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THE GULF STREAM

METHODS OF THE INVESTIGATION

AND

RESULTS OF THE RESEARCH

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By JOHN ELLIOTT PILLSBURY, Lieutenant U. S. Navy,
Assistant, U. S. Coast and Geodetic Survey

APPENDIX No. 10—REPORT FOR 1890

WASHINGTON
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1891

National Oceanic and Atmospheric Administration

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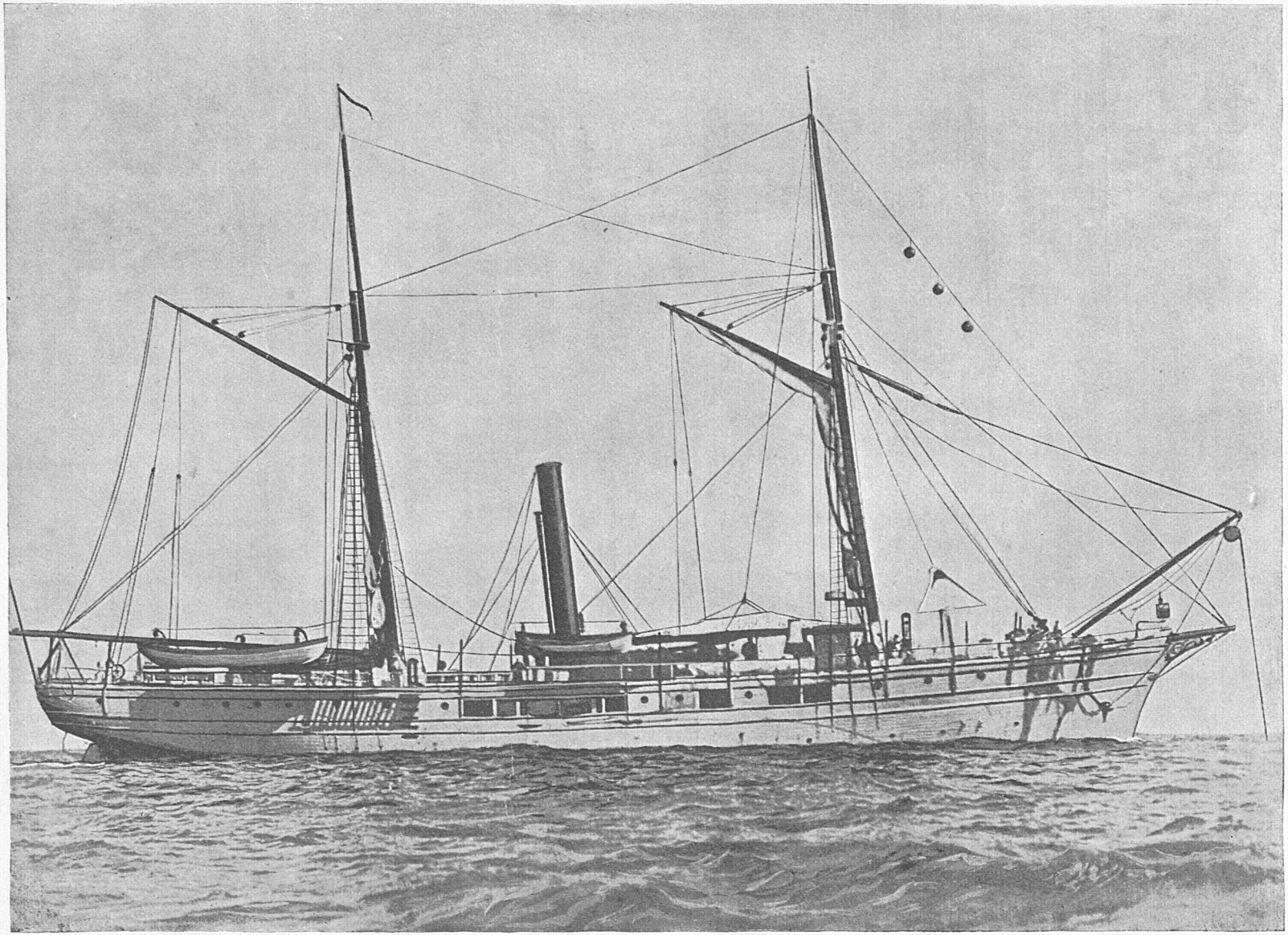

U. S. COAST AND GEODETIC SURVEY STEAMER GEORGE S. BLAKE.

APPENDIX No. 10—1890.

THE GULF STREAM—A DESCRIPTION OF THE METHODS EMPLOYED IN THE INVESTIGATION, AND THE RESULTS OF THE RESEARCH.

By JOHN ELLIOTT PILLSBURY, Lieutenant, U. S. Navy,
Assistant U. S. Coast and Geodetic Survey.

[Submitted for publication August 30, 1890.]

PREFACE.

The writer, while executive officer of the United States Coast and Geodetic Survey steamer *Blake*, devised an instrument in 1876 for the purpose of ascertaining the direction and velocity of the currents at any depth. This was intended to be used from a boat at anchor and to replace the system then in use, viz, floating and submerged cans with a log line.

Before the model could be tried he was ordered to other naval duty, and nothing further was attempted with the instrument until he was detailed for command of the same vessel in 1884. Permission was then granted by the Superintendent of the Coast and Geodetic Survey, at the request of the Hydrographic Inspector, Commander C. M. Chester, U. S. Navy, to have one of these instruments made with a view of using it on board the *Blake* while at anchor in the Gulf Stream. This current-meter has been used since that time, and the method devised for anchoring the vessel has been entirely successful up to 2,180 fathoms, the greatest depth attempted. This memoir has been written to describe the methods employed in the investigation of the Gulf Stream and the results of the research.

During the five years the writer commanded the *Blake* he received every encouragement and support from the officers of the Coast Survey.

The Hydrographic Inspectors, Commanders C. M. Chester and C. M. Thomas and Lieut. Commander W. H. Brownson, who were charged with the duty of supervising all hydrographic work, left it to the discretion of the commanding officer to decide all questions connected with the work. The Superintendents, Mr. F. M. Thorn and Dr. T. C. Mendenhall, have been most liberal in the allotment of the necessary money, and their instructions have been only the most general as to the time and locality of the examinations.

As a preliminary to the report of the work of the *Blake*, a history of previous investigations of the Gulf Stream has been inserted. Great assistance in preparing this portion has been derived from the manuscripts on the subject which were written for the Coast Survey by Dr. J. G. Kohl, Prof. W. P. Trowbridge, and Mr. O. H. Tittmann, Assistant, and also from the valuable collection of maps at the library of Harvard University, to which I have had free access through the kindness of the librarian, Mr. Justin Winsor.

JOHN ELLIOTT PILLSBURY,
Lieutenant, U. S. Navy,
Assistant Coast and Geodetic Survey.

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THE GULF STREAM.

INTRODUCTION.

Geography, the science that gives to us a knowledge of the earth's surface, is divided into two branches: first, all that pertains to the configuration, usually called geography, and second, everything relating to the natural forces acting thereon, called physical geography. These subjects are interlaced with the study of nearly every branch of human knowledge tending toward the good of the race in its struggle toward improvement. At first the pursuit of wealth by the discovery of new lands and peoples, brought about a study of the configuration of the surface, but little by little it was seen that the study also of the physical forces assisted toward this end and to the ease and comfort of mankind at large.

The Sun without doubt is the greatest factor in the support of terrestrial life, but his intense heat is tempered and governed by the elements, air and water, without which life as at present constituted on our globe would be unsupportable. The total area of the earth's surface is about 200,000,000 square miles, and of this only about one-fourth is land. The mean elevation of the land above the sea is less than 2,500 feet, while the mean depth of the ocean is probably about 12,000 feet. The total volume of the land above the sea level, therefore, is only about one twentieth of the volume of the ocean.

The surface of the ground quickly becomes heated by the direct rays of the sun, but it also quickly radiates its heat into the air, producing an aërial current. The surface of the water, on the other hand, absorbing the sun's heat, rapidly communicates it to the adjoining stratum, and, radiation from its surface being comparatively slow, its currents transfer the heat so acquired to distant points. The tempering influence on the climate is the wind, taking the heat and moisture from this heated water and transferring

it to the land. It is argued most forcibly that such a stupendous change in the climatology of the world as existed during the glacial period was caused by the precession of the equinoxes and the change in the eccentricity of the earth's orbit effecting an alteration in the great heat distributors, the ocean currents.

To commerce and navigation the study of these currents is of the utmost value. The length of the voyage is shortened, and the chance of safety to vessel, cargo, and lives is increased. A strong wind against a current produces a dangerous sea, and, by a knowledge of the laws of the water's flow, a vessel, by a trifling change of course, may escape the danger.

I venture to quote from a brochure on the subject of the Gulf Stream, by His Highness, Albert, Prince of Monaco. He says:

> Zoological geography may consider them [ocean currents] as highways which unite the zones of the ocean, and consequently cause the dissemination of species, and at the same time by the intensely progressive attenuation of salt and the temperature of these waters this highway facilitates the evolution of species. It is thus that the currents enter into the question so important to origins, monogenism, or polygenism.
>
> Anthropology, for example, holds them responsible for the solution of the great problem, that of human migrations, which spread even to the distant archipelagos the different varieties of the race *man*, at the time when there was scarcely a discernible difference between man and beast, and he had at his disposal only rudimentary means for struggling against the brute forces of nature.
>
> Botany and zoology ought to be interested in our researches, for the conditions of organic life in all its bearings are governed by these currents either warm or cold, which give to subterranean regions a veritable climate; and it is perhaps owing to certain disturbances which have taken place in the volume, direction, and temperature of these currents that the almost entire disappearance of several kinds of migratory fish is attributed, as, for example, that of the sardines, which formerly lined the coasts of France in countless numbers.
>
> It concerns geology also, for the oceans receive a deposit, the organic and mineral detritus which the winds and waves bring to it, the stones which the glaciers wrest from the polar regions and which the icebergs carry to the temperate regions. The sea currents charge themselves with distributing all these minerals

according to certain laws, and in this manner collections are formed which in later times convulsions of the earth bring to light.

Paleontology itself ought to be interested in our researches, for is it not evident that the rivers, drifting dead bodies across the continents, deposit them on sand banks far from their habitat to become the fossils of the future?

There is another reason for studying these currents which will ultimately have the most beneficial influence on mankind. It is now known that the currents vary through certain forces acting upon them, by periodic changes, entirely according to law, and again through apparently erratic forces. Probably every motion of these vast bodies is absolutely governed by laws which can be ascertained. The moisture and varying temperature of the land depends largely upon the positions of these currents in the ocean, and it is thought that when we know the laws of the latter we will, with the aid of meteorology, be able to say to the farmers hundreds of miles distant from the sea, "you will have an abnormal amount of rain during next summer," or "the winter will be cold and clear," and by these predictions they can plant a crop to suit the circumstance or provide an unusual amount of food for their stock. We will be able to say to the mariner, at such time the current will be so much an hour in such a direction, and the percentage of error will be but trifling. From a study of these great forces, then, we derive our greatest benefits, and any amount of well-directed effort to gain a complete mastery of their laws will revert directly to the good of the human race.

In the Atlantic Ocean the currents are probably more pronounced than in either the Pacific or Indian Oceans. Without entering upon a discussion at this point as to the causes of ocean flow or of any particular current, a brief description of the main streams will not be out of place, for they are all connected more or less intimately with our own Gulf Stream. The equatorial current is usually described as being a broad band of water moving slowly across the Atlantic in the tropics. The portion situated south of the equator is divided into two parts upon meeting the resistance of Cape St. Roque, the eastern salient point of the South American coast. One branch turns to the southward toward the Antarctic, and the other is forced to the westward along the shores of Brazil and Guyana. This

branch is called the Guyana Coast current. The equatorial current has north of the equator an almost uninterrupted progress until it reaches the Windward Islands, but a portion of it impinges against the South American coast and perhaps increases the volume of the northern branch of the south equatorial current. At the Windward Islands all are united, and a portion of the water enters the Caribbean to assist in forming the Gulf Stream. Between the northern and southern portions of the equatorial current is the Guinea current, setting toward the east and southeast into the Gulf of Guinea. It was formerly thought to be a continuation of the North African current, "but later investigation," Findlay says, "seems to point to the fact that it is a flowing back of the waters heaped up to the westward by the prevalent winds." It seems to run strongest in the summer months, when it is felt as far west as longitude 45°, while in the winter it reaches only as far as the twenty-third meridian. In the Northern Atlantic Ocean the Labrador current sweeps down from the Arctic along the eastern shores of Greenland and from Baffin's Bay and passes the coasts of Labrador and Newfoundland, bearing with it vast fields of ice and enormous bergs. Reaching the Gulf Stream, it is said to underrun the latter, and also in part form a counter-current to the southward along our coast as far south as Cape Hatteras, or even to Cape Canaveral.

The Gulf Stream, the grandest and most mighty of any terrestrial phenomenon, receives its waters from the Caribbean Sea through the Straits of Yucatan. It is commonly said that a portion doubles Cape San Antonio and enters the Straits of Florida at once, while another part, after making the tour of the Gulf of Mexico, joins the first in its flow to the northward. Its waters are characterized by a deep blue color, great clearness, and high temperature. The eye can penetrate it to considerable depths, and frequently its meeting with the colder water from the polar regions can be at once distinguished.

It is difficult for the mind to grasp the immensity of this great ocean river. The observations taken at its narrowest point were between three and four thousand in number, surface and subsurface, and a calculation of the average volume passing Cape Florida in one hour gives the enormous sum of 90,000,000,000 tons. If this one hour's water were evaporated, the

remaining salt would require more than one hundred times the number of sea-going vessels now afloat in the world to carry it. That this wonderful body is governed by law in all its motions there can be no doubt. It has its daily and monthly variations in velocity, direction, and temperature, changing with as perfect regularity as the tides in a harbor. Nor do I doubt that it has also a yearly fluctuation, and perhaps others occupying a cycle of many centuries to complete.

The Gulf Stream after leaving the Straits of Florida pursues a general northeasterly direction, pressing close to Cape Hatteras, passing between Bermuda and Nova Scotia, and as a defined and permanent stream is soon afterwards lost. Currents are found in the vicinity of the Azores Islands setting about southeast, and also on the coast of Africa setting south, which are sometimes called the southeast extension of the Gulf Stream. Warm water is found off the coasts of Ireland, Scotland, and Norway, giving evidence of a tropical flow, and this is called the northeast extension of the Stream. Whether or not these currents are wholly formed of the water issuing from the Straits of Florida remains to be discussed later.

Man stands with bowed head in the presence of nature's visible grandeurs, such as towering mountains, precipices, or icebergs, forests of immense trees, grand rivers, or waterfalls. He realizes the force of waves that can sweep away light-houses or toss an ocean steamer about like a cork. In a vessel floating on the Gulf Stream one sees nothing of the current and knows nothing but what experience tells him; but to be anchored in its depths far out of the sight of land, and to see the mighty torrent rushing past at a speed of miles per hour, day after day and day after day, one begins to think that all the wonders of the earth combined can not equal this one river in the ocean.

CHAPTER I.

GENERAL HISTORICAL ACCOUNT OF THE GULF STREAM AND ITS INVESTIGATIONS UP TO THE TIME OF FRANKLIN.

Before the time of Columbus's grand discovery of the New World the coasting vessels of the Old must have recognized that there were currents in the Atlantic Ocean which were entirely independent of the tides; but the first indication that currents on the coast of North America were noticed is found in the writings of the Northmen in their description of voyages to America. Several suggestive names were given to prominent objects of discovery, such as Straumsoe (Isle of Currents), Straumsfjörde (Bay of Currents), and Straummes (Cape of Currents), but their exact location can not be identified. Some claim that the voyages extended even to Florida, but it seems probable from later investigations that the points named were all in the vicinity of Cape Cod.

Columbus, before undertaking his voyage of discovery toward the west, resided for some time on the island of Porto Santo, and it was here that he was shown a piece of curiously carved wood that had evidently drifted there from other lands. Strange woods and other floating objects were continually being thrown upon the shores of Norway, Scotland, and Ireland, all of which, to a thoughtful mind like that of Columbus, must have induced the belief that there were other lands at no great distance to the west, and so it is probable that to the Gulf Stream in part the world owes the discovery of America.

In actual observations in the Gulf Stream, or rather in the currents contributing to it, Columbus was the pioneer. It is related that September 19, 1492, he sounded with a deep-sea line, and the lead, passing through the surface drift into the dead water below, showed at once that there was a current setting his vessels to the southward and westward. On his subsequent voyages he remarked the strong currents of the Caribbean Sea. He says, for example, "When I left the Dragon's mouth" (the northern

entrance to the Gulf of Paria) "I found the sea ran so strongly to the westward that between the hour of Mass, when I weighed anchor, and the hour of Complines, I made 65 leagues of 4 miles each with gentle winds." He also says of the currents entering the Caribbean between the Windward Islands, "I hold it for certain that the waters of the sea move from east to west with the sky, and that in passing this track they hold a more rapid course, and have thus carried away larger tracts of land, and that from hence has resulted the great number of islands."

On his fourth voyage Columbus discovered and noted the strength of the current on the coast of Honduras, although it is probable that at this time the Gulf Stream itself in the Straits of Florida had been found by independent navigators. Peter Martyr says "he left in wryting that sailing from the Island of Guanassa toward the east he found the course of the waters so vehement and furious agaynst the fore part of his ship that he could at no time touch the ground with his sounding plummet, but that the contrary violence of the waters would bear it up from the bottom. He affirmeth also that he could never in one day with a good wynde wynn one mile of the course of the waters."

Columbus speculated as to the cause of these currents. He thought that the equatorial waters followed the motions of the heavens about the world—that is, the rotary motion by which the stars and air revolve about the globe (as was the opinion of the time), so also the water was supposed to partake of the same motion.

John and Sebastian Cabot, in 1497, crossed the North Atlantic Ocean, rediscovering the coast of Labrador. From this point they steered to the southward and westward, "so coasting still by the shore that he was brought so far into the south by reason of the land bending so much to the southward that he was then almost equal in latitude to the sea called Fretum Herculeum, having the north pole elevate in manner in the same degree. He sayled likewise in this track so far towarde the weste that he hadde the Island of Cuba in his left hande in manner in the same degree of longitude." * * * "He sayeth that he found the like course of the waters towarde the west, but the same to run more softly and gently than the swift waters which the Spanyards found in their navigation southward."

It is probable that the Cabots did not double Cape Hatteras and discover the Gulf Stream. It is thought by some that they entered the Straits of Florida, but from the testimony of Peter Martyr, quoted above, they were north of Hatteras and probably in the vicinity of the Delaware, but in the longitude of Columbus's discoveries in the West Indies. They did, however, notice the fact that a gentle counter current existed.

The Cortereals, between 1500 and 1502, on several voyages extending from Labrador toward Cuba, probably crossed the Gulf Stream and may have recognized its strength, but very little is known as to the exact localities visited.

In the year 1508 the Island of Cuba was for the first time circumnavigated. Sebastian de Ocampo, under the authority of the Governor of Hispaniola, sailed along the northern coast of the island through the old Bahama Channel and around the western point, Cape San Antonio. In this voyage eight months were occupied, and as it was against the Gulf Stream it would seem that he must have noticed it. As the times demanded however the custom of secrecy on all expeditions, no record has been left of the fact.

The first record, on which the evidence is satisfactory, of the discovery of the Gulf Stream current, is that of Ponce de Leon in his expedition in 1513 in search of the fountain of youth. In company with the after wards famous navigator, Antonio de Alaminos, he sailed from Porto Rico, along the northeastern side of the Bahamas, and crossed the Gulf Stream somewhere above Cape Canaveral. After reaching a latitude of about 30° north he turned and skirted the coast as far as Tortugas, thus stemming the current for a distance of several hundred miles. Referring to these currents, their journal says that they saw a current which, though they had a good wind, they could not stem. It seemed that they were going through the water fast, but they soon recognized the fact that they were being driven back and that the current was stronger than the wind. Two vessels, which were somewhat nearer the coast, came to anchor; the third vessel, a brig, being in deeper water, could not anchor, and was soon "carried away by the current and lost from sight although it was a clear day." Ponce de Leon, on this expedition, crossed the stream no less than four times, and Alaminos

received his first apprenticeship in its navigation, which in after years proved to be of great benefit to him.

During the next few years the Spaniards crossed and recrossed the Stream between Cuba and Florida many times in their search for gold, and of course gained much practical knowledge of the strength and velocity of its currents.

It is interesting to note the speculations of the day as to the cause of this startling phenomenon, and its result on the sailing route to Europe. Peter Martyr in one of his letters written in 1515, being evidently as yet uninformed as to results of Ponce de Leon's expedition, says;

> Here we must somewhat digresse from cosmography, and make a philosophical discourse to search the secret of Nature. For when as they all affirm with one consent that the sea runneth there from east to west, as swiftly as if it were a ryver falling from high mountaynes, I thought it not goode to let such matter slipp untouched. The which, while I consider I am drawn into no small ambyguetie and doubt, whyther those waters have their course which flowe with so continual a tract in the circuite from the easte, as though they fledde to the weste never to retourne, and yet neyther the weste thereby any whit more fylled nor the east emptied.
>
> If we say that they fall to their centre (as in the nature of heavier things) and assign the equinoctial hyll to be the centre (as some affirme), what centre shall we appoint to be able to receive so great abundance of water, or what circumference shall be found wet. They which have searched those coasts have yet found no like reason to be here.
>
> Many think that there should be certayne large strayghts or entrances in the corner of that great land which we describe to be eight times larger than Italie, and the corner of that land to be full of gulfes, whereby they suppose that some strayghts should pass through the same lying to the weste side of the Island of Cuba, and that the said strayghts swallowe up those waters and so conveys the same into the weste, and from thence again into the easte ocean or north seas as some think. Others will, that the Gulf of that great lande be closed up and the lande to reach far to the north in the back side of Cuba, so that it embrace the north landes which the frozen sea encompasseth under the north pole, and all the lande of these coasts should joyne together as one firme lande. Whereby they conjecture that these waters should be turned about by the object or resistance of that lande

so tending toward the north, as we see the waters turned about the crooked banks of certayne ryvers. But this agreeth not in all points, for they also who have searched the frozen sea, and sayled from thence into the weste doe likewise affirme that those north seas flowe continually toward the weste although nothing so swiftly. * * * Wherefore it is not only more likely to be true but also of necessity to be concluded, that between both these landes hitherto unknown, there should be great certayne open places whereby the waters should thus continually passe from easte into the weste, which waters I suppose to be driven about the Globe by the incessant moving and impulsion of the heavens, and not to be swallowed up and cast out again by the breathing of Demo-gorgon as some have imagined, because they see the seas increase and decrease, flowe and reflowe.

The same writer continues at a later date:

Let us now therefore speake somewhat again of the later news and opinion as concerning the swift course of the sea toward the weste about the Coast of Paria. So it is therefore that Andreas Moralis, the pilot, and Ouidas (of whom we have made mention before) repayred to me at my house in the time of Matrite. As we met thus together there arose a contention between them two as concerning this course of the ocean. They both agree that these landes and regions pertayning to the Dominion of Castile, do with one continuale tract and perpetual bond embrace as one whole firme lande or continent all the mayne lande lying to the north of Cuba and the other islands, being also northwest from both Cuba and Hispaniola. Yet as touching the course of the waters they vary in opinion; for Andreas will, that his violent course of the water be received into the lappe of the supposed continent, which bendeth so much and extendeth so farre toward the north, as we have said, and that by the object or resistance of the lande so bending and crooking the water as it were, rebounde in compasse and by the force thereof be driven about the north side of Cuba and the other islands excluded outside the circle called Tropicus Cancri, where the largeness of the sea may receive the waters falling from the narrow streams and thereby represse that inordinate course by reason that the sea is there very large and great.

The Admiral himself, Diegas Colonus, sonne and heyre of Christophorus Colonus the first finder of these landes, being demanded of me what he found or perceived in sayling to and from, answered that there was much difficultie in retourning the same way by which they go; but whereas they first take their way by the mayne sea toward the north before they direct their course to

Spayne, he sayth that in that tract he felt the shippe sometymes a little driven back by the contrary course of the waters, yet supposed that this chaunceth only by the ordinary flowing and reflowing of the sea, and the same not to be enforced by the circumflection of the water rebounding in compass as we have sayde; but thinketh that this mayne lande or supposed continent should somewhere be open.

* * * * * * * * *

Ouidas agreeth with Andreas Moralis as touching the continual adherence of closeness of the sayde continent, yet neither that the water shoulde so beat agaynst the bending back of the weste lande, or be in such sort repulsed and driven into the mayne sea; but sayth that he hath diligently considered that the waters runne from the deepest and wyddest of the mayne sea toward the weste. Also that sayling near into the shore in small vessels, he found the same waters retourne agayne toward the east, so that in the same place they runne together with contrarie course. * * * Thus have we made you partner of such things as they have given us and written their divers opinions. We will then give more certayne reasons when more certayne truth shall be known. We must in the meantime leane to opinions until the day come appointed of God to reveal this secret of nature with the perfect knowledge of the pointe of the pole Starre.

It is certainly most remarkable, when we consider how imperfect was their knowledge of the form or extent of the continent, that their views should have been so near the truth. The Gulf of Mexico was not discovered until 1517, and explored the year after, when the current on the western side of the Straits of Yucatan must have been found. Ocampo, in circumnavigating Cuba, judging from experiences of the present day, could have found only the tidal currents in the vicinity of Cape San Antonio. The current in the passages in the eastern Caribbean was known to be strong and westerly, and on the Honduras coast the same. Alaminos and Ponce de Leon had found the current in the Straits of Florida, and evidently some of the speculators determined that the land was continuous and in some way the two parts of the flowing stream of water were connected.

Antonio de Alaminos was without doubt the most experienced navigator and pilot in the West Indian waters. He had been chief pilot with Columbus on his last voyage, had been with Ponce de Leon around and

among the Bahamas and along the coast of Florida from St. Augustine to Tortugas, and had crossed and recrossed the stream several times. He had afterwards been with Cordova and Grijalva exploring the coast of Yucatan and the Gulf of Mexico. He was familiar with the fact that there was a passage north of Cuba from the Gulf to the Ocean, but beyond the Straits to the northward was unknown to him. He thought, however, as Herrera says, "that these mighty currents ought to empty somewhere into an open space." Upon fitting out the expedition for the conquest of Mexico, Cortez gave the chief command of the fleet to Alaminos, and when, later, it was thought necessary to send dispatches and presents to Spain, he was given the fastest vessel to carry the Envoys. Instructions were given him to hold his course north of Cuba and pass into the Atlantic through the Straits of Florida, not touching at any port or island in the West Indies. Probably this route was suggested to Cortez by Alaminos as being most favorable for a quick passage, and one by which he would be sure to avoid a chance meeting with an enemy either of his own or of a foreign country. The vessel sailed from Vera Cruz July 26, 1519, and after disobeying his instructions by making a stop at the port of Marien on the north side of Cuba, Alaminos passed through the Straits of Florida and reached Spain in safety. It is of course doubtful how far he followed the Gulf Stream, but it is probable that he did so well up the coast toward Cape Hatteras. His voyage changed the course of navigation from the West Indian ports and contributed largely toward the growth of Havana. This port soon became the rendezvous of the West Indian trading fleet, the distributing point of goods from Europe, and the starting port for the return home.

During the half century following the remarkable voyage of Alaminos, there were expeditions without number to the West Indies and the mainland, and while there are minute and detailed descriptions of the land, products, and people, yet scarcely anything is said of the sea currents.

Sir Humphrey Gilbert, writing before 1576, says that all the waters of the ocean "run by nature circularly from east to west, following the diurnal motions of the Primum Mobile." He traces the motion of the waters from the south of Africa and says that from there it strikes over to America. Not finding free passage "it runs all along the eastern coast of that continent

northward as far as Cape Freddo, being the farthest known place of the same continent toward the north, which is about 4,800 leagues." He thinks that even if this current has not been traced all along the coast of America, "still it must exist either in uppermost or the nethermost part of the sea." For the reason that this current must have a free passage somewhere Gilbert says "it must either flow around the north of America into the South Sea or it must needs strike over upon the coasts of Iceland, Norway, and Finmark." He adopts the first of the alternatives, as he is anxious to prove the existence of the Northwest Passage. In the journal of his last voyage he mentions that in 50° north latitude they saw ice being carried to the southward, and so conjectured that a current must be setting in that direction. In 1579 and again in 1583 he made two unsuccessful attempts to establish colonies on the east coast of the present United States, and it is curious to see how great was the influence of the Gulf Stream, even at that time, in directing navigation. In considering the advisability of taking the southern passage from England or the more direct but more difficult northern one, he says, "by what way to shape our course, either from the south northward, or from the north southward. The first course, that is, beginning south, without all contraversie was the likeliest wherein we are assured to have commoditie of the currents, which from the Cape of Florida setteth northward, and would have furthered greatly our navigation, discovering, from the foresaid cape toward Cape Breton and all these lands lying to the north." The advantage of being able to provision the vessel at the Banks of Newfoundland led them to decide upon the northern route "although contrariety of currents descending from the Cape of Florida into Cape Breton and Cape Race would fall out to be great and irresistible impediments unto our further proceeding for that year, and compel us to winter in those northern regions."

The records of the voyages of Martin Frobisher are of great interest as showing the gradual extension of knowledge on the subject of ocean currents. He crossed the northern Atlantic six times during the years 1576–'77–'78. In the account of his third voyage he says:

> Sayling toward the northwest parts of Ireland we mette with a great current from out the southwest, which carried us [by our reckoning] one point toward the northeastward of our said

> course, which current seemed to us to continue itself toward Norway and other of the northeast parts of the world, whereby we may be induced to believe that this is the same which the Portugese mette at Capo de Buong Speranza [Cape of Good Hope], where, stricking over from thence to the Straits of Magellan and finding no passage there for the narrowness of the sayde Straits, runneth alongue to the great Bay of Mexico, where also having a let of land it is forced to strike back again toward the northeast, as we not only here but in another place also further northward by goode experience this year have found.

How the currents returned to the Cape of Good Hope from the "northeast parts of the world" is not stated, but the general course of the Atlantic system is very fairly laid out.

About this time there appeared the theory in "La Cosmographie" that the currents in the Straits of Florida were caused by the rivers emptying into the Gulf of Mexico, and this theory has been held by writers at much later dates. In 1596 it is recorded by D. Layfield, chaplain of the Earl of Northumberland, that between Bermuda and the Azores they thought they observed a current, but shortly before arriving at the latter they were sure of a current setting southward. The next expedition to that of Gilbert, for settling Virginia and North Carolina, was under Captains Amadas and Barlow. They took the southern passage, as did also all of those under Raleigh. Some of these left the Caribbean east of Cuba, and others continued to the westward and passed through the Straits of Yucatan and Florida.

In 1590 John White, who had been Governor of the colony at Roanoke, referring to the portion of the voyage from Florida Keys to Virginia, says: "We lost sight of the coast and stood to sea for to gaine the helpe of the current, which runneth much swifter farre off than in sight of the coast, for from the Cape of Florida to Virginia, all along the shore, are none but eddie currents setting to the south and southwest." This is the first instance in which there is indicated a knowledge of an approximate position of the axis of the Stream.

In 1606 an observation is recorded by Lescabot, which is evidently a meeting of the Labrador and Gulf Stream currents. He noticed that while in latitude 45° and "six times 20 leagues to the eastward of the Banks

of Newfoundland, we found for the space of three days the water very warm, whilst the air was cold as before, but on the 21st of June quite suddenly we were surrounded by fogs and cold that we thought to be in the month of January, and the sea was extremely cold." He attributes this to the ice from the north which comes floating "down from the coast and sea adjoining to Newfoundland and Labrador, which is brought thither by the sea in her natural motion."

The influence of the Gulf Stream in the colonization of North America was about this time very great. In 1606 the English divided their possessions into two parts, the northern part of Virginia (New England and vicinity) was one, and the present North Carolina and Chesapeake Bay region the other, and for each a company was established and commissioned by the King. The route used in going to the first was that tried in 1602 by Capt. Bartholomew Gosnold, crossing the Atlantic on about the fortieth parallel, while the southern expeditions held the old passage through the trades and Caribbean. The Dutch vessels bound to New York adopted the West Indian route, so that Nantucket really became the dividing line of travel, and a difference in destination of a degree in latitude necessitated a difference of thirty degrees in route. This seems only to be accounted for by the real or imaginary assistance of the winds and currents in one and the impediment of the Stream in the other. After the English and Dutch settlements became firmly established and crossing the Atlantic a common thing, the personal experience of navigators was no longer thought to be of sufficient importance to print, and the time had not yet arrived for adopting a plan of collecting ship's journals and publishing such nautical information from them as would be of value to others. The writers on the subject, however, must have had access to these journals and corrected and improved their ideas on the subject of currents, and in the latter half of this century many works on hydrography appeared.

In 1650 Varenius gave the most complete description of currents which had been issued up to this time. He classified them into perpetual and periodical, special and general. The system of which the Gulf Stream forms a part he placed as a perpetual special motion of the sea, and describes it as a gigantic Stream beginning at the eastern Capes of Brazil, flowing from

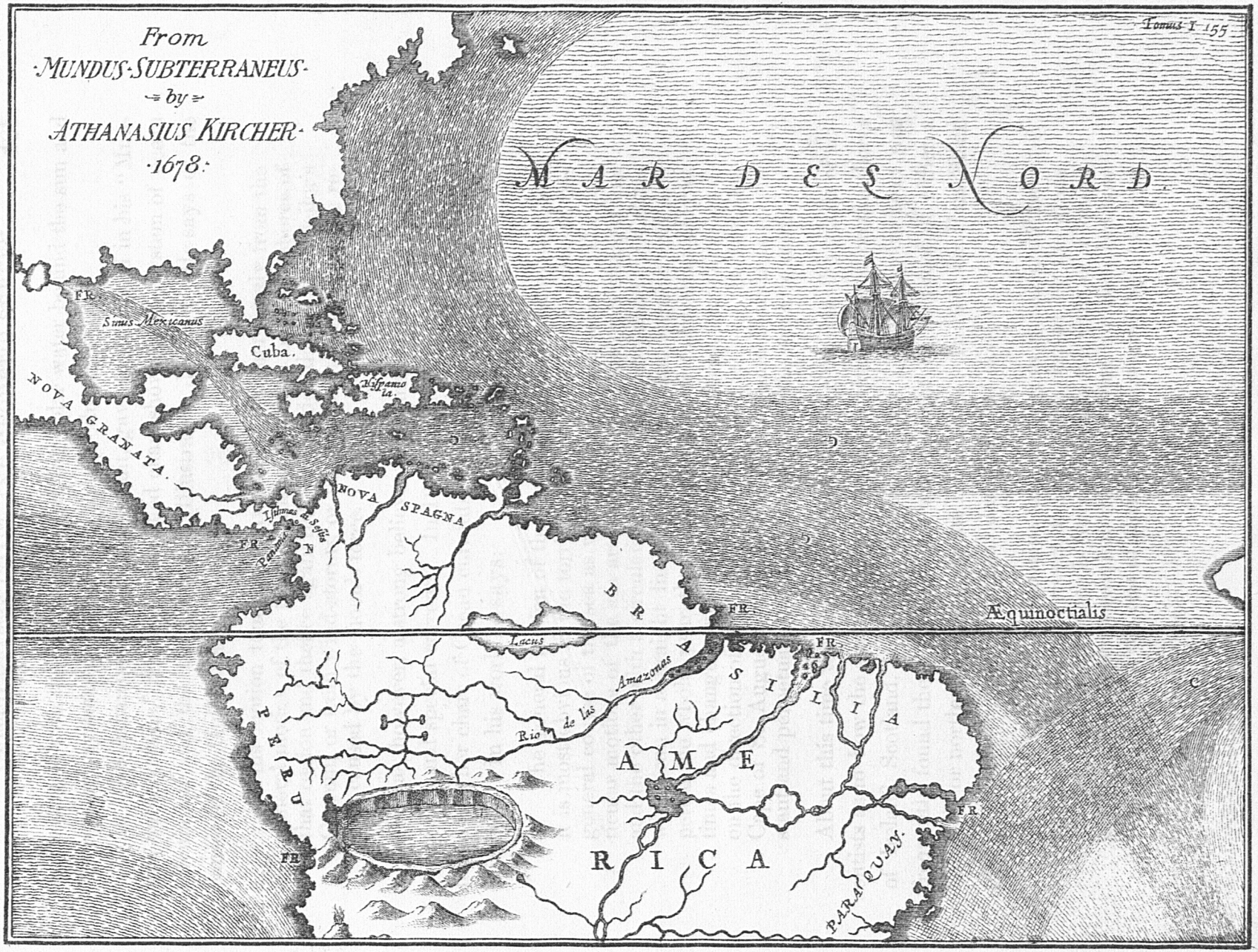
south to north and ending toward Florida. He adds, "a similar current from south to north is observed along the Philippine Islands and toward Japan." He also wrote that "some Copernicans, as for instance Keppler, pretend that also the movement of our globe contributes not a little toward it" (the currents), "because the water, not being adherent to the earth but only in a loose contact with it, cannot follow the quickness of its motion toward the east, but is left behind toward the west, so that the sea does not move from one part to the other, but on the contrary it is the earth which quits or leaves the parts of the sea, one after the other."

In 1663 Isaac Vossius wrote a work entirely devoted to the motion of wind and sea, and in it particularly describes most of the currents known in the present day. He says:

> With the general equatorial current, the waters run toward Brazil, along Guyana, and enter the Gulf of Mexico. From there, turning obliquely, they pass rapidly through the Straits of Bahama. On the one side they bathe the coasts of Florida and Virginia and the entire shore of North America, and on the other side they run directly east until they reach the opposite shores of Europe and Africa; from thence they run again to the south and join the first movement to the west, perpetually turning in this manner circuitously.

He emphasizes this by saying that "a ship without sails and sailors might be conveyed solely by the force of the currents from the Canary Islands to Brazil and Mexico, coming back from there by way of the Florida Stream toward Europe on a route some 4,000 German miles in length." Vossius's theory as to the cause of the ocean circulation was that the heat of the tropical sun attracted the ocean and at the same time increased its bulk and formed, as it were, a long mountain of water, "to which the vessels even have some difficulty in ascending when they sail toward the line." He concluded that the sun carried this mountain of water toward the South American shore, where it broke and ran along the coasts. A French hydrographer, George Fournier, some years later propounded a theory almost the opposite. It was that the sun evaporated enough water in the tropics to make a deep valley, and therefore the water from the poles was forced to run toward the equator along the coast of Africa to replace the lost water. He thought that the depression always

No. 31.


From
MUNDUS SUBTERRANEUS
by
ATHANASIUS KIRCHER
1678.
Tomus I 155
MARE DEL NORD
Sinus Mexicanus
Cuba.
Hispaniola.
NOVA GRANATA.
NOVA SPAGNA
Istmus di Sylla
Panama
FR.
Aequinoctialis
Lacus
Amazonas
Rio de las
AMERICA
PARAGUAY.

ran before or with the sun and the arriving polar water behind the sun and the rotatory system of currents was thus produced.

In 1678 Athanasius Kircher, a Jesuit, gave to the world in his "Mundus Subterraneus," the first published chart showing the system of ocean circulation and the Gulf Stream (Illustration No. 31). He says of the causes of the Gulf Stream:

> This motion touches many things, whether partly from the general motion of the trade winds against the opposing shores of that region and thence again reflected, which they call the Sailor's Current, or from wind-storms, or finally from the flow and the reflow caused by the moon's force.

He was, however, a strong believer in submarine abysses as the cause of vortices and special currents. In 1685 a German named Happelius published another chart of Ocean currents (illustration No. 32) quite similar to Kircher's. In his work he says:

> The general motion of the Ocean goes from east to west, and it is most obvious in the torrid zone. The sun is the cause of this general course of the sea as well as of the trade winds. The particular motions of the sea are of two kinds, one on a straight line and the other with a circulating or whirling movement. Of those which run in a straight line some are constant, regular, and perpetual the whole year through. Some show themselves only at times and change even in direction, are irregular, depending much on the direction of the wind. In the Atlantic from the Brazilian Cape of St. Augustine toward the Antilles and Florida is a constant and perpetual course of the sea from the south to north.

About this time the question began to be agitated in the minds of scientists as to how the strange fruits and woods were deposited on the shores of Ireland, Scotland, and other northern lands. The molucca bean was frequently found there, and the fact was thought to be proof of either a northeast or northwest passage to the East Indies. In 1696 Dr. Hans Sloan proved that these beans came from Jamaica. He says:

> It is very easy to conceive that, growing in Jamaica, and having got to sea by the rivers, they may be carried by the winds and by the current which is forced through the Gulf of Florida, going there constantly east into the North American Sea; but how they should come the rest of their voyage I can not tell, unless it

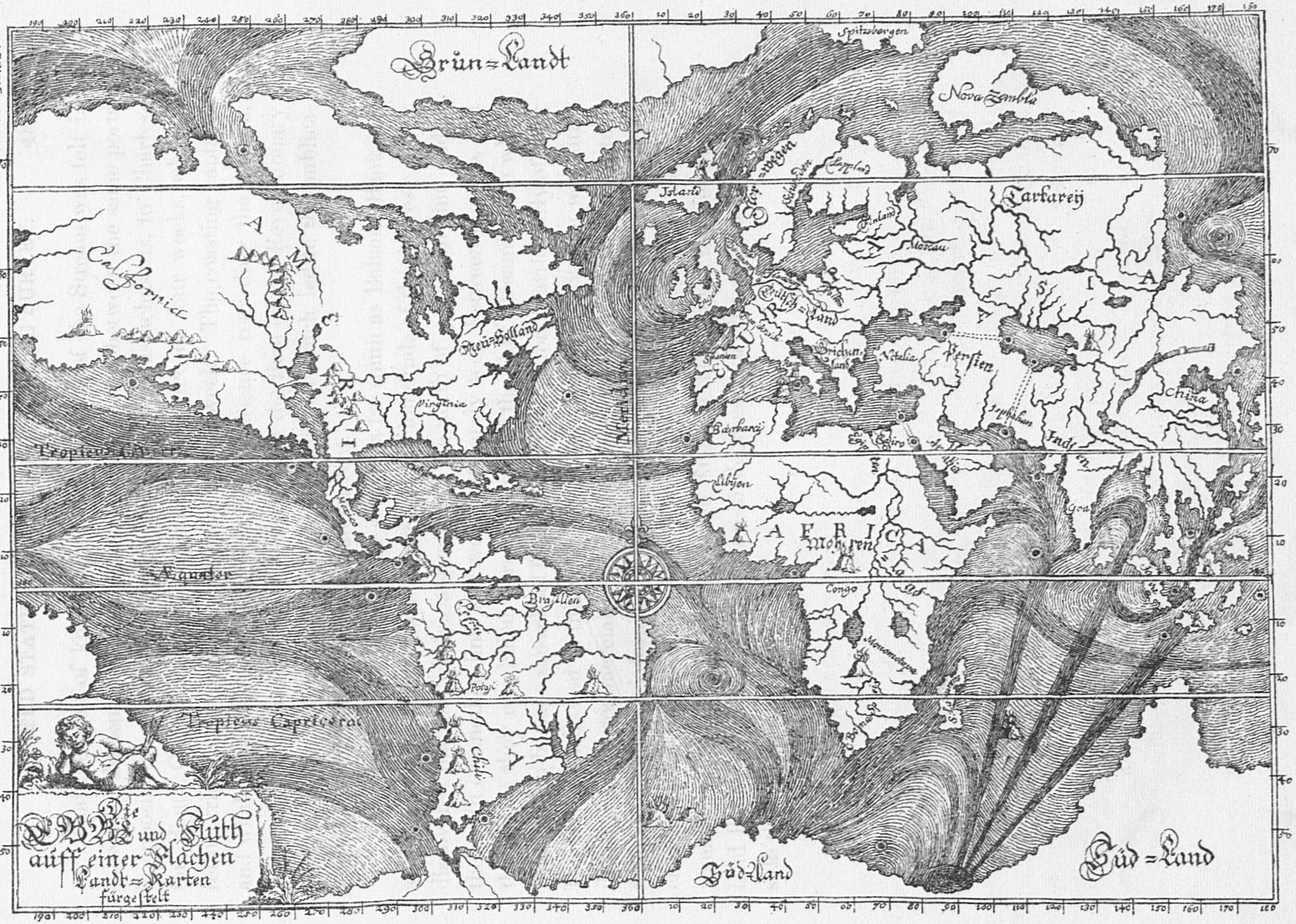
> be thought reasonable that the beans, being brought north by the current from the Gulf of Florida, are put into the westerly winds' way, and may be supposed by this means at last to arrive at Scotland.

This is exactly the opinion of many people at the present day.

In 1702 and again in 1720 the fact was stated that the Gulf Stream ran the strongest in the Straits of Florida during strong northerly winds, and as an explanation of this phenomenon Professor Leval thought that it could only be accounted for by the supposition that during the north winds in the channel in the Gulf of Mexico they were blowing from a more northwesterly direction, and in this way pushed the waters of the Gulf into the Straits and so forced them through the latter with increased velocity. The French route from Louisiana to Europe followed the Gulf Stream along the North Atlantic coast toward the Banks of Newfoundland, differing considerably from the more southern route taken by the Spaniards, but while adopting this most expeditious track they went to the other extreme in sailing from their Gulf to their West Indian possessions. They followed the Stream well up toward the Grand Banks, then south to the trade winds and west to their port.

Up to this time, with the exception of Kircher and Happelius in 1679 and 1685, there seems to have been no attempt to indicate the Gulf Stream upon the charts, and even these were more for scientific interest than for the practical benefit of mariners. One chart published in 1630 by the Earl of Northumberland gave the words "Corrento verso Greco," placed about half a degree from Cape Hatteras; but with this exception up to the first half of the eighteenth century, charts generally only show an inscription between Cuba and Florida, "Canalis Bahama versus Septentrionem semper fluit," or its translation into other languages. About the middle of the eighteenth century arrows appeared on the charts of the British colonies to indicate coast currents, and at the same time French charts indicated currents in the Caribbean and in the Straits of Florida in like manner. In 1772 detached indications of the Gulf Stream currents appear, and in 1775 on a special map of Carolina there are arrows near the coast pointing to the southward and westward, and farther off the coast pointing north.

No. 32.



FROM HAPPELIUS RELATIONES CURIOSAE

1685.

That the want of knowledge as to the limits of the Stream was felt is shown by the length of time consumed in passages between the same ports in opposite directions. A voyage from Boston, Massachusetts, to Charleston, South Carolina, would sometimes take three or four weeks, while a return trip would frequently be made in one week. The coasting captains and whalemen, however, were gaining experience regarding the Stream, and to the latter more than all others, up to the time of the Revolutionary War, Franklin was indebted for the information which led to the publication of his chart of the great Ocean current.

These whalers extended their search as far south as Bahama Bank and as far east as Newfoundland, or even to the longitude of the Azores. They discovered that the whales appeared to the north of a certain line and to the south of another line, and were but rarely seen between the two, and these lines they concluded were the limits of the Gulf Stream. The whale fishery soon became the school for American navigators, particularly of New England vessels, and in this way knowledge of the Gulf Stream was introduced into the commercial traffic of the times. The American shipmasters, from their superior information on the subject of currents, inaugurated a change in the sailing route from Europe, by which they could save two weeks or more in the passage. From England they crossed the Newfoundland Banks in about latitude 44 or 45 degrees, and thence on a course inside the limits of the Stream.

CHAPTER II.

GULF STREAM INVESTIGATIONS FROM THE TIME OF FRANKLIN TO THOSE MADE BY THE U. S. COAST SURVEY.

How long the American fishermen had been acquainted with the secret of the Gulf Stream's peculiarities before it was brought to the notice of Franklin it is impossible to state. They kept the secret, however, until, as Franklin says—

> About the year 1769 or 1770, there was an application by the Board of Customs at Boston to the Lords of the Treasury at London, complaining that the packets between Falmouth and New York were generally a fortnight longer in their passage than the merchant ships between London and Rhode Island, and proposing instead of New York that for the future they should be ordered to Newport.
>
> Being then concerned in the management of the American Post-Office, I happened to be consulted on the occasion, and it appearing strange to me that there should be such a difference, especially when the merchant ships were generally deeper laden and more weakly manned than the packets, and had from London the whole length of the river and channel to run before they left the land of England, while the packets had only to go from Falmouth, I could not but think the fact misunderstood or misrepresented.
>
> There happened then to be in London a Nantucket sea captain of my acquaintance, to whom I communicated the affair. He told me he believed the fact to be true, but the difference was owing to this, that the Rhode Island captains were acquainted with the Gulf Stream, while those of the English packets were not. "We are well acquainted with that stream, because in our pursuit of whales, which keep near the sides of it but are not met with in it, we run along the side and frequently cross it to change our side; and in crossing it have sometimes met and spoke with those packets who were in the middle of it and stemming it. We have informed them that they were stemming a current that was against them to the value of 3 miles an hour and advised them to cross it, but they were too w ise to be councelled by simple American fishermen

No 33.

THE GULF STREAM ACCORDING TO BENJAMIN FRANKLIN

1770

When the winds are light," he added, "they are carried back by the current more than they are forwarded by the wind, and if the wind be good the subtraction of 70 miles a day from their course is of some importance."

I then observed that it was a pity that no notice was taken upon the charts, and requested him to make it out for me, which he readily complied with, adding directions for avoiding it in sailing from Europe to North America. I procured it to be engraved by order from the General Post-Office on the old chart of the Atlantic, at Mount & Page's, Tower Hill, and copies were sent to Falmouth for the captains, who slighted it, however, but it has since been printed in France, of which edition I hereto annex a copy (illustration No. 33).

Franklin's theory on the subject of the cause of the Gulf Stream is given in the same report. He says:

This stream is probably generated by the great accumulation of water on the eastern coast of America between the tropics by the trade winds which constantly blow there. It is known that a large piece of water, 10 miles broad and generally only 3 feet deep, has, by a strong wind, had its water driven to one side and sustained so as to become 6 feet deep, while the windward side was laid dry. This may give some idea of the quantity heaped upon the American coast, and the reason of its running down in a strong current through the islands into the Bay of Mexico and from thence proceeding along the coasts and banks of Newfoundland where it turns off towards and runs down through the Western Islands.

Franklin did not press his new chart on the notice of the English ship captains after they had once rejected it, but for the time being suppressed it, for political reasons, until the conclusion of the War of Independence. In the mean time, in 1775–'76, and in later years, whenever he made a voyage across the Atlantic, he took observations of the surface temperature of the ocean. He says:

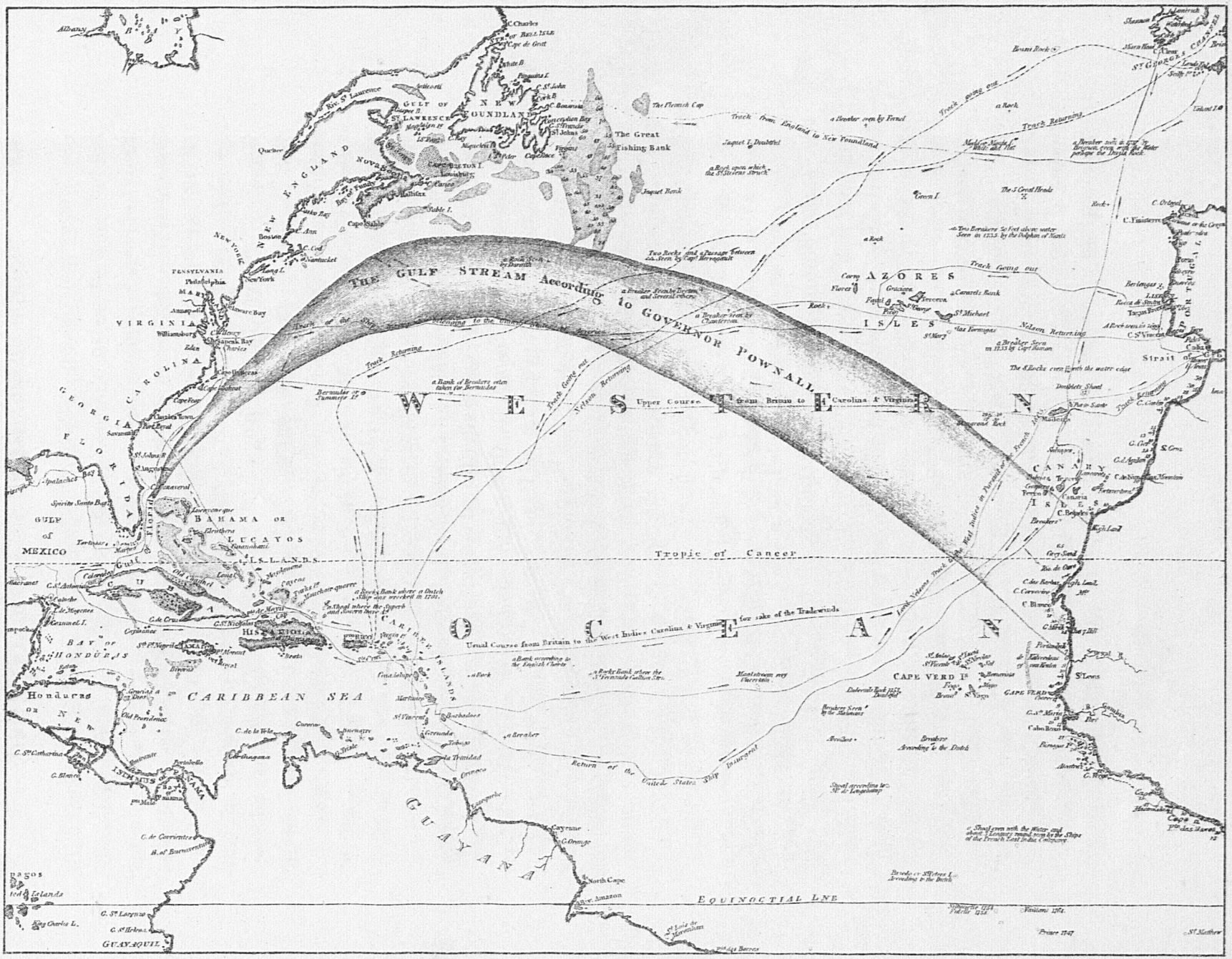
I find that it [the Gulf Stream] is always warmer than the sea on each side of it, and that it does not sparkle in the night. I annex hereto the observations made in two voyages and may possibly add a third. It will appear from them that the thermometer may be a useful instrument to the navigator, since currents coming from the northern into southern seas, will probably be found colder than the water of those seas as the currents from southern seas into northern are apt to be warmer.

On his last voyage, in 1785, he made the first attempt in submarine temperatures at moderate depths, using a bottle up to 20 fathoms, and afterwards a cask with valves in each end. Off the Delaware, in 18 fathoms, he discovered that the water at this depth was 58°, which was 12° colder than at the surface.

Although Franklin's chart of the Gulf Stream, published in London, had been rejected by the English shipmasters in 1770, it was certainly adopted by writers on hydrography. The information was given to the public through these works, and the name Gulf Stream came into general use. The importance, too, of gaining all possible information about this mighty river seems to have been realized at this time, and consequently nearly all government vessels were instructed to observe its phenomenon whenever opportunity offered. Among the most prominent investigators was Dr. Charles Blagden, of the Royal Army, while with the British fleet going to and in the American waters in 1776–'77. He observed the temperature in crossing the stream off Cape Fear, and also off the Chesapeake, communicating his results to the Royal Society, in 1781, in a letter urging the essential advantage to be derived by the use of the thermometer. These two, Franklin and Blagden, were the first to demonstrate the usefulness of that instrument, and, since the time of Alaminos, no discovery of like importance had been made which bore so directly on the question of utilizing this great river to the purposes of man's welfare.

Soon after Franklin's and Blagden's discoveries, Mr. Pownall, formerly Governor of Massachusetts, published in 1787 a large chart and a volume on Hydraulic and Nautical Observations on the Currents of the Atlantic Ocean. On this chart the Gulf Stream is laid down closely approximating to that of Franklin's (illustration No. 34). He also gives the correct course or tracks which vessels should take; that to Boston "along and beyond the northern edge of the Gulf Stream." To Virginia and Carolina he urged one in about latitude 35° instead of running down to 20°, as was usual.

Franklin on his last voyage was accompanied by a nephew, Col. Jonathan Williams, who was of great assistance in the thermometrical observations and record of results. Such interest was awakened in the mind of Williams that he was led to continue the experiments begun by his uncle.



THE GULF STREAM ACCORDING TO GOVERNOR POWNALL
1787.

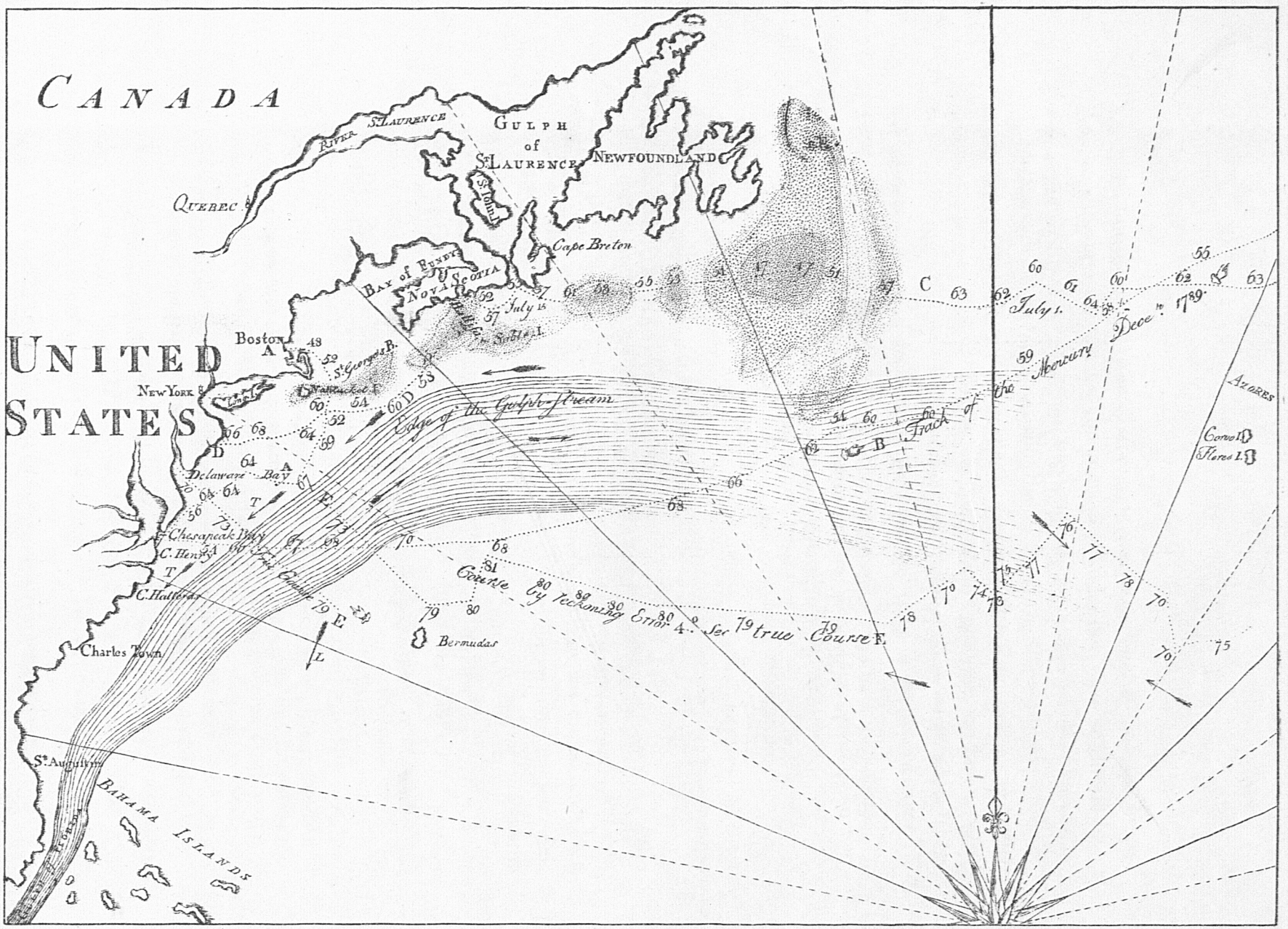
In a memoir read before the American Philosophical Society in 1790 he confirmed Dr. Franklin's account of the temperature of the Stream, and also advanced the theory that banks, shoals, and coasts might be discovered by the use of the thermometer. Williams published a work in 1799 on Thermometrical Navigation, containing a chart of the Gulf Stream (illustration No. 35) and the temperature of the water on adjacent banks. In 1800 a paper was read by Capt. William Strickland on the use of the thermometer in navigation. In his voyages across the Atlantic he had kept daily and sometimes hourly observations of surface temperature, in order to test the theory of Colonel Williams. His investigation was valuable from the discovery of the warm northeasterly extension of the Gulf Stream, for he found in latitude 46° 47′ north and longitude 38° 35′ west, a temperature of 68°. He says, of this northeast extension, "it probably continues in about a northeast direction entirely across the Atlantic till it ultimately strikes the coasts of Ireland and the Hebrides, after having lost, in its long course in these northern latitudes, much of its heat, and at last being reduced to the temperature of the sea through which it flows." He recommended the employment of vessels to define the limits of this northern branch between latitudes 47° and 60° by the use of the thermometer. Although others before Strickland had noticed floating weeds and American woods in these northern localities, and even Cabot had remarked upon the fact of the beer in the hold of his vessel getting warm, thus surmising a warm current, yet no one seems up to this time to have declared its existence a fact, based upon actual experience and scientific observation.

At the beginning of the nineteenth century, the subject of ocean currents was a favorite one for investigation by the navigator and hydrographer. The thermometer was the accepted instrument in the research, and by the chronometer, which was becoming of greater value and more generally used, the difference between the dead reckoning and the observed positions could be determined with greater accuracy. As we shall see later, from the time of Franklin and Blagden, for more than a century, all the investigation of ocean currents was based solely upon these two instruments, the thermometer and the chronometer, and upon, what in effect is the same as the latter, the drift of bottles. In the year 1802 the first bottle

experiments seem to have been inaugurated, the English ship *Rainbow* throwing overboard several in the North Atlantic, and at intervals these experiments have been continued in all parts of the world up to the present day.

A remarkable thermometrical voyage was made in 1810 by the packet *Eliza*, from Halifax to England. It was found that in the midst of the warm water of the stream there existed patches of cool water of 10° to 15° lower temperature than the surrounding sea, and having a diameter of over 200 miles. They were thought to have been caused by icebergs and floes which had entered and been melted in the Gulf Stream. In 1811 and 1812, Sir Philip Broke made a great number of observations in the Gulf Stream and described its characteristics. Among other things he states "that beyond the southern boundary of the stream, from the Azores toward Bermuda and the Bahamas, there is a strong set to the southwest or west-southwest, that when this countercurrent arrives opposite the outfall of the Florida or Gulf Stream it turns to the southeast along the outer side of the Bahama Archipelago, receiving into its body a large offset of the Gulf Stream which rounds the Matanilla Bank." Another alleged characteristic of the current began to appear in the nautical works of the early part of the century: "That easterly winds press the current toward the American coast, and that the consequences of this pressure are that the breadth of the Stream and its distance from the shore is diminished and its velocity increased, and that in the contrary, winds which blow from the coast produce contrary effects."

Capt. John Hamilton gave to the American Philosophical Society, in 1825, the observations made by him during twenty-six voyages to and from Europe. They consist of temperature of air and water, current of the Gulf Stream for different months, average temperature of the water on soundings off the Delaware, Georges Bank, and on the coast of Ireland. Some of the conclusions arrived at by Captain Hamilton were of great value at the time. He decided that it was impossible to define the limits of the current of the Gulf Stream, owing to the variable influence of the wind; that after it passes the Grand Bank the main Stream proceeds to the southward, while several ramifications, generally not very strong, branch off to the northeast and from that to the east, with countercurrents in the



THE GULF STREAM ACCORDING TO JONATHAN WILLIAMS.

1799

intermediate spaces; that by the frequent use of the thermometer the navigator may always discern where he touches the Gulf Stream, and take advantage of its current or avoid its influence. He further remarks:

> I was for a long time almost induced to conclude that some of these currents, particularly those which prevail between the coast of Newfoundland and Europe, were periodically running half the time in one direction and half the time in the other, and the foregoing tables seem to strengthen this conclusion, except the countercurrents near the edge of the stream.
>
> * * * * * * *
>
> When the current from the northward prevailed to any great extent, a set in the opposite direction near the bank of Newfoundland and on the west coast of Ireland were always observed.

The celebrated German, A. von Humboldt, published in 1814 a valuable description of the Gulf Stream, the result of his own observations in crossing it no less than sixteen times, as well as of all the information he could collect from the journals of navigators who had been possessed of the necessary means for exact astronomical observations at sea. He decided that the Gulf Stream was not the same in all seasons of the year, but that its force and direction depended to a large extent upon the changes in the trade winds, and also, that the general torpidity of the ice in the Arctic in the winter, and its melting in the summer, influenced it. Regarding the directions of ocean currents he says:

> Considering the velocity of the fluid elements which, in different latitudes, in consequence of the earth's rotation, is different, one should be tempted to think that every current from south to north ought to have at the same time a tendency to the east, and, *vice versa*, a current from north to south a tendency to the west.

He published a chart of the Gulf Stream in which he depicted its changeable limits as he believed they were.

During the next few years many navigators cruised in and examined the Gulf Stream, more particularly however in the vicinity of the route between Halifax and Bermuda. One of them in May, 1821, in about 64° west longitude remarked the fact that he observed a vein of cool water of a temperature of 54° between 72° and 73°, which seems to be the first time this phenomenon was noticed. The celebrated Englishman, Capt. W.

Scoresby, investigated the northern extension of the stream, and discovered in the vicinity of Spitzbergen that an under stratum of water was generally warmer than that at the surface. He believed that the warmer water, though of similar specific gravity was, in this case, the most dense, and that sea water followed the same law as fresh water with regard to extreme of density, being a few degrees above its freezing temperature. To this he attributed the fact that the polar ice in these waters could not extend far to the southward, and Humboldt adopted the same. The latter says: "In those regions which are warmed by a current from the southwest, navigation is uninterrupted even in the midst of the strongest winter."

Col. E. Sabine, in 1822 was a member of an expedition organized for the purpose of making experiments to determine the figure of the earth. Sailing from England he went to Madeira and to Sierra Leone, through the Caribbean and the Straits of Florida to New York and thence to England, thus making the complete circuit of the warm Atlantic currents. In his observations on ocean temperatures he found in the eastern Atlantic a body of water very much warmer than normal, and attributed this fact to an unusual elevation of the Gulf of Mexico and the Caribbean, due to abnormally strong trade winds. The weather was so unusual in the southern parts of Great Britain and in France as to have excited general remark, as "most extraordinary hot, damp, stormy, and oppressive," and that in November and December gales from the west and southwest were almost without intermission. We here see, not so much the direct influence of the warm water of the stream on the climate of England and France as the effect of the westerly and southwesterly gales.

During the first quarter of this century the British admiralty office had collected a great quantity of material on the subject of ocean currents and meteorology, most of which had never become known to the public. Mr. James Rennell, who had devoted his life to the subject of geography, and particularly to ocean currents, was given the task of compiling and collecting the data. He combined the results on large charts of the ocean which were the admiration of the day, and also wrote a volume on "An investigation of the subject of the currents of the Atlantic Ocean." He died, however, before its entire completion, but two years later (1832) it was published by

his daughter Lady Radel. In the charts were embodied the general courses of the currents with the limits of variations, the directions of the winds, accompanied by the date of observation, the depth and temperature of the sea, and some of the tracks of the vessels making specially important scientific observations.

Major Rennell adopted Dr. Franklin's theory as to the principal cause of ocean currents and divided them into two classes: Drift currents, caused by the effect of constant or long-continued winds on the surface of the water, and stream currents, which are formed by the accumulation of water by the drift current meeting an obstacle and thrown sideways or out of its usual course. The Gulf Stream he placed in the latter class, but concluded that it turned south toward the Azores and was lost, while he considered the movement of water in the northern part of the North Atlantic a drift current impelled by the prevailing westerly winds, and these also were the cause of the African current.

From his investigations he pronounced it to be abundantly proved—

(1) That there existed a change in the position and breadth of the column of warm water from time to time.

(2) That the breadth varied at times in the proportion of more than two to one.

(3) That these changes had been observed sometimes to be very sudden—as, for instance, it had once been found to be 140 miles in width, and ten weeks later at the same spot to be 320 miles broad.

(4) That these changes did not follow any regular course of season, for it was 320 miles wide in May, 1820, and only 186 miles in May, 1821, nearly at the same place.

(5) That on the northern side of the stream the body of warm water is more permanent than to the south, and also that the warmest water is found to the north, as if indicating the strongest part of the stream there.

(6) That the existence of warm water does not necessarily indicate the presence of the stream, but must be regarded as an overflowing or deposit of superabundant water, or even form a counter current.

(7) That there were without doubt veins of colder water within the body of warm current.

He pointed out the fact, and, indeed, it exists at the present day, that the position of the Stream east of Cape Hatteras is but imperfectly known, and that notwithstanding the great number of observations at his disposal, a want of system in their collection, the isolated and unconnected facts obtained by different observers at different seasons, and errors in determining longitude made it impossible at that time to state where the borders of the Stream should be placed. The observations discussed by Major Rennell were of the surface temperature, and we shall see later how great is the influence of the wind in spreading the warm water of the Stream without carrying the current with it. His work was the most valuable collection of results that had been made, and while some of his conclusions have since been disproved, it is a remarkable fact that he should have arrived at so near the truth in many of them. An index of his currents is shown in illustration No. 36.

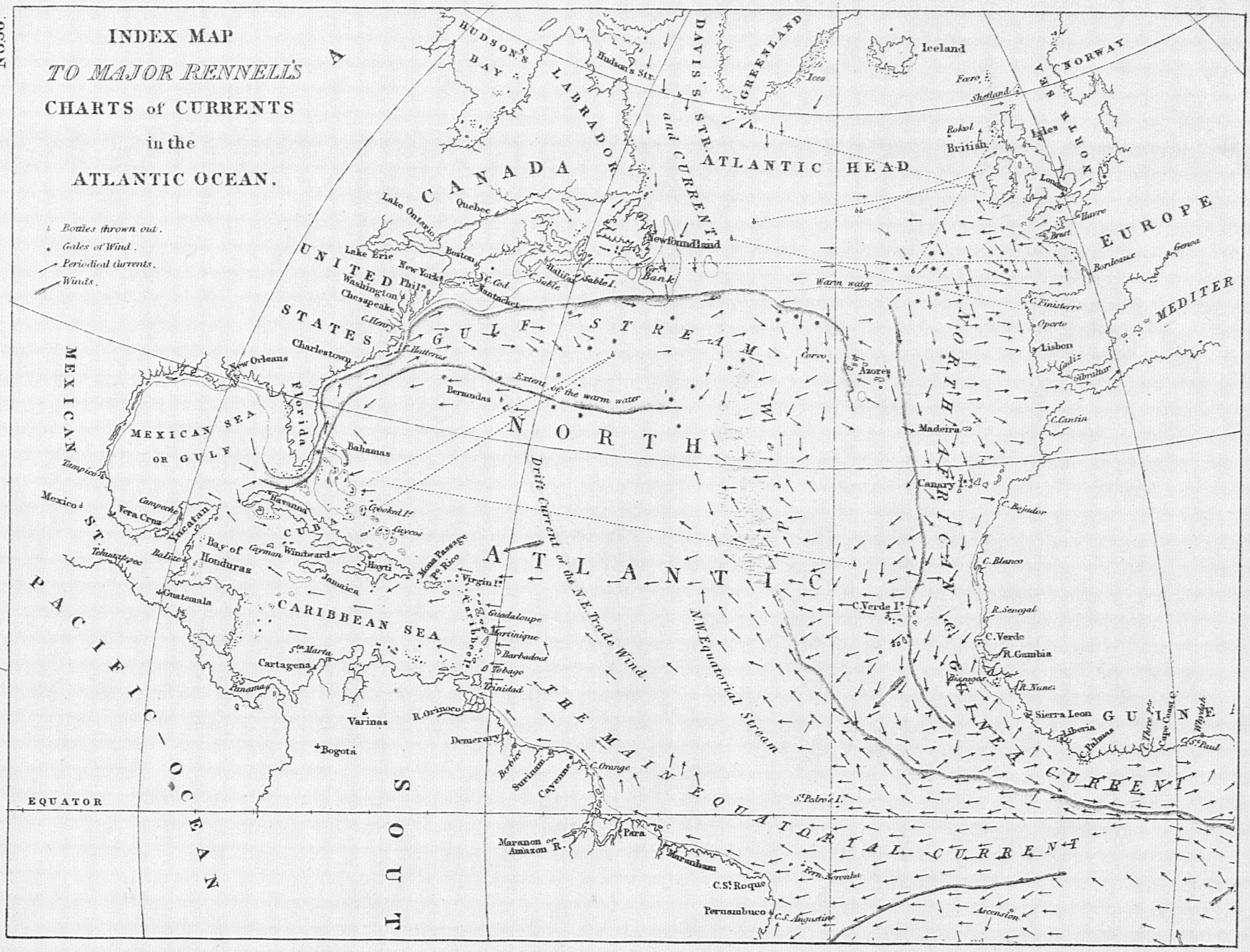
For several years after the death of Major Rennell, observation of the Atlantic currents did not possess the attraction that it had previously, probably for the reason that his elaborate compilations were considered to have settled the question. Isolated observations were made, but no one took the trouble to combine them into average results. Rennell's theory of the elevation of the Gulf of Mexico and the Caribbean Sea was much shaken by Arago, who called attention to the observations made to ascertain the differences of level of the two oceans at the Isthmus of Panama. Triangulation was carried from Chagres to Panama, and a report made that the Atlantic might be from 3 to 5 feet lower than the Pacific.*

About this time a line of levels was carried across Florida from St. Mary's River to Apalachee Bay, with a difference of 7½ inches, the latter being the highest. It was thought, however, to be due to error of observations rather than to difference of level.

Arago believed "that with respect to currents the rotation of the earth ought principally to be taken into view, and that this, together with the cooling and warming of the water in the north and south, is the main cause of their more rapid or slower deviation and progress toward the east or

* The engineers in charge of the Panama Canal have accurately leveled across the Isthmus in recent years with entirely different results, as will be seen later.

No. 36.



THE GULF STREAM ACCORDING TO JAMES RENNELL.

1832.

west." He remarks, too, that "we ought to apply to the ocean the same theory which has already afforded a satisfactory explanation to the trade winds if we will decipher the question of currents."

During the first half of the century bottle experiments were numerous. The results were published, chiefly in magazines, in the shape of charts, giving the positions and dates of departure and arrival of these floats, connected by straight lines. Another chart, indirectly relating to ocean currents, was published by Mr. W. C. Redfield. It gave the positions of icebergs and fields observed by British and American navigators in the Atlantic from the year 1832 to 1844. Over one hundred of them were marked on this chart, and the fact observed that they sometimes entered the supposed limits of the Gulf Stream, thus showing the existence of an undercurrent.

In 1838 and 1840 a scientific mission was sent out by the King of France, under the direction of Paul Gaimard, to northwestern Europe. Among other subjects they observed the depth and temperature of the ocean, and concluded that "a broad current sets through the northern Atlantic in a NNE. direction toward the coasts of Great Britain and, passing between the Faroe and Shetland Islands, runs along the coast of Scandinavia as far as North Cape, from which it turns toward Cherry Islands and Spitzbergen."

The winter of 1845–'46 in England, and in fact in all of western Europe, was very abnormal. The weather was exceptionally mild, being 8 degrees above the average, and was accompanied by much rain and high southwesterly gales, similar to the winter of 1821–'22, when Colonel Sabine had observed an exceptional extension of the warm water of the Gulf Stream toward the shores of Europe. Struck by the similarity of weather, Colonel Sabine endeavored to discover if the same conditions of ocean temperature prevailed, but although hundreds of vessels crossed and recrossed this part of the ocean he could find none on which observations had been taken. He thought it reasonable to believe that through a course of years there might be a difference between the usual and extreme initial velocities, and consequently in some years, as 1776, 1821, and perhaps 1845, it might reach the shores of Europe. He thought, too, that it would be of the greatest practical value for Europe to be informed in advance of the yearly

state and tendency of the Stream and the changes in its velocity. His idea was that ships might observe its elevation in the Gulf of Mexico and Straits of Florida, and that they, sailing faster than the flow, might make the changes known in England in advance of the arrival of the climate-influencing warm water.

After the death of Major Rennell the first renewed attempt to take up the task of collecting data on ocean meteorology was made by Lieut. M. F. Maury, U. S. N. While he was collecting, however, the U. S. Coast Survey, under Prof. A. D. Bache, began, in 1844, a systematic investigation, which continued with greater or lesser regularity until 1860. Before describing the latter, however, we will consider the labors of Lieutenant Maury and others up to the outbreak of the civil war. Lieutenant Maury, while Superintendent of the U. S. Naval Observatory, had collected all the log-books of vessels between the years 1840 and 1850, and averaging the data, gave to the public the results in a series of wind and current charts and sailing directions. After the first edition was published, he proposed a general Maritime Conference for devising a uniform system of observations at sea, and the meeting was held at Brussels in 1853. A plan of observations was adopted and the co-operation of nearly every nation assured. As a result, a mass of data was collected from which other editions of more elaborate charts and sailing directions were compiled. The charts were issued in condensed form by other governments, and his sailing directions, as well as his famous work entitled the "Physical Geography of the Sea," were translated into many languages.

It is stated in some recent works that it is difficult to ascertain from Maury's writings exactly what his ideas were as to the causes of the great ocean currents. He says in "Physical Geography of the Sea:"

> But they [modern investigations] seem to encourage the opinion that the Stream, as well as all constant currents of the sea, are due mainly to the constant difference produced by temperature and saltness in the specific gravity of the water in certain parts of the ocean. Such difference of specific gravity is inconsistent with aqueous equilibrium, and to maintain this equilibrium these great currents are set in motion. The agents which derange equilibrium in the waters of the sea, by altering the specific gravity, reach from the equator to the poles, and in these operations they are as

ceaseless as heat and cold, and consequently call for a system of perpetual currents to undo their perpetual work.

These agents, however, are not the sole cause of currents. The winds help to make currents by pressing upon the waves and drifting before them the water of the sea; so do the rains, by raising its level here and there; and so does the atmosphere by pressing with more or less superincumbent force upon different parts of the ocean at the same moment, as indicated by the changes of the barometric column. But when the winds and rains cease and the barometer is stationary, the currents that were the consequence also cease. But the changes of temperature and of saltness, and the work of other agents which affect specific gravity of sea water and derange its equilibrium are as ceaseless in their operations as the Sun in his course, and in their effects they are endless. Philosophy points to them as the chief cause of the Gulf Stream and of all the constant currents.

In another place, however, he says:

The dynamical forces which are expressed by the Gulf Stream may with as much propriety be said to reside in those northern waters as in the West India seas; for on one side we have the Caribbean Sea and Gulf of Mexico, with their waters of brine, and on the other the great Polar basin, the Baltic, and the North Sea, the two latter with waters that are but little more than brackish.

This fact would of itself simply neutralize the differences in density due to heat, but later he expresses his conviction that—

If we except the tides and the partial currents of the sea, such as those that may be created by the wind, we may lay it down as a rule that all the currents of the ocean owe their origin to difference of specific gravity between sea water at one place and sea water at another, for wherever there is such a difference, whether it being owing to difference of temperature or to difference of saltness, etc., it is a difference that disturbs equilibrium and currents are the consequence.

His belief was, then, in effect that differences of density caused the main currents, and that this might be modified by winds, rain, barometric pressure, evaporation, and the fauna and flora of the ocean.

CHAPTER III.

GULF STREAM INVESTIGATIONS MADE BY THE U. S. COAST SURVEY UNTIL 1884 AND THOSE CONTEMPORARY WITH THEM.

We have now reached the point in the history of Gulf Stream investigation where, for the first time, can be described a systematic and extensive examination into its secrets. Research had been going on for years in a casual way, data collected when chance offered, and at any point, but under the direction of no one who had the authority to say to the observers when, where, and how they should search. The scope of the Coast Survey only contemplated an examination of the Gulf Stream in the portions adjacent to the coast of the United States, but the laws have since been changed so as to include the Sargasso Sea and the Japan Stream, a study of these being considered advantageous to the commercial and scientific interests of this country and the world at large.

In 1842 a report was made by Admiral Sir Francis Beaufort urging the British Admiralty to undertake the work. The importance of an examination of the great rivers emptying into the Atlantic, to whose influence the Gulf Stream had been attributed, was suggested, and the details of a plan were given for a survey of the Stream from the Gulf of Mexico to the shores of Europe.

This plan proposed the employment of three steamers and one sailing vessel. One steamer was to remain in the Gulf of Florida for the purpose of keeping a continuous record of temperature and velocity at that point. The sailing vessel was to drift along in the axis of the Stream, while the other two steamers were to operate from the axis to the edges in conjunction with the sailing vessel.

When Prof. A. D. Bache assumed the direction of the Coast Survey, he formulated a complete method of administration and included in it the systematic exploration of the Gulf Stream. The plan first adopted, based upon the knowledge of the general features of the Stream, was as follows, but it

naturally was modified by deductions and inferences from new facts which were brought to light as the Survey progressed:

I. To refer the observations to a medial line or axis, on each side of which it would be more or less similar in its temperatures, and to run sections perpendicular to this line across the whole width of the Stream.

II. To start from points on the coast whose positions are well known, and to determine by the best means known to nautical astronomy the position of the vessel at frequent intervals, and to check these results if necessary by a return to the coast.

III. To occupy positions at which the temperatures at different depths would be determined, the frequency of which would depend upon the greater or less rapidity of the change of temperature.

As regards seasons for explorations, the summer was regarded as the most favorable for the greater part of the Stream, for the reason that the winter season, at which time the storms and cold rendered observation more difficult, is also the season in which the equilibrium of the currents would be most disturbed by the rapid cooling of the water. Sounding in winter in stormy weather (with rope) was hardly practicable, and the results obtained were liable to great inaccuracies.

In the spring of 1845 the brig *Washington* was commissioned and placed under the command of Lieut. C. H. Davis, U. S. N., and the following instructions were given him. The first part is quoted almost in full, to show the clearness with which Professor Bache saw the details necessary for such an investigation in order to establish the laws of the Stream in the best manner with the instruments available at that time.

Professor Bache says:

> The following questions should be examined:
>
> First. What are the limits of the Gulf Stream on this part of the coast of the United States, at the surface and below the surface?
>
> Second. Are they constant or variable, do they change with the season, with the prevalent and different winds; what is the effect of greater or less quantities of ice in the vicinity?
>
> Third. How may they best be recognized, by the temperature at the surface or below the surface, by soundings, by the character of the bottom, by peculiar forms of vegetable or animal life, by meteorology, by the saltness of the water?

Fourth. What are the directions and velocities of the currents in this Stream and adjacent to it at the surface, below the surface, and to what variations are they subject? What peculiar arrangement of the currents takes place at the edge of the Stream in passing from the general waters of the ocean into those of the Gulf? Some of these questions will require long-continued observations to solve. If you can obtain something like approximation to the normal condition of the Stream in this summer's work it will be quite satisfactory. Make, then, as many cross sections of the Stream as convenient and as the investigation may show to be necessary. In these sections (1) determine the temperature at the surface and at different depths; (2) the depth of water; (3) the character of the bottom; (4) the direction and velocity of the currents at the surface and at different depths; (5) as far as practicable notice the forms of vegetable and animal life.

Project or note the results as obtained. In the diagram for the temperature at the surface the abscissa will correspond to distance, the ordinates to temperatures, upon a convenient scale arbitrarily assumed. The distance apart at which the observations should be made must depend upon the more or less rapid change of temperature; thus, on the borders of the Stream, they should be more frequent than on either side or within it. The diagrams of the scale of temperature, if made large, will be good guides to the work.

Examine the depth and character of the bottom at the same time. To determine the temperature at a great many depths and at or near the same position, will be difficult and tedious. To avoid the necessity for it, make a complete investigation of the change from the surface to the bottom, at as many points as may appear necessary; thus, for example, make an investigation on the several sections above referred to, on the following lines. Sound before reaching the edge of the stream two lines at or near the edge, two lines within, or as many as appear necessary, two at or near the outer edge and several beyond. As for the lines within the Gulf Stream which are the most interesting, the investigation will show how many will be required. The frequency of the observations in a given depth will be determned by the more or less rapid changes in temperature. Suppose a conjectural diagram to represent the results, the temperature changing rapidly near the surface about a point *a*, then slowly to a certain depth. A counter cold current being met at *b*, the change becoming rapid there, this low temperature ranging but slowly toward the bottom at *a* and *b*, the observations should be frequent. All the observations on depths and character of the bottom and temperature should be carried quite across the Stream.

It may and probably will turn out that there is a certain depth at which the temperature is invariable for the same position uninfluenced at least by season or by winds, and the assemblage of these points will give a line below the surface constant in direction and velocity, and to determine this will be a valuable practical result.

These sections, with the addition of lines run in the general direction of the Stream, will enable you to represent it on a chart in the usual way, showing the limits and axis, the velocity and direction and temperature at the surface and at any depth which is desirable as that of the line of invariable temperature. As to the character of the bottom, use the Stellwagen Cup and the apparatus which I have requested Lieutenant-Commanding Blake (if he can dispense with it) to send to you at New York. They may both answer the purpose. Characteristic specimens should be preserved, as heretofore, and duly marked with date and position. They will be arranged on your return to the office. The temperature at the surface obtain in the ordinary way or by using the instrument furnished to Commander Gedney last year, and which I shall speak of as the marine thermometer. The velocities and directions of the currents you should ascertain as far as practicable by comparing the positions determined by astronomical observations and by reckoning, by anchoring the vessel or a boat when such a thing is practicable, by the change of position in time of calm. The way of the vessel by Massey's Log.

The existence of a counter current of cold water from the poles below the warm current from the equator has been supposed. This current would produce a position of rest, in which if a heavy body attached to a light one at the surface were immersed, the light one would drift off down the stream of the superior current. If a light body were sent down to the counter current and then detached, it would rise at a point up the stream of the surface current. A boat might be anchored on it by attaching to it a body which would produce a considerable resistance to motion. Two boards put together crosswise would answer the purpose well. It may be that if there is no counter current the velocity near the bottom is so much checked as to cause a variation to be discernible in some such way.

The remainder of the instructions is devoted to details of observation.

Lieutenant Davis made two or three trips into the Gulf Stream, and although the means of observation were tentative on this first year's work, much valuable information was obtained.

In 1846 Lieut. George M. Bache, U. S. N., was detailed to continue the Gulf Stream investigation under practically the same instructions as his predecessor. After a summer's successful work in tracing the temperature across the Stream on three sections, the little vessel was overtaken by a hurricane off the North Carolina coast and Lieutenant Bache and ten of the crew were swept overboard by a sea and lost. The vessel managed to reach port almost a wreck, and the observations, made at such a cost in life, were preserved. Lieutenant Bache gave the name "Cold Wall" to the remarkable change in temperature usually found at what is supposed to be the inner edge of the stream, and he also confirmed the fact that there were alternations of hot and cold water across the stream.

In the following year the *Washington* was commanded by Lieut. S. P. Lee, U. S. N. His instructions contemplated tracing the axis of the Stream, and testing, on his return from the Gulf of Mexico, the existence of the cold wall south of Cape Hatteras. They also called for a resurvey of the section off Cape Henry in order to connect the series of observations made in different years. The observations made by Lieutenant Lee were in the main a confirmation of those of previous years. He found the alteruations of hot and cold water, but their positions did not correspond. Lieutenant Bache found a second branch of the Gulf Stream separated by cold water, while Lieutenant Lee found more than one alternation, and the positions of the highest and lowest temperatures were different in the two years.

In 1848 the work was continued, but with improved means. Two Six's thermometers and two larger on the same plan were used, and also a metallic self-registering thermometer, designed by Mr. Joseph Saxton especially for this work. Instead of a sailing vessel, the U. S. steamer *Legaré* was commissioned under the command of Lieut. Richard Bache, U. S. N., and the section off Cape Henry resurveyed and a first examination of the Cape Hatteras section made. The observations of this year furnished data for comparison of the results obtained during three consecutive years on the Cape Henry sections, and were thought to develop the fact that, beginning with a minimum at the cold wall, the temperature rises to a maximum in the axis of the Stream, beyond which are two minima and two maxima.

After the observations above mentioned and until 1853, circumstances connected with the work of the Survey prevented the prosecution of Gulf Stream investigation, but in this year a party under Lieut. T. A. M. Craven, U. S. N., on board the steamer *Corwin*, was directed to run four sections across the Stream from Cape Canaveral, St. Augustine, St. Simon's Sound, and Charleston, and Lieut. J. N. Maffitt, U. S. N., on board the schooner *Crawford*, to run the sections from Charleston, Cape Fear, and Cape Hatteras.

In addition to copies of the instructions that had been sent to the former officers engaged in the work, Professor Bache also issued detailed instructions as to the special methods of prosecuting the examinations. The axis of the Stream or the point of highest temperature was to be traced by zigzags, by Lieutenant Craven, from Key West to Charleston, and afterwards as far north as the latitude of New York, and, with the exception of the latter, which was unavoidably prevented, all the work laid out was most faithfully executed. The soundings taken by both parties were with rope or by Massey's sounding machine, and from the depths obtained they supposed there were two submarine ridges running parallel to the coast. The soundings since taken with pianoforte wire have proved this to have been an error. The temperature curves obtained this year are of the same form as those previously found farther north, and in the duplication of the Cape Hatteras section it was found that the similarity of curve and the positions of the various warm and cold bands were remarkable.

It was concluded that there were alternations of temperature across the Gulf Stream, the cold water intruding and dividing the warm, making thus alternate streaks or streams of warm and cold water, and it was thought that the observations of Lieutenant Maffitt, on the Charleston and Cape Fear sections, showed a counter current where the cold streaks were found. That such is not always the case will be shown later in discussing the observations of the *Blake* in recent years. Professor Bache also decided that "the observations of this year have fully proved that in the Charleston section, and those south of it, the bands of cold and warm water are produced by the shape of the bottom of the sea." The progress of the explorations up to 1853 furnished data for the construction of a chart of the Gulf Stream from Cape Canaveral to the section off Sandy Hook, the alterna-

tions of temperature being shown by shading, the darker the shade the higher the temperature. (See illustration No. 37.)

The curves limiting the various bands were not in all cases drawn precisely through the points obtained on the several sections, but in no case but one was the distance from the point actually determined as great as the probable error in the determination of the points themselves. The bands appeared to be invariable in number and position. The supposed axis of the Stream (the highest temperature) was the best determined. The cold wall was the next best to that of the axis, and in the case of the other warm and cold bands the limits of uncertainty in their position at the point of crossing any section were less than half the average distance between the positions in that part of the section.

In 1854 it was thought to be desirable to continue the examination of the St. Simon's and Canaveral sections in winter for a comparison with the summer's work, and Lieutenant Craven was assigned to the duty. The temperatures obtained showed a remarkable dissimilarity of form from those of the summer. The thermometer at most of the positions was nearly constant from 20 to 100 or 120 fathoms, and below that depth it changed rapidly. At Canaveral the double division of the Stream was shown, but the first maximum was about 7 miles nearer the Cape than in 1853, and the second maximum was warmer. What would generally be taken by navigators as Gulf water was 65 miles from the Cape, "but there had evidently been some great disturbance of temperature just before these results were obtained."

Later in the year Lieutenant Craven investigated the Nantucket section, running a line SE. by S. from the Davis South Shoal light-vessel and making observations at about 20-mile intervals for a distance of 230 miles. He found the warmest water at this distance, which was 40 or 50 miles farther south and east in October, 1854, than it was in August, 1845. The alternations of warm and cold water were discernible, but, as in the case of the warmest, they were a greater distance off shore. In 1855 the work of research was continued, Lieutenant Craven running a section off Cape Florida in May, and Lieutenant Sands along the axis of the Stream in June, and also a section off Nantucket in October. The section off Cape Florida was completed successfully and the axis of the Stream followed as far as

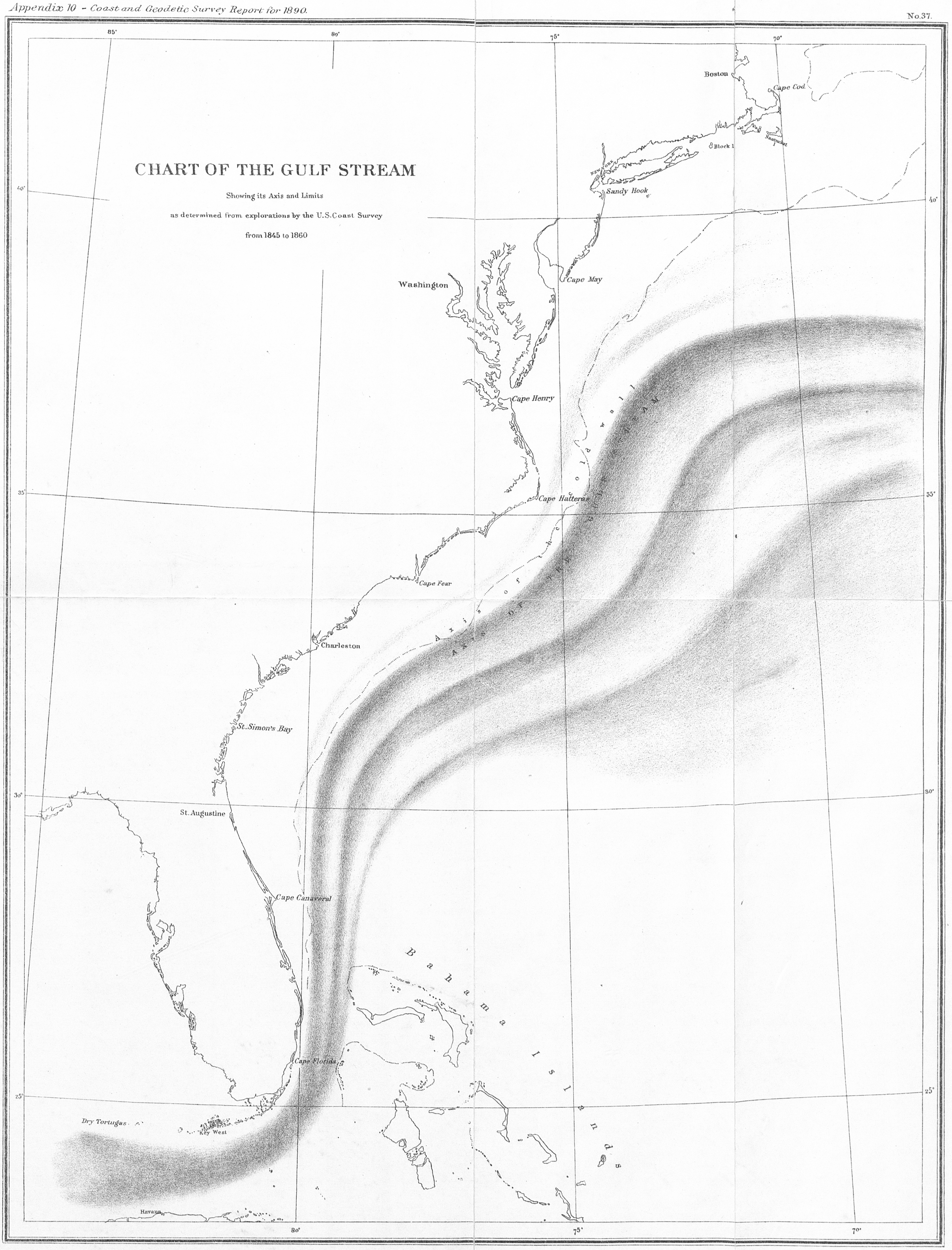


CHART OF THE GULF STREAM
Showing its Axis and Limits
as determined from explorations by the U.S. Coast Survey
from 1845 to 1860
85°
80°
75°
70°
40°
35°
30°
25°
Boston
Cape Cod
Nantucket
Block I
NEW YORK
Sandy Hook
Washington
Cape May
Cape Henry
Cape Hatteras
Cape Fear
Charleston
St. Simon's Bay
St. Augustine
Cape Canaveral
Cape Florida
Dry Tortugas
Key West
Havana
Axis of the Gulf Stream
Bahama Islands

Cape Lookout, but in the attempt to finish the Nantucket section only the warm water of the axis was reached. In 1857 a number of interesting observations were added to the Gulf Stream exploration. A section was run from Havana to Sand Key, Florida, the inner edge of the Stream was traced from Cape Canaveral to Cape Fear, the axis was traced from Tortugas to Cape Hatteras, and a line was run from Halifax in the direction of Bermuda. It was unfortunate, however, that the thermometers were not always in working order, as many temperature observations on both the Havana and the Halifax lines had to be discarded. During the next three years the work was chiefly confined to investigating the temperatures across the Straits of Florida.

Although the plan for the exploration of the Stream contemplated the determination of the density of the water and the direction and velocity of the currents, the actual work performed was the determination of temperature and depth. The existence of a polar current underlying and running counter to the Gulf Stream was assumed by Professor Bache, the assumption being founded mainly upon theoretical considerations, and not on actual current observations. Generally the only record of current was obtained by the difference between the dead reckoning and the astronomical positions of the vessels, as, for example, in the record of observations of one party it says:

> August 16.—A comparison of the afternoon with the morning sights for chronometer show a current of 5 miles eastwardly. The vessel was lying-to in the interval. The meridian observations showed a northerly current during the last 24 hours.

Another record was:

> August 18.—Tried the current with a boat anchored with 1,200 fathoms line (no bottom). Found it on the surface setting SW. by W. 0.29 mile per hour. At 25 fathoms depth, SSW., same velocity. This agrees with chronometer sights of morning and evening, the brig lying-to all day and drifting a little to the west with the sea.

The instruments employed in the investigation under Professor Bache were of the most approved patterns, were handled with the greatest care, and every observation scrutinized closely, but the difficulties against which they had to contend rendered the work very laborious and the results sometimes liable to doubt, which necessitated discarding the observation.

The thermometers were as follows: The self-registering instruments of Dr. Rutherford, of Edinburgh, and Six, of Canterbury; a metallic thermometer made by Breguet, of Paris, and another by Mr. Saxton, of the Coast Survey Office. Rutherford's is a minimum thermometer, the cohesion of the spirit drawing an enamel index to the lowest point reached by the contraction, where it is left as the fluid expands. To render it applicable to deep-sea temperatures it is inclosed in a glass globe made strong enough to withstand moderate pressures. In use it is necessary to keep the tube horizontal, which is not always possible. In using rope, too, for lowering, the centrifugal motion caused by the twisting or untwisting of the rope prevents accuracy or certainty of registration.

Six's thermometer is composed of a bent tube of glass, one of the branches terminating in a large expansion to form a cylindrical chamber and the other only slightly enlarged at the end. The lower part of the tube contains mercury, which partly fills both branches on either side of the bend. The upper part of each branch, including the chambers, is filled with highly rectified spirits of wine. A rise or fall of temperature will cause a greater expansion or contraction of the spirits in the larger end than in the smaller, which will cause the column of mercury in that branch to rise and fall, and thus a motion is communicated to its surface in both branches. A small index of steel, coated with glass and lightly held in place by a delicate spring, is pushed along by the surface of the mercury and remains at the farthest position when the mercury withdraws.

The Breguet metallic thermometer is constructed on the principle of the unequal expansion of metals. The compound bar is composed of laminæ of brass and steel united together and bent into horseshoe form. One end is firmly fixed and the other, being free to move under the influence of the unequal expansion or contraction of the two metals, gives rotary motion to an index and registers on a dial by means of an auxiliary hand held by friction at the highest or lowest point of temperature. The whole is inclosed in a brass case made sufficiently strong to withstand pressure.

The Saxton thermometer is the same as the Breguet in principle, but the laminæ are composed of silver and platinum and wound in a spiral instead of being bent into horseshoe form. It is heavily gilded and inclosed

in a metal case, into which the sea water is admitted. According to our ideas at the present day these instruments were faulty.

The conclusions adopted by Professor Bache from the observations taken under his direction between 1854 and 1860 were as follows: That between Cape Florida and New York the Gulf Stream is divided into several bands of higher and lower temperatures of which the axis is the warmest, the temperature falling rapidly inshore and more slowly outside. This is not only the case at the surface, but, with modifications easily understood, at considerable depths. That between the coast and the stream there is a fall in temperature so abrupt that it has been aptly called the "cold wall." The cold wall extends, with varying dimensions and changes of its peculiar features, along the coast from Cape Florida northward as far as examined. Inside this wall of marked colder temperature there is another increase, while outside the warmest band, which is next the cold wall, there is another warm and one other cold band. The distances these are situated from the coast are shown in the following table:

Name of section.	Distance of cold wall from shore.	Width of first warm band.	Width of second cold band.	Width of second maximum.	Width of Gulf Stream proper.	Width of third minimum.	Width of third maximum.	Width of fourth minimum.
	Miles.	*Miles.*	*Miles.*	*Miles.*	*Miles.*	*Miles.*	*Miles.*	
Sandy Hook	240	60	30	37	127	60	50	Indefinite.
Cape May	125	55	30	40	125	70	65	70
Cape Henry	94	45	32	47	124	80	60	50
Cape Hatteras	30	47	25	45	117	37	75	70
Cape Fear	60	30	20	37	87	30	60	25
Charleston	62	25	15	30	67	26	35	------
St. Simon's	87	25	13	20	58	25	25	------
St. Augustine	70	20	13	12	47	22	20	------
Cape Canaveral	35	20	------	------	35	14	12	------
Cape Florida	------	25	------	------	25	5	------	------

In the sections on which the work was duplicated, viz, the Cape Henry and the Cape Hatteras sections, the positions of the cold wall and axis of the Stream agreed within 5½ miles, and those of the succeeding points of maximum and minimum temperature within 7½ miles.

After the year 1860 Gulf Stream investigation ceased almost entirely until 1867, when Prof. Henry Mitchell of the Coast Survey sounded between Key West and Havana and observed the currents to the depth of 600 fathoms, the deepest ever attempted to that date. The method adopted to observe these currents was the following: Two globes or cans of equal surface were attached to each other by a line of the desired length. One of the globes was loaded so as to sink to the length of the connecting line, while the other was on the surface supporting its mate. Within the latter was a light reel upon which a small log line, passing through an aperture, was wound by a crank from without. To the end of the line was secured a third globe floating freely upon the surface of the water. When making an observation the log line was reeled in until the surface globes were together. At a signal the reel was released, and, if the currents influencing the two were different, the amount of separation in a given time indicated the relative velocities.

A trial was made of surface currents and at 300 and 400 fathoms depth, at a station 3.7 miles from Fort Chorrera, Cuba, and a velocity of about one knot was found at each. Another trial was made about 3 miles farther off shore, with the result, that at 600 fathoms depth the current was about 10 per cent. less than on the surface. From these experiments, Professor Mitchell was led to conclude that "the Gulf Stream has a nearly uniform velocity and constant course for a depth of 600 fathoms, although its temperature varies in this depth 40° F." In the following year Professor Mitchell continued current observations in the Santaren and St Nicholas Channels, using an anchored buoy for the initial point from which to start the float for service observations. His conclusion was that the water in these channels was motionless.

In 1868–'69–'70 expeditions were fitted out by the British Admiralty, and, under the scientific direction of Dr. William B. Carpenter, Mr. J. Gwyn Jeffreys and Prof. C. Wyville Thomson, sounded and dredged off the coast of Europe from the Faroe Islands to Gibraltar. Accurate tempera-

ture observations were taken, and from these Professor Thomson has given the course of the currents in what is called the northeastern extension of the Gulf Stream. By the term Gulf Stream he explains:

> I mean that mass of heated water which pours from the Straits of Florida across the North Atlantic and likewise a wider but less defined warm current, evidently forming part of the same great movement of water, which curves northward, to the eastward of the West Indian Islands. I am myself inclined, without hesitation, to regard this stream as simply the reflux of the equatorial current, added to, no doubt, during its northeasterly course by the surface drift of the anti-trades which follow in the main in the same direction.

Of the cause of the Gulf Stream he says: "It seems to me that the Gulf Stream is the one natural phenomenon on the surface of the earth whose origin and principal cause, the drift of the trade winds, can be most clearly and easily traced." He concludes that the Stream enters the North Atlantic and accumulates. Finding no free passage toward the northeast, a portion of it goes toward the Azores, but the accumulation to the northward forces a return eddy current to underrun certain portions of the warmer flow.

In 1873, the *Challenger* expedition, under the command of Capt. Sir George Nares, R. N., with a full staff of scientific gentlemen, of which Prof. C. Wyville Thomson was the head, added some most valuable data to the record of Gulf Stream investigation. They crossed the North Atlantic twice, and made passages north and south along the shores of both hemispheres, making the most accurate observations of temperature and specific gravity. In the passage of the *Challenger* across the Gulf Stream off New York, and between Halifax and Bermuda, the alternations of warm and cold water were found. They also at times made observations of the strength and direction of the currents, both surface and subsurface, using practically the same method as that employed by Professor Mitchell in the Straits of Florida in 1867.

The Coast Survey continued its examinations in the Gulf Stream in sounding and dredging during the years 1868 to 1878, with the steamers *Bibb*, under Acting Master Robert Platt, U. S. N., the *Bache*, under Commander J. A. Howell, U. S. N., and the *Blake*, under Lieut. Commander C. D. Sigsbee, U. S. N. Mr. L. F. Pourtales and Prof. Louis Agassiz accompanied the vessels at different times for the purpose of collecting and arrang-

ing the results of the dredging operations. In 1879 the investigation was extended into the Caribbean, and a theory advanced as to the flow of its waters by Commander John R. Bartlett, U. S. N., who commanded the vessel.

In his report accompanying the record of the season's work, he concludes that the equatorial current, which sets directly against the Windward Islands, is by them and their connecting ridges deflected northward, and so following their outer edge passes around the Virgin Islands to the westward and through the deep channel to the northward of San Domingo. He suggests, also, that on reaching Cuba the current divides, a part flowing northwest through the old Bahama Channel and a part through the Windward passage between Cuba and San Domingo, and thus by Cape San Antonio into the Gulf of Mexico. His report states that the specimens of bottom taken in the Windward passage give evidence that the current moves in depths greater than 800 fathoms and that it reaches the bottom. He remarks, too: "The current, always found flowing north along the eastern side of South America, on reaching the island of Tobago divides, part joining the equatorial current setting north along the chain of islands, the remainder following the coast line of Trinidad and the Spanish Main, and so around the entire circumference of the Caribbean Sea, finding at last an outlet at the Mona Passage and the Anegada Channel to join the equatorial current on its way to the Gulf of Mexico." This circulation is so contrary to that found in the later investigation made by the *Blake* that it is given in full. Prof. Alexander Agassiz accompanied Commander Bartlett on this cruise, and while he quotes the latter on this subject he does not seem to adopt these ideas without question, for he says: "In the present state of our knowledge it is difficult to trace the path of the equatorial water as it is forced into the eastern Caribbean."

In 1877 the first attempt was made by the U. S. Coast Survey to systematically observe ocean currents from a vessel anchored at sea. The schooner *Drift* was built for this purpose, and under command of Acting Master Robert Platt, U. S. N., successfully observed the currents between Nantucket and Nova Scotia, occupying eight stations for varying periods, the longest time being over 90 hours and the greatest depth of water 135 fathoms.

The first reliable soundings which developed the bed of the Gulf Stream from the Straits of Florida to George's Bank were made by Commander Bartlett in 1881 and 1882. It will be remembered that the soundings by Lieutenants Davis, Lee, Craven, and others before 1860 were made with rope or registering devices, such as Massey's, and when these are used in a strong current or in considerable depths they are unreliable. Commander Howell, when in command of the Coast Survey steamer *Bache*, was provided with one of the Thomson wire sounding-machines, which had been so successfully used by Captain Belknap on board the U. S. S. *Tuscarora* in the Pacific. The principle of sounding with piano-forte wire was much improved by his successor, Lieutenant-Commander Sigsbee, so that any depth could be ascertained with certainty and accuracy in almost any weather, and since that time the *Blake* has used nothing else for the purpose.

Commander Bartlett ran lines about normal to the coast at intervals of 60 miles from Jupiter Inlet north. He says:

> Instead of a deep channel which had previously been reported, our soundings show an extensive and nearly level plateau extending from a point to the eastward of the Bahama Banks to Cape Hatteras. Off Cape Canaveral it is nearly 200 miles wide, and gradually decreases in width to the northward until reaching Hatteras, where a depth of more than 1,000 fathoms is found 30 miles off the shore. This plateau has a general depth of 400 fathoms, suddenly dropping on its eastern edge to 2,000 fathoms. The soundings in the strength of the current were all taken with a 60-pound shot, the time allowed for the sinker to reach the bottom being less than one minute to each 100 fathoms in depth.

In the lines crossing the Stream from Nantucket to Bermuda and returning to Cape Hatteras, Commander Bartlett took serial temperatures at short intervals and surface observations every mile. He says:

> In regard to the results of the investigation of this last season's work, I have been particularly interested in what I was expected to find—that is, the bifurcation of the stream into warm and cold bands. The warm and cold bands have been accepted for so long a time as a fact and have been reported by such reliable authorities that there must have been different conditions of weather during our observations. I have already stated that our observations did not indicate anything of the kind.

In 1883 Lieut, J. C. Fremont, jr., U. S. N., in command of the schooner *Drift*, was detailed for the first Gulf Stream current investigation to be made from a vessel at anchor. The vessel was supplied with 700 fathoms of galvanized wire rope three-quarters of an inch in diameter, and instructions issued to observe currents at various places near the 100-fathom curve along the coast, and also in the stream between Jupiter Inlet and Memory Rock. The *Drift* is a small deep-draft schooner of about 100 tons. Not being fitted with a steam windlass, the rope, which was coiled on deck, was veered and hove in by hand. In spite of this, Lieutenant Fremont succeeded in occupying five stations across the channel, the deepest anchorage being over 400 fathoms. The currents were observed by floating cans attached to a log line. It was discovered that, "contrary to expectation, the greatest velocity was not found at the supposed center of the stream, but somewhat to the westward of it. The greatest velocity noted was 4.7 knots in latitude 27° 05′ north and longitude 79° 44′ west. The depth here was only 190 fathoms, the distance west from the supposed axis 10 miles, and from the Florida coast about 20 miles."

Before beginning the description of the *Blake's* examinations of the Gulf Stream under my command there is one other investigation to which allusion should be made. His Highness the Prince of Monaco during the past years has been engaged in scientific researches on the coast of France. The object of his examination was primarily for the purpose of discovering the cause of the departure of the sardines from the Bay of Biscay; but in connection with this he has devoted much of his time to a study of the eastern portion of the Gulf Stream. In order to discover the velocity and direction of this current he adopted the method of floats, but carried it out in a manner and magnitude never before attempted. His floats were barrels and bottles to a limited number, but mostly were specially constructed copper globes, and all were ballasted so as to expose as little surface as possible to the wind and waves. The ballast of the barrels and globes was suspended several feet below the surface of the water, and so arranged that by the time the float accumulated a quantity of material (barnacles, grass, etc.) the ballast would become detached.

He put overboard from his yacht no less than one thousand six hundred and seventy-five of these floats. In 1885, one hundred and thirty-nine in

a distance 170 miles northwest of Azores. In 1886, over five hundred more were placed along the twentieth meridian off the coast of France. In 1887, nine hundred and thirty-one were set adrift between the Azores and Newfoundland, and afterwards another line farther to the northward and eastward in the region of the supposed northeast extension of the stream near the fiftieth parallel. Dividing each of the lines into thirds for purposes of study, he found that most of the floats traveling to the southward came from the southward and middle groups, and of those going to the northward and eastward most of them belonged to the northern groups, but there were some from each group which had traveled in the opposite directions. Of those placed between the Azores and Newfoundland, one from near the northern end of the line and one from near the middle were found in Ireland, others from near the same points traveled to the coast of Norway, and more were distributed along the shores of France, Spain, and Africa. None of those started near the Azores were found north of Lisbon. Two of those from the northern end of the line off the coast of France found their way to the West Indies.

CHAPTER IV.

OUTFIT OF THE BLAKE FOR ANCHORING AT SEA AND OBSERVING THE CURRENTS.

From this brief history of the Gulf Stream investigation it is seen that all the theories as to causes, and all the facts as to limits, velocity, and direction have been based entirely upon drift of vessels, or inferences drawn from temperature observations, character of the bottom soil, presence of Gulf weed, tide rips, etc., the best of them only giving evidence of the existence of a current when it is strong, and not one of them giving anything conclusive or accurate as to velocity or direction, or an indication even of a regular variation either daily or monthly. The establishment of the axis of the Stream by the thermometer was at once proved to be an error, by Lieutenant Fremont's observations, and it has since been found that a current may be flowing south with a much warmer temperature than when, a few hours later, it is flowing north. It will be shown, too, that while a warm current may be flowing in its customary place, its warm water may be transported by the winds and waves to other localities, without an accompanying current. A conclusion drawn as to the direction or velocity of a current based upon temperatures is very apt to be wrong, unless expressed in the most general terms.

The drift of vessels, while showing the existence of a current within certain limits is open to many objections. When in sight of known objects on land and in the smoothest water, the determination of the difference between the actual and the supposed run of the vessel does not accurately show the current. The errors in steering, of the compass and log, of plotting on a chart distorted by unequal shrinking in the process of manufacture, all tend toward error. How much less the chance of accuracy when a vessel is at sea, the winds and waves driving her to leeward to an unknown amount, the motion of the vessel swinging the compass, the personal error or lack of judgment in the helmsman, the faulty astronomical position, never

true except by chance, and often miles out, and last, the patent log, varying in accuracy with the speed of the ship and the height and direction of the waves. The surface current too is continually changing, and even if the drift of vessels did, by rare good luck, give the current from the time of one fixed astronomical position to the next, the positions are separated by so wide an interval of time that it is impossible to detect even the daily variation. The necessity, then, is obvious, that in order to gain a knowledge of the limit, velocity, direction, variations, and laws of any current, observations must be taken from a fixed point within the current.

In attacking the problem of the Gulf Stream, so important to all the commercial interests of the United States, and indeed to most of the civilized world, the Superintendent of the Coast and Geodetic Survey, Prof. J. E. Hilgard, authorized the attempt to anchor off Jupiter Inlet. Commander C. M. Chester, U. S. N., the Hydrographic Inspector, carried out the scheme, and the valuable observations of Lieutenant Fremont were the results. Although this attempt at arriving at a knowledge of the actual flow of water was made with inadequate instruments, at a considerable expense of time and money and under great difficulties, it was the greatest stride toward a solution of the problem that had been made. The use of a sailing vessel for the purpose was found to be impracticable. The long delay in arriving at the station when good weather appeared, and the fact that this was impossible in a calm, which was the very time when observations would be most accurate; the long hours necessary in heaving up the anchor by the hand windlass, and the danger to the vessel during this delay if bad weather was the cause of departure, all of these reasons brought about the decision that in the continuation of the work a fully equipped steamer should be used. The *Blake* was decided upon, as she was a substantial steamer, and, having the hoisting engines, reels, etc., used for dredging, a slight change in outfit would prepare her for anchoring.

As before stated, the surface of the ocean is most liable to fluctuations, and it would be necessary to go below the surface and ascertain what were the movements of the volume of the water in order to determine the laws of the flow. Upon being detailed for the command of the vessel in the summer of 1884, permission was readily granted the writer to try new

methods of search, to fit the vessel for the work as he desired, and to have a current meter of his own design constructed for trial. The *Blake* (frontispiece) is a wooden schooner-rigged steamer of 218 tons, new measurement, built at Baltimore in 1873. Her length on the keel is 139 feet; greatest beam, 29 feet 6 inches. She has compound engines, giving her a speed of about 200 miles per day under favorable circumstances, on a consumption of coal of but little over 4 tons. In the dredging operations on board this vessel under former commanding officers steel-wire rope had been used and the jerking strains eased by means of a rubber accumulator. The working gear, however, was only called upon to withstand a maximum strain at any point of but little more than the breaking strain of the dredge rope, which was from 5,000 to 8,000 pounds. The first thing to do, therefore, in preparing for the cruise was to fit the vessel so that the operation of anchoring could be performed expeditiously and with safety. From motives of economy all the parts of the gear used for dredging that could be utilized were tried in the first anchorage, but changed in arrangement to meet the new requirements. The idea always kept in mind was that none of the parts should receive an undue share of strain, and that as far as possible the mast and booms should receive the force exerted upon them in the direction of their length.

The anchoring boom.—This is a hard pine spar 30 feet long and 13 inches greatest diameter, slightly tapered in both directions from the middle and banded with iron every 3 feet. At its outer extremity is a heavy iron band, into which is shackled the topping-lift on the upper side, and the pulley for the anchoring rope below. Just inside this band is another with eyes on the sides, to which are shackled the guys. At the inner end of the anchoring boom there is a ball-and-socket joint, the socket being placed on the pawl-bitt 7 inches to starboard of the middle line, in order that the boom shall be clear of the head stays when it is secured on the knightheads.

Extending from the pawl-bitt are two smaller spars (see illustration No. 38), 8 inches in diameter, which project over the vessel's side and serve as spreaders for the guys which hold the head of the anchoring boom in its proper position laterally. They are so placed that a line joining their outer extremities shall pass through the center of the ball at the heel of the anchor-

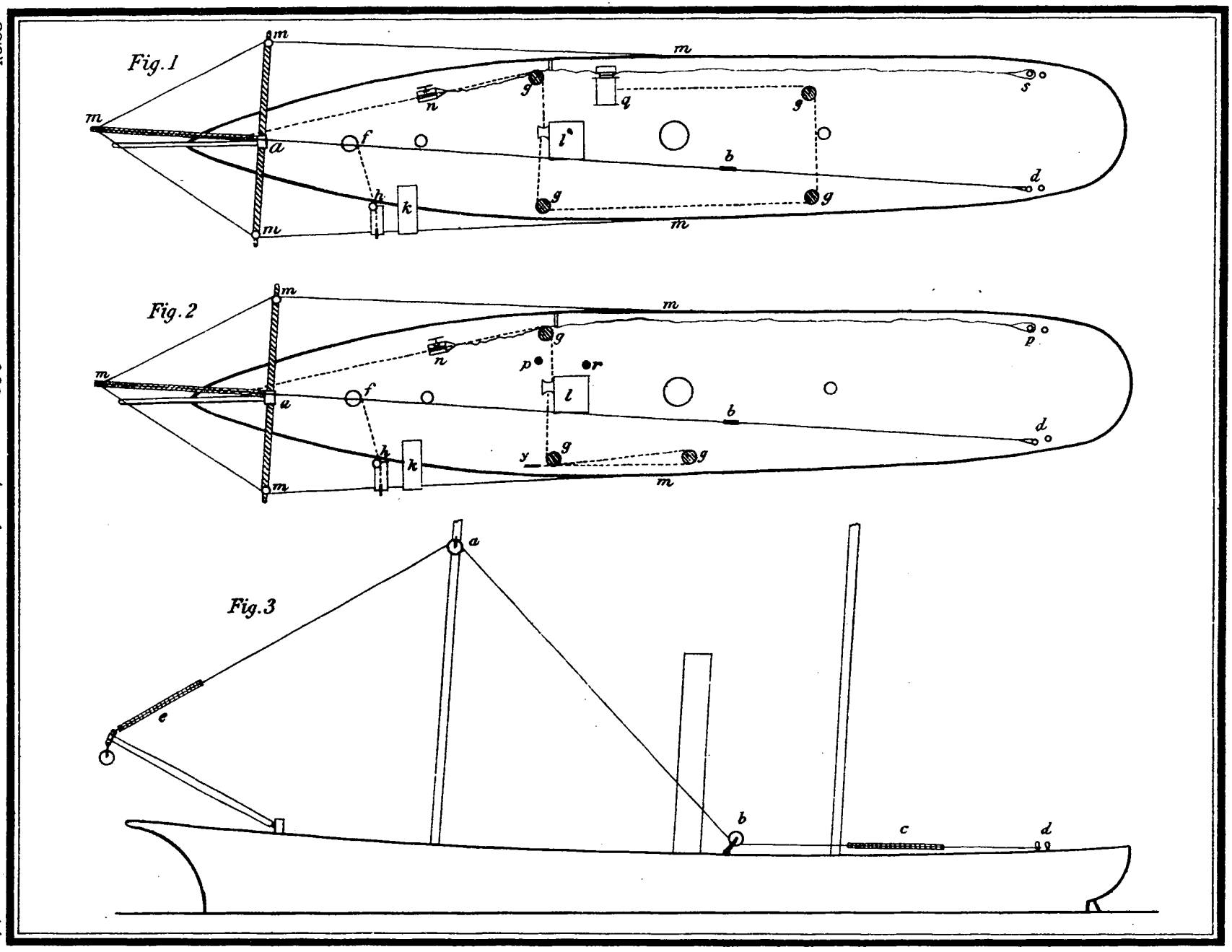


DIAGRAM SHOWING LEAD OF ANCHORING GEAR STEAMER BLAKE

ing boom, and shall be at right angles to the plane of the latter's vertical motion. The outriggers or spreaders are held in position by straps at their heels, lashings at the rail, and at their outer ends steel-wire rope jumper-stays, set up by turnbuckles to heavy bolts in the ship's side near the water-line. The guys (*m. m. m.*) are of steel-wire rope five-eighths of an inch in diameter, shackling to the horizontal eyes at the head of the anchoring boom, passing through leaders at the ends of the outriggers, and setting up by heavy turnbuckles to wire-rope straps at the warping chocks on the main deck. The guy-leaders are iron sheaves, 6 inches in diameter, made to shackle to the wire-rope strap at the ends of the outriggers.

The accumulator and topping-lift.—The end of the anchoring boom projecting over the bow is held up at an angle of about 45 degrees (when with no weight other than its own) by a steel-wire rope topping-lift 1 inch in diameter passing to the foremast head, thence through a leader on the deck, and aft to the bitts on the port quarter (see Fig. 3, illustration No. 38). Interposed in this topping-lift is a rubber accumulator for the purpose, as already stated, of relieving the anchoring rope and the vessel of the sudden jerking strains due to the pitching. The bolt *b*, placed in the deck for the change of direction of the topping-lift, is situated so that when the anchoring boom is pulled down with the greatest strain allowable, the angle formed by the two legs of the topping-lift at the masthead shall be bisected by the mast. The anchoring boom being out of the middle line of the vessel to starboard, the topping-lift leads to the port side of the masthead, so that the boom, the masthead, and the bolt in the deck, previously mentioned, are all in the same vertical plane. When in use the boom is held by its guys in this same plane, and thus the strains give only a downward thrust on the mast (see *d. b. a. m.* Fig. 1, illustration No. 38). The horizontal angle made by the plane of the topping-lift with a vertical plane through the keel is about 11 degrees, and consequently the axis of the socket at the pawl-bitt points to starboard by this amount.

The accumulator, shown in illustration No. 39 is an arrangement of rubber springs devised by Lieutenant-Commander Sigsbee for use in dredging, and afterwards changed in some ways to meet the new requirements in anchor-

ing. It consists of a number of rubber disks or buffers on a middle rod, so arranged that by compression they act as a spring. The middle rod *b* (Fig. 2, illustration No. 39) is $1\frac{1}{4}$ inches in diameter, and the side rods *c* 1 inch, all of tool steel. The rubber buffers *a*, cylindrical in shape, are 5 inches in diameter, $2\frac{1}{4}$ inches in thickness, with a cylindrical hole through the middle $1\frac{5}{8}$ inches in diameter. These buffers are separated from each other by a brass disk or washer $7\frac{1}{4}$ inches in diameter and one-eighth of an inch in thickness except at the middle, where an increase in the thickness of the metal gives a bearing surface as they slide on the rod, and at the same time prevents the rubber from grasping the rod as it is compressed. The diameter of the washers, it will be noticed, is over 2 inches larger than the rubbers. This is to give the latter a bearing surface as they expand in diameter when under strain. There are 70 rubbers in all, which will admit an effective compression of about 5 feet. The composition is known as "No. 23" by the New York Belting and Packing Company, from whom they have always been purchased.

In assembling the different parts of the accumulator the middle rod is lubricated with black lead and tallow, care being taken not to allow it to get on the rubbers. Exposure to the sun causes the surface of the rubbers to crack slightly, and undue compression, causes an extension of the cracks. In order to prevent undue compression an additional wire rope, shown on the frontispiece, is shackled to the upper end of the accumulator and to the outer end of the anchoring boom. This rope (five-eighths of an inch in diameter) is called the preventer topping lift, and is of such a length that it will take the strain when the boom is pulled down before the rubbers are compressed to a dangerous limit. Except with a large anchoring rope the danger is but little with new rubbers, but as they become old they are liable to split.

In the first trial of the anchoring gear the topping lift passed over a large leader at the foremast head, and the accumulator was interposed in its after leg, as shown at *c*, Fig. 3, illustration No. 38. The play of the wire rope over the pulleys *a* and *b* caused the wires in the strands to break in a very short time. Fortunately it was discovered in time to prevent accident, when after a night of heavy pitching over sixty were found broken at *a* and more

Fig. 2

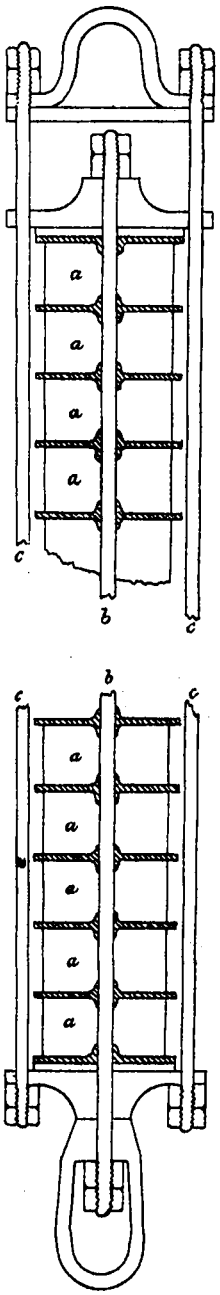
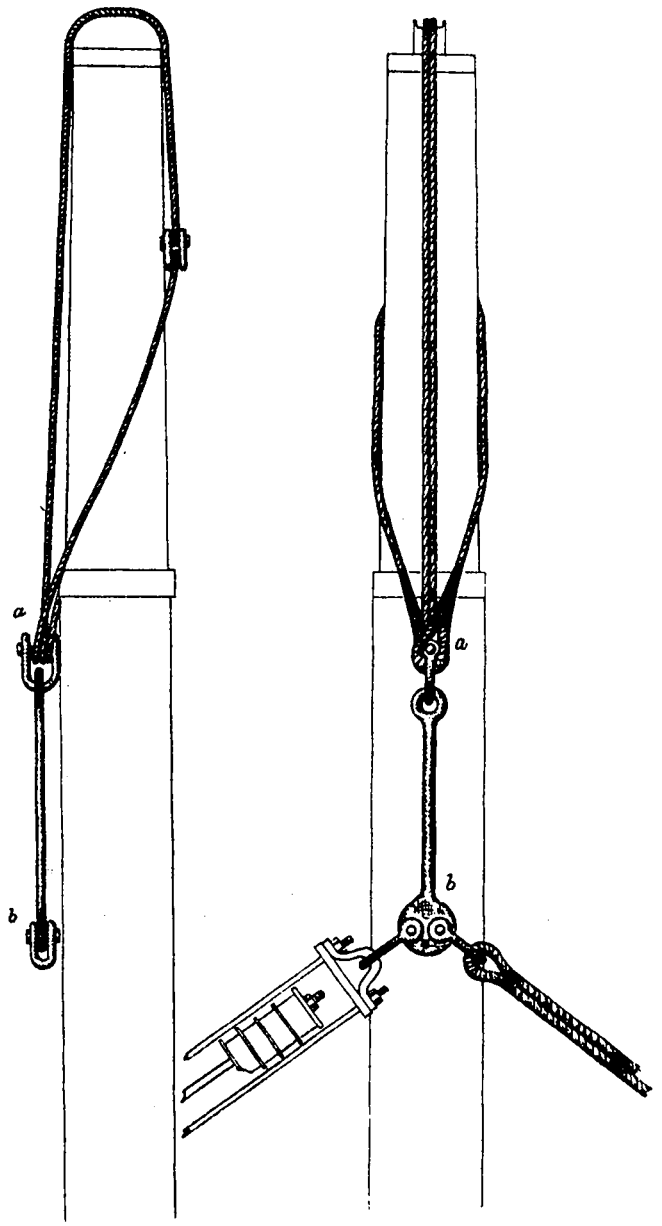
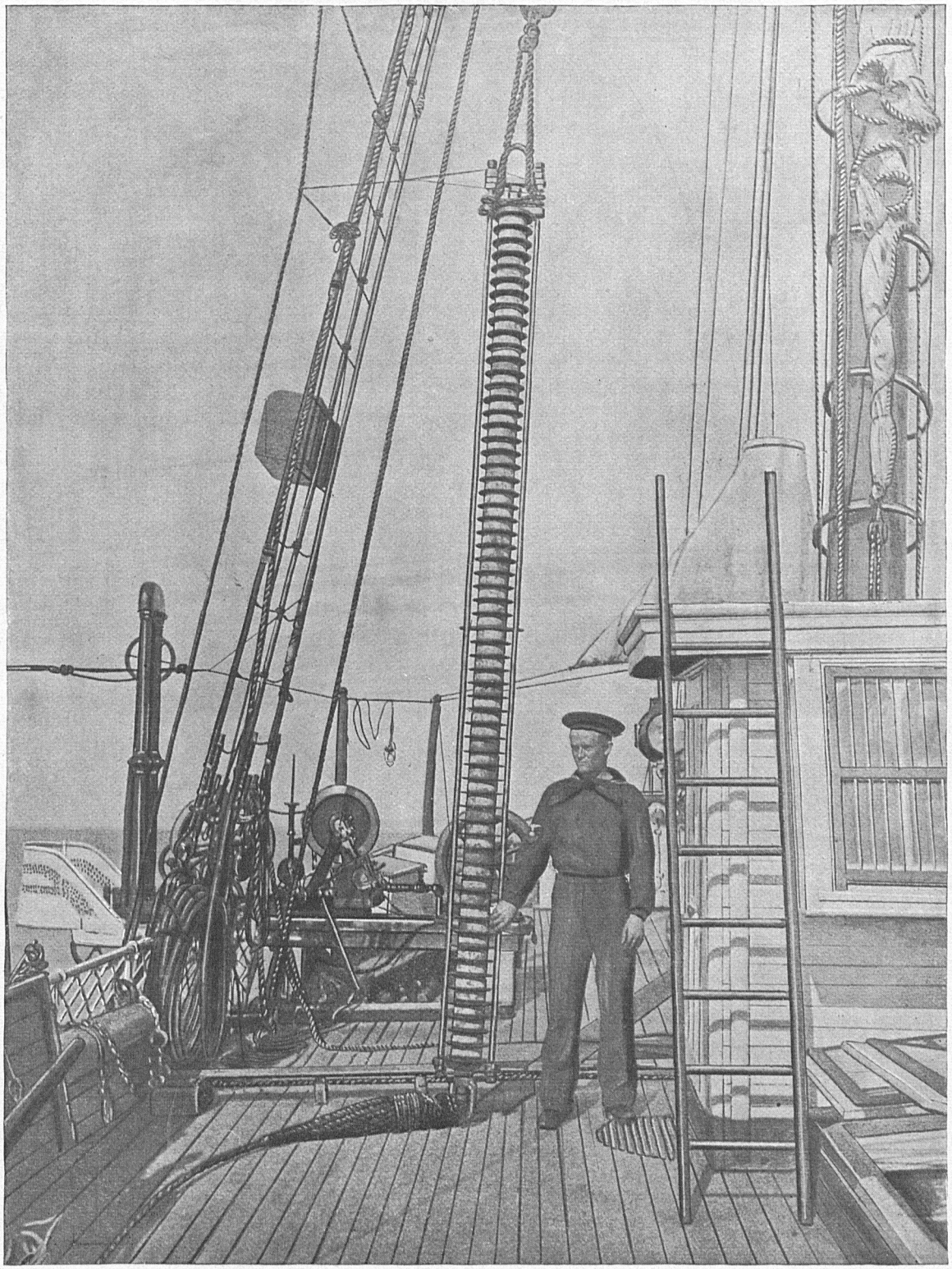


Fig. 1



DETAILS OF THE ACCUMULATOR USED IN DEEP-SEA ANCHORAGES.

STEAMER BLAKE



ACCUMULATOR USED IN DEEP-SEA ANCHORAGES.

at *b*. The accumulator was then changed from *c* to *e*, but this position was not satisfactory, as it was very difficult to examine and oil the side rods when in use. It was then placed at the masthead, in which position, by a foot rope from the fore-rigging to the stay, a man can easily reach it. (See frontispiece.) The change of the accumulator to forward of the foremast did not entirely remedy the danger of stranding the topping-lift. The sudden relief of strain due to pitching caused sufficient sag in the two parts of the lift to give a slight motion over the pulleys, so another device was adopted, which accomplished the desired end.

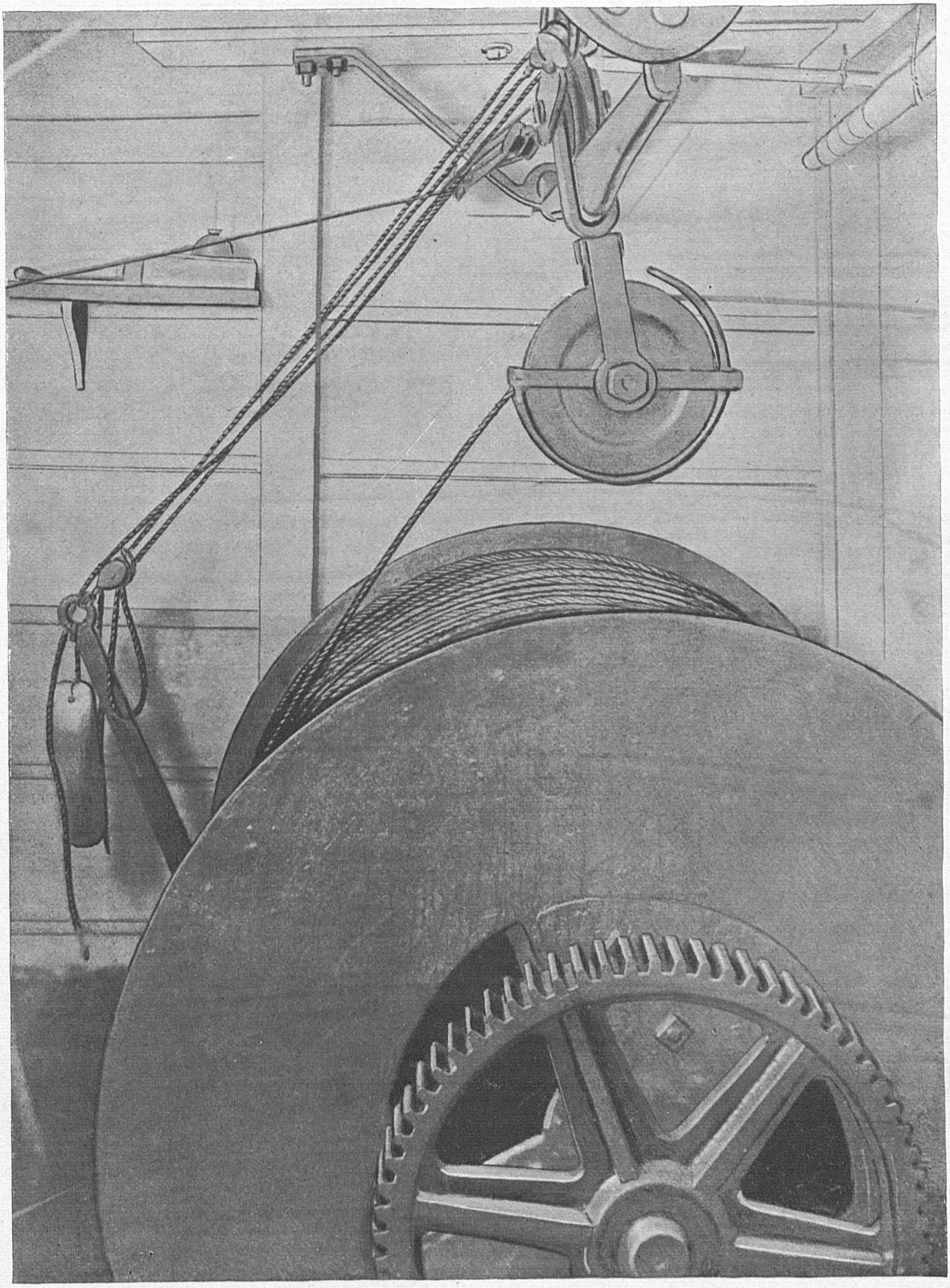
From the sling at the foremast head is a bar of iron (*a b*, Fig. 1, illustration No. 39), 3 feet long and 1½ inches in diameter. The two parts of the topping-lift, or, rather, the after-leg of the lift and the accumulator, shackle into this pendulum, and any change of strain simply vibrates it slightly back and forth. The part of the topping-lift from *b* to *d* (illustration No. 38), being a short length, causes but little vibratory motion at *b*, and consequently a long pendulum at the latter is unnecessary, and a shackle a foot long between the pulley and the deck bolt filled all requirements. In fitting the topping-lift there are no splices except on the forward leg at the accumulator, this one being necessary to prevent chafe on the forestay. The three other ends are turned up and seized. The length of the after-leg, of course, must be just sufficient to allow the pendulum at the masthead to assume a position exactly in line with the mast, when the strain is greatest.

The anchoring rope.—On the first cruise, in 1885, there was a quantity of old dredge rope on board (some 4,000 fathoms), and an attempt was made to use it, but it was quickly found to be altogether too weak. Of the wire rope purchased for the *Drift's* trial about 500 fathoms remained, and this had been taken on board before sailing. It was three-quarters of an inch in diameter, and this, supplemented by 300 fathoms more, five-eighths of an inch in diameter, was used in the first season's work. It answered very well, but was too large for the vessel. In a strong and deep current the skin friction on the wire is very great, and this causes a strain on the accumulator, which increases very rapidly as the size of the rope is increased. It was thought advisable to diminish the diameter in the next purchases, and after the experience of one more season the size finally adopted was a

tapered rope, the inboard end being one-half inch, and the outboard seven-sixteenths and three-eights. The latter is perhaps a trifle small for all conditions, but it always held the vessel unless it was badly kinked.

This rope was manufactured by the Warrington Steel Works in England for the *Blake*, through the agents of the company, Hinkley Brothers & Co., of Boston. The specifications demanded the greatest breaking strain for the size, with no indication of brittleness in splicing, and clean and smooth galvanizing. Great pliability was not essential. The breaking strains guarantied were $\frac{3}{8}$-inch, 14,560 pounds; $\frac{7}{16}$-inch, 19,040 pounds; $\frac{1}{2}$-inch, 25,700 pounds; $\frac{5}{8}$-inch, 34,660 pounds, and no tests made have fallen below these figures. For convenience in transportation it is coiled on a rough reel in lengths no greater than 2,000 fathoms. The splices, made on board, are about 20 feet in length and are usually so smooth that it requires close inspection to detect where the ends are tucked. As received from the manufacturer there is a tendency to kink, and it frequently happens if the current is weak that the rope is paid out faster than the vessel drifts, and instead of being straight from the anchor, a few fathoms will be loose on the bottom. When a strain is brought on it in this condition the kinks straighten and the rope is weakened. This is not objectionable when the kinks are near the anchor, for in the event of the anchor becoming caught on the bottom, necessitating the breaking of the rope, this will occur with the least loss of material. Each time the anchor is hove up the lay of the rope as it is pulled through the water acts as a screw and the twist of the rope is taken out. After long use this process has gone to such an extent that upon slacking the rope it takes a reverse kink, and then, upon straightening under strain, the rope is easily broken.

The reel on which the wire rope is carried is shown in illustration No. 41. It has cast-iron flanges 4 feet in diameter between which is riveted a boiler-iron barrel 2 feet in diameter and 4 feet long. One of the flanges is provided with an ordinary strap brake lined with oak to control its revolutions. Within the barrel are two oak diaphragms bearing against its interior surface to support the crushing strain due to the accumulation of pressure as the turns of rope multiply on the outside. At one end of the shaft is a compact double engine, geared about 5 to 1, for revolving the reel in either



REEL CARRYING ANCHOR ROPE, STEAMER BLAKE.

direction. This reel was originally placed on the upper deck at the point *q*, fig. 1, illustration No. 38, and the lead of the wire rope is shown by the dotted line through the pulleys *g g g* to the large hoisting engine *l*, thence through the pulley *g* to another at the heel of the anchoring boom at *a*. The last mentioned is for the purpose of giving the rope a straight lead along the line of the boom.

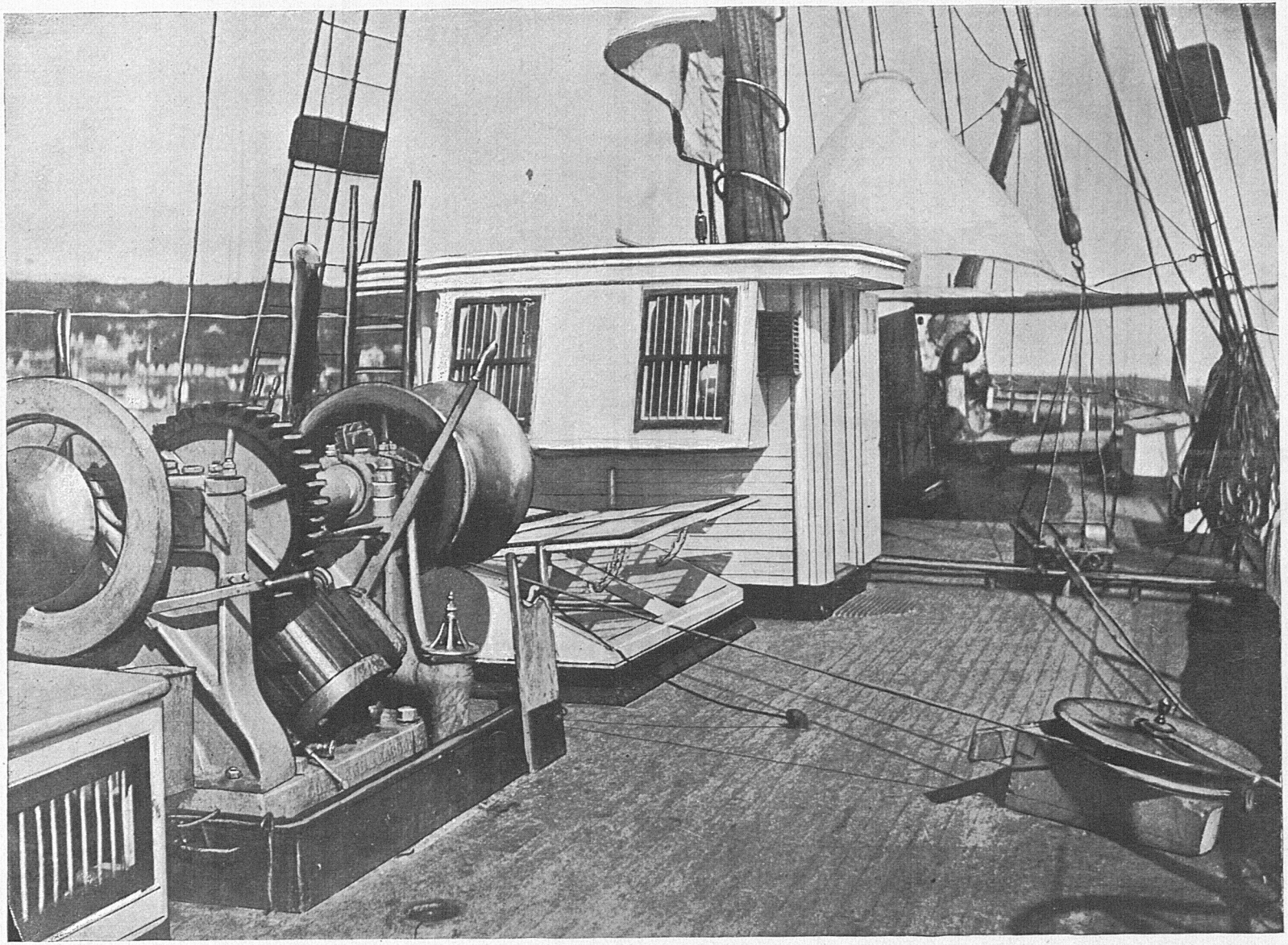
The great weight of the reel and rope on the light upper deck of the vessel made it impossible to keep the deck tight and caused considerable unnecessary strain on all the upper works. It was therefore determined to place it below, and for this purpose a space was bulkheaded from the bunkers, the reel and engine firmly secured to the keelsons, and fittings made for guiding on the wire properly. (See illustration No. 41.) In order that the control of the reel might be from the deck under the immediate supervision of the officer in charge, the throttle governing the engine was placed at *r*, and the line from its strap brake passed through the two decks in a tube at *p* (fig. 2, illustration No. 38). These are seen on illustration No. 42 also. The lead of the wire rope then is from the reel to the starboard hold across the vessel, and changing direction through the decks, appears at a vertical pulley at *y*, fig. 2, afterward following the dotted line through the pulleys *g g g*. It is seen by this arrangement that during the operation of anchoring or heaving-in the rope is always taut, the engine at the reel holding back from the hoisting engine and winding up the wire as fast as it is pulled in. This was the result of the experience of Lieutenant-Commander Sigsbee, who started the dredging operations, and who found, after many trials, that it was necessary in handling the wire rope to allow no slack between the hoisting engine and the reel.

The hoisting engine (illustration No. 42) is a most compact engine of about 30 horse power, driving a winch head by means of gearing of 3½ to 1. Formerly the circumference of this winch head was 6 feet and revolutions were registered by means of a counter reading up to 10,000. It was found to be inadequate to the work in deep water and a strong current. One was ordered, therefore, of 4½ feet in circumference, the register being so altered as to still read fathoms, and this one is now used. The grinding of the high tempered steel wire rope on the winch head renders it inadvisable to use

iron at the wearing surface, and for this reason it is made with a steel ring on a cast-iron hub. Formerly the winch head was fitted with a strap brake for controlling the wire in paying out, the break at the reel being insufficient. This has been discarded and the engine alone used for the purpose. With but little weight of rope out, steam is used to drag it from the reel below. As the weight overboard increases steam is shut off. Increasing still more, the link is reversed notch by notch until it is entirely over. The steam chests are fitted with relief valves. When the engines are reversed and the strain on the rope is not quite enough to revolve the winch head against the compression of air in the cylinders, these are opened slightly and gradually closed as the strain becomes greater. A still greater strain is controlled by the admission of a little steam into the cylinders, and an increase of this stops the revolutions altogether.

The anchors.—Probably the best for use under all circumstences is what is known as a "Cape Ann" anchor. It is of very long shank, fairly large palms, and long wooden stock, and whenever an anchor was purchased for the *Blake* this pattern was selected if possible. The stock must be of hard wood, as the compression of a soft wood stock at great depths causes its loss. In coral rock bottom any anchor will answer, for it is only at a crack or coral head that it will nip, and an old condemned anchor of the ordinary type is as effective as the most costly new one, but in soft bottom the "Cape Ann" is the best. The weight used is generally from one-quarter to one-third the weight of the starboard bower, 400 to 500 pounds.

The pulleys.—Those at the anchoring boom end and on the starboard side of the hoisting engine, taking as they do the greatest strain in heaving up, are made very heavy. They are 24 inches in diameter with a 2-inch score, 3 inches thick at center, the pin of steel 2½ inches in diameter, an oil cup in the end communicating with channel ways, and the pin hole bushed with brass. The straps are very heavy and made to shackle to their bolts. The pulley at the boom end has flat iron sides connected by socket bolts to prevent the anchoring rope from jumping between the sheave and strap. The other pulleys are of the same diameter, but less in thickness, and with pins 1¼ inches in diameter. All of those on the deck are provided with wooden beds, which hold them at the proper angle to receive and deliver the rope.



HOISTING ENGINE AND DECK OF STEAMER BLAKE.

The clamp.—In order to relieve the hoisting engine of the strain, when the vessel is at anchor, a heavy screw vise rests on a bed at *n*, Fig. 1, illustration No. 38. It is provided with brass jaws having scores cut in their faces to fit the various sizes of rope, and in order to allow its removal when not in use, it is not made a permanent fixture to the deck, but is attached by a long wire rope pendant to the bitts on the starboard quarter. Resting as it does immediately beneath, and with the opening between its jaws fair with the anchoring rope, it is only a moment's work to bear the latter into the score and set up on the screw. When the vessel is rolling heavily, the clamp, not being bolted to the deck, is apt to capsize, and for this reason the sling is made which shows on illustration No. 42.

Ironwork.—Whenever it is possible, the use of iron is discouraged and wire rope substituted. Each part is so dependent upon all sustaining their own strains, that if one gives way under stress, the others receive their work at an unexpected angle, and a wreckage of the whole system is liable, perhaps with an accompaniment of loss of life. At first, the leaders at the ends of the outriggers were shackled into eye bands, and a defective weld in one of these came near causing just such an accident. Upon its breaking, the anchoring boom swung to starboard at an angle of about 40° with the keel, until the jumper, extending from the boom end to the hawse-hole, restrained it from farther deflection. A trifle more would have pried the ball from the socket, the heel of the boom would have launched violently inboard, and probably carried away the mast. As it was, the loss of the bowsprit was the extent of the damage, and since that time wire rope straps have replaced the wire bands. In case the anchoring rope breaks at or near the surface of the water, the accumulator, being suddenly relieved of its strain, acts like a catapult on the boom end, tending to throw it over on the deck. A defective shackle almost caused this accident at one time. To guard against such a mishap, a steel wire rope is shackled to the boom, the other end being secured on the main deck through the hawse-hole (see frontispiece).

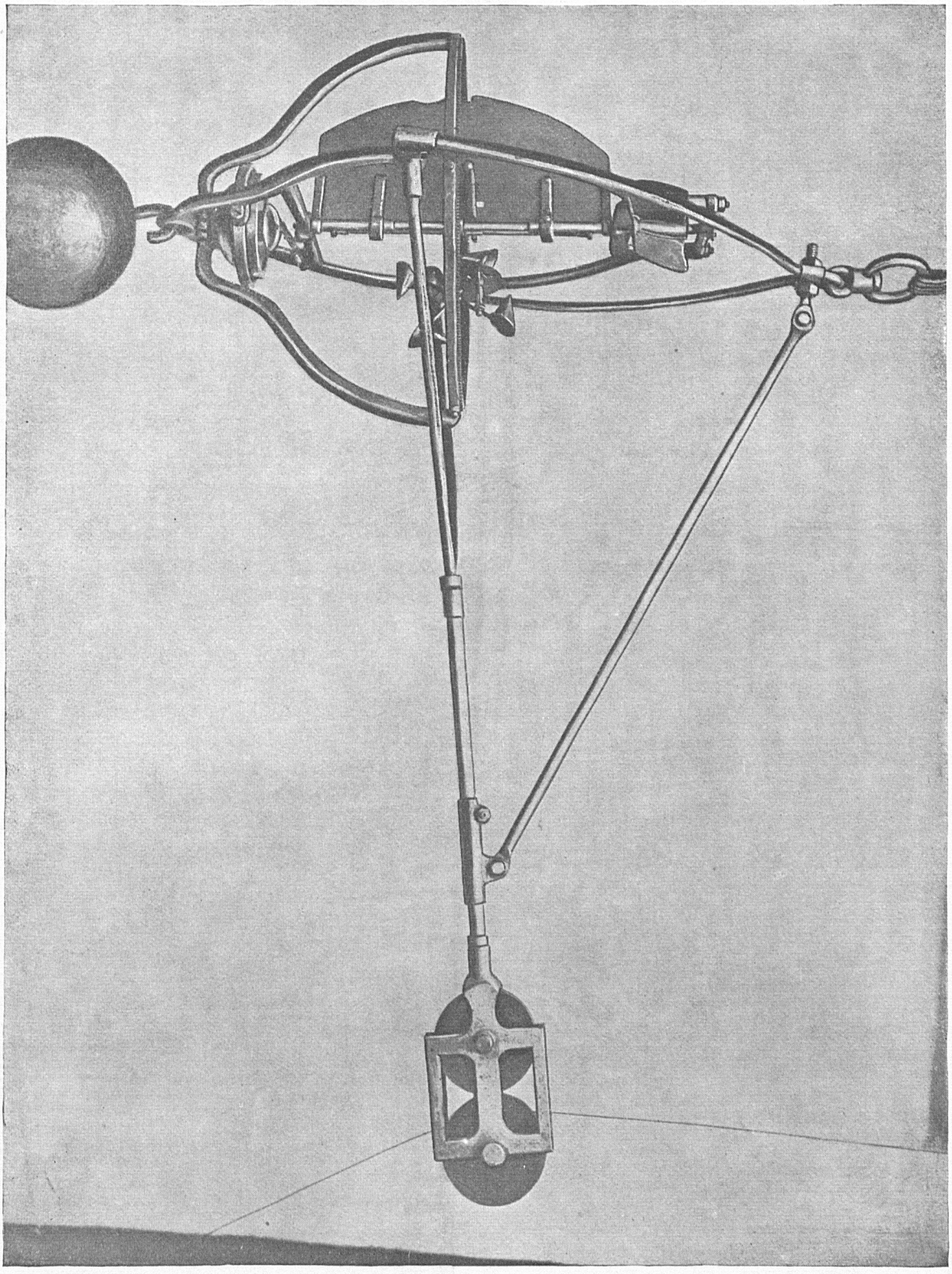
In order to obtain the velocity and direction of the current at any depth it is necessary to have a registering apparatus recording the flow of water, a rudder which is free to assume a position in the direction of the

flow, a compass to show the azimuth of the rudder, and a system by which these may be stopped at any desired time and held fast until the instrument can be hoisted to the surface and the data read.

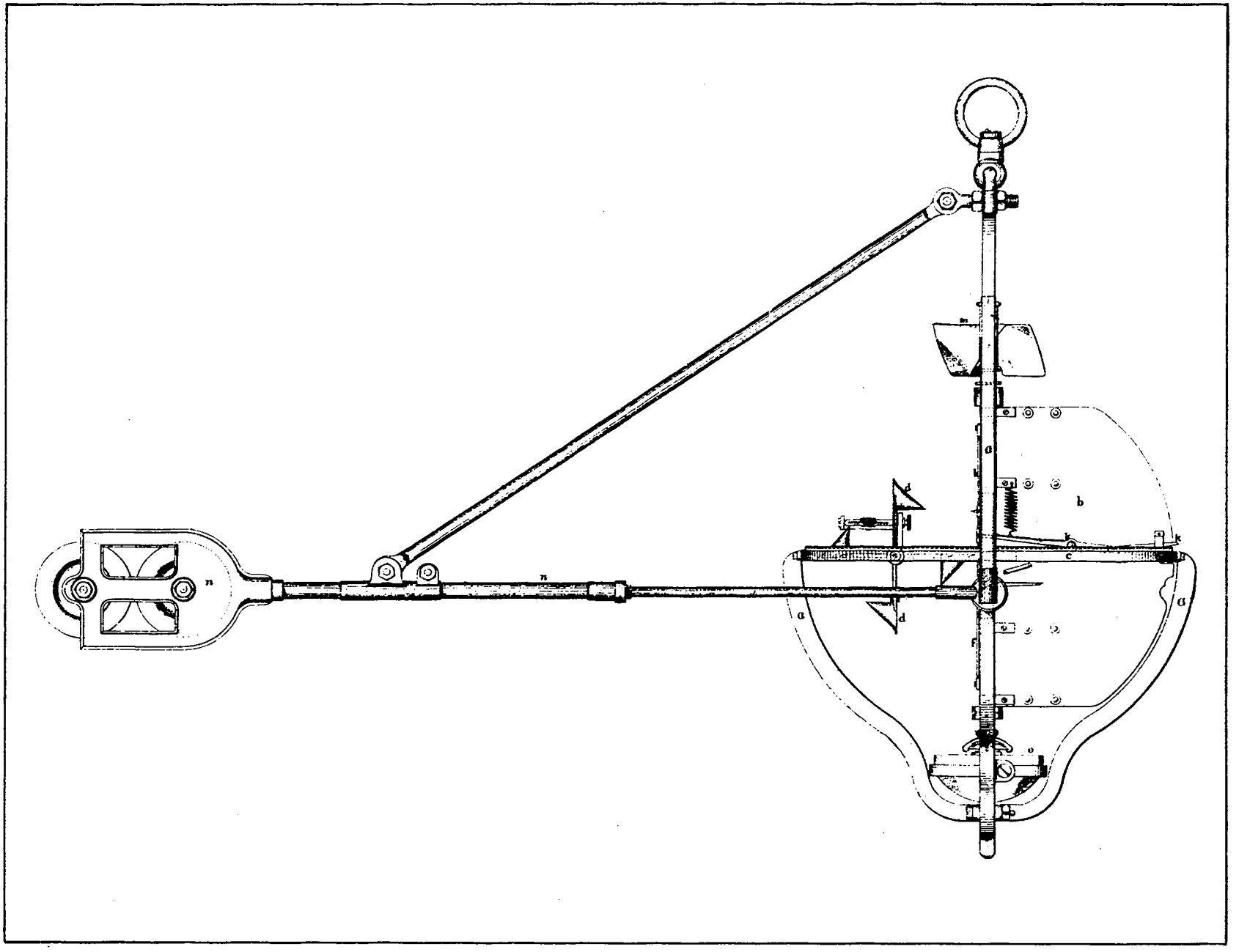
The current meter.—The instrument which the writer devised for this purpose (see illustrations Nos. 43, 44, and 45) consists of an elliptical framework of composition, around the minor diameter of which is a notched ring, *c* (illustration No. 44). Within the frame and ring is a freely moving rudder, *b*, having its stem in bearings at the major diameter of the elliptical frame. On the sides of the rudder are two fins, *k*, of thin metal, to which are attached levers ready to engage one of the notches of the ring whenever pressure is brought to bear upon their upper surfaces. A small spring of sufficient strength to overcome the weight of the fins holds the lever from the notches until a pressure is applied in the opposite direction.

Attached to the rudder on the opposite side of its stem and revolving with it is the velocity apparatus *d*. This consists of 4 cones placed at the extremities of arms or spokes, which are at right angles to each other. The cones are attached in such a way that the apices of all, point in the same direction with reference to the spokes, so that when in a current the base of the cone above the center and the apex of the one diametrically opposite are toward the current. They are placed also with the center of their bases and their apices at the same length of radius. At the axis of the system is a small shaft, which by a worm actuates geared wheels registering its revolutions. The number of these revolutions per knot is determined by the average of many hundred observations taken simultaneously with the meter and log, using with the latter a weighted pole 21 feet long instead of a log-chip.

Below the rudder stem is a compass needle in a weighted bowl, *o*, which is hung in gimbals, and between the rudder and bowl is a system of levers so arranged that they will lift and hold the needle whenever desired. Passing through the center of the rudder stem at its lower bearing is a small rod, its lower end communicating with the levers provided for locking the compass needle and with its upper end attached by the rod *f* to the fins at the side of the rudder. Pressure on the fins, therefore, simultaneously secures the rudder and the compass needle, thus giving the azimuth of the



THE PILLSBURY CURRENT METER.



DETAILS OF THE PILLSBURY CURRENT METER.

former. The glass top of the compass bowl is perforated so as to freely admit water. To prevent the needle being attacked by galvanic action it is coated with shellac, and when in use this must be done every three or four days. A deposit of gold or silver on the needle does not seem to be efficient for this purpose.

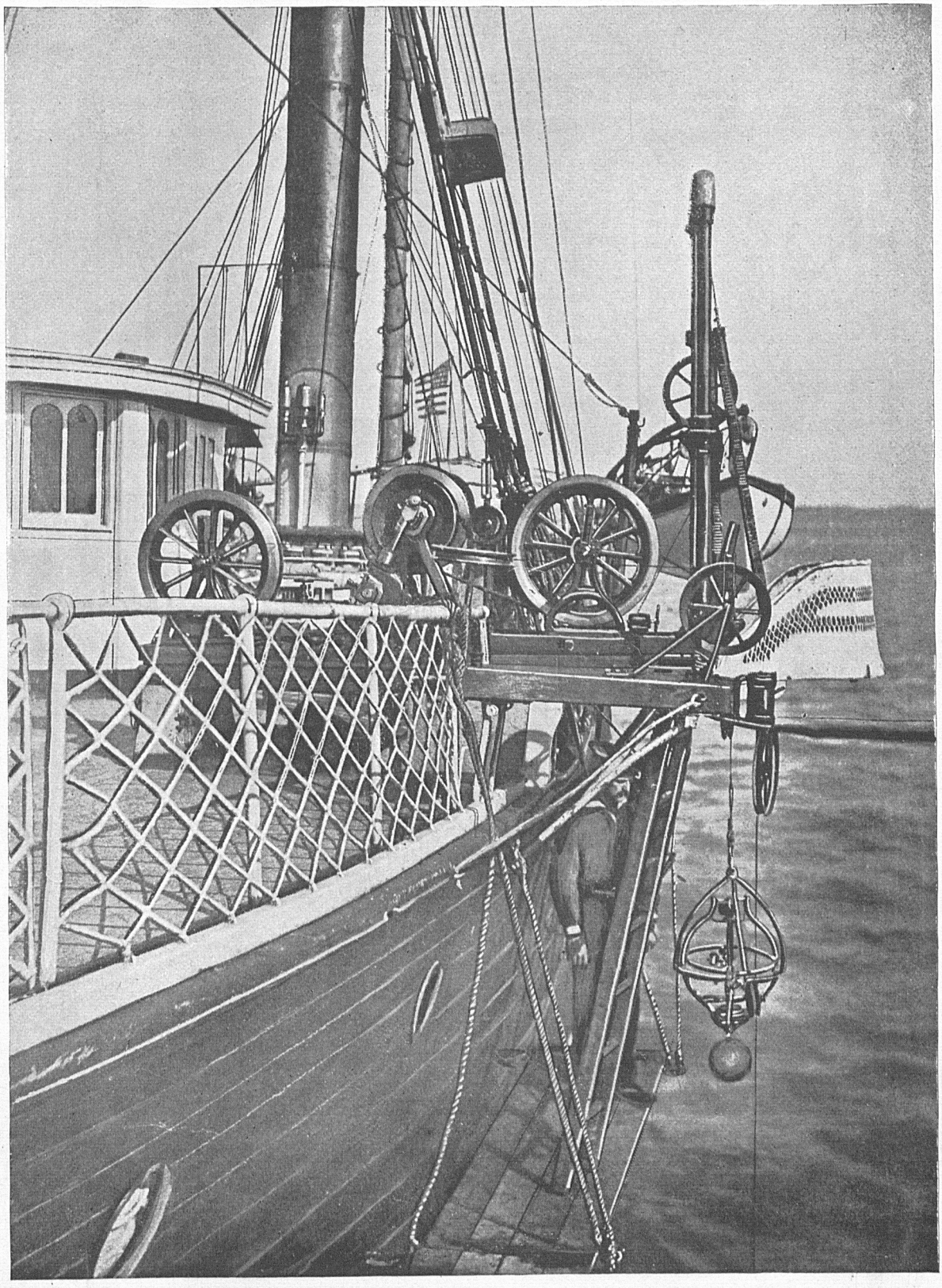
Above the rudder is a propeller having a clutch so arranged that upward motion through the water will give downward motion to a small rod passing through the center of the rudder stem, while motion in the contrary direction will not alter the position of the rod. Its office is to lock the fins after they have performed their duty of securing the rudder and compass. The action then is: the meter is lowered to any desired depth and a certain time allowed for it to register the velocity of the current. At a given signal it is hoisted, and immediately upon starting to rise through the water the pressure upon the fins secures the rudder and the compass needle, and as long as there is a continuous motion in the same direction both will remain secured until the surface of the water is reached. The propeller, however, also begins to revolve at the instant of hoisting, and, pushing its rod downward, locks the fins that have already caught the compass needle and rudder.

A device has been attached to the rudder by which the revolving cones were held fast in descent and were released upon stopping. Another attachment has been applied, by which the propeller would lock the cones upon hoisting, but both were discarded for this reason: the propeller by quick hoisting may be made to lock the fins through an ascent of but 6 feet, and again by lack of speed it will not lock through 60. If it was lowered fairly fast the cones would be certainly stopped, but if through carelessness the men should slow or cease lowering they would be released. This uncertainty led to their abandonment, and the following plan was adopted: The record is kept of the number of minutes and seconds occupied in lowering to the desired depth and in ascending from this depth to the surface of the water. During this time the cones were revolving from their movement through the water vertically and also from the passage of the flowing water transversely. These two in terms of revolutions are represented by the base and altitude of a right-angle triangle, and the hypotenuse represents

the number of revolutions made during the operation. This is subtracted from the total reading for the whole interval to give the number due to the current alone during its stay at the desired depth.

The whole instrument is hung in trunnions at about its center of figure, so that it maintains an upright position when in the water. The total weight is about 25 pounds, and to this is added a lead shot of 75 pounds, and the whole is lowered by a steel wire of No. 16 gauge. In a strong current, in spite of the smallness of the wire and size of the weight, the meter is swept far astern. To force it to travel in nearly a vertical direction, the arm, *n*, illustration No. 44 (called a traveler), seen projecting from the bale of the meter, moves down a jackstay wire, which is held against the current by additional weight, etc.

The traveler is provided with two rollers or sheaves at its forward end which can readily be removed. Its rear end is secured to the bale alone, at the trunions and top, so as not to restrain the movable parts of the meter in assuming a vertical position. The jackstay wire is carried on a reel secured to the top of the steam capstan, and leads from that to guide wheels on a small wooden bed placed at the ship's side, the length of the traveler forward of the sounding machine, from which the meter is lowered (see *h*, fig. 1, illustration No. 38, and also illustration No. 45). Attached to the end of the jackstay is a shot weighing about 200 pounds, and from it a line, called the distance line, secured to the anchoring rope. (See fig. 1.) The length of the latter depends upon circumstances; depth of water, strength of current, and depth of current, all of which must be judged before lowering. In shallow water (300 or 400 fathoms) and a strong current, the anchoring rope tends well ahead, and to lower the jackstay wire to 150 fathoms will require about 100 fathoms of distance line. In 1,500 fathoms of water with the same strength of current, 25 or 30 fathoms will be sufficient. The point to be aimed at is that the jackstay shall be as nearly vertical as possible. In practice, the distance line is fastened to the anchoring rope after the vessel is at anchor. The wire rope is veered, and at the same time the shot is lowered, care being taken that the former does not exceed the latter, for in that event the jackstay will be broken. To observe currents to 200 fathoms, 225 fathoms are veered on both anchoring rope and jackstay,



SOUNDING MACHINE AND CURRENT METER IN PLACE, STEAMER BLAKE.

and when both are out the full length the latter should leave the water about perpendicular. In a very weak current the distance line is apt to "hawser

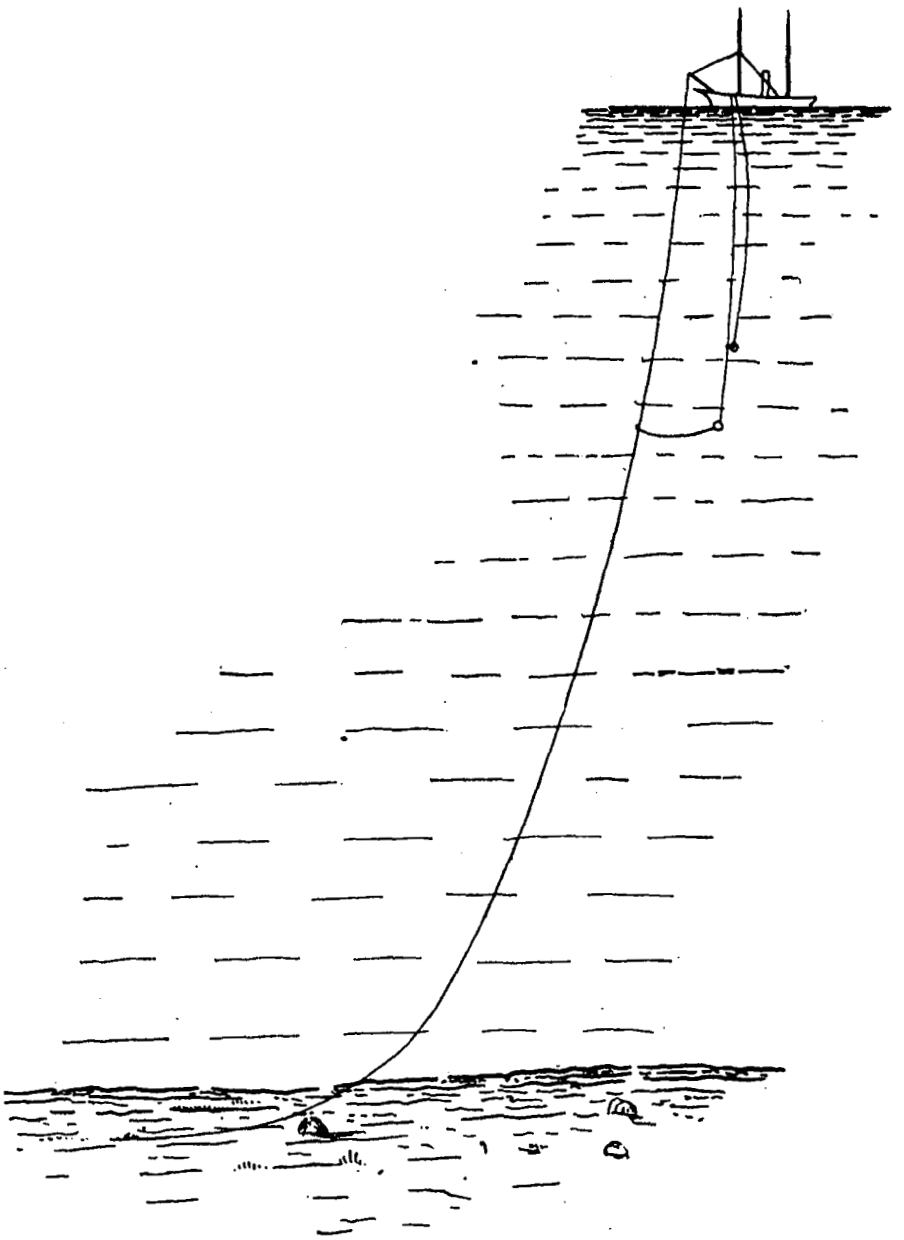


Fig. 1.—Jackstay and distance line in position for observing currents.

lay" around the anchor rope, from the torsion of the latter in veering and heaving in. To avoid this, it is sometimes fastened to a metal hank or thimble

slipped over the anchoring rope, and then allowed to slide down to the depth it will assume upon lowering the shot. In a strong current, however, the inclination of the anchoring rope and the pull aft of the distance line, due to the friction of the current, prevents the hank from sliding more than a few fathoms. It sometimes happens that there has been a wrong conclusion arrived at, and the distance line is too long or too short, or an unexpected change in the volume of the current has altered the conditions. The only thing to do in such a case is to heave in and bend on afresh.

The wire used in lowering the meter is carried on the sounding reel, and the sounding machine designed by Lieutenant Commander Sigsbee is used in lowering. The usual depths observed are in fathoms, 3½, 15, 30, 65, 130, and 200. The friction of the current sweeps the wire astern in spite of its small size and the 100 pounds in weight at its lower end. To determine how much wire to pay out in order to allow the meter to reach the desired depth, many experiments were made by sending down a pressure sounding rod with the meter. In a 5-knot surface current, 195 fathoms of wire is veered to reach 130 fathoms depth, and in this strength of current to attain 200 fathoms with a fair degree of certainty is impracticable.

The care of the meter and jackstay wires should receive much attention. The latter, remaining as it does in the water during the whole anchorage, is galvanized. The meter wire is bright and both are rubbed and oiled every time they are hoisted. In their ends are thimbles, to which to attach lashings, and these are frequently renewed, that of the meter wire every day, if possible, during the observations, and of the jackstay wire after each anchorage. At the same time a few fathoms of wire are thrown away so as to change the position of wear and of galvanic action due to continually lowering the meter to the same point. The oil generally used is a neutral grease called cosmic, a preparation accompanying the manufacture of vaseline or cosmoline. Lime water or oil baths have not been used on board the *Blake* during the past five years even for the pianoforte sounding wire, but either cosmic or a neutral cylinder oil applied with the best results.

Considerable difficulty and loss of time was at first experienced in getting the anchor on board after it was at the surface of the water. Suspended from the end of the boom high up in the air, by the rolling of the

ship it would swing from side to side, almost defying an attempt to "hook the fish." The following plan was soon adopted, which has since been found to be very convenient. A block is secured to the end and underneath the starboard outrigger, through which is rove a stout rope. In the forward end of the latter a small metal open snatch-block is lashed. When the anchor is nearing the surface a man standing on the bowsprit end hooks this block over the anchoring rope, while another passes the hauling part around the steam capstan. In an instant the bight of the anchoring rope is run up to the end of the outrigger (see Fig. 2), and, the hoisting engine going slowly at the same time, the ring is ready for passing the stopper, the anchor being well clear of the ship's side. A line is then thrown over the palm and the anchor fished with the shank parallel and close up to the outrigger. In the meanwhile the ship's engines have been started and the vessel put on her course before the anchor is even out of the water.

The operation of anchoring and observing currents is as follows: Two men are stationed in the reel-room, one at the anchor to slip, and the

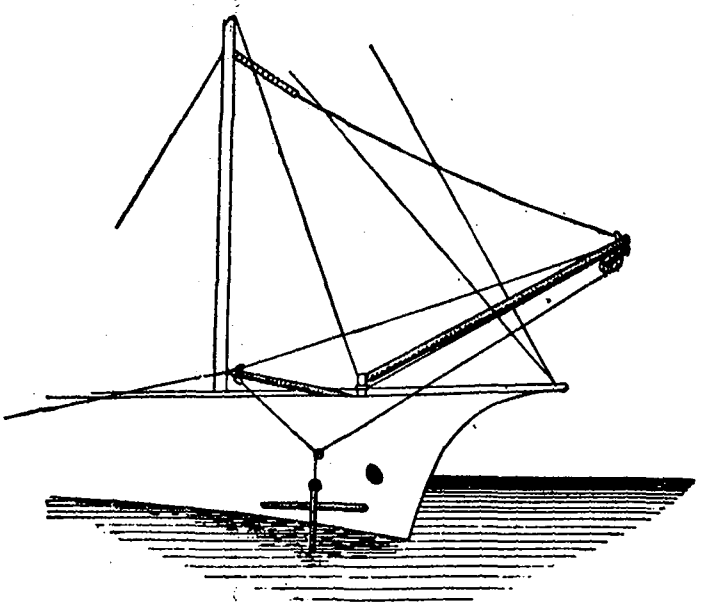


Fig. 2.—Securing the deep-sea anchor.

"leading man" at the hoisting engine and the line from reel-brake. The others prepare the jackstay wire, ship the platform over the side, and sling the meter to its wire. The vessel is stopped. She usually lays broadside

to the wind when she is dead in the water. The wind is brought, therefore, on the side which will bring the expected current nearest ahead. The ring stopper is let go, leaving the anchor hanging from the boom end. When all is ready, a little steam is turned on the hoisting engine, the reel-brake lifted, and the anchor descends at the rate of from 50 to 80 fathoms per minute. If the water is but a few hundred fathoms deep the higher is the speed of veering. If very deep, the long-continued use, combined with high speed, heats the brake strap and reel and runs the risk of charring the wooden lining of the former.

Steam is gradually reduced on the hoisting engine as the length paid out increases, until at last the throttle is closed entirely. The vessel is drifting broadside to the wind and the anchoring rope stands well out on the weather beam. After a while it is noticed that the heading of the vessel is changing somewhat and the anchoring rope, instead of tending abeam, is coming ahead. This shows at once that the anchor is in dead water and is holding the vessel up against the surface current. A few fathoms before bottom should be reached the reel is checked, so that the anchor shall not be fouled, and the rope shall be fair on the bottom. The rate of paying out from this time on depends upon the indications as to strength of current. The only sure one is the speed of the water passing the vessel, or after the anchor is surely on the bottom a tremble in the anchoring rope as the anchor drags. If the current is deep, the vessel, the anchor, and the rope may be drifting with it almost as fast. If there are no indications of current the rope should be veered very slowly, 10 or 12 fathoms a minute, but under some circumstances 50 fathoms may be the speed. Gradually the rate of veering is diminished as the proper number of fathoms is approached, using the hoisting engine for controlling the rope. If the anchor is dragging over a smooth rock bottom and suddenly catches, the strain of bringing up the vessel is enormous. At the first indication of this, the main engines are started ahead full speed and the anchoring rope is slackened for an instant. The accumulator, by the amount of its compression, shows at once when the anchor is holding the vessel. If the anchor ceases to hold, the strain is released and the boom jumps. If this is the case another hundred fathoms is veered.

The proportion of anchoring rope to the depth varies with the character of bottom, the strength of current, and the depth of water, and somewhat with the size of the rope. In water less than 600 fathoms from two to three times the depth is required, and in 2,000 fathoms of water 3,000 fathoms of rope is generally sufficient. With a small rope, an advantage is gained by splicing a piece of larger size on the anchor end about 100 fathoms in length, to give additional weight at that point. When the vessel is at anchor, the distance line is fastened to the anchoring rope and the shot is lowered by the jackstay wire to the length of the former. The order is then given to veer together. The man at the hoisting engine calls out as he veers each 25 fathoms, as a mark to the officer at the jackstay. The latter, having started ahead by the length of the distance line, has lowered during the interval a proportionately less number of fathoms, so that both reach the desired depth at the same time. The rope is then clamped, the current meter is connected to the jackstay, and the men take their stations for lowering the meter.

The officer of the deck and a quartermaster are on the platform outside the vessel (see illustration No. 45); a man is at the friction line to control the revolutions of the reel carrying the meter wire, and the Recorder is at the timepiece in the pilot-house. The officer of the deck orders, "Lower to 3½ fathoms." The instant of striking the surface of the water he cries "Mark," for the Recorder to note the time. When the meter reaches the desired depth, the man at the friction line, who has before him the register showing the amount of wire out, cries "Time," and the Recorder again notes the hour, minute, and second. The meter is to remain at the depth 30 minutes from the last entry. Two minutes before the time has expired the Recorder informs the officer of the deck, who orders the machine to be manned. The engine is cleared of water, the belt shipped in the V-shaped score and tautened, a man with oil and canvas stands ready to guide on the wire, and the quartermaster and officer of the deck go on the platform. Upon the expiration of the 30 minutes the Recorder calls "Time," and the man at the engine hoists the meter. The instant it reaches the surface of the water the officer calls "Mark," whereupon the Recorder makes a record of this time and also the readings of the revolutions and direction shown

by the meter as soon as the officer of the deck has read them. "Lower to 15 fathoms" is the next order, and the work continues.

At anchor.—The various conditions of wind and tide experienced by vessels at anchor in harbors are of course found at sea. The wind and current may form any angle and the vessel heads to the strongest force or a combination of the two. The *Blake* can remain at anchor with the wind blowing a force of six or even more, unless the wind is accompanied by a heavy sea, or unless it is about contrary to the current and the latter is strong. Steam in the boilers is always kept at full pressure and the engines ready to turn over at a moment's notice. The approach of a norther, the probability of collision with a vessel drifting in a calm, the breaking of a jackstay or meter wire, all require the use of the main engines at once.

The motions of the anchoring rope and the accumulator when the vessel is anchored in a current are of great value, and in fact are sure indications of whether or not the anchor is holding. The bow of the vessel falls in pitching. As it does so the strain on the accumulator is partially relieved, and the rubbers expanding, the boom rises. When the bow changes direction, the accumulator rubbers are compressed at once by the strain of lifting the wire rope, but there are two motions to it, the first part apparently being caused by the lift of the bow and the second by the stoppage and change of direction of the wire rope, which had just been descending. When the anchor nips on the bottom the accumulator rubbers are compressed steadily. If the anchor breaks ground, the re-action causes the boom end to rise more or less suddenly, depending on the character of the bottom. If it breaks from a rock, the rise is a jump of feet; if from ooze, the motion is so slow that it scarcely can be seen, and breaking out of clay gives a result between the two. In dragging, the accumulator will show the fact at once, except in ooze, and in this case even by a close watch it can generally be detected. The cause was correctly ascribed in one instance to a foul anchor dragging crown first over smooth rock bottom. In this case it was the tremble of the rope that gave the indication, there being no differences of strain to cause the accumulator to show the fact.

In a strong current, the rope has a vibration due to the passing water, and this is communicated to the wire rope clamp pendant, giving a hum of

very low note. Sometimes with a very deep current the vibration seems to be started far down below the surface, and ascending, becomes more and more violent; but these are not to be mistaken for the trembling that is due to dragging. When the vessel remains at one anchorage for a considerable length of time, the anchoring rope and jackstay wire are veered 2 or 3 feet daily to change the nip in the pulleys. A man is generally at the ship's wheel to keep the anchoring rope "up and down" ahead, steering the vessel the same as at sea. The only time when he is not needed, is when there is but little or no current. In order that he can see the rope at night time a small white cotton flag is attached to it, and this is illuminated by a bull's-eye lantern fastened to the bowsprit end.

Getting underway.—Two men are stationed in the reel-room, one to guide the rope over the reel by the tackles shown in illustration No. 41, and the other to look out for the engines. The metre is sent below, and a man stands ready to guide on and oil the jackstay wire. The man at the hoisting engine lifts the break of the reel and turns the steam on to its engine. When the reel has turned over, and has taken in the slack between it and the winch-head, steam is admitted to the hoisting engine, the rope is removed from the clamp and everything is ready to heave-in. If the current is strong or the vessel is riding to a strong breeze, the main engines are started ahead for a few moments to relieve the strain, and afterwards at intervals if necessary. The anchoring rope and jackstay come in together, the man at the register calling out as each 25 fathoms is passed. When the distance line reaches the bow-sprit end, it is cast off and hauled on board with the shot.

There is of course more strain on the accumulator when heaving in than there is while at anchor in deep water, because of the increased skin friction on the rope due to its upward motion. At first the rate of progress is slow, not more than 8 or 10 fathoms per minute. The vessel is held up toward the anchor as much as possible, and particularly is this necessary on rocky bottom, for if the anchor breaks out at fairly long scope it is liable to catch again with a greater chance of loss. The instant the accumulator jumps, showing that the anchor has tripped, the throttles of the engine are opened, so as to make the anchor clear the bottom as soon as possible.

The speed then is from 50 to 80 fathoms per minute. If too much steam is on the reel engines, the tension of the rope between the reel and the winch-head will be too much, and there will be danger of crushing the barrel of the reel by the accumulation of pressure. The man at the hoisting engine regulates the speed of both, judging as to the one below by the amount of curve of the rope between the pulleys on deck. If, on the other hand, it is not running fast enough, the rope will either become slack, with danger of kinking, or it will slip on the winch-head. A very much preferable arrangement for reeling the rope under proper tension is one fitted to the dredge reel of the Fish Commission steamer *Albatross*. By an automatic spooling machine the wire rope is properly placed on the reel, and by a self-adjusting valve the tension is maintained fairly constant. When the anchor is off the bottom the vessel's head is allowed to pay-off as it will. A man is sent with the open snatch cat-block to the bowsprit end, and another man to be ready to take the rope to the capstan. About 12 fathoms from the anchor a "square-mark" of canvas has been placed, and when this appears the block is hooked, the vessel put on her course, and everything made secure.

Sometimes it happens that the anchor becomes caught on the bottom so that it is impossible to release it. The hoisting engine pulls until it can pull no more, the last being only by a single revolution at a time as the bow falls. If the sea is smooth and the rope free from kinks the *Blake's* hoisting engine can not break the rope. If there is much motion to the vessel, however, it can take in enough to cause the lift of the bow to do so, but there is more or less risk in this method. All the parts of the gear are under great strain, the sudden relief of which is not unlike an earthquake to the sensations of those on board. Breaking in one instance 200 fathoms from the bow, the anchoring rope was pulled through the water so violently, in spite of the great friction of such a length, that a great loop was thrown high into the air, falling as it came back around the end of the boom. The boom too gave a leap, and breaking the shackle of the jumper rose almost perpendicular, stopped an instant, and fortunately fell forward instead of aft. If the rope parts at the anchor no harm is likely to happen. To cut the rope is attended by no danger if the strain is eased first. A flogging chisel, heavy maul, and an anvil, or some other heavy piece of metal, are

prepared for the cutting, which is best done between the hoisting engine and reel. When all is ready a few fathoms of the rope are payed out by steam as rapidly as possible. There is then only a strain on the gear equal to the weight of the wire rope, and before the vessel can be drifted by the current far enough to increase this strain the order is given to cut. The wire rope in slipping around the winch-head turn by turn with gradually increased speed relieves the gear of any sudden shock.

CHAPTER V.

CHARACTERISTICS OF THE GULF STREAM IN THE STRAITS OF FLORIDA AND IN THE YUCATAN PASSAGE.

In alluding to the different points of examination, each cross-section of the Stream has, for the sake of brevity, been given a letter, the initial one being the first section examined between Fowey Rocks, Florida, and Gun Cay, Bahama. This is called Section A, and those to the northward are given single letters, while those to the westward have double letters, as follows:

Section A, from Fowey Rocks, Florida, to Gun Cay, Bahama.

Section B, from Jupiter Inlet, Florida, to Memory Rock, Bahama.

Section F, from Cape Hatteras Shoals, about southeast.

Section C C, from Rebecca Shoal, Florida, to near Havana.

Section D D, from Cape San Antonio, Cuba, to Yucatan Bank.

Section E E, across the extreme western part of the Straits of Florida.

This last section has just been completed by Lieut. C. E. Vreeland, U. S. N., now commanding the *Blake*, and through his kindness I am enabled to combine his observations with those made by myself in former years. The sections to which the intervening lines belong have not been examined.

In the first season, work was contemplated on Sections A and D D, but the results from the beginning were so surprising, and the methods of anchoring and observing the currents so successful, that I was constrained to ask authority to abandon all idea of visiting the latter and to devote two seasons to the former section alone. This request was granted, and until the month of June in both the years 1885 and 1886 all the observations were made between Fowey Rocks and Gun Cay. In the following year, 1887, examinations were made between Rebecca Shoal, Florida, about south to a point 10 miles west of Havana, (Section C C,) and also from Cape San Antonio, Cuba, to Yucatan Bank (Section D D). During the early months

of 1888 and 1889 the equatorial and Caribbean Sea currents were investigated, in order to ascertain the relation between these and the Gulf Stream in the Straits of Florida. The research was also extended to the current in the Old Bahama Channel, and, when opportunity offered during the summer seasons, to the flow off Cape Hatteras and Nantucket. The extent of the examination, however, that has been made at the latter points has not been sufficient to warrant conclusions on all the phenomena of the localities, and the results, therefore, are not complete.

For those navigating the Gulf Stream the most important questions to be answered are: What is the surface strength of the current and what is the direction of the flow? It is well known that these vary at many if not at all parts of the stream. Can a fair knowledge of these variations be predicted?

Section A, from Fowey Rocks, Florida, to Gun Cay, Bahama.—As the labors of two seasons were concentrated at this section the results are more complete than at the others, and in studying these results carefully we find the key to the solution of many of the apparent anomalies at points where there are fewer observations on which to base conclusions. The whole width of the Straits from shore to shore is 43 miles, and between the curves of 100 fathoms 39 miles. On the east side the bank is abrupt, 100 fathoms being found within one mile of Gun Cay. The current of the Stream sometimes runs in as far as the depth of 10 fathoms, but generally it is farther off shore. On the west side the slope is more gradual, but still the surface current frequently is found quite close to Fowey Rocks. The bottom varies at the different anchorages. At the station nearest the Bahama side of the channel, the anchors always dragged a considerable distance before taking hold. The dredge twice brought up quantities of small branch coral. At the axis, 11½ miles from Fowey Rocks, the anchor fouled the bottom three times, making it necessary to cut the anchoring rope to get under way. At the other anchorages there were evidences of rock bottom, but apparently only as outcroppings, for frequently the anchor or dredge brought up clay or mud.

The time actually employed in the observations at Section A amounted to over 1,100 hours, and the longest continuous anchorage 166 hours. In the first season, the anchorages were held as long as it was then thought to be

possible, but during the second year changes were made from point to point, in the endeavor to discover the relative velocities at the different parts, and thus to establish, if possible, the axis of the Stream.

It will be remembered that the few observations made by Lieutenant Fremont off Jupiter Inlet, in 1884, indicated that the maximum surface flow was not situated where it was supposed to be by Professor Bache, but at some point farther to the westward. It required but few observations in the *Blake* to determine positively that this was the case. At Station 1, 8 miles distant from Fowey Rocks, the velocity at times was found to be greater than at Station 2, 7 miles nearer the middle of the stream, while the average at the latter exceeded the average at the former. Observations were then taken at a station midway between the two, and, whenever possible, changes were quickly made from this station to Station 1. Whenever this was done the velocity of the surface flow at the latter was generally less than at the former, and the average of all the observations at Station 1½ far exceeded those at stations on either side. At Station No. 2, however, the total volume was found to be much the greater, the area of a section of the prism representing 1 hour's current being 30 per cent. more than at Station No. 1½.

The hourly average in knots of all the observations taken at the various depths and stations is shown in the following table:

Station.	Distance in miles east of Fowey Rocks.	Velocity.				
		3½ fathoms.	15 fathoms.	30 fathoms.	65 fathoms.	130 fathoms.
1	8	2.661	2.346	2.252	1.590	0.634
1½	11½	3.461	2.895	2.936	2.421	1.611
2	15	3.156	3.062	3.182	2.947	2.202
3	22	2.727	2.667	2.695	2.503	1.860
4	29	2.123	2.099	2.116	1.975	1.450
5	36	1.707	1.572	1.489	1.565	1.449

These velocities are shown as curves in illustration No. 51 (see p. 550), placed at their proper stations in the cross section of the stream, but revolved around the initial point 90° from the direction of the current. From the table and from the vertical curves, it will be seen, that, with the exception of the

surface velocity, the flow is greater at every depth at Station 2 than at a corresponding depth at other stations, and that the one exception is at Station 1½, where the surface velocity is greater than at any other station. This is the average position of the axis of surface velocity; but, as will be seen later, its flow is not at all times superior. The position of the maximum at different times during the month is intimately associated with the changes in the declination of the moon, and indeed, not only the position of the maximum but the velocity and width of the whole Stream as well. Other factors also enter the problem to cause regular variations, but they seem to be small in comparison with the influence of the moon. The effect of the barometric pressure is exerted to cause an irregular variation, and it is difficult for a single observer to be always sure that a certain result is to be assigned to this cause and not to some fixed and invariable law. It is only by a general average of all the observations that this can be reduced to a minimum

The monthly variation.—Following the changes in the declination of the moon, the velocity of the stream at any given point is accelerated or diminished, but while it is running faster at one place, at another it is running slower. It is in fact a reduction in velocity at the sides accompanying an increase in velocity at the axis, and the reverse, or in effect, an alternate expansion and contraction of the Stream in width. This is not marked on the east side of the Straits of Florida, and, as will be seen later, this is hardly to be expected. It is very marked on the west side of the Stream.

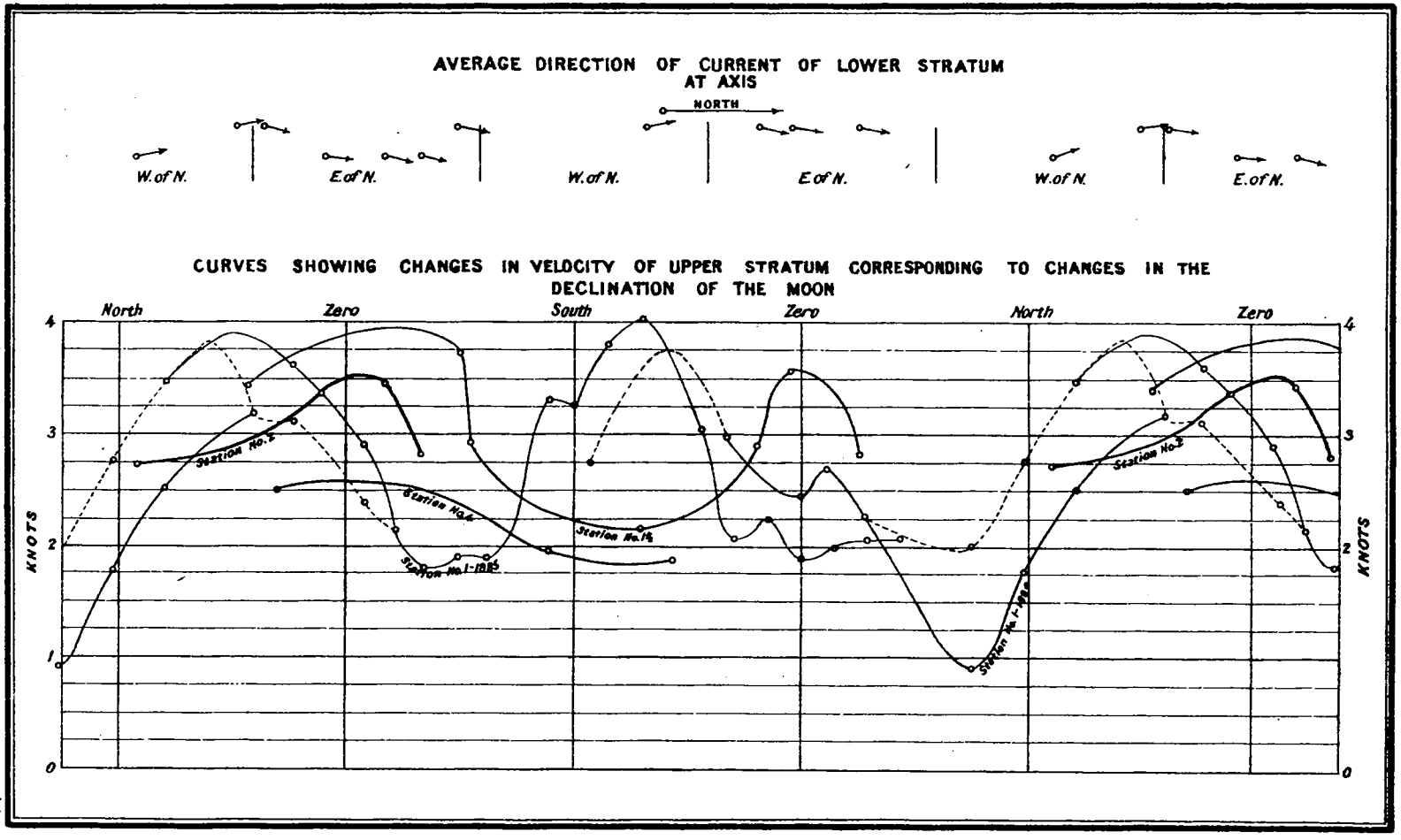
Illustration No. 46 shows the changes in the surface velocity for the different stations. The average of each day's observations is plotted at its proper position with reference to the declination of the moon, using, however, for the "surface" the observations obtained at 3½, 15, and 30 fathoms depth. The actual surface current follows the mean curve very closely, but by taking the average of the 3 depths, single errors of observations are thus reduced. It will be remarked at once that at northern declination, in the observations of 1886, the velocities at Station 1 were far below those at southern declination taken in 1885. This was a case of an abnormal condition of barometer in the Gulf of Mexico and Atlantic, and the dotted line represents more nearly the true current conditions. In passing the next zero

declination the curve of Station 1 is excessively high. This part depends upon half day's observations taken at the time of the daily maximum. They are inserted to show the decrease in velocity as the moon changes its position. Above the curves are arrows showing the mean direction of the flow of the lower strata (65 and 130 fathoms). The short vertical lines separating the arrows into groups are drawn at intervals equal to the changes of declination of the moon, and it will be seen that within the limit of any space, all the arrows are inclined in the same direction. Those inclining upward indicate a current moving to the westward of north, and those inclining down a movement to the eastward of north.

The curves of velocity at Stations 1½ and 2 increase as the moon approaches zero declination, and at the same time the current at Station 1 is rapidly diminishing. The direction of the flow, as shown by the arrows, is then inclined slightly toward the east of north or toward the middle of the Stream and away from Station 1. As the moon approaches its greatest declination, the velocities at Stations 1½ and 2 decrease, the direction changes to the westward of north, and the speed of current at Station 1 rapidly increases. In this vibration it appears that the maximum velocity at the axis and the minimum at Station 1 arrives at two or three days after zero declination, and in the course of one-fourth of the lunar month the total expansion has taken place and the reverse conditions prevail. During this periodic change, the directions of the currents at the side stations follow the movements of the axis. At the time when the line of maximum velocity is moving toward east or near low declination, the lower currents at the side stations incline toward the center, and at the opposite movement of the axis, they incline outward or more nearly parallel with the axis. For example:

Declination.	Station 1.	Station 3.	Station 4.	Station 5.
High.	N. ¼ E	N	N. ½ W	N. by W.
Low.	N. by E. ¼ E	N. by W. ¼ W.	N. by W.	N. by W. ¾ W.

During the lunar month the temperature of the surface at the different parts of the Stream follows the direction of the lower currents at the axes most intimately. When the moon is in the vicinity of its greatest declination the


AVERAGE DIRECTION OF CURRENT OF LOWER STRATUM AT AXIS
NORTH
W. of N.
E. of N.
W. of N.
E. of N.
W. of N.
E. of N.
CURVES SHOWING CHANGES IN VELOCITY OF UPPER STRATUM CORRESPONDING TO CHANGES IN THE DECLINATION OF THE MOON
North
Zero
South
Zero
North
Zero
KNOTS
0
1
2
3
4
Station No. 2
Station No. 4
Station No. 1-1885
Station No. 1½
Station No. 1-1886
Station No. 2

lower currents at the axis being then inclined to the westward of north, the mean temperature of the surface water on the west side of the Stream is colder and on the east side warmer than it is when the currents are inclined toward the Bahama side of the channel:

	Station 1.	Station 1½.	Station 2.	Station 3.	Station 4.	Station 5.
	°	°	°	°	°	°
Mean of all surface temperatures observed	80.24	81.60	80.33	80.38	79.66	78.65
Temperature at surface with the current at axis setting westerly (high declination)*	[79.87]	[81.08]	[80.19]	80.65	79.82	79.19
Same with current setting easterly (low declination)*	80.36	81.86	80.42	[80.20]	[79.51]	[77.42]

*The lower temperatures are in brackets.

The table above gives these temperatures, and from it we see that at Station 2, the axis of volume, the difference is but little, and that the temperature at any of the other stations is lowest when the currents at the axis are setting in its direction. In other words, the axis inclining toward one side, its lower currents, which change most in azimuth and with greater constancy and regularity, force the colder water to the surface and lower the temperature at the sides. It is probable that the temperatures at an anchorage near the 100-fathom curve between Station 1 and Fowey Rocks would follow the same changes as those on the east side of the Straits.

Another illustration of the change in the velocity of the Stream following the declination of the moon is to be found on illustrations Nos. 47 and 48. In these the mean horizontal flow has been plotted *in situ* at the various sections in the Straits of Florida and Yucatan at which observations have been made. Illustration No. 47 shows the mean of the observations down to 30 fathoms and No. 48 the average at all depths, but for the sake of clearness on so small a scale the velocities have been exaggerated ten times greater than the scale of the chart. In obtaining the results, the observed speeds have been resolved in case of much departure from the general direction of the flow and only the one component taken; as, for instance, at Section C C the flow

at the sides is toward the middle. The general direction of the Straits being east, these are resolved into their components and the easterly one taken. The directions accepted are north for Sections A and D D and east for Sections C C and E E. The mean of the results is obtained by combining all those falling within the limit of time represented by a westerly inclination to the currents at Section A as shown on illustration No. 46 and calling it "high declination," and all those at the time of the easterly set "low declination." This division includes in time one-fourth of a lunar month, beginning at nearly three days before and extending to about four days after the highest and zero declination.

Referring to illustrations Nos. 47 and 48 it is seen at Section A that at the time of highest declination, the mean velocity is about equal from the middle of the Stream to the western point at which observations were made; that is, the curve is flattened. At the time of zero declination, the axis is localized and much increased in velocity. In the first, however, the expansion of the axis very much increases the surface current at the westernmost stations at the time of its maximum, as seen from the adjoining cut, which represents for No. 1 station simply the average of the observations taken at and just after the highest declination instead of the mean of the observations for 2 lunar weeks as in illustration No. 46. This shows the strongest current on the west side at the time of high declination and a movement to the right at low declination. Referring to Section C C, off Havana, the curve of high declinations is flattened and the concentration of the axis takes place toward the right at low declination, or, in this case, to the southward. At Section E E the velocities at high declination are again the greatest on the northern side, and, as the moon is near

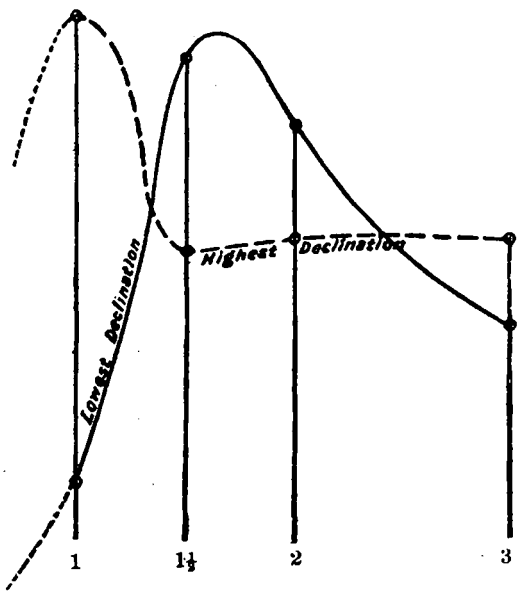
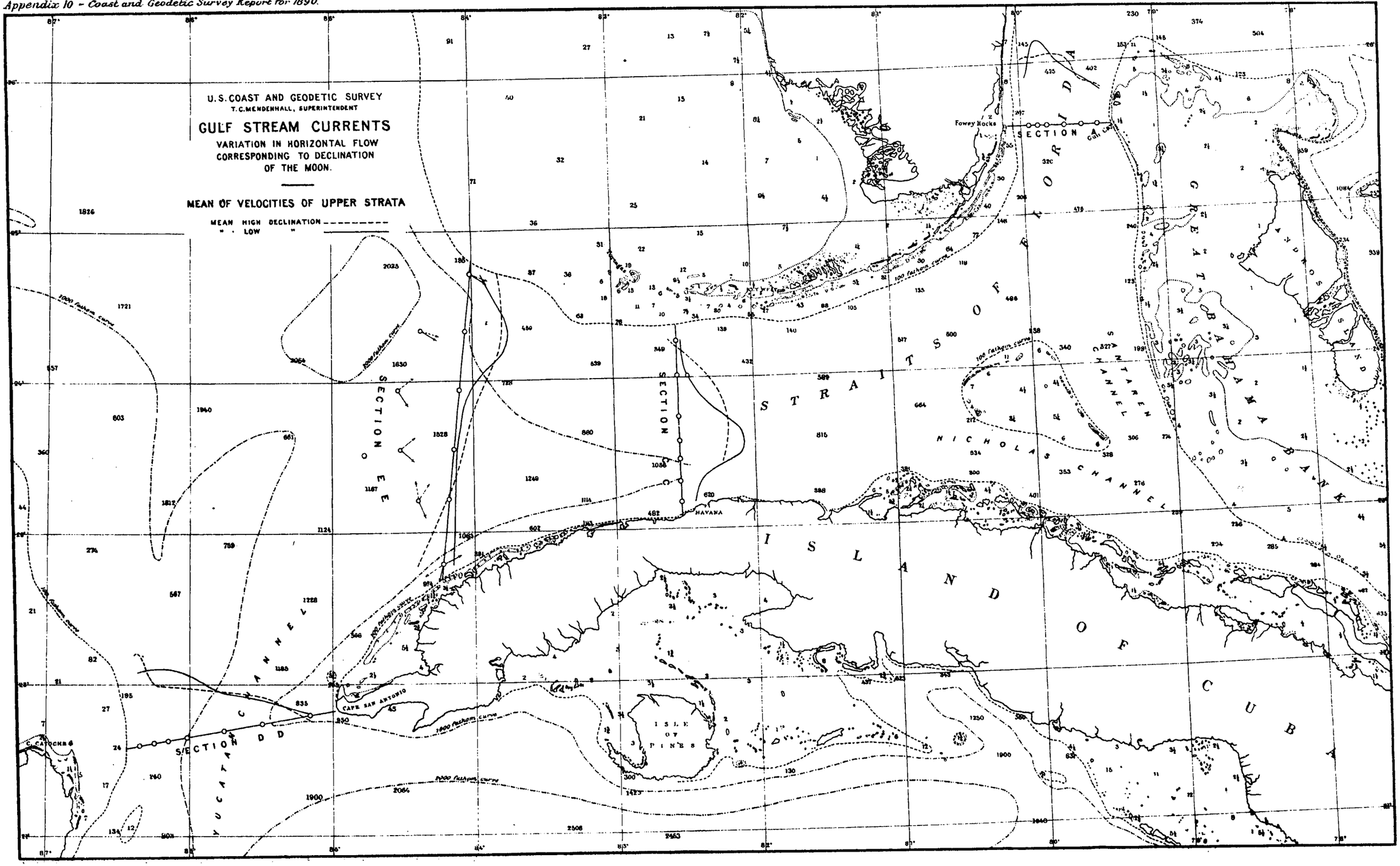
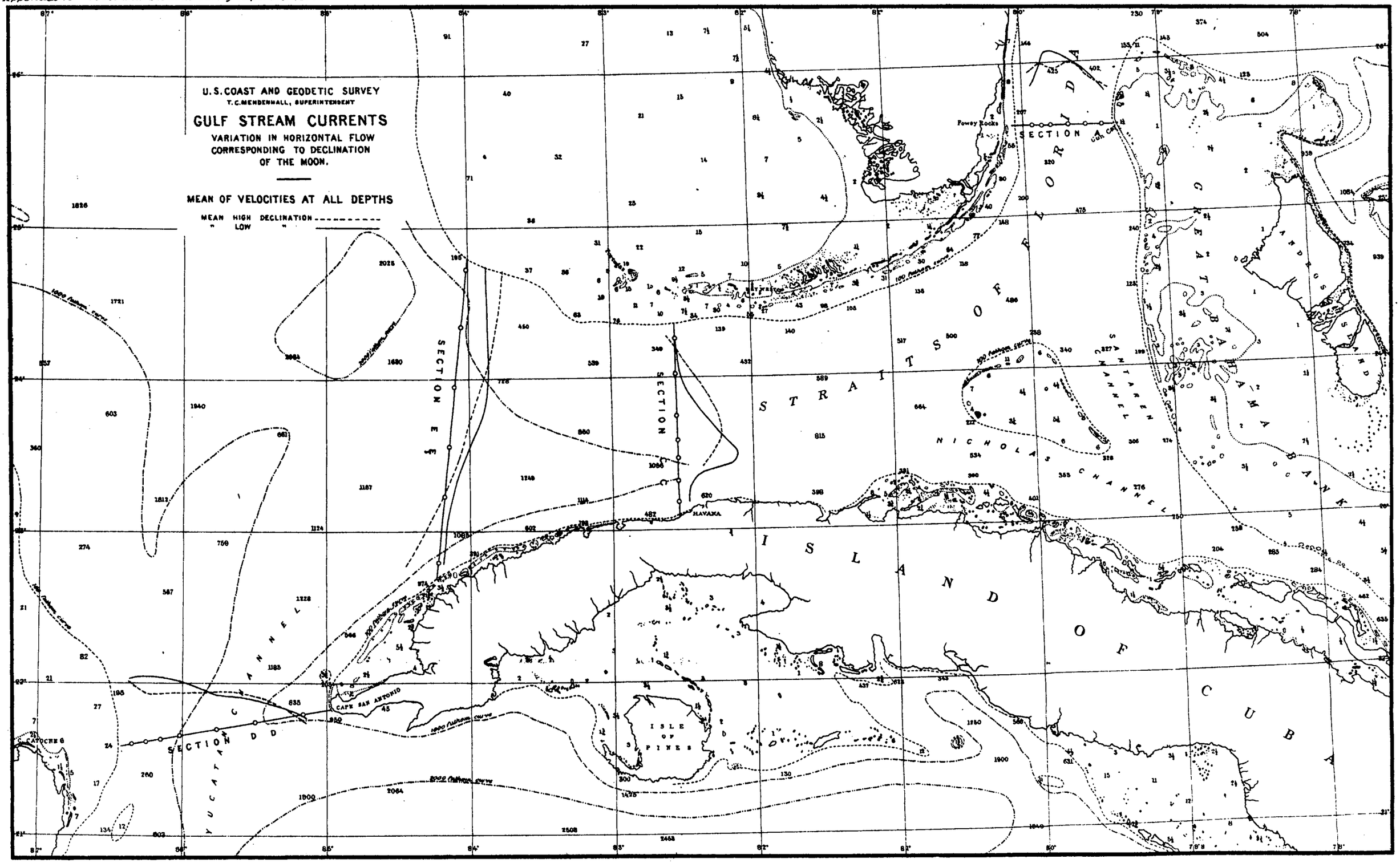


Fig. 3.


U.S. COAST AND GEODETIC SURVEY
T.C. MENDENHALL, SUPERINTENDENT
GULF STREAM CURRENTS
VARIATION IN HORIZONTAL FLOW
CORRESPONDING TO DECLINATION
OF THE MOON.
MEAN OF VELOCITIES OF UPPER STRATA
MEAN HIGH DECLINATION
" LOW "
STRAITS OF FLORIDA
ISLAND OF CUBA
GREAT BAHAMA BANK
NICHOLAS CHANNEL
TARENTUM CHANNEL
YUCATAN CHANNEL
SECTION A
SECTION B
SECTION C
SECTION D
Fowey Rocks
HAVANA
CAPE SAN ANTONIO
ISLE OF PINES
C. CATOCHE
100 fathom curve
1000 fathom curve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STRAITS OF FLORIDA
ISLAND OF CUBA
NICHOLAS CHANNEL
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GREAT BAHAMA BANK
BAHAMA ISLANDS
YUCATAN CHANNEL
SECTION A
SECTION B
SECTION C
SECTION D
Fowey Rocks
HAVANA
CAPE SAN ANTONIO
ISLE OF PINES
CAPOCHE
100 fathom curve
1000 fathom curve
2000 fathom curve

the equator, the speed increases and localizes at some point to the right and diminishes in velocity at the stations to the left. At Section D D the same is indicated, but here, unfortunately, the times at which the westernmost stations were occupied were at the maximum flow alone.

Still another illustration of the monthly change in the Stream following the changes in the moon's declination is shown in illustration No. 49. In its construction the vertical curves of velocity are divided into groups similar to those in which the arrows on illustration No. 46 are separated into high and low declination. The curves are carried to zero velocity (not the bottom) and the depths reached are joined by a continuous line. In plotting the points at the different stations the distances from the shore are expanded or contracted to a common width of Stream between the 100-fathom line. The distance below the surface of any part of the curves of one station bears no relation to the distance of another, for they depend upon the relative velocities at 65 and 130 fathoms. The curves only show that at the same relative point there is a difference in the depth of the Stream in the same direction at all the sections.

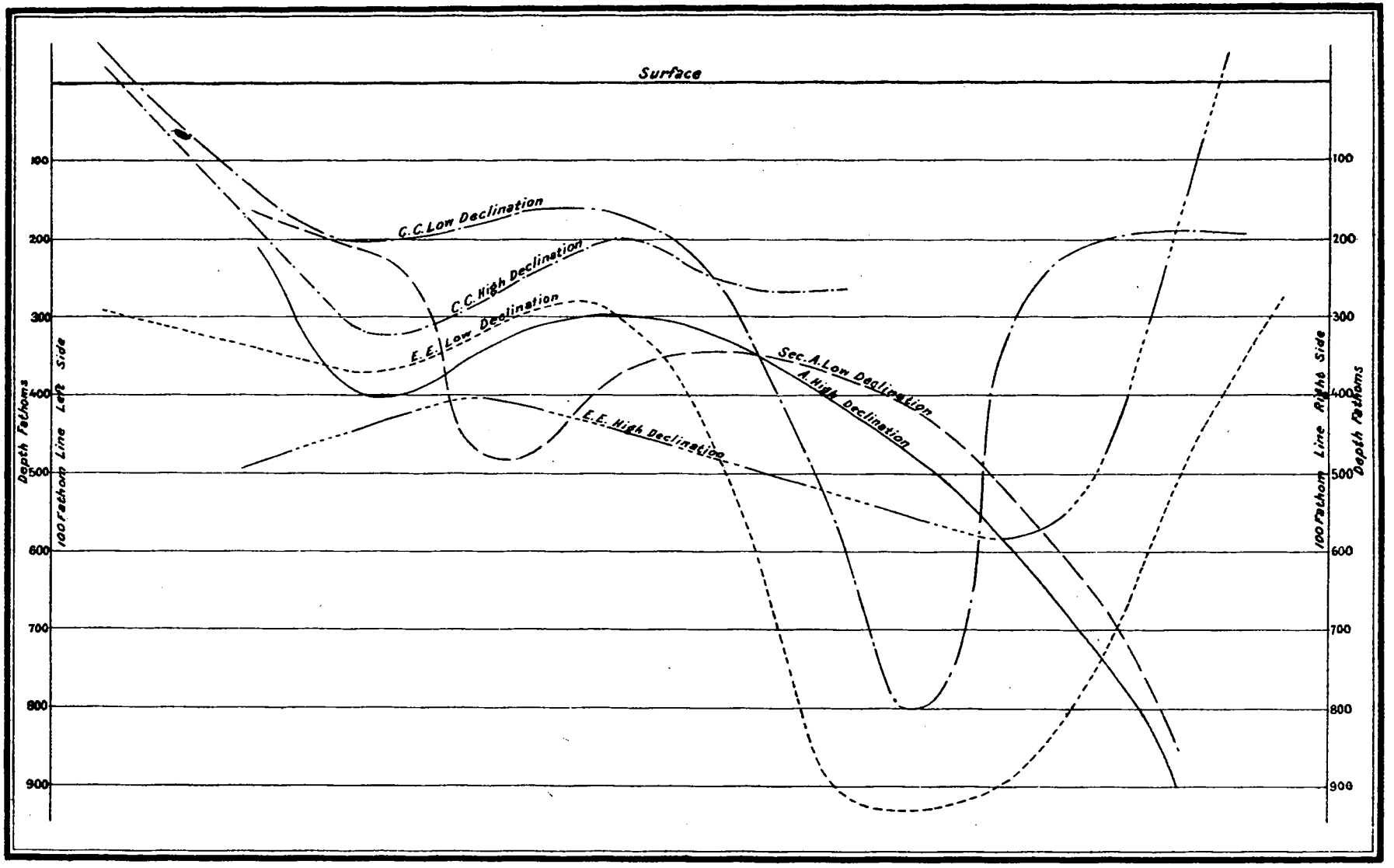
At Sections E E and C C it will be noticed that at low declination the curves drop to nearly double the depth of Section A at the same relative position from the 100-fathom curve, but that the latter shows a very deep current on the eastern side at both high and low declination. The cause of this is without doubt due to the inertia of the water which has been flowing east off Havana and is forced against the bank in rounding the curve of the Straits of Florida at Section A. At the latter section the lowest point of the western part of the curves is at low declination, and is situated approximately at the point of greatest contraction of the axis velocity. The lowest point of high declination is to the left or westward and corresponds to the movement of the axis. At Sections E E and C C the depth at high declination is the greatest on the extreme north, or, as in Section A, on the left of the Stream. There are other points of co-ordination or agreement in the curves and directions of the currents, as shown in the plates. At the time of high declination at Sections E E and D D, the strongest current being on the left side of the Stream, the eddy current is the strongest on the extreme

right along the Cuban shore, and where the reverse conditions prevail, the axis being nearer the middle of the Stream, the eddies are lessened or entirely obliterated.

It seems, therefore, to be abundantly proved that the monthly variation in the Straits of Florida consists of an expansion at high declination and a contraction with an increased localized speed at low declination; that at the time of the contraction there is a deepening of the current at the axis, and at the time when the Stream has spread out it has diminished its depth, but has increased its velocity on the sides; that the most marked movement at high declination is an increased speed toward the left side and but little toward the right.

While this monthly change is taking place there is another rythmical oscillation, which is also governed by the moon. This is a regular *daily variation* in velocity which amounts in some instances to nearly 2½ knots. Sometimes when the wind is favorable for the formation of a "rip" this accompanies it, at which time the velocity of the current has been known to increase over one-half knot in a few moments. On May 21, 1886, when at anchor at Station 1, a rip was observed at 2 p. m., extending about north and south, at a distance of about three-quarters of a mile to the eastward of the vessel. The surface current for the previous half hour had been flowing at the rate of 3.29 knots. In the next 20 minutes the velocity increased to 3.9 knots, during which time the rip reached the vessel and passed to the westward. In the next 30 minutes the speed became 4.6 knots, the rip still very marked and moving to the westward.

The daily variation is most marked on the surface, and, like the monthly change, is far greater on the west side of the stream than it is on the east. There are in reality two periods of increase and two of decrease during the lunar day, somewhat similar to the tide and half-tide of the Gulf of Mexico, but this is chiefly confined to the upper currents, while the lower strata frequently flows with but a single daily fluctuation, indicating a solar influence. In the mean movement of the water, the first or highest maximum generally arrives at 9 hours before the upper transit of the moon, and the lesser at 9 hours before the lower transit.



CURVES REPRESENTING THE CHANGE IN SHAPE OF CURRENT PRISM FOLLOWING THE DECLINATION OF THE MOON

In order to show graphically the regularity of the changes, a diagram (illustration No. 50) has been constructed. The lunar days are represented by the heavy vertical lines. The mean of the hourly observations at all depths at each station has been plotted at its proper place with reference to the transit, and as nearly as possible at the declination of the moon at the time. This mean curve forms the lower side of the irregular shaded spaces. The upper side of each of these spaces is formed by the curve of surface velocities alone, drawn in the same manner, in order to show how closely the surface variations follow the average of the whole volume in point of time. The left side of the rectangular shaded spaces near the middle line represents the time at which the mean current reaches its maximum, and the hours intervening between this and the transit of the moon give what may be called the establishment of the current. This is only intended as a graphic illustration, to show the regularity of the changes to the eye. In the data from which the actual establishment has been fixed the curves were drawn on a scale sufficiently large to render it an easy matter to plot one one-hundredth of a knot or 2 minutes in time.

It has been seen that the currents change monthly in velocity, following the declination of the moon. This increase and decrease has a great influence in forming the curve of daily changes. At the time of the monthly increase, the minimum current for the day follows the greatest maximum by about 6 hours. In the next 6 hours there is an increase in velocity equal to or perhaps greater than the preceding maximum. In the third interval there is a halting or fall in speed to be succeeded by a still greater maximum 9 hours before the next upper transit. At the time of the monthly decrease in velocity the conditions are reversed, the minimum preceding the maximum and each succeeding maximum or minimum is less than the preceding. In the interval of change there is a short time of irregular velocities when the maximum for the day arrives before the lower transit instead of the upper, somewhat similar to certain tides in the Gulf of Mexico, where, as the declination changes its name, a high tide takes nearly the place of a low in time.

The average of all the daily differences of surface current at Section A is given in the table below:

Station.	Distance east of Fowey Rocks.	Mean variation in surface velocity.	Average surface velocity.
	Miles.	*Knots.*	*Knots.*
1	8	1.07	2.66
1½	11.5	1.64	3.46
2	15	0.92	3.16
3	22	0.56	2.73
4	29	0.42	2.12
5	36	0.55	1.71

The table shows that the daily variation is greatest at the point of greatest average velocity and is also more excessive to the westward of the axis than toward the east.

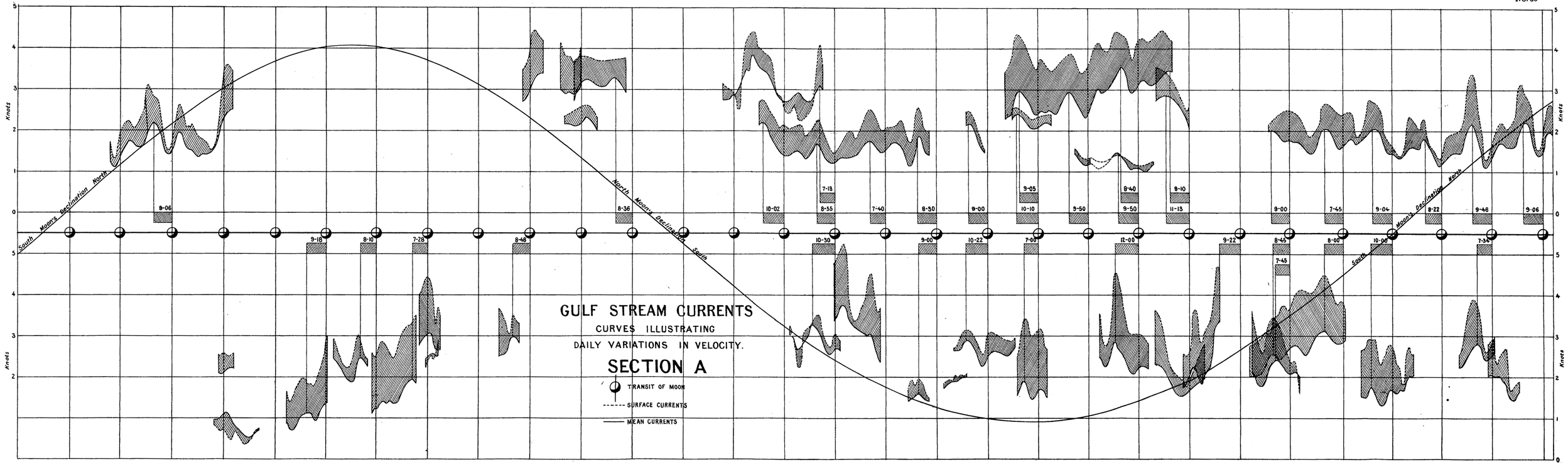
We have seen that the surface temperatures vary during the lunar month. In the same manner they change during each lunar day. The differences are most marked at the extreme Stations, No. 1 and No. 5. These are given in the table below together with Station 1½, for each 12 hours before and after the superior transit of the moon.

SECTION A.—*Daily temperatures at extreme stations.*

Before transit.	After transit.	Before transit.	After transit.	Before transit.	After transit.
°	°	°	°	°	°
----------	80.25	[81.14]	81.83	81.90	[81.13]
[79.67]	79.93	[81.46]	82.33	[81.40]	82.40
[79.67]	79.93	[81.08]	81.83	[82.17]	82.66
80.50	----------	[81.00]	82.17	[82.00]	83.60
[80.01]	80.20	80.69	[80.50]	[78.66]	79.83
[79.17]	79.78	[80.00]	80.70	----------	80.00
[79.57]	79.98	----------	----------	[78.50]	78.81

NOTE.—The lower temperatures are in brackets.

It will be noticed that in every instance but two the temperature before the transit, which is during the period of decreasing current, is lower than


GULF STREAM CURRENTS
CURVES ILLUSTRATING
DAILY VARIATIONS IN VELOCITY.
SECTION A
TRANSIT OF MOON
SURFACE CURRENTS
MEAN CURRENTS
Knots
South Moon's Declination North
North Moon's Declination South
South Moon's Declination North
9-06
9-18
8-10
7-28
8-48
8-36
10-02
7-13
8-55
10-30
7-40
9-30
9-00
10-22
9-05
10-10
7-00
9-50
8-40
9-50
12-00
8-10
11-13
9-22
9-00
8-45
7-45
7-45
9-04
10-00
9-22
9-48
7-34
9-06

it is during the 12 hours after. In a part of these observations the moon's transit was such that the 12 hours succeeding included the hours of day when the surface temperature would naturally be warmer. In about one-half of them, however, the conditions are reversed, the transit being between 6 p. m. and midnight.

This daily change in temperature is accompanied by a change in direction of the currents at the extreme stations and is more marked in the lower strata than in the higher. As the moon approaches the transit, or practically during the period of decreasing velocities, the currents at the extreme stations incline toward the axis, and during the 12 hours after the transit they are running more nearly parallel. The effect of this upon the surface temperature of the intermediate stations is to cause a lower temperature with an increasing current, as seen from the following table:

SECTION A.—*Daily temperature at intermediate stations.*

Before transit.	After transit.
°	°
80.0	[79.5]
[79.8]	79.9
80.5	[80.25]
80.7	[80.3]
81.2	[80.5]
81.2	[80.5]
80.0	[79.4]

NOTE.—The lower temperatures are in brackets.

These changes in velocity, temperature, and direction, all point to the fact that the Stream contracts and expands daily as well as monthly. In the daily fluctuations the expansion is but trifling, and being short in duration in comparison with the monthly change, the surface temperatures at the sides increase with the velocity. As the monthly changes progress, however, the surface temperature is lowered and then raised, reaching its maximum and minimum at some time after the axis has actually changed its direction.

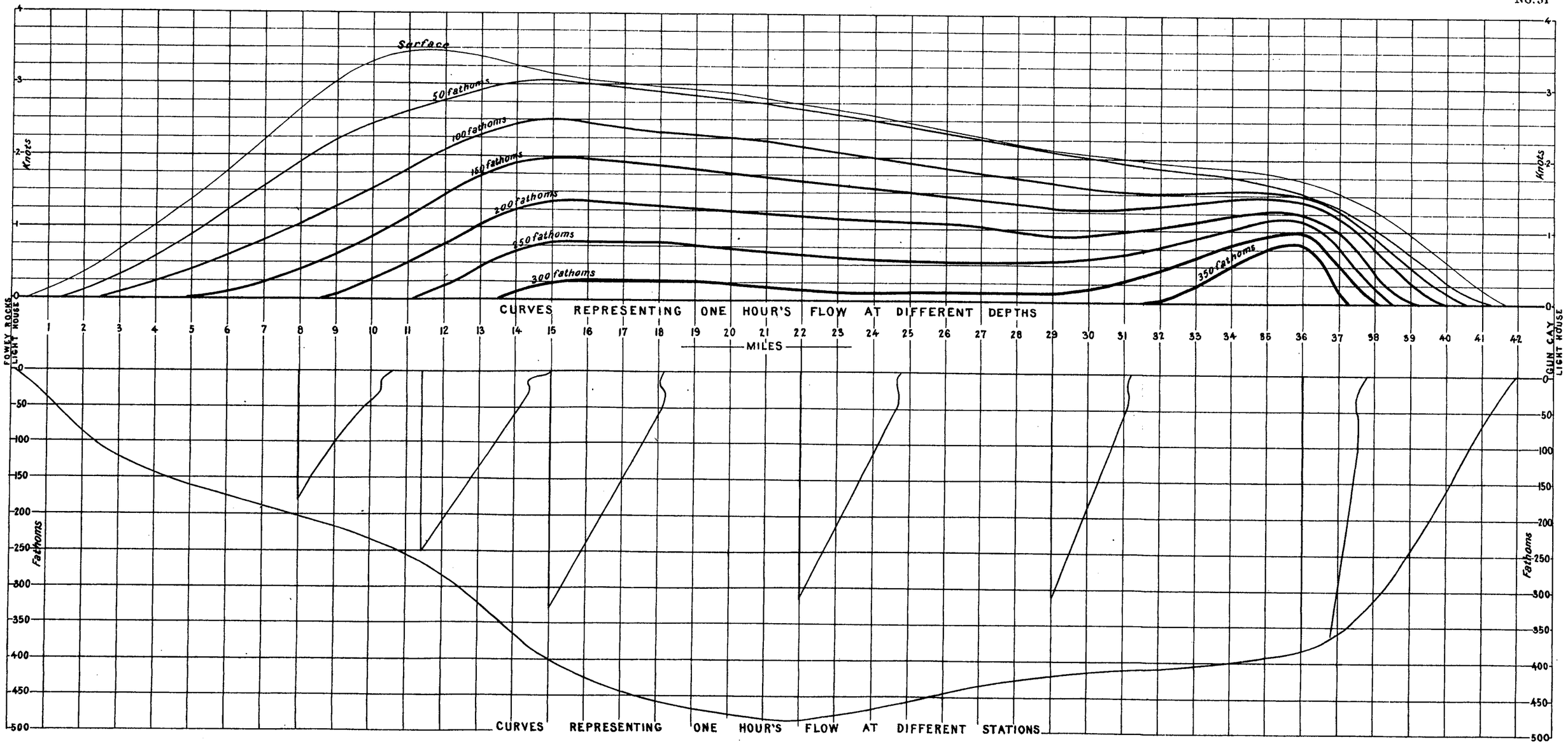
The *volume of the Stream* is best determined at Section A, for here it is confined in width by earth instead of water walls, and practically all its

water passes into the Atlantic. At the next section (off Jupiter Inlet) at certain times there probably is an eddy current along the Little Bahama Bank and through the Northwest Providence Channel. Farther to the westward off Havana a small quantity passes, under certain conditions, through the Old Bahama Channel, but at Section A these variable conditions are eliminated. In calculating the volume the averages of all the observations at each station have been plotted on a large vertical scale, and from the deepest point of observation (130 fathoms) the curves have been continued to zero. The ordinates at different depths were then transferred to a horizontal or plan view, and curves were drawn through corresponding depths and from the extreme stations to the initial line. Deflections in the direction of the current, which varied much from north, were resolved into their component parts and only the northerly component taken. The thickness of the laminæ used in the computation was, 10 fathoms thick from the surface to 50 fathoms, thence 50 fathoms thick to the bottom, and the volume was calculated by Simpson's rules.

The result is a grand total of nearly 90,000,000,000 tons per hour, or, to give more nearly the actual figures, 89,872,000,000 tons, and of this amount almost exactly one-half is carried within 100 fathoms of the surface.

It will be noticed by referring to illustration No. 51 that, on the western slope, the mean depth to which the current reaches is near the bottom. At times, without doubt, it actually did so, and occasionally there was a reverse current. In every instance, however, when the average for the day was negative at 130 fathoms, the barometer in the Gulf of Mexico was lowest for the month or it was highest for the month along the Atlantic coast of the United States. It will be remarked that at Stations Nos. 2, 3, and 4 the average depth at which zero is reached is uniform at about 325 fathoms. The curve representing the vertical current line (illustration No. 51) should not in fact reach the zero so abruptly, for without doubt the actual speed diminishes by smaller and smaller increments as the effect of friction becomes greater. The actual volume, however, would be increased but little, probably not more than one or two per cent., a trifling amount relatively, although at the same time so large actually that the mind can hardly grasp it. At

GULF STREAM CURRENTS
SECTION A



Station 5 the curves show that the current actually reaches the bottom. In the discussion of the section off Havana the cause of this phenomenon will be seen.

The Straits of Florida, at Section C C, are about 73 miles in width between the curves of 100 fathoms depth. Situated as they are near the beginning of the Gulf Stream proper, with the direction of their flow at right angles to that of both the Straits of Yucatan and Section A off Cape Florida, they are a most interesting study. The current does not fill the banks as is generally the case at Section A, but has on its northern side a neutral zone of varying width, in which, at times, there is an eddy current setting to the westward. At Station 1, which is within this zone and about 3 miles from the 100-fathom curve, tidal currents were always found except on one occasion, at which time the barometer was the highest for the month at the Signal Service stations in the eastern part of the Gulf of Mexico, which without doubt caused the abnormal current. While the current is generally tidal, it is probable that in this part of the Stream the barometric influence is greater than elsewhere in this section. In the observations actually obtained, the predominating flow was easterly on the surface at low declination, but the current was so slight that it is difficult to decide in what direction the gentle flow would go with varying conditions. Resolving the directions into their east and west components, it is found that when the moon is near the equator the currents are more easterly than westerly, and when near the highest declination they are the reverse, although they are still so weak that, for the purposes of navigation, they are not of much value and are readily overcome by abnormal meteorological conditions.

At Station 2, 16 miles farther to the south, the currents are still irregular, this station being on the edge, as it were, of the Gulf Stream, sometimes wholly within its borders and again in the variable zone. Whether it has a true Stream current or not depends still upon the moon's declination, but, situated as it is between the Stream and the neutral zone, its lower currents are perhaps apt to partake of the characteristics of the latter when the meteorological conditions cause irregularities.

At high declination, as explained previously, the Stream spreads out its limits and increases the velocity at its sides. This fact is most beautifully exemplified at this station. The first time it was occupied, the wind was from the eastward and the vessel was generally lying broadside-to. The surface flow was easterly and quite constant in direction, the intermediate stratum was variable, and the lower current had a southerly set. Suddenly the surface velocity would increase a knot or more in 10 or 15 minutes, forcing the vessel to tail to it for a short time against the wind, and then return to its original heading. The next time the station was occupied, the declination of the moon was about the same, near zero, but instead of the surface water setting east, it was irregular, and the intermediate and lower strata had a southerly set. This difference was probably due to the meteorological conditions prevailing. The high barometer mentioned in connection with Station 1 had passed off, and was followed by a low area in the vicinity of the Mississippi Delta and Mobile, Alabama. The third time the station was occupied the moon was within a day of its highest declination. The surface and intermediate strata had a strong easterly current, while only the lower was irregular. The following table shows the varying conditions:

Stations.	Date.	Declination of the moon.	Surface strength.	Depth, having easterly set.	Depth, having irregular current.	Depth, having southerly set.
	1887.		*Knots.*	*Fathoms.*	*Fathoms.*	*Fathoms.*
2[b]	May 9	High.	1.76	3½-15-30	65-130	----------
2	Feb. 4	Zero.	0.86	3½	15-30	65-130
2[a]	Feb. 11	do.	0.38	----------	3½	15-30-65-130

The easterly components of the velocities are shown graphically in Fig. 4, from which it is seen that at high declination the edge of the Stream was well to the northward of the station. At No. 2 it was nearer, and at 2[a] it was practically to the southward. Although the set was still slightly to the eastward with a variable current of two-tenths of a knot, it can hardly be called Gulf Stream.

The position of the axis at Section C C varies during the month in the same manner as at Section A, except on its northern side. The movement

at high declination is to the left, but there is not an excessive increase in velocity at the extreme station. The maximum current at this time is to be found between Stations 3 and 3½, or about 34 miles from the light-house house at Havana, and at low declination about 16 miles distant.

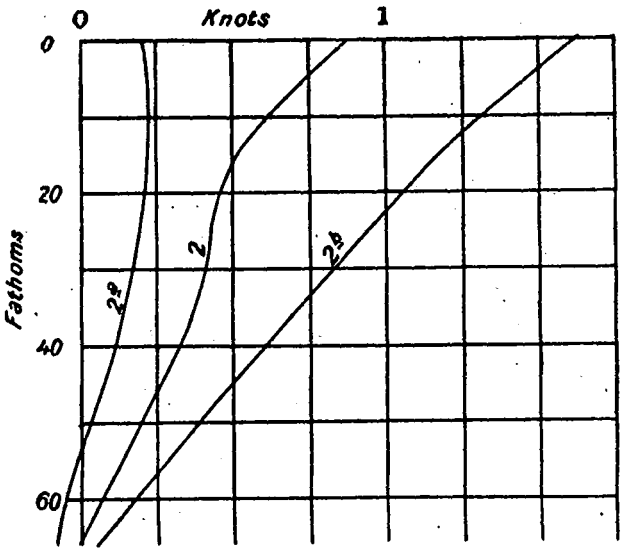


FIG. 4.

The average direction of the currents at the sides is more toward the axis at the latter time than at high declination. The directions are shown in the table below, togetherwith the temperature at each.

Declination.	Station 2.		Station 3.		Station 3½.	
		°		°		°
High	SE. ¼ E.	79.1	E. ¼ S.	77.7	E. ½ S.	79.8
Low	SE. ½ S.	77.5	E. ½ S.	77.4	--------	------

Declination.	Station 4.		Station 4½.		Station 5.	
		°		°		°
High	E. ¾ N.	77.5	----------	------	---------	------
Low	E. ½ S.	80.25	ENE. ¼ E.	77.6	NE. ½ E.	77.3

The temperatures show but little, for the reason that the observations were taken in two groups separated by an interval of about 3 months. The observations suitable for comparison, taken during the same month, were all on the northern side of the Stream, and in every instance the water was colder at low declination than it was at high. This is to be attributed directly to the changing direction of the current, and is the same in principle as at Section A, but with this difference in its execution. The latter section is narrow, and the current fills the strait with the axis nearest the western (left) shore. The surface is most constant in direction while the lower

currents are changeable, thus causing the rise and fall in temperature shown in table on page 542. At Section C C the current does not fill the Strait, and the axis being nearer the right bank, the left-hand part of the Stream follows the same changes as the eastern portion at Section A, viz, warmer at high declination than at low.

The daily variations at Section C C are not as great as in the narrower part of the Stream, but they arrive with as great regularity. The time of the establishment is computed in the same manner as at Section A, by constructing a mean curve from all the observations and taking the average. This gives the time of the arrival of the maximum flow at $9^h\ 22^m$ before the transit of the moon, but there seems to be a difference between the arrival of the wave at the middle and at the side stations, though this may simply be a coincidence. The times are, beginning with the northern station, No. 2, $8^h\ 53^m$, $9^h\ 24^m$, $11^h\ 30^m$, $9^h\ 28^m$, and $8^h\ 22^m$. Section A shows nothing of the kind, but at the next section to the westward there are indications of the same system.

The observations at Section D D, extending across the Straits of Yucatan, resemble those of Section A more than those off Havana. The profile of the bottom is in general the same, except in depth. It rises precipitously on the eastern side from a considerable depth, and to the westward the slope is more gradual to the 100-fathom curve of Yucatan Bank.

The current does not fill the space from shore to shore. At Station No. 1, in 23 fathoms, and about 5 miles inside the 100-fathom curve of Yucatan Bank, the interference of the Stream current with the tidal current is very noticeable. On the surface, the flood tide, combining with the overflow from the Stream, runs about northwest for 18 hours. On the ebb tide, the resultant was east at the time of the observations, and the change from one to the other was by way of north. At 15 fathoms the direction was mostly to the eastward, the mean being ENE. ½ E. It seems probable that, at high declination of the moon, the overflow from the Stream may entirely overcome the ebb-tide current on the surface, in the vicinity of the 100-fathom curve.

On the east side of the Passage there was a light but persistent eddy current from the Gulf of Mexico into the Caribbean. The general direction

of the surface current at the time of low declination of the moon was between NE. by N. and ESE., the mean of all being NE. by E. At high declination on the other hand, the surface direction was between E. and SE. by S. with a mean of ESE.

The table below shows the average strength of the current at the various depths under the two conditions, the value of the northerly component and the mean directions:

Station 6, *Section D D.*

Stations.	High declination.			Low declination.		
	Observed velocity.	Mean direction.	Northerly component.	Observed velocity.	Mean direction.	Northerly component.
3½	0.47	ESE.	—0.26	0.60	NE. by E.	0.27
15	0.64	E. by S.	—0.11	0.78	ENE.	0.30
30	0.73	SE. y E	—0.24	0.70	ESE.	—0.28
65	0.60	SE. ¾ E.	—0.40	0.57	SE. by E.	—0.35
130	0.43	SE.	—0.21	0.45	SE.	—0.18

We see from this table that the velocities and directions at and below 30 fathoms are about the same, but the surface currents vary in direction, flowing toward the Straits of Florida at the time of low declination of the moon, when the strength of the main current is farthest from the west side of the Straits, and that they are flowing toward the Caribbean Sea when the axis is nearest Yucatan. At the time of the observations at low declination the meteorological conditions were possibly abnormal. The Signal Service Review gives an account of an area of high pressure which appeared in Montana on March 18 and, moving southward, left the coast of Texas on the evening of March 22 with a maximum pressure of 30.25 inches. The review says: "The unusual southerly course of this high area appears to have been influenced by the presence of an area of low pressure in the western portion of the Gulf of Mexico having an easterly course." The area of low pressure had moved rapidly to the eastward and probably the high barometer had also disappeared when, two days later, the observations in question began. The mean barometer at the station during the time was

30.04, which was not far from normal. Even if the high pressure had not moved away from the Gulf regions at the time of the observations, the effect of its presence would be to make the eddy, which was running as a sub-current, either too strong or wrong in direction, neither of which would affect the principle established, that in this part of the Yucatan Passage the upper currents move northeastwardly at low declination of the moon. The other stations at this section present the same characteristics as Section A. The directions of the surface currents vary but little from north, and the average of all is N. by E. There is no evidence at any station but the one nearest Cape San Antonio, described above, of a movement of the water directly into the Straits of Florida, and this station belongs to the eddy rather than to the main current.

The axis of the flow is situated west of the middle of the Stream, the same as at Section A, and the same movement to the right and left is well marked. At the time of high declination it is without doubt near the 100-fathom curve of the Yucatan Bank. Stations were occupied about this time as follows:

Station.	Time after highest declination of moon.		Distance from 100-fathom curve.	Average of velocity at all depths observed.
	d.	*h.*	*Miles.*	*Knots.*
2¼	0	12	10	2.11
2¼	1	11	10	1.80
2½	2	09	15	1.91
2	3	12	5	2.37

The first day at Station 2¼ the expansion was taking place, and probably at this point the velocity was greater than at any other part of the channel. On the second day the axis was farther to the westward, and changing the anchorage to Station 2½, was moving away from the axis. The mean of all was a trifle above the second day's currents at No. 2¼, but the surface velocity was $\frac{27}{100}$ of a knot below. Changing the position of the vessel to Station 2 placed her very near the axis at the time of its maximum flow. The actual current found, however, at this anchorage was probably in excess of the normal, due to the presence of an area of low barometer in

the Gulf of Mexico. Station No. 3 was only occupied once with a middle declination of $1^d\ 17^h$ before zero and a mean velocity of 2.14 knots, which would certainly indicate a maximum three or four days later fully equal to that found at Station 2 with opposite conditions.

The daily variation is as marked here as elsewhere, and, as at Section A, is excessive on the west side. At one time it increased in five hours nearly 3 knots, and decreased in the next nine hours; at another time it increased 3¼ knots in three hours. The average time of the arrival of the maximum is ten hours before the moon's transit.

Section E E is situated at the extreme western entrance to the Straits of Florida, and is in reality the starting point of the Gulf Stream proper. Six stations were occupied by Lieutenant Vreeland, two or more times at each. The extremes were placed near the eighty-fifth meridian and about 5 miles distant from the 100-fathom curves of the Florida bank on the north and the Cuban shore on the south. The other stations were at about equal distances apart and on a curve (toward the Gulf) having a radius of about 90 miles. The northern stations are therefore on a line about perpendicular to a possible flow from the Gulf into the Straits of Florida, and the southern stations are similarily placed with reference to a current from the Yucatan Passage. The 100-fathom curves from Sections E E to C C converge, and the former section being at the large end of the funnel and near the source from which the supply of water comes (taking the source as either the Caribbean or the Gulf of Mexico), its currents vary greatly in direction. Owing to the great width of the section (about 125 miles) the velocities are more feeble and the characteristics which mark the other sections are less pronounced.

Station 1, situated near the Florida bank, occupies a position near the usual limit of flow of water to the southward and eastward. Its currents at the times of observation were always setting toward the Straits of Florida, except on one occasion, when the surface was moving to the westward, thus showing that at times the eddy of the neutral zone at Section C C sometimes reaches this point. The lower stratum was still flowing to the southeast. The direction of the currents at the next station was also to the southward and eastward, but at Stations 3, 4, and 5 they were running in

that direction only during the period of low declination, while at high declination they were mostly in the northeast quadrant. Indeed, at Stations 1 and 2 the effect of the moon is visible on the directions, for during the former period the set was more to the eastward than during the latter. Station No. 5 is near the line between the Stream and an eddy, its currents at high declination varying between NE. and NW. Station No. 6 is entirely within the limit of a neutral zone which is sometimes flowing in one direction and sometimes in another. At high declination it was running the strongest to the southward and westward, in opposite directions to the currents at the other stations, while at low declination it belonged to the Stream current, although very feeble in strength.

The radical difference in the direction of the flow at all the stations is accompanied by the usual variation in velocity following the changes in declination. In the description given on page 541 illustrating the monthly variation, the velocities are resolved into their components. In the table below, the mean of the observed currents is shown, but all the observations at the various depths are taken and an equal value given to each set, whether it be for a greater or less number of hours:

Stations (Section E E).	High declination.	Low declination.
1	1.60	0.84
2	1.39	2.07
3	1.28	1.52
4	0.58	1.21
5	0.63	0.87
6	1.31	0.46

It is seen from this table that at high declination the maximum velocity was at Station 1, that it gradually diminished to Station 5, and that at Station 6, on the Cuban shore (where the direction was entirely negative—an eddy current), it increased considerably. At low declination the maximum was at Station 2, a change to the right in its position of about one-fifth the width of the Straits at this point.

The daily variation at Section E E is not as marked as elsewhere either as to time or amount. The differences between the extreme daily velocities

are greater at the northern Stations 1, 2, and 3, Station 2 having the greatest. At these stations, too, it is greater at high declination than at low, while at the southern stations the reverse is the case. The time of the arrival of the maximum, using the observations of eight of the anchorages mostly at low declination, is 10 hours before the transit. Most of those at high declination give no result as to time, but four of them give 5 hours as the "establishment." The table below shows the data:

Stations.	High declination.		Low declination.	
	Amount of daily variation.	Time of establishment.*	Amount of daily variation.	Time of establishment.*
		h. m.		*h. m.*
1	0.62	5 30	0.34	9 35
		None.		
2	1.10	10 06	0.40	10 00
		5 38		
3	0.64	3 50	0.54	10 10
4	0.26	5 00	0.45	10 12
5	0.22	None.	0.32	None.
6	0.62	9 32	0.62	9 07

* At 130 fathoms.

CHAPTER VI.

THE GULF STREAM OFF JUPITER INLET AND CAPE HATTERAS. THE EQUATORIAL CURRENT.

Having drawn conclusions as to the characteristics of the Gulf Stream in the narrower parts, we will now continue the examination at points where a few isolated observations have been taken, to see if there are indications that the same laws prevail or if new characteristics present themselves. Observations of this kind have been made at Section B, between Jupiter Inlet and Memory Rock, at Section F, extending about southeast from Cape Hatteras Shoals, and in the equatorial current and Caribbean Sea. While it is a fact that at any one of these places the data are insufficient to definitely establish a law as to the current, yet it is thought that, viewed by the light we have obtained through the study already made, we shall be able to show that all currents are governed by the same laws.

At Section B, off Jupiter Inlet, two stations were occupied, one on the west side of the Stream about 18 miles distant from the light-house and the other on the extreme east about 5 miles from Memory Rock. The first observations were continued during a period of over 3 days, beginning at 7 p. m., May 30, 1886. From its situation we should place this anchorage very near the axis of the Stream, but as we have no data obtained under other conditions by which to establish the fact, we can only study it by itself. Separating the observations into equal periods of 24 hours each we find that the mean of the currents at all depths decreased in velocity, and the average temperature during those periods diminished. The middle declination of the moon for the first day was north and 3 days after passing the equator. The next day's declination was on the dividing line established at Section A between "high" and "low" declination, and the third day was within the limit of "high." It will be remembered that as the axis moves toward the east or west the temperature of the water rises and falls,

the average during the time of the westerly movement being lower on the west side and higher on the east side than it is during the opposite period. At this anchorage the temperatures were high at first, it being the time of the easterly movement, and each day there was a decrease. Observations were not taken at 130 fathoms, and so a comparison of directions will not be of much value. The mean of all was N. by E. $\frac{1}{8}$ E. At 85 fathoms the last day's direction was N. by E. and the others N. by E. $\frac{1}{4}$ E. and NNE.

A comparison of the curves of surface current with those of Stations $1\frac{1}{2}$ and 2, Section A (Fig. 5), shows that the change in velocity accompanying the declination of the moon is as true here as elsewhere, and its shape and position fixes the anchorage at a point a little west of the mean position of the axis.

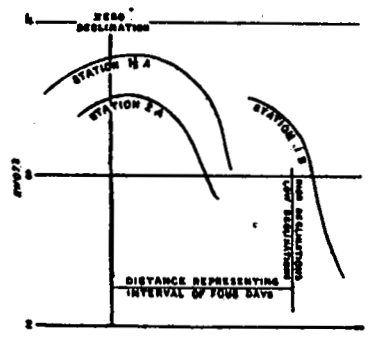


Fig. 5.—Comparison of Section B with Section A.

The other anchorage on this section was occupied for 36 hours, with the moon at about its highest southern declination. The directions seem to indicate that as the axis moves to the westward there may be an eddy current along the Bahama bank the same as at Sections E E and D D under similar conditions. Separating the data into intervals of 12 hours, we find that at all depths except at 130 fathoms, the directions change to the eastward. For the first 12 hours the mean was N. by W. $\frac{1}{4}$ W., for the second N. $\frac{3}{4}$ W., and for the third NE $\frac{3}{4}$ N.

The surface temperatures show the same regularity of change as at Station 1. Being on the east side of the Stream and the axis moving west, the lowest temperature had been reached and a rise was taking place. For the three 12-hour intervals the means were, 80°.17, 80°.40 and 80°.70. At Station 1, the time being at the change in direction of the axis, and, as stated on page 131, the actual minimum arriving at some period after the changes in direction, the temperatures were falling. The average of each 24 hours is given at all the depths in the table below. (At Station 6 only the surface temperatures were taken.)

Temperatures, Station 1, *Section B.*

Depths.	3½ fms.	15 fms.	30 fms.	65 fms.	85 fms.
	°	°	°	°	°
First 24 hours.	83. 26	77. 00	70. 33	66. 97	63. 00
Second 24 hours.	83. 10	75. 70	69. 17	65. 10	62. 00
Third 24 hours.	82. 05	74. 20	66. 25	63. 00	60. 00

As far as the observations go, this section seems to follow the laws as determined by the data obtained at the sections farther to the southward.

At Section F, off Cape Hatteras, the bottom deepens gradually from the extremity of the shoals, about 9 miles from the Cape, to the 100-fathom curve, 21 miles distant. From this point the bottom drops suddenly to nearly 2,000 fathoms in the next 20 miles.

The mean position of the three anchorages at Station 1, is about 5 miles outside the 100-fathom curve, in latitude 34° 52′, longitude 75° 15′. Its situation with reference to the general direction of the flow of the current (about NE.), would lead us to look for characteristics resembling those of Station 1 at Section A, where the current is flowing north, and also expect that they should somewhat partake of the peculiarity of Stations 1 and 2 of Section C C, where the general direction of the Stream is east; that is to say, as the current off Cape Hatteras flows in a direction which is a mean of the other two, its extreme left-hand station should resemble the corresponding stations of the other sections. It is very unfortunate that at every time observations were made at this station the weather either just before or after was so abnormal that there may be a doubt entertained as to whether the currents actually found were normal or not. It will be seen later, however, that while they may not be normal in velocity, the meteorological conditions were such that the departure in each case will not affect the principle established of changes according to declination, for all were influenced in the same way. This station was first occupied on the morning of May 28, 1887, and observations were continued over 50 hours. During this time the barometer was low at the Signal Service stations to the northward, a depression developing on the New England coast and moving in a curve to the southward on the 29th, receding toward

Nova Scotia on the 30th. It was relatively shallow and was unaccompanied by disturbances of marked strength, but still it is possible that the low area influenced the current to make it more rapid than usual toward the latter part of the time of observation.

The declination of the moon was near the dividing line between the high and low as previously established by the study of the observations in the Straits of Florida, the first half of the time being about 3½ days before zero declination. The current during the latter period should be less, according to theory, than during the former period, but, in fact, the reverse was the case, the average of all the depths being two-tenths of a knot greater. This was the time, however, when the effect of the barometer should be most potent in its influence on the current, for the low area reached its southern limit on the 29th and then moved away. The strength of the current was on the surface, the lower stratum apparently obeying the law, while the upper currents were possibly under the influence of the abnormal conditions. The first half of the observations, therefore, was probably about normal for the declination of the moon at the time, and during the last half the velocities were too great.

The next observations were taken on May 5 and 6, 1889, with the declination of the moon one day after its highest north. The directions were all to the northward and eastward and the current was strong and deep. There was a large area of high barometer covering the Atlantic and Gulf States during the 5th and 6th, which finally disappeared after reaching the South Atlantic coast. At the same time there was a depression about midway between Bermuda and the Bahamas, which moved to the northward and eastward. The effect of these areas would be somewhat the same as in the case of the first observations except, of course, in amount. The last observations, however, can well spare half their velocity, and even then the volume will be many times greater than during the first set.

The third time the station was occupied was on June 20 and 21, 1890, with a middle declination of zero. The directions were all to the southward and westward, averaging SW. ¼ S. On the morning of the 19th a tropical storm, which had made its way from the vicinity of Cuba, was central to the east of the Middle Atlantic coast. During the 19th it continued its

northeasterly course, and it is probable that it united with a low area to the northward after that disturbance reached the lower St. Lawrence Valley. The latter is said to have disappeared to the northeastward of the Gulf of St. Lawrence during the 21st. At the time of the observations on the 20th and 21st the low area had moved so far away that probably its influence was hardly felt off Cape Hatteras. At all events its effect would have been to make the Stream either run in its normal direction (northeast) or to lessen the velocity of the current, which was setting to the southwest, neither of which would change the principle involved. Figure 6 shows the vertical curves of velocities at each of the three anchorages. From these it is seen at a glance that at high declinations the current is strong to the northeast, at mid-declination it runs to the northeast but with much less volume, and at zero declination the set is southwest. It seems hardly possible to ascribe enough influence to barometric effect to warrant the conclusion that these currents are not under the same law of changes according to declination of the moon which we have found in the Straits of Florida.

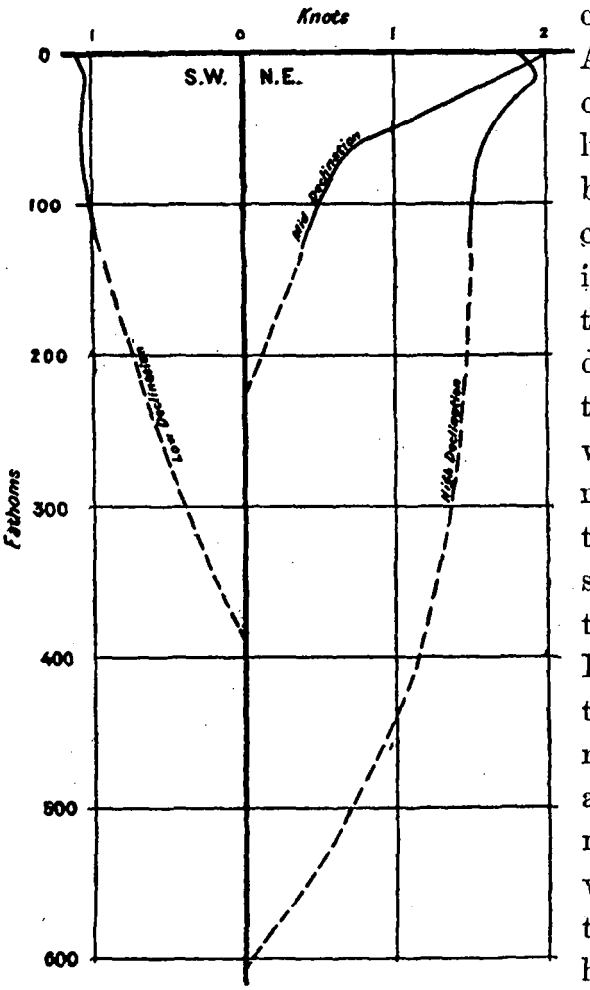
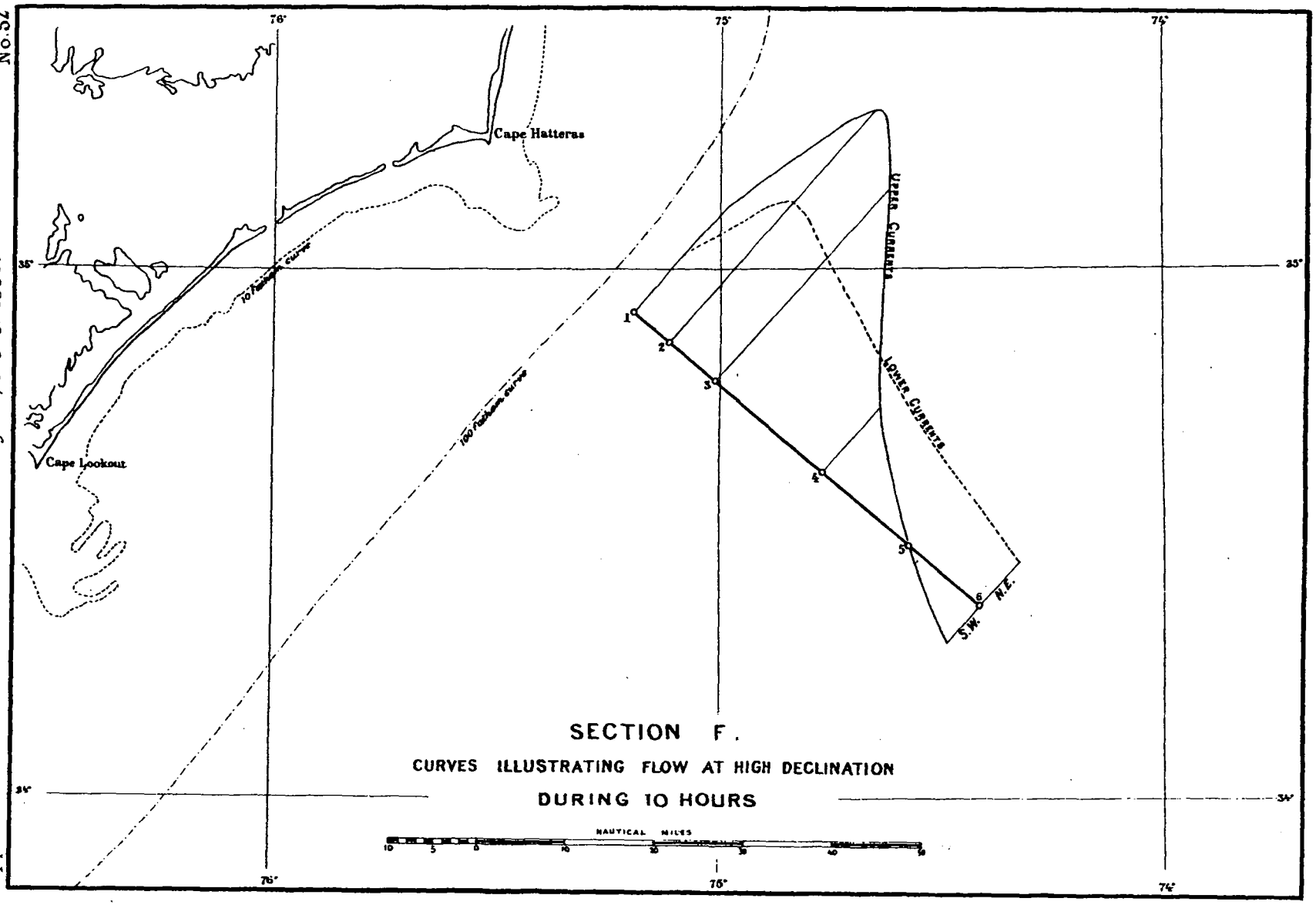


Fig. 6.—Station 1, Section F (Off Cape Hatteras).

The other anchorages at Section F were nearly in a southeast line from Station 1, and extended to a distance of about 76 miles from Hatteras lighthouse. With the exception of Station 5 all were at high declination and were occupied from 9 to 27 hours each. The directions at Stations 2, 3,



SECTION F.

CURVES ILLUSTRATING FLOW AT HIGH DECLINATION

DURING 10 HOURS

and 4 were mostly to the northward and eastward at all depths, while at 5 and 6, only the stratum below 65 fathoms was flowing steadily in that direction. Here again we find evidence of the movement of the axis to the right and left following the declination of the moon. Illustration No. 52 shows the curve of surface flow (above 30 fathoms) at high declination. Having no data obtained under opposite conditions with which to compare it, the illustration is only evidence that, at the time of the observations, the axis was situated about 10 miles outside the 100-fathom curve; that the surface width was practically the same as in the Straits of Florida; that there was a surface eddy current on the south side of the Stream, exactly the same as at Station 1 at low declination; and last, that there was a body of water on the right of the Stream setting to the northeast below the surface.

There is reason to believe, and indeed the proof is positive, that the current flowing along our coast is divided into warm and cold bands. At two anchorages, Nos. 4 and 5, the vessel happened to be placed at points where the fluctuations in temperature were excessive. A study of the relations existing between the directions of their currents and the temperatures at these stations, together with the position of the moon, seems to confirm the truth of the theory of the movement of the Stream to the right and left. The moon at Station 4 was 16 hours after passing its highest northern declination. At Station 5 it was 2 days before reaching zero. Both anchorages were in the year 1889, the first on May 4th and 5th and the second May 9th and 10th. It has been stated that at high declination the direction of the current at the sides is more nearly parallel to the general direction of the flow than at low declination, and this is more marked in the subcurrents than on the surface. The table below shows the currents in question averaged for each quadrant of the compass, with the number of observations:

Directions of the currents at Stations 4 and 5, Section F.

	3½ fathoms.		15 fathoms.		30 fathoms.	
	No.	Direction.	No.	Direction.	No.	Direction.
Station 4 (high declination)	3	N. by W.	----	----------	2	N. by W. ½ W.
	4	NE. ½ N.	7	NE.	4	NE.
	2	SE. ½ E.	----	----------	2	SE. ½ E.
Station 5 (low declination)	5	NW. ½ N.	4	NW. ½ W.	6	NNW.
	3	NNE.	3	N. by E.	4	N. by E.
	4	SE. by S.	4	SE. by S.	2	S.

	65 fathoms.		130 fathoms.		200 fathoms.	
	No.	Direction.	No.	Direction.	No.	Direction.
Station 4 (high declination)	----	----------	----	----------	----	----------
	3	NNE.	7	NE.	3	E. by N.
	4	SE.	2	E. by S.	----	----------
Station 5 (low declination)	----	----------	4	NNW.	----	----------
	10	N. by E.	6	NE. by N.	10	NNE.
	----	----------	----	----------	----	----------

From this it is seen that at Station 4 the mean directions are much more to the eastward than at Station 5. Comparing the surface temperatures and directions (Fig. 7) we find that not only is the daily movement indicated at each station, but also the monthly. At both stations the directions changed with fair regularity; at Station 4 from the southeast quadrant to the northwest, and in the reverse direction at Station 5. In the first case the temperature curve shows an abrupt fall, with an indication of a gradual rise to the end of the observations, and in the other case it is a gradual fall and a quick rise. It seems as if, at the time of the anchorage at Station 4, the maximum flow being on the north side of the stream, the southern edge, as represented by a cold band, was situated in its vicinity. At low declination this cold band had moved out some 13 or 14 miles and was at Station 5. If observations can be continued for a period of two lunar weeks at either of the stations, it probably will be found that the directions predominate first toward the north and then toward the east, and that the abrupt change in temperature

will be less and less or more and more marked each day, as the edge of the Stream is progressing or retrograding; that the limit of northerly movement is somewhere not far north of Station 4, and of southerly movement outside Station 5.

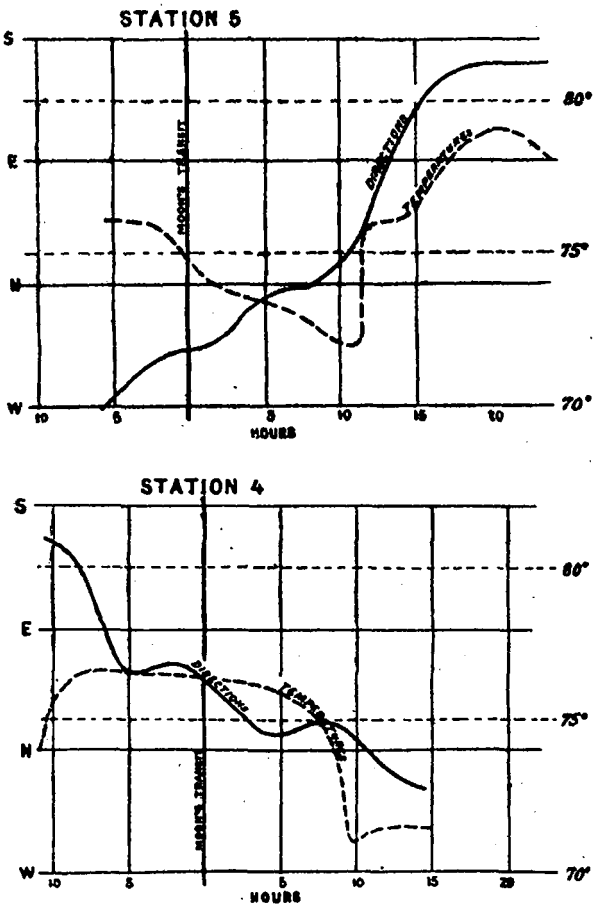


Fig. 7.—Comparison of temperatures and directions near Cold Wall, off Cape Hatteras.

The temperatures of all the stations form a peculiarly interesting study, as they show how absolutely unreliable is the commonly accepted idea that the warmer the water the stronger the current from the south. In the curves just referred to, it will be noticed that the temperature is warm in both cases when the flow is toward the southeast quadrant, and that the abrupt change comes in one instance where the flow is altering its direction from the northeast to the northwest, and, in the other, from the northwest to the northeast. At Station 1 the warmest water at the surface and at 15 fathoms was observed at low declination with a current setting southwest; it was cooler at mid-declination, and the coldest was found at high declination when the current was strongest to the northward and eastward. At the same time the temperatures at the lower depths were exactly the reverse, the coldest water coming from the north and the warmest from the south. The table below gives the mean temperature at the different points of observation:

Station.	Date.	Average direction of surface current.	3½ fathoms.	15 fathoms.	30 fathoms.	65 fathoms.	130 fathoms.	200 fathoms.
			°	°	°	°	°	°
1	May, 1887	NE. ¾ E	77.28	75.60	72.38	59.40	51.67	46.50
1[a]	May, 1889	N. by E. ½ E	75.06	74.39	72.12	64.69	53.06	-------
1[b]	June, 1889	SW. by S	80.19	76.19	69.13	58.13	49.56	44.75
2	May, 1889	NNE. ½ E	79.80	79.50	79.00	73.20	-------	-------
3	May, 1887	NE. by E	78.56	-------	-------	-------	-------	-------
3[a]	May, 1889	E. by N	77.90	75.79	74.38	70.94	64.50	62.63
4	May, 1889	Variable / NE. by E	74.48	73.90	71.64	67.21	64.28	-------
5	May, 1889	Variable / NNE	74.82	73.20	71.38	70.83	65.06	61.11
6	May, 1889	W	77.50	76.70	74.85	70.81	64.50	62.20

The observations made within the limits of the *Equatorial current* were as follows: One anchorage about 60 miles north of Barbados, 8 between that island and Tobago, and also in all the principal passages between the islands from Trinidad to Cuba. The current reaching the Windward Islands is, according to generally accepted belief, composed of two bodies of moving water. One part is said to be from the South Equatorial current, which after crossing the Atlantic from Africa divides at Cape St. Roque, the eastern salient of South America, and forces a portion of its flow to the northward and westward along the coast of Brazil, past the mouth of the Amazon and the shores of Guyana, until it reaches the barrier of the Windward Islands. The other current is the drift caused by the northeast trade winds. Whatever may be the component parts or the cause of each it is a fact that the currents in the vicinity of Tobago are of a different character from those near Barbados. The first, moving as it does along the coast of South America, leaves the island of Tobago with a direction about NNW. The other, flowing in the general direction of the trade winds, causes a resultant direction at the point of meeting dependent upon the relative velocities of the two. The coast current has the most rapid flow, is deeper, and is probably more changeable than its mate. These conditions, in the combined current where the observations were made, render it difficult to determine whether the

same laws hold good here which have been found farther to the westward.

The data obtained in the coast current would at first glance seem to point to a reversal of the law of change following the declination of the moon—that is, instead of the strongest surface current being found on the extreme left at high declination with a movement toward the right as the moon passes the equator, there are indications that the reverse is the case. The data are so slight on which to base a conclusion that this is true, and the conditions tending to produce irregularities are so strong, it is probable that the exceptions found are due to variations in the force of the primal cause of the flow. All of the anchorages between Barbados and Tobago were placed nearly on the line joining the islands, and were made, with one exception (Station 4[a]), between January 26 and February 13, 1888. Station 1 was about 35 miles from Barbados, while Station 5 was about 3 miles from the 100-fathom curve off Tobago Island, and rather under the lee of the most salient point of the shoal water. At each station the flow of the upper stratum was quite constant in direction, and at 65 and 130 fathoms depths it was variable, generally between northeast and northwest, and the variation was more marked at the northern than at the southern stations.

Station No. 32, situated about 60 miles north of Barbados, was occupied 30 hours, during which time it was calm or the wind was very light and variable. The body of the current therefore may be considered as the normal drift for the date and season. The table below shows the character of the currents. The directions given are means of those falling within the limit of each quadrant of the compass separated by the intercardinal points. The number of observations is also given, together with the velocity.

Station 32.

3½ fathoms.			15 fathoms.			30 fathoms.		
No.	Direction.	Velocity.	No.	Direction.	Velocity.	No.	Direction.	Velocity.
5	W. by S	0.84	7	W. by S	0.92	6	W	0.98
4	SW. by S.	0.77	2	SSW	0.81	3	SW. by S.	0.76

65 fathoms.			130 fathoms.			200 fathoms.		
No.	Direction.	Velocity.	No.	Direction.	Velocity.	No.	Direction.	Velocity.
8	WSW	0.88	2	N. by E.	0.51			
2	SSW	0.81	1	WNW	0.63			
			5	S. by E.	0.53	8	S. by W.	0.53
			2	ESE	0.55			

This table shows that to the depth of 65 fathoms there is a gentle flow to the southward and westward, predominating at W. by S.; that at 130 fathoms the character of the flow has changed from a steady current to a tidal current, but with a predomination to the southward; and that at 200 fathoms the current is again constant but at right angles to that of the surface. The same drift current exists south of Barbados, with the same tidal influence at the lower depths, but with the difference that the stronger coast current, meeting the drift current nearly at right angles, changes the direction of the latter.

The following table shows the velocities and directions, the distance of each station from Barbados toward Tobago, and the declination and age of the moon:

Station.	Distance from Barbados.	Moon.		3½ fathoms.		15 fathoms.	
		Age.	Declination.	Direction.	Velocity.	Direction.	Velocity.
	Miles.	*Days.*					
1	34	13.4	20° 26′ N.	W. ¼ S.	0.86	W. by S.	0.63
2	60	14.9	19° 30′ N.	WNW	0.58	NW. by W. ½ W.	0.54
3	80	16.2	16° 52′ N.	NW	1.09	NW	0.83
4	91	18.6	7° 21′ N.	NW. by N.	1.24	NW. ½ N.	1.08
4[a]	91	28.3	22° 00′ S.	N. by W	1.98	N. by W.	2.13
5	109	23.7	15° 25′ S.	NNW	2.46	NW. by N.	1.45
5[a]	109	25.1	19° 17′ S.	NW. by N.	1.90	NW. by N.	1.44
5[b]	109	0.2	13° 41′ S.	N. by W. ½ W.	1.76	N	1.35

Station.	30 fathoms.		65 fathoms.		130 fathoms.	
	Direction.	Velocity.	Direction.	Velocity.	Direction.	Velocity.
1	W.	0.68	NW	0.72	NW. by W	0.83
			NE	0.31		
2	W. by N	0.53	NW. by W. ½ W.	0.70	NNW. ½ W.	1.13
			NE	0.30	NE	0.36
3	NW. ½ N.	0.75	NNW	0.90	N	0.65
			NNE	0.82		
4	NNW. ½ W.	0.80	NNW. ½ W.	0.61	N. by W	0.98
4[a]	N. by W	2.16	WNW	0.56	SW. ¼ S.	0.58
			E	0.86	SE. by S	0.69
5	N. ½ W	1.17	SE. by E.	0.72	N. ¼ E.	1.37
			NW. ½ W	1.32		
5[a]	NW. by N.	0.93	NW. by N.	1.27	N. by W. ¾ W.	0.97
5[b]	N. by W	0.90	N. by W	0.97	NNW	1.20

Taking the mean of the currents at 3½, 15, and 30 as the surface flow, we see that at one extreme of the line the drift has a course of W. ½ S., the same as at Station 32 north of Barbados, and at the other end (Station 5) the coast current sets N. by W. ¾ W., a difference of six points and three-quarters. In the portions of the Gulf Stream investigated, where the general flow is not on the meridional line, the differences in the direction of the current at the extreme stations have been found to be as great as those shown in the table above, and this would seem to warrant the conclusion that the coast current sometimes nearly fills the passage between Barbados

and Tobago with a general axial direction of about NW. Comparing the directions at Station 1 with those at Station 32, we see that there is a considerable deflection of the lower currents at the former, which is probably due to the coast current.

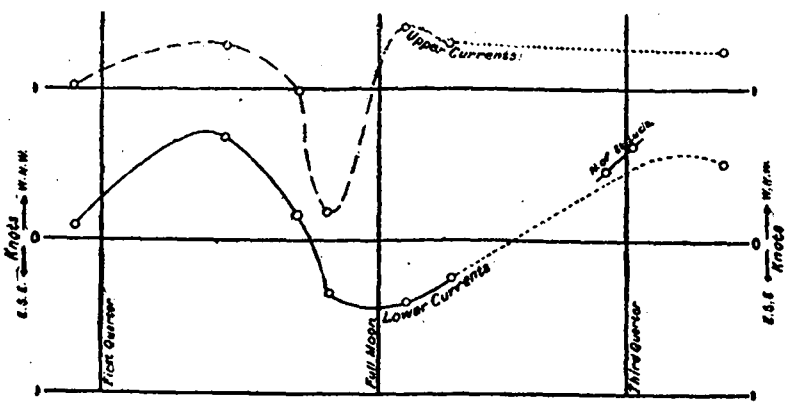
The only stations occupied more than once were Nos. 4 and 5, and from the table it is seen that at high declination the velocity at Station 4 is greater than it is at low declination. At Station 5, however, the velocities show an exception to the rule established. At the first anchorage, with the moon midway between the equator and its highest declination, the current was strongest, and at the last anchorage, with the conditions exactly reversed, it was weakest. The situation of this station, however, makes it probable that its currents are fluctuated irregularly, and particularly so on the surface. This fluctuation is due to variations in either the strength or the direction of the trade winds, and is observable to a greater or less degree at all the stations in this passage.

Remembering the fact that there are two moving streams of water, one along the coast and the other inclined toward it, and assuming that they are governed partly at least by the same laws of changes that control the Gulf Stream in the Straits of Florida, the following would seem to reconcile all apparent discrepancies. The surface velocity of the coast current varies daily with great regularity, as will be seen later. The wind, however, is continually forcing the water toward the shore at a greater or less angle with its current, and the velocity of the escaping water depends largely upon this angle and the relative strength and persistency of the wind. After zero declination the regular current should be deep and strong at its axis, which, according to theory, should be farther to the northward and eastward, or off shore, than at high declination. At Station 4 this was the case with the lower stratum, but the reverse was true with the surface currents. To account for the latter, however, the wind at one anchorage was blowing NE. by E. ½ E. with a force of 3, which would cause a less velocity to the escaping surface water than at the time of the other anchorage, when the wind was blowing from ESE. ½ E. with a force of from 3 to 4.

The relative velocities of the currents at Station 5 should have been the reverse of those found, but the wind seems also to have been the cause

of the irregularity. At the three anchorages this was as follows: Station 5, ENE., force from 3 to 7. Station 5[a], ENE., force from 3 to 4, and Station 5[b], NE. by E. force 4: that is, for the first two, the same direction of wind but with lessening force at the second anchorage, and for the last anchorage a direction more across the current and normal to the shore. The strong current which was observed at 130 fathoms on February 5, was found at 65 fathoms, when the station was occupied a day and a half later, and had again dropped to 130 fathoms at 5[b], as the time of the normal maximum had passed.

While the velocity of the surface currrent seems to be governed to a considerable extent by the wind, the lower stratum is apparently influenced by the phases of the moon, and this helps to mask the declination variation. When we examine the observations taken at the seven anchorages in the passage south of St. Lucia Island, we find but little evidence of the effect of the declination, but every evidence that the lower currents vary with the phases. The velocity from the surface to 30 fathoms depth is remarkably regular and constant, the former having a direction about WNW., seemingly the resultant of the trade drift and the coast current, and the latter inclining more to the westward as the depth increases. At the lower depths there was a decided tidal flow into and out of the Caribbean. The greatest daily fluctuation at all depths was found to be at the time of full and change, with a predominating easterly flow at the lower stratum.



Variations of currents outside of the St. Lucia Passage.

The following table, together with Fig. 8, will best explain the phenomenon. Where there is much departure in direction, the velocities are resolved and the WNW. components taken. All the stations given in the table were in the passage except Stations 20 and 21, which were to the eastward, opposite the middle of the passage.

Number of station.	Date.	Moon's age.	3½ fathoms.		15 fathoms.	
			Direction.	Velocity.	Direction.	Velocity.
		Days.				
20	Mar. 19, 1888	7.3	WNW.	1.52	WSW.	0.62
21	Mar. 21, 1888	8.4	WNW.	1.39	NW. by W.	1.58
9	Feb. 28, 1888	17.2	NW. by W. ½ W.	1.29	NW. by W.	1.35
10	Feb. 22, 1888	11.3	WNW. ½ W.	1.31	W. by N.	1.23
10[a]	Feb. 24, 1888	13.2	WNW.	0.91	WNW.	0.91
10[b]	Jan. 25, 1890	24.4	WNW.	1.32	W. by N.	1.17
11	Feb. 25, 1888	14.0	W. by N. E.	0.22	S. E. WSW.	0.29
12	Feb. 27, 1888	16.0	W. by N.	1.39	W. ½ N.	1.39

Number of station.	30 fathoms.		65 fathoms.		130 fathoms.	
	Direction.	Velocity.	Direction.	Velocity.	Direction.	Velocity.
20	WSW.	0.90	SW. NNW.	0.33	NE. by N. S.	—0.14
21	W. by N.	1.17	WSW.	1.00	S. by W.	0.01
9	WNW. ½ W.	1.27	W. by N. E. by S.	0.20	W. by N. ESE. ½ E.	—0.71
10	W. by N.	1.26	WNW.	1.11	SSE. ½ E. NW. ½ N.	0.26
10[a]	W. by S.	1.12	W. by S. NNE.	0.74	NW. ESE.	—0.39
10[b]	W. by S.	1.20	NW. by N.	0.97	S. by E. NW. ¾ W.	0.03
11	SSE. SW.	0.00	SW. SSE.	—0.10	S. by E.	—0.55
12	W.	1.39	E. by S. NW. by W.	0.34	ESE.	—0.58

The sketch and the table above show how constant the surface flow is at all the stations with the exception of Station 11, and how sharply defined

is the curve of the lower velocities. The observations of two days in the passage north of St. Lucia show the same rule governing the deep flow, and with the exception of Station 5, near Tobago, all the anchorages in the passage between that island and Barbados give like indications.

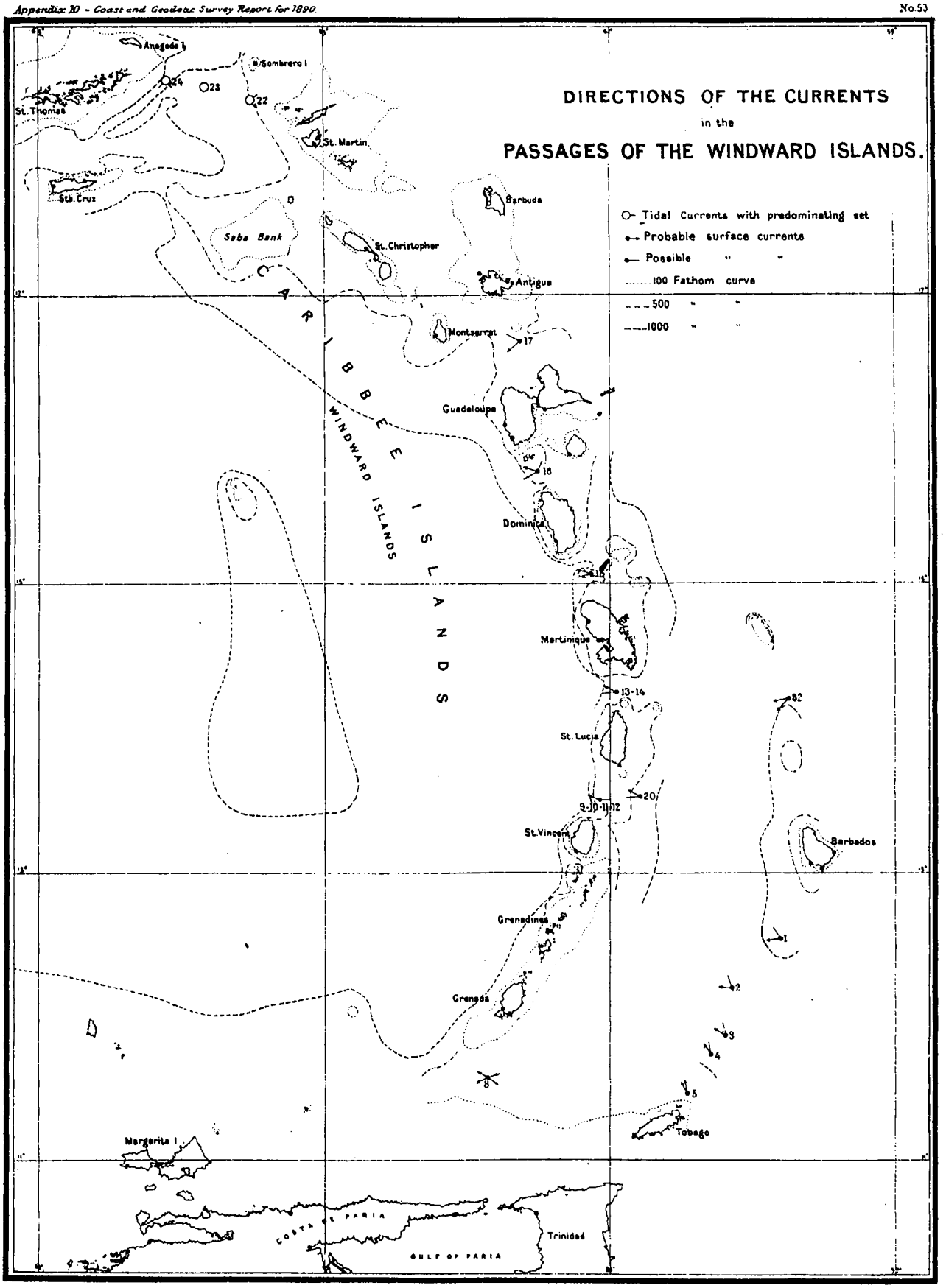
There can be no doubt that this last-mentioned passage is sometimes completely filled by the shore current, but it probably occurs only after a period of abnormally strong trade winds blowing from a point well to the eastward. Evidence of this increased width was observed on one occasion. Observations were made at Station 20, about 15 miles east of the passage between St. Lucia and St. Vincent, and an average surface velocity of 1.52 knots was found. Twenty miles farther to the eastward an anchorage was made on the following day, when the surface current was found to be 2.28 knots setting WNW. Unfortunately, bad weather prevented a continuance of the observations beyond five hours, but the same hours of the previous day, at Station 20, gave an average of 1.68 knots. It seems probable that either the general strength of the current was increasing during the time or else the change of anchorage placed the vessel nearer the axis. Upon steaming to Barbados after getting underway, and also during the passage to St. Lucia, the day after, the same strong current was found. It was common report among the nautical people at Bridgetown (Barbados) that the trade winds were and had been blowing with unusual strength along the South American coast. This strong current was only superficial, however, for, as will be seen from the table, the direction at 130 fathoms was S. by W., with a resultant force of but one one-hundredth of a knot toward the passage. These anchorages, Stations 20 and 21, happened to be within one day of highest northern declination, but the evidence does not seem to be in favor of increased strength due to this cause.

The daily variation seems to be well marked at all the anchorages here considered, except at Station 32 north of Barbados. An average of 25 maxima in the passages north and south of St. Lucia and south of Barbados give for the "establishment," or the time of the arrival of the maximum currents, 6 hours and 16 minutes before the transit of the moon. The two surface current waves follow almost exactly the same form as the curve of the tides. The differences between the daily maximum and minimum currents at the

various stations in the vicinity show the mutual interference of the coast with the drift current. At the stations nearest Barbados the average variation is about one-half knot, at Station 4 it is six-tenths and at Station 5 nearly one knot. In the vicinity of the passage south of St. Lucia a mean of all the daily differences in velocity is seven-tenths of a knot, the greatest being observed just after full and probably it also occurs after new moon. The variation north of St. Lucia was found to be six-tenths of a knot.

As we proceed north from the island of Martinique the influence of the coast current on the flow of water through the passages disappears. It is seen between Martinique and Dominica only at the surface, where the direction is about WNW., with all the lower currents running to the southward and westward. Its effect is not observed north of Dominica, where the gentle flow of the drift current, complicated by tidal action, has taken its place.

In the Anegada, Mona, and Windward Passages a steady flow is not to be found, but only tidal currents, with an inclination in one direction or another depending upon local causes. In general, the predominating set in all these passages seems to be outward on the eastern and toward the Caribbean on the western sides. The opinion advanced by others that the flow through the Windward Passage is always toward the Caribbean, and that it reaches the bottom as evidenced by the character of the bottom soil specimens, is not confirmed by the observations of the actual current. That it is mostly tidal and feeble in force will be seen from the table below. The directions given are the means of all those falling within the quadrants limited by the intercardinal points. Station 27 is nearest Haiti; Station 28 is near the middle of the passage, and No. 29 is nearest the Cuban shore.


DIRECTIONS OF THE CURRENTS
in the
PASSAGES OF THE WINDWARD ISLANDS.
Tidal Currents with predominating set
Probable surface currents
Possible " "
100 Fathom curve
500 " "
1000 " "
Anegada I.
Sombrero I.
St. Thomas
St. Martin
Sta. Cruz
Saba Bank
St. Christopher
Barbuda
Antigua
Montserrat
Guadeloupe
Dominica
Martinique
St. Lucia
St. Vincent
Barbados
Grenadines
Grenada
Tobago
Margerita I.
Trinidad
GULF OF PARIA
COSTA DE PARIA
WINDWARD ISLANDS
LEEWARD ISLANDS

Observed currents, Windward Passage.

Station.	Date.	3½ fathoms.			15 fathoms.			30 fathoms.		
		No.	Direction.	Velocity.	No.	Direction.	Velocity.	No.	Direction.	Velocity.
27	Apr. 19–20, 1888	2	NNE	0.51	4	N. by E	0.61	5	NNE	0.53
		7	E. ¾ N	0.67	4	E	0.55	4	E. by N	0.66
		1	S. by E	0.72	2	S. by W	0.59			
27[a]	Mar. 24–25, 1889	7	N. by E	0.45	6	N. by E	0.40	3	W. by N	0.47
		2	SE	0.46	2	SSE	0.54	3	N	0.49
								2	S. by W	0.61
28	Apr. 20–21, 1888	1	NW. by W	0.63	8	N	0.51	1	NW. by W	0.33
		9	NNE	0.60	2	NE. by E	0.61	8	N. ½ E	0.46
		1	E. by N	0.50				1	NE. by E	0.48
28[a]	Mar. 25–26, 1889	3	S	0.50	2	SSW	0.62	2	SSW	0.58
29	Apr. 21–22, 1888	9	SE. by S	0.89	10	SSE	1.01	10	SE. by S	0.86
29[a]	Mar. 22–23, 1889	6	NW. by N	0.73	5	N. by E	0.67	1	NNW	0.69
					2	W. ½ S	1.15	3	E. by N	0.63
								1	S. by E	0.67
								2	WSW	1.07

Station.	Date.	65 fathoms.			130 fathoms.			200 fathoms.		
		No.	Direction.	Velocity.	No.	Direction.	Velocity.	No.	Direction.	Velocity.
27	Apr. 19–20, 1888	3	N. by E	0.43	3	WNW	0.22	----	----------	------
		6	E. ½ N	0.44	2	NNE	0.27			
					2	E. ½ S	0.35			
					2	S. by W	0.36			
27[a]	Mar. 24–25, 1889	2	WSW	0.57	2	W. by S	0.42	2	SSW	0.22
		2	N	0.42	3	N. by E	0.35	5	NE. ½ E	0.33
		4	S. by W	0.69	3	S. by E	0.29			
					1	E. by S	0.44			
28	Apr. 20–21, 1888	3	NW. by W	0.47	7	WNW	0.69	----	----------	------
		5	N. by E	0.43	3	NNE	0.40			
		2	NE. by E	0.55						
28[a]	Mar. 25–26, 1889	2	S	0.62	2	N	0.43	1	N. by W	0.39
					1	SW. by S	0.54			
29	Apr. 21–22, 1888	9	S. by E	0.75	9	S. by E	0.48	6	SE. by S	0.43
								3	W. by S	0.39
29[a]	Mar. 22–23, 1889	4	S	0.72	1	N. by W	0.59	1	NW	0.51
		4	W	0.81	2	ENE	0.74	5	ESE	0.79
					2	SSW	0.36	1	SW. by S	0.10
					2	W. by N	0.63			

It certainly seems that no large body of water passed through the passage in either direction at the time of the observations. The current is evidently tidal, with a decided prominence of northeasterly directions at Stations 27, 27[a], and 28, and with a southerly set at Station 29. The feeble current always found, and the diminishing velocities as the depth of observation increased, seem to warrant the conclusion that the flow is only superficial.

On the southern side of the Caribbean Sea the currents are apparently erratic, and yet they probably are governed by the same laws as elsewhere. Between Grenada and Trinidad, at the time the observations were taken in 1888, the current at the deep-water station near the middle of the passage was found to be setting to the eastward at all depths. A year later at the same anchorage the flow was in the opposite direction, except at 65 and 130 fathoms, where it changed from WSW. to NE. and back again. These anchorages happened to be under almost identically the same conditions of moon's transit, age, distance, parallax, etc., and yet at one the set was always outward and at the other it predominated inward. This passage is peculiarly situated with regard to the two streams composing the Equatorial Current, and it is probable that on their relative strength the direction of the flow in the Grenada Passage is determined. At the lower depths there is probably a normal current setting east. The portion of the drift current which can enter the passage in question meets the coast current at nearly a right angle. If the latter is strong the former is deflected to the northward and the current in the passage is to the eastward at all depths. If, on the other hand, the coast current is weak, the drift current is able to reach the passage, thus causing a westerly surface current, a tidal current at intermediate depths, and probably an easterly set at the lowest. Of course this is in a measure complicated by the phase of the moon.

Between Curacoa and the mainland the eddy subcurrent was strong, constant, and perfectly marked. At an anchorage near the middle of the deep water, the current was northwest as far as 45 fathoms and southeast below that depth. Nearer the mainland, but still in fairly deep water (425 fathoms), the northwesterly current, only a stratum of 25 fathoms in thickness, was flowing with a velocity of 1.87 knots at the surface and 0.88 knot

at 15 fathoms. This eddy subcurrent probably does not reach Grenada, for there is a barrier of shoal water extending to the northward from Margarita Islands which would prevent; but the evidence is that there is a similar eddy current in the deep water leading to the Grenada Passage, which, together with the relative values of the two streams forming the equatorial current, rule the direction of the surface current between Grenada and the bank off the Dragon's Mouth of the Gulf of Paria.

In the western Caribbean, anchorages were made between Jamaica and Pedro Bank, between the latter and Rosalind Bank, and in the shoal water east of Gorda Bank. The passage between Pedro and Rosalind Banks (Station 37), about 700 fathoms deep in the middle, has a strong, shallow current, but its direction is much inclined to the general axis of the channel It is a part of the flow through the Caribbean, and probably has the same characteristics as the current outside the Windward Islands in the vicinity of St. Lucia. The surface has a direction between west and southwest with considerable velocity. The lower currents incline more to the northward of west as the depth increases, but the strength is maintained to 65 fathoms, below which there is a rapid diminution until 200 fathoms is reached, where tidal action appears. On the shoal east of Gorda Bank (Station 38), the direction of the flow is nearly at right angles to surface current in the passage mentioned above.

The following table gives the data obtained at these anchorages:

Station.	Date.	3½ fathoms.		15 fathoms.		30 fathoms.	
		Direction.	Velocity.	Direction.	Velocity.	Direction.	Velocity.
37	May 10–11, 1889	SW. by W.	1.97	SW. by W.	1.86	WSW	1.84
38	May 12–13, 1889	NNW	1.29	N. by E.	1.25		

Station.	Date.	65 fathoms.		130 fathoms.		200 fathoms.	
		Direction.	Velocity.	Direction.	Velocity.	Direction.	Velocity.
37	May 10–11, 1889	W. by S.	1.51	W. by N.	0.67	W. by N.	0.47
						E. by N.	0.57
38	May 12–13, 1889						

CHAPTER VII.

CAUSES OF THE GULF STREAM AND OF ATLANTIC CURRENTS.

We have nearly completed the examination of the Gulf Stream observations taken in the *Blake* under my command, and it seems proper to take up the question of causes of the Atlantic currents before drawing conclusions for the benefit of "those who go down to the sea in ships." The facts which I have obtained may not prove positively what these causes are, but in the personal experiences of five years' work, watching the winds and waves and observing the currents, there are many things which may be considered as indicating very decidedly what it is that produces and keeps in motion these vast bodies of water.

It is necessary to an understanding of the subject to recapitulate some of the prominent theories which have been advocated. Although there were many ideas advanced before the time of Franklin, he seems to have been the first to give his theories widespread publication. He says:

> This stream is probably generated by the great accumulation of water on the eastern coast of America between the tropics by the trade winds which blow there. It is known that a large piece of water, 10 miles broad and generally only 3 feet deep, has by a strong wind had its waters driven to one side and sustained so as to become 6 feet deep while the windward side was laid dry. This may give some idea of the quantity heaped upon the American coast and the reason of its running down in a strong current through the islands into the Bay of Mexico.

Humboldt published in 1814 a description of the Gulf Stream, in which he says it is not the same at all seasons of the year, but that its force and direction depend to a large extent upon the changes in the trades, and also that the general torpidity of the ice in the Arctic in the winter and its melting in the summer influences it. He says also:

> Considering the velocity of the fluid elements, which in different latitudes in consequence of the earth's rotation is different,

one should be tempted to think that every current from south to north ought to have at the same time a tendency to the east, and *vice versa*, a current from north to south a tendency to the west.

Arago advocated the same theory in part. He says that—

> With respect to currents, the rotation of the earth ought principally to be taken into view, and this, together with the cooling and the warming of the water in the north and south, is the main cause of their more rapid or slower deviation and progress toward the east or west. * * * We ought to apply to the ocean the same theory which has already afforded a satisfactory explanation to the trade winds if we will decipher the question of currents.

Lieutenant Maury, at the time of the publication of the last edition of the "Physical Geography of the Sea," was without doubt one of the hardest students and the most popular writer on the subject of the air and ocean. Many of his conclusions were entirely new and antagonized the ideas of others. At first glance he seems to attribute ocean circulation in part to forces which act diametrically opposite, viz, evaporation, whereby the specific gravity is increased on the surface near the equator, and heat, whereby its density is diminished; but later he expresses his conviction that—

> If we except the tides and the partial currents of the sea, such as those caused by winds, we may lay it down as a rule that all the currents of the ocean owe their origin to difference of specific gravity between sea water at one place and sea water at another; for wherever there is such a difference, whether it be owing to difference of temperature or to difference of saltness, etc., it is a difference that disturbs equilibrium, and currents are the consequence.

His belief was that while local currents might be caused by winds, rain, barometric pressure, etc., differences of density caused the grand circulation of the ocean.

Prof. C. Wyville Thomson has been a member of several scientific expeditions fitted out by the British Government on board H. M. S. *Porcupine* and *Lightning* in the years in 1868–'69 and '70, and in the famous *Challenger* expedition from 1873 to 1876. In both, the investigation as far as currents were concerned was mainly confined to the most accurate determination of temperatures, specific gravity, depth, and character of bottom

specimens, from which Professor Thomson has drawn conclusions as to ocean circulation. He says, in "The Depths of the Sea," on this subject:

> The investigation is one of singular difficulty. Some currents are palpable enough, going at a rate and with a force which make it easy to detect them and even comparatively easy to gauge their volume and define their path; but it seems that the great movements of the water of the ocean, those which produce the most important results in the transfer of temperature and the modification of climate, are not of this character. These move so slowly, that their surface movement is constantly masked by the drift of variable winds, and they thus produce no sensible effect upon navigation. The path and limits of such bodies of water can only be determined by the use of the thermometer. The equalizing of the temperature of bodies of water in contact with one another and differently heated, by conduction, diffusion, and mixture, is, however, so slow, that we usually have but little difficulty in distinguishing currents from different sources.

This statement, in my opinion, is in the main true; for without doubt warm ocean water must come from the equatorial and cold water from the polar regions, and, whatever may be the cause of the transfer, the modification of climate is due to the presence of the water and not to the method of its delivery.

Professor Thomson says:

> By the Gulf Stream I mean that mass of heated water which pours from the Straits of Florida across the North Atlantic, and likewise a wider but less defined warmer current, evidently forming a part of the same great movement of water, which curves northward to the eastward of the West Indian Islands. I am myself inclined without hesitation to regard this stream as simply the reflux of the equatorial current, added to, no doubt, during its northeasterly course, by the surface drift of the anti-trades, which follow in the main the same direction.

Of the Gulf Stream he says:

> It seems to me that the Gulf Stream is the one natural phenomenon on the surface of the earth whose origin and principal cause, the drift of the trade winds, can be most easily traced.

He concludes that this whole flow, upon reaching the western shores of Europe and not finding a ready exit to the northward, banks down, filling

the Northwestern Atlantic to a considerable extent. Owing to this resistance a portion of the current turns southward toward the Azores, while the accumulation to the northward forces an eddy current of colder water to the southward. The general bottom circulation he supposes comes from the southern oceans. The southern hemisphere is chiefly water, while the northern includes most of the land. The Atlantic and the North Pacific Oceans, therefore, are merely bays of the great water hemisphere. Later he says:

> Over the central part of the water hemisphere, precipitation is certainly greatly in excess of evaporation, while the reverse is the case in its extension to the northward. The water is therefore carried off by evaporation from the northern portion of the Atlantic and the Pacific, and the vapor is hurried down toward the great zone of low barometric pressure in the southern hemisphere, the heavy cold water welling up from the southward into the deepest parts of the northward-extending troughs to which it has free access, to replace it.

In effect, Professor Thomson's theories are that the surface currents are chiefly caused by wind drift, and that the lower currents are caused by unequal evaporation.

The most recent exponent of the specific gravity theory is Dr. Carpenter, who was a colleague of Professor Thomson on the scientific cruises of the *Porcupine* and *Lightning*. He based his belief largely upon the temperature observations of these expeditions, and upon the results of his examination of the current in the Strait of Gibraltar. In a lecture to the Royal Geographical Society, in 1870, to illustrate his ideas, he supposes two basins, one under equatorial conditions and the other under polar, connected by a strait:

> The effect of the heat of the tropical basin will be for the most part limited to its uppermost stratum, and may here be practically disregarded. But the effect of the surface cold upon the water of the polar basin will be to reduce the temperature of its whole mass below the freezing point of fresh water, the surface stratum sinking as it is cooled, by virtue of its diminished bulk and increased density, and being replaced by water not yet cooled to the same degree. The warmer water will not come up from below * * * but will be drawn into the basin from the surface of the surrounding area; and since what is thus drawn away must be supplied from a

> yet greater distance, the continual cooling of the surface stratum in the polar basin will cause a *set* of water toward it to be propagated backward (so to speak) through the whole intervening ocean in communication with it until it reaches the tropical area.

This is practically the theory of Lieutenant Maury expressed more in detail.

To repeat the oft-told story of the Mediterranean circulation is unnecessary. Dr. Carpenter considers that it aptly illustrates the whole system of ocean currents. He says:

> The vertical circulation is maintained in the Strait of Gibraltar by the excess of evaporation in the Mediterranean over the amount of fresh water returned into its basin, which at the same time lowers its level and increases its density, so that the surface inflow of salt water which restores the level (exceeding, by the weight of salt contained in it, the weight of fresh water which has passed off by evaporation) disturbs the equilibrium and produces a deep outflow, which in its turn lowers the level. * * * Circulation must, on the same principles, be maintained between polar and equatorial waters by the difference of their temperatures; the level of the polar water being reduced and its density increased by the surface cold to which it is subjected, whilst a downward motion is also imparted to each stratum successively exposed to it, and the level of equatorial water being raised and its density diminished by the surface heat to which it is exposed. * * * Thus a movement will be imparted to the upper stratum of oceanic water from the equator toward the poles, whilst a movement will be imparted to the deeper stratum from the poles to the equator.

It is difficult to reconcile this reasoning with what seems to me the actual state of the case. The Mediterranean is lowered by the excess of evaporation over the precipitation, and an inward surface current caused at Gibraltar. The ocean surface current, on the other hand, chiefly flows from the point where the evaporation is greatest toward the point where there is an excess of precipitation. Dr. Carpenter claims, however, that the difference of ocean level is from the difference of expansion due to heat. Without doubt there is a difference in expansion, but it is a question whether he is correct on the matter of level.

The temperature of the ocean in the vicinity of the equator reaches 37° at a depth of about 1,000 fathoms, below which the changes are slight

to the bottom. The surface has a temperature not far from 80°. The expansion of the sea water due to this change in temperature is about .005, which for the column of 1,000 fathoms would be about 30 feet, giving a grade from the equator to the poles of about six one-hundredths of one inch to a mile. It would seem as if this infinitesimal difference might be easily obliterated by the excess of evaporation at one place and of precipitation at the other. In the immediate vicinity of the equator the rains are considerable, but it is without question that in both hemispheres the rainfall is least within the limits of the trade winds, outside of which it increases somewhat with the latitude. Of the total annual rainfall most of it is evaporated from the ocean direct, in latitudes lower than the thirty-fifth parallel. There must therefore be much more than the average taken from the equatorial belt and much more than the average deposited in the polar regions where the evaporation is but trifling, so that instead of an equatorial elevation from the expansion of the sea water by heat there ought to be a tendency toward depression due to evaporation.

Mr. J. J. Wild, one of the scientific staff of the *Challenger* expedition, seems to imply in "Thalassa" that he is a believer in the wind theory as the cause of ocean currents, but he says as a last word on the subject:

> The southern ocean is the main feeder of its three gigantic offshoots—the Atlantic, the Pacific, and the Indian Oceans—which it supplies through the medium of both surface and under currents. The former, driven by the westerly winds against the west coasts of Africa, Australia, and South America, are driven northward toward the equator; the latter, piled up by the rotating earth against the east coasts of these continents, flow as under currents in the same direction, both entering as warm currents toward their old home, the pole.

I confess that I am unable to fully understand the meaning of Mr. Wild in either of these statements. Most authorities agree, and, indeed, Mr. Wild gives an illustration showing it, that the west coasts of Africa and Australia are included within the limits of the trade winds or the belt of calms. It therefore does not appear how the westerly winds can cause the surface currents which he mentions. The same difficulty is experienced in the matter of the subcurrents which are said to be caused by the earth's rota-

tion piling up the water on the east coasts, for Africa and South America, at least, present a wrong angle to allow the escape of water from this cause alone to flow in the direction of the equator.

At this day, after so many thinking men have investigated and have written on the subject of ocean physics, particularly on the Gulf Stream, and have advanced and advocated every possible theory as to the causes of currents, the only question for a new explorer to decide is toward which of the ranks will his own research lead him to incline.

We have seen that the two prominent theories are, first, surface drift, due to permanent or semi-permanent winds, and, second, gravity, due to differences of density of sea water. I place myself with those who advocate the wind theory as the chief cause of the Gulf Stream proper and of most ocean currents, but to differences in density we may attribute some variations in surface indications of the current. The prime mover, however, is generally wind, and I think my observations of the currents during the past five years will add much weight to the theory.

The winds, of which the trades are the most permanent, act in two ways to produce a surface movement. The friction of the air causes the particles of water with which it is in contact to move in its direction. Friction between the particles transmits the motion from layer to layer with a continually diminishing force as the depth increases.

Prof. Alexander Agassiz says in his recent publication, "Three cruises of the *Blake:*"

> Theoretically it has been calculated by Boeppritz that 100,000 years is ample time to allow the friction of the particles to extend from the surface to the bottom, say 2,000 fathoms, were the winds to blow without intermission in one direction during that time with the average power they are known to possess.

While the trade winds predominate in a westerly direction they do change sufficiently to prevent any great depth of current, even if there were no other conditions to prevent its consummation. In the Eastern Atlantic they incline much more toward the equator than they do in the western parts, and any currents established by these winds will, by their inertia, attempt to continue in the same course, and will be lessened in velocity by the currents produced by winds from other directions with which they may

come in contact. That there are other causes tending to prevent any great depth of the frictional current is evident from the reports of skillful navigators, who have, in the midst of the region of the trade winds and at points where usually a drift current is to be reckoned upon, found a reverse set. This is generally a local influence, extending over a small space and for a short interval, but still, every such instance tends to break up or lessen the persistency of the flow and to diminish the depth of the frictional current.

The waves formed by the wind carry water to leeward, by the pressure of the wind on the back of the wave, which causes each particle near the surface to advance to a greater or lesser extent during each oscillation. This, in effect, is an increase of the frictional current and not readily distinguishable from it. It is, however, a very shallow movement, depending upon the height of the waves and the strength of the wind.

Another and far greater cause of the set to leeward is the break of the wave. Every ripple as it topples over sends a portion of its crest a certain distance in the direction of its travel, and, in a gale, tons of water drive a hundred or two feet to leeward in a few seconds.

Upon meeting an obstruction the water must either come to a stop or escape in the line of least resistance. The frictional current, upon reaching shoal water, becomes less and less as the friction on the bottom becomes greater. If the obstruction is at right angles to the course of the current there is a stoppage, an escape of a portion at the sides, and a reverse undercurrent. A current of this character does not seem to run readily over shoal water, the interference of the bottom quickly retarding it. The experience of our anchorage on the outside of the Grenadine Bank showed a set between southeast and southwest, which is parallel to the general trend of the shoal. Although the Sal Key Bank, in the Straits of Florida, is in the direct line of the current, there is only the ebb and flow of the tides over it. Even on the west side of the Bahama Bank the current does not extend to the very shore. If the obstruction is not at right angles to the current there is an escape of some portion to leeward, the amount depending upon the angle; but I believe a considerable proportion of the velocity is destroyed by the act of impinging and changing direction.

The action of the onward movement of the wave in causing the particles of its upper stratum to move in the same direction has been strongly

impressed upon my mind during the past five years. When at anchor the surface currents were always observed with the meter at a depth of 3½ fathoms, and also by an ordinary log line, using a weighted pole instead of the "chip." This pole was 21 feet long and 3 inches in diameter, weighted at its lower end so that but 6 inches of its length would show out of the water in a smooth sea, and with this slight amount of surplus buoyancy every wave would go over it. When there happened to be a light current and a fresh wind the vessel would ride to the latter, while the pole, from its small exposed surface above water and its deep draft would tail to the former. As the seas would roll over the pole it always disappeared in an upright position, but when it appeared again its upper end was always inclined in the direction of the traveling wave. This continual knocking or pushing to leeward caused the direction of the current as observed by this means to be an erroneous record, depending in amount on the relative strength and direction of the current and the velocity and height of the wave. The current meter suspended below the wave influence, to which the upper end of the pole was subjected, generally gave a direction from one to three points to windward of that given by the pole. As long as there are waves there is a quantity of water going slowly to leeward by this means.

A far greater amount, however, is being thrown violently in the same direction by the break of the sea, and unlike the frictional current it reaches to the very shore. The accumulation of water escapes by the line of least resistance. If the sea is directly on shore, with no chance of lateral escape, a reverse undercurrent is caused. This is noticed where the water is shoal by a deep draft and heavily laden vessel being set to windward, where a light draft vessel will be thrown on shore. Harbors are filled by this accumulation and the tides made very irregular. In the great hurricane at Samoa, which caused such destruction of life and property, the amount of water thrown into the harbor of Apia produced tremendous currents, not only along the beaches and reefs, but setting directly out of the harbor, and this assistance to the great engine power of H. M. S. *Calliope* may have turned the balance and rendered her escape from destruction possible. How many times do we read in the accounts of wrecks on shore of the great velocity

of the currents. All along the shores of Long Island and New Jersey the fishermen report abnormal currents at times when the wind is blowing strong toward the land. These are caused, I believe, simply by the escape of the accumulated water thrown by the waves, and do not extend far off shore. I doubt if a single ordinary gale will produce an *ocean current* having a velocity of one-half knot per hour, and any current that is formed will be very shallow.

The gulf weed, so called, shows the effect of the break of the waves. Its home is the Sargasso Sea, near the northern edge of the trade wind region. Transported chiefly by the waves, it is found entering the Caribbean in the passages north of Guadeloupe, and is in greater quantities north of the West Indian Islands. In large masses, it acts like oil on the water to still the waves, and consequently the break of the sea can only detach fragments from the edges of the mass. As a rule it is seen streaming in long lines in the direction of the waves and not in the direction of the current unless the latter is very strong. In this case it accumulates at a point where there is a rip or a changing current in the same way that drift collects at the edge of an advancing tidal current. The fact of meeting it in strange regions is not necessarily an indication of a current, but that the wind has caused a sea which has thrown the weed to leeward.

The influence of the wind to transport the water without an accompanying current is seen in Key West. With a strong southerly wind the clear water from the Gulf Stream is thrown into the harbor in spite of an ebb tide, but upon a change of wind from the gulf, its water quickly clouds that of the harbor. Along the edge of the reefs in 20 fathoms, with the wind from the southward, the bottom can easily be seen. The Gulf Stream water has been thrown in by the waves, but the current maintains its normal position.

What, then, is the action of the wind in causing the Gulf Stream?

In the tropical regions east of the continent of America, the northeast and southeast trade winds are continually blowing, with an interval of calms between them. The southeast trades accumulate a mass of water on the South American coast, causing a shore current in both directions from Cape St. Roque. The volume of the northern branch (the Guyana current) for

a considerable portion of the year is probably not as great as the accumulation of water thrown against the coast of South America by the northeast trades. The frictional currents of each of these drift streams will be shallow, but meeting each other, as they do, at quite an angle, the resultant velocity will not be the sum of the two. The act of impinging on the coast will give the combination a reduced value, and will form a counter subcurrent running to the eastward, the strength of which will depend upon the velocity and upon the angle of the currents with the coast.

The coast current thus formed sets toward the Windward Islands with varying strength, and, having received its final impulse, leaves the farthest point of its restraining shore (the Island of Tobago) with a course about NNW. The frictional current of the northeast trades has, in the mean time, been sending a certain amount of surface current toward the Windward Islands, and the two join forces southwest of Barbados. The flow then is through the passages between the islands, the strongest being in the one south of St. Lucia, and lessening in velocity in the others as the latitude of the passages increases.

During the winter months the northeast trades blow from a more northerly direction than they do during the summer, and at the same time they extend farther toward the equator. The observations taken on board the *Blake* were during this period, and no evidence was found that the coast current maintains its integrity as a separate current after it encounters the drift of the northeast trades, but there was every indication of a return subcurrent extending even into the southeastern Caribbean. At the stations outside the St. Lucia Passage the lower currents tended east and south; north of Barbados S. by E., and between that island and Tobago there was generally some indication of a deflection to the eastward. In the deep passage between the Leeward Islands and the mainland it was east below the surface stratum, while south of Grenada the same easterly set was observed at the greater depths. This all tends to show that in the escape of the accumulation, the surface goes to leeward, while some of the water of the lower stratum returns in a reverse direction.

During the summer months the southeast trades reach farther to the westward along the South American coast, while the northeast trade winds

although not extending so far south, have a more easterly direction. There is therefore a larger body of water transported at this season from the African shore into the North Atlantic, and consequently the Guinea current is stronger and extends farthest west, reaching in August, according to Findlay, as far as the forty-fifth meridian. This, I believe, shows simply cause and effect. The increased volume of the accumulation of water from the south, and the more easterly direction of that from the north, both tend to produce the reverse subcurrent which appears on the surface farther to the eastward as the Guinea current.

The average of all the westerly flow between the islands from St. Vincent to Antigua gives a volume equal to about one-half that found in the narrowest part of the Straits of Florida. We have seen from the discussion of the observations of the currents in the Anegada, Mona and Windward passages, that the volume entering the Caribbean through these entrances, is little if any in excess of the outflow. What then can account for the other half? I am convinced that it is the water thrown to leeward by the waves, and does not appear as a current while it is in transit, except indirectly by the assistance it gives to the frictional current.

The total width of the passages south of Antigua is available for the entrance of water by this means, whereas the drift current of the trades is confined to the deeper portions only. The waves dash over shoals where a drift current can not flow. The former then have about three times the available space for entrance that the latter has, and, when we include the broader passages to the westward, we can realize what an enormous quantity of water may enter the sea whenever there is a wind to cause a wave. Once in the Caribbean, every wave formed gives the surface current an additional push by its momentum, so that by the time the Western Caribbean southwest of Jamaica is reached, the flow has greater velocity than in any of the passages between the Windward Islands or at any of the anchorages outside the islands, with the exception of those near Tobago, which are in the full strength of the Guyana current.

We have thus followed the water, driven by the *vis a tergo* of the trade winds from the coast of Africa to the Yucatan Channel, from which it flows into the Gulf of Mexico and through the Straits of Florida into the Atlantic.

We will leave it for the present to inquire whether there is any force to assist it on its march toward the European coast. It is true the Guyana current is but trifling in volume or velocity in comparison with the Gulf Stream as it issues from the Straits of Florida. But seeing, as we have, what a comparatively short distance the former is projected from its confining bank, one is led to agree with those who doubt whether even so large a body as the Gulf Stream can be driven very far toward the coast of Europe by the *vis a tergo* of the trades without the assistance of some force in the northern Atlantic.

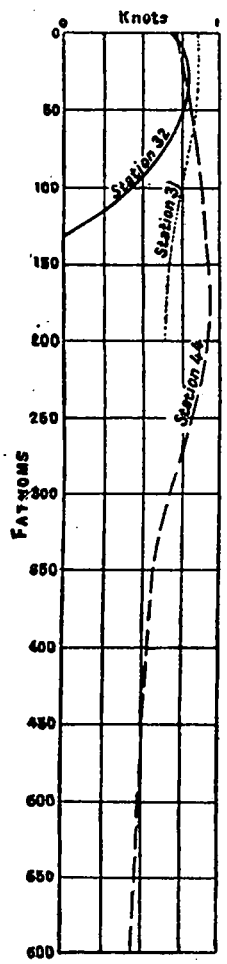


Fig. 9.—Vertical curves Stations 31-32-44.

It seems evident that two contributions are to be found which tend to force the Gulf Stream onward. One a current outside the West Indian Islands caused by the northeast trade winds, and the other the prevailing westerly direction of the anti-trades. In fact the whole system of winds in the North Atlantic tends to produce an oval-shaped flow, with the region known as the "horse latitudes" at the major axis. We have direct evidence of the flow outside the West Indian Islands in the observations taken on the line between Great Abaco Island, Bahama, and the extremity of Cape Hatteras Shoals. At the first anchorage (No. 31), about sixty miles from the Bahamas, the currents were all to the northward and westward, the surface NW. and at 200 fathoms NW. by N.

Midway between the ends of the line (Station 44), observations were carried to 600 fathoms where it was found, as seen in Fig. 9, that a deep but slow movement reached to a great depth. The directions here were all between NNE. and NE. by E. at all depths, with the exception of a single observation at 375 fathoms and at 600 fathoms, where the set was in the reverse direction. This current might be considered as an overflow from the Gulf Stream

were it not for the fact that the observations at the outside station off Cape Hatteras show the direct effect of the impingement of one on the other. At the time of the observation at Station 6, Section F, the full width of the Stream proper did not extend as far off shore, and there was an eddy surface current between it and the current coming from outside the islands. The eddy current was but superficial (see Fig. 10), and the outside current showed itself as a subcurrent setting in the normal direction of the Stream. The question arises, why did it not appear on the surface and increase the visible velocity of the Gulf Stream. The answer to this is because its density was less.

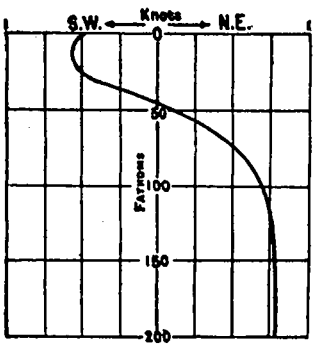


Fig. 10.

In order to avoid repetition, the cause of the alternations in temperature of the Gulf Stream is inserted here, as it is necessary in its discussion to enter upon the question of differences of density.[1] There has been a great deal of speculation and surmise on the subject of the alternations of warm and cold bands in the Stream, the existence of which Professor Bache established as beyond a doubt. He was led to believe that they are caused by irregularities in the ocean bed over which the current flows. The soundings on which he based this belief were made with rope or registering apparatus, neither of which is valuable in deep water or in the presence of a strong current. By more improved methods it has been shown that the ocean is not divided into hills and valleys along our coast. At one place off South Carolina there is a spot on the submarine plateau which has a depth of about 50 fathoms greater than the water outside of it, but it seems very doubtful if this can cause a variation in temperature off Cape Hatteras or still farther to the eastward, where the current certainly does not reach the bottom, nor could it cause the fluctuations found in the temperature at points farther to the south toward the Straits of Florida.

[1] The term density is used to mean the specific gravity of the water *in situ*, and specific gravity, the density of the water at 60° F.

In this part of the discussion by the term Gulf Stream is intended the whole flow from the western Atlantic.

It has been thought that the cause was to be found in an opposing cold counter-current forking out the warmer water into bands or ribbons. It is possible that this may be the case where two currents are directly opposed, but there is no evidence that there is a cold current flowing in a direction opposite to the portion of the Gulf Stream along our coast, and even if such a current does exist, it does not seem to be probable that it can fork the Stream into gradually converging lines which maintain their relative position throughout and follow the curves and turning of the Stream its whole length.

As before stated, the warm water upon approaching Europe is divided into two parts by the obstruction it meets. As the northern extension approaches the Arctic regions it is probably more or less forked by alternations in the temperature, for the following reasons: The warm water of the Gulf Stream from its greater heat is of very much less density than the polar water, but, owing to the superior amount of saline matter held in solution, it has a greater specific gravity. At a certain time in its progress northward it has cooled sufficiently to bring its density down to that of its opponent, and at the same times is actually warmer. A fall of another degree makes its density even less than the other, at which time the polar water gains the ascendency and slips over the warmer, the two strata arranging themselves according to their relative weights. For example, the equatorial flow may have a density of 1.027 at a temperature of 36° and the opposing Arctic current at 32° a density of 1.028. The latter being the heavier assumes a lower position, but when the former has lost something of its heat it becomes the heavier, and, although still at a higher temperature than the other, it seeks a lower level.

The whole width of the opposing waters is considerable and the different parts are under varying conditions. A single northerly gale will cool the warmer water in a certain locality, while an adjacent limited area may be subjected to reverse conditions. The low barometer accompanying the gale will help to change the temperature of the water by inducing a vertical current. Unusual temperature in the seasons north and south will produce a higher or a lower temperature than normal. From all these causes, as

well as others, the position, the depth, and the angle of the line of meeting is continually changing. In the case of our equatorial water meeting the polar, both being under these variable conditions, the small differences in density will determine which water will override the other, and thus produce the alternations in the temperature at the Arctic end of the line. That the alternations exist both horizontally and vertically is abundantly proved. Prof. H. Mohn, the scientific head of the "Voringen" expedition found on the dividing line between the Atlantic and Arctic water very many instances of alternations in temperature vertically, the warm and cold layers of water being repeated between the surface and the bottom, or to some intermediate depth.

An illustration in "Thalassa," which I take the liberty of reproducing here (see Fig. 11), perfectly illustrates the point. The temperatures (centigrade) were taken in the *Challenger* expedition between the Antarctic ice barrier and Kerguelen Island. The curves show plainly how the cold water

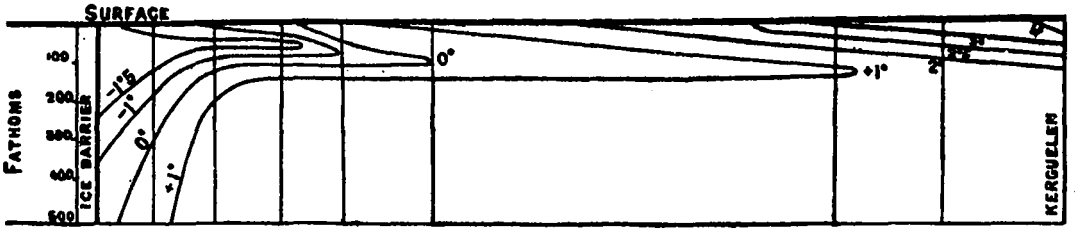


Fig. 11.

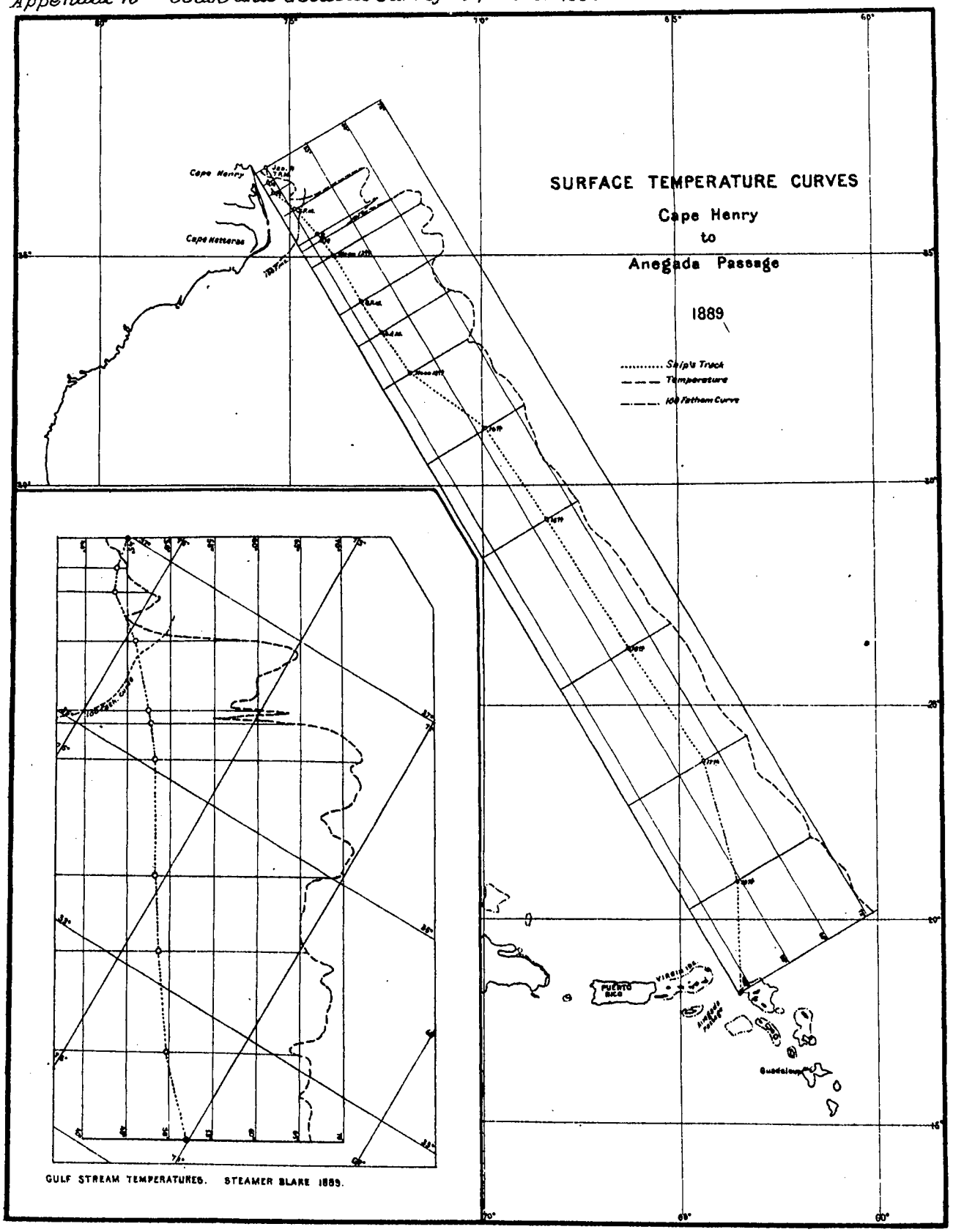
intrudes itself into the warmer, and the two arrange themselves according to their densities. Mr. Wild, the author of "Thalassa," says:

> The melting of these ice masses produces a quantity of water which, being fresher, is of less specific gravity than the salt water of the surrounding sea, and therefore floats in the immediate vicinity of the ice on the surface of the latter. But as the fresher water derived from the icebergs mixes by degrees with the surrounding salt water, the mixture being of lower temperature is rendered heavier and sinks below the surface, forming an intermediate stratum or wedge.

In the Gulf Stream along the coast of North America, the case is different. We find here a comparatively permanent alternation from the Straits

of Florida to beyond the line between Bermuda and Halifax. Not only are the alternations found within the supposed limits of the Stream, but they are also both inside and outside of it. They are shown graphically in an illustration prepared by Professor Bache, illustration No. 37. Another example of the actual changes in temperature at about four feet below the surface is to be seen in illustration No. 54. These observations were taken on board the *Blake* with a thermometer, which, by an electric current, automatically recorded the temperature continuously. The positions of the various bands agree fairly with those of Professor Bache. It is seen on both these plates that there are fluctuations inside the Stream, off New York, for example (illustration No. 57), where, according to all belief, there is a current setting to the southward. There is certainly no northeasterly current in the vicinity of the inside warmer band extending from Cape Canaveral along the 100-fathom curve to Nantucket. The cause of this one at least can not be a cold current opposing a warm one.

In running lines of soundings, as the writer has, normal to the coast as far as the 100-fathom curve, and at intervals from Cape Hatteras to beyond George's Bank, it has been generally noticed that in the vicinity of a depth of from 40 to 80 fathoms, the temperature of the water suddenly changes, the colder being always found on the land side. It is very marked on George's Bank, and is probably due to the cold water from the outside being forced on the shoal by the advancing tidal impulse. It is generally conceded that this tidal impulse is in direction about normal to the coast of the United States, from the fact of its arrival at the salient points of the continent at the same hour. The Gulf Stream's course is at right angles to this advance. I believe that to this we may look for the cause of the lesser thermometrical variations, and that they are due to an interference of successive tidal impulses meeting the obstruction of the shore, whereby a vibratory motion is produced on the ocean's surface. This motion causes the alternation by what might be called attenuation and condensation of the warmer temperature; that is, in the former the surface stratum of warm water becomes thin, and the colder lower stratum rising, the temperature of the vertical column is lowered. In the latter the reverse operation takes place.


SURFACE TEMPERATURE CURVES
Cape Henry
to
Anegada Passage
1889
Ship's Track
Temperature
100 Fathom Curve
Cape Henry
Cape Hatteras
PUERTO RICO
Guadeloupe
GULF STREAM TEMPERATURES. STEAMER BLAKE 1889.

The differences are more abrupt when the extremes of temperature are closest together; that is, in a shallow hot current or on the northern border of the Stream. They are less noticeable north of the current because the differences between the surface and lower temperatures are not so great, and consequently the intermingling of the surface and lower waters can not reduce the temperatures to so great an extent. The same is true south of the Stream, because the current is warm to a great depth, and also, because the vibrations diminish in intensity as the distance from the land increases. These alternations probably will be found on every coast where there is a warm surface current, if the trend of the land is nearly at right angles to the direction from which the tidal impulse comes.

To return now to the current off Cape Hatteras. The current outside the Bahamas curves to the northward as it meets the resistance of the coast. Its line of meeting the Gulf Stream proper varies in position because the latter changes its position according to the forces acting upon it. The width of the Stream off Cape Hatteras, however, is such that one of the cold bands is near the average position of its southern edge. When the outside current meets the Gulf Stream and the edge of the latter is to the northward of this cold band, the temperature of the latter will be lowered and it will underrun the former. In the curve of surface temperatures taken between Cape Henry and the Anegada Passage (illustration No. 54) it will be noticed that there is an abrupt rise at leaving the 100-fathom curve above Cape Hatteras and a fall at a distance of about 35 miles outside. This is the Gulf Stream itself. It is lower in temperature than the water next outside of it, although coming from the Caribbean, because its strong currents are continually changing in direction (as described in Chapter V.) and intermingling its waters from the surface to the bottom layer. The high temperatures just outside the Stream are from the waters which have swung around from the higher part of the curve in the vicinity of the Islands, the southerly portion with its high temperature coming next to the Stream. It is warmer than the Stream because its currents are slow, and are not interfered with by the bottom or mixed by excessive changes in direction. We have no means of knowing the width of this outside current except by taking the width of the higher fluctuations in temperature

outside the Stream. This gives over 200 miles. It is slower in movement than the latter, but it is of much higher temperature, and by its addition to the Gulf Stream the amount of heat transferred to the northern Atlantic is very much increased.

The water is thus delivered by means of these two currents into the region of the westerly winds. It has had the confining bank of the continental line to the westward as far as Cape Hatteras, after leaving which its flow must depend upon something else than the force imparted to it by the trade winds. North of the calms of Cancer, the winds are mostly from the westward. The effect of this wind is to drive the surface water across the Atlantic in the form of a current, and to bank it up on the shores of Europe. These winds, however, are not persistent enough to cause as deep a current as the trades. Many authorities agree that the Gulf Stream itself ceases to be felt as a separate current to the eastward of the Grand Bank. After leaving this point it becomes a simple drift current. The mean direction of the wind between the latitudes of 30° and 50° north, deduced from numerous observations, has been determined by Kaemtz as follows: France, S. 88° W.; England, S. 66° W.; Germany, S. 76° W.; Denmark, S. 62°W.; Sweden, S. 50° W.; Russia, N. 87° W.; America, S. 86° W. When the sun is north of the equator the prevailing winds are from SW. to WSW. On the contrary, if the sun is in the southern hemisphere the winds are from WNW to NW.

Temperatures, Stations 44 and No. 6, Section F.

Station.	3½ fathoms.	15 fathoms.	30 fathoms.	65 fathoms.	130 fathoms.	200 fathoms.	375 fathoms.	600 fathoms.
6	77.5	76.7	74.8	70.8	64.5	62.2	------	------
44	73.0	72.5	72.5	70.5	68.1	65.2	58.4	43.6

Approaching the shores of Europe the drift current meets an obstruction nearly at right angles to its course, and the "banking down" mentioned by Sir Wyville Thomson takes place. A similar banking down is also seen in the temperatures of Station 44, on the coast of the United States, where the outside trade-wind current meets the obstruction of the continent. The

latter escapes to the right inasmuch as that is the only avenue left open. The banking down on the shores of Europe has room to escape both to the northward and to the southward. The set to the northward, however, quickly encounters opposition in the Polar Sea, but is strong enough to overcome the obstacle and force the colder water before it to escape by the Labrador current. This current is said to partly underrun the Gulf Stream, and partly to flow as a countercurrent inside the Stream along the coasts of Nova Scotia and the United States. The countercurrent is certainly very feeble. Practically the main body of the current underruns the Stream, and, intermingling with its waters, joins the southern branch in its flow past the Azores and along the African coast. This branch is assisted on the way by the prevailing winds of that region, for the westerly winds gradually change in direction and merge into the northeast trade winds.

We must now examine the question as to whether there is a sensible elevation of the water in any part of the Gulf Stream's flow. The most accurate levels between the Atlantic and the Pacific Oceans have probably been run by the Panama Canal Company in the construction of the canal across the Isthmus. The result is in favor of the superior elevation of the Atlantic by about three-quarters of an inch, which difference may possibly be attributed to errors of observation. At Nicaragua, the levels run by the promoters of that canal have been of too rough a nature to determine small differences, and therefore the two oceans are considered to be on the same mean level. The actual result, however, was still in favor of the Caribbean Sea being the highest.

The reported difference of about 40 inches in level between the Gulf of Mexico at Biloxi, Mississippi, and the ocean at Sandy Hook is probably largely in excess of the actual difference, but at the same time it is probably a fact that the former is considerably higher than the latter. An accurate line has been run by the U. S. Coast and Geodetic Survey from Sandy Hook to St. Louis, Missouri. The levels from the Gulf of Mexico to St. Louis were executed in part by the Mississippi River Commission, a small portion by the U. S. Coast and Geodetic Survey, and another part by the U. S. Army as far as Lake Pontchartrain, which was said to be at the same level as the Gulf. The fact of the correctness of the total difference

reported is to be questioned, but the existence of some difference, probably many inches, is hardly to be doubted.

There is certainly a yearly difference in the mean level of the Gulf of Mexico, as shown by the tide gauges. The result of two years' record at each of three stations in this Gulf gives a departure from the mean sea level in decimals of feet, as follows:

Station.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
Biloxi, Miss	—.34	—.22	—.07	+.08	+.11	+.08	—.04	+.11	+.38	+.45	—.17	—.39
Fort Morgan, Ala	—.39	—.26	—.12	—.02	—.03	+.03	+.18	+.08	+.30	+.34	—.05	—.14
Key West, Fla	—.21	—.27	—.21	—.23	—.32	—.03	+.08	00	+.26	+.45	+.40	+.10
Mean	—.31	—.25	—.13	—.06	—.08	+.03	+.07	+.06	+.31	+.41	+.06	—.14

We see that in September and October the mean level is highest above the average and in January and February it is lowest. (See Fig. 12.) How much of this is caused by the trades and how much by local winds it is impossible to state. The maximum elevation follows by a short interval the time when the northeast trade winds are blowing with their greatest easting and the southeast trades extend farthest into the northern hemisphere.

Variation in Mean Level of Gulf of Mexico.

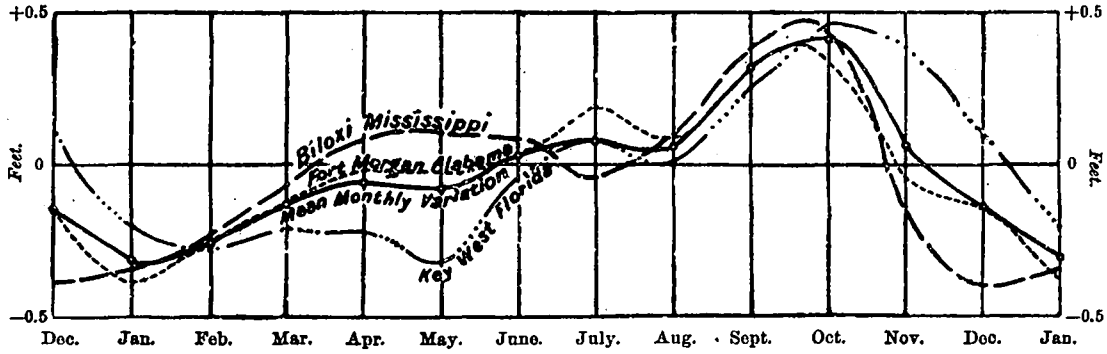


FIG. 12.

In the western Caribbean at Jamaica, and also on the coast east of Yucatan and Honduras, the winds during the summer months have the most southing in them, thus sending a great quantity of water toward the Yucatan Passage.

Most writers agree that the velocity of the Stream increases during the latter part of the year. Findlay places the strongest current in the winter

months, but other writers state that its maximum flow is at the end of August or at the commencement of September. The evidence is, that the periodic changes of level of the Gulf of Mexico follow the changes in the trade winds, the highest level coming at the time when the winds are throwing the greatest amount of water into the western Caribbean, and that the yearly variation in the Gulf Stream's velocity follows this change in the level of the Gulf of Mexico.

I am led to the belief that the prevailing winds of the ocean raise the level of the sea on the leeward coasts, and, if we could but measure it, we should find that the Gulf of Mexico and western Caribbean are higher than the western Atlantic; that the Atlantic south of Cape Hatteras is above the level of the ocean northeast of that Cape; that on the northern European coast it is higher than at Labrador and Newfoundland; and, lastly, that on the tropical African shores the sea is lower than the same latitudes in South America. Probably, however, all of these differences are very small except that of the Gulf of Mexico.

The effect of atmospheric pressure on the surface of the ocean is to force or crowd the water away from the point of greatest to one of less pressure, thus causing a depression at the first and an elevation of the surface at the second place. In the case of two well-defined areas of high and low barometer over the deeper parts of the ocean there can be no great transfer of water from one to the other. The pressure exerted at one spot simply causes a rise at the other depending upon the relative size and differences of weight of the two, and the actual movement of water is along the bottom and is about equal to the amount of the rise. There is probably a trifling flow outward on the surface at the point of highest pressure and an inward flow at the center of the lowest pressure, but this surface influence can hardly have time enough to extend to any great distance, as the force exerted is but temporary.

In a partially confined body of water the case is different. While the elevation of water at the point of low pressure is no greater, the transfer of the water into or out of the confined body from the point of high pressure can not take place without an increase of velocity through the connecting strait. The Gulf of Mexico is a confined sea and is so placed that variations

in the pressure between that exerted on its surface and on the western Atlantic causes a considerable retardation or acceleration of the current. The flow generally takes the direction of the Atlantic because the barometric variations in that ocean are very much in excess of those in the Caribbean.

A difference of 1 inch in the barometric column, or about one-half pound in atmospheric pressure, will give over 1 foot difference in the elevation of the surface of the sea. When we consider what the volume is which it may be necessary to supply to or take away from the Gulf of Mexico, we can imagine what abnormal variations there must be in the velocity of the current in the Straits of Florida. The study of the observations seems to show that the weaker parts of the currents are first influenced; that is, the bottom currents and at the sides, particularly on the left. It is exactly the same condition of affairs as is found at the entrances of many rivers, harbors, and sounds. Upon the arrival of the flood wave the current slips into the harbor along the bottom and at the sides, while the ebb current is still running on the surface in the middle. If the barometer is high in the vicinity of Cape Hatteras the pressure on the surface of the ocean probably elevates it in the neighborhood of the northern end of the Straits of Florida and retards the lower currents. A low barometer in the Gulf of Mexico has the same effect, and a high barometer in the Gulf acts in the opposite direction.

To explain the action of the variations in pressure we will examine some of the actual observations thought to be abnormal from this cause. The observations in the Straits of Florida in 1885 were apparently quite free from the influence of unusual atmospheric pressure. Observations were in progress from May 7 to 14 at Station 1. On May 10 and 11 a small Atlantic storm was reported east of Cape Hatteras, with a maximum barometer of 29.66, but it does not seem to have affected the currents off Cape Florida. On the 13th, however, a low area appeared off the southern coast, disappearing to the northward on the 15th, with a wind of 50 miles an hour at Block Island. The currents on the 14th were abnormal at all depths, but particularly on the surface where the current was very great. Station 1[g] was occupied February 28 and March 1, 1886. The averages in

knots of all the observations at each depth were: 3½ fathoms 2.90, 15 fathoms 1.86, 30 fathoms 1.81, 65 fathoms 1.42, and at 130 fathoms a southerly set with a velocity of 0.18. Just preceding the time of these observations the barometer was very low in the Gulf of Mexico, the lowest reading for the month at the Coast Stations east of New Orleans being on the 27th and 28th. In the Atlantic there was a storm center in the vicinity of Newfoundland from March 1 to 5, with a high barometer to the westward. The high pressure outside and the low pressure in the Gulf of Mexico united in causing the reverse current at 130 fathoms depth. The conditions had been so long continued that all the velocities were about a knot less than they should have been.

Station 1[1] was occupied April 30 and May 1. The current at 130 fathoms was southerly for about 18 hours, and then changed to northerly on May 1, increasing considerably in force. At 65 fathoms the velocity steadily increased during the anchorage. The lowest barometer for the month of April at all the Signal Service stations in the Gulf of Mexico occurred on April 27, 28, and 29, with the exception only of Key West. This extensive and slow moving area of low pressure was the evident cause of the abnormal subcurrent. On May 2 the currents had not returned to normal, as was shown by a partial obliteration of the daily variation.

The next observation of abnormal current was on May 5 and 6, at which time the surface velocity was far below what it should have been, followed on the 7th, 8th, and 9th by reverse lower currents and a surface velocity too small by over one knot. The Weather Review says that on the 3d of May an area of high pressure appeared off the southeastern coast of the United States, and was succeeded by lower pressure from the 7th to the 10th. The high area was the evident cause of the low surface velocities on the 5th and 6th, while the low area is responsible for the reverse bottom currents on the 7th, 8th, and 9th. The next noticeable variation from the normal velocity was on February 12, 1887, the anchorage being No. 3, Section CC. The surface velocity was decidedly too high, and was caused by the great atmospheric disturbances of the three previous days. An area of low barometer had traveled across the country, reaching the Atlantic coast on the afternoon of the 11th and causing the lowest barometer

for the month at all the stations from Hatteras to Portland. This was followed by an extensive area of high barometer which arrived at the Atlantic on the 12th and embraced within its limits the entire coast. On account of the accompanying bad weather, observations could not be continued until the reverse effect of the latter was felt.

The unusual velocity observed at Station 1, Section CC, on March 2 and 3, is another instance of atmospheric pressure. At the end of February an area of high pressure was forming in the Rio Grande Valley and on the 1st day of March this had extended so as to embrace most of the Gulf of Mexico, if not the whole of it. The barometer on the latter date was the highest recorded for the month of March at all the stations near the Gulf coast from Key West to Brownsville. During the evening of May 4 and on May 5 currents were observed at Station 2*. On the 2d and 3d there had been an area of low barometer in the Rio Grande Valley and on the coast of Texas which had moved north, but its influence was felt at the anchorage by the irregularity of the currents found.

At Station 1, Section EE, on December 21 and 22, 1889, there was evidently a disturbance which caused a WNW. current at all depths except at 130 fathoms. This was the station nearest the edge of the Florida Bank. Examining the weather maps we find that there was an extensive area of low barometer extending from the Rio Grande Valley to British America. The center moved away from the Texan coast into the Gulf of Mexico on the 22d, and then, curving to the northward, passed over the mouth of the Mississippi, causing heavy winds on the Gulf coasts. This was evidently the cause of the reverse current found by the observers.

Sufficient illustrations have been given to show the certain influence of differences of pressure within and without the Gulf of Mexico. In every instance where an abnormal current seems to be evident there is reason to be found in the state of the barometer. In every instance, when the barometric differences were sharp at the time of an anchorage in the weaker currents, the effect of the former on the latter is visible. Not being able with one party to observe the currents at two places in the Stream at the same time, it is impossible to assert positively that the influence is not felt at all parts alike, but it seems that the weakest portions

are first influenced, the bottom current is materially lessened or reversed, and the current in what has been called the neutral zone is quickly changed. In one or two instances, when at anchor in the deeper water, the effect of the abnormality on the current has not been found, and this is one reason for the conclusion that it is the weaker current at the bottom and at the sides which is first influenced. A long-continued difference of pressure will cause the effect to appear in the upper stratum.

CHAPTER VIII.

CONCLUSIONS.

The Gulf Stream receives its water from the Atlantic, partly by means of a current driven by the force of the southeast trade winds along the northeast coast of South America, and partly by a current from the northeast trade winds. The water, as a current, flows only through the passages between the Windward Islands, and not through the Anegada, Mona, or Windward Passages. All the water entering the Caribbean as described does not flow the length of that sea as a current, but a portion of it returns to the eastward through the Passages, usually as a subcurrent. In addition there is a large body of water thrown by the waves into the Caribbean through all the passages. The current found along the South American coast between Trinidad and Curaçoa is chiefly produced by the escape of water thrown there by the waves, no large body permanently entering the sea through the passage south of Grenada. The flow of water across the Caribbean is of the same character as that found outside the islands, a scarcely perceptible current on the surface at first, but increasing in its velocity as the longitude increases. The water accumulated in the western Caribbean escapes into the Gulf of Mexico, raising its surface level above that of the Atlantic.

The general circulation of the water of the Gulf of Mexico is erratic in direction and feeble in force. Lieutenant Vreeland's observations at twelve anchorages between the Mississippi Delta and the Yucatan Bank show a predominating direction to the southward and westward in the northern half of the Gulf, and also close to the Yucatan Bank, while between the two the flow was to the eastward. The passage of water into the Straits of Florida is sometimes from the Gulf and again from the Yucatan Passage. At the high declination of the moon it is from the latter, and at low declination it is from the former.

Passing through the Straits of Florida, the axis of the stream off Havana is nearest the southern edge of the current prism, but after making the bend between Salt Key Bank and Florida Reefs the axis is from 4½ to 11½ miles outside the 100-fathom curve on the west side. There is another body of water to the northward of the West Indian Islands, which, driven by the trade winds, is moving to the westward. This is a slow current, but when it joins the Gulf Stream proper off the southern Atlantic Coast of the United States it materially adds to the latter on its way toward the northern seas.

The width of the Gulf Stream off Cape Hatteras is about the same as when it leaves the Straits of Florida. It is, however, liable to more fluctuations in directions, particularly along its edges; and in its progress to the eastward, by the time the Newfoundland banks are reached, it is probable that these fluctuations entirely obliterate the Stream as a body distinguishable from its mate which has come by the outside passage from the trade region. In these latitudes, however (about 40° N.), the whole surface is slowly moving to the eastward, driven by the prevailing westerly winds. Approaching the shores of Europe it meets the obstruction of the Continent and escapes laterally, one branch to the southward from the Azores towards the coast of Africa; the other branch into the Arctic, where it forces a cold return surface current to escape along the shores of Greenland and Labrador.

The characteristics of the Gulf Stream and of also what may be called its tributaries are as follows: When the flow is in the vicinity of the land there is a marked daily variation in the velocity, caused by the elevation or depression due to the attraction of the moon and sun. There is a retardation in the effect produced by this tidal influence of about 3 hours. In the open sea the daily variation is not marked. The following table shows the time of the arrival of the maximum current *after* the moon's transit, or what has been called the "establishment" in these pages.

Localities.	Current establishment.	
	h.	*m.*
Equatorial Current near Tobago and St. Lucia Islands	6	10
Yucatan Passage	2	26
Straits of Florida off Havana	3	04
Straits of Florida off Cape Florida	3	26

In the vicinity of Barbados the time of high water is about 3 hours after the transit of the moon, giving retardation of the maximum flow of 3 hours and 10 minutes. The maximum in the Straits of Florida is the reverse of that of the Equatorial, its arrival being 2 hours and 15 minutes after mean low water at the southern Atlantic ports of the United States.

The following tables show the maximum daily variation observed at the various stations, the mean daily variation and the velocity of the surface flow. In the Straits of Florida, off Cape Florida, there is but one prominent maximum each day, usually arriving 9 hours before the upper transit of the moon.

Between Fowey Rocks, Florida, and Gun Cay, Bahama.

Station.	Distance east of Fowey Rocks.	Mean surface velocity observed.	Maximum daily variation observed.	Mean daily variation.
	Miles.	*Knots.*	*Knots.*	*Knots.*
1	8	2.66	2.38	1.07
1½	11½	3.46	1.83	1.64
2	15	3.16	1.67	0.92
3	22	2.73	0.56	----------
4	29	2.12	0.58	0.42
5	36	1.71	0.95	0.55

The surface directions of the currents at the extreme stations incline toward the center of the stream at low declination of the moon and run more nearly parallel with the axis at high declination.

Between Rebecca Shoal Light-house, Florida, and Cuba, near Havana.

Station.	Distance south of Rebecca Shoal.	Mean surface velocity observed.	Greatest daily variation observed.	Mean daily variation.
	Miles.	*Knots.*	*Knots.*	*Knots.*
1	20	0.30	0.62	0.49
2	35	0.74	1.15	0.77
3	50	2.24	0.65	0.62
4	68	2.23	0.80	0.46
5	86	0.77	0.82	0.61

The surface directions of the currents at the side stations incline toward the axis at the time of low declination of the moon, and run more nearly parallel with the axis at high declination. Station 1 is outside the limit of the Stream and its currents are usually tidal in character and not strong. At the time of considerable differences of barometer between the Gulf of Mexico and the Atlantic, the currents at Station 1 are apt to run toward the area of low pressure.

Between Cape San Antonio, Cuba, and Contoy Island, Yucatan, the extreme daily variation was found at Station 2, at 5 miles distant from the 100-fathom curve of the Yucatan Bank; this was 3.95 knots at high declination of the moon. The mean of the velocities at the various stations is given in the table below, but it does not truly represent the average current to be expected, for at many of the stations the observations were only under one condition of the moon.

Station.	Distance east of Contoy Island, Yucatan.	Mean surface velocity observed.
	Miles.	*Knots.*
2	25	3.65
2¼	30	3.25
2½	35	2.37
3	45	2.79
4	60	1.56
5	76	1.07
6	90	0.51

The current at Station 6, nearest the Cuban shore, varies between NE. by N. and ESE. at the time of low declination of the moon, and between E. and SE. by S. at high declination. In other words, the current predominates to the southward at the latter time, and toward the Straits of Florida at the former.

At Section EE, between the Cuban shore and the 100-fathom curve 60 miles west of Tortugas, the direction of the currents is from the Straits of Yucatan at the middle stations during the period of high declination. Nearest the Cuban shore at this time they set toward the Straits of Yucatan, and on the north side they set from the Gulf of Mexico, but with a

more easterly direction. At the time of the moon's low declination the currents are all to the southward and eastward.

The following table gives the position of the axis or the point where the greatest velocity may be found on the third day after the moon's highest and after zero declination. The *velocity* of the current at the point given as the position of the axis at high declination, changes more than at the other point; or in other words, the difference between the maximum and the minimum currents during the month is greatest near the place where the movement to the left ceases. At the mean position of the axis, however, a good current is always to be found.

	High declination.	Low declination.	Mean position.
	Miles.	*Miles.*	*Miles.*
East of Contoy Island, Yucatan	25	45	35
North of Havana, Cuba	16	34	25
East of Fowey Rocks, Florida	7	15	11
East of Jupiter Light-house, Florida	15	23	19
Southeast of Cape Hatteras Light-house	31	.....	.....

It is probable that from Jupiter Inlet to Cape Hatteras, the average position of the maximum current will be found between 11 and 20 miles outside the curve of 100 fathoms depth, disregarding the irregularities in the curve.

To gain the advantage of the strongest current, it is a question of judgment to be decided by the navigator at the time, how much he shall cut off in rounding the bends of the Stream. At high declination he can edge out so as to pass Fowey Rocks light-house 7 miles distant, and be sure of a good current, while, at low declination the maximum velocity at this distance will be found much less, and it will be necessary to go 4 or 5 miles farther to the eastward.

The data obtained off Cape Hatteras are not sufficient to enable us to assert positively how much the movement of the axis is. The width of the Stream at high declination is about 40 miles, reckoning from the 100-fathom curve, which is about the same width as in the narrowest parts of the Straits of Florida. It is probable that at low declination the position of the axis

at Cape Hatteras is not more than 12 or 15 miles farther offshore than the distance given in the table, but the conditions of the current outside the Stream at this point cause a slow surface flow at times which may lead to the belief that the Stream itself is very broad.

I am convinced that the so-called "Cold Wall" is not the inner edge of the Stream, but is near the dividing line between the Gulf Stream proper and the outside Atlantic current, and that the maximum velocity will always be found some miles inside (to the northward) of it. The current outside the Stream is not comparable with the latter in point of velocity. Its speed probably is never much over one knot and usually much less. Its direction is to the northward and westward outside the Bahamas and to the northward and eastward off Cape Hatteras.

A steamer bound from Cape Hatteras to Havana or the Gulf ports crosses the Stream off Cape Hatteras. A fair allowance to make in crossing the Stream at right angles is 1½ knots per hour for a vessel's speed of 5 knots for a distance of 40 miles from the 100-fathom curve. In the run from the southern edge of the Stream to Matanilla Shoal, no allowance for current can be given. Upon sighting the Bahama Bank, time will be saved by running down the Stream on the east side as far as Gun Cay instead of crossing at Jupiter and running the latitude down on the Florida side of the channel. The current is weak on the Bahama side, and on the shoals there is practically none. This route will be difficult and perhaps impracticable until a light-house is built at Matanilla, unless the green water of the northwest corner of the bank is sighted before dark. Arriving at Gun Cay, Bahama, an allowance of 2¼ knots per hour for speed of the vessel of 5 knots per hour will make a course of west good to Fowey Rocks. This is for the average velocity of the Stream. The weakest current will be experienced about 3 hours before the transit of the moon, and if the crossing is made so as to arrive at the axis at about this hour time will be saved.

A vessel running inside the Stream from Cape Hatteras to Cape Canaveral should keep inside the 100-fathom curve, and, after passing the latter cape, as close to the Florida shore as prudence will allow.

Along the Florida Reefs the neutral zone which borders the northern edge of the Stream probably begins in the vicinity of "The Elbow," near

Carysfort Reef light-house, and gradually widens as the longitude increases, until off Rebecca shoal, it extends from 15 to 20 miles outside the 100-fathom curve. It is narrowest at high declination of the moon, at which time it probably begins at some point to the westward of "The Elbow." The direction of the current in this zone is ordinarily tidal in its character, but it is easily overcome by an abnormal current caused by differences in atmospheric pressure within and without the Gulf of Mexico.

Crossing the Stream from Havana, a fair allowance for the average current between the 100-fathom curves, is $1\frac{1}{10}$ knot per hour for a 5-knot speed of vessel.

A vessel rounding Cape San Antonio from the southward will find an eddy current from the Straits of Florida setting along the Colorado Reefs at a high declination of the moon. Thirty miles off shore it will be setting to the northward and eastward.

The current in the Santaren Channel is irregular in direction and very weak. In the St. Nicholas Channel and Old Bahama Channel the direction of the current depends upon the relative elevations of water in the Straits of Florida and Atlantic, and consequently flows in either direction for irregular intervals of time.

The subject of temperatures has already appeared incidentally in these pages. So much has been written on the question in times past, and the belief is so widespread at the present day, that the thermometer may be relied upon to indicate the presence of a current, that I wish to particularly accentuate the fallacy of the idea. In the Straits of Florida we have found that the highest average temperature is at the axis of the Stream, but there are times during the month when the sides are warmer than the axis was at some other recent time. Isolated observations are of but little value, for at the same place the variations are great even in an interval of a few days or perhaps hours. All we can say positively is that cold surface water comes from either a polar direction or from a lower stratum. The direction of its flow may be toward any point in the compass.

At Section A the temperatures were the most numerous. They are given in the table below for each month and at each station together with the number of anchorages. Equal value is given to the observations of each anchorage, whether it was 24 hours in duration or 7 days.

Station.	February.		March.		April.		May.	
	No.	Temperature.	No.	Temperature.	No.	Temperature.	No.	Temperature.
		°		°		°		°
1	1	75.80	2	78.77	2	80.04	13	79.98
1½	----	--------	----	--------	----	--------	6	81.61
2	----	--------	----	--------	1	79.80	3	80.52
3	----	--------	----	--------	----	--------	5	80.40
4	----	--------	----	--------	2	79.67	----	--------
5	----	--------	2	78.14	2	78.30	2	79.52

I can see no way of utilizing the thermometer for the purposes of accurate navigation, nor indeed of using it to indicate with certainty that the current is favorable or the reverse. Referring to the table on page 598, it is seen that the surface current at Station 44 was 73°, while at Station No. 6, Section F, it was 77°.5. The current at the first was to the northward and eastward, and at the second to the southward and westward. At Station 4 the current toward the SE. quadrant had an average temperature of 73°.75, NE. quadrant 76°.82, and NW. quadrant 73°.30. In this case it was warmer when flowing toward the northeast. At Station 1, in May, a northeast current had a temperature of 75°.06, and in June, flowing southwest, it was 80°.19. At 15 fathoms depth the temperatures were 74°.39 and 76°.19 respectively, so the phenomenon could not have been due to the immediate action of the sun's heat. The warm water did not extend to 30 fathoms depth, however, and below it was much colder than at any other point in the Section. Any navigator, in rounding Cape Hatteras, upon meeting a temperature of over 80° would certainly conclude that his vessel was in a current setting to the northeast instead of toward the southwest.

The inner edge of the Stream, then, is not necessarily marked by a change of temperature. An abrupt difference may be encountered at the true edge of the current, the cold water may be moving northeast or the warm water may be flowing southwest. It is probable, however, that at about the time of high declination warm water off Cape Hatteras indicates a northeast current, and that at low declination the edge of the warm water has a set in the opposite direction.

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