narrowing toward the head. The average depth is about 275 feet, with the depths decreasing toward the head from a maximum of approximately 1000 feet at the mouth. At Cape Sable on the southwestern tip of Nova Scotia, the mean range of the tide is 9.1 feet while at Noel Bay in Minas Basin it is 44.2 feet. During spring tides, the range at Noel Bay is approximately 50.5 ft. The nature of the bottom varies from mud, sand and stones to ledges and rock.

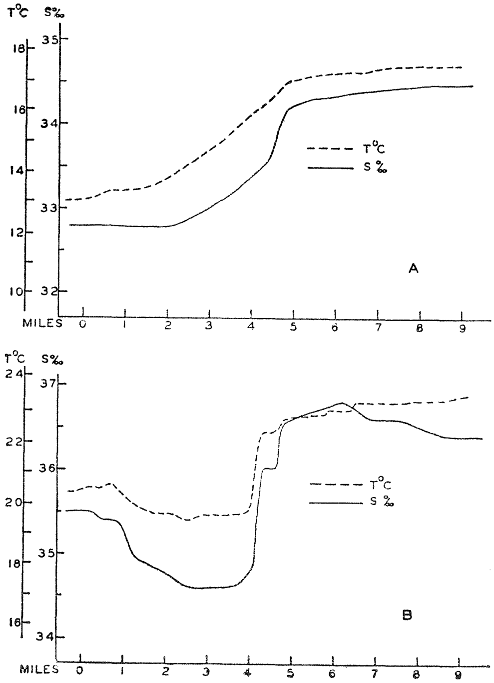
Tidal action brings about mixing of the waters of varying characteristics which are transported to the area. This mixing modifies the normal annual temperature and salinity ranges, as summer temperatures are subnormal for such latitudes along the North American coast, and winter temperatures are above normal. The water column in the greater part of the Bay of Fundy is compara-



Surface salinities, August 1950 (after Bailey)

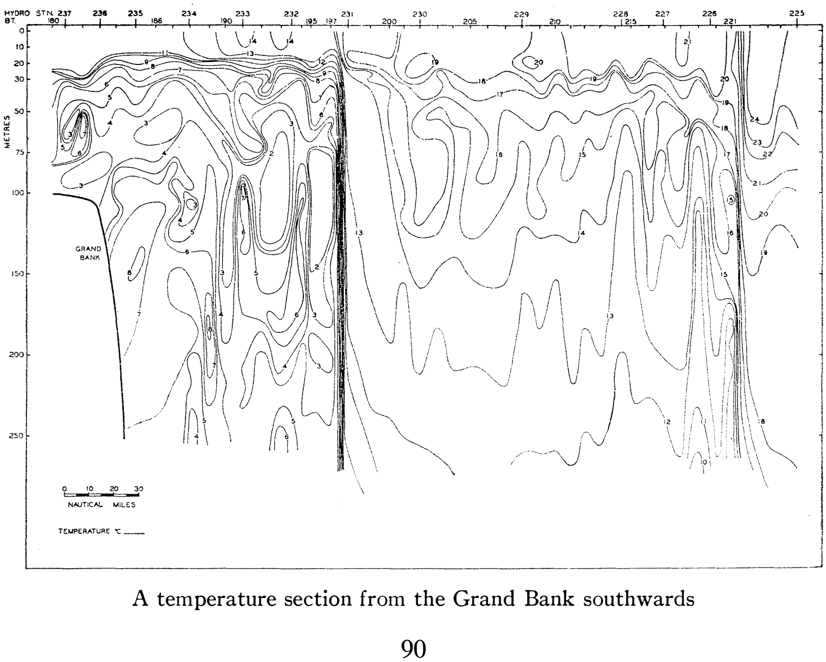
tively uniform in temperature and salinity. The tidal mixing also contributes to the opacity of the water, and this opacity is an important limiting factor in the productivity of the waters in the area.

The large tidal amplitude creates an intertidal zone which in some areas because of a gradually sloping sea floor is several miles in width.

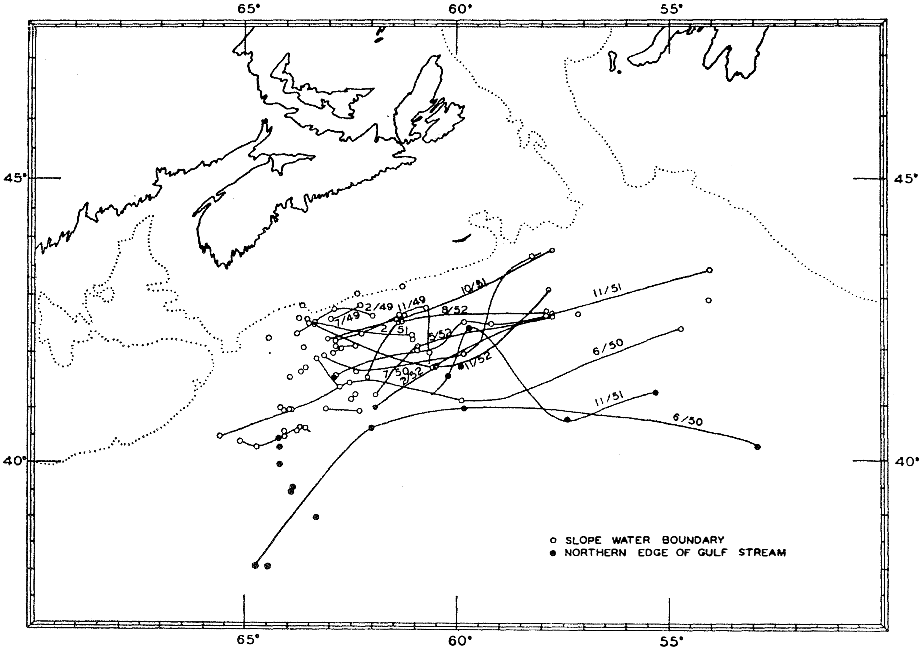


A. The changing surface temperature and salinity, passing from coastal to slope water

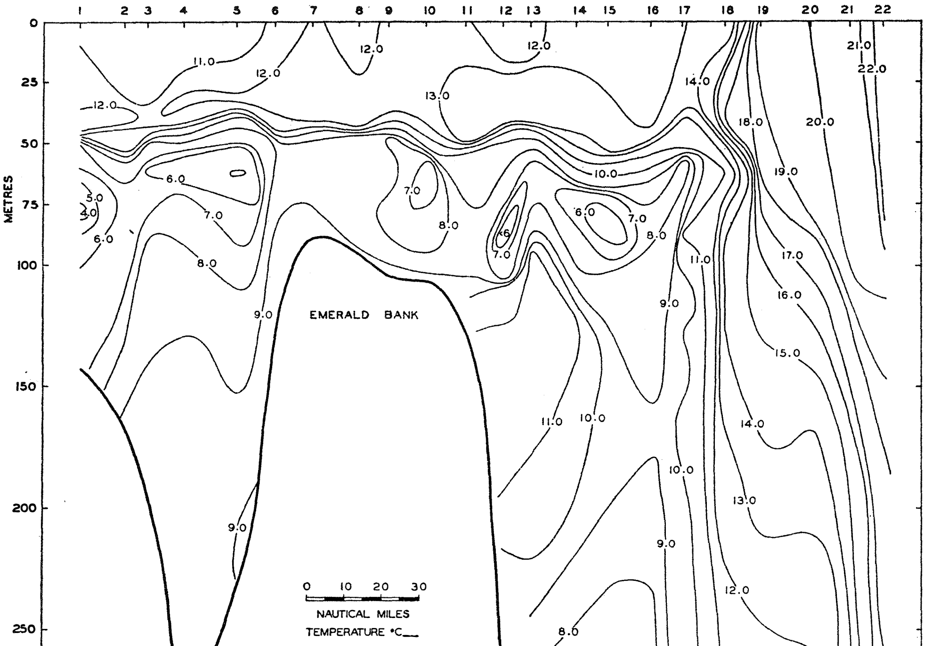
B. The changing surface temperature and salinity, crossing the northern edge of the Gulf Stream



A temperature section from the Grand Bank southwards



The varying positions of slope water and Gulf Stream boundaries, 1949–1951



A temperature section showing slope water boundary off Emerald Bank

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At the head of the Bay of Fundy, temperatures range from approximately 2.0°C in winter to 14.0°C in summer. At the mouth of the bay winter temperatures range from 2.0°C at the surface to greater than 4.0°C at depths of 100 fathoms, while summer surface temperatures attain 13.0°C. At 100 fathoms temperatures have been as high as 10°C. Salinities throughout the bay range from 30.0‰ at the surface to approximately 34.0‰ at 100 fathoms, the higher salinities at depth being typical of the late fall and winter months.

The general circulation of the waters of the Bay of Fundy is, as has been noted, anti-clockwise, the resultant inward movement holding to the Nova Scotia side of the bay. Studies of the replacement of its waters have shown that the main factors are land drainage, tidal action and wind. Other things being equal, an excess of southwesterly winds favours the retention of surface waters within the bay and thus nullifies the normal dynamic tendency for surface outflow and renewal of the waters at greater depths. Under such conditions a type of "closed circulation" is set up within the bay, as opposed to an "open circulation" when surface waters are carried out of the bay to be replaced by inflowing deeper waters. The replacement of Bay of Fundy waters is not a regular progressive process even when the "open circulation" system prevails. While average flushing times of 75 days have been calculated, observations have shown that the waters of the bay can be almost completely replaced in a much shorter time. The source of the waters that are drawn into the bay is a matter of considerable interest. The amount of slope water drawn into the area constitutes from 25 to 65% of the water found at a depth of 85 fathoms. The greatest change in this amount is seasonal, the greater amounts of slope water being found in the fall and early winter months. It has been shown that the source of surface flow into the Bay of Fundy expands from a minimum during January in the offing of the eastern side of the bay to a maximum in May which includes most of Georges Bank, the Gulf of Maine, and the southwestern Scotian Shelf. Commencing in September the surface flow gradually contracts toward the minimum.

CANADIAN PROBLEMS IN OCEANOGRAPHY

The Problems

Canada has an enormous coast line, being bounded north, east, and west by three oceans, which are sources of food, means of transportation, factors in climate, and aids to defence.

As a source of food, the oceans present us with increasing economic and conservation problems as the world needs for protein bring greater pressure on fish stocks that at one time were considered inexhaustible. The major fish stocks off both the east and west coasts of Canada are being exploited as never before. The many international fisheries commissions now furthering research in these areas of Canadian concern indicate the importance that is attached to these ocean resources. While there are yet untapped resources of the sea, the economics of some of our present fisheries are of some concern to Canada at the present time. Some fisheries are not exploited to the full, and the efficiency of catching leaves much to be desired in others.

As a means of transportation, the oceans present a host of problems over a varied and extended coast line. Here the tides, currents, water characteristics and bottom configurations combine with wind, waves, swell, ice and icebergs to present a maze of challenging requirements for safe navigation, for the construction of wharves, harbours, causeways and bridges, and for defence. The recent developments of the large ore bodies in eastern Quebec, the industrialization of areas around the northern part of the Gulf of St. Lawrence, the operation of the Great Lakes–St. Lawrence waterway, and the requirements for sea-borne traffic in the Arctic have crystallized national requirements for a thorough study of ice in navigable waters. These studies, which have recently expanded, have already opened up further problems in the physics of ice, meteorology, and even in the design of ships for navigation through or under the ice.

As a factor in governing climate, the oceans are an important phase in the cycle of evaporation, cloud formation and precipitation. With oceans on three coasts, the interactions between sea and atmosphere are fundamental processes, and eventually must enter as parameters in long-range weather forecasts. While the waters on our northern coastline have ice cover for the greater part of the year, meteorologists have observed for example the very marked effect of the waters of Hudson Bay on the temperature of the overlying air mass, as conditions change from ice cover to open water and vice versa. However the problem is more than local, and involves the interactions of sea and atmosphere on a world-wide basis.

The oceans can still be considered an effective item of continental defence. They can also serve as an effective cover for under-sea craft which can remain submerged for long periods. Until recent years, the North American continent, relatively untouched by modern wars, was looked upon as a bastion, well removed and protected from warring nations by the oceans on three coasts. In particular, defence of our Arctic was deemed unnecessary because of the difficulties of operation. Navigation under the arctic ice by atomic-powered submarines has now been shown to be feasible. This in itself has opened up a host of problems relating to defence. Methods of detecting the modern submarine are much more involved than heretofore, and a very technical knowledge of the ocean itself is required for efficient application of modern defence methods.

Three Oceans

On the Atlantic coast the main water body of particular Canadian concern is contained within the area of confluence of two great ocean systems, the Gulf Stream and the Labrador Current. Thus the characteristics of the waters on our eastern sea coast are determined in the main by the mixing and layering of contributions from these two water masses, and modified in coastal areas by the contribution from land drainage systems. Of Canada's eastern land drainage systems, that of the St. Lawrence River predominates, incorporating as it does some drainage from almost half way across the continent. The water areas within 200 miles or more of our eastern coast support an enormous fishery, which has been known and exploited for centuries. The great contrasts in the waters of the Gulf Stream and the Labrador Current, the climatic variations in the mid-latitudes, the seasonal changes in the wind systems, the variety in the configuration of the sea floor and the coastline, the contrasting types of tide, the ice coverage, and drift of icebergs, establish a pattern of environments with a wide variety of parameters. To the oceanographer, whether interested in problems of food production, of transportation, of meteorology, or of defence, the area offers a particular challenge in many of its fundamental aspects.

In the northern latitudes of the northern hemisphere, the land masses offer considerable barriers to the exchange of waters as between the polar seas and the Atlantic and Pacific Oceans. The annual water balance of the Arctic Ocean has been calculated, in which the inflow and outflow of waters through the Faeroes, the Shetland Islands and the Danish and Bering Straits, also the continental run-off, have been taken into account. It has been indicated that there is a surplus of 45,000 km^3 (16×10^{14} ft^3) of inflowing waters which must be carried away annually from the Arctic Ocean through the numerous straits of the Canadian Archipelago. Hence on the Atlantic seaboard and in the eastern Canadian Arctic, this outflow through Foxe Basin, Hudson Strait, Lancaster, Jones and Smith Sounds, and Kennedy Channel accelerate the Baffin Land and Labrador Currents which transport these arctic waters with their ice and icebergs to the mid-latitudes of the Canadian Atlantic. In the western Canadian Arctic, west of Barrow Strait, the deeper waters are characteristic of those of the Polar Basin. The Canadian oceanographic problem in these far northern areas is concerned with the food resources of the sea for an Eskimo population, with navigation through ice-infested waters relating to supply missions, with development of natural resources, and with phases of continental defence.

The rugged Pacific coast of Canada is indented with many deep inlets which present water bodies of various magnitudes with fjord-like characteristics. The oceanography of the immediate coastal seas is dominated by the outflow from the larger river systems and by the turbulent tidal currents in many straits and passages. The basic features of the ocean circulation in the North Pacific is the North Pacific Current, a part of the Kuroshio System. This North Pacific Current or west wind drift is the general eastward flow of comparatively warm water to the east of Long. 160°E. To the north of the North Pacific Current and centered at about Lat. 50°N is found an entirely different sub-arctic type of water which flows to the east and which is generally referred to as the Aleutian Current. As it nears the American coast one branch of this Aleutian Current turns south to form the California Current. Another branch turns north moving in a slow counter-clockwise gyral around the Gulf of Alaska. An extension from the head of the Gulf of Alaska which turns westward and then southwest, all the while undergoing acceleration, has been named the Alaskan Stream. Recent estimates of the volume transport of the gyral give values of 18 km^3/day (64×10^{10} ft^3/day), with surface velocities of 2 to 5 miles/day. It appears that the area of division of the west wind drift shifts from time to time to the south, the volume transport of the Alaska Gyral increases, and water warmer than usual moves northward past the Canadian coast. Many features of the oceanography of the North Pacific are related to the wind system which is variable in time and space. The dominant winds change with the season; the northwesterly winds favour upwelling on the coast, while southerly winds favour transport of surface water towards the coast.

The Northeast Pacific Ocean is a prolific feeding ground for the various species of salmon that provide the valuable salmon fisheries on the Pacific coast. The enrichment of the waters is provided through physical processes that bring the nutrients from the greater depths to levels where they enter into the cycle of production. These processes are enhanced in part by wind action. In this Northeast Pacific area in recent years, the successful application of oceanography to a major fisheries problem on an international scale has been ably demonstrated. The distribution of the salmon throughout this area, and the dependence of the North American coastal fishery on the well-being of the salmon in the sea have been demonstrated. This has emphasized the necessity of international control of fishing on the high seas.

International Oceanography

There are a variety of problems of deep ocean circulation that are of fundamental importance to world well-being. The number of years during which a particle of water has been removed from contact with the atmosphere can be determined today, for example by measuring the relative concentrations of carbon-14 and carbon-12 in a sample of sea water. The disposal of radioactive wastes, whether by burying on land or by dumping in the sea, constitutes a real problem which is being given attention by international bodies. The disposal of such wastes has been carried out today without too much consideration to the possible end result. Eventually, whether buried on land or dumped in the sea, these materials will be carried about in the great circulation systems of the oceans. The time factor is of course the major concern.

The sun provides the energy to move both sea water and air between the "furnace" of the tropics to the "condensers" of the polar regions. The circulation of the working fluids is demonstrated by the wind systems and the currents of the sea. In the circulation system of the oceans, the equatorial currents and the other major currents, such as the Gulf Stream and Kuroshio, are well known. The vertical circulations and the return currents at the abysmal depths are however at present only matters of very rough estimates. The rate of transport of deep water between high and low latitudes and the rate of exchange of heat with surface water in high latitudes determine the total gain or loss of heat by the oceans. The time element may be a year, a decade or centuries. Hence a very small temperature change in the deep waters would be indicative of a departure from a radiation balance between the sun and the earth. This radiation balance is a prime parameter in the problem of long-range weather forecasting.

The practical end result of productivity in the sea is measured by man in the amount of food he actually takes from it. In this sense we can look upon the areas of Canadian fisheries as most productive. At the same time, we are by no means harvesting the total protein crop available to us. We are aware, however, that there are fluctuations in the abundance of some of the more prized species of fish and animal life, and we are reaching the point in some areas and in some species where man takes all that can be readily caught. We can therefore expect that in some species there will be greater fluctuations in abundance, unless the particular fishery is brought under proper management. It is fundamental that knowledge of the factors affecting the production of stocks is necessary to proper management. Fundamentally, productivity has a much broader meaning. The food cycle in the sea involves the process of photosynthesis wherein plants grow under the action of sunlight. The great bulk of this primary production exists in the seas in the form of phytoplankton, and it is estimated that the amount produced per year exceeds the production of living matter on land. In the complete food chain from the minute plants to the full-grown fish and other marine life there are many weak links or "limiting factors". The amount of sunlight available for plant production and growth varies with latitude, time of year, state of the sky and sea surface, and qualities of the water. The necessary nutrient materials vary in quantity and availability. As all growth is a chemical process, temperature is a factor in the rate of production. The food chain is broken down at times by the ferocious grazing of animal organisms on plant life or by one animal organism on another. For these reasons, the productivity is more accurately measured by the actual determination of the decrease of carbonate or the increase of dissolved oxygen in a sample of sea water where photosynthesis is taking place. The supply of nutrients, particularly those containing nitrogen and phosphorus, is renewed by the decomposition of dead plants and animals through the action of bacteria. The factors affecting the bacteria and other agencies of decay, particularly at the mud–water interface at the bottom of the sea, are not very well known.

As on land, if the marine end product is not harvested, it dies and returns to the cycle of the sea. A population explosion or an excessive schooling of fish may overgraze a portion of the sea, or may deplete the oxygen, and hasten the extinction of that population from the living chain. Another type of population explosion is involved in the phenomenon of the red tide, which proves toxic to higher forms of life in the sea.

The geological history of the oceans is, to a large extent, recorded in the sediment of the deep ocean basins. The processes of sedimentation are associated, in part, with the deep ocean circulation, one phase of which may involve turbidity currents of considerable magnitude. During recent years, man has conquered the outer shell of "inner space" by means of the bathyscaphe. This new tool may now offer extraordinary facilities for penetrating the earth's crust to depths only dreamed of to date by geophysicists. We know that a great diversity characterizes the floor of the ocean basins and in the general plan we can distinguish between abysmal and shallow depths, shoals, ridges, and canyons. In detail, a knowledge of the ocean floors would offer insight into the building and erosion processes which we might consider at least in some areas as more accelerated than those on land. We are aware of mountain ranges under the surface of the sea mightier than those we know of on land. In the investigations of "inner space" the geophysicist has a particular interest in comparing his theories of mountain building as between the continents and the oceans.

Fish in the Sea

In 1957, the Russian oceanographic ship *Vityaz* while working in the Indian Ocean between Colombo and the Gulf of Aden recorded large quantities of dead fish floating on the surface within an area approximately 300 by 150 miles. The quantity of dead fish in this area was estimated at 20 million tons, an amount about half the total annual world fish catch. During this same period smaller fish kills were reported in nearby parts of the Arabian Sea. This recalls the disaster to the tilefish which first came to light in March 1882 and which has been well recorded. In this case multitudes of dead fish were observed floating on the surface between the latitudes of Nantucket and Delaware Bay on the Atlantic coast. The area of destruction was at least 170 by 25 miles, and covered the entire zone inhabited by the tilefish north of Delaware Bay. It was estimated that at least 1.5 billion dead tilefish were sighted. As these are very large fish weighing up to 35 lb the disaster involved an amount which was much in excess of the total annual world fish catch at that time. There is evidence to indicate that the destruction of the tilefish was caused by a sudden temporary flooding of the bottom by abnormally cold water. It has been shown that the tilefish occupies a very definite environment for it lies only along the upper part of the continental slope where the water temperatures are approximately 10°C, and never ventures into the lower temperatures on the shoaling bottom nearer the land. The records of this event point up the significance of a temporary incursion of waters of contrasting temperatures, which in this case brought disaster to a fishery. The cause of the destruction of so many fish in the Indian Ocean in 1957 is not known, but there is a suggestion of oxygen depletion in the surface layers.

For the fourth time in 10 years, the waters of the Gulf of Mexico were again in 1959 plagued by the "red tide", a term which refers to a sudden and explosive blooming of a marine organism which kills fish by the multi-million. This 1959 occurrence was the thirteenth since 1844, and seven have taken place in the present century. Japanese waters also know the "red tide", where it occurs even more frequently than in the Gulf of Mexico. It is also known in Australia and California waters. One of the most destructive outbreaks took place in the 19th century in Walvis Bay, South Africa, when enormous quantities of fish were destroyed. The bloom of the organism *Gymodinium brevis* gives off a toxic substance which consumes all the dissolved oxygen in the water, and all the fish that swim in such water die for lack of oxygen. At the height of the bloom, the water has a dirty chartreuse or yellowish-brown colour, which for some unknown reason led to the term "red tide".

The warm Humboldt Current, which sweeps the shores of Peru, is tremendously rich in fisheries resources, especially anchovies and bonito. Countless millions of guano birds feed on these anchovies, and their droppings on the rainless islands and coast make an excellent fertilizer which developed a major Peruvian industry. Research has shown that the guano birds consume 30 million tons of fish a year, equivalent to about three-quarters of the annual world catch of commercial fish.

On January 23rd, 1960, the U.S. Navy's bathyscaphe *Trieste* designed and built by Auguste and Jacques Picard, father and son, descended to the floor of the Marianas trench in the Pacific Ocean in a record dive of 37,800 feet, or more than 7 miles. This was man's deepest descent into "inner space". At this great depth, under pressures of more than 8 tons per square inch, it was observed that marine animal life existed. This was a most significant observation. In particular it indicated the presence of sufficient oxygen to support animal life. This points to either an efficient vertical circulation preventing depletion of oxygen at these great depths, or production of oxygen through chemical reactions at the mud–water interface. When we recall that the oceans cover 70% of the earth's surface, and that depths exceed 7 miles, this observation further emphasizes the great potential productivity of the sea, and reminds us of the great lack of knowledge we have of these waters.

To paraphrase an old saying, "there are more fish die in the sea than ever were caught". This is not only pointed up by the events cited above, but by other smaller-scale observations on the herring and oyster diseases with which we are all familiar, and by many recorded observations of quantities of dead fish floating on the surface of the sea. Based on our present knowledge, which is remarkable for its meagerness, most of the catchable bottom fish of the world are found in the comparatively shallow waters of the continental shelf. Pelagic fish, however, in their vast and mysterious movements, are ocean-wide as has been particularly well demonstrated for Pacific salmon and tuna.

As the world need for protein continues to expand attention is being focussed on the vast possibilities in the ocean and we become faced with conflicting economic, conservation, and exploitation problems. While there are specific Canadian problems, we cannot ignore the world-wide problems. The Indian Ocean, for example, has been described as the last unexplored frontier. Here is an ocean, 28,000,000 square miles in area, constituting 14% of the earth's surface. Almost one-quarter of the world's population is located on its margins. Protein deficiencies for this population, in parts of India, Ceylon, Indonesia, Malaya, and the east coast of Africa, have directed world attention to this area.

CANADIAN ORGANIZATION FOR OCEANOGRAPHY

Canadian Committee on Oceanography

As noted earlier, oceanographic activities in Canada are furthered under the Canadian Committee on Oceanography (CCO). This Committee, which succeeded the former Canadian Joint Committee on Oceanography, came into being on December 14th, 1959. The present Committee is a co-ordinating and advisory body representing the following organizations:

The Royal Canadian Navy,
The Fisheries Research Board of Canada,
The Department of Mines and Technical Surveys,
The Defence Research Board,
The National Research Council,
The Meteorological Branch, Department of Transport,
The Marine Services, Department of Transport,
The Institute of Oceanography, University of British Columbia,
The Institute of Oceanography, Dalhousie University,
The Great Lakes Institute, University of Toronto, and
The Royal Canadian Air Force.

The functions of the CCO are to:

(*a*) co-ordinate the oceanographic activities of all Canadian Government agencies,

(*b*) act, as designated by the National Research Council, as the national committee for the Scientific Committee on Oceanographic Research (SCOR),

(*c*) act, as designated by the National Research Council, as the Section on Oceanography of that Council's Associate Committee on Geodesy and Geophysics, and to

(*d*) serve as the governmental agency charged with Canadian responsibilities consequent upon Canadian membership in the Intergovernmental Oceanographic Commission under UNESCO.

Each of the co-operating organizations is either actively engaged in oceanographic investigations or contributes in ships, laboratory facilities, personnel or funds towards the overall Canadian program. The total effort is co-ordinated through CCO.

Working Groups of CCO have been established on the east and west coasts and on the Great Lakes, to develop such liaison and co-operation among the agencies concerned as are needed to best attain their respective objectives and the maximum utilization of facilities, and specifically to:

(*a*) arrange for the co-ordination of programs when appropriate,

(*b*) program research ship time when or where ships are available for shared use amongst two or more of the agencies concerned,

(*c*) foster the co-operative use, as feasible, of special facilities or equipment available in the individual agencies, and to

(*d*) consider the oceanographic and limnological programs in areas of responsibility, and give opinions and recommendations concerning them to the CCO.

The CCO Working Group on Ice in Navigable Waters also serves to co-ordinate and encourage research in the field of ice in navigable waters. Particular attention has been given to the following activities:

(*a*) the development of techniques for forecasting, ice growth, degeneration and movement,

(*b*) studies of the physical properties of ice,

(*c*) studies of the dynamics of the ice–air and ice–water interfaces,

(*d*) climatological studies, and

(*e*) the promotion of a standard terminology and codes for reporting ice.

Responsibilities

While the contributions of the co-operating organizations are determined by each individual agency in accordance with its authorities and responsibilities as established by the Canadian Government, general areas of prime responsibility and co-operation have been agreed upon.

Under the Canadian Committee on Oceanography Canada has re-examined its present-day oceanographic resources, and has drawn up a new and enlarged program of development in order to:

(*a*) meet national requirements for a knowledge of the waters of the oceans on our three coasts and inland seas,

(*b*) increase the knowledge of the continental shelf off our coasts and the mineral potential of the sediments in continental waters, and to

(*c*) fulfill international obligations in the study of the world oceans.

Accomplishments

Within a few years the Canadian Committee on Oceanography, by developing the ideas nurtured by its predecessor the Joint Committee on Oceanography, has, above all, succeeded in co-ordinating our national efforts in oceanography by effecting the means and the methods for full co-operation between federal agencies, research groups, and specialized institutes. This has contributed to steady and sound development. The deliberations of the Committee have developed a good basis for policy decisions in the national sphere, and allowed, as well, for a logical approach to problems in the field of international oceanography.

CONCLUSION

While the foregoing, in part, provides the historical background of the oceanographical investigations of Canadian Atlantic waters, and an outline of the organization for oceanography in Canada today, the full story of the development of Canadian oceanography has yet to be written. To complete it, the complementary developments over the years relative to Canadian North Pacific waters, and the extensive investigations of Canadian Arctic waters in recent years, need to be recorded.

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GENERAL BIBLIOGRAPHY OF CANADIAN CONTRIBUTIONS

ANON. 1901. The Currents in the Gulf of St. Lawrence. *Nature*, **63**: 601–3.

1931, 1932, 1933, 1934. Annual Reports Newfoundland Fishery Research Laboratory.

1946. Monthly sea and air temperatures on the official North Atlantic tracks from Canadian and U.S. ports to Liverpool. Canada Dept. Mines and Resources, Hydrographic and Map Service, Ottawa.

1953. Newfoundland Pilot. Ottawa, 484 pp.

1955. Tidal changes in the Strait of Canso region. Tidal and Current Survey. Ottawa, 9 pp.

1958. Mean sea level observations, 1958. Canada Dept. Mines and Technical Surveys. Ottawa, 143 pp.

1958. Canadian Hydrographic Service, Dept. Mines and Technical Surveys. *Canadian Shipping and Marine Engineering News*, Nov. issue.

1959. Aerial ice observing land reconnaissance, 1957. Canada Dept. Transport, Meteorological Branch, Circular 3254. Toronto.

1959. Aerial observing and reconnaissance programme in the St. Lawrence River, the Gulf of St. Lawrence, and the Strait of Belle Isle, 1958. *Ibid.*, Circular 3273. Toronto.

1959. Catalog of IGY oceanographic data. Ship program—Canada. IGY WDC-A, Oceanography. A and M College of Texas, pp. 5–8.

1959. *Ibid.*, p. 36.

1959. Pilot of Arctic Canada, Vol. 1 (183 pp.); Vol 2 (434 pp.); Vol. 3 (370 pp.). Canada Dept. of Mines and Technical Surveys, Ottawa.

1959. Break-up and freeze-up of rivers and lakes in Canada. Canada Dept. Transport, Meteorological Branch, Circular 3159. Toronto.

1960. Organization and Training of the Professional and Technical Personnel of the Canadian Hydrographic Service. *Inter. Hydrographic Review*, **37**(1): 7–12.

ACLAND, F. A. 1930. Tide tables for eastern coasts of Canada, etc. Canada Dept. Marine and Fisheries, Tidal and Current Survey, Ottawa.

ANDERSON, F. 1928. Tables of hourly direction and velocity of the currents and time of slack water in the Bay of Fundy and its approaches. Canada Dept. Marine and Fisheries. Ottawa, 15 pp.

1934. The currents in the St. Lawrence Estuary. Ste. Anne des Monts to Father Point. Canadian Hydrographic Service, Ottawa.

ARMSTRONG, T., AND B. ROBERTS. 1956. Illustrated ice glossary. *Polar Record*, **8**(52): 4–12.

BAILEY, L. W. 1917. The geological features of the St. Croix River and Passamaquoddy Bay. *Contr. Canadian Biol.*, **1915–16**: 109–112.

BAILEY, W. B. 1955. Arctic Oceanography. Canada Dept. Fisheries *Trade News*, **7**(7): 14.

1955. Summer surface temperatures in the Canadian Atlantic. *Fish. Res. Bd. Canada, Prog. Rept. Atl.*, No. 63, pp. 16–18.

1956. Water temperatures around North America. *Ibid.*, No. 64, pp. 16–18.

1956. On the origin of deep Baffin Bay water. *J. Fish. Res. Bd. Canada*, **13**(3): 303–308.

1957. Oceanographical features of the Canadian Archipelago. *Ibid.*, **14**(5): 731–769.

1958. On the dominant flow in the Strait of Belle Isle. *Ibid.*, **15**(6): 1163–1174.

BAILEY, W. B., AND H. B. HACHEY. 1951. An increasing Atlantic influence in Hudson Bay. *Proc. Nova Scotia Inst. Science*, **XXII**, Pt. 4.

1951. The vertical temperature structure of the Labrador Current. *Ibid.*, **XXII**, Pt. 4.

BAILEY, W. B., D. G. MACGREGOR AND H. B. HACHEY. 1954. Annual variations of temperature and salinity in the Bay of Fundy. *J. Fish. Res. Bd. Canada*, **11**(1): 32–47.

BARNES, H. T. 1906. Ice formation with especial reference to anchor ice and frazil. John Wiley & Sons, New York, 250 pp.

1910. Marine microthermograms and the influence of icebergs on the temperature of the sea. *Nature*, **85**: 131–138.

1912. The rise of temperature associated with the melting of icebergs. *Nature*, **90**: 408–410.

1913. Report on the influence of icebergs and land on the temperature of the sea, as shown by the use of the microthermometer, on a trip of the Canadian Government Ship *Montcalm* on the Gulf of St. Lawrence and the coast of Labrador. Canada Dept. Marine and Fisheries, Suppl. to the Annual Report for the Fiscal Year 1911–1912. Ottawa, 37 pp.

1914. Icebergs and their location in navigation. *Proc. Royal Society*, **20**: 161–168.

1926. Theory and use of thermite heat units in relieving ice conditions. *Jour. N.E. Water Works Assoc.* **40**(3).

1927. Some physical properties of icebergs and a method for their destruction. *Proc. Royal Society*, **114**: 161–168.

1927. Experimenting with icebergs. The Meteorological Committee, Air Ministry. *The Marine Observer*, **4**(41): 91–93.

1928. Ice engineering. Renouf Publishing Co., Montreal, 364 pp.

1928. Ice destruction. The Meteorological Committee, Air Ministry, *The Marine Observer*, **5**(59), p. 234. London.

1929. Thermiting ice bergs. *Science and Invention*, **16**(186): 494–5.

BEAUGÉ, L. 1956. Le Golfe du Saint-Laurent. *Rev. Trav. de l'Instit. des Pêches Maritimes*, **20**(1): 5–39.

BELL, R. 1879. Report on an exploration of the east coast of Hudson's Bay. *Geol. Surv. of Canada*, **877–78** (c): 1–37, Ottawa.

BINNEY, G. 1929. Hudson Bay in 1928. *Geographical J.*, **34**(1): 1–27.

BJERKAN, PAUL. 1919. Results of the hydrographical observations made by Dr. Johan Hjort in the Canadian Atlantic waters during 1915. Canadian Fish. Exped., 1914–15. Dept. Naval Service, Ottawa, pp. 1–495.

BLACK, W. A. 1956. Extracts relating to the navigability of Canadian Inland Waterways. Canada Department of Mines and Technical Surveys, Geographical Branch, Miscellaneous Papers Series, Geographical Paper No. 7. Ottawa, 55 pp.

1956. A report on sea ice conditions in the Eastern Arctic, Summer 1956. *Ibid.*, Geographical Paper No. 9. 32 pp.

1957. An illustrated glossary of ice types in the Gulf of St. Lawrence. *Ibid.*, Geographical Paper No. 11. 50 pp.

1957. Gulf of St. Lawrence Ice Survey, Winter 1956. *Ibid.*, Geographical Paper No. 12. 32 pp.

1957. Gulf of St. Lawrence Ice Survey, Winter 1957. *Ibid.*, Geographical Paper No. 14. 29 pp.

1958. A report on sea ice conditions in the Eastern Arctic, Summer 1957. *Ibid.*, Geographical Paper No. 15. 32 pp.

1958. Gulf of St. Lawrence Ice Survey, Winter 1958. *Ibid.*, Geographical Paper No. 19. 56 pp.

1959. A report on sea ice conditions in the Eastern Arctic, Summer 1958. *Ibid.*, Geographical Paper No. 20. 36 pp.

BLACK, W. A.—*Concluded*

1959. Gulf of St. Lawrence Ice Survey, Winter 1959. *Ibid.*, Geographical Paper No. 23. 56 pp.

1960. Gulf of St. Lawrence Ice Survey, Winter 1960. *Ibid.*, Geographical Paper No. 25. 64 pp.

BOUSFIELD, E. L. 1955. Some physical features of the Miramichi Estuary. *J. Fish. Res. Bd. Canada*, **12**(3): 342–361.

BROCHU, MICHAEL. 1960. Dynamique et caracteristiques des glaces de derive de l'estuaire et de la partie nord-est du golfe Saint-Laurent, hiver 1957–58. Canada Department of Mines and Technical Surveys, Geographical Branch, Geographical Paper No. 24. Ottawa, 93 pp.

BUMPUS, DEAN F. 1960. Sources of water contributed to the Bay of Fundy by surface circulation. *J. Fish. Res. Bd. Canada*, **17**(2): 181–197.

BURWASH, L. T. 1929. Across Arctic Canada, 1925–26. *Geographical J.*, **74**(6): 553–560.

CAMPBELL, N. J. 1958. Recent oceanographic activities of the Atlantic Oceanographic Group in the Eastern Arctic. *Fish. Res. Bd. Canada, Prog. Rep. Atl.*, No. 69, pp. 18–21.

1959. An International Geophysical Year project of the Fisheries Research Board of Canada, Atlantic Oceanographic Group. *Ibid.*, No. 72, pp. 33–36.

CAMPBELL, N. J., AND A. E. COLLIN. 1957. The discoloration of Foxe Basin Ice. Assoc. d'Ocean. Physique, Reports and Abstracts of Communications, p. 91.

1958. The discoloration of Foxe Basin ice. *J. Fish. Res. Bd. Canada*, **15**(6): 1175–1188.

CAMERON, H. L. 1952. The measurement of water current velocities by parallax methods. *Photogrammetry Engineering*, **18**: 99–104.

CAMU, P. 1958. Etude du Port de Québec. Canada Department of Mines and Technical Surveys, Geographical Branch, Geographical Paper No. 17. Ottawa, 79 pp.

CARTER, N. M., AND J. P. TULLY. 1937. A graphical method for the conversion of chlorinity per litre to chlorinity per kilogram in sea water analysis. *J. du Conseil*, **12**(1): 36–39.

CARTON, E. L. 1954. The ice budget on the Arctic pack and its application to ice forecasting. U.S. Hydro Office, Tech. Rep. No. 6, 13 pp.

CHEVRIER, J. R., AND R. W. TRITES. 1960. Drift bottle experiments in the Quoddy Region, Bay of Fundy. *J. Fish. Res. Bd. Canada*, **17**(6): 743–762.

CROSS, C. M. 1951. An investigation of the hydrography of Miramichi Bay. Canada Dept. Mines and Tech. Surveys, Tidal and Current Survey. Ottawa, 15 pp.

CHURCH, PHIL. 1932. Canadian work on surface temperatures of western North Atlantic. *Bull. Amer. Meteor. Soc.*, **13**(2).

COPELAND, G. G. 1912. The temperature and densities and allied subjects of Passamaquoddy Bay and its environs. *Contr. Canad. Biol.*, **1906–1910**: 281–294.

CRAIGIE, E. H. 1916. Hydrographic investigations in the St. Croix River and Passamaquoddy Bay in 1914. Suppl. 5th Ann. Rept. Canada Dept. Naval Service, Fisheries Branch. Ottawa, pp. 151–161.

1916. A hydrographic section of the Bay of Fundy in 1914. *Ibid.*, pp. 163–167.

CRAIGIE, E. H., AND W. H. CHASE. 1918. Further hydrographic investigation in the Bay of Fundy. Suppl. 7th Ann. Rept. Canada Dept. Naval Services, Fisheries Branch. Ottawa, pp. 127-148.

DAWSON, W. B. 1898. Survey of tides and currents in Canadian waters. 1896–97. Canada Dept. Marine and Fisheries, Report of Progress. Ottawa, 32 pp.

1898, 1899, 1900, 1901, 1902. Survey of tides and currents in Canadian waters. Canada Dept. Marine and Fisheries, Ottawa.

1905. The currents at the entrance of Bay of Fundy. Canada Dept. Marine and Fisheries. Ottawa, 17 pp.

1906. The currents on the south eastern coasts of Newfoundland. *Ibid.*

1910. Effect of the wind on currents and tidal streams. *Trans. Roy. Soc. Canada*, 3rd Ser., **3**, Sec. III: 179–196.

1911. Progress of the tide in deep inlets and ordinary estuaries. *Ibid.*, 3rd Ser., **5**, Sec. III, 123–128.

1913. The currents in the entrance to the Gulf of St. Lawrence. Canada Dept. Naval Service. Ottawa, 50 pp.

1913. The currents in the Gulf of St. Lawrence. *Ibid.*, 46 pp.

1917. Tide levels and datum planes of eastern Canada from determinations by the tidal and current survey up to the year 1917. *Ibid.*, 99 pp.

1917. Tides at the head of the Bay of Fundy. *Ibid.*, 34 pp.

1920. The tides and tidal streams with illustrative examples from Canadian waters. *Ibid.*, 43 pp.

1920. Tidal investigations and results. Reports Can. Arctic Exped. 1913–18. X. Plankton, hydrography, tides, etc., Ottawa.

1922. Temperatures and densities of the waters of Eastern Canada. Canada Dept. Naval Service. Ottawa, 102 pp.

1927. Report to the Section of Physical Oceanography at the International Conference in Madrid in 1924 (The Gulf Stream). Cons. Internat. de Recherche, Sect. D. Oceanog. Bull. No. 8. Venice, pp. 9–11.

1927. The currents in Belle Isle Strait. Canada Dept. Marine and Fisheries, Ottawa.

1928. Tables of direction and velocity of currents in the Bay of Fundy. Canada Dept. Marine and Fisheries, Ottawa.

DOHLER, G. C. 1958. Construction of tide stations at Brevoort Harbour and Resolute, N.W.T. Canada Dept. Mines and Technical Surveys. Ottawa, 43 pp.

DUGAL, L. P. 1934. Observations sur la chlore total et l'oxygène dissous de l'estuaire du St. Laurent. *Naturaliste Canadien*, **61**: 168–181.

1934. Essais de détermination de pH. Contr. Stat. Biol. St. Laurent, No. 5, Laval University, Quebec.

DUNBAR, M. J. 1946. The state of the West Greenland Current up to 1944. *J. Fish. Res. Bd. Canada*, **6**(7): 460–471.

1949. New Arctic research vessel. *Arctic*, **1**(2): 56–57.

1952. The Ungava Bay problem. *Ibid.*, **5**(1): 4–16.

1953. Arctic and Sub-Arctic marine ecology. Immediate problems. *Ibid.*, **6**(2): 75–90.

1954. A note on climatic change in the sea. *Ibid.*, **7**(1): 27–30.

1955. Water masses, circulation, ice cover. Geography of the North lands. (Kimble and Good), Chap. III, pp. 36–57. Wiley, New York.

1955. Marine life. Geography of the North lands. *Ibid.*, Chap. VI, pp. 119–138.

1955. Density inversions in Canadian eastern waters. *Nature*, **176**(4484): 703.

1955. The present status of climatic change in the Atlantic sector of northern seas, with special reference to Canadian eastern arctic waters. *Trans. Roy. Soc. Canada*, **49**, Ser. III: 1–7.

DUNBAR, M. J. 1956. The *Calanus* expeditions in the Canadian Arctic, 1947 to 1955. *Arctic*, **9**(3): 178–190.

1958. Physical oceanographic results of the *Calanus* expeditions in Ungava Bay, Frobisher Bay, Cumberland Sound, Hudson Strait and northern Hudson Bay, 1949–55. *J. Fish. Res. Bd. Canada*, **15**(2): 155–201.

Dunbar, Moira. 1954. The pattern of ice distribution in Canadian Arctic seas. *Trans. Roy. Soc. Canada*, **48**, Ser. III: 9–18.

1956. Note on sea ice observed from *C.G.S. D'Iberville* and *C.D. Howe.* Defence Research Board, Arctic Rep. No. 4/55. Ottawa, 3 pp.

1960. Thrust structures in young sea ice. *J. Glaciology*, **3**(28): 724–732.

Ellis, D. V. 1956. Some temperature and salinity records from the Canadian Arctic during 1954 and 1955. *J. Fish. Res. Bd. Canada*, **13**(4): 591–598.

Farquharson, W. I. 1957. Cotidal charts of the Gulf of St. Lawrence, Assoc. d'ocean. Physique, Reports of Abstracts and communications, pp. 59–60.

Fish, Charles J., and Martin W. Johnson. 1937. The biology of the zooplankton population in the Bay of Fundy and Gulf of Maine with special reference to production and distribution. *J. Biol. Bd. Canada*, **3**(3): 189–322.

Fjarlie, R. L. I. 1953. A seawater sampling bottle. *J. Marine Research*, **12**(1): 21–30.

Fofonoff, N. P. 1959. Interpretation of oceanographic measurements—thermodynamics, physical and chemical properties of sea water. National Academy of Sciences–National Research Council, Publ. 600. Washington, pp. 38–66.

Fofonoff, N. P., and R. B. Montgomery. 1955. The equatorial undercurrent in the light of the vorticity equation. *Tellus*, **7**: 518–521.

Ford, W. L., J. R. Longard and R. E. Banks. 1952. On the nature, occurrence, and origin of cold low salinity water along the edge of the Gulf Stream. *J. Marine Research*, **11**(3):, 281–293.

Ford, W. L., and A. R. Miller. 1952. The surface layer of the Gulf Stream and adjacent waters. *Ibid.*, **11**(3): 267–280.

Forrester, W. D. 1958. Current measurements in Passamaquoddy Bay and the Bay of Fundy 1957 and 1958. Canada Dept. Mines and Technical Surveys, Tidal Publication, No. 40. Ottawa, 18 pp.

1960. Current measurements in Passamaquoddy Bay and the Bay of Fundy 1957 and 1958. *J. Fish. Res. Bd. Canada*, **17**(5): 727–729.

Fortier, Y. O., and L. W. Morley. 1956. Geological unity of the Arctic Islands. *Trans. Roy. Soc. Canada*, **50**, Ser. III: 1–12.

Forward, C. N. 1954. Ice distribution in the Gulf of St. Lawrence during the break-up season. *Geographical Bulletin*, No. 6: 45–84.

1958. Ice conditions in the Gulf of St. Lawrence during the Spring seasons, 1953–57. Canada Dept. Mines and Technical Surveys, Geographical Branch, Geographical Paper No. 16. Ottawa, 13 pp.

1959. Sea ice conditions in the Northumberland Strait area. *Ibid.*, Geographical Paper No. 21. 14 pp.

Fothergill, N. O. 1951. The currents along the Atlantic coast of Nova Scotia. Canada Dept. Mines and Technical Surveys, Tidal and Current Survey. Ottawa, 9 pp.

1953. Tidal circulation in Miramichi Bay. *Ibid.* 18 pp.

Fraser, R. J. 1951. Oceanographic observations on the Atlantic and Pacific coasts. Canadian Hydrographic Service, Ottawa.

Frost, N. 1938. The genus Ceratum and its use as an indicator of hydrographic conditions in Newfoundland waters. Nfld. Dept. Nat. Resources, Bull. 5. St. John's, 12 pp.

Gaudry, R. 1938. Les températures d'estuaire du St. Laurent. Contr. Stat. Biol. du St. Laurent à Trois-Pistoles, No. 13, Laval, Quebec.

Giguère, P. A., and L. Lauzier. 1945. Le dosage polarographique de l'oxygen dans l'eau de mer. *Canadian J. Research*, **23**: 223–233.

Gold, L. W. 1960. The cracking activity in ice during creep. *Canadian Jour. Physics*, **38**(9): 1137–1148.

GORDON, A. R. 1887. Report on the Hudson's Bay expedition of 1886 under the command of Lt. A. R. Gordon, R.N. Canada Dept. Marine and Fisheries, Sessional Papers No. 15. Ottawa, 133 pp.

GRAINGER, E. H. 1954. Station list of the "Calanus" Expedition, 1951–52, together with Frobisher Bay Stations, 1948, 1950 and 1951, and Resolution Island Stations, 1950. *J. Fish. Res. Bd. Canada*, **11**(1): 98–105.

1959. The annual oceanographic cycle at Igloolik in the Canadian Arctic. I. The zooplankton and physical and chemical observations. *Ibid.*, **16**(4): 453–501.

GRAINGER, E. H., AND M. J. DUNBAR. 1956. Station list of the "Calanus" Expeditions, 1953–54. *Ibid.*, **13**(1): 41–45.

GRAINGER, E. H., AND J. H. HUNTER. 1959. Station list of the 1955–58 field investigations of the Arctic Unit of the Fisheries Research Board of Canada. *Ibid.*, **16**(4): 403–420.

GRAN, H. H., AND T. BRAARUD. 1935. A quantitative study of the phytoplankton in the Bay of Fundy and the Gulf of Maine (including observations on hydrography, chemistry and turbidity). *J. Biol. Bd. Canada*, **1**(5): 279–467.

HACHEY, H. B. 1929. Seeing the world in a catsup bottle. *The Glass Container*, **9**(1).

1930. Hudson Bay a desert sea. *Canadian Fisherman*, **17**(11).

1931. Report on the Hudson Bay fisheries expedition of 1930. *Contr. Canadian Biol. Fish.*, [N.S.] **6**(23): 465–474.

1931. The general hydrography and hydrodynamics of the waters of the Hudson Bay region. *Ibid.*, **7**(9): 93–118.

1933. The temperature relations between water and air at St. Andrews, N.B. *Mon. Weather Rev.*, **61**(9).

1934. The weather man and coastal fisheries. *Trans. Amer. Fish. Soc.*, **64**: 382–389.

1934. The trend of water temperatures on our Atlantic seaboard. *Biol. Bd. Canada, Prog. Rep. Atl.*, No. 11, pp. 3–5.

1934. North Atlantic cyclones and coastal waters. *Ibid.*, No. 11, pp. 6–9.

1934. The probable effect of tidal power development on Bay of Fundy tides. *Jour. Frank. Inst.*, **217**(6): 747–756.

1934. A derivation of Bjerknes' fundamental hydrodynamical concept. *Inter. Revue gesamten Hydrobiol. Hydrograph.*, Heft 3/4, Band **31**: 311–336.

1934. Movements resulting from mixing of stratified waters. *Jour. Biol. Bd. Canada*, **1**(2): 133–143.

1934. Replacement of Bay of Fundy waters. *Ibid.*, **1**(2): 121–131.

1935. The circulation of Hudson Bay waters as indicated by drift bottles. *Science*, **82**(2125): 275–276.

1935. Tidal mixing in an estuary. *Jour. Biol. Bd. Canada*, **1**(3): 171–178.

1935. The effect of a storm on an inshore area of markedly stratified waters. *Ibid.*, **1**(4): 227–237.

1935. The waters of the Scotian Shelf. *Biol. Bd. Canada, Prog. Rep. Atl.*, No. 16, pp. 3–6.

1936. Transgressions in the Atlantic Ocean. *Science*, **83**(2154): 349–350.

1936. The submarine physiography and oceanographical problems of the Scotian Shelf. *Trans. Amer. Fish. Soc.*, **66**: 237–241.

1937. Ekman's theory applied to water replacements on the Scotian Shelf. *Trans. Nova Scotia Inst. Science*, **19**(3): 264–276.

1937. Is the Gulf Stream coming closer? *Biol. Bd. Canada, Prog. Rep. Atl.*, No. 20, pp. 11–14.

1937. Highest water temperatures on record. *Ibid.*, No. 21, pp. 14–15.

HACHEY, H. B.—*Concluded*

1937. Exceptional temperatures of Central Atlantic Water. *Science*, **87**(2253): pp. 219–220.

1938. The cold water layer of the Scotian Shelf. *Ibid.*, **88**(2283): pp. 307–308.

1938. The origin of the cold water layer of the Scotian Shelf. *Trans. Roy. Soc. Canada*, 3rd Ser., Sec. III, **32**: 29–42.

1938. "Jellyfish" forecast the hurricane of September 21st. *Biol. Bd. Canada, Prog. Rep. Atl.*, No. 23, pp. 13-15.

1939. Hydrographic features of the waters of Saint John Harbour. *J. Fish. Res. Bd. Canada*, **4**(5): 424–440.

1939. Surface water temperatures of the Canadian Atlantic coast. *Ibid.*, 378–391.

1939. Temporary migrations of the Gulf Stream Water on the Atlantic seaboard. *Ibid.*, 339–348.

1939. The probable significance of temporary migrations of Gulf Stream water on the Atlantic seaboard. *Assoc. Inter. Oceanog. Phys., Procès-Verbaux*, **3**: 156–157.

1941. Winter flooding of the Scotian Shelf. *Biol. Bd. Canada, Prog. Rep. Atl.*, No. 29, pp. 3–4.

1942. The waters of the Scotian Shelf. *J. Fish. Res. Bd. Canada*, **5**(4): 377–397.

1947. Water transports and current patterns for the Scotian Shelf. *Ibid.*, **7**(1): 1–16.

1949. The present status of oceanography in Canada. *Assoc. Inter. Oceanog. Phys., Procès-Verbaux*, **4**: 104–105.

1949. Canadian Interest in Arctic oceanography. *Arctic*, **2**(1): 28–35.

1952. Physical oceanography in Canada 1948–51. *Assoc. Inter. Oceanog. Phys., Procès-Verbaux*, **5**: 86–89.

1952. Vertical temperature distribution in the Great Lakes. *J. Fish. Res. Bd. Canada*, **9**(7): 325–328.

1953. A winter incursion of slope water on the Scotian Shelf. *Ibid.*, **10**(3): 148–153.

1954. The Continental Shelf. *Trade News*, **7**(2): 10–11.

1954. The hydrography of Hudson Bay. *Proc. Roy. Soc. Canada*, **48**, Ser. III: 19–23.

1955. Water replacements and their significance to a fishery. *Deep-Sea Research*, **8**(supp.): 68–73.

1955. A review of Canadian oceanography. *Assoc. Inter. Oceanog. Phys., Procès-Verbaux*, No. 6.

1955. Storm surges and internal adjustments in the water mass. *Ibid.*, No. 6.

1956. Oceanography—its part in the International Geophysical Year. *Trade News*, **8**(11): 5–8.

1957. Oceanography in Canada, 1954–57. Queen's Printer, Ottawa, 19 pp.

1960. Oceanography in Canada, 1957–60. Queen's Printer, Ottawa, 19 pp.

HACHEY, H. B., AND R. A. MCKENZIE. 1939. The cod fishery and the water temperatures on the Scotian Shelf. *Fish. Res. Bd. Canada, Prog. Rep. Atl.*, No. 24, pp. 6–8.

HACHEY, H. B., AND H. J. MCLELLAN. 1948. High surface sea-water temperatures in 1947. *Fish. Res. Bd. Canada, Prog. Rep. Atl.*, No. 42, pp. 4–6.

1948. Cycles of temperature in surface water of the Canadian Atlantic coast. *Ibid.*, No. 43, pp. 7–9.

1948. Trends and cycles in surface temperatures of the Canadian Atlantic. *J. Fish. Res. Bd. Canada*, **7**(6): 355–362.

HACHEY, H. B., AND N. O. FOTHERGILL. 1953. The wind currents and dominant surface flow at Sambro Lightship. *Trans. Roy. Soc. Canada*, **47**, Ser. III: 1–14.

HACHEY, H. B., F. HERMANN AND W. N. BAILEY. 1954. The waters of the ICNAF Convention Area. ICNAF Annual Proc., Vol. 4, pp. 67–102.

HACHEY, H. B., L. LAUZIER AND W. B. BAILEY. 1956. Oceanographic features of submarine topography. *Tran. Roy. Soc. Canada,* **50**, Ser. III: 67–81.

HARPER, E. L. 1953. Semi microdetermination of dissolved oxygen. *Ann. Chem.*, **25**: 187.

HART, J. L. 1958. Fisheries Research Board of Canada Biological Station, St. Andrews, N.B., 1908–1958. Fifty years of research in aquatic biology. *J. Fish. Res. Bd. Canada,* **15**(6): 1127–1161.

HART, J. L., AND D. L. MCKERNAN. 1960. International Passamaquoddy Fisheries Board Investigations 1956–59. Introductory account. *J. Fish. Res. Bd. Canada,* **17(2)**: 127–131.

HARTLEY, C. H., AND M. J. DUNBAR. 1938. On the hydrographic mechanism of the so-called brown zones associated with tidal glaciers. *J. Marine Research,* **1**(4): 305–311.

HEEZEN, B. C., D. B. ERICSON AND M. EWING. 1954. Further evidence for a turbidity current following the 1929 Grand Banks earthquake. *Deep-Sea Research,* **1**: 193–202.

HELK, J. V., AND MOIRA DUNBAR. 1953. Ice islands—evidence from North Greenland. *Arctic,* **6**: 263–271.

HJORT, JOHAN. 1919. Canadian fisheries expedition, 1914–15. Canada Dept. Naval Service, Ottawa, 495 pp.

HOOPER, KENNETH. 1959. X-Ray absorption techniques applied to statistical studies of foraminifera populations. *J. Paleontology,* **33**(4): 631–640.

HUNTSMAN, A. G. 1918. The effects of the tide on the distribution of the fishes of the Canadian Atlantic coast. *Trans. Roy. Soc. Canada,* Ser. III, **12**, Sec. IV, pp. 61–67.

1920. Climates of our Atlantic waters. *Trans. Amer. Fish. Soc.*, **50**: 326–333.

1923. The influence of tidal oscillations on vertical circulation in estuaries. *Trans. Roy. Soc. Canada,* Ser. III, **17**, Sec. V: 11–14.

1923. The importance of tidal and other oscillations in oceanic circulation. *Trans. Roy. Soc. Canada,* Ser. III, **17**, Sec. V: 15–20.

1924. Circulation and pollution of water in and near Halifax. *Contr. Biol. Bd. Canada,* N.S. **2**(3): 71–79.

1924. Oceanography. Handbook of the British Assoc. Adv. Science, pp. 274–290, University of Toronto Press, Toronto.

1925. The ocean around Newfoundland. *Canadian Fisherman,* January, pp. 5–8.

1927. The oceanography of the Canadian Atlantic. *Bull. National Res. Council,* No. 61. Washington, pp. 520–536.

1930. Arctic ice on our eastern coast. *Biol. Bd. Canada, Bull.*, No. 13, 12 pp.

1931. Biological and oceanographic conditions in Hudson Bay. I. Hudson Bay and the determination of fisheries. *Contr. Biol. Bd. Canada,* N.S. **6**(22): 455–462.

HUNTSMAN, A. G., W. B. BAILEY AND H. B. HACHEY. 1954. The general oceanography of the Strait of Belle Isle. *J. Fish. Res. Bd. Canada,* **11**(3): 198–260.

HUNTSMAN, A. G., A. THOMPSON, J. T. WILSON, D. C. MACGREGOR AND H. B. HACHEY. 1949. Canada's oceans—known and unknown. *Tran. Roy. Soc. Canada,* Ser. III, **43**, Sec. IV: 153–190.

JARLAN, G. E., AND M. BROCHU. 1959. Observations of frazil in the St. Lawrence River (Quebec). NRC Division of Mechanical Eng., NRC MH-86. Ottawa, 19 pp.

KASK, J. L. 1960. Oceanography and Fisheries. *Canadian Fisheries Annual,* pp. 49–54.

KELLY, W. 1836. On the temperature, fogs and images of the river St. Lawrence. *Trans. Lit. and Hist. Soc. of Quebec,* Ser. I, **3**: 1–45.

1837. On the temperature of the surface water over the banks and near the shores of the Gulf of St. Lawrence. *Ibid.*, Ser. I, 3(4).

KERRY, J. G. G. 1947. Ice blockade of Canadian ports. The Dock and Harbour Authority. 27 (317 and 318), London.

1948. The St. Lawrence waterway. *Shipbuilding Register and Shipbuilder*, September.

KERSWILL, C. J. 1960. Effects of proposed Passamaquoddy Power project on anadromous fishes in Canadian waters. *J. Fish. Res. Bd. Canada*, **17**(5): 713–20.

KETCHUM, BOSTWICK, AND D. JEAN KEAN. 1953. The exchanges of fresh and salt waters in the Bay of Fundy and in Passamaquoddy Bay. *J. Fish. Res. Bd. Canada*, **10**(3): 97–124.

KINDLE, E. M. 1924. Observations on ice-borne sediments by the Canadian and other arctic expeditions. *Amer. Jour. Science, Fifth Series*, **7**(40): 251–286.

KING, E. J. 1931. On the colorimetric estimation of silica. *Contr. Canadian Biol. and Fish.*, N.S. **7**(10): 119–125.

KING, N. M. 1931. On the occurrence of silica in the waters of the Passamaquoddy Bay region. *Ibid.*, **7**(11): 127–137.

KLUGH, A. B. 1927. Light penetration into the Bay of Fundy and into Chamcook Lake, N.B. *Ecology*, **8**(1): 90–93.

KOENIG, L. S., K. R. GREENAWAY, M. J. DUNBAR AND G. HATTERLY-SMITH. 1952. Arctic ice islands. *Arctic*, **5**(2): 67–103.

KUENEN, P. N. 1952. Estimated size of the Grand Banks turbidity current. *Amer. J. Science*, **250**: 874.

KULLENBERG, B. 1954. Remarks on the Grand Banks turbidity current. *Deep-Sea Research*, **1**: 203–210.

LAUZIER, L. 1940. Contribution à l'océanographie physique du Saint-Laurent. *Ann. l'Acfas*, **6**: 98.

1941. Contribution à l'océanographie physique de la baie des Chaleurs. *Ibid.*, **7**: 124.

1941. Contribution à l'océanographie physique du golfe Saint Laurent. *Ibid.*, **7**: 124

1943. Étude de trois stations de 24 heures dans la baie des Chaleurs. *Ibid.*, **9**: 94.

1944. Contribution à l'étude des différentes masses d'eau dans le Saint Laurent. *Ibid.*, **10**: 101.

1952. Effect of storms on water conditions in the Magdalen Shallows. *J. Fish. Res. Bd. Canada*, **8**(5): 332–339.

1952. Recent water temperatures along the Canadian Atlantic coast. *Fish. Res. Bd. Canada, Prog. Rep. Atl.*, No. 53, pp. 5–7.

1953. The St. Lawrence Spring run-off and summer salinities in the Magdalen Shallows. *J. Fish. Res. Bd. Canada*, **10**(3): 146–147.

1954. Recent surface water temperatures along the Canadian Atlantic Coast. Cold and warm years. *Fish. Res. Bd. Canada, Prog. Rept. Atl.*, No. 58, pp. 6–10.

1957. Hydrographic features of the waters of the Bay of Islands, Newfoundland, in the autumn. *Fish. Res. Bd. Canada, Bull.*, No. 111, pp. 287–317.

1957. Variations of temperature and salinity in shallow waters of the southwestern Gulf of St. Lawrence. *Ibid.*, pp. 251–268.

1958. Surface sea water temperatures along the Canadian Atlantic coast, 1954–57. *Fish. Res. Bd. Canada, Prog. Reports Atl.*, No. 71, pp. 8–12.

LAUZIER, L., AND W. B. BAILEY. 1957. Features of the deeper waters of the Gulf of St. Lawrence. *Fish. Res. Bd. Canada, Bull.*, No. 111, pp. 213–250.

LAUZIER, L., W. B. BAILEY AND H. B. HACHEY. 1957. Some features of the surface of the surface layer of the Gulf of St. Lawrence. *Ibid.*, pp. 213–250.

LAUZIER, L. M., AND N. J. CAMPBELL. 1959. Comparison of some oceanographical features in the Labrador Sea and Davis Strait regions, 1928–1935 and 1950–1955. International Oceanographic Congress, Preprints, pp. 103–104.

LAUZIER, L., AND G. FILTEAU. 1948. Observations de température et de salinité à la station Laval 290 en 1946. Rapp. Stat. Biol. du Saint-Laurent, Univ. Laval, Appendix No. 5, Quebec.

LAUZIER, L., AND C. OUELLET. 1943. Détermination colorimétrique des nitrates dans l'eau de mer. *Ann. l'Acfas*, **9**: 94.

1943. Détermination colorimétrique de l'azote ammoniacal dans l'eau de mer. Nesslerization directe, modification de la méthode de Wattenberg. *Ibid.*, p. 24.

LAUZIER, L., AND J. L. TREMBLAY. 1945. Contribution à l'étude de l'oxygène dissous dans l'estuaire du St. Laurent. *Ann. l'Acfas*, **2**: 78.

1945. Oscillations de la nappe d'eau froide dans l'estuaire du Saint-Laurent. *Ibid.*, p. 78.

LAUZIER, L., AND R. W. TRITES. 1958. The deep waters in the Laurentian Channel. *J. Fish. Res. Bd. Canada*, **15**(6): 1247–1257.

LAUZIER, L., R. W. TRITES AND H. B. HACHEY. 1957. Some features of the surface layer of the Gulf of St. Lawrence. *Fish. Res. Bd. Canada, Bull.*, No. 111, pp. 195–212.

LEIM, A. H., AND H. B. HACHEY. 1936. A transgression of marginal waters over the Scotian Shelf. *Trans. Amer. Fish. Soc.*, **65**: pp. 279–283.

LEIM, A. H., S. N. TIBBO, L. R. DAY, L. LAUZIER, R. W. TRITES, H. B. HACHEY AND W. B. BAILEY. 1957. Report of the Atlantic Herring Investigation Committee. *Fish. Res. Bd. Canada, Bull.*, No. 111, 317 pp.

LONGARD, J. R. 1953. Modern instruments of physical oceanography and their uses in waters of Canadian interest. *Engineering Journal*, September.

LONGARD, J. R., AND R. E. BANKS. 1952. Wind induced vertical movement of the water on an open coast. *Trans. Amer. Geophys. Union*, **33**(3): 377–380.

LONGUET-HIGGINS, M. S., AND R. W. STEWART. 1960. Changes in the form of short gravity waves on long waves and tidal currents. *J. Fluid Mechanics*, **8**: 565–583.

MANCHESTER, LORNE. 1950. Science in fisheries. *Canadian Geograph. J.*, **41**(5): 1–23.

MARTIN, W. R. 1960. Predicted effects of proposed tidal power structures on groundfish catches in Charlotte County. *J. Fish. Res. Bd. Canada*, **17**(2): 169–173.

MAVOR, J. W. 1920. Circulation of waters in the Bay of Fundy and the Gulf of Maine. *Trans. Amer. Fish. Soc.*, **50**: 334–344.

1920. Drift bottles as indicating a superficial circulation in the Gulf of Maine. *Science*, N.S. **52**(1349): 442.

1921. On a bottle which drifted from the Gulf of Maine to the Azores. *Ibid.*, 53(1365): 187–188.

1921. Another drift bottle which crossed the Atlantic. *Ibid.*, 53(1373): 389.

1922. The circulation of water in the Bay of Fundy. I. Introduction and drift bottle experiments. *Contr. Canadian Biol.*, N.S. **1**(7): 103–124.

1923. The circulation of the water in the Bay of Fundy. II. The distribution of temperature, salinity and density in 1919 and the movements of the water which they indicate in the Bay of Fundy. *Ibid.*, **1**(8): 101–124.

MCCRACKEN, L. H. 1955. The salinity of sea water. *Fish. Res. Bd. Canada, Prog. Rept. Pac.*, No. 102, pp. 24–26.

M'GONIGLE, R. H. 1925. Marine borers of the Atlantic coast of Canada. Rept. 15, National Research Council of Canada. Ottawa, 67 pp.

1926. A further consideration of the relation between the distribution of Teredo Navalis (Linné) and the temperature and salinity of its environment. Rept. 20, National Research Council of Canada. Ottawa, 31 pp.

MACGREGOR, D. G. 1900. Currents and transport in Cabot Strait, 1956. *J. Fish. Res. Bd. Canada*, **13**(3): 435–448.

MacGregor, D. G., and H. J. McLellan. 1952. Current measurements in the Grand Manan Channel. *Ibid.*, **9**(5): 213–222.

McIntosh, D. S. 1915. Notes on an abnormal wave occurrence on the northern Cape Breton coast. *Proc. and Trans. Nova Scotia Inst. Sci.*, **14**: 41–46.

McKenzie, R. A., and H. B. Hachey. 1939. The cod fishery and the water temperature on the Scotian Shelf. *Fish. Res. Bd. Canada, Prog. Rept. Atl.*, No. 24, pp. 6–9.

McLean, N. B. 1927. Report on the Hudson Strait Expedition to Dec. 21st. King's Printer, Ottawa, 76 pp.

McLean, N. B. 1929. Report of the Hudson Strait Expedition. F. C. Acland, Ottawa, 221 pp.

McLellan, H. J. 1952. Fluctuating inshore water temperature in the autumn. *Fish. Res. Bd. Canada, Prog. Rept. Atl.*, No. 53, pp. 3–5.

1954. Bottom temperatures on the Scotian Shelf. *J. Fish. Res. Bd. Canada*, **11**(4): 404–418.

1954. Temperature–salinity relations and mixing on the Scotian Shelf. *Ibid.*, **11**(4): 419–430.

1954. Bottom temperatures on the Scotian Shelf. I. Spring (1952). *Fish. Res. Bd. Canada, Prog. Rept. Atl.*, No. 58, pp. 23–27.

1954. Water conditions in the Strait of Canso before closing. *Fish. Res. Bd. Canada, Prog. Rept. Atl.*, No. 59, pp. 7–12.

1954. Bottom temperatures on the Scotian Shelf. II. Summer (1952). *Ibid.*, No. 59, pp. 12–15.

1955. Bottom temperatures on the Scotian Shelf. III. Autumn (1952). *Ibid.*, No. 60, pp. 19–21.

1955. Bottom temperatures on the Scotian Shelf. IV. Winter (1952). *Ibid.*, No. 61, pp. 10–11.

1955. Bottom temperatures on the Scotian Shelf. V. Summary. *Ibid.*, No. 62, pp. 14–17.

1955. Changes in bottom temperatures on the Scotian Shelf. *J. Fish. Res. Bd. Canada*, **12**(3): 375–386.

1955. Major offshore projects of the Atlantic Oceanographic Group. *Trans. Am. Geophys. Union*, **36**(3): 520.

1955. Hydrography can help you haul in more fish. *Canadian Fisherman*, **42**(10): pp. 6, 8, 31.

1956. On the sharpness of oceanographic boundaries south of Nova Scotia. *J. Fish. Res. Bd. Canada*, **13**(3): 297–301.

1957. On the distinctness and origin of the slope water off the Scotian Shelf and its easterly flow south of the Grand Banks. *Ibid.*, **14**(2): 213–239.

1958. Energy considerations in the Bay of Fundy. *Ibid.*, **15**(2): 115–134.

McLellan, H. J., and L. Lauzier. 1956. The prediction of water temperatures. *Canadian Fisherman*, **43**(9): 11–12.

1957. Refroidissement probable des eaux dans l'Atlantique du nord-ouest. *La Pêche Maritime*, **36**(948): 104.

McLellan, H. J., L. Lauzier and W. B. Bailey. 1953. The slope water off the Scotian Shelf. *J. Fish. Res. Bd. Canada*, **10**(4): 155–176.

MacNeil, D. J. 1956. The transverse troughs of Cabot Strait and the Strait of Canso. *Trans. Roy. Soc. Canada*, **50**: Ser. III: 39–46.

Melvill, C. D., A. R. M. Lower and Nap. A. Comeau. 1915. Reports on fisheries investigations in Hudson and James Bay and tributary waters. Dept. of Naval Service, Sessional Paper No. 39A. Ottawa, 85 pp.

METCALF, W. G. 1954. A note on Arctic oceanography and the Lomonosov Range. *Arctic*, **7**(2): 108–109.

MONTGOMERY, MARGARET R. 1952. Further notes on ice islands in the Canadian Arctic. *Ibid.*, **5**(3): 183–187.

MURPHY, M. 1888. The tides of the Bay of Fundy. *Proc. and Trans. Nova Scotia Inst. Sci.*, **7**(1): 48–62.

NADEAU, A. 1938. Salinité des eaux de l'estuaire du Saint-Laurent. Contr. de la Stat. Biol. du Saint-Laurent. Univ. Laval, N° 11.

NEEDLER, A. W. H. 1941. Temperatures and salinities under the ice in a shallow inlet. *J. Fish. Res. Bd. Canada*, **5**(3): 236–243.

NUTT, DAVID C. 1951. The "Blue Dolphin" Labrador Expedition, 1949 and 1950. *Arctic*, **4**(1): 3–11.

1953. Certain aspects of oceanography in the coastal waters of Labrador. *J. Fish. Res. Bd. Canada*, **10**(4): 177–186.

NUTT, DAVID C., AND LAWRENCE K. COACHMAN. 1956. The oceanography of Hebron Fjord, Labrador. *Ibid.*, **13**(5): 709–758.

OLSEN, STEINAR. 1960. Observations on sound scatterers in Newfoundland waters. *Ibid.*, **17**(2): 211–219.

POOLE, N. S. 1904. Subsidence of Atlantic Coast of Nova Scotia. *Trans. Nova Scotia Inst. Sci.*, **2**.

PRIEST, W. H. 1901. On drift ice as an eroding and transporting agent. *Trans. Nova Scotia Inst. Sci.*, **10**(3).

RIDDELL, W. A. 1936. The reduced strychnine method for determining nitrates in sea water. *J. Fish. Res. Bd. Canada*, **2**(1): 1–11.

SANDSTROM, J. W. 1919. The hydrodynamics of Canadian Atlantic waters. Canadian Fish. Exped. 1914–15. Ottawa, pp. 211–345.

SAWYER, W. R. 1931. The spectral absorption of light by pure water and Bay of Fundy waters. *Contr. Canadian Biol. and Fish.*, N.S. **7**(8): 73–89.

SMITH, M., AND E. R. POUNDER. 1960. Impurity concentration profiles in ice by an anthrone method. *Canadian J. Physics*, **38**(3): 354–368.

STEWART, R. W. 1956. A new look at the Reynold's stresses. *Canadian J. Physics*, **34**: 722–25.

1959. The problem of diffusion in a stratified fluid. *Advances in Geophysics*, **6**: 303–11.

1959. The natural occurrence of turbulence. *J. Geophysical Research*, **64**: 2112–15.

STRICKLAND, J. D. H. 1958. Solar radiation penetrating the ocean. A review of requirements, data and methods of measurement, with particular reference to photosynthetic productivity. *J. Fish. Res. Bd. Canada*, **15**(3): 453–493.

1959. Assessment of the accuracy and precision of data. Physical and chemical properties of sea water. National Academy of Sciences—National Research Council, Publ. 600. Washington, pp. 68–100.

1960. Measuring the production of marine phytoplankton. *Fish. Res. Bd. Canada, Bull.*, No. 122, 172 pp.

STRICKLAND, J. D. H., AND K. H. AUSTIN. 1959. The direct estimation of ammonia in sea water. *J. du Conseil*, **24**(3): 446–451.

STRICKLAND, J. D. H., AND T. R. PARSONS. 1961. A manual of sea water analysis (With particular reference to the more common micronutrients and to particulate organic material). *Fish. Res. Bd. Canada, Bull.*, No. 125, 185 pp.

TEMPLEMAN, W., AND A. M. FLEMING. 1953. Long term changes in hydrographic conditions and corresponding changes in the abundance of marine animals. *Ann. Proc. Inter. Comm. Northwest Atlantic Fisheries*, **3**: 79–86.

THOMPSON, H., AND A. M. WILSON. 1934. Hydrographic and biological investigations. A. Hydrographic conditions in 1934. Report Newfoundland Fishery Research Laboratory. Appendix B, Department of Resources, 2(3), St. John's.

1935. Hydrographic and biological investigations. A. Hydrographic conditions in 1935. *Ibid.*, 2(5).

TREMBLAY, J. L. 1946. L'évolution de la température des eaux superficielles à Grande Rivière, Baie des Chaleurs en 1943. Stat. Biol. du St. Laurent, Cinquième rapport, Quebec.

TREMBLAY, J. L., AND L. LAUZIER. 1940. L'origine de la nappe d'eau froide du St. Laurent. *Le Naturaliste Canadien*, **67**: 5–23.

1942. Explication de minimum de température des eaux de surface à Grande Rivière en juillet 1940. *Ann. l'Acfas*, No. 7.

TRITES, R. W. 1956. The ocean floor and water movements. *Trans. Roy. Soc. Canada*, **50**, Ser. III: 83–91.

1960. An oceanographical and biological reconnaissance of Kennebecasis Bay and the Saint John River estuary. *J. Fish. Res. Bd. Canada*, **17**(3): 377–408.

TRITES, R. W., AND R. E. BANKS. 1958. Circulation on the Scotian Shelf as indicated by drift bottles. *Ibid.*, **15**(1): 79–89.

TULLY, J. P. 1948. Prediction of pulp mill pollution. *Western Pulp and Paper*, December.

1953. Oceanography–Science of the sea. *Canadian Geograp. J.*, **47**: 148–165.

1958. On structure entrainment and transport in an estuarine embayment. *J. Marine Research*, **17**: 523–535.

1960. Recent advances in oceanography. American Peoples Encyclopedia Yearbook 1960. Chicago, p. 764.

1960. The Northwest Passage. McGraw-Hill Encyclopedia of Science and Technology, New York.

1960. Arctic Ocean. *Ibid.*

VACHON, ALEXANDER. 1918. Hydrography in Passamaquoddy Bay and vicinity. Canada Dept. Naval Service, Suppl. 7th Ann. Rept. Fish. Branch, Ottawa.

VACHON, A., R. GAUDRY AND R. BERNARD. 1938. Contribution à l'étude des phosphates dans l'estuaire du St. Laurent. Contr. Stat. Biol. St. Laurent à Trois Pistoles, No. 12, Quebec.

VAVASOUR, G. R., AND A. A. BLAIR. 1955. Pollution survey of Humber Arm and Exploits River. *J. Fish. Res. Bd. Canada*, **12**(5): 682–697.

WAKEHAM, W. 1898. Report of the expedition to Hudson Bay and Cumberland Gulf in the steamship "Diana". Ottawa, 83 pp.

WATSON, E. E. 1936. Mixing and residual currents in tidal waters as illustrated in the Bay of Fundy. *J. Biol. Bd. Canada*, **2**(2): 141–208.

1950. The Gulf Stream. *Queen's Quarterly*, **57**(1).

1953. An experiment to determine the hydrodynamic forces on a cable inclined to the direction of flow. *J. Marine Research*, **12**(3): 245–248.

WHITEAVES, J. F. 1872. Report on a deep sea dredging expedition to the Gulf of St. Lawrence. Canada Dept. Marine and Fish. 4th Ann Report.

WILDER, D. G. 1960. Possible effects of Passamaquoddy tidal power structures on the Canadian lobster industry. *J. Fish. Res. Bd. Canada*, **17**(4): 553–63.

WILLIAMS, G. P. 1959. Frazil ice. A review of its properties, with a selected bibliography. *Engineering J.*, 42(11): 55–60.

1961. A study of winter water temperatures and ice prevention by air bubbling. *Ibid.*, 44(3): 79–84.

WILLMORE, P. L., AND A. E. SCHEIDEGGER. 1956. Seismic observations on the structure of the St. Lawrence Gulf. *Trans. Roy. Soc. Canada*, **50**, Ser. III: 21–38.

WILLMORE, P. L., AND R. TOLMIE. 1956. Geological observations concerning the history and structure of Sable Island. *Ibid.*, 13–20.

WILSON, A. M. 1938. Hydrographic conditions in the Newfoundland area for years 1931–35. Newfoundland Fishery Research Laboratory, Annual Report, 1936–37.

WILSON, J. T. 1900. Hidden Ranges of the Sea. Navy. *Navy League of the United States*, 2(7): 28–29.

YOUNG, E. GORDON, D. G. SMITH AND W. M. LANGILLE. 1959. The chemical composition of sea water in the vicinity of the Atlantic Provinces of Canada. *J. Fish. Res. Bd. Canada*, **16**(1): 7–12.

SELECTED BIBLIOGRAPHY

ANON. 1934. James Johnstone Memorial Volume. Lancashire Sea-Fisheries Laboratory. Univ. Press, Liverpool, 348 pp.

1942. A report on the climatology and tropical synoptic situations of the North Atlantic. Mass. Inst. Technology, Cambridge, 87 pp.

1952. Contributions to special scientific meetings, 1951. Fisheries hydrography. *Cons. Per. Inter. pour l'Exporation de la Mer, Rapports et Procès-Verbaux*, **81**: 1–113.

1955. Bibliography on tides 1665–1939. Association of Physical Oceanography, Scientific Publ. No. 15. Göteborg.

1957. Bibliography on tides, 1940–1954. *Ibid.*, No. 17. Göteborg, 63 pp.

ARMSTRONG, E. F., AND L. M. MIALL. 1946. Raw materials from the sea. Constructive, Leicester, 164 pp.

BERRILL, N. J. 1951. The living tide. Dodd, Mead & Co., New York, 256 pp.

BIGELOW, H. B. 1927. Physical oceanography of the Gulf of Maine. *U.S. Dept. Comm. Bur. Fish. Bull.*, **40**(2), Doc. 969. Washington, pp. 511–1027.

BIGELOW, H. B. 1931. Oceanography. Haughton Mifflin, Boston, 263 pp.

BIGELOW, H. B., AND W. R. EDMONDSON. 1947. Wind waves at sea, breakers and surf. U.S. Hydrographic Office, Publ. No. 602. Washington, 177 pp.

BISHOP, YVONNE, NEAL M. CARTER, DOROTHY GAILUS, W. E. RICKER AND J. MURRAY SPEIRS. 1957. Index and list of titles, publications of the Fisheries Research Board of Canada, 1901–1954. *Fish. Res. Bd. Canada, Bull.*, No. 110, 209 pp.

BOLIN, BERT. 1959. The atmosphere and the sea in motion. Oxford Univ. Press, 509 pp.

CARSON, Rachael. 1951. The sea around us. Oxford University Press, 230 pp.

CHURCH, PHIL. E. 1937. Temperatures of the Western North Atlantic from thermograph records. Assoc. d'Océanographie Physique, Publ. Scientifique No. 4, 32 pp.

DEFANT, ALBERT. 1960. Physical oceanography, Vol. 1 and 2. Pergamon Press, Oxford, 1200 pp.

DOODSON, A. T., AND H. D. WARBURG. 1941. Admiralty manual of tides. H.M. Stationery Office, 270 pp.

DUNBAR, M. J. 1946. The state of the West Greenland current up to 1944. *J. Fish. Res. Bd. Canada*, **6**(7): 460–71.

1951. Eastern Arctic waters. *Fish. Res. Bd. Canada, Bull.* No 88, 131 pp.

DUNBAR, MOIRA, AND KEITH R. GREENWOOD. 1956. Arctic Canada from the air. Defence Research Board. Queen's Printer, Ottawa, 541 pp.

EWING, MAURICE, J. LAMAR WORZEL AND C. L. PEKERIS. 1948. Propagation of sound in the ocean. Geological Society of America, Memoir 27.

GANS, M. 1926. Das Hudsonmeer. *Arch. Deutsch. Seewarte*, **44**(1): 133.

GREGORY, J. W. 1929. The earthquake South of Newfoundland and Submarine Valleys. *Nature*, **124**: 945.

HARE, F. K., AND M. R. MONTGOMERY. 1949. Ice, open water, and winter climate in the Eastern Arctic of North America. II. The problem of winter ice. *Arctic*, **2**(3): 149–64.

HARVEY, H. W. 1928. Chemistry and physics of seawater. Cambridge Univ. Press, 194 pp.

1955. The chemistry and fertility of seawaters. Cambridge Univ. Press, 224 pp.

HECK, N. H., *et al.* 1932. Physics of the earth. V. Oceanography. *National Research Council, Bull.*, No. 85. Washington, 581 pp.

HJORT, JOHAN. 1919. Canadian Fisheries Expedition 1914–15. Canada Dept. of Naval Service. King's Printer, Ottawa, 495 pp.

HERDMAN, W. A. 1923. Founders of oceanography and their work. Arnold & Co.

HUMPHREYS, W. J. 1929. Physics of the air. McGraw-Hill Book, Co., New York, 527 pp.

HUNTSMAN, A. G. 1930. Arctic ice on our Eastern Coast. *Biol. Bd. Canada, Bull.*, No. 13, 12 pp.

INTERNATIONAL ATOMIC ENERGY AGENCY. 1960. Conference Proceedings Monaco, 16–21 November, 1959. Disposal of radioactive wastes. Vol. 1 (603 pp.); Vol. 2 (575 pp.). Kartner Ring, Vienna.

ISELIN, C. O'D. 1936. A study of the circulation of the western north Atlantic. *Papers in Physical Oceanography and Meteorology*, **4**(4): 1–101, Cambridge, Mass.

1940. Preliminary report on long-period variations in the transport of the Gulf Stream System. *Ibid.*, **8**(1): 1–40.

JOHNSON, D. W. 1925. The New England–Acadian shoreline. John Wiley and Sons, New York, 608 pp.

JOHNSTONE, J. 1923. An introduction to oceanography. Hodder and Stoughton, London, 351 pp.

KNUDSEN, M. 1901. Hydrographic tables. Copenhagen, 63 pp.

KRUMMEL, O. 1907. Handbuch der ozeanographie. Vol. 1. Stuttgart, 526 pp.

1911. *Ibid.*, Vol. 2, pp. 526–766.

KUENEN, P. H. 1950. Marine geology. John Wiley & Sons, New York, 568 pp.

LE DANOIS, ED. 1934. Les transgressions océaniques. *Offi. Sci. Tech. Peches Maritimes, Revue des Travaux*, **7**(4), No. 28: 369–462.

1936. Les transgressions océaniques. Bull. Inter. océaniques, No. 613, Monaco.

MACINTYRE, R. L. 1961. Lists of titles of publications of the Fisheries Research Board of Canada, 1955–1960. *Fish. Res. Bd. Canada Circular*, No. 58, 94 pp.

MARMER, H. A. 1926. The tide. Appleton, New York, 282 pp.

1930. The sea. Appleton, New York, 312 pp.

MOUTON. 1952. The continental shelf. Martinus Nijholl, The Hague, 367 pp.

MURRAY, SIR JOHN, AND J. HJORT. 1912. The depths of the ocean. MacMillan and Co., London, 821 pp.

O'HARE J. E., O. H. CARLSON AND W. E. TAMBLYN. 1954. Some results of a tanker survey of the Gulf Stream. *Trans. Amer. Geophysical Union*, **35**(3): 420–430.

PETTERSON. 1954. The ocean floor. Yale Univ. Press, New Haven, 181 pp.

PROUDMAN, J. 1952. Dynamical Oceanography. John Wiley & Sons, Inc., New York, 409 pp.

RUSSELL, R. C. H., AND D. H. MACMILLAN. 1953. Waves and tides. Philosophical Library, New York, 348 pp.

SEIWELL, H. R. 1937. Short-period vertical oscillations in the western basin of the North Atlantic. *Papers in Physical Oceanography and Meteorology*, **5**(2): 1–44, Cambridge, Mass.

SHEPARD, F. P. 1931. The St. Lawrence submarine trough. *Bull. Geol. Soc. Amer.*, **42**: 853–64.

1948. Submarine geology. Harper & Bros., New York, 348 pp.

1959. The earth beneath the sea. The John Hopkins Press, Baltimore, 265 pp.

SMITH, EDWARD H. 1926. A practical method for determining ocean currents. *U.S. Coast Guard Bull.*, No. 14. Washington, 50 pp.

SMITH, N. E., F. M. SOULE AND O. MOSBY. 1937. The Marion and General Greene expeditions to Davis Strait and Labrador Sea. *U.S. Coast Guard Bull.*, No. 19. (Pt. 1, 81 pp., 1932; Pt. 2, 199 pp., 1937; Pt. 3, 216 pp., 1931). Washington.

STOMMEL, HENRY. 1958. The Gulf Stream. Univ. California Press, 202 pp.

SVERDRUP, H. U., M. W. JOHNSON AND R. H. Fleming. 1942. The oceans. Prentice-Hall, Inc., New York, 1087 pp.

SVERDRUP, H. U., AND W. H. MUNK. 1947. Wind, sea and swell: Theory of relations for forecasting. U.S. Hydrographic Office, Publ. No. 601. Washington, 44 pp.

SWITHINBANK, CHARLES. 1960. Ice atlas of Arctic Canada. Queen's Printer, Ottawa, 67 pp.

TRASK, P. D. 1939. Recent marine sediments. American Association of Petroleum Geologists. Tulsa, Oklahoma, 736 pp.

TREMAINE, MARIE. 1953–60 (not complete). Arctic bibliography. Vol. I–IX. Arctic Institute of North America. Montreal.

UNITED STATES DEPT. COMMERCE, COAST AND GEODETIC SURVEY. 1938. Manual of current observations. Special Publ. No. 215. Washington, 75 pp.

UNITED STATES TREASURY DEPT. COAST GUARD BULLETINS. 1912 to date. Annual Reports of the International Ice Patrol, Washington.

WALFORD, LIONEL A. 1958. Living resources of the sea. Ronald Press Co., New York, 321 pp.

WARBURG, H. D. 1922. Tides and tidal streams. Cambridge University Press, London, 95 pp.

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