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RADAR ALTIMETRY AND GLOBAL CLIMATIC CHANGE

The circulation of the Earth's fluid envelope, the coupled two-fluid atmosphere-ocean system, is central to climate dynamics. Ocean circulation, fluxes, variabilities, dynamic processes, biogeochemical fluxes, and ecosystem dynamics are high-priority areas of research for scientists studying climate dynamics and global change. The Geosat Follow-On program is designed to provide measurements of mesoscale circulation over a ten-year period, using radar altimeters mounted on lightweight, low-cost satellites. This article examines the Geosat Follow-On altimeter as a climate research tool and discusses its application to North Atlantic Ocean climate studies and to experiments designed to clarify processes associated with biogeochemical cycles and ecological dynamics.

INTRODUCTION

Climatic Changes

Understanding our planet's climate, its fluctuations and trends, is perhaps the most challenging and important problem facing Earth scientists today. Only recently have the basic disciplines of Earth science achieved sufficient maturity to allow feasible studies of the fundamental processes that maintain and alter the mean state or climate of the Earth.[1]

Natural variations in climate occur on interannual to geological time scales. Moreover, chemical changes induced by human activity are now known to be occurring in the environment, which in turn may lead to changes in mean temperature and other climatic properties. Industrial and other pollution, deforestation, and agriculture are the primary causes of these changes. Atmospheric carbon dioxide (CO_2) is now increasing at a rate of 1% per year. Together with other increasing greenhouse gases, CO_2 is generally believed to be warming the globe at a rate that will lead to a 3°C increase in the Earth's mean temperature by the end of the next century. It is not obvious what climatic effects will accompany this change. Vigorous research efforts, especially in meteorology and oceanography, are being undertaken in climate dynamics and global change. A broad-based U.S. program[2] is part of the major and increasing international cooperative research effort[3] needed to provide a rational basis for managing the future of our planet.

Climate science is inherently interdisciplinary and involves observational, experimental, theoretical, and modeling components. Although we may be most interested in the atmospheric climate over our inhabited land areas, the entire complex multicomponent climate system that determines the atmospheric climate must be studied. The physical climate system that couples atmospheric, oceanic, cryospheric (ice), terrestrial, and biospheric components is shown schematically in Figure 1. Many internal dynamic processes, exchanges, and fluxes play important roles in this system. Incoming short-wavelength solar radiation provides the energy source for the climate system, which is maintained in near-steady-state equilibrium via long-wavelength back-radiation. This back-radiation is modulated by albedo factors, water vapor, cloud processes, and atmospheric gases (Fig. 1). Determination of the concentration and distribution of a gas or element in the atmosphere requires the determination of its concentration, distribution, and cycling throughout the entire Earth system, which is called its biogeochemical cycle.

The biogeochemical cycle for carbon must be understood and quantified to define the processes that control atmospheric CO_2 concentration and to predict the fate of CO_2 arising from human activities. A schematic of the CO_2 cycle is shown in Figure 2.

Estimates of flux rates and integrated storage are also indicated in Figure 2. The ocean contains about 50 times more carbon than the atmosphere, and has a complex internal cycle involving organic and inorganic processes. The ocean is believed to be taking up about 40% of the CO_2 generated by human activities, but the processes regulating the CO_2 balance between air and sea are not yet well understood.[4] Since the marine biological component contributes to the maintenance and evolution of the physical climate system, predicting the effect of global change on marine ecosystems and animal abundances is also crucial if marine resources are to be

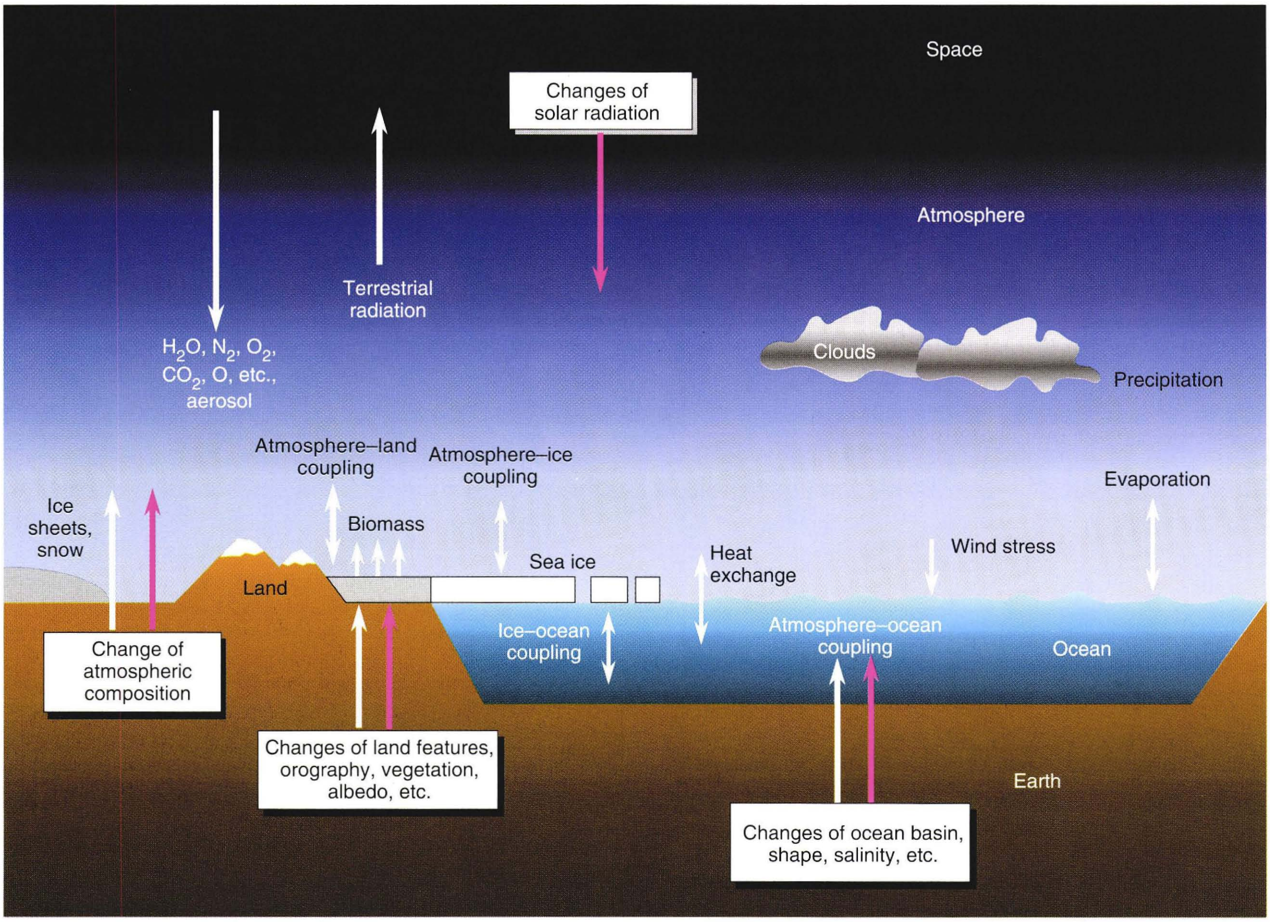

Figure 1. Schematic diagram of coupling between oceans, atmosphere, and land. (Reprinted, with permission, from Ref. 1, p. 18: © 1975 by Global Atmospheric Research Programme, Geneva.)

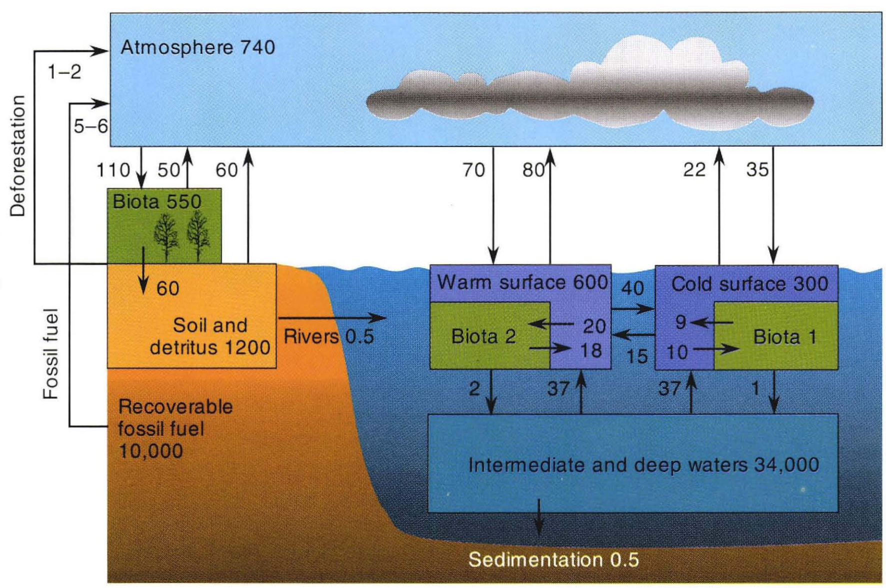

Figure 2. Schematic diagram of the Earth's biogeochemical cycles. Numbers indicate units of 10^{15} grams of carbon per year. (Reprinted, with permission, from *From Pattern to Progress: Strategy of the Earth Observing System*, Vol. II, Earth Observing System [EOS] Science Steering Committee Rep., NASA, Washington, D.C., p. 45, 1989.)

managed rationally. Such predictions require an understanding of the fundamental processes by which the physical environment contributes to the patterns and variabilities of production and the abundance of marine animal populations.[5]

Climatic Research Priorities

The dynamics of the climatic system are complex, and determination of the dominant processes and sensitivities is a necessary but formidable task. The U.S. Global Change Research Program has made a comprehensive list of research priorities within the broader context of research on global change.[2] The program's priorities for fiscal year 1992 are shown in Figure 3. Studies of climatic and hydrologic systems, biogeochemical dynamics, and ecological systems and dynamics rank first, second, and third in importance, respectively. Ocean circulation and fluxes and physical biogeochemical interactions are crucial components of all three areas of research. In climatic and hydrologic systems research, studies of ocean circulation and heat flux are ranked second in importance among the six research topics designated.

The circulation of the Earth's fluid envelope, the coupled two-fluid atmosphere-ocean system, is central to climate dynamics. The gaseous atmosphere is nearly transparent to incoming sunlight, but the nearly opaque liquid ocean absorbs short-wavelength radiation within the first few tens of meters of water depth. Since equatorial regions receive more heating per unit of surface area, a poleward temperature gradient results in both the ocean and the atmosphere. This gradient, which is transverse to the direction of the force of gravity, causes meridional (vertical-latitudinal) cellular motions, with warm water and air rising and cold fluid descending. These cellular motions (Hadley cells), pictured schematically in Figure 4, transport heat.

The Earth's daily rotation provides strong deflecting forces (Coriolis accelerations), and zonal winds and currents are the predominant flows in the atmosphere and ocean. Geometry and topography modify the real responses as well as important internal dynamic processes, including the instabilities that produce weather systems, waves, eddies, and meandering. The two-fluid problem is fundamental; fluxes (e.g., momentum and heat) are continuous at their interfaces, but the air and the sea have quite different properties. The ocean has a much greater heat capacity and much slower time constants (except near the equator) than the atmosphere. For time scales of days to weeks, the atmosphere is the dominant fluid; however, for time scales of months to millennia, the ocean dominates.

Ocean Circulation and Its Implications

The actual thermohaline convective circulation of the Earth's global ocean is not equatorially symmetric as depicted in Figure 4. There is a single dominant cell, called the "conveyor belt,"[6,7] shown in Figure 5, which

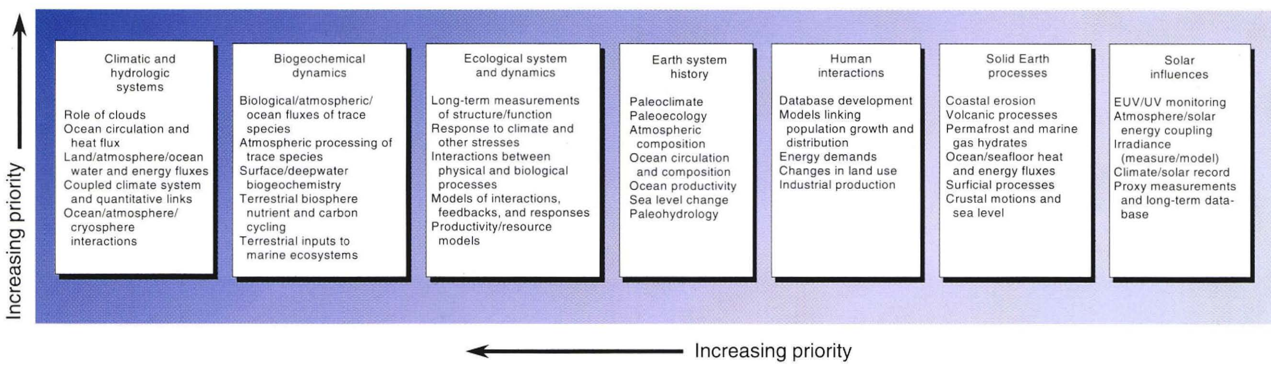

Figure 3. Research priorities of the U.S. Global Change Research Program. Arrows indicate the direction of increasing priority. (Reprinted, with permission, from Ref. 2., p. 6)

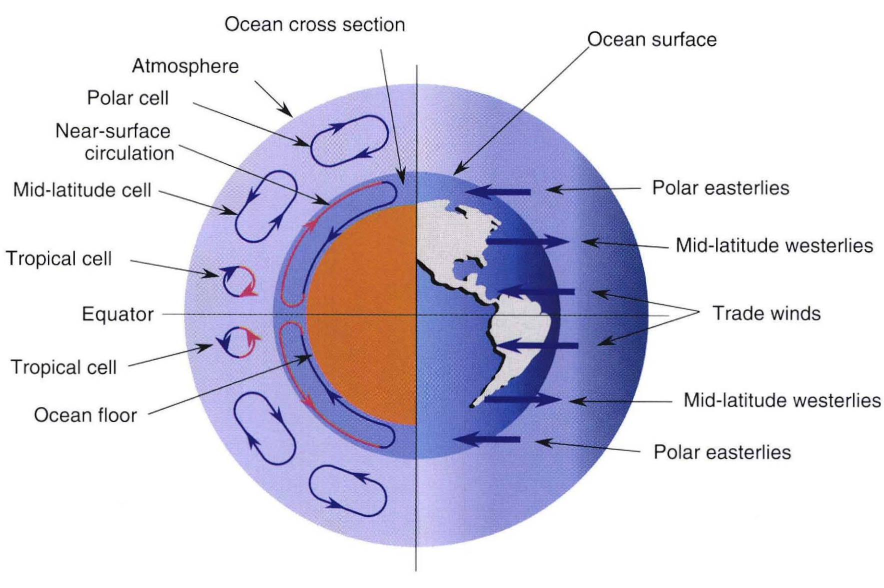

Figure 4. A system of prevailing currents in the atmosphere and oceans carry heat from one part of the planet to the other. The forces that drive them are provided by incoming solar energy and the spinning motion of the Earth. (Adapted from *Reports to the Nation on Our Changing Planet*, 1, *The Climate System*, University Center for Atmospheric Research Office for Interdisciplinary Studies, Boulder, Colo., p. 9, Winter 1991.)

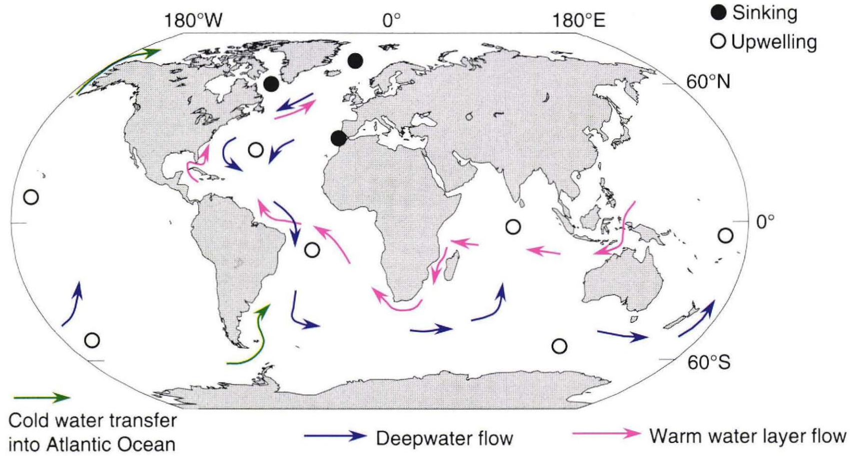

Figure 5. The conveyor belt of global thermohaline circulation. Surface water sinks in the North Atlantic and flows through the world's oceans. (Reprinted, with permission, from Ref. 7, p. 5040: © 1986 by the American Geophysical Union.)

also depicts the major basins through which the conveyor belt flows; the exact location, width, extent, and volume of the flow are subjects of much research.

The North Atlantic plays a particularly important role in the circulation of the ocean because surface water sinks in the Arctic seas (north of 60°). Winter storms act on highly saline water to produce North Atlantic Deep Water via vertical convection. Rising takes place in the Pacific and Indian oceans. As the water moves in the upper branch of the conveyor belt, that is, in the main thermocline regions of the Pacific, Indian, and Atlantic oceans, it is warmed and evaporates. Salinity in the North Atlantic is significantly higher than in the North Pacific. The poleward heat flux in the North Atlantic associated with this flux of seawater is very important climatically. A significant portion of this warm, salty seawater flux is carried by the Gulf Stream system.

The Gulf Stream system and the northern branch of the Gulf Stream extension are climatically significant not only because of their contributions to the oceanic thermohaline circulation, but also because of direct, intensive, air-sea interactions. The interannual sea-surface temperature anomaly for the North Atlantic has been analyzed[8] using the empirical orthogonal function (EOF) technique, which reveals independent recurrent patterns and orders them according to their relative energies. The first EOF, containing the most energy in the sea-surface temperature anomaly, is shown in Figure 6. It indicates a strong maximum in the western North Atlantic off the Canadian coast.

This North Atlantic pattern has been correlated with interannual atmospheric pressure changes and with European weather anomalies.[9] The North Atlantic was the site of the first major Joint Global Ocean Flux Study (JGOFS) biogeochemical field program[4] and will be the location of the first major Global Ocean Ecosystem (GLOBEC) Dynamics program.[5]

Because the oceans are a vital part of the climatic system, their circulation, fluxes, variabilities, dynamic processes, biogeochemical fluxes, and ecosystem dynamics are high-priority areas of research for investigators of climate dynamics and global change. Real-time nowcasting (where the model is applied to present conditions) and forecasting are also crucial for efficient and effective experiments at sea.[5,10,11] The research and monitoring associated with all these oceanographic activities can benefit enormously, both qualitatively and quantitatively, from altimetric data in general, and from Geosat Follow-On (GFO) altimetric data in particular.

The APL-Harvard University-Rutgers University altimetric validation program has developed a synthetic geoid for the Gulf Stream (region G in Fig. 7),[12] which makes possible direct, quantitative use of Geosat-type altimetric data and allows the data to be assimilated into models.

Geosat validation has also been carried out in Iceland and in the vicinity of the Project Athena and JGOFS experiments (Fig. 7). Development of a synthetic geoid for the western North Atlantic is under way, with plans to extend it into all the North Atlantic regions shown in Figure 7.

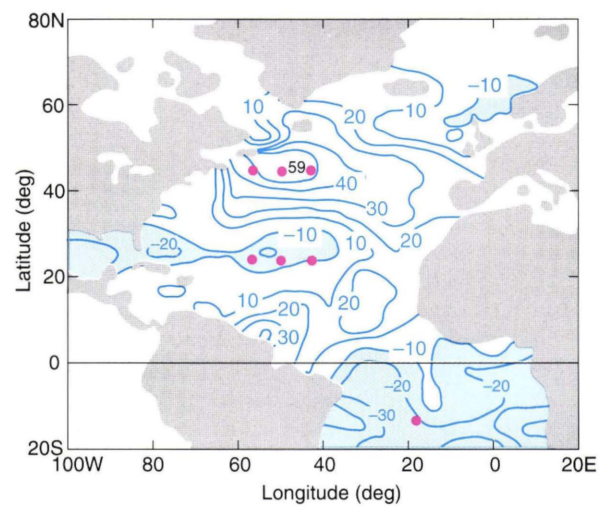

Figure 6. Distribution of the correlation coefficients (percent) of the amplitude of the first empirical orthogonal function for a sea-surface temperature interannual anomaly. Note the positive maximum at about 45°N, 40°W. (Reprinted, with permission, from Ref. 8, p. 972.)

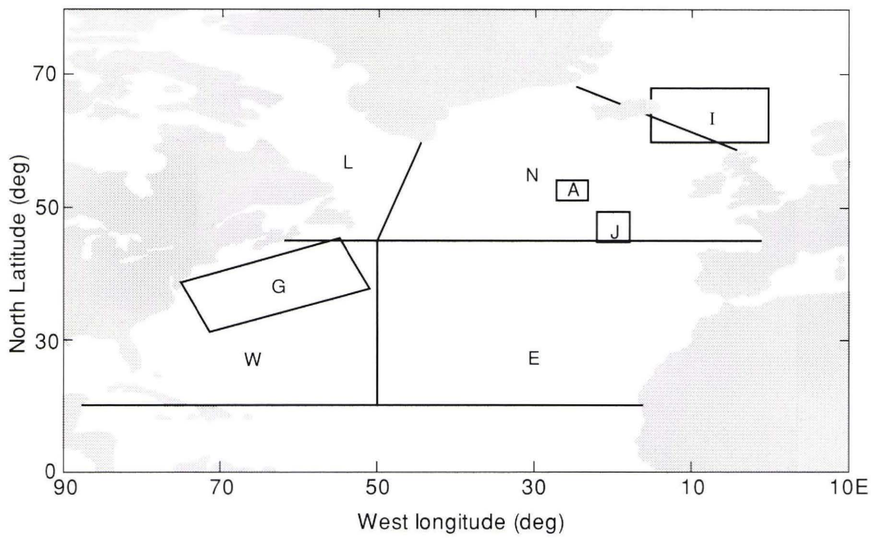

Figure 7. Chart showing research areas of the North Atlantic. Previously studied areas are the Gulf Stream (G) and Iceland (I), and the Project Athena (A) and Joint Global Ocean Flux Study (J) areas. New regions are the western North Atlantic (W), eastern North Atlantic (E), northern North Atlantic (N), and the Labrador Sea (L).

THE SPACEBORNE RADAR ALTIMETER AS A CLIMATE RESEARCH TOOL

Spaceborne radar altimeters make three fundamental measurements relevant to understanding and monitoring processes associated with long-term climate change:

1. The range between the satellite and the ocean or land surface.
2. The radar return power (cross section) from the surface beneath the satellite.
3. The shape of the pulse after reflection from the surface.

The range between the altimeter and the surface below is the primary measurement and can be used to monitor both the topography of the ocean surface associated with the water's circulation and the topography of ice sheets. Ocean surface wind speed, as inferred from radar cross sections, can be used to monitor wind speed globally.[13] The ice/water boundary can be estimated from changes in return radar pulse shape.

Geosat Results and Climate Applications

Geosat data have already been used to make geophysical measurements for use by the U.S. Global Change Research Program. This program places special emphasis on the use of the altimeter to measure sea-surface height and the ice edge.

Mesoscale Variability and Circulation. One of the key challenges in using altimetric height data is to discriminate between sea-surface height changes caused by oceanographic dynamics and height changes due to other causes. In the absence of ocean motion, the sea surface would conform to a surface of constant gravitational potential (i.e., a geopotential surface). This surface is often referred to as the marine geoid. Undulations in the geoid are not generally known well enough to correct altimeter height signals for this effect.

The problem is circumvented by making use of the fact that the geoid is stationary in time. When altimetric height data are averaged along collinear tracks, oceanographic height signals tend to average out, leaving an estimate of the geoid signature along the ground track. This averaged signal is then subtracted from the altimetric height data for an individual track, yielding an estimate of the ocean's dynamic topography. In regions such as the Gulf Stream, where the ocean circulation has a mean height signature, removal of the mean height data also removes much of the mean oceanographic signal.

A more sophisticated approach to calculating dynamic topography involves the computation of a synthetic geoid. The mean altimetric height signal is calculated as before, but the mean oceanographic signal is also computed from a circulation model initialized and constrained by observational data. Subtraction of the mean ocean signal from the mean altimetric height signal yields a synthetic geoid along the ground track. The difference between the synthetic geoid and an individual collinear track of altimetric data is a measurement of absolute dynamic topography. The conception and development of this technique and the appropriate implementation software are direct consequences of the Geosat experience.[12,14,15]

The use of altimetric height data, processed using the synthetic geoid technique, to measure sub-basin–scale and mesoscale circulation features has been validated. Figure 8A shows the absolute dynamic height measured across the Gulf Stream compared with dynamic heights derived from measurements by aircraft-launched expendable bathythermographs (AXBT), the extension of those measurements below the base of the thermocline, and a temperature–salinity relationship. The large change across the Gulf Stream, approximately 1 m in height, agrees with measurements from AXBT data to better than 10 cm root-mean-square (less than 10% of the signal amplitude). These data and related results demonstrate that the synthetic geoid method works extremely well in measuring the Gulf Stream's synoptic-scale and mesoscale signals. Similar lines of research were undertaken by Mitchell et al.,[16] who also developed geoid estimates as well as synthetic temperature profiles.

Figure 8B shows the absolute dynamic height measured in the Project Athena region (northeast Atlantic Ocean). The Athena experiment was a joint French and U.S. effort demonstrating that, in a region of zero mean

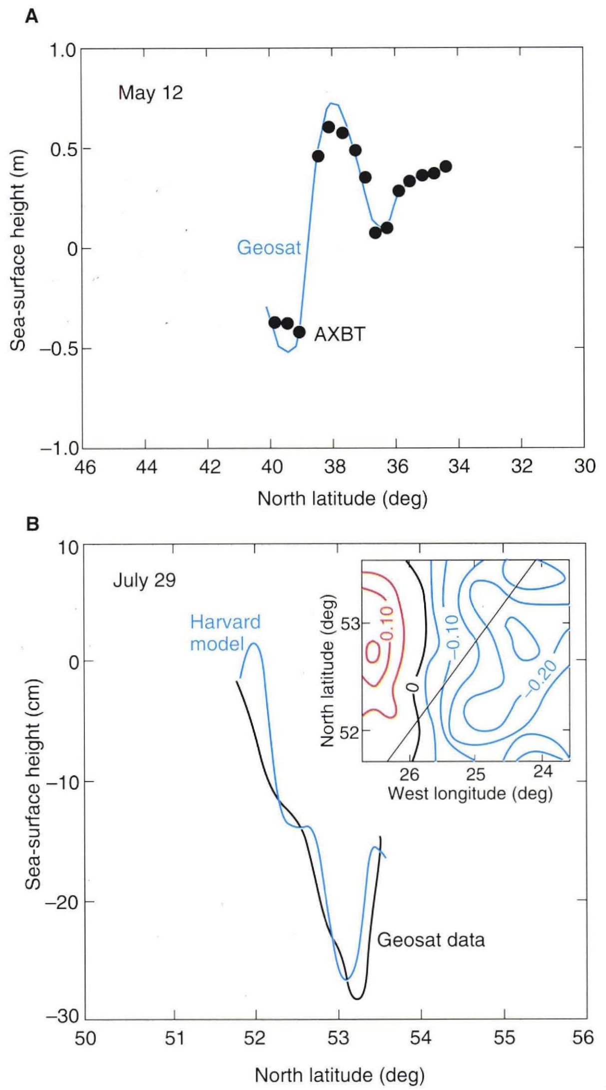

Figure 8. Plots of sea-surface height using Geosat altimetric data. **A.** The sea-surface height (solid curve) determined from the Geosat altimeter for a pass on 12 May 1987, in the Gulf Stream region. The dots are heights computed from aircraft-launched expendable bathythermographs (AXBT) dropped along the Geosat ground track nineteen hours later. **B.** A comparison of sea-surface height determined from the altimeter minus a mean sea surface and the sea surface derived from a nowcast model in the Project Athena region. Inset shows the ground track of the altimeter over the nowcast of the Athena experimental area.

circulation, the mean altimeter height signal equals the synthetic geoid and can be used to compute dynamic ocean topography. The Athena results showed very good agreement between the dynamic height measured by altimeters and the dynamic height measured from *in situ* sensors.

Measurement of mesoscale and sub-basin–scale ocean circulation patterns is extremely important in monitoring the processes of climatic change. For example, the annual phytoplankton bloom in the North Atlantic is a crucial part of the Earth's biogeochemical cycle, and important aspects of its causes and dynamics are dependent on mesoscale circulation patterns.

The JGOFS experiment, conducted from April to August 1989, demonstrated that altimetric data could be used in near real time to aid ships at sea in deploying measurement resources and in interpreting measurements in the light of the local circulation patterns.[11] The goal of this experiment was to measure the dynamics associated with the annual phytoplankton bloom in the North Atlantic. After processing at APL, Geosat height data were sent to Harvard University, where nowcasts were prepared and forwarded in near real time to ships at sea. The capability of near-real-time altimetric data was thus demonstrated with JGOFS. The requirements for similar near-real-time data for model assimilation, needed to meet operational requirements in climate monitoring, have been clearly stated in the research plans of GLOBEC[17] and the Atlantic Climate Change Program Science Plan.[9]

Interannual Variability. Since changes in mean sea level will accompany any global warming, measuring the interannual variability of sea level is an important aspect of research in global change. By combining Geosat altimetric heights measured along collinear tracks and at track crossover points, Miller and Cheney[18] computed time series of sea-level measurements for the tropical Pacific. Comparison with tide-gauge data showed an accuracy of better than 1 cm for zonal averages. These data were used by Miller and Cheney[18] to obtain the first detailed basin-wide measurement of meridional transport of surface water in the tropical Pacific during El Niño. Wyrtki and Mitchum[19] point out the need for coupling Geosat data with tide-gauge bench marks, thus increasing their relative accuracies.

The importance of long-term altimetric data in measuring global sea-level change was reflected in the recommendations of the Woods Hole Sea-Level Workshop,[20] which concluded that continuous altimetric measurements of the ocean to study long-term sea-surface topography and ocean circulation are essential.

Ice Edge. Using parameters based on the shape of the return Geosat altimeter waveform, Hawkins and Lybanon[21] developed an ice index, which flags the presence of ice in the footprint of the altimeter. Using this index, they were able to validate the Geosat altimeter ice-edge detection capability. The variation of the ice edge over the course of years is an indicator of changes in mean atmosphere and water temperature as well as ocean circulation. The GFO altimeter will record those waveform parameters necessary to determine the ice-edge index.

The Geosat Follow-On Altimeter

The goal of the GFO program is to provide, over a ten-year period, radar altimetric height data for the measurement of mesoscale circulation, which has tactical relevance for the U.S. Navy. To keep launch costs at a minimum, GFO satellites are to be lightweight (less than 400 pounds) and low-power.[22] These satellites will employ a Geosat-class radar altimeter, but the GFO satellite system will have the following additional capabilities not provided by the Geosat satellite:

1. Each GFO satellite will include a radiometer for measuring water vapor. This will minimize the contamination caused by the variation in radar path length associated

with atmospheric water vapor and will help extend the horizontal spatial scales over which altimetric height data can be used to measure ocean circulation.

2. The GFO altimeters will have a precision orbit-determination system that will permit removal of the orbit signature in the altimetric height data over basin scales, extending the horizontal spatial scale over which dynamic topography can presently be measured.

3. The GFO altimeters will fly along the same ground track that Geosat did during the exact repeat mission. This will permit immediate use of the existing synthetic geoid to remove the height signal associated with the Earth's geopotential surface from the altimetric data.

ALTIMETRIC DATA APPLICATIONS FOR CLIMATIC STUDIES

Although some differences are found between the Geosat and GFO satellites, the specific applications of altimetric data for climatic research discussed in the following sections will rely only on validated Geosat capabilities. Enhancements to the GFO system will probably increase the applicability of altimetric data to climatic research.

Ocean Circulation and Climate

Owing to the ocean's enormous heat capacity, and the large fluxes of heat across the air/sea interface, ocean circulation is significantly involved in variations in climate. Both models and empirical data have indicated that the Atlantic Ocean plays a unique and crucial role in climatic variability.

Warm surface water is transported via a pathway in the sea from the world's oceans to the Labrador and Greenland and Norwegian seas, where it sinks and returns once again to those seas as an abyssal current. This phenomenon, illustrated in Figure 5, is called the thermohaline conveyor belt and is driven by deepwater convection in the northern North Atlantic Ocean.

The saline waters of the North Atlantic that flow into the Arctic seas are cooled. The cooling increases the density of the fluid, causing the water to sink to considerable depths, forming a water mass called the North Atlantic Deep Water. The North Atlantic Deep Water flows southward, in an intensified, deep western boundary current that hugs the coast of North America. To replace the water lost through this process, the warmer saline waters of the South Atlantic flow northward to high northern latitudes, bringing water from the Southern Hemisphere to the Northern Hemisphere and resulting in a large transport of heat from both hemispheres toward the North Pole.

South of the North Atlantic Deep Water boundary current is a deep northern recirculating gyre (Fig. 9) that is confined between the New England Seamount Chain and the Grand Banks.[23] This gyre is bounded on its south by the northward flowing Gulf Stream. The northern recirculating gyre transports about 20 to 30 Sv (Sverdrup) ($1\ \text{Sv} = 1 \times 10^6\ \text{m}^3/\text{s}$) of water westward, north of the Stream, and then returns eastward. Recent results from moored arrays that were part of the Abyssal Circulation Experiment (ABCE) and the Synoptic Ocean Prediction (SYNOP) experiment have further documented the northern recirculation gyre (N. G. Hogg, personal communication, 1992). Although in the mean this gyre appears smooth, the region containing the gyre is a high-variability area, replete with eddies and filaments.[24] The importance of these eddies in driving the northern recirculation gyre[25] and the gyre's role in the total thermohaline circulation are poorly understood.

After the North Atlantic Deep Water leaves the Northern Hemisphere, it spreads southward into the South Atlantic and ultimately moves via the Antarctic Circumpolar Current into the other oceans.[7] The return upper-surface flow is derived either from Pacific water, with the introduction of Antarctic Intermediate and sub-Antarctic mode water in the southwest Atlantic, or from the warm, salty thermocline of the Indian Ocean. The process for the Indian Ocean is primarily forced by large pools or eddies of Agulhas water (the current that flows westward around South Africa) that drive into the subtropical South Atlantic. Each of these mechanisms has a unique impact on the Atlantic meridian heat and freshwater fluxes. When the water reenters the Arctic seas and sinks again,

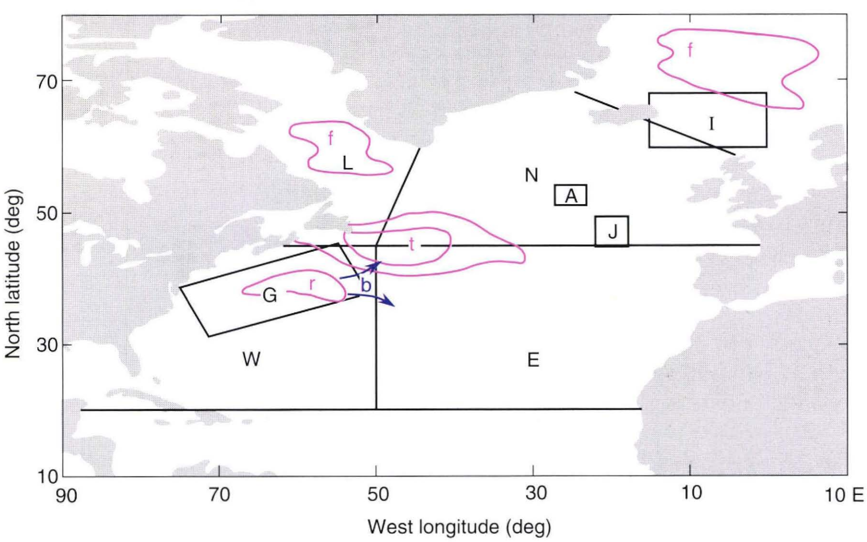

Figure 9. Approximate locations of the formation area for North Atlantic Deep Water (f), the Gulf Stream bifurcation area (b), the northern recirculating gyre (r), and the area of teleconnection between the atmospheric climate and sea-surface temperature (t). Letters indicating research areas are the same as in Figure 7.

it has completed a global circuit on the thermohaline conveyor belt.

There is no counterpart to this sinking phenomenon in either the Indian Ocean or the Pacific Ocean, because those oceans have a much lower salinity. It is estimated that between 15 and 20 Sv of surface water cools and sinks to lower levels in the very limited area of the Greenland and Norwegian seas,[7] and this process is thought to account for a major fraction of the renewal of all the abyssal waters of the world's oceans.

By employing models, Manabe and Stouffer[26] and Marotzke and Willebrand[27] have shown what appears to be at least two stable equilibria for coupled ocean-atmosphere models. In one equilibrium, the North Atlantic Ocean has a vigorous thermohaline circulation like that just described, where there is relatively saline and warm surface water. In the other equilibrium, there is no thermohaline circulation, and an intense halocline (a sharp vertical gradient in the salinity) exists in the surface layer at high latitudes. This second equilibrium condition is attained when a pool of fresh water forms a buoyancy barrier in the Greenland and Norwegian seas, blocking the deepwater convection.

When the deepwater convection is blocked, surface waters become cooler in the northern North Atlantic, with drops in temperature as large as 6°C. Bryan[28] labeled the phenomenon a "halocline catastrophe." Manabe and Stouffer[26] suggested that this phenomenon has paleoclimatic importance and may have been responsible for the abrupt transition from glacial retreat to glacial expansion that occurred about 11,000 years ago. A similar, but smaller, event occurred in the northern North Atlantic between 1968 and 1982 and is referred to as the "great salinity anomaly." Referring to this anomaly, Dickson et al. stated that

> The widespread freshening of the upper 500-800 m layer of the northern North Atlantic represents one of the most persistent and extreme variations in global ocean climate yet observed in this century.[29]

Teleconnection is defined as the "significant simultaneous correlation between temporal fluctuation in meteorological parameters at widely separated points on Earth."[30] The work of Lau and Nath[8] showed that teleconnections exist between the North Atlantic and global climate. In particular, they found that sea-surface temperature variations off the Newfoundland coast were correlated with the strongest interannual pressure anomalies (Fig. 9). The contour map given in Figure 6 shows the North Atlantic's first EOF for a sea-surface temperature interannual anomaly. Further analysis correlating the teleconnection between the sea-surface temperature anomaly and the 515-mbar or pressure surface showed that sea-surface temperature perturbations in the northern latitudes are associated with displacement of storm tracks, the relocation of areas of high rainfall, and other phenomena.

Four important points about the relationship between ocean circulation and climate need to be emphasized:

1. The thermohaline conveyor belt is a crucial part of climatic balance and can be shut down at times by the advection of fresh water over the Arctic seas.
2. The Gulf Stream is responsible for the advection of warm saline water poleward in the North Atlantic. At about 50°W and 35°N, the stream bifurcates and transports about 20 Sv of water northward into the Arctic seas where North Atlantic Deep Water is formed.
3. The area east of Newfoundland represents an area of intense variability and heat exchange in the atmosphere.
4. The abyssal northern recirculation gyre and the deep western boundary undercurrent that exist in the western North Atlantic are part of the thermohaline conveyor belt and are responsible for the transport of North Atlantic Deep Water southward.

The working group that drafted the Atlantic Climate Change Program Science Plan described the significance of the North Atlantic as follows:

> East of Newfoundland, a branch of the Gulf Stream, directed towards the northeast, transfers warm-salty thermocline water towards the North Atlantic Deep Water formation regions. The branching takes place in a complex area full of meanders and eddies. Variability is likely to be associated with the strong sea surface temperature anomalies characteristic of the region. Within the deep water, the deep western boundary current carries the fresh production of North Atlantic Deep Water southward to slip eventually below the thermocline structure of the subtropics. The latitude band of the Canadian Maritime Provinces is an important interactive arena for the subtropical and subpolar gyres, linking the North Atlantic Deep Water formation regions with the warmer oceans, and should be monitored to detect variations associated with larger-scale climate changes.[9]

Data Assimilation and Monitoring

What can a GFO altimeter contribute to our understanding of the North Atlantic gyres and ongoing circulation processes? And, how can the GFO system be used to monitor the teleconnections that indicate global climate change? The excellent results obtained by Glenn et al.[12] for the validation of the Geosat altimeter indicate the powerful scientific utility of the Geosat data set for mesoscale and sub-basin–scale ocean circulation studies. This is true for strong signal areas, such as the Gulf Stream, as well as less intense current systems, such as the eastern North Atlantic (Fig. 8). The synthetic geoid method developed by Glenn et al.[12] has two major advantages: the increased information content of the signal and the greater ease in interpretation of the signal.

The dynamic topography derived from an altimeter and the synthetic geoid is absolute, and the data on the structure and strength of the mesoscale sea-surface height and surface geostrophic flow are directly available. This availability increases the usefulness of the altimetric data for assimilation into models. For real-time scientific or operational use of altimetric data, the synthetic geoid permits rapid interpretation of a large data set, thereby increasing its value. The accuracy of the validation arrived at by Glenn et al.[12] indicates that the Geosat database is a rich source for novel synoptic and statistical mesoscale dynamic research.

The analysis of the altimeter-derived absolute topography is of importance in itself. By assimilating altimetric data into a model as an additional data source, velocity and temperature, and therefore heat transport, can also be calculated. This incorporation procedure is so important that the Atlantic Climate Change Program Science Plan[9] strongly recommends "support for the development of different assimilation methods such as the adjoint method...[and then] decade-long retrospective data-assimilation experiments on past data..."

The plan points out the need to improve assimilation methods, to correct for systematic errors, and to incorporate new data sets, such as those provided by satellite altimetric sea-level measurements. The assimilation analysis will provide a sensitive check on the consistency of the surface fluxes.

Thus, we conclude that the melding of altimetric data into models will increase the accuracy of model predictions. At the same time, these models will provide information in space and time by dynamically interpolating the oceanographic field. When coupled with ancillary data, such as temperature, it will be possible to compute the heat transport. This information is especially important because the Gulf Stream alone transports more heat toward the North Pole at 26°N than does the atmosphere. The Atlantic Climate Change Program Science Plan calls for a

> suite of observations [that] should be compiled and analyzed to determine which properties of circulation at 26°N should be monitored in a long-term observational grid and what measurement strategies will provide an efficient monitoring array.[9]

When used with model assimilation and field estimates, the altimetric data can form an important element of this monitoring system.

Synthetic Geoids and Dynamic Topography

The present synthetic geoid has been computed and validated in the Gulf Stream region. Research in the western North Atlantic (i.e., Project Athena and JGOFS) has demonstrated that a synthetic geoid could also be obtained and validated for these areas.[10] Altimeter-derived sea-surface heights from these regions show excellent agreement with *in situ* data.

At present, we are developing the synthetic geoid for the entire North Atlantic (Fig. 7). The North Atlantic is divided into four large regions: the western North Atlantic (W), the eastern North Atlantic (E), the Labrador Sea (L), and the northern North Atlantic (N). These regions encompass the specific areas where identified climatic processes occur: the formation areas of North Atlantic Deep Water, the Gulf Stream bifurcation area, the northern recirculating gyre, and the area that exhibits a teleconnection between sea-surface temperature and the global climate. The regions were divided so as to include the important meridional fluxes of water mass and tracers at 50°N and 26°N that are identified in the Atlantic Climate Change Program Science Plan[9] with the subpolar and subtropical gyres, respectively.

The altimetric data, when used with the synthetic geoid, give absolute dynamic topography measurements, which are vital for monitoring the flow of the warm, salty Atlantic water northward in the Gulf Stream. The northern recirculation gyre and its role in the thermohaline circulation are poorly understood, especially its driving mechanisms. The altimetric data, which provide mesoscale and sub-basin–scale measurements of high accuracy, can be used to compute the mesoscale field over the northern recirculating gyre. Thus, the altimeter will provide information crucial for understanding the processes responsible for the gyre's generation. The gyre's role in the circulation of the abyssal currents can then be investigated.

Air-Sea Interactions and Teleconnections

In the area where the sea-surface temperature and the atmosphere show a teleconnection, it may be possible, by employing the altimeter and synthetic geoid, to look for correlations between the climate and the circulation processes (e.g., advection of eddies or frontal genesis) occurring at particular sites. The near-real-time capabilities of the altimetric system, demonstrated in the JGOFS experiment,[11] may be used to compute the absolute dynamic topography in near real time.

The Atlantic Climate Change Program Science Plan[9] calls for development of an operational model of the Atlantic for real-time data assimilation. The working group's report cites the need for a significant effort to improve the assimilation methods, to correct for systematic errors, and to incorporate new data sets such as those provided by satellite altimetric sea-level data. Thus, the proven near-real-time capabilities of the sea-surface height measurements from Geosat are needed to monitor climatic change.

The data collected from the altimetric satellites are only as good as their accuracy. This important fact was recognized by Glenn et al.,[12] who validated their dynamic topography measurements with *in situ* data. Similarly, the Atlantic Climate Change Program Science Plan states that the program

> should include a data-analysis effort to insure an understanding of the use of this type of data in relation to the climate program. In particular, it is important that the stability of the satellite sea-level estimates be determined and ground-truthed in relation to high-quality sea-level networks and long-term steric height determinations at key sites. These include the major water-mass formation regions and areas involved in the major sea surface temperature anomalies.[9]

The continuous validation of altimetric data and the development of long time series with consistent instrumentation can be accomplished with GFO altimeters.

BIOGEOCHEMICAL CYCLES AND ECOLOGICAL DYNAMICS

The Carbon Cycle and Ocean Ecosystems

The carbon cycle plays a major role in global climate and is one of the cycles most affected by human activities. Deforestation, the burning of fossil fuels, and ocean upwelling result in increased absorption of carbon by the atmosphere. Carbon undergoes almost no changes while in the atmosphere, but it is released to the oceans, where a portion is deposited as sediment on the ocean floor, a portion is returned to the atmosphere, and the remainder is stored in the ocean (Fig. 2). The amount of carbon dioxide being released to the atmosphere is increasing at a rate of 1.18 ppm each year.[28] The effects that increased atmospheric CO_2 will have on biogenic systems are not known, but they are being studied as part of the U.S. Global Climate Change Program.

The JGOFS and GLOBEC experiments are two major programs designed to improve our knowledge of some of the basic components of the biogeochemical system.

The JGOFS is designed to study the carbon cycle and the effects of oceanic and atmospheric circulation on this cycle. Specifically, the JGOFS goals are as follows:

1. To determine and understand, on a global scale, the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, seafloor, and continental boundaries.
2. To develop a capability to predict, on a global scale, the response of oceanic biogeochemical processes, particularly those related to climate change, to perturbations imposed by human activity.

The approach of GLOBEC is

> to understand how physical processes, both directly and indirectly, influence the success of individual animals in the sea, their feeding, growth, reproduction and survivorship. From this information can be derived the consequences of changing physical processes on animal populations and ecosystems.[5]

The altimeter offers unique and important capabilities necessary to meet the research goals of both of the studies cited above. Accomplishment of those goals will significantly enhance our understanding of climatic change and its effects. In the carbon cycle and ecosystems of animal populations, ocean circulation, eddies, and fronts are intimately linked to the entire system. All living organisms in the ocean, from the smallest to the largest, are at the mercy of ocean circulation patterns at some point in their existence.

The Role of Altimetry in GLOBEC and JGOFS

If significant global warming occurs and precipitation patterns change, rapid melting occurs in the ice glaciers and fields, thus causing large quantities of fresh water to be released into the Gulf of Alaska. This influx of fresh water can change the magnitude and direction of the Alaska Coastal Current, which in turn can remove the larvae upon which certain fish feed and significantly affect the populations of these fish. Similar effects may be produced in the Gulf of Mexico as a result of changes in freshwater runoff from the Mississippi River. An altimeter can provide continuous monitoring of both of these currents as well as the circulation patterns in the regions. When used as inputs to circulation models in conjunction with other satellite data sets, such as infrared and ocean color, altimetric data can give a fairly complete picture of the surface circulation patterns in time and space. Present plans envision having altimeters in flight continuously over the next decade, with a possibility of having two or more altimeters in orbit at the same time. The potential for these instruments should be considered in the planning of various experiments over the next decade.

An example of how the altimeter might be used to monitor ecological systems in the Gulf of Alaska is shown in Figure 10. After removal of the geoid height signature using a synthetic geoid, the altimeter height signal along with infrared imagery can be assimilated into a regional ocean-circulation model. Altimeter ice-edge measurements can be used to compute freshwater content. The locations of freshwater regions, along with isopleths of height and temperature, can be used to position ships for making *in situ* measurements. These data from strategically placed *in situ* instruments, together with the isopleths of temperature and height, can then be used in predictive models to assess the immediate and long-term effects on fish populations in the region.

Another phenomenon being investigated by GLOBEC is the concentration of biological activity in the vicinity of

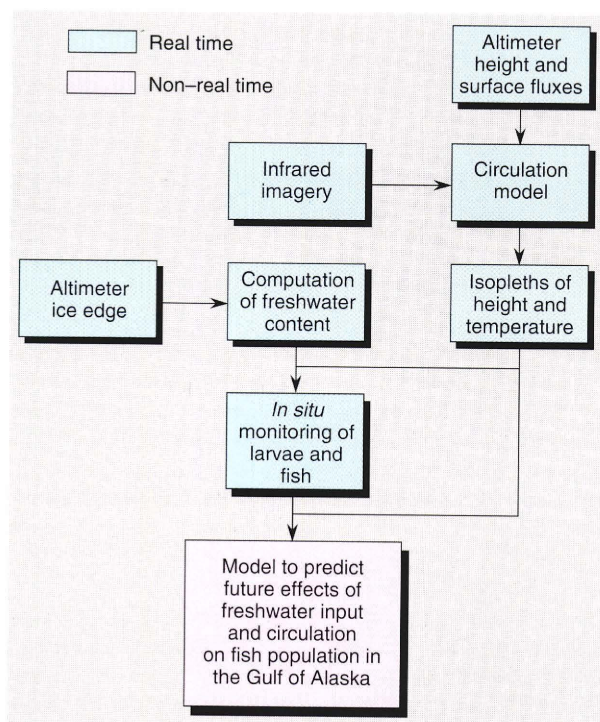

Figure 10. Monitoring of ocean circulation and the ice edge in the Gulf of Alaska.

fronts. Fronts in the ocean, with surface signatures (heights) above the altimeter noise level, are detectable by the altimeter. The same is true of rings and eddies. Although the altimeter will have no means of determining the type or quantity of biological activity present along these fronts, the data can serve to locate fronts, direct experimenters performing *in situ* measurements, and serve as inputs to models. Altimetric data can also be used synergistically when correlated against additional data, such as satellite-measured ocean color.

The GLOBEC committee, when attempting to define specific experiments and procedures that can be accomplished using present technology aboard a ship, emphasized the need for near-real-time inputs to models and analysis.

The ability of GFO-class altimeters to provide important, near-real-time data was demonstrated during the 1989 JGOFS program, which investigated the spring phytoplankton bloom in the North Atlantic. The role of the altimeter in the experiment and the results are described by Robinson et al.[11] One large, kidney-shaped eddy was detected, as well as one standard and one small eddy. The altimetric results were confirmed by *in situ* data. The movement of eddies is on sufficiently long time scales that there is a high probability that eddies will be sampled by the altimeter at some point in their existence.

Figure 11 shows how a future JGOFS-type experiment might be conducted. After removal of the geoid, the dynamic topography can be relayed to a ship in near real time (i.e., in less than twenty-four hours). The location of rings and/or fronts can be determined, and ships can be routed for *in situ* measurements. At some other location (or possibly aboard ship), altimeter height, wind speed, and infrared data can be used in forecast models of the region. The output from these models can be forwarded to the ships.

The combination of these measurements forms a database, which is then used in a biogeochemical model to forecast and monitor oceanic and biogeochemical fluxes. The results from a quasi-geostrophic surface boundary layer model coupled with a simple two-constituent biogeochemical model are shown in Figure 12 (D. J. McGillicudy, Harvard University, personal communication, 1992).

The biological quantities in Figure 12 are nutrients (in the form of nitrate) and phytoplankton. Figure 12 shows vorticity (nondimensional) at 50 m, mixed layer nitrate (in micromoles per liter), phytoplankton concentrations (measured in micromoles of nitrogren per liter), and vertical velocity (in meters per second) at 25 m in the initial condition (top) and after eight days of integration (bottom). The nitrate field is initialized with an empirical nitrate-density relationship derived from observations during the experiment.

Initially, phytoplankton concentration is assumed to be spatially uniform. After eight days of integration, almost all of the nitrate in the mixed layer has been converted into phytoplankton. Patches of vertical velocity have developed, associated with the deformation of the big

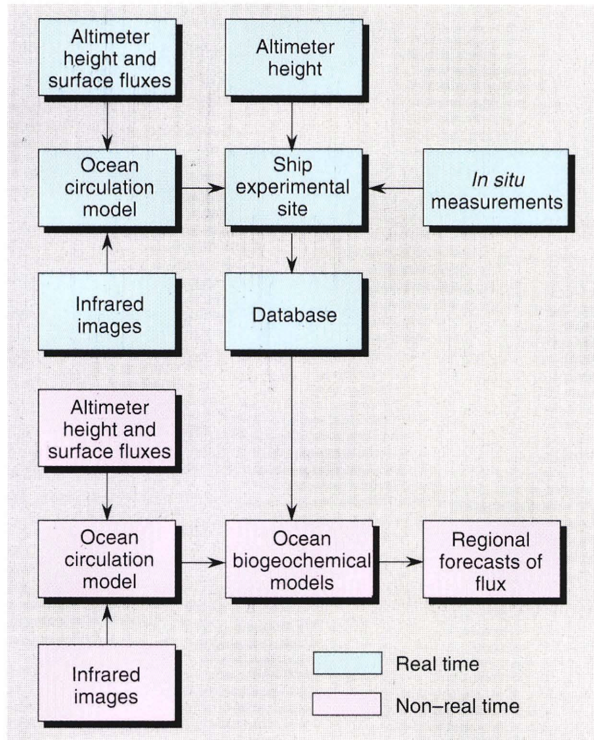

Figure 11. Schematic showing the use of altimetric data for a regional experiment similar to the Joint Global Ocean Flux Study.

eddy. This vertical transport process serves to pump nutrients into the mixed layer, resupplying phytoplankton growth.

Since in many instances the altimeter will be used in conjunction with data from other instruments and models, it should be considered a valuable instrument in any biogeochemical cycle or ecological dynamic studies, because the water-mass flow affects all living and fossil entities in the ocean at some point in their cycle. Geosat-type altimeters can provide input on the changes in this flow on length scales up to approximately 1500 km. This input can enhance our ability to assemble the entire complex climate puzzle.

CONCLUSIONS

The oceans are a vital part of the climate system. Circulation, fluxes, variabilities, dynamic processes related to the general circulation, biogeochemical fluxes, and ecosystem dynamics are high-priority areas of research for scientists studying climate dynamics and global change.

Studies of the processes that affect climate directly, such as the thermocline conveyor belt, and those that are secondary effects, such as the uptake of CO_2 and biogeochemical changes, all require information that can be provided by a spaceborne radar altimeter. A spaceborne altimeter of the GFO class is an important instrument for meeting the requirements of studies of climatic and hydrologic systems, biogeochemical dynamics, and eco-

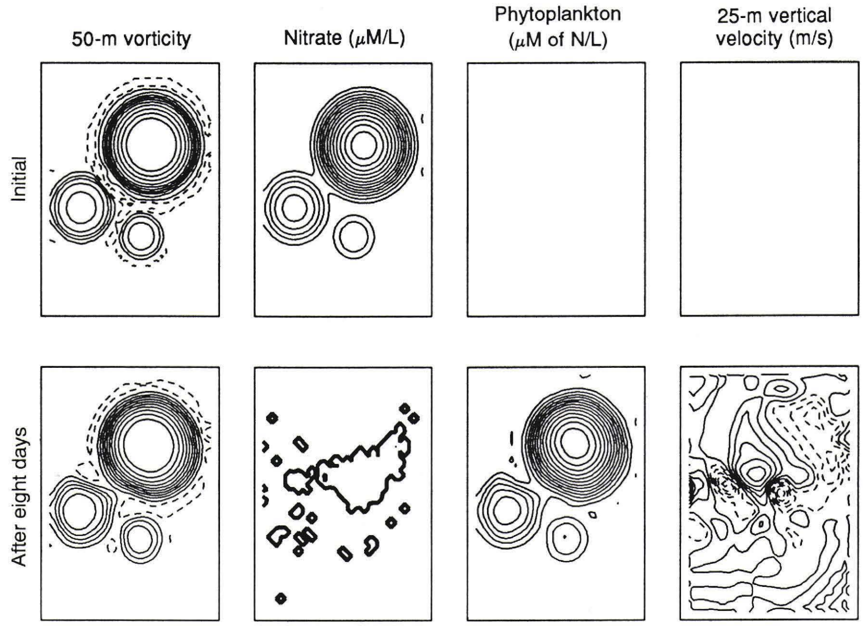

Figure 12. A biogeochemical model coupled to a mesoscale-surface boundary-layer model. This figure shows the initial shape of ocean eddies and nutrients (in the form of nitrate) and their development after eight days. (From D. J. McGillicudy, unpublished dissertation, Harvard University, Cambridge, Mass., 1992.)

logical systems and dynamics, the top priorities of the U.S. Global Change Research Program.

The Atlantic, and especially the western North Atlantic, is a critical region for the study and measurement of the thermohaline circulation, Gulf Stream bifurcation and variability, the northern recirculation gyre, and air–sea interactions and teleconnection, aspects of ocean circulation of particular importance according to the Atlantic Climate Change Program Plan.

The thermohaline conveyor belt is a crucial element of climatic balance that at times can be interrupted by the advection of fresh water into the North Atlantic. Understanding and measuring this phenomenon is essential to studies of climatic dynamics and global change.

Studies of the area east of Newfoundland are also of particular importance, because there the Gulf Stream bifurcates and a branch flows into the region where North Atlantic Deep Water is formed. The northern recirculation gyre interacts with the Gulf Stream and the abyssal western boundary current in the Gulf Steam meander region. Deepwater circulation is significantly influenced by this abyssal gyre, but the processes that drive the gyre are not well understood.

In the North Atlantic there is a demonstrated teleconnection or correlation between sea-surface temperature and global atmospheric climate that needs to be explored further. Clearly, spaceborne radar altimeters are important and necessary instruments in the effort to understand and to monitor these processes and others that affect and are affected by climatic change.

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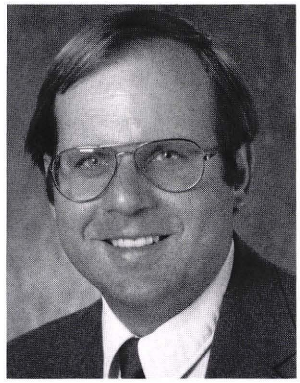

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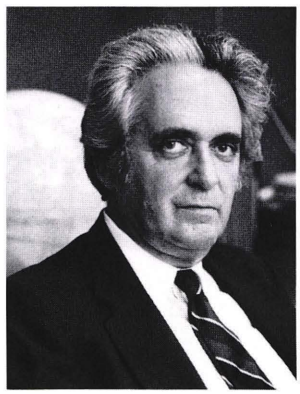

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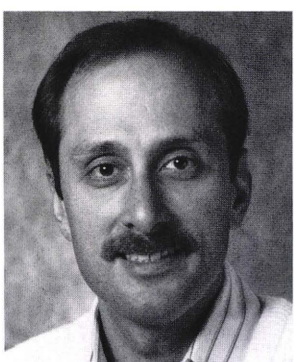

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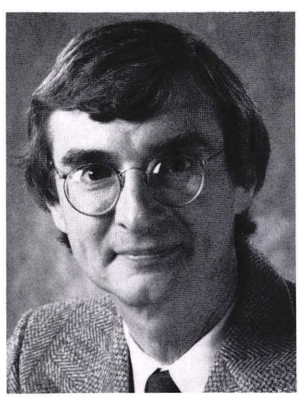

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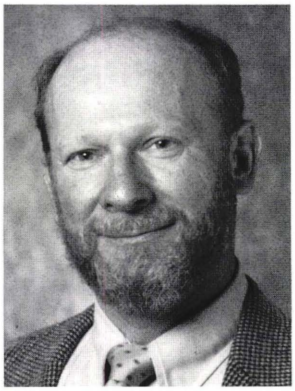

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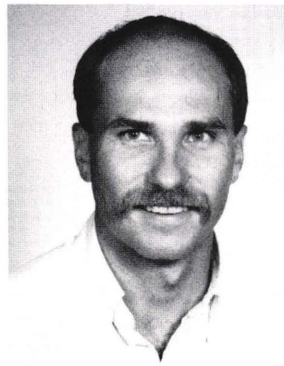

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