TOPEX
Observing The Oceans From Space
North America
Europe
Matthew Fontaine Maury
Benjamin Franklin
Africa
South America
EAN
Atlantic Ocean
Alexander Dallas Bache

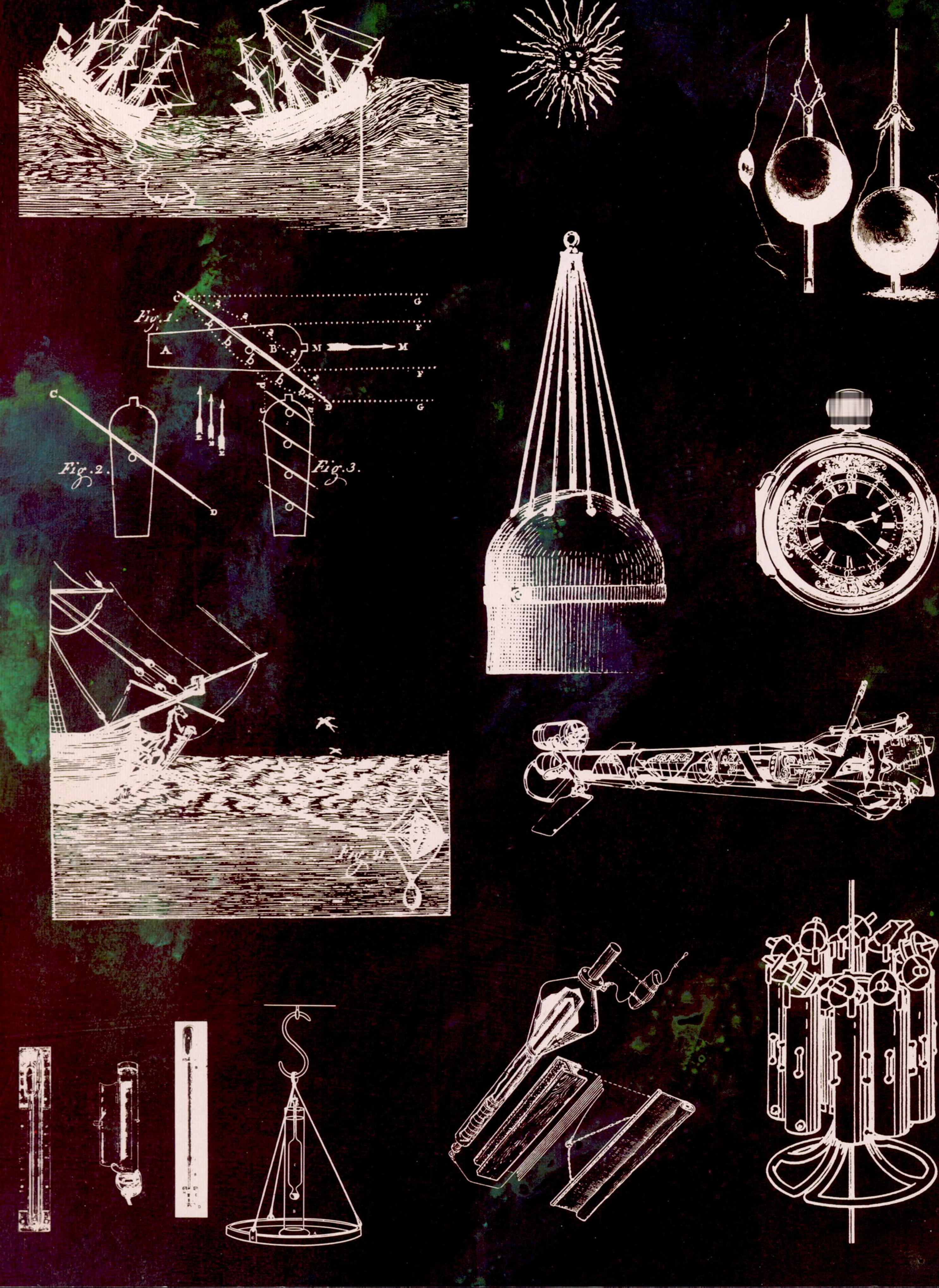


Fig. 1
Fig. 2.
Fig. 3.

PROLOGUE

SAILING SHIPS AND EARLY MEASUREMENTS OF OCEAN CIRCULATION

Wednesday, September 28

We had very variable winds and weather last night, accompanied with abundance of rain; and now the wind is come about westerly again, but we must bear it with patience. This afternoon we took up several branches of gulph weed (with which the sea is spread all over from the Western Isles to the coast of America); but one of these had something peculiar in it.

B Franklin

IN THE YEAR 1768, SIX YEARS BEFORE AMERICAN REBELS WOULD HOLD THE First Continental Congress in Philadelphia, Benjamin Franklin lived in London while serving King George III as Deputy Postmaster General for the American colonies. Great Britain's lords of the treasury complained to Franklin that mail packets sailing from Falmouth, England to New York typically took two weeks longer than merchant ships traveling a longer route from London to Rhode Island. The problem sparked Franklin's curiosity, and his investigation launched the first scientific inquiry into the ocean's circulation.

Franklin went to an expert sailor of those seas, his cousin, Nantucket sea captain Timothy Folger, and asked him to explain why the shorter voyage took so much longer. Folger, familiar with whaling techniques, told of a powerful stream in the sea that whales avoided by swimming only at its edges. The current, he said, emerged from the Florida Gulf and flowed up the New England coastline until it finally turned sharply toward the east.

The Yankee captain offered that if the Falmouth captains would take the advice of American sailors and avoid this stream instead of stemming it, British mail delivery across the Atlantic would be much more prompt. Folger reported that because American whalers "cruise along the edges of the stream in quest of whales," they learned the current's "course, breadth, strength and extent. . . ." Oftentimes, whaling ships would slip into the Gulf Stream, their crews finding themselves quickly separated from fellow whalers as the current carried them away.

Sometimes, Folger said, American whalers met with unlucky British packets stuck in the middle of this Gulf Stream, fighting the current. "We have informed them that they were stemming a current. . . and advised them to cross it and get out of it," Folger recalled. But the British sailors scoffed at the colonists and held their course, thereby adding days to their voyage. As Folger wryly concluded: "They were too wise to be counselled by simple American fishermen."

Franklin's interest in this mysterious current never faltered, and in 1775, he made the first scientific examination of the Gulf Stream as he crossed the Atlantic, sailing from London to Philadelphia. Franklin took temperature readings of the water around the Gulf Stream, marking the readings in a log. The information in the log would later be combined with Captain Folger's knowledge of the current to produce a chart of the Gulf Stream and its surroundings and thereby to serve as a navigational aid.

Part of the legacy that Franklin left to the fledgling United States was his scientific interest in the ocean and its currents. It is said that he regretted being unable to return a hundred years after his death to see how much progress had been made. If he were to return today, a little less than 200 years after his death, he might be surprised to learn that we now have the ability to map global ocean currents in detail by means of a satellite called TOPEX.

HISTORICAL OCEANOGRAPHY

IN 1843, ALEXANDER DALLAS BACHE, GREAT-GRANDSON OF BENJAMIN FRANKLIN, became the second superintendent of the U.S. Coast Survey. The new chief targeted hydrography as an important area of study for the Survey, and in this category were included the practical duties of sounding, marking shoals and rocks, measuring the direction and velocity of inshore currents, and maintaining tide gauge stations. Following in his great-grandfather's footsteps, Bache concentrated the Survey's efforts on the Gulf Stream, and his became the first governmental agency to undertake a sustained oceanographic study of the Gulf Stream, using devices and techniques developed by scientists and sailors over the past century, including soundings, bottom samplings, and temperature, speed, and direction measurements of the current itself.

As Bache's Survey ships crisscrossed the Gulf Stream, his officers took temperature measurements with thermometers that measured maxima and minima at the surface and at several intervals from top to bottom. Their study of ocean temperatures gave the Survey a map of the approximate borders of the Gulf Stream, but to investigate the four-mile-per-hour flow of waters within it required other tools. Survey scientists used drift bottles, which they hoped would be picked up and returned, or calculated the current's speed and direction by the drift of their ship.

At this same time, Matthew Fontaine Maury of the U.S. Navy was organizing a much broader program, the systematic collection of current observations from around the globe. Maury informed his naval colleagues that he was collecting whatever records of currents that might exist in ships' logs.

In his book, *The Physical Geography of the Sea*, Maury wrote of the effectiveness of his efforts:

"They were told that if each one would agree to cooperate in a general plan of observations at sea, and would send regularly, at the end of every cruise, an abstract log of their voyage to the National Observatory at Washington, he should, for so doing, be furnished, free of cost, with a copy of the charts and sailing directions that might be founded upon those observations . . .

"The quick, practical mind of the American shipmaster took hold of the proposition at once. . . So in a little while, there were more than a thousand navigators engaged day and night, and in all parts of the ocean, in making and recording observations according to a uniform plan; . .

Alexander Dallas Bache
1806-1867

and in furthering this attempt to increase our knowledge as to the winds and currents of the sea, and other phenomena that relate to its safe navigation and physical geography."

Sailing ships using Maury's charts dramatically shortened the duration of their ocean voyages.

Maury's work attracted international attention, and an 1854 calculation of the impact of his charts and sailing directions set savings at millions of dollars in Britain alone.

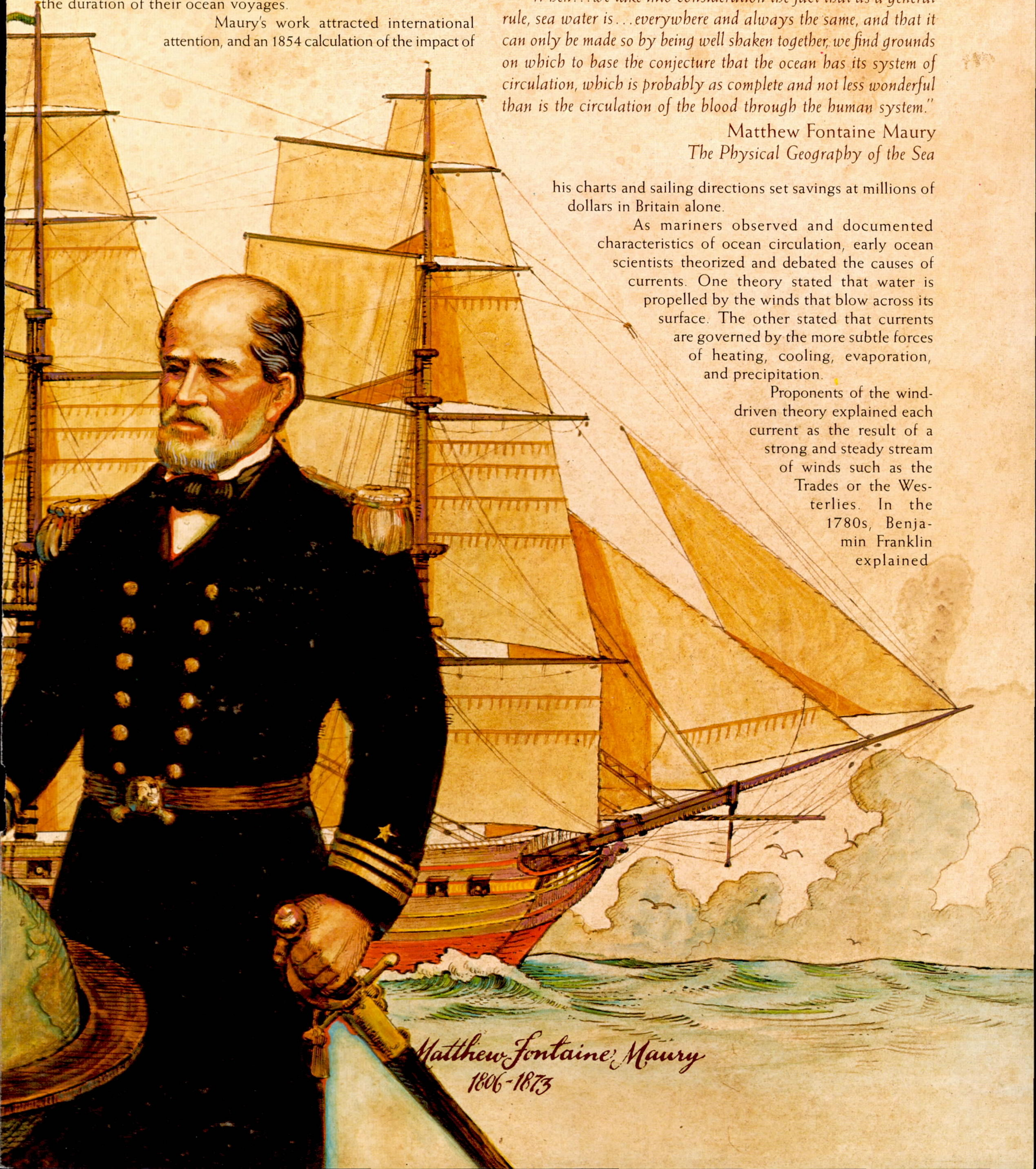
Maury recognized the sea as a single dynamic mechanism, with "a system of ocean circulation as complete, as perfect and as harmonious as is that of the atmosphere or the blood.

"When...we take into consideration the fact that as a general rule, sea water is...everywhere and always the same, and that it can only be made so by being well shaken together, we find grounds on which to base the conjecture that the ocean has its system of circulation, which is probably as complete and not less wonderful than is the circulation of the blood through the human system."

Matthew Fontaine Maury
The Physical Geography of the Sea

As mariners observed and documented characteristics of ocean circulation, early ocean scientists theorized and debated the causes of currents. One theory stated that water is propelled by the winds that blow across its surface. The other stated that currents are governed by the more subtle forces of heating, cooling, evaporation, and precipitation.

Proponents of the wind-driven theory explained each current as the result of a strong and steady stream of winds such as the Trades or the Westerlies. In the 1780s, Benjamin Franklin explained



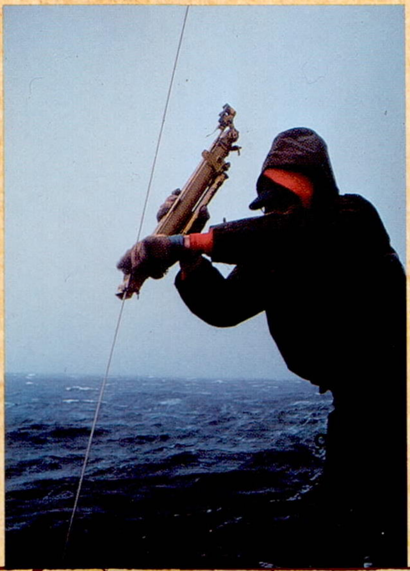
that the Gulf Stream must be caused by the Trades, recalling his observations of a strong wind driving water in a lake so that the water on one side stood several feet higher than normal. He reasoned that huge quantities of water from the mid-Atlantic could be piled against the tropical and subtropical coasts of the Americas. Water flowing westward would be pushed against the land and deflected northward, creating the Gulf Stream.

A second theory was put forth by French physicist Francois Arago in 1836. He contended that differing water densities must cause currents, especially one as powerful as the Gulf Stream. Currents were caused, he said, by unequal solar heating of the Earth, which made polar waters colder and heavier — and tropical waters warmer and lighter. As cold water sank, warm water moved in to fill the gap. This constant sinking and refilling, he said, caused currents.

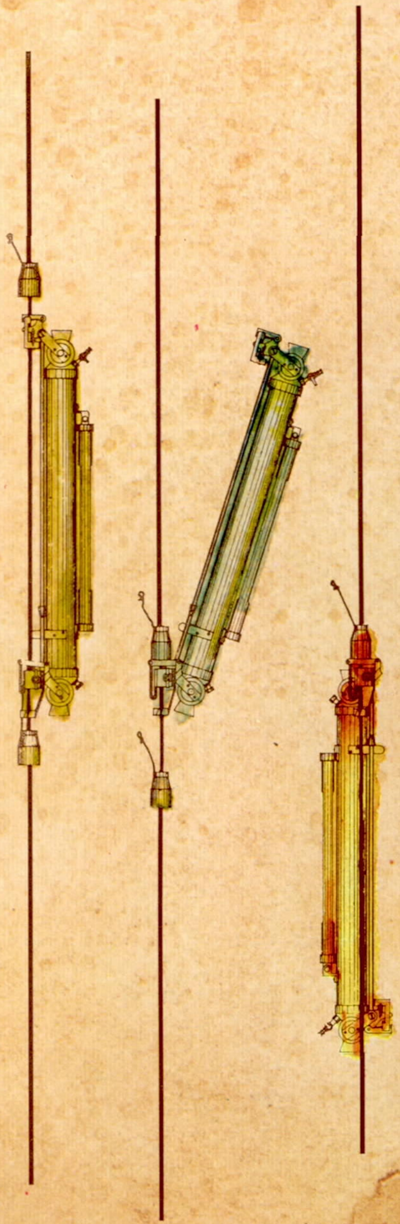
Both schools of thought were partly correct; winds, temperature, and density differences all affect the flow of currents.

According to modern theories, the elementary concept of ocean circulation begins with the sun's energy focused on the Earth's equatorial region. Heated water expands, causing a rise in the level of the sea in the tropics; this mound of expanded water flows from the equator to the north and south; as it moves away, it is replaced by a steady flow of cold water from the deep, which is immediately subjected to the same process.

The wind's most visible effect is in the form of surface waves, but the wind's impact goes deeper than that. As the air brushes the ocean surface, it drags the surface layer of the water along as current. Wind also piles water up against the continents,



Invented by the Norwegian oceanographer Fridtjof Nansen, the Nansen bottle for decades provided the primary means of collecting ocean-water samples and measuring temperature and depth in the ocean.



The 1786 version of the Franklin–Folger Gulf Stream chart, the first map of a major ocean current, was engraved by James Poupard and used as a figure in Benjamin Franklin's article recounting his maritime observations. The chart reflected the oceanographic knowledge accumulated by Nantucket ship captains, including Franklin's cousin Timothy Folger.

A Nansen bottle is shown at left.

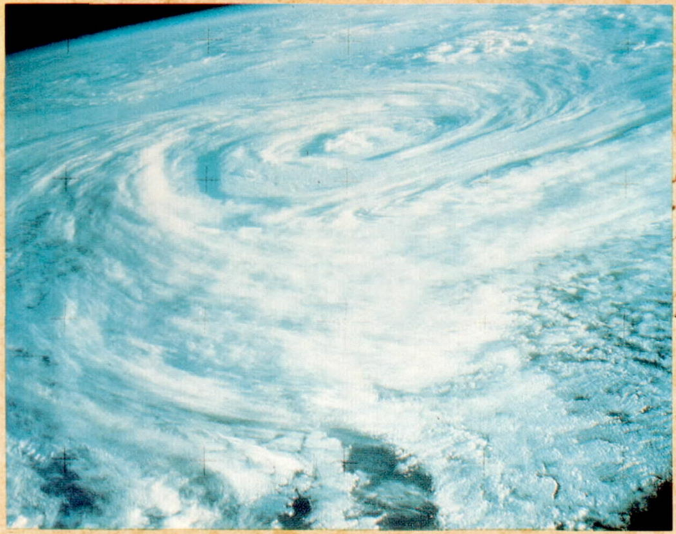
resulting in slopes in the sea surface. Thus, currents produced by the wind and solar heating change the level of the sea, appearing as hills and valleys on the ocean surface.

Whether driven by heat or wind, these currents are further influenced by the Coriolis effect. Due to Earth's rotation, the path of an ocean current is curved to the right in the northern hemisphere, and to the left in the southern.

As a result, on the sea surface, the hills and valleys associated with currents can have height differences as large as 90 centimeters (3 feet), and are collectively known as ocean topography. It is the height of these hills and valleys which TOPEX will measure, and from which a precise map of the ocean's circulation can be made.

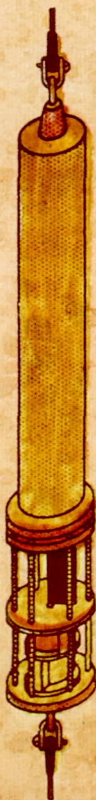
Until TOPEX is launched, however, modern physical oceanographers following the early traditions of the Coast Survey will continue to go to sea in ships, and will still rely upon descendants of those rudimentary methods for obtaining data about ocean currents.

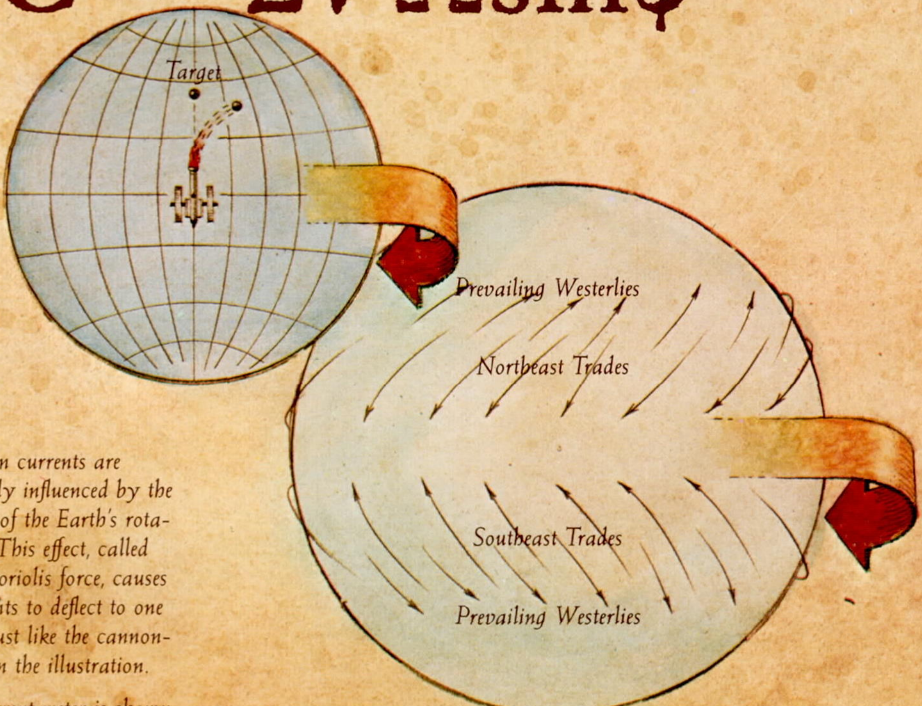
Nansen bottles, cylindrical containers that sample sea temperature and salinity, are typical of tools used in the mid-twentieth century from which data were obtained to model ocean circulation. They have generally been replaced by modern electronic instruments, but measurements are still made from ships in the same manner.



In 1973, NASA's Skylab took this photograph of Hurricane Ava lying off the Mexican coast. Earth's winds have considerable impact on the ocean's currents.

$$C = 2V\Omega\sin\phi$$



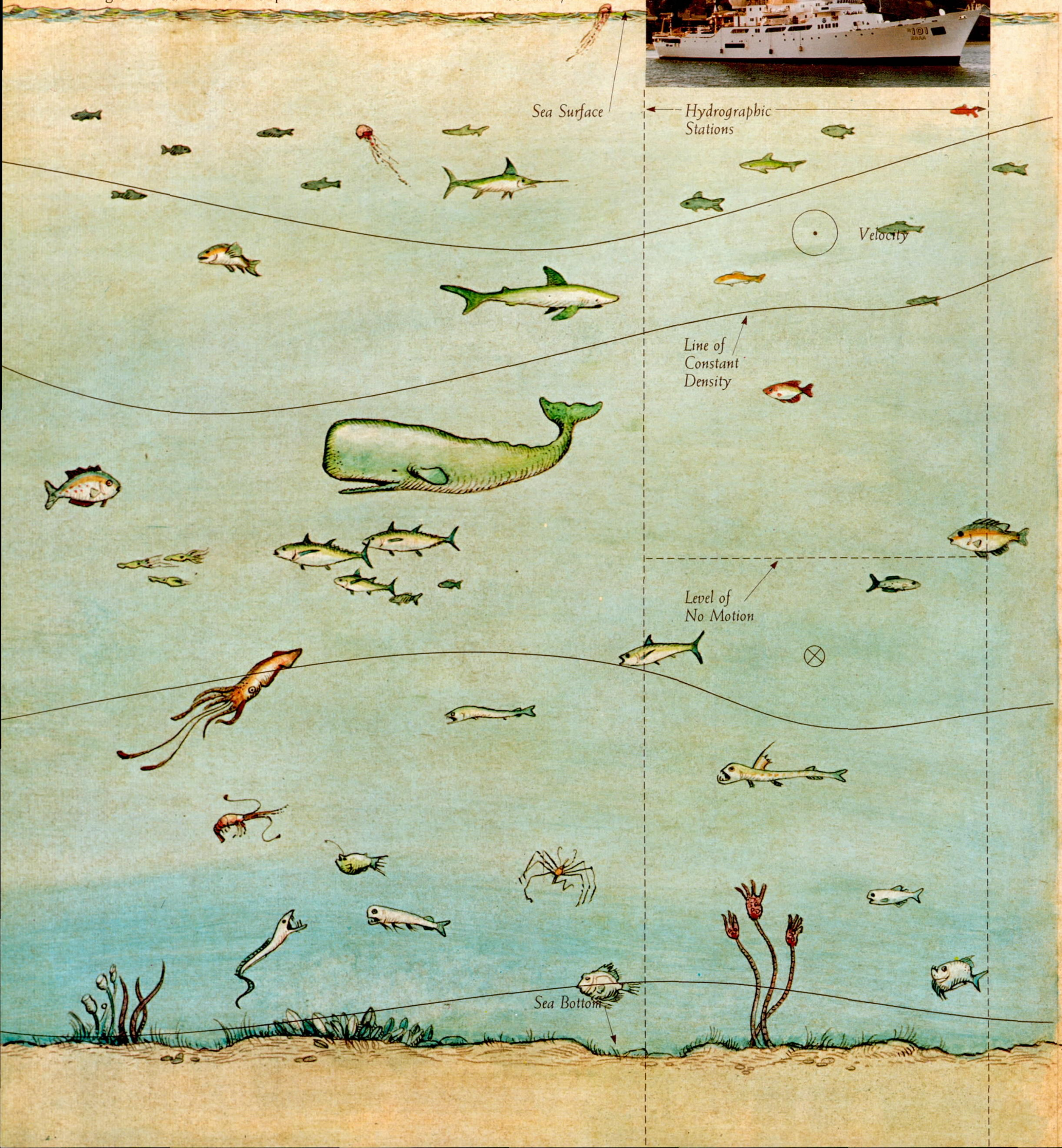


Ocean currents are heavily influenced by the effect of the Earth's rotation. This effect, called the Coriolis force, causes currents to deflect to one side just like the cannonball in the illustration.

A current meter is shown at left.

Samples are usually taken at a number of depths at fixed locations at sea, called hydrographic stations. The devices are lowered in the water on cables and measure water properties from the surface to the bottom. The ship is then moved on to the next hydrographic station.

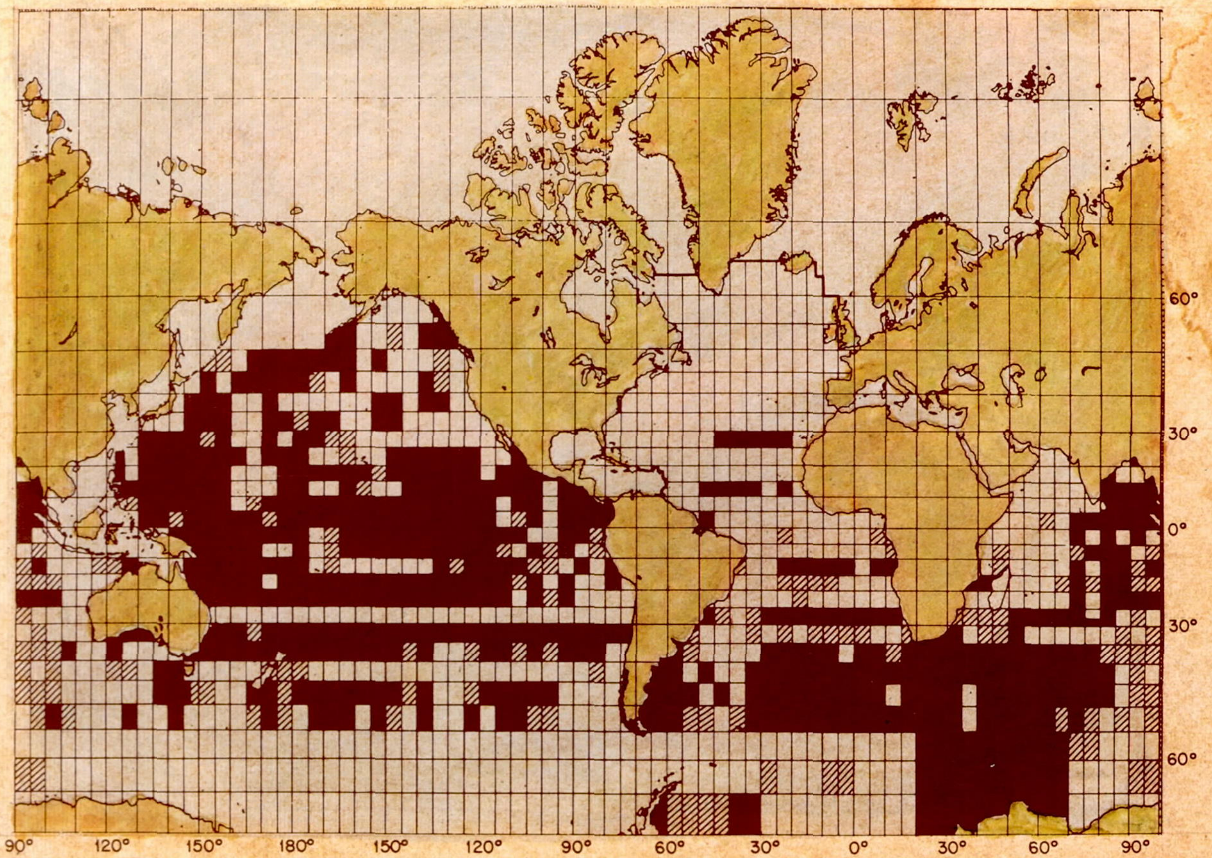
The process is slow, and the regions that can be covered are small compared to the size of the ocean. Still, oceanographic charts are based on the analysis of samples such as these — collected from many ships at different times from different regions and different depths within the sea. From these data, currents can be calculated, but the results produce very general maps of the average arrangement of water masses, implying an average pattern of circulation. The charts do nothing to show how the masses of warm or cold water vary, how they swell or



diminish, nor how their positions change from one season or year to the next.

Current meters, which directly measure the speed and direction of seawater, are a more recent development. Equipped with a propeller turned by the flowing water and with vanes to point out the direction of flow, current meters are often left anchored to the seafloor to be recovered later.

Using current meters, oceanographers began to make more detailed measurements of the ocean circulation, and they consequently discovered a new class of smaller phenomena — mesoscale eddies — which are to the ocean what high and low pressure systems are to the weather of the atmosphere. The discovery that the ocean too has "weather," unappreciated as recently as a decade ago, promises new insights into the fluid dynamics of the ocean, as well as important practical applications, because the eddies, a hundred or so miles across, affect the transport of heat, the speed of ships, the Navy's use of underwater sound, and many other uses of the sea.



While some areas of the ocean are well-explored, other areas are virtually unknown. The black squares do not contain even one high-quality hydrographic station useful for studying ocean circulation. The cross-hatched squares contain at least one high-quality shallow-water station. Only the unshaded areas contain at least one high-quality deep-water hydrographic station.

The ocean, like the atmosphere, has its own weather in the form of localized storms called "mesoscale eddies"—vortices that continually build and dissipate across the ocean surface.

Ocean Circulation And The Atmosphere

Most of Earth's energy received from the Sun is stored and later released by the seas. The ocean currents, in association with the atmosphere, move the planet's heat from one latitude to another, delivering warm water to cold climes, and cold water from the deep to the warm equatorial regions. They moderate temperature and weather fluctuations on the continents, and ultimately determine their climates.

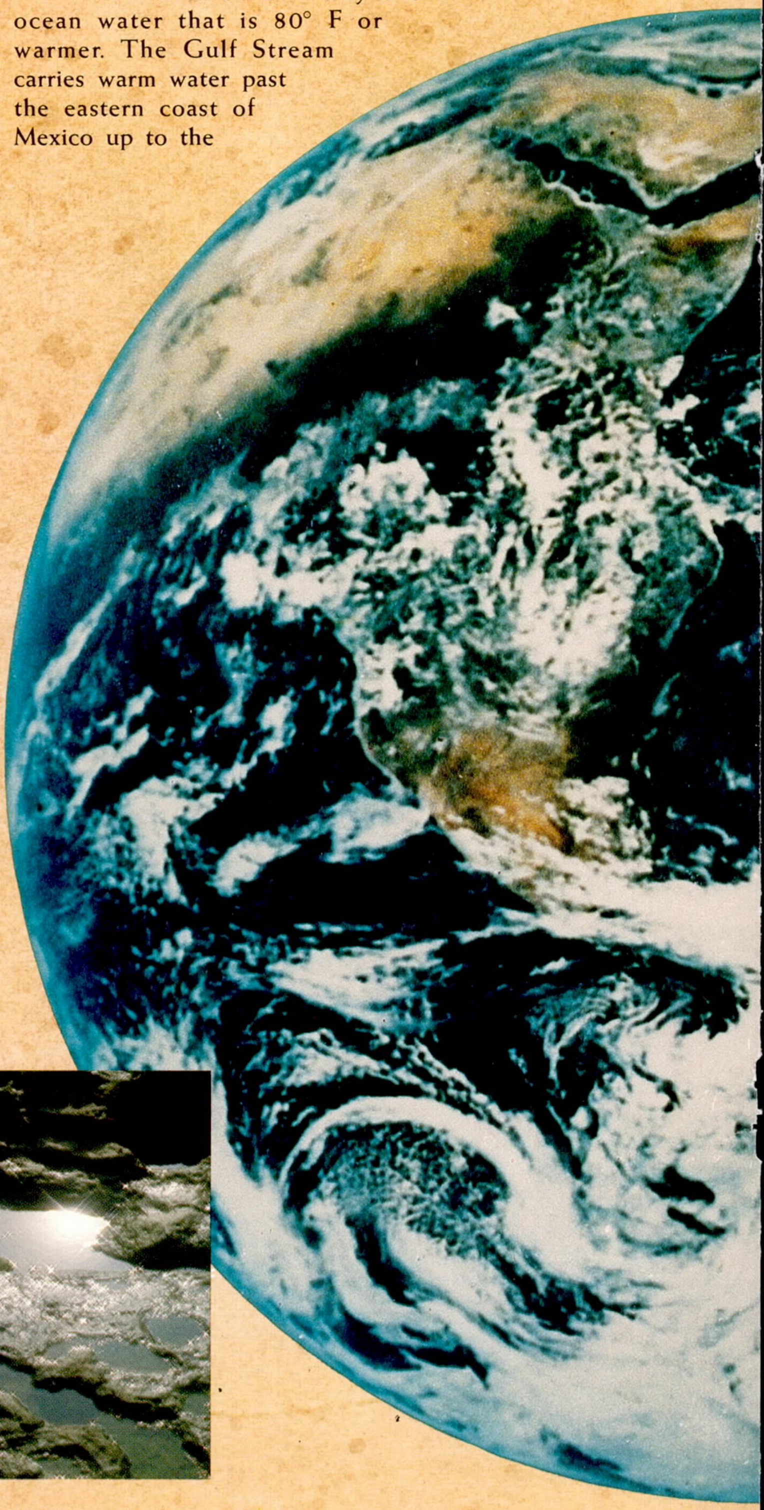
As storms are important to meteorology, eddies are important to oceanography. Eddies transport energy on a local scale, contribute to the large currents, and move the bulk of Earth's absorbed energy.

Just where the oceans release that energy to the atmosphere is a deciding factor in establishing regional climate. For example:

☆ Although Great Britain is at the same latitude as Labrador, its climate is far more moderate, due to the warming influence of the Gulf Stream. Variations in the current may mean variations in the region's climate and weather.

☆ Michigan, located near the center of the continent, experiences temperatures ranging from 100° F to many degrees below zero, while the coastal area of Washington state, situated at the same latitude, but located on the Pacific coast, seldom experiences temperatures outside a range from freezing to 70° F.

☆ Hurricanes form only over ocean water that is 80° F or warmer. The Gulf Stream carries warm water past the eastern coast of Mexico up to the

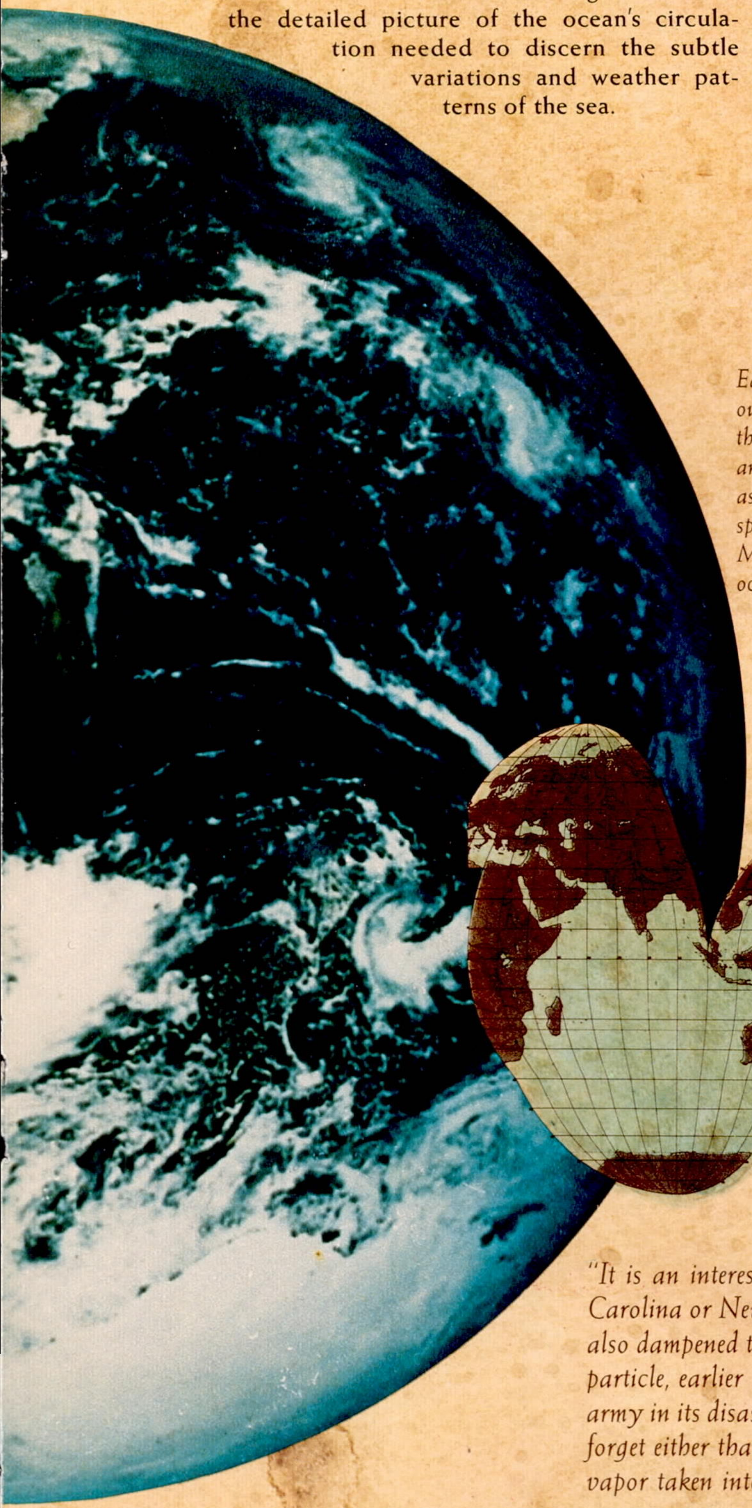


southeastern coast of the United States, where hurricanes are common. By contrast, the Southern California coast is spared hurricanes because of the coastal upwelling of cold water that results from the southward current flowing from the Aleutian Islands.

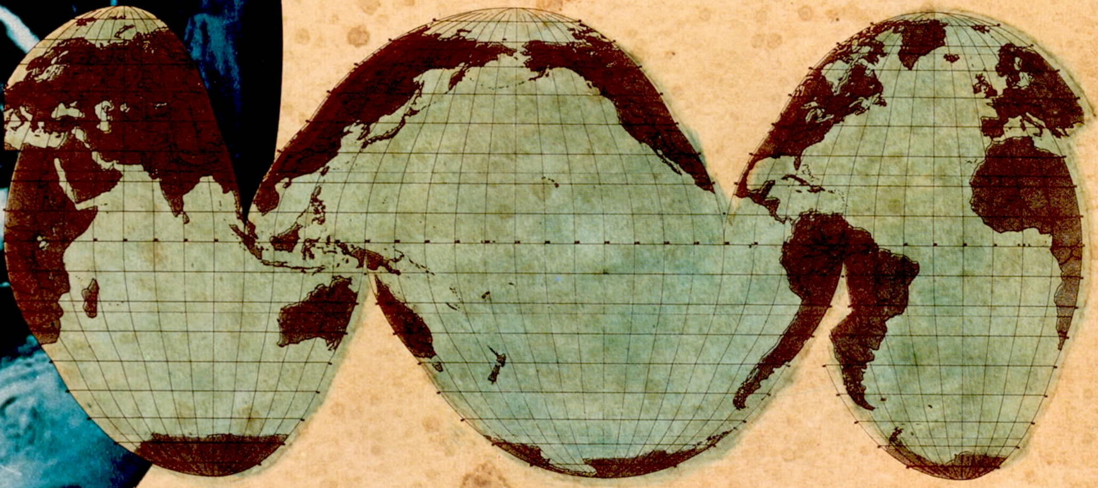
Progress in the study of currents and the ocean's general circulation is limited by the difficulty of making observations. The means to accomplish a global, detailed study of the ocean circulation now exist with satellite altimetry.

An altimeter satellite like TOPEX would give scientists the detailed picture of the ocean's circulation needed to discern the subtle variations and weather patterns of the sea.

This sketch of the ocean's currents, circa 1900, is still being used in texts; yet those currents are variable and much more complex than is indicated by this simple drawing.



Earth, as can be seen in the Apollo photograph of our planet, is a water world. The ocean covers more than 70 percent of Earth's surface, and its circulation and large-scale gains and losses of energy affect all aspects of our environment. Together with the atmosphere, the ocean governs Earth's climate and weather. Map projections which split the continents show the ocean's true expanse.



"It is an interesting thought that a particular particle of water moistening one's toe on a Carolina or New Jersey beach may have engaged in considerable global travel: it may have also dampened the toe of a South Sea islander, and that of a penguin in Antarctica; the same particle, earlier in its travels, may even have contributed to the drowning of the Pharaoh's army in its disastrous attempt to follow the children of Israel across the Red Sea. We need not forget either that the same water may sometimes engage in aerial travel in the form of water vapor taken into the atmosphere by evaporation."

R. E. Coker,
This Great and Wide Sea

Satellite Altimetry

Currents, Eddies, and Other Features of ocean circulation show up as hills and valleys on the sea surface. If this topography can be discerned, so can the details of ocean circulation.

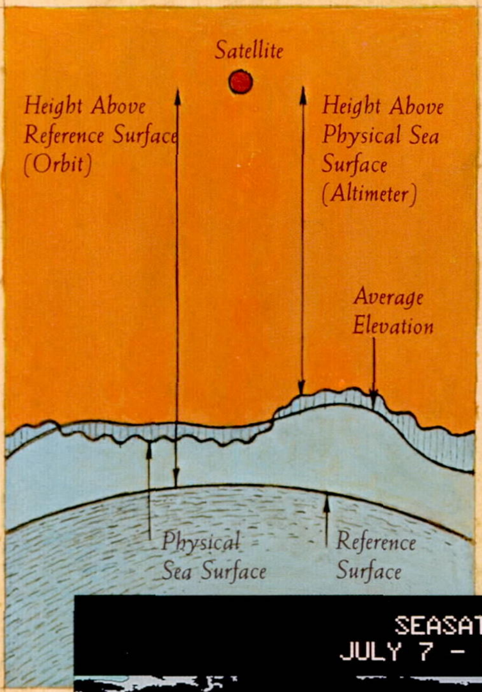
A radar altimeter aboard a satellite can provide this information by sending short pulses of energy toward the ocean surface, which are bounced back and captured by the altimeter antenna. The time required for the round trip, and the intensity and structure of consecutive returned signals, form a record of the elevation of the sea surface and the height of its waves, and of the wind speed directly beneath the spacecraft.

Data from previous NASA satellites, Seasat and Geos-3, have demonstrated that radar altimetry can observe, in detail, the global ocean topography. Such an observation cannot be made from ground- or ocean-based platforms.

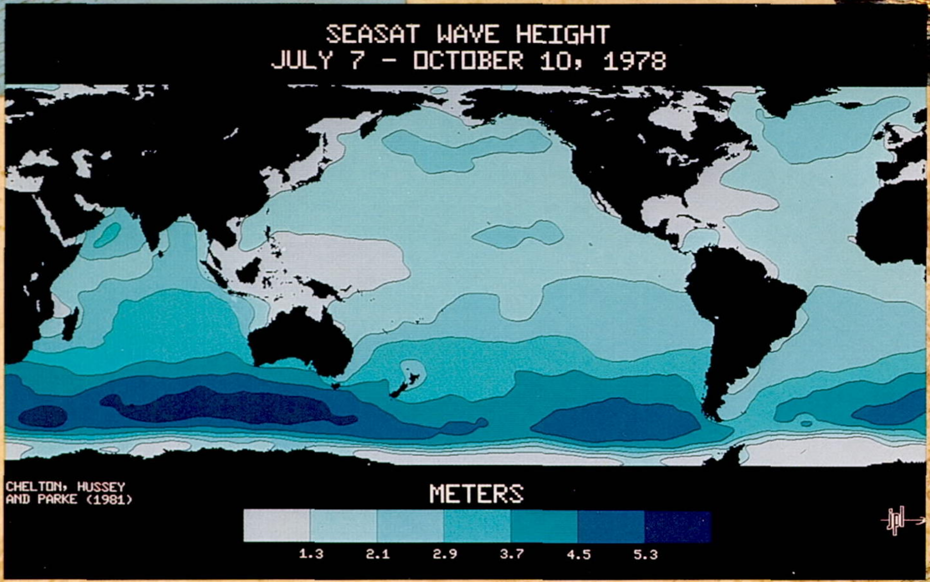
There is a complication: the Earth's nonuniform gravity field, due to the uneven arrangement of the Earth's mass, also produces changes in the surface of the ocean topography. Since both circulation and gravity affect ocean topography, scientists need to be able to separate the effects. If they have accurate measurements of Earth's gravity, they can subtract out its effect.

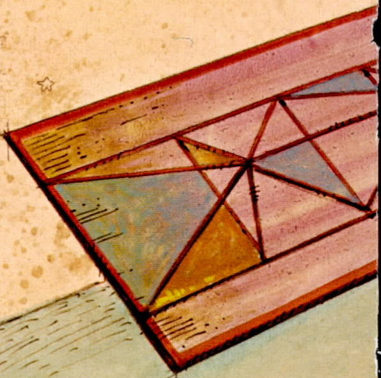
If they do not have gravity measurements, they can look at changes in the surface topography over a period of time. Because the effect of gravity is constant, the resulting changes in the topography reflect changes in the ocean circulation.

TOPEX would provide a series of topographical maps of the elevation of the sea surface. These maps would not only reveal the overall behavior of the sea surface, but also smaller-scale changes and fluctuations.



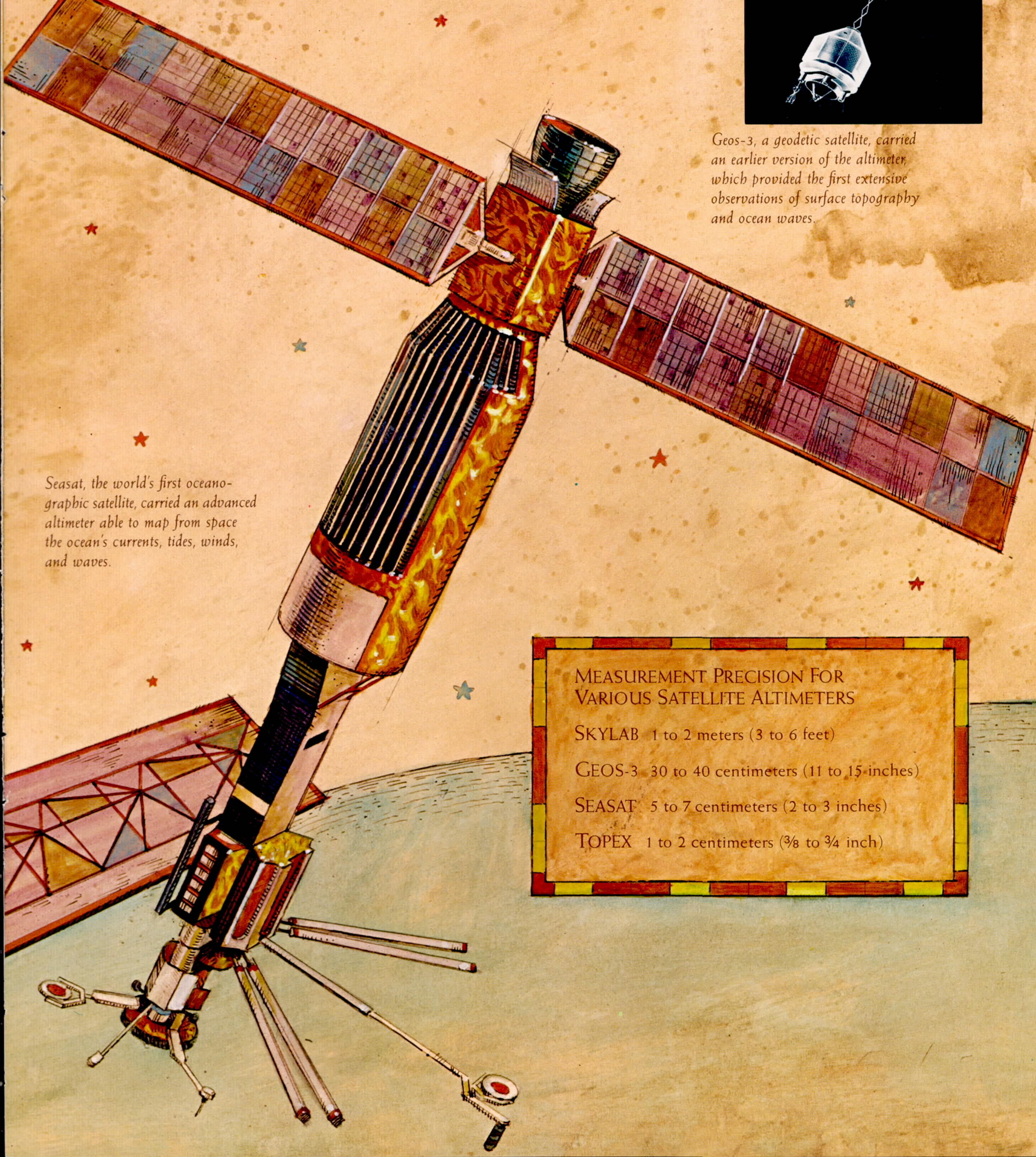
The basic geometry of taking ocean-surface measurements with satellite altimetry. Typically, the vertical departure of the sea surface from its average elevation is 1 to 2 meters while the average elevation of the sea surface globally varies from 100 to 200 meters relative to a reference surface.





The wave-height picture constructed from Seasat data is believed to be the first accurate global wave map ever produced.

Geos-3, a geodetic satellite, carried an earlier version of the altimeter, which provided the first extensive observations of surface topography and ocean waves.



Seasat, the world's first oceanographic satellite, carried an advanced altimeter able to map from space the ocean's currents, tides, winds, and waves.

Measurement Precision For Various Satellite Altimeters

SKYLAB	1 to 2 meters (3 to 6 feet)
GEOS-3	30 to 40 centimeters (11 to 15 inches)
SEASAT	5 to 7 centimeters (2 to 3 inches)
TOPEX	1 to 2 centimeters (3/8 to 3/4 inch)

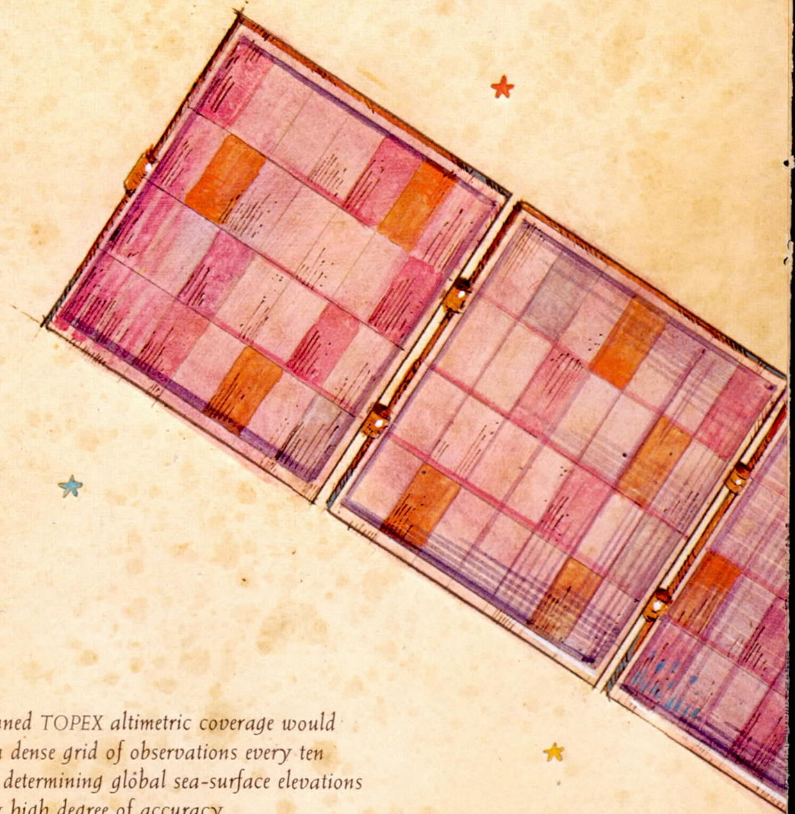
The Topex Mission

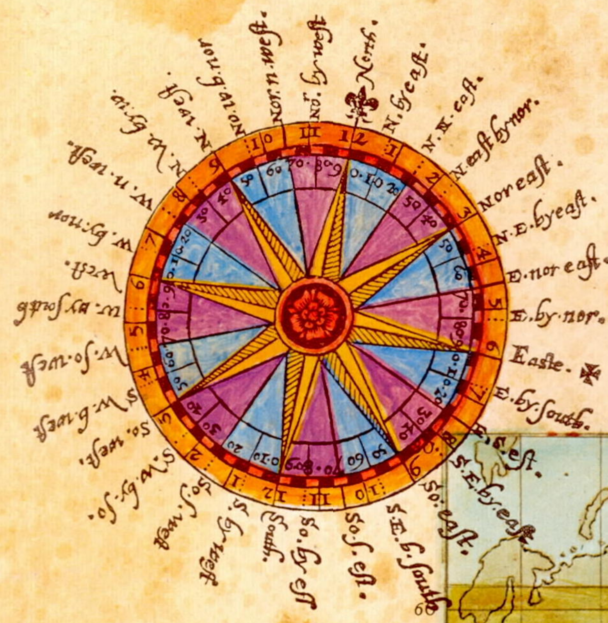
Mission Plans Call For the TOPEX satellite to be carried to Earth orbit by the Space Shuttle in the late 1980s and to operate for a three-to-five-year period. Its principal instrument is a radar altimeter.

The usefulness of altimetric data is dependent upon the accuracy with which the satellite's position is known. To achieve the accuracy needed for studies of the ocean circulation, the orbit of the TOPEX satellite, circling at an altitude of 1,300 kilometers (800 miles) must be known with an accuracy of 5 centimeters (2 inches). This will be achieved through special radio and laser tracking systems.

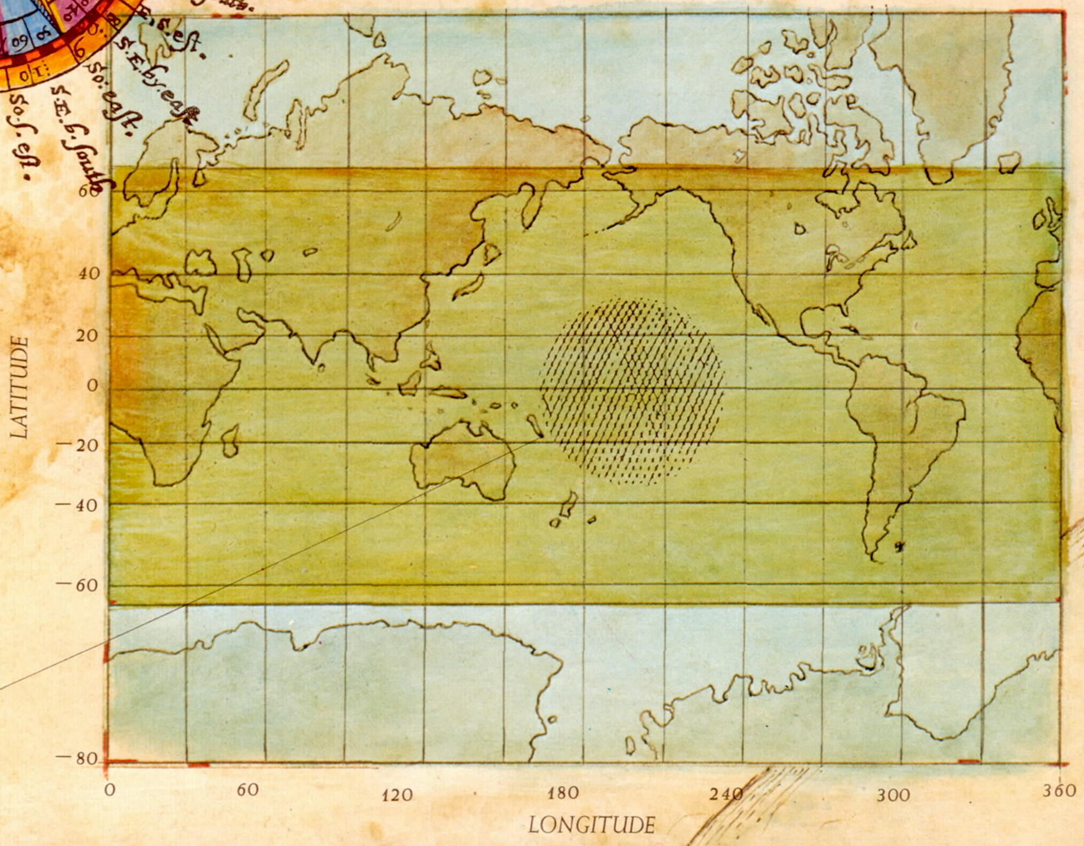
The TOPEX altimeter is designed to operate at two frequencies; these measurements taken together will help correct for interference caused by electrons in the ionosphere.

A second instrument, a microwave radiometer, measures radiation emitted from water vapor between the satellite and the ocean. The measurement will be used to correct for any interference in the altimetric data caused by water vapor.





The planned TOPEX altimetric coverage would provide a dense grid of observations every ten days for determining global sea-surface elevations to a very high degree of accuracy.

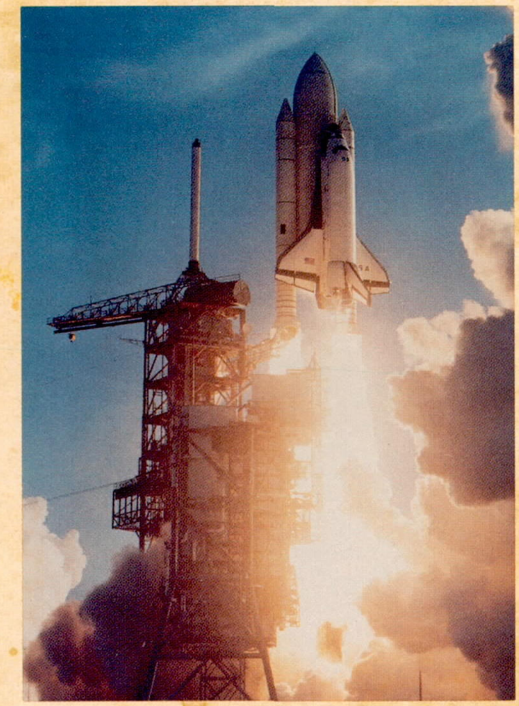


Section of Ground-Track Pattern

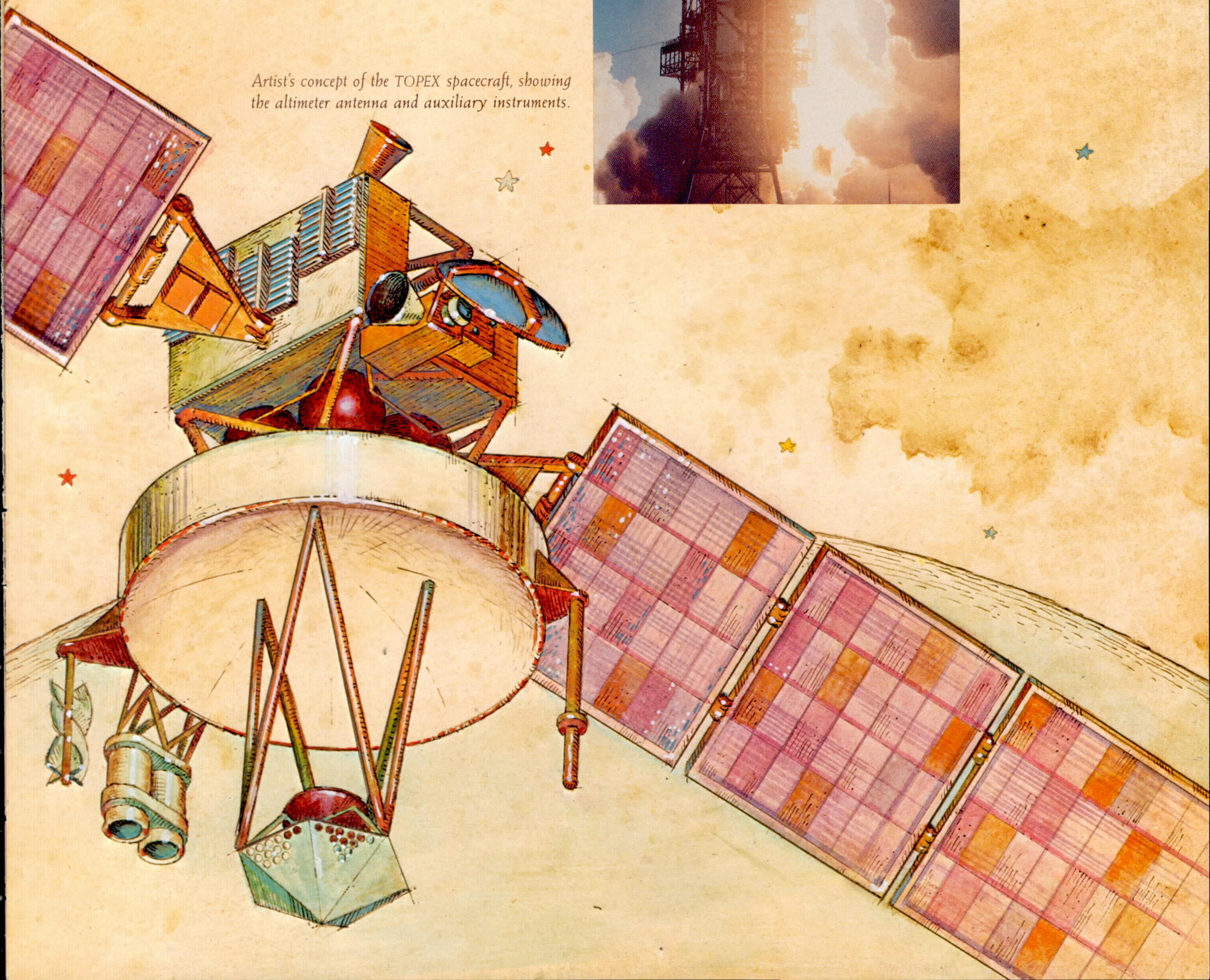
In order to observe changes in a current's character, TOPEX will measure the same area of ocean every 10 days. To be successful in mapping the overall ocean circulation, TOPEX data will be combined with the latest information regarding ocean density and with theories of ocean dynamics to produce for the first time an accurate model of how the global ocean circulation, from the surface to the seafloor, changes over time. For this purpose, TOPEX is designed to coincide with an international oceanographic effort to study the ocean's general circulation. The worldwide oceanographic community, under the auspices of the International Council of Scientific Unions, the United Nations Educational, Scientific and Cultural Organization, and the World Meteorological Organization, is planning the World Ocean Circulation Experiment (WOCE) to be conducted in the late 1980s.

Oceanographers around the world will participate in the WOCE, conducting conventional surface and subsurface studies of the seas. Their observations and comprehensive experiments conducted from oceanographic vessels will be coordinated by the WOCE. TOPEX will play a key role.

Late in the decade, the NASA Space Shuttle will carry TOPEX into orbit from Cape Canaveral, Florida.



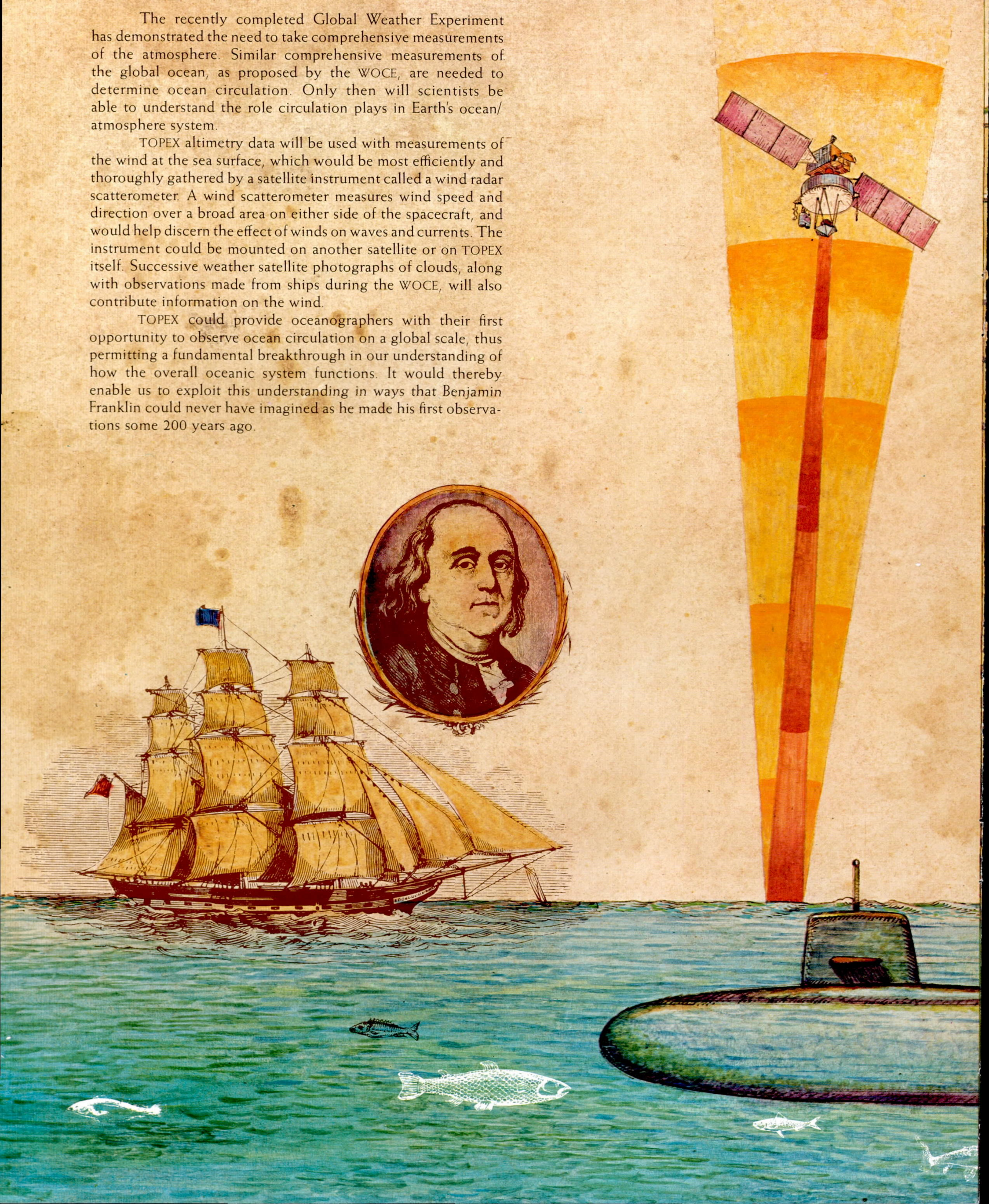
Artist's concept of the TOPEX spacecraft, showing the altimeter antenna and auxiliary instruments.



The recently completed Global Weather Experiment has demonstrated the need to take comprehensive measurements of the atmosphere. Similar comprehensive measurements of the global ocean, as proposed by the WOCE, are needed to determine ocean circulation. Only then will scientists be able to understand the role circulation plays in Earth's ocean/atmosphere system.

TOPEX altimetry data will be used with measurements of the wind at the sea surface, which would be most efficiently and thoroughly gathered by a satellite instrument called a wind radar scatterometer. A wind scatterometer measures wind speed and direction over a broad area on either side of the spacecraft, and would help discern the effect of winds on waves and currents. The instrument could be mounted on another satellite or on TOPEX itself. Successive weather satellite photographs of clouds, along with observations made from ships during the WOCE, will also contribute information on the wind.

TOPEX could provide oceanographers with their first opportunity to observe ocean circulation on a global scale, thus permitting a fundamental breakthrough in our understanding of how the overall oceanic system functions. It would thereby enable us to exploit this understanding in ways that Benjamin Franklin could never have imagined as he made his first observations some 200 years ago.



Benefits And Applications

Considered as a purely scientific endeavor, TOPEX is of great importance because it would provide the first comprehensive, global insight into ocean dynamics. But beyond this lie a wide range of other benefits:

☆ Safe navigation along coastal areas depends upon an accurate knowledge of tides, tidal currents and surface winds. Supertankers, for example, frequently cross hazardous shoal areas (like the approach to the English Channel) only slightly deeper than their drafts. Their safety in many areas is reliant upon incomplete tidal forecasts based on sparse, shore-based data. Satellite altimetry measurements will provide an improved basis for accurate tidal predictions for deep water and coastal regions.

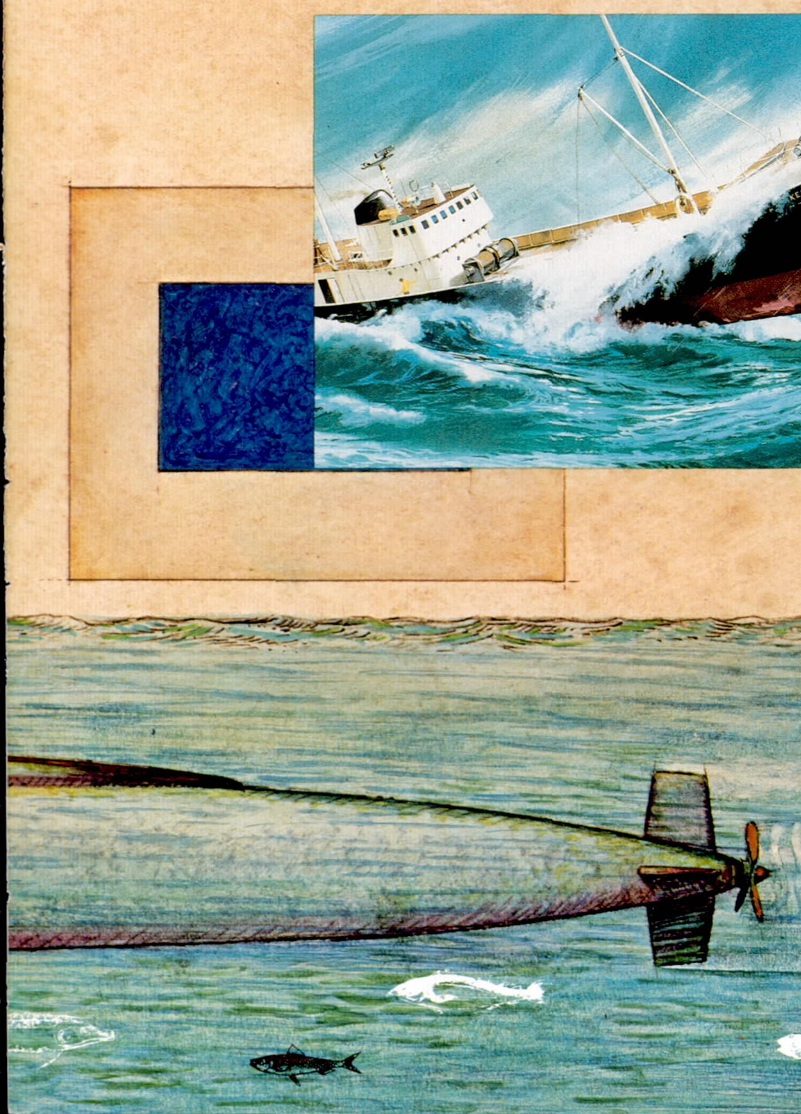
☆ Offshore structures and facilities must be designed to withstand severe wave and current surges. The placement and architecture of oil rigs, drill ships, mining operations, coastal nuclear power plants, and ocean-thermal energy conversion facilities all require reliable estimates of wave and current climates. Altimetric observations over a period of years will provide information for improved planning in the location and construction of such facilities.

☆ TOPEX altimetry measurements of the sea topography will also aid geophysicists in studying Earth's interior because the sea topography is determined by the distribution of mass within Earth as well as by ocean currents.

☆ The concerns of oceanographers often coincide with those of the U.S. Navy, and TOPEX will provide data to help answer pressing questions concerning our maritime defense. TOPEX will help discern areas of acoustical variation where opposing or diverging currents interact with one another and distort or obscure submarine sonar. Improved surface current and wave information will lead to the faster and more economical operation of commercial and naval vessels.

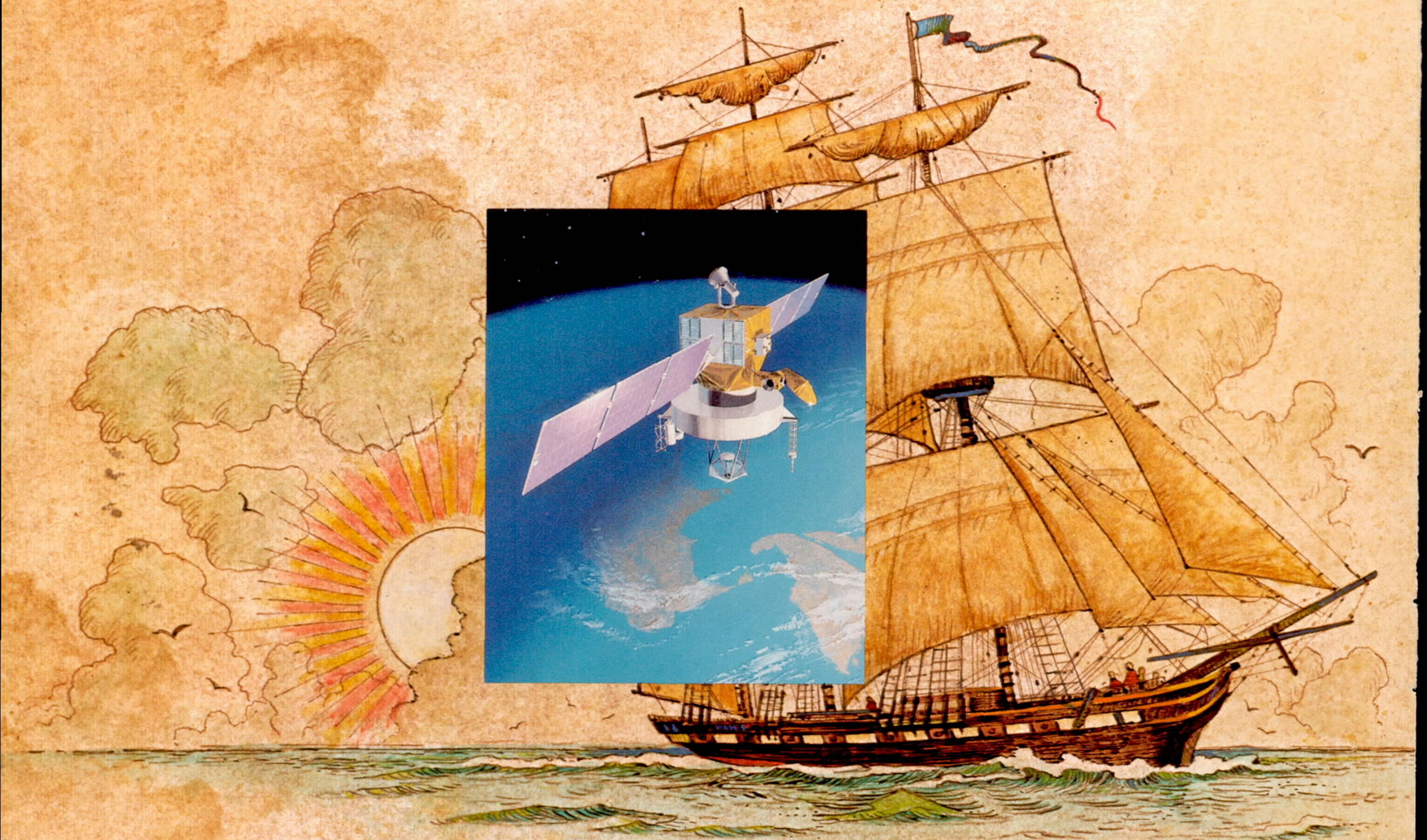
☆ The safety of seabed disposal of dangerous wastes depends in part on the rate at which currents will carry potentially dangerous leakage from disposal sites toward fishing grounds and coastal areas.

☆ A significant increase of carbon dioxide in the atmosphere, due to the burning of fossil fuels and deforestation, is a potential threat to our climate. This increase may be moderated by the uptake of carbon dioxide by the ocean. The rate of uptake depends, in part, on ocean currents. Knowing how the ocean circulates could help scientists determine what kind of a threat increased carbon dioxide in the atmosphere may pose for Earth's future.



TOPEX PROJECT CHARACTERISTICS

Dual-frequency altimeter	Measures the height of the satellite above the sea surface, wave height and wind speed directly beneath the spacecraft; corrects for influence of free electrons in the ionosphere.
Nonscanning radiometer	Corrects for the influence of water vapor on the altimeter measurement.
1,300-km (810-mi) orbit; *65-degree inclination*	Height minimizes the effects of atmospheric drag and slightly reduces the influence of errors *in the measurement of Earth's gravity field. Inclination provides high crossing angles between* ascending and descending tracks at mid-latitudes, while providing good coverage of world's oceans.
10-day repeat orbits	Makes it possible to study ocean variability even where the gravity field is poorly known.
Laser or radio tracking of satellite for orbit determination	Provides information necessary to calculate an accurate orbit.
Three-to-five-year mission	Minimum lifetime of satellite, necessary to observe the annual and long-term variability of the ocean.
Launch from Space Shuttle	Delta launch compatibility also planned.



"The moisture and varying temperature of the land depends largely upon the positions of the 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 circumstances or plant an unusual amount of food for their stock."

Lt. John E. Pillsbury,
The Gulf Stream, 1891


The Figure of the Quadrant
Fig. 20.
Fig. 18.
Fig. 17.
Fig. 16.
Fig. 10.
Discovery net
Hensen net
Nansen net open
Nansen net closed
canvas
fine mesh net nylon
after

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