TOPEX/POSEIDON
SCIENCE INVESTIGATIONS PLAN

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TOPEX/POSEIDON
Science Working Team

Cover: An artist's rendition of the TOPEX/POSEIDON satellite and a color-coded map of the large-scale dynamic ocean topography derived from the Geosat altimeter data collected in November and December of 1986. The map was produced by the investigation team led by Byron Tapley of the University of Texas at Austin. The ocean topography is equivalent to the surface pressure of the atmosphere; ocean currents flow around the hills (the regions in red/orange) and the valleys (the regions in blue/green) of the topography just as winds blow around the centers of high and low pressure. The range of the topographic relief is about 2 m. The white contours denote the streamlines of the ocean surface circulation associated with the topography (clockwise around the hills in the Northern Hemisphere). The contour interval is 10 cm. The hill in the northwest Pacific Ocean has the highest elevation—74 cm. Observations from TOPEX/POSEIDON are expected to result in maps similar to this, but of much greater accuracy.

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September 1, 1991

ORIGINAL CONTAINS
COLOR ILLUSTRATIONS

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Preface

Recognizing the pressing concern to understand the potentially detrimental effects of global change to our planet, NASA has identified Mission to Planet Earth as its central contribution to the U. S. Global Change Research Program. NASA's contribution will involve an integrated program consisting of the Earth Observing System and a series of Earth Probes that will be launched in the latter part of this decade. Preceding these launches is a series of missions focused on understanding specific critical elements of the Earth System. Among these, the TOPEX/POSEIDON mission scheduled for launch in mid-1992 will study the global ocean circulation. This mission will greatly improve our understanding of the ocean's coupling with the atmosphere during strong climatic variations such as the El Niño Southern Oscillation phenomenon and of the large-scale movement of currents of the global oceans which modulate the Earth's climate by redistributing heat from the equatorial to the polar regions.

TOPEX/POSEIDON, jointly conducted by NASA and the French Centre National d'Etudes Spatiales, will use a radar altimeter system deployed in an orbit specifically designed for precise measurements of large-scale ocean surface currents. The mission represents the culmination of the development of satellite altimetry over the past two decades. These data will be used by an international science team of 38 investigators to conduct a variety of studies in ocean circulation, tides, and marine geophysics. This document provides brief descriptions of the planned investigations as well as a summary of the major elements of the mission. Coordinated with the TOPEX/POSEIDON mission are two international scientific programs sponsored by the World Climate Research Program: the World Ocean Circulation Experiment and the Tropical Ocean and Global Atmosphere Program. The satellite data will be used in conjunction with the *in-situ* data collected from these two programs.

It is anticipated that the scientific results from this mission will make major contributions to the understanding of global ocean circulation, its role in global climate change, and also lay the foundation for long-term monitoring of the ocean and its role in the Earth climate system. I wish all the scientists participating in this exciting altimetry mission a bon voyage of discovery.

S. G. Tilford

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Earth Science and Applications Division
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National Aeronautics and Space Administration

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I. Introduction

The global change of our planet is a well-recognized phenomenon. The ocean, through its interaction with the Earth's atmosphere, biosphere, and cryosphere, plays an important role in regulating the change of the Earth as a system. For examples, the potentially severe contrasts in climate between the poles and equator are greatly ameliorated by the presence of the ocean because of its large heat capacity and its contribution to the movement of heat from the equator to the poles; much of the weather we experience is spawned over the ocean through complex air–sea transfer processes; the important global fishing grounds are limited to small geographic areas dominated by special oceanic flows that result from the prevailing winds; the mixing and transport of chemical tracers and pollutants in the sea profoundly affect the Earth system. In regard to the latter, the rate at which the temperature of the air rises in response to the increase in atmospheric CO_2 due to the burning of fossil fuels and deforestation, the greenhouse effect, is determined to a large extent by the rate at which the ocean is able to absorb the CO_2.

Yet much about the global aspects of the circulation of the ocean is poorly understood, largely because the ocean is so difficult to observe; its fluctuations occur over a wide range of spatial and temporal scales. Satellite systems are the most effective in providing the data necessary to understand the oceans on a global scale. TOPEX/POSEIDON is a satellite mission designed to use a radar altimeter system for the study of the global ocean circulation and its variabilities.

The utility of a satellite altimeter system for ocean circulation studies has been demonstrated by three previous missions: GEOS-3 (Stanley, 1979), Seasat (Born et al., 1979), and Geosat (Douglas and Cheney, 1990). However, none of these missions was optimally designed for ocean circulation studies, especially for ocean variabilities at the basinwide scales that are most difficult to observe using shipboard techniques and that bear significant effects on global change. Given this shortcoming, TOPEX/POSEIDON was specifically designed to observe large-scale ocean circulation with unprecedented accuracy. The results from the mission are expected to make significant contributions to the knowledge of ocean circulation and its interaction with the atmosphere.

A satellite altimeter system employs two techniques: radar altimetry and precision orbit determination. Radar altimetry is the precise measure of the satellite's altitude above the ocean surface. Precision orbit determination is the measure of the satellite's orbital distance from the center of the Earth. The difference between these two measurements is the height of the sea surface in coordinates relative to the center of the Earth. This height is called sea level, which is directly affected by ocean currents and their variabilities.

Sea level is determined primarily by gravity. If the ocean were at rest, sea level would be a surface of constant gravitational potential: the geoid. The deviation of sea level from the geoid, after removal of the effects of (1) ocean tides, (2) the static response of the ocean to atmospheric pressure forcing, and (3) wind setup in certain coastal regions, is defined as the dynamic ocean topography. The gradient of dynamic ocean topography is proportional to the velocity of the slowly varying, large-scale ocean currents (called geostrophic currents) at the sea surface. Surface geostrophic currents can be related to the currents at depth if the density field of the ocean is known.

Satellite altimeter measurement of sea level, when coupled with knowledge of the geoid and the ocean's density field, provides a feasible approach for determining the three-dimensional geostrophic currents in the global ocean. Knowledge of the geoid and the ocean's density field must be obtained from independent sources, however. The latter will be acquired from a number of international oceanographic field programs planned in coordination with the TOPEX/POSEIDON Mission. (These programs are mentioned later in this introduction.)

To be useful for global ocean circulation studies, the global geoid must be known with an accuracy of less than 10 cm at a scale of 100 km and less than 1 cm at scales greater than 1000 km. Such accuracy can be achieved only by a spaceborne gravity mission such as the ARISTOTELES Mission (Benz and Hieber, 1989). However, knowledge of the geoid can be improved to a lesser degree by shipboard gravity measurements and by analysis of altimeter and satellite tracking data. Both approaches are addressed in a number of the Principal Investigators' science investigation plans described in Section III. Repeated altimeter measurements at the same locations can detect the variability of ocean currents without the requirement of geoid knowledge because the geoid does not change significantly over the time scales of ocean current variability.

The sea level measurement made by altimetry is also useful in the study of ocean tides, marine geodesy, and geophysics. In addition to the sea level measurement, ocean wave height and wind speed can also be measured by the shape and strength, respectively, of the altimeter's return pulse. These measurements are useful for the study of ocean-surface wave physics.

Over the past two decades, the key issue in developing the techniques of satellite altimetry and precision orbit determination has been the accuracy of the measurements. To make useful measurement of the large-scale ocean currents, sea level measurements with an accuracy of a few centimeters over spatial scales of hundreds to thousands of kilometers are needed. Achieving this level of accuracy with a spaceborne altimeter is a great challenge that involves the reduction of errors from a variety of sources, including the altimeter instrument, the determination of the satellite orbit, range delay of the radar pulse in the atmosphere, and the interaction of ocean waves with the radar pulse. Additionally, sea level variabilities caused by ocean and solid-earth tides and atmospheric-pressure loading effects can also interfere with the sea level signatures of ocean circulation.

TOPEX/POSEIDON will meet the challenges raised by these stringent requirements for accuracy by taking the following approaches. First, to achieve an unprecedented accuracy in orbit determination, which is the dominant error source, a long-lead prelaunch effort has been made to develop a state-of-the-art model for the Earth's gravity field. This model will be used in conjunction with laser and Doppler tracking data to compute a precise orbit for the mission. Second, the instrument package is designed to minimize the altimeter measurement errors induced by the atmosphere. The altimeter will make simultaneous measurements in two frequency channels (5.3 and 13.5 GHz) to allow corrections for the range delay caused by ionospheric free electrons. A three-frequency (18-, 21-, and 37-GHz) microwave radiometer is designed to correct the range delay caused by tropospheric water vapor. Third, the configuration of the mission orbit (altitude: 1336 km; inclination: 66 deg; repeat period: 10 days) is selected to optimize the performance of the mission. Details of the mission design can be found in Section II.

TOPEX/POSEIDON is jointly conducted by the United States National Aeronautics and Space Administration (NASA) and the French space agency, Centre National d'Etudes Spatiales (CNES). The current plans call for a launch of the satellite in mid-1992 by an Ariane 42P launch vehicle. The mission has also been coordinated with a number of international oceanographic and meteorological programs, including the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean and Global Atmosphere Programme (TOGA), both of which are sponsored by the World Climate Research Programme (WCRP). The observations of TOPEX/POSEIDON are timed to provide a global perspective for interpreting the in situ measurements collected by these programs, which in turn will be combined with satellite observations to achieve a global, four-dimensional (time plus the three physical dimensions) description of the circulation of the world's oceans.

Science investigations using the unique capabilities of TOPEX/POSEIDON will be carried out by the Science Working Team, which is composed of 38 Principal Investigators selected by NASA and CNES through the process of Announcement of Opportunity. The selection was based on the scientific merit of the proposed investigations and their relevance to the mission's science goals. To maximize the mission's science return, the Principal Investigators participate in mission design and planning before the launch of the satellite. After launch, they are expected to deliver the main scientific results from the mission. The investigators and the titles of their investigations are listed in Table 1. There are 16 Principal Investigators from the United States, 13 from France, 2 from Japan, 2 from Australia, and 1 from each of the following countries: United Kingdom, South Africa, West Germany, Norway, and the Netherlands.

The main objective of the mission—knowledge of ocean circulation—is addressed by 29 investigations. Eight of them are focused on the variability of basin-scale circulation of the ocean with no emphasis on any particular region—those of De Mey, Fu, Liu, Minster, Olbers, Tai, Tarits, and Wunsch. Seventeen investigations have a regional focus (see Figure 1)—those of Born (the northeast Pacific and the South Pacific), Burrage (north-Australian regional seas), Chelton (the Southern Ocean), Church (the East Australian Current, the western South Pacific, and the eastern Indian Ocean), Desaubies (the tropical Atlantic), Douglas (tropical oceans), Gründlingh (the Agulhas Current), Katz (the tropical Atlantic), Lukas (the tropical Pacific), Merle (the tropical Atlantic), Mitchell (the Gulf Stream and Kuroshio current), Ollitrault (the South Atlantic), Pettersson (the Norwegian/Nordic Seas), Picaut (the tropical Pacific), Strub (the eastern Pacific), Taira (the western Pacific), and Woodworth (the Southern Ocean). Four investigations are focused on the determination of the mean circulation and the geoid—those of Marsh, Rapp, Tapley, and Wakker.

The remaining nine investigations address a variety of subjects including (1) geodesy and geophysics: Barlier, Boucher, Cazenave, Segawa, Souriau, and Wahr; (2) ocean tides: Le Provost and Sanchez; (3) altimetry calibration and validation: Menard. The results of these investigations, such as altimetry calibration and improvements in the knowledge of the geoid, ocean tides, geodetic reference frames, and polar motions, are of critical importance to the success of achieving the mission's main objective.

Many of the 38 investigations cover a wide range of subjects; the grouping described above is based on the primary emphasis of each investigation. For instance, ocean winds and waves are not the main subject of any of the investigations; however, they are a secondary objective of Woodworth's investigation.

A major purpose of this document is to provide a description of the science investigation plans of the 38 Principal Investigators. This description is presented in Section III, which is preceded by a brief description of the TOPEX/POSEIDON Mission given in Section II. Various key elements of the mission are described in Section II to provide the background for the rationale and the basis of the science investigations described in Section III.

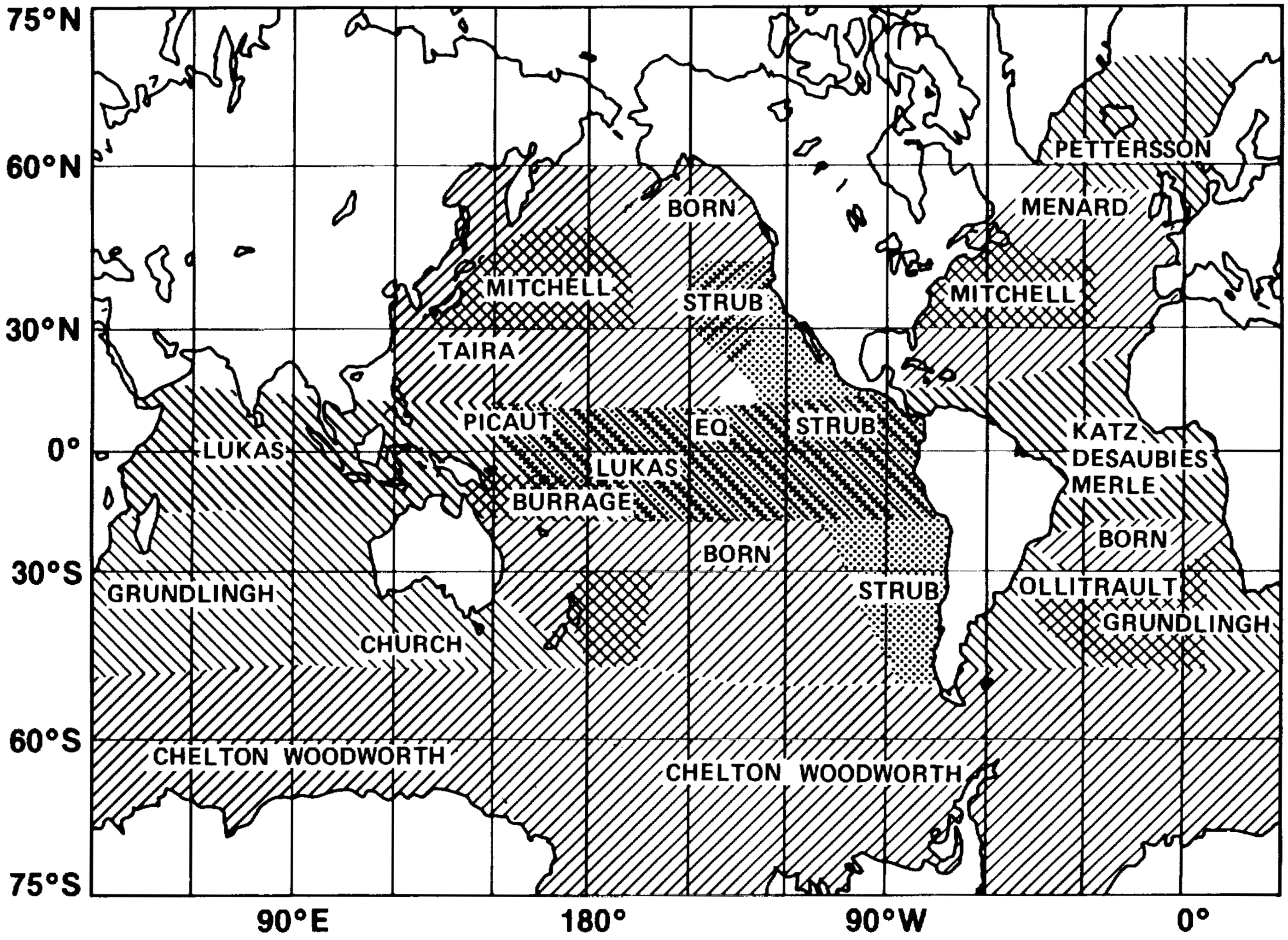

Figure 1. Coverage of the regional studies by the TOPEX/POSEIDON investigators.

Table 1. TOPEX/POSEIDON Principal Investigators

Name and affiliation	Title of investigation
François Barlier Observatorie de la Côte d'Azur Groupe de Recherches de Géodésie Spatiale Grasse, France	The Western Mediterranean Sea: An Area for a Regional Validation for TOPEX/POSEIDON and a Field for Geophysical and Oceanographic Studies
George H. Born Colorado Center for Astrodynamics Research Boulder, Colorado	The Use of Satellite Altimetry in the Study of Weakly Defined and Variable Ocean Gyres
Claude Boucher Institut Géographique National Saint-Mandé, France	Terrestrial Reference Systems Related to the TOPEX/POSEIDON Project
Derek Burrage Australian Institute of Marine Science Queensland, Australia	North-Australian Tropical Seas Circulation Study
Anny Cazenave Centre National d'Etudes Spatiales Toulouse, France	Geophysical Investigations With TOPEX/POSEIDON Altimetry Data
Dudley B. Chelton Oregon State University Corvallis, Oregon	Mesoscale and Large-Scale Variability of the Antarctic Circumpolar Current
John A. Church Commonwealth Scientific and Industrial Research Organization Marine Laboratories Hobart, Tasmania, Australia	Ocean Transport and Variability Studies of the South Pacific, Southern, and Indian Oceans
Pierre De Mey Groupe de Recherches de Géodésie Spatiale Toulouse, France	Assimilation of Altimeter Topography Into Oceanic Models
Yves Desaubies Institut Français de Recherche pour l'Exploitation de la Mer Brest, France	Studies of the Intermediate and Deep Circulation in the Western Equatorial Atlantic
Bruce Douglas NOAA/National Ocean Service Rockville, Maryland	Application of TOPEX/POSEIDON Altimetry to Ocean Dynamics and Geophysics
Lee-Lueng Fu Jet Propulsion Laboratory California Institute of Technology Pasadena, California	Circulation of the Gyres of the World Ocean: Observation and Modeling Using TOPEX/POSEIDON Altimeter Data
Marten L. Gründlingh National Research Institute for Oceanography Stellenbosch, South Africa	South African TOPEX/POSEIDON Altimeter Experiment
Eli Joel Katz Columbia University Palisades, New York	Sea Level Response to Wind Forcing in the Tropical Atlantic

Table 1. (contd)

Name and affiliation	Title of investigation
Christian Le Provost Institut de Mécanique de Grenoble Grenoble, France	Global Ocean Tides Through Assimilation of Oceanographic and Altimeter Satellite Data in a Hydrodynamic Model
W. Timothy Liu Jet Propulsion Laboratory California Institute of Technology Pasadena, California	Low-Frequency Variability of Sea Level as Related to the Heat Balance of Global Oceans
Roger Lukas University of Hawaii Honolulu, Hawaii	Studies of Tropical Ocean Dynamics Using the TOPEX/POSEIDON Altimeter-Derived Sea Surface Topography
James G. Marsh Goddard Space Flight Center Greenbelt, Maryland	Ocean Topography Mapping, Improvement of the Marine Geoid, and Global Permanent Ocean Circulation Studies From TOPEX/POSEIDON Altimeter Data
Yves Menard Centre National d'Etudes Spatiales Toulouse, France	Geophysical Validation of TOPEX/POSEIDON Altimetry Products
Jacques Merle Université Paris VI Paris, France	Study of Mass and Heat Transport of the Tropical Atlantic Ocean Using Models and Altimeter Data
Jean-François Minster Centre National d'Etudes Spatiales Toulouse, France	Ocean Circulation Using Altimetry
James L. Mitchell John C. Stennis Space Center, Mississippi	The Dynamics and Energetics of Midlatitude Western Boundary Currents: A Comparison of the Kuroshio Extension and the Gulf Stream
Dirk Olbers Alfred Wegener Institut für Polar- und Meeresforschung Bremerhaven, Federal Republic of Germany	Ocean Circulation Modeling by Use of Radar Altimetry Data
Michel Ollitrault Institut Français de Recherche pour l'Exploitation de la Mer Brest, France	General Circulation of the South Atlantic Between 5°N and 35°S
Lasse H. Pettersson Nansen Environmental and Remote Sensing Center Solheimsvik, Norway	Ocean Dynamics in the Nordic Seas Using Satellite Altimetry
Joel Picaut Centre ORSTOM de Nouméa Nouméa, New Caledonia	Application of TOPEX/POSEIDON Altimetry Measurements to Observational and Modeling Studies of the Low-Frequency Upper Ocean Mass and Heat Circulation in the Tropical Pacific

Table 1. (contd)

Name and affiliation	Title of investigation
Richard H. Rapp Ohio State University Columbus, Ohio	Mean Sea Surface and Gravity Investigations Using TOPEX/POSEIDON Altimeter Data
Braulio V. Sanchez Goddard Space Flight Center Greenbelt, Maryland	Global Ocean Tide Mapping Using TOPEX/POSEIDON Altimetry
Jiro Segawa University of Tokyo Tokyo, Japan	Application of Precise Altimetry to the Study of Precise Leveling of the Sea Surface, the Earth's Gravity Field, and the Rotation of the Earth
Annie Souriau Centre National d'Etudes Spatiales Toulouse, France	Present-Day Plate Motions: Retrieval From the TOPEX/POSEIDON Orbitography Network (DORIS System)
P. Ted Strub Oregon State University Corvallis, Oregon	Equatorial and Eastern Boundary Current Variability in the North and South Pacific Oceans
Chang-Kou Tai Scripps Institution of Oceanography La Jolla, California	An Integrated Research Program for TOPEX/POSEIDON With Emphasis on the Pacific Ocean
Keisuke Taira University of Tokyo Tokyo, Japan	Oceanic Transports of Mass, Heat, and Salt in the Western North Pacific
Byron D. Tapley University of Texas Austin, Texas	The Determination and Interpretation of Ocean Surface Topography Using TOPEX/POSEIDON Altimeter Data
Pascal D. Tarits Institut de Physique du Globe de Paris Paris, France	Analysis of Altimeter Data Jointly With Seafloor Electric Data (Vertically Integrated Velocity) and VCTD-Yoyo Data (Detailed Profiles of VCTD)
John Wahr University of Colorado Boulder, Colorado	A TOPEX/POSEIDON Study of Oceanic Effects on Observations of the Earth's Interior
Karel F. Wakker Delft University of Technology The Netherlands	Precise Orbit Computation and Sea Surface Modeling
Philip L. Woodworth Proudman Oceanographic Laboratory, Bidston Observatory Birkenhead, Merseyside, United Kingdom	Marine Research Using Data From TOPEX/POSEIDON
Carl Wunsch Massachusetts Institute of Technology Cambridge, Massachusetts	Global Ocean Circulation by Altimetry

II. The Mission

A. Science Goals and Requirements

The primary science goal of the TOPEX/POSEIDON Mission is to substantially increase our understanding of global ocean dynamics by making precise and accurate observations of sea level for several years. These observations will be used by Principal Investigators and the wider oceanographic community, in conjunction with large-scale international Earth-observing programs, for studies that lead to

(1) Determination of the general circulation of the ocean and its variability; this will be achieved through combining sea level measurements with internal density field measurements of the ocean and models of ocean circulation.

(2) A test of the ability to compute circulation that results from forcing by winds.

(3) A description of the nature of ocean dynamics.

(4) Calculation of the transport of heat, mass, nutrients, and salt by the oceans.

(5) Determination of the geocentric ocean tides.

(6) An investigation of the interaction of currents with waves.

(7) Improvement in the knowledge of the marine geoid.

(8) Increased understanding of lithospheric and mantle processes.

To achieve the science goals, the following mission requirements have been established:

(1) Sea level (geocentric) shall be measured at each ground track repeat cycle to an accuracy of ±14 cm[1] (1 sigma) under typical ocean conditions, with small, geographically correlated errors.

(2) Sea level distance from the satellite, when averaged along track over a distance of 20 km, shall be measured to a precision of ±2.4 cm (1 sigma) under typical ocean conditions.

(3) Sea level shall be measured at least every 20 km along a grid of subsatellite tracks to minimize the spatial aliases of small-scale sea level variability.

(4) Sea level shall be measured along a grid of subsatellite tracks fixed to the Earth to minimize the influence of the geoid on measurements of time-variable topography.

(5) Sea level shall be measured such that tidal signals shall not be aliased into semiannual, annual, or zero frequencies, or frequencies close to these.

(6) Sea level shall be measured along a grid of subsatellite tracks that makes it possible to determine two orthogonal components of surface slope with comparable accuracy.

(7) Sea level shall be measured for a minimum of 3 years, with a potential for measuring sea level for an additional 2 years.

(8) Sea level shall be measured at least as far south as the southern limit of the Drake Passage (62°S).

(9) A minimum of 81% of the possible oceanic data shall be provided to the Principal Investigators, with no systematic gaps.

(10) Interim data shall be recovered, processed, and delivered to Principal Investigators soon enough to influence oceanographic experiments coordinated with satellite observations.

(11) Final data shall be recovered, corrected, processed, verified, and delivered to the Principal Investigators within 6 months of data acquisition.

(12) Final data and the data used to calculate the final data shall be archived.

(13) All elements involved in producing the geophysical measurements shall be adequately documented.

(14) The CNES design goal for the accuracy of sea level measurements is ±14 cm (1 sigma) under typical oceanic conditions.

(15) The design goal for the CNES altimeter is to satisfy the above set of science requirements, except that in (2) precision is ±2.5 cm, and (7) is not applicable to the CNES altimeter.

B. The Satellite

The TOPEX/POSEIDON satellite is an adaptation of the existing Multi-Mission Modular Spacecraft (MMS), which has successfully carried the payloads of the Solar Maximum Mission in 1980, the Landsat-4 in 1982, and the Landsat-5 in 1984. The MMS design has been modified to meet the

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[1] The 14-cm uncertainty is dominated by the orbit errors (see Table 4), which can be ameliorated by further analysis to be performed by the Principal Investigators. The accuracy of the analyzed sea level data is expected to be well below 10 cm.

TOPEX/ POSEIDON requirements. The satellite bus consists of the MMS and the Instrument Module. Shown in Figure 2 is the fully deployed TOPEX/POSEIDON satellite featuring the major modules, sensors, and antennas.

Within the MMS, the Command and Data Handling Subsystem includes the onboard computer and tape recorder and provides control for all satellite engineering subsystems and sensors. The Attitude Determination and Control Subsystem, the Earth Sensor Assembly Module, and the Propulsion Module control the satellite attitude throughout the mission. The Electrical Power Subsystem on the MMS provides power from the solar array and batteries to the satellite systems for the duration of the mission. The solar array is mounted to the Instrument Module, and its motion is controlled by the Solar Array Drive Assembly via the onboard computer. The Radio Frequency Communications Subsystem includes the high-gain antenna and the omni antennas and provides forward- and return-link telecommunications capability.

C. Science Instruments

There are six science instruments in the mission payload, four from NASA and two from CNES. They are divided into operational and experimental sensors as follows:

(1) Operational Sensors.
  (a) Dual-Frequency Radar Altimeter (ALT) (NASA).
  (b) TOPEX Microwave Radiometer (TMR) (NASA).
  (c) Laser Retroreflector Array (LRA) (NASA).
  (d) Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) Dual-Doppler Tracking System Receiver (CNES).

(2) Experimental Sensors.
  (a) Single-Frequency Solid-State Radar Altimeter (SSALT) (CNES).

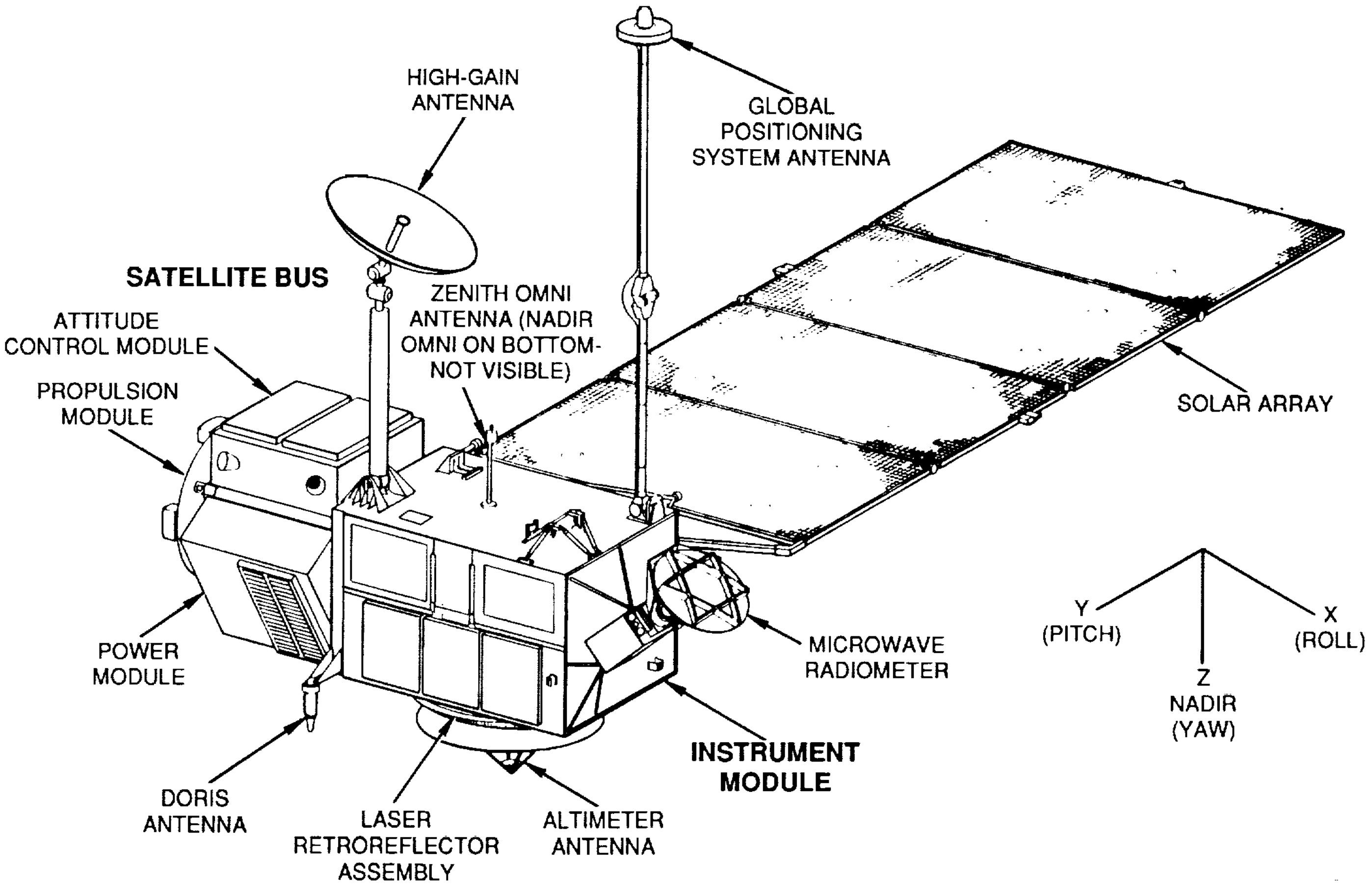

Figure 2. Satellite configuration (deployed).

Table 2. TOPEX/POSEIDON instrument characteristics

Instrument	Purpose	Frequency	Accuracy (required)	Mass	Power draw
Dual-Frequency Radar Altimeter (ALT)	Measures height of satellite above the sea, wind speed, wave height, and ionospheric correction	13.6 GHz 5.30 GHz	±2.4-cm altitude	206 kg	237 W
TOPEX Microwave Radiometer (TMR)	Measures water vapor along the path viewed by the altimeter; this measure corrects altimeter data for pulse delay due to water vapor	18.0 GHz 21.0 GHz 37.0 GHz	±0.2-g/cm^2 water-vapor density (equivalent to 1.2 cm)	50 kg	25 W
Laser Retroreflector Array (LRA)	Used with ground-based lasers to track the satellite and to calibrate and verify altimeter measurements of height	—	±2-cm overhead ranging	29 kg	—
Single-Frequency Solid-State Radar Altimeter (SSALT)	Measures height of satellite above the sea, wind speed, and wave height	13.65 GHz	±2.5-cm altitude	26 kg	55 W
DORIS Dual-Doppler Tracking System Receiver	Receives signals from ground stations for satellite tracking, gravity field measurements, and ionospheric correction for the SSALT	401.25 MHz 2036.25 MHz	≤0.3-mm/s radial velocity	43 kg	21 W
GPS Demonstration Receiver (GPSDR)	Provides a new tracking data type (range differences) for precision orbit determination	1227.6 MHz 1575.4 MHz	10-cm altitude	28 kg	29 W

(b) Global Positioning System Demonstration Receiver (GPSDR) (NASA).

Listed in Table 2 are the characteristics of these instruments. The ALT is the primary instrument for the mission. The altimeter measurements made at the two frequency channels will be combined to obtain precise altimeter height measurements over the oceans of the world. This measurement will be free from errors caused by ionospheric free electrons, of which the total content will be obtained as a by-product of the measurement. The TMR will use the measurement of sea surface microwave brightness temperature at three frequencies to estimate the total water-vapor content in the atmosphere; this estimate will correct errors in the altimeter measurement that result from this source. The 21-GHz channel is the primary channel for water-vapor measurement. The 18-GHz and 37-GHz channels are used to remove the effects of wind speed and cloud cover, respectively, in the water-vapor measurement. The LRA will be used with a network of Satellite Laser Ranging (SLR) stations (see Figure 3) to provide the baseline tracking data for precision orbit determination and calibration of the radar altimeter bias. The DORIS tracking system will provide an alternate set of tracking data using microwave Doppler techniques for precision orbit determination. The DORIS system has been successfully demonstrated by the SPOT-2 Mission. The system is composed of an onboard receiver and a network of ground transmitting stations (see Figure 4). The signals are transmitted at two frequencies to allow the removal of the effects of the ionospheric free electrons in the tracking data. Therefore, the total content of the ionospheric free electrons can also be estimated from the DORIS data and used as ionospheric correction for the SSALT.

The two experimental instruments are intended to demonstrate new technology. The GPSDR will use the new technique of differential ranging for the precise, continuous tracking of spacecraft with decimeter accuracy. The SSALT, a solid-state Ku-band altimeter, will validate the technology of a low-power, low-weight altimeter for future Earth-observing missions. It will share the antenna used by the ALT. During the initial 6-month verification phase of the mission, the SSALT will operate for about 12% of the time to assess its performance. For the rest of the mission, an antenna-sharing plan will be determined by the Joint Steering Group, a NASA–CNES management group overseeing the conduct of the mission. This decision will take into account the recommendation of the Science Working Team.

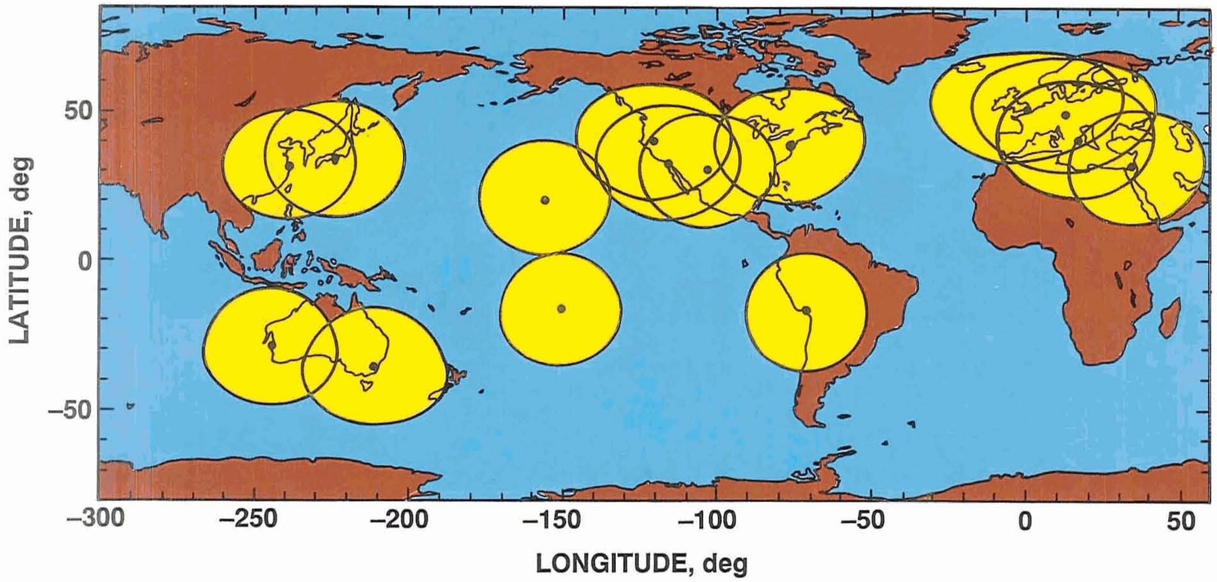

Figure 3. TOPEX/POSEIDON satellite laser ranging network. Circles indicate visibility masks around the stations.

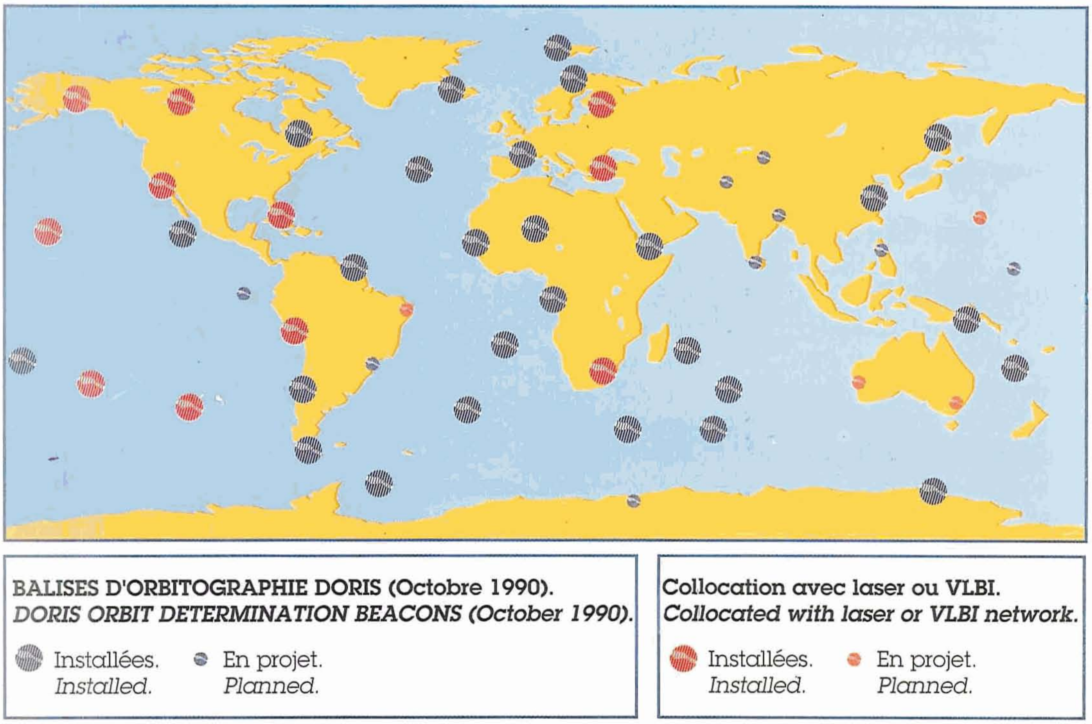

Figure 4. DORIS beacon network. Large circles indicate installed stations and small circles indicate those stations planned as of October 1990. Red circles are the stations collocated with the laser or VLBI network.

D. Orbit Configuration

Many factors influence the determination of the mission's orbit configuration. The inclination and repeat period of the orbit determine how the ocean is sampled by the satellite. A major concern is aliasing the tidal signals into frequencies of ocean current variabilities. Inclinations and repeat periods that lead to undesirable aliased tidal frequencies—such as zero, annual, and semiannual—are to be avoided. To reach the mission science goal of accurate estimates of ocean tides, inclinations and repeat periods that make different tidal constituents aliased to the same frequency should also be avoided. To satisfy these constraints and yet cover most of the world oceans, an inclination of 66 deg has been selected by the Science Working Team.

For a single satellite mission, temporal resolution and spatial resolution are in competition: the higher the temporal resolution, the lower the spatial resolution, and vice versa. A repeat period of 10 days (127 revolutions) has been chosen by the Science Working Team as a compromise that also takes the tidal aliasing problem into consideration. This choice results in an equatorial cross-track separation of 315 km.

To maximize the accuracy of orbit determination, a high orbit altitude is preferred because of the reduced atmospheric drag on the satellite. A major disadvantage of a high orbit is the increased power needed by the altimeter to achieve the required level of signal-to-noise ratio. A compromise is in the range of 1200 to 1400 km. Within this range, the exact altitude that allows the orbit to satisfy all other constraints and fly over the two verification sites (Point Conception off California and Lampedusa Island in the Mediterranean Sea) is 1336 km. Shown in Table 3 are the characteristics of the baseline mission orbit.

Table 3. Characteristics of the operational orbit

Parameter	Symbol and value
Mean elements	
Semimajor axis, km	$a = 7714.4278$
Eccentricity	$e = 0.000095$
Inclination, deg	$i = 66.039$
Inertial longitude of ascending node, deg	$\Omega = 116.5574$
Argument of perigee, deg	$\omega = 90.0$
Mean anomaly, deg	$M = 253.130$
Auxiliary data	
Reference equatorial altitude, km	$h = 1336$
Nodal period, s	$P_N = 6745.72$
Cycle (127 revs) period, days	$T = 9.9156$
Inertial nodal rate, deg/day	$\Omega = -2.0791$
Longitude of equator crossing of pass 1, deg	$\lambda = 99.947$
Acute angle of equator crossings, deg	$\alpha = 39.5$
Ground-track velocity, km/s	$v = 5.8$

E. Precision Orbit Determination

The satellite orbit tracking provided by the laser ranging and DORIS is not continuous in time. Orbit computation based on dynamic equations and the tracking data is required to produce a continuous, precise orbit for the mission. Precision orbit determination teams have been established by both NASA and CNES to accomplish this task. Because orbit error is the most significant error source for the sea level measurement, a long-lead prelaunch effort has been made by these teams to develop a much improved model for the Earth's gravity field to be used for the orbit determination. A hierarchy of progressively improved models has been produced by this effort (e.g., Marsh et al., 1988 and 1990). After the launch of the satellite, these teams will use the satellite tracking data to further "tune" the gravity model to optimize it for the mission. Knowledge of the spectral characteristics of the remaining orbit errors will be used by the Principal Investigators for further improvement of the orbit accuracy.

F. Measurement Accuracy

Based on the expected performance of the instruments and orbit determination, an attempt has been made to estimate the error budget for the TOPEX/POSEIDON altimetry system. The uncertainty in the altimeter measurement of sea level can be ascribed to altimeter instrument errors, media errors, and orbit errors. Given in Table 4 is an estimated budget for the various errors and their decorrelation scales. Note that this error budget is based on a one-measurement-per-second sampling rate, which corresponds to an along-track resolution of 6 km. The required instrument precision of 2.4 cm as stated in Subsection A is imposed for a distance of 20 km (3-s average). The estimated instrument precision is thus consistent with this requirement. It is anticipated that the dominant orbit errors will be further reduced by the research work of the Principal Investigators. The accuracy of the resultant analyzed sea level data is expected to be significantly less than 10 cm.

G. Verification

Verification of the performance of the satellite and the instruments and the integrity of the science data is a continuing process involving participation from both the project teams and the Principal Investigators. However, during the first 6 months of the mission, an intensive campaign will be conducted jointly by NASA and CNES to calibrate and verify satellite measurements of geophysical parameters against in situ data at two verification sites. In addition, satellite laser ranging will be used to validate precision orbit determination and to tune the gravity field model that is to be used during the Observational Phase of the mission.

Table 4. Estimated error budget for TOPEX/POSEIDON measurements of sea level (1-s average)

Error source	Uncertainty, cm	Decorrelation distance, km
Altimetry		
Instrument noise[a]	4.1	6
Bias drift	2.0	>>10,000
Media		
Electromagnetic (EM) bias	2.0	50 to 1000
Skewness	1.0	50 to 1000
Troposphere, dry	0.7	1000
Troposphere, wet	1.2	50 to 1000
Orbit		
Gravity	10.0	10,000
Radiation pressure[b]	6.0	>10,000
Atmospheric drag	3.0	>10,000
GM (gravitational constant × mass of the Earth)	2.0	10,000
Earth and ocean tides	3.0	10,000
Troposphere	1.0	10,000
Station location	2.0	10,000
RSS absolute error	13.8	

Major Assumptions:

1. Dual-frequency altimeter
2. Three-frequency radiometer
3. Fifteen laser tracking stations
4. Altimeter data averaged over 1 s
5. $H_{1/3} = 2$ m; wave skewness = 0.1
6. Tabular corrections based on limited waveform-tracker comparisons
7. 1300-km altitude
8. No anomalous data, no rain
9. Improved gravity model: postlaunch adjustment of prelaunch solution
10. ±3 mbar surface pressure from weather charts
11. 100-μs spacecraft clock

[a] Including the noise in the ionospheric correction by the dual-frequency altimeter measurements.

[b] Solar, Earth, and Thermal Radiation.

NASA will instrument an oil platform 12 km west of Point Conception, California, to obtain data on sea level and related parameters. Sea level measurements will be made by an acoustical device and pressure gauges mounted on the oil platform. The sea level data along with laser data and GPS survey data from nearby tracking sites will be used to determine the distance between the satellite and the sea surface; this distance will then be compared with the altimeter range measurement to determine the altimeter bias and bias drift. Other instrumentation at the oil platform will include a GPS receiver for station positioning and calibration of the total electron content, a surface pressure gauge for dry-troposhere correction, and an upward-looking water-vapor radiometer for the wet-troposphere correction. The current plan also calls for the deployment of two other upward-looking water-vapor radiometers at two widely separated locations to calibrate the TMR measurement.

CNES will instrument a small islet, Lampione, located 18 km west of Lampedusa Island in the Mediterranean Sea. The minimum instrumentation configuration includes a laser on Lampedusa, a tide gauge on Lampione, a tide gauge on the west side of Lampedusa, deep-sea pressure gauges between the two islands, a DORIS station on Lampedusa, radio soundings and a ground-based radiometer, a meteorological station, and wind and wave buoys. These instruments will be used to verify sea level, atmospheric pressure, wind speed, wave height, water vapor, electromagnetic bias, wave skewness, and precision orbit determination. Ionospheric corrections will be verified by comparison of DORIS and GPS measurements with the ALT-derived ionospheric corrections and with data from the European Incoherent Scatter Radar System (EISCAT).

H. Data Processing and Distribution

The primary data product for oceanographic research is the Geophysical Data Record (GDR), which includes the altimeter sea level height measurements, associated corrections, useful ancillary data, and measurement locations based on the precision orbit ephemeris. The GDR will be generated on a global basis as an archival data product after the completion of the initial verification activities conducted during the first 6 months of the mission (the Initial Verification Phase). During the Initial Verification Phase, an Interim Geophysical Data Record (IGDR) will be generated for verification purposes. This data record will be based on unverified data and the operational orbit ephemeris (as opposed to the precision ephemeris).

NASA and CNES will process GDRs and IGDRs for each agency's own altimeter measurement. The two products will be exchanged and shared by all the Principal Investigators through the services of the NASA Ocean Data System (NODS) and the French data center, AVISO. Access to the data by the general science community will also be provided by these two data centers.

I. Mission Phases

The mission will be conducted in five phases: Launch, Assessment, Initial Verification, Observational, and Extended Observational. Each phase is characterized by and named for its main priority. However, the primary activities of a phase are not necessarily limited to that phase. Such is the case with the Assessment Phase, where engineering assessment begins almost immediately and continues, although limited, for the duration of the mission. The timeline of the five phases and the major activities in each phase are shown in Figure 5.

The Launch Phase begins approximately 45 days before launch with the arrival of the satellite at the Ariane Launch Complex at Kourou, French Guiana. Priorities during this phase center on preparing the satellite for launch (integration with the launch vehicle, communications testing, and operation teams testing). This phase officially ends when the satellite separates from the launch vehicle, nominally 18.3 minutes after launch.

The Assessment Phase begins with the separation of the satellite from the launch vehicle and injection of the satellite into the initial injection orbit. At the end of this phase, nominally 32 days after launch, the satellite and sensor systems will have been deployed, activated, and functionally certified, and the satellite will have achieved the operational orbit. All sensor data collected before the operational orbit is achieved will be used for engineering evaluation only and will not be processed as science data.

Although some verification activities may begin when the sensors have been turned on and continue through the mission, the Initial Verification Phase properly follows the Assessment Phase. During the Initial Verification Phase, in situ data and laser ranging data will be collected from the two verification sites for verifying the altimeter measurement. Up to 40% of the sensor data will be processed into IGDRs using the operational-orbit ephermeris data; these IGDRs will be distributed to the Principal Investigators for verification studies. Tracking data from the Satellite Laser Ranging Network will be used by the Precision Orbit Determination Task Group to develop a specially "tuned" gravity model for use in subsequent precision orbit determination. At the end of this phase, approximately 6 months after launch, all the geophysical measurements will have been calibrated and verified, and the parameters necessary for the production of the GDRs will have been approved.

The Observational Phase begins at the completion of the Initial Verification Phase and continues to the nominal end of the mission, 3 years after launch. The priorities in this phase are recording scientific data and maintaining the satellite in a state that insures satisfaction of the science requirements. Sensor data are collected and processed into GDRs for distribution to the Principal Investigators and the general science community. The Principal Investigators will use the data to conduct their science investigations. All data collected before the Observational Phase and after the satellite has been placed in operational orbit will be processed retroactively into GDRs, with the operational orbit ephermeris replaced by the precision orbit ephermeris.

At the end of the 3-year mission, if resources permit and the satellite and instruments are in good condition, the mission will enter into the Extended Observational Phase for 2 additional years. The activities of this phase will be similar to those of the Observational Phase.

J. Management

The Jet Propulsion Laboratory of the California Institute of Technology, under a contract with NASA, has the responsibility of project management for the TOPEX/POSEIDON Mission. This responsibility includes mission planning and control, acquisition of the satellite, development and acquisition of the NASA sensors, design and development of the NASA ground data system, and control of the system interfaces. Within CNES, Centre Spatial de Toulouse is responsible for the Ariane launch-vehicle system and launch services; participation in mission design, management, and development of the CNES sensors; and development of the CNES ground data system.

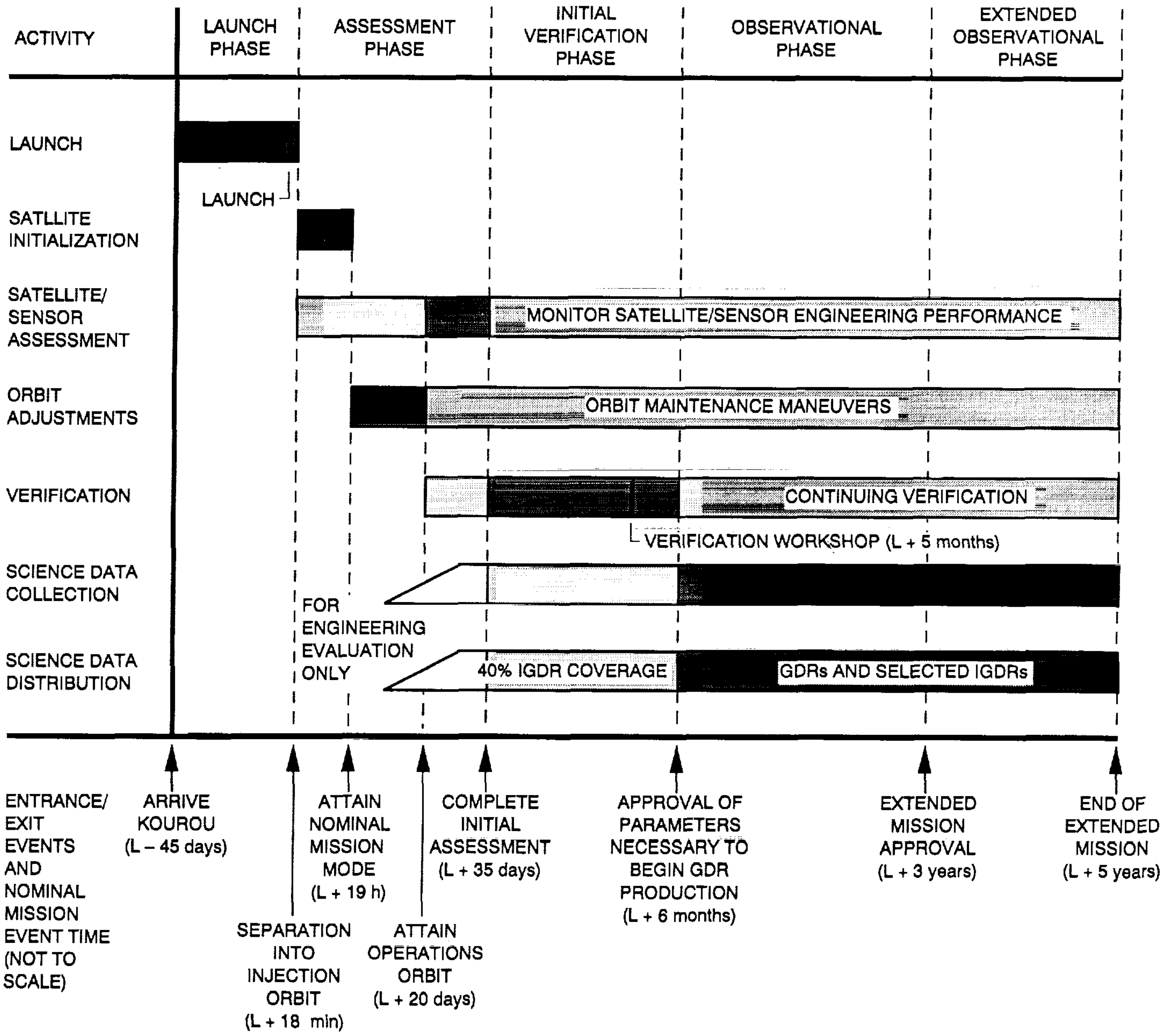

Figure 5. Mission timeline (time is not to scale). Top-priority activities in a given phase have the darkest shading.

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III. The TOPEX/POSEIDON Science Investigations

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The Western Mediterranean Sea: An Area for a Regional Validation for TOPEX/POSEIDON and a Field for Geophysical and Oceanographic Studies

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The research project has two kinds of objectives. The first is focused on the regional validation of the altimeter, orbit, and mean sea surface; it will be performed in close cooperation with the local validation performed at Lampedusa/Lampione (Italy). The second deals with the geophysical and oceanographic research of interest in this area.

I. Objectives of the Regional Validation

(1) To compute a reference mean sea surface determined over a certain interval of time. This reference mean sea surface will be based on Seasat and Geosat data by taking into account the constraints given by tide gauge data.

(2) To estimate local altimeter measurement corrections and oceanographic and meteorological effects on the sea surface topography, thanks to models and observations.

(3) To compare, pass by pass, the altimetry profile measured with the profile computed from the orbit data and the reference mean sea surface, taking into account all the different corrections (oceanographic, meteorological, and ionospheric).

(4) To compare the computed orbits, which are referred to the same geodetic system and based on different tracking systems (Global Positioning System (GPS), laser, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and laser/DORIS) and/or different gravity field models.

(5) To compute a very good regional orbit in the reference system for comparison with global orbits (short-arc orbit determination based on regional laser and DORIS data).

(6) To compare the different mean sea surfaces based on TOPEX/POSEIDON data and computed on a periodic basis with a reference mean sea surface (Seasat/Geosat data), taking into account oceanographic and meteorological effects.

(7) To compare the gravimetric geoid and the mean sea surfaces, taking into account the oceanographic and meteorological effects.

(8) To validate the precise orbit determination and the mean sea surface computation from the different comparisons, taking into account the error budgets. Interpretation of results in terms of the

TOPEX/POSEIDON mission objectives and altimeter calibration.

II. Scientific Objectives

(1) To interpret the altimeter signal and the sea surface topography in terms of geophysics and oceanography. The mesoscale and seasonal variability of the altimeter data in the whole western Mediterranean Sea will be compared with both in situ data (current and sea level data) and other remotely sensed data (temperature and color). The comparison between theoretical oceanographic models under development and the observed mean sea surface should also make possible an improvement of models, thanks to assimilation techniques. A specific effort will be performed around the Straits of Gibraltar to connect the sea surface of the western Mediterranean Sea to the sea surface of the Atlantic Ocean; the approach has to be defined.

(2) To study the secular changes of the mean sea level (long-term study).

(3) To study the crustal motion deduced from the geodetic-network deformation. The order of magnitude of displacements in this region is thought to be below 1 cm/year. In spite of this small value, the existence of geodetic measurements performed in the past century between Italy, France, Spain, Morocco, Algeria, and Tunisia and the recent geodetic campaign (transit, laser, GPS) could make the reliable determination of deformation possible in the years to come by pursuing measurements with the different techniques available (very long baseline interferometry (VLBI), laser, GPS, Precise Range and Range-rate Equipment (PRARE), and DORIS) (long-term study in the frame of the Wegener-Medlaser Experiment, chaired by P. Wilson). The geophysical interpretation will be made later.

III. List of Different Actions

The regional validation requires consideration of the geodetic, oceanographic, and meteorological concerns. For each of these, several features have been identified.

A. Geodetic Concerns

Our purpose is to establish a homogeneous geodetic network around the western Mediterranean Sea (Figure 1). The different techniques used are

(1) Laser telemetry.

  (a) A regional laser network located at Lampedousa, Matera, and Cagliari, Italy; Grasse, France; Graz, Austria; Zimmerwald, Switzerland; Wettzell, Germany; Royal Greenwich Observatory, England; and San Fernando, Spain (Wegener-Medlaser network). A regional coordinated network has been constituted: EUROLAS.

  (b) A new mobile laser station for calibration.

(2) The DORIS network. There are three fixed stations located at Toulouse, France; Dyonissos, Greece; and Arlit, Algeria.

(3) GPS network. Presently, there are several fixed stations in Europe, located at Tromosö, Norway; Onsala, Sweden; Wettzell, Germany; and Madrid, Spain. An important densification campaign, European Reference Frame (EUREF), was carried out in Europe in May 1989; it involved most of the geodetic institutions. The results should be available in 1991. Another cooperative campaign widely open is scheduled between 1991 and 1993 for North Africa (Tunesia, Algeria, and Morocco) and includes a tide gauge network around the Mediterranean Sea (Figure 2).

(4) VLBI network. Presently there are several fixed stations in southern Europe, located at Madrid, Spain; Wetzell, Germany; and Bologna, Matera, and Noto, Italy. An extension of the existing network was achieved in the summer of 1989 in the frame of a cooperative effort between America and Europe, thanks to an American mobile VLBI station; seven collocations have been established (two locations are in France (Brest and Grasse)). Unfortunately, it has been not possible to visit Algeria (Tiaret) as scheduled. A decision on a new campaign could be reached in 1992 or 1993. Data obtained in 1989 have been processed.

(5) Tide gauges. The tide gauges have to be tied to the geodetic network by reason of the GPS. Cooperation with the different countries surrounding the western Mediterranean Sea is foreseen (point (3) above).

(6) Gravimetric geoid. Cooperation with other European institutions involved in similar work will be desirable.

Assessment. The schedule of the different geodetic efforts seems quite compatible with the TOPEX/POSEIDON schedule.

B. Oceanographic Concerns

Our purpose is to model the oceanographic aspects. Several models are already available in Europe (in Italy, France, and Belgium) and several efforts have been undertaken already. Moreover, an international oceanographic program, Programme de Recherche International en Méditeranée Occidentale (PRIMO), has been initiated in the western Mediterranean Sea to bring together resources and expertise primarily to gather knowledge of the general circulation of the basin. This program will be of very great use in the regional validation of TOPEX/POSEIDON.

Specific concerns have been identified:

(1) Circulation and seasonal flux variation. It must be emphasized that many data exist in some specific areas such as the Ligure Sea, where hydrological data have been regularly collected between 1950 and 1973 and during other long, uninterrupted periods. Current measurements have also been collected in the Algerian Basin during the Mediprod-5 experiment. All these data should permit interesting comparison with the altimeter data. Moreover, taking into account the development of physical models, including one of seasonal variability, the comparison of these models with the altimeter data should yield an improvement in the models because of assimilation techniques. These studies will start with Geosat data. A cooperation will be developed with Groupe de Recherches de Géodésie Spatiale (GRGS), Toulouse and Lodyc, as well as with our Italian and Spanish colleagues.

(2) Mean sea surface topography. Computations have already been carried out with Geosat and Seasat data; softwares exist.

(3) Oceanic Tides.

Assessment. The schedule of these efforts seems compatible with the schedule of the TOPEX/POSEIDON. It requires a lot of computing time and manpower, but many data already exist.

C. Meteorological Aspects

Meteorological information is needed for corrections and, at first, altimeter measurements. As a matter of fact, information will be made available by the data bank. However, regional and specific analyses will be of great interest. These objectives will be taken in charge by the "Direction de la Meteorologie Nationale," but the required actions have to be precisely defined.

D. Orbitography Aspects

The quality of the global orbit will improve in the local areas because of short-arc orbit determination. Software has been developed at GRGS/Toulouse and at GRGS/Grasse. The orbitography will be based first on laser then on DORIS and PRARE (for European Remote Sensing satellite (ERS-1) studies to prepare for TOPEX/POSEIDON); a comparison between both systems will be performed.

E. Verification by an Independent Technique

A radar located at Valensole, France, can probe the sea state as well as the ionosphere because of electromagnetic waves emitted from Valensole, reflected by the ionosphere, and then rediffused by the sea before returning to Valensole.

This original experiment could permit comparison of the results obtained totally independently by the altimeter data in the Mediterranean Sea near southern Italy and the radar Valensole data.

IV. Synthesis of the Different Efforts: Conclusions for the Regional Validation

This task is of a cooperative nature and includes all the participants, particularly those of GRGS/Grasse.

A specific comparison will be made with the results of the local calibration performed at Lampedusa/Lampiona.

Assessment. We expect to validate the orbits, the mean sea surface determination, and the quality of the altimeter measurements as a whole. In spite of some uncertainties of support, particularly manpower, the schedule seems a priori consistent with the requirements of the TOPEX/POSEIDON mission. International cooperation with the countries surrounding the Mediterranean Sea is under a more precise definition. The program begins with the analysis of Seasat/Geosat data.

V. Data Required From the TOPEX/POSEIDON Project

(1) Global and precise orbital elements.

(2) Laser and DORIS regional tracking data (European–African area).

(3) Altimeter data on the Mediterranean Sea and the adjacent Atlantic Ocean.

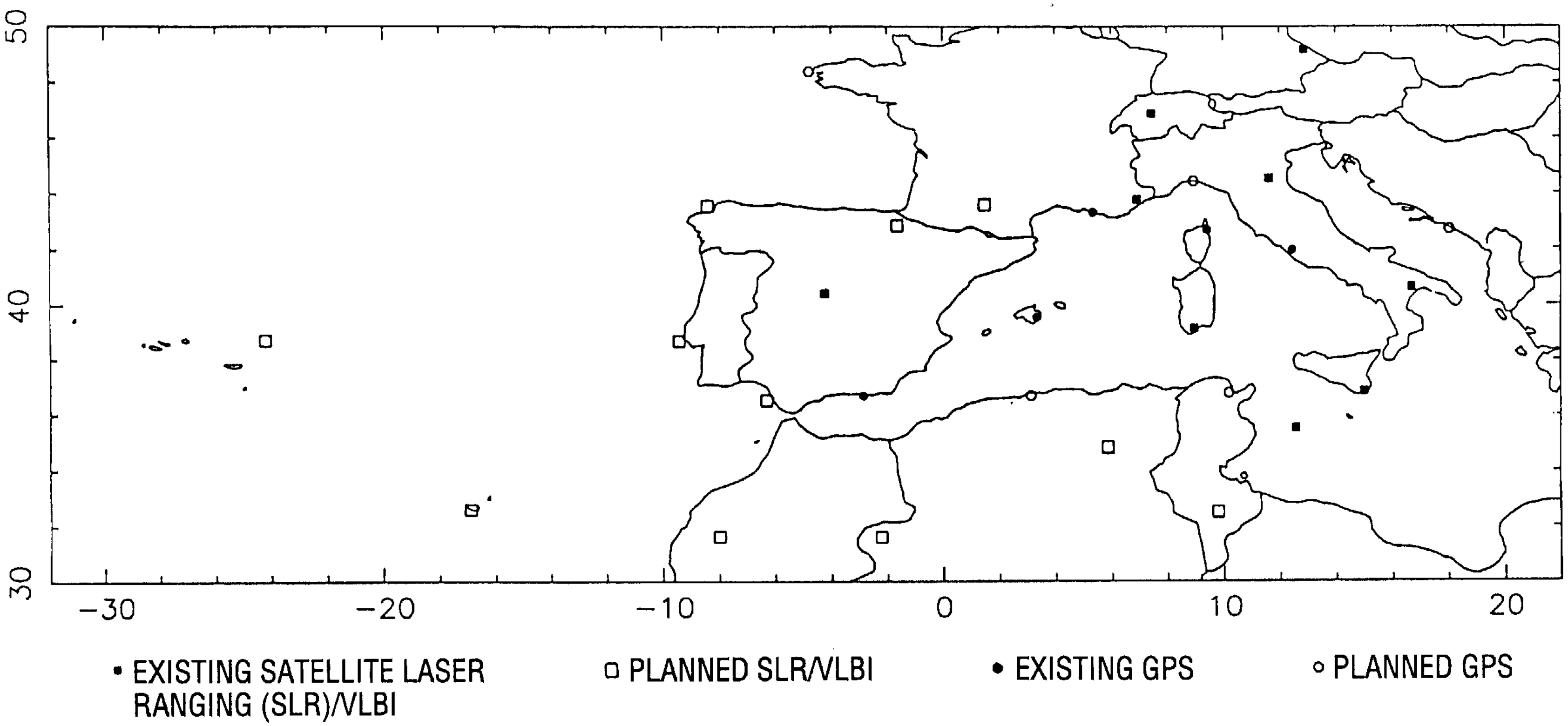

Figure 1. Possible occupation sites.

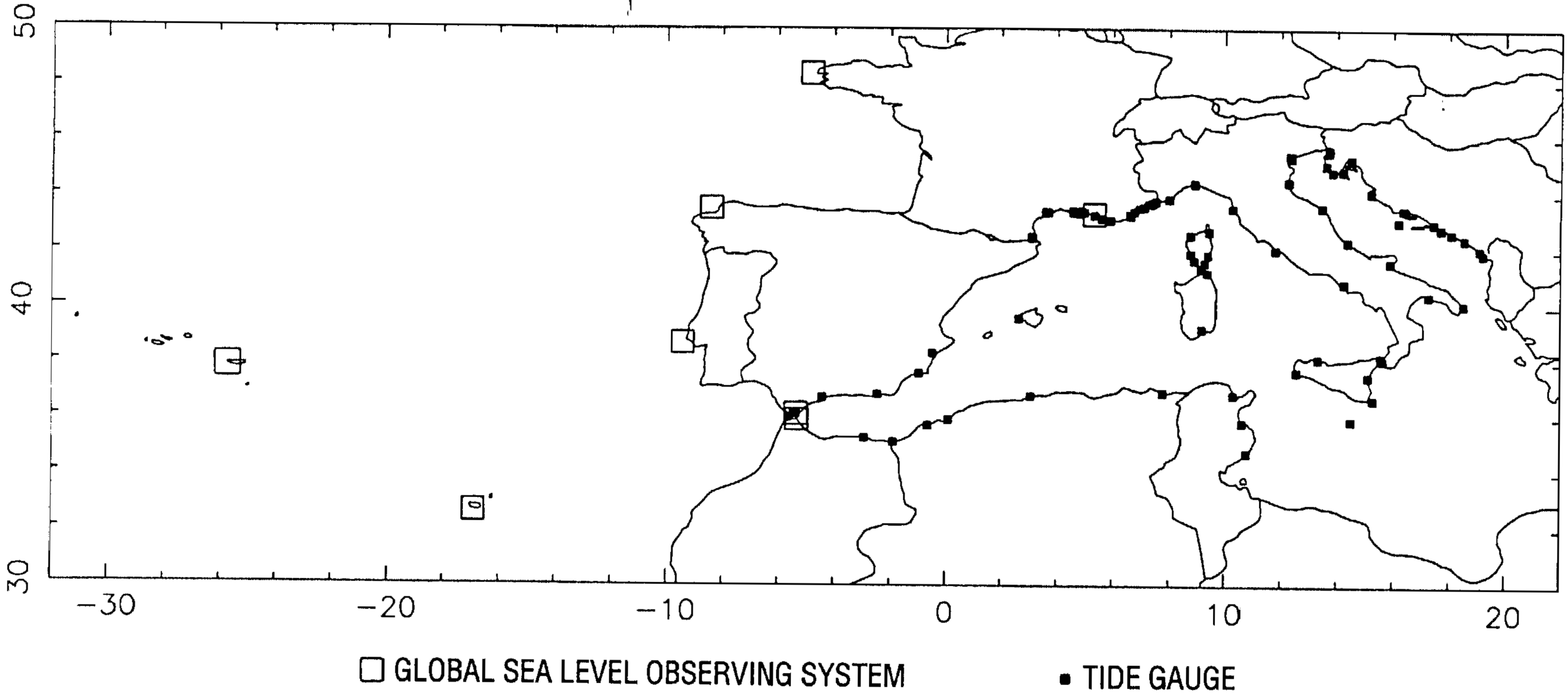

Figure 2. Tide gauge network (global sea level monitoring system).

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P-4

The Use of Satellite Altimetry in the Study of Weakly Defined and Variable Oceanic Gyres

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I. Introduction

Most of what is known about oceanic gyres comes from studies of the two main Northern Hemisphere subtropical gyres. Also important in the overall circulation of the world's oceans are the Southern Hemisphere subtropical gyres and the cyclonic Alaskan Gyre in the northern Pacific. Due in part to their weaker surface topography signatures and their variable character, these gyres have not been observed and studied as well as the northern subtropical gyres. The combination of satellite altimetry with in situ ocean measurements will lead to improved resolution of the interannual and seasonal change in the circulation of these ocean gyres. Also, it will provide initialization input and verification for numerical modeling work designed to better understand internal gyre dynamics. The objective of this proposal is to combine satellite and in situ data in a study dedicated to a better understanding of the basic structure and dynamics of the weakly defined Southern Hemisphere gyres and the Alaskan Gyre and their roles in oceanic heat and mass transport of the world ocean. Emphasis will be on description of the Alaskan Gyre.

The Alaskan Gyre offers an opportunity to use satellite altimetry to study a gyre forced primarily by wind and the salinity field rather than temperature, as is the case for both Northern Hemisphere subtropical gyres. Starting in late 1986 and early 1987, an extensive program of in situ data collection, called the Northeast Pacific Circulation Study (NEPCS), was started in the Gulf of Alaska (W. Emery, Principal Investigator). This program has been renamed the Gulf of Alaska Recirculation Study (GARS) by Tom Royer of the University of Alaska, who is now the Principal Investigator. In this study, repeated hydrographic sections (including conductivity/temperature/depth), moored current meters, and satellite-tracked drifting buoys are being used to properly resolve the mean Alaskan Gyre circulation and its variability. Fortuitously, the Geosat Exact Repeat Mission (ERM) gathered satellite altimetry data coincident with the GARS in situ data. While Geosat altimetry is limited in accuracy compared to that anticipated for TOPEX/POSEIDON, this combination of satellite altimetry and in situ data provides an excellent opportunity to develop analysis procedures for the more accurate TOPEX/POSEIDON data in order to define the weaker Alaskan gyre and monitor its variability.

Our primary emphasis, therefore, will be the study of the Alaskan Gyre in order to define its variability and determine the relationship of this variability to changes in the forcing by wind and fresh-water runoff. Our prelaunch phase approach will involve limited methodology development for ingesting satellite and other in situ data into numerical models of the circulation in this subpolar gyre. The feasibility of these methods will be tested using Geosat altimetry and GARS in situ data. To the extent that numerical modeling of the gyre circulation is required, we will collaborate with the science team headed by Lee-Lueng Fu. This team is also studying ocean gyres and has a strong numerical modeling element under the direction of William Holland. The postlaunch phase will concentrate on the exploitation of TOPEX/POSEIDON and available in situ data to define the long-term mean and seasonal changes in the circulation of the Alaskan Gyre.

If time and resources allow, we will also apply the methods developed for the study of the subtropical gyre in the South Pacific. Unlike gyres in the other Southern Hemisphere oceans, a gyre in the South Pacific has not been well established. Climatological mean maps of surface dynamic topography do not show a well-developed anticyclonic circulation. Thus, we will explore the use of Geosat altimetry to define at least the variability of the surface signature of the subtropical gyre in the southern Pacific. While it may prove that such a gyre does not exist in the classical sense, it will be useful to define the primary surface signatures of the circulation in this region. Specific questions to be addressed are

(1) What is the overall structure and long-term (months to years) variability of the Alaskan and South Pacific Gyres?

(2) How is the circulation in the Alaskan Gyre related to its forcing by wind and fresh-water input?

(3) What is the role of the Alaskan Gyre in the transport of heat between the equator and the poles?

(4) How does the circulation of the Alaskan Gyre relate to that of the subtropical gyre in the North Pacific?

(5) How is the circulation of the subtropical gyre in the South Pacific related to that in the Antarctic Circumpolar Current and how do these circulations affect the meridional transport of heat and mass in the oceans?

II. Preliminary Results: Annual and Seasonal Variability in the Gulf of Alaska

To get the first altimetry view of the circulation in the Gulf of Alaska, yearly and seasonal variabilities for the area were computed. To do this, the first 22 cycles (approximately one year) of data from the Geosat Exact Repeat Mission were extracted from the Geophysical Data Records and interpolated to a regular grid. A mean track was computed and removed for each pass in the region. Then orbit error was removed from the residual heights by subtracting a linear trend and bias whose coefficients were computed by a weighted, iterative, least-squares procedure. Then the root-mean-square (rms) variability along each track was calculated. To map the along-track rms variability to a regular grid, a biquadratic surface estimation procedure was used with a cap size of 1.5 deg, and all points within the cap were weighted equally. The resulting maps are shown in the two figures in color-image form. The area shown on these maps covers 30° to 60°N and 180° to 240°E.

Figure 1 shows the rms variability for the entire year. The result agrees fairly well with what is known about the gulf from hydrographic data, although magnitudes of the variability are somewhat higher than expected because very little spatial smoothing was used. A band of high variability corresponding to the Alaskan Stream extends along the coast. South of where the Aleutian Islands start, there is a tongue of fairly high energy that extends southward and eastward and seems to indicate the existence of recirculation back into the gyre. Another high-variability region is off the California coast where the North Pacific Current bifurcates into northward- and southward-flowing components.

Figure 2 shows the rms variability for each season about the yearly mean. The four frames start with the winter variability in the upper left; this is followed by the spring in the upper right, and the summer and fall in the bottom left and right, respectively. The seasonal variability maps clarify the picture given in the yearly map. It can be seen that winter has the highest amount of activity, with clear evidence of recirculation of part of the Alaskan Stream back into the gyre. This recirculation is not evident in either spring or summer. During fall, the pattern seems to be heading back to the winter condition, although, due to high data outage, this season was sampled less than the others. The extreme high values in all the frames in the Aleutian Islands region and in the Bering Sea are probably caused by inexact modeling of tides in shallow waters. Still, the maps do seem to show part of the Alaskan Stream flowing into the Bering Sea, especially in fall.

We also have computed mean sea surfaces in the Gulf of Alaska using Geosat data. An accurate mean surface (geoid) is required to determine the general circulation in the Gulf of Alaska.

III. Conclusion

Preliminary processing of Geosat and in situ data to determine a mean surface and seasonal variability in the Gulf of Alaska has been successful. We will continue our prelaunch plans to learn as much as possible about the Gulf of Alaska from Geosat and in situ data. After the launch of TOPEX/ POSEIDON, this information, together with the techniques developed during the prelaunch phase of the project, will be used to maximize information obtained from the more accurate TOPEX/POSEIDON data.

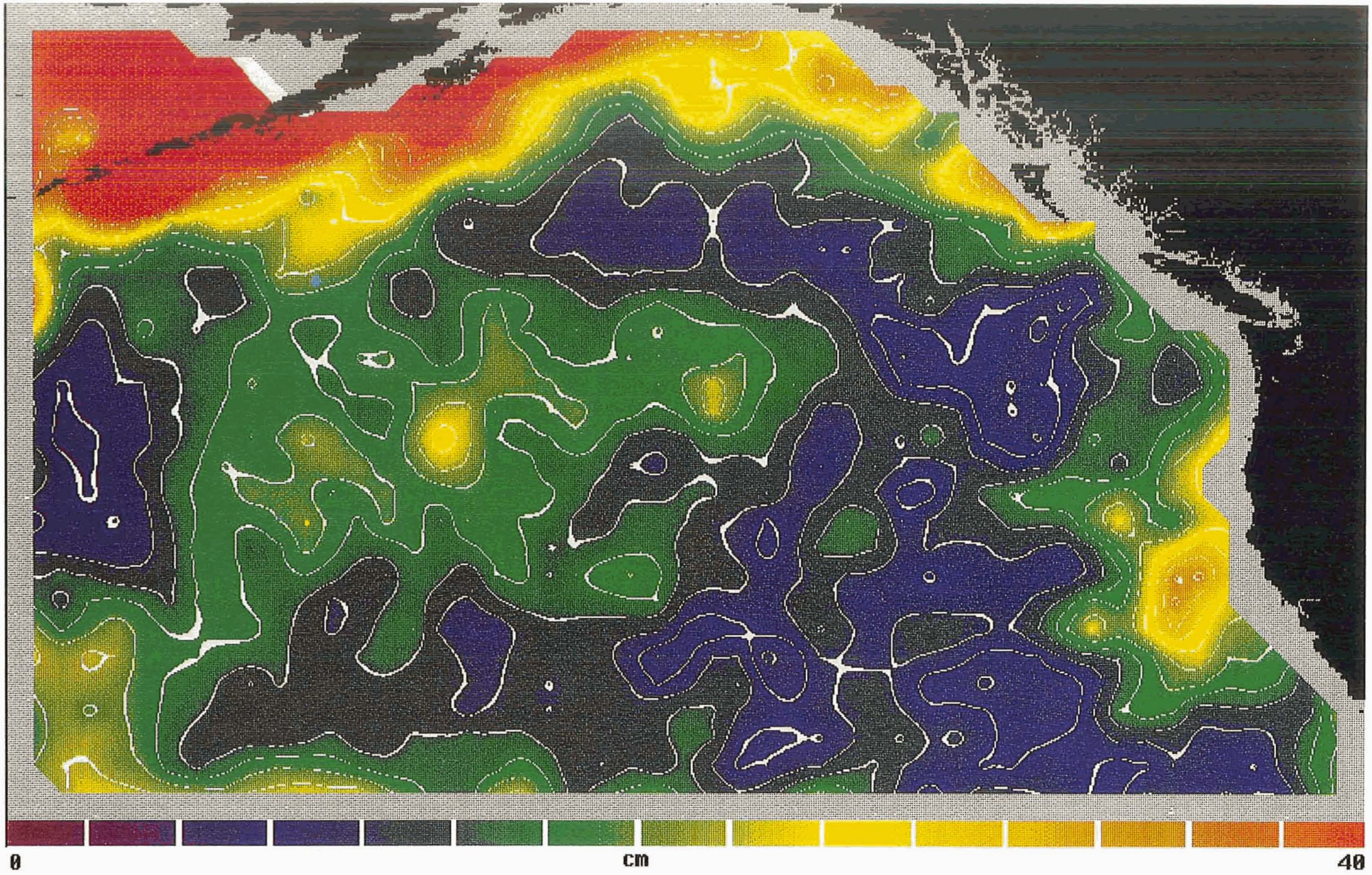

Figure 1. Yearly variability in the Gulf of Alaska.

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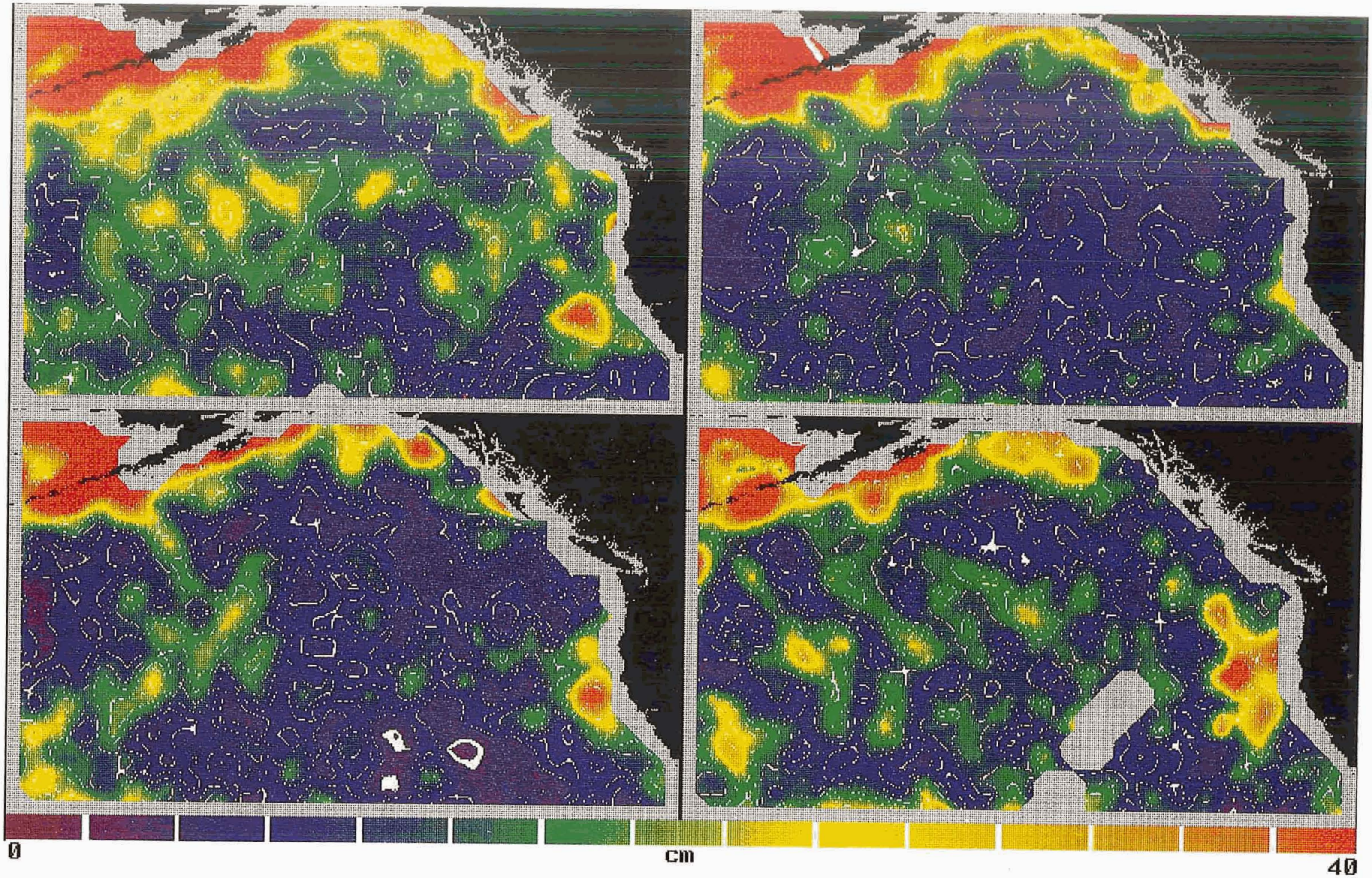

Figure 2. Seasonal variability in the Gulf of Alaska: upper left, winter; upper right, spring; bottom left, summer; bottom right, fall.

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Terrestrial Reference Systems Related to the TOPEX/POSEIDON Project

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I. Scientific Objectives

In the TOPEX/POSEIDON project, several satellite positioning systems, such as Laser, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and Global Positioning Satellite (GPS) (on an experimental basis), will be used to track the satellite and to provide accurate orbits. Unfortunately, these systems will provide their dedicated tracking-station coordinates and the satellite orbits in different reference frames. Each technique will use, de facto, a different reference frame. In fact, even for the same technique, each group, depending on the hypothesis used in its computation, will use a different reference frame. This problem is not new for geodesists and can be overcome, in large part, but could create trouble for other scientists when they compare or combine different coordinate data sets.

The main purpose of this investigation is to *determine a consistent terrestrial system for TOPEX/POSEIDON* in which all the tracking-station coordinates, all the orbit ephemerides, and all the other station coordinates of specific interest (such as tide gauges) could be expressed. Another issue of this investigation is the *provision of reliable information concerning the relationships between all the possible reference frames of interest* for the TOPEX/POSEIDON project. To be more explicit, we plan to provide the possible transformation formula between the TOPEX/POSEIDON terrestrial reference frame and the Laser, DORIS, GPS, and other internationally recognized frames such as the International Terrestrial Reference Frame (ITRF).

All this information will be of great importance for any investigation that requires the combined use of different techniques, such as the calibration of the two radar altimeters used for the computations of sea surface topography models.

II. Detailed Proposal

First of all, one of the basic tasks of this investigation is to collect and record, from among the different scientific groups involved in this project, all the available data related to terrestrial reference frames. These data will consist primarily of different data sets of coordinates for Laser (L), DORIS (D), or GPS (P) tracking stations provided by the different dedicated computation groups (α): $X^{\alpha}_{L}, X^{\alpha}_{D}, X^{\alpha}_{P}$. It must be noted that for several sites in the world, these stations are in proximity. Also included in these potential data sets will be the position of the TOPEX/POSEIDON satellite at given epochs, computed by these groups, using one or several of these positioning techniques: $XS^{\alpha}_{L}, XS^{\alpha}_{D}, XS^{\alpha}_{P}$. We may also imagine that some groups may use combinations of these geodetic measurements to obtain a better orbit: $XS^{\alpha}_{L+D}, XS^{\alpha}_{D+P}$. Other position information will be available for some specific points, such as the ellipsoidal heights of tide gauges (T) in a specific reference frame (α): h^{α}_{T}.

By combining all these available data sets in a combined adjustment, we will determine a consistent terrestrial system for TOPEX/POSEIDON. All the previous terrestrial points will have precise coordinates (X_L, X_D, X_P, XS, h_T) expressed in this new reference frame.

Then we will compute the best possible relationships (T_{α}) between this new system and the previous systems (α): $X = T_{\alpha}(X^{\alpha})$. This should allow any group of the project to transform, as possible, any coordinates that they have computed or want to use into this unique reference frame.

In the same way, we will compute the best possible relationships (TS_{α}) between the TOPEX/POSEIDON terrestrial reference system and the previous system (α), using the orbit ephemerides expressed in those different reference systems (α): $XS = TS_\alpha (XS^\alpha)$. We will compare these TS_α relationships with the previously determined formula T_α. After a careful analysis, we will recommend the best transformations to be used for the TOPEX/POSEIDON project.

To be consistent with internationally recognized terrestrial systems (such as the International Terrestrial Reference Frame or the World Geodetic System 1984), we will also compute the best possible relationships (T_α) between these systems and the TOPEX/POSEIDON reference system.

III. Anticipated Results

By using these precise positioning systems (Laser, DORIS, and GPS), we expect to increase the accuracy of global and terrestrial reference systems. This investigation should also improve our knowledge of the precise connection of these systems.

Concerning the TOPEX/POSEIDON project, we will propose a new, precise, terrestrial-reference system (the so-called TOPEX/POSEIDON reference system) that could be used as a standard to present the terrestrial results of the different scientific groups involved.

For this purpose, a document will be issued for all the different terrestrial points of interest (e.g., tracking stations and tide gauges), including their coordinates in the different reference frames in use and also in the derived TOPEX/POSEIDON terrestrial reference frames. In this document, the best transformation formulas T_α between those systems and the TOPEX/POSEIDON terrestrial reference frame will be provided. These transformations will also be available as a subroutine and released to the project with the appropriate documentation.

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North-Australian Tropical Seas Circulation Study

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I. Introduction

This investigation is intended to fully address the stated objectives of the TOPEX/POSEIDON mission (National Aeronautics and Space Administration, 1986). Hence, we intend to use TOPEX/POSEIDON altimetry data to study the large-scale circulation of the Coral Sea Basin and the Arafura Sea and the mass exchange between these and adjoining basins. Figure 1 (adapted from Andrews and Clegg, 1989) shows volume transport streamlines in the Coral Sea for the upper 1000 m, obtained by analyzing hydrogrographic data from a 1985 cruise on the R.V. Franklin. We will obtain similar data from two such cruises in 1993 and 1994 and combine them with TOPEX/POSEIDON radar altimetry data to identify interannual and seasonal changes in

(1) The location of the major ocean currents and the South Equatorial Current bifurcation in the Coral Sea.

(2) The source region of the South Tropical Counter Current (STCC).

(3) The water exchange between the Coral Sea and the adjoining seas.

We will also estimate seasonal and interannual variations in the horizontal transport of mass and heat associated with near-surface geostrophic and wind-driven currents. In addition, the tidal components of the Coral Sea will be studied to provide a correction for altimetry subtidal sea level changes and to develop a regional numerical model for tidal forcing in the Great Barrier Reef (GBR) and Papua New Guinea Reef regions.

Our major hypotheses are

(1) That the strength of the major currents and the positions of the East Australian Current (EAC) bifurcation and of the STCC in the Coral Sea vary seasonally and interannually in accordance with corresponding changes in the wind field.

(2) That the intensity of mesoscale circulation in the Coral Sea varies seasonally and interannually in association with the intensity and location of the major current systems, and that, in particular, there is a change in the intensity of mesoscale forcing of the shelf break and GBR in the alongshore direction that is related to the position of the EAC bifurcation.

II. Objectives

(1) To study the large-scale circulation of the Coral Sea Basin and transport between this and the adjoining basins.

(2) To identify interannual and seasonal changes in

    (a) The location of the major ocean currents and the South Equatorial Current (SEC) bifurcation.

    (b) The exchange between the Coral Sea and the adjoining seas.

    (c) Horizontal mass and heat flux of near-surface geostrophic and wind-driven currents.

(3) To estimate tidal constituents in the Coral Sea to

    (a) Provide corrections for subtidal altimetry sea levels.

    (b) Produce altimetry tidal sea level records.

(c) Develop a regional numerical tidal model for the Coral Sea.

(4) To model the subtidal wind-driven circulation in the western Pacific, while resolving seasonal and mesoscale variability.

III. The Approach

The approach to this investigation is based on these assumptions:

(1) The Western Coral Sea and GBR circulation is forced by

   (a) The local wind field (monosoonal).

   (b) The subtropical gyre (SEC).

(2) The region's boundary currents (e.g., EAC) and mesoscale frontal instabilities are modulated by changes in the intensity of the SEC.

The approach will be implemented by

(1) Using radar altimetry to estimate mesoscale energy levels and fluctuations of the SEC on seasonal and interannual time scales.

(2) Using current moorings, tide gauges, hydrographic surveys, and satellite thermal imagery to simultaneously monitor

   (a) Vertical structure of Coral Sea circulation.

   (b) Mesoscale variability in the Coral Sea.

   (c) Boundary currents and associated frontal instabilities.

(3) Analyzing satellite altimetry data at crossover points and in conjunction with high-precision tide gauge data to

   (a) Provide tidal corrections for radar altimetry data; the corrected data will be sufficiently accurate for studies of the Coral Sea circulation and boundary currents.

   (b) Derive sea level data from radar altimetry with sufficient precision to determine tidal response characteristics of the Coral Sea Basin.

   (c) Use all available tide gauge data (e.g., Port Moresby, a good standard port, has not been used in global models).

   (d) Improve open boundary conditions for regional tidal models.

   (e) Develop regional numerical models using global tidal models to set open ocean boundary conditions.

IV. Methodology

(1) The following research cruises (circumnavigating the Coral Sea) will make use of hydrographic and acoustic Doppler current survey techniques:

R.V. Franklin (WBC)	August 1990 (executed)
R.V. Franklin (NATS I)	October 1991 (approved)
R.V. Franklin (NATS II)	July 1993 (planned)
R.V. Franklin (NATS III)	March 1994 (planned)

(2) The following in situ data acquisition platforms will be installed:

Current moorings	GBR continental slope
Tide gauges	GBR shelf and slope Selected reefs and islands offshore
ARGOS drifters	SEC EAC

(3) Altimetry processing procedures for crossover and colinear track analysis with tidal corrections will be developed.

(4) A wind-driven reduced gravity model of the Indo-Pacific region with a resolution of 1/4 deg will be developed (see Figure 2 for model domain).

(5) Regional numerical tidal models will be developed using global tidal models to set open ocean boundary conditions and solving the Laplace tidal equations with a resolution of 1/3 deg (e.g., see Figure 3 for model domain).

V. Anticipated Results

A. Regional Significance

It has been hypothesized that deep ocean forcing of the GBR circulation by EAC meanders and associated mesoscale eddies is an important mechanism for water mass exchange at the shelf break and hence a mechanism for injecting nutrients into the GBR zone. To date, there has been no attempt to directly resolve length scales and intensities of mesoscale current energy in the Coral Sea; this energy may also be forcing these interactions.

Although surface current speeds and volume transport in the STCC are small compared with those in the other currents of the Coral Sea, the STCC appears to be important in the regional biogeography. The presently known distributions of coral species in the equatorial and tropical Pacific Ocean suggest an important role of the STCC in distributing larvae and various coral species, and the STCC may also be relevant to the annual migration and life cycle of the black marlin.

B. Innovative Aspects

Altimetry studies of the seasonal and interannual variability of the SEC bifurcation will be a new achievement. This will be the first seasonal and interannual survey of the south-tropical counter current near its source region and of the Torres Strait throughflow.

C. Significant Results

The following significant results are anticipated from the proposed study:

(1) Seasonal and annual maps for near-surface geostrophic velocities in the Coral Sea derived from TOPEX/POSEIDON altimetry data.

(2) Verification of seasonal and year-to-year variability in the wind-driven circulation.

(3) Seasonal and annual maps of wind-driven circulation in Coral Sea waters derived from TOPEX/POSEIDON radar winds and scatterometer data, where available.

(4) Data on seasonal and year-to-year variations in the strength and location of the STCC and EAC and the location of the EAC/STCC bifurcation.

(5) Data on seasonal variations in geostrophic transport through selected transects across the STCC, EAC, and SEC from TOPEX/POSEIDON altimetry and ancillary ship hydrographic data.

(6) Statistics on mesoscale variability associated with the major ocean currents in the Coral Sea.

(7) Improved understanding of the forcing effects on the Coral Sea circulation by the inflowing SEC, of the source regions for the STCC, and of deep ocean forcing of the GBR circulation, and up-to-date estimates of the Coral Sea horizontal advection, volume, and heat-flux budgets on a seasonal basis.

References

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National Aeronautics and Space Administration (1986), *Altimetry Research in Ocean Circulation Announcement of Opportunity*, AO No. OSSA-2-86, p. 22, National Aeronautics and Space Administration, Washington, D.C.

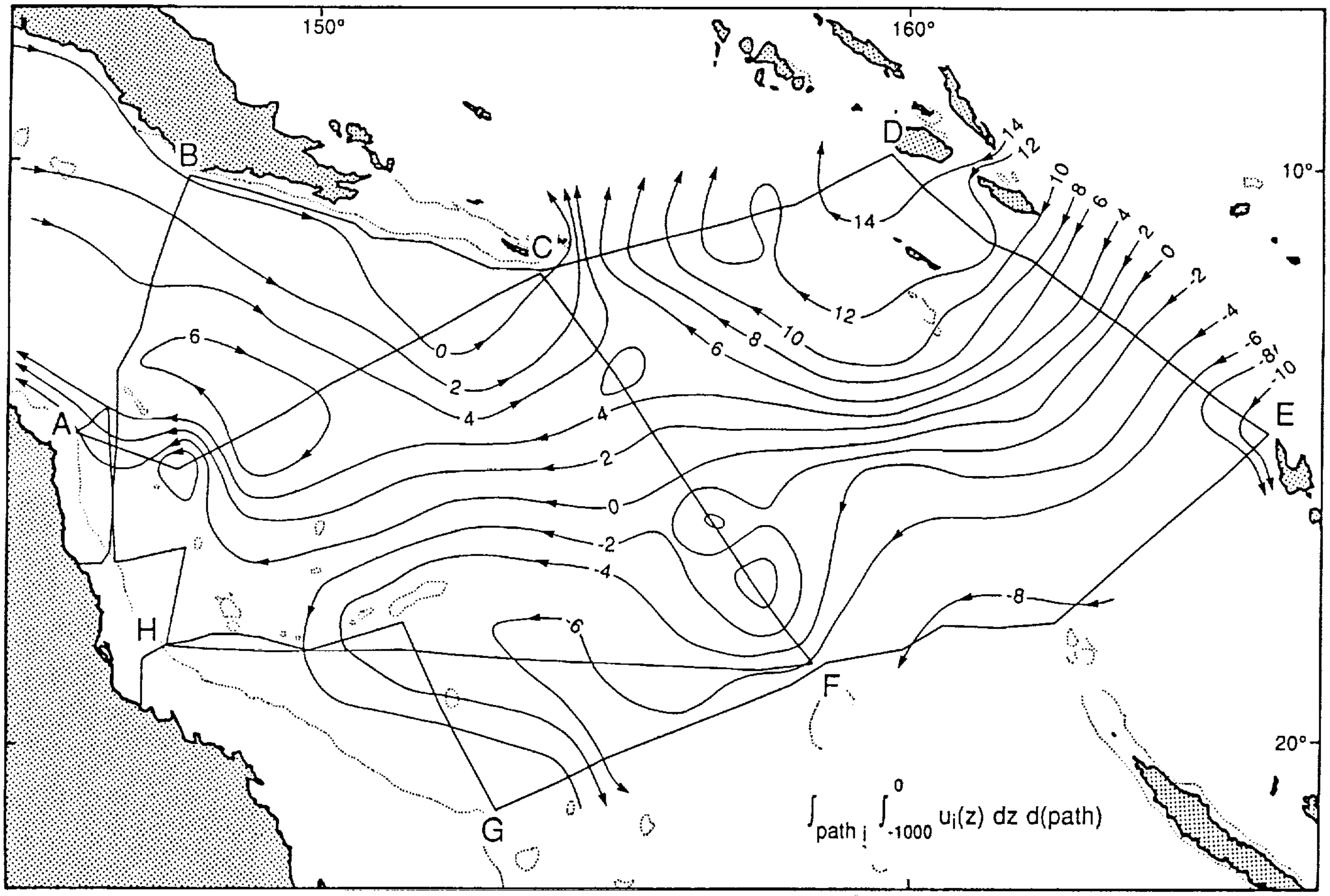

Figure 1. Coral Sea circulation as deduced from hydrographic data obtained during the R. V. Franklin cruise FR0385. The contour lines are for transport in Sverdrup units relative to 1000 m during winter, 1985 (adapted from Andrews and Clegg, 1989). The South Equatorial Current flowing into the Coral Sea from the northeast strongly dominates flow within the basin and at the continental margin.

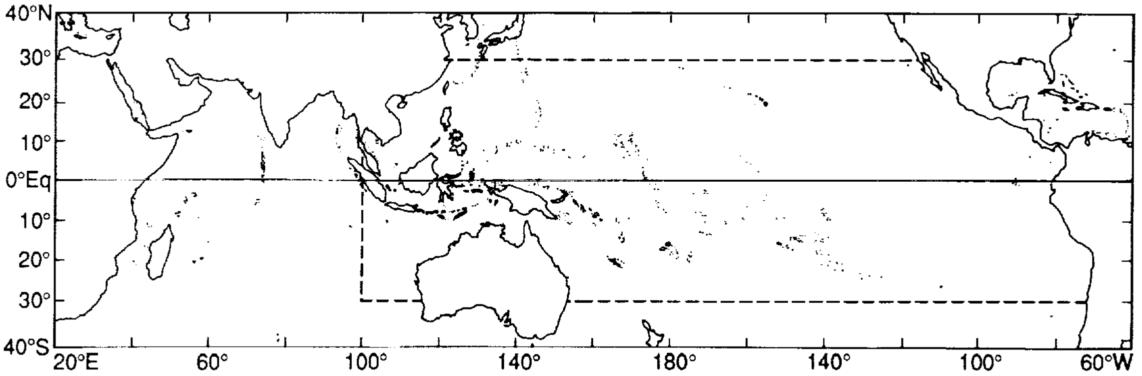

Figure 2. Domain for wind-driven reduced gravity model. This model will provide boundary conditions for regional models of the circulation in the Coral Sea.

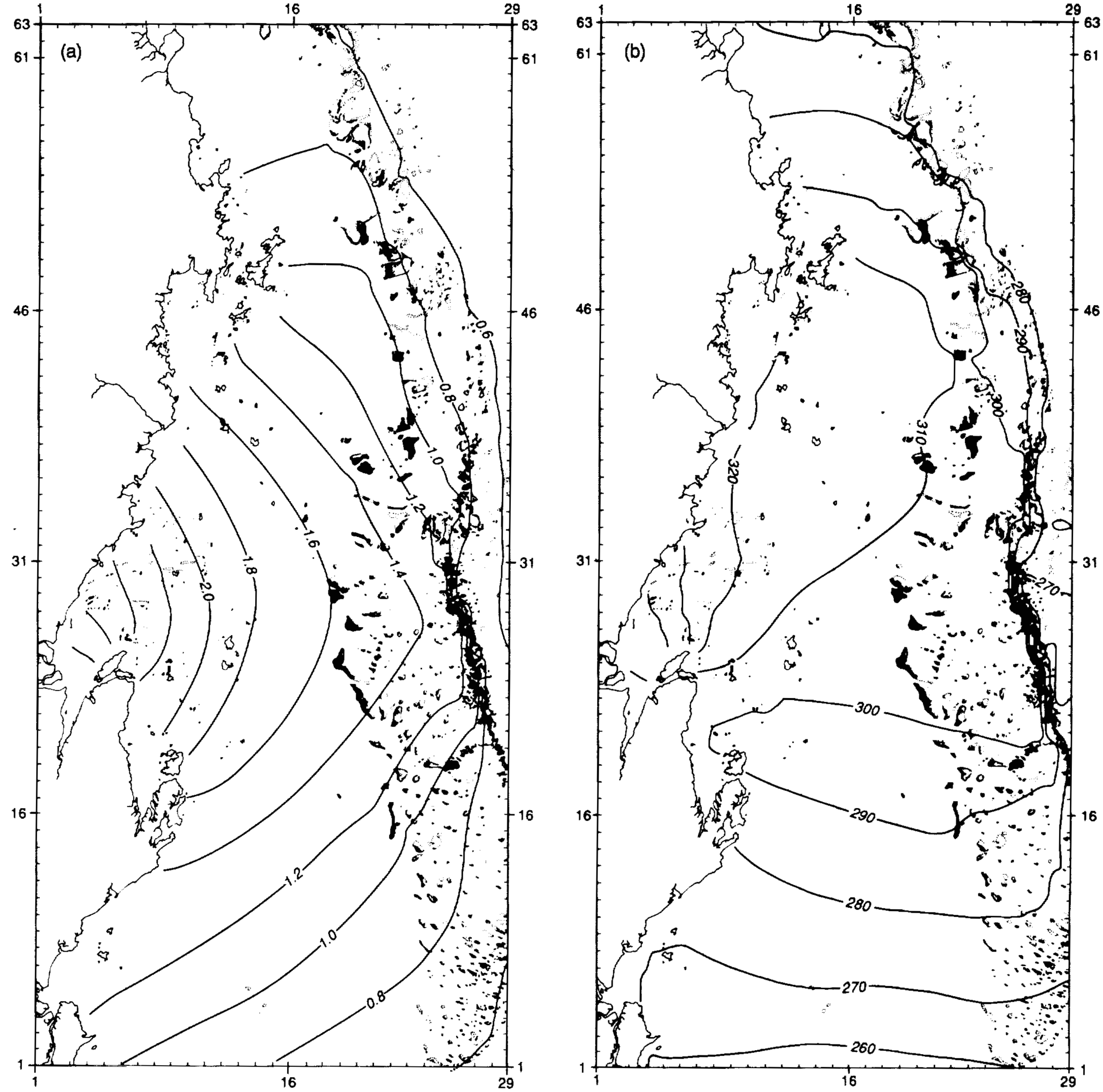

Figure 3. A numerical tidal model of the Great Barrier Reef continental shelf near Broad Sound: (a) M_2 tide co-amplitude (m); (b) phase (deg). Tidal predictions from the model will be used to provide accurate corrections to altimetery data and to investigate the apparent high mesoscale variability detected in the region by previous altimetry missions.

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Geophysical Investigations With TOPEX/POSEIDON Altimetry Data

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I. Introduction

During the past decade, altimetry missions have provided gravity field observations over the oceanic domain that have led to major advances in our understanding of the oceanic lithosphere (rigid layer of plate tectonics) structure and of its interaction with the mantle below.

Owing to the global coverage of the GEOS-3, Seasat, and Geosat satellites, systematic studies have been conducted over oceanic tectonic features. Global trends have been established, but also deviations with respect to mean trends have been detected. Unsuspected features have been discovered, such as gravity lineations in the central Pacific possibly related to small-scale convection occurring just below lithospheric plates. Also, new problems have been raised: as an example, the departure from pure conductive cooling of the aging lithosphere beneath fracture zones.

Several important problems concerning the oceanic lithosphere and mantle remain to be solved. Among others, let us mention processes of magma accretion at midocean ridges and the nature of small-scale convection beneath the lithosphere.

(1) High-resolution bathymetry has revealed important small-scale (10- to 100-km) discontinuities of spreading centers that were unrecognized until recently. These are ascribed to the discrete upwelling of magma, suggesting that crustal accretion beneath spreading centers is 3-D rather than 2-D. Several questions remain unanswered: It is not known to what depth extend upwelling magmas and how they are anchored in the asthenosphere (the low-viscosity layer beneath the lithosphere). High-resolution (10- to 20-km) geoid data would bring strong constraints on these problems in providing the depth of compensation of bathymetric discontinuities and in discriminating between the mechanisms responsible for magma upwelling (Rayleigh-Taylor-type instabilities or small-scale convection).

(2) Seasat geoid data have led to the discovery of lineated gravity anomalies to 150- to 200-km wavelength, possibly due to small-scale convection beneath lithospheric plates or to intraplate deformations. Due to severe limitations (lack of resolution and accuracy) of presently available altimetry data, the gravity lineations cannot be precisely examined. We do not know, for example, if they are seen everywhere in oceanic areas, if they start at mid-oceanic ridges or at some distance from them, and how they evolve with increasing crustal age. High-resolution geoid data, no doubt, will offer new constraints on their origin.

These phenomena produce essentially a short-wavelength signature in the geoid. To be studied, they need dense geoid coverage of the oceans.

II. Scientific Objectives

In the proposed research, TOPEX/POSEIDON altimeter data will be used with Geosat and European Remote Sensing satellite (ERS-1) data to compute global, region, and local oceanic geoid surfaces. These observations will then be analyzed to conduct geophysical studies relative to the structure of the oceanic lithosphere and mantle.

A. Lithospheric Studies

1. **Spreading centers.**
    (1) 3-D accretion at fast-spreading ridges.
    (2) Asymmetrical expansion.
    (3) Axial valley of slow-spreading ridges.
2. **Intraplate domain.**
    (1) Thermal structure of oceanic plates.
    (2) Hot-spot swells.
    (3) Intraplate seismicity.
3. **Back-arc regions.** The tectonics of marginal basins.

B. Mantle Convection

1. **Small-scale convection.**
2. **Interaction of mantle plumes with oceanic plates.**

These phenomena produce mainly short-wavelength signatures in the geoid, and their study requires altimeter data of Geosat, ERS-1, and TOPEX/POSEIDON.

III. Background

This research project is part of a long-term program under development at Groupe de Recherches de Géodésie Spatiale (GRGS) of the Centre National d'Etudes Spatiales (CNES) for nearly a decade. The program is based on the geophysical interpretation of altimeter-derived geoid anomalies. Studies conducted during the past years with GEOS-3, Seasat, and Geosat altimeter data concerned

(1) Rigidity of oceanic plates; regional variations of elastic thickness; interface on the rheology of the lithosphere.

(2) Thermal evolution of the oceanic lithosphere: the determination of thermal parameters of cooling models, in particular the thermal plate thickness.

(3) Detection of uncharted tectonic features from altimeter geoid data: the consequence for plate reconstitution.

(4) Convection in the upper mantle: constraints from geoid and topography data; small-scale convection in the asthenosphere.

(5) The local structure of
    (a) Deep-sea trenches: detection of sediment accumulation at trenches (accretionary prisms).
    (b) Slow-spreading ridges (axial valleys).

(6) The origin of hot-spot swells.

IV. Experiment Plan

(1) Analysis of altimeter data: computation of 2-D geoid and altimeter-derived gravity maps using classical methods of interpolation and inverse methods.

(2) Development of theoretical models (e.g., convection models).

(3) Quantitative comparison between observed and predicted geoid; determination of best-fitting models parameters; geophysical interpretation.

TOPEX/POSEIDON altimeter data will be mixed with the Geosat Exact Repeat Mission altimeter (ERM ALT) data and ERS-1 data available at the time of the TOPEX/POSEIDON mission. TOPEX/POSEIDON altimeter data will constrain global geoid surfaces because of their reduced orbital error.

V. Anticipated Results

High-resolution geoid data will be used together with other geophysical data (bathymetric, magnetic, and seismic) to constrain geophysical models. Anticipated results concern (1) accretion processes at midocean ridges, (2) the properties of the shallow low-viscosity zone beneath oceanic plates, and (3) small-scale convection and mantle plumes.

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Mesoscale and Large-Scale Variability of the Antarctic Circumpolar Current

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I. Objectives

The general circulation in the Southern Ocean (35° to 75°S, accounting for 26% of the world ocean) is known from historical data to be a generally continuous flow from west to east around the continent of Antarctica (see the upper panel in Figure 1). The volume transport of this Antarctic Circumpolar Current (ACC) is approximately $130 \times 10^6\ m^3s^{-1}$, one of the largest of any currents in the world ocean. The ACC links the circulation in the three major ocean basins and intervenes and mediates between the southern high-latitude deep water formation regions around Antarctica and the midlatitude temperate regions. The cooling required for surface waters to sink and form bottom and intermediate waters implies a large transfer of heat from the ocean to the atmosphere at high southern latitudes, and hence a large poleward transport of heat across the ACC. A description and a dynamic understanding of the circulation in the Southern Ocean and its relation to the global heat budget are important goals of physical oceanography.

Because of hostile environmental conditions (high winds and large waves) and logistical difficulties due to the size and remoteness of the region, there have been few detailed observational studies of the Southern Ocean. Consequently, much of the traditional view of the physical oceanography of the Southern Ocean is speculative, based on field measurements at a very small number of locations (primarily Drake Passage between South America and Antarctica). With the launch of TOPEX/POSEIDON, a detailed description of seasonal and longer period variability in the Southern Ocean will be possible. The altimeter measurements of sea level will provide a measure of the variability of surface geostrophic flow. When combined with suitable in situ observations and modeling through data assimilation, the altimeter observations of the sea surface can be extrapolated deep into the water column to infer variability of the interior ocean.

The overall goals of this investigation are to understand the dynamics of the large-scale circulation and mesoscale variability in the Southern Ocean and to relate these to horizontal fluxes of heat and momentum. TOPEX/POSEIDON altimeter data will be used to describe the seasonal and year-to-year variability of mesoscale and large-scale, low-frequency variability of surface geostrophic velocity in the Southern Ocean. Techniques for such studies have been established with Seasat altimeter data, but Seasat provided only a 24-day glimpse of mesoscale variability. The techniques are also being applied now to Geosat altimeter data, which are significantly less accurate than those expected from TOPEX/POSEIDON because of several compromises in the Geosat mission design.

Accomplishing the goals of this investigation will also involve the development of techniques for assimilation of time-variable sea level in local-area models of the ACC. A combination of altimetry observations, available in situ measurements, modeling, and data assimilation will be used to generate the most accurate flow fields possible, given the limitations of the model and the measurement and sampling errors in the observations. The four-dimensional velocity fields can then be used to study geostrophic advection and eddy transports of heat and momentum in the Southern Ocean.

II. The Approach

This investigation of the physical oceanography of the Southern Ocean will carry out two parallel efforts during the years preceding the launch of TOPEX/POSEIDON. First, the Geosat data will be used to develop a preliminary descriptive picture of the mesoscale and large-scale, low-frequency surface circulation of the Southern Ocean. Some of this analysis of Geosat data has already begun. For example, as a measure of the geographical distribution of mesoscale variability, a color-coded map of the standard deviation of sea level from two years of Geosat data is shown in Figure 1. Efforts are presently under way to investigate the seasonal and year-to-year variability of this mesoscale energy. The data are also being used to generate low-pass filtered fields of sea level from which the temporal evolution of large-scale variability in the Southern Ocean may be investigated.

The second parallel effort is the development and test of modeling and data assimilation techniques that will later be applied to TOPEX/POSEIDON data during the postlaunch phase. One objective of the modeling and data assimilation is to investigate the relation between mesoscale sea level variations and eddy flux in the Southern Ocean. Uncertainties in present estimates of the various components of meridional oceanic heat transport are large. The evidence presented indicates that the very energetic mesoscale variability in the ACC apparently accounts for much of the estimated 0.45×10^{15} watts of poleward heat transport across the ACC required to balance the heat budget. Eddy variability is strongly coherent vertically in the ACC, at least in the vicinity of Drake Passage where nearly all of the historical in situ data have been collected.

These facts give reason to hope that, if a skillful model of baroclinic eddy structure can be devised, an estimator of eddy heat transport can be formed from altimeter observations of mesoscale sea level variability. Testing such an estimator would require simultaneous in situ current and temperature measurements and altimetry sea level observations. We expect the requisite in situ data to come from the World Ocean Circulation Experiment (WOCE) that will take place at the same time as the TOPEX/POSEIDON mission; the Southern Ocean is the focus of one of three Core Projects of WOCE. The requirements for the necessary model are that it account for observed in situ velocity and temperature variability and remotely sensed sea level variability, and be able to relate the two fields.

There are two unique aspects of altimeter data that must be addressed in the data assimilation model. First, the model must accommodate the unique sampling pattern characteristic of satellite altimeter data, namely, dense sampling along the satellite ground tracks with relatively coarse zonal spacing of neighboring ground tracks; the diamond-shaped areas traced by the intersections of ascending and descending ground tracks are unsampled by the altimeter. The second aspect involves the nature of the altimeter sea level measurements. The use of altimeter data to investigate absolute sea surface topography that results from dynamic processes in the ocean is limited by present inaccuracies in the geoid; the data are presently known globally to an accuracy of only 1 to 2 m. However, sea level variability (in which the time-invariant geoid is removed) can be easily extracted from altimeter data. The data assimilation techniques developed here will be tailored to these two characteristics of altimeter data. We have already developed a preliminary version of the altimeter data assimilation model that incorporates the satellite-sampling pattern and sea level variability about an unknown mean for the case of linear dynamics.

An important step in creating the data assimilation model is the selection of the dynamic aspects of the limited-area model necessary to describe mesoscale variability in the ACC. Because of the novelty of these techniques in oceanographic modeling, very simple dynamic models will be used initially to build intuition and progress to more complex models. The simplest appropriate model of mesoscale dynamics is a barotropic, linear, quasi-geostrophic model, which can represent only barotropic Rossby waves. We shall progress from the barotropic model to n-layer or n-mode (where $n = 2, 3, 4...$) linear quasi-geostrophic models, thereby adding the dynamics necessary to represent baroclinic Rossby waves and to support eddy heat flux.

A close relation between the geographic distribution of mesoscale variability and the strength of the mean flow is evident from the upper panel of Figure 1. This association suggests that hydrodynamic instabilities are an important aspect of the dynamics of the ACC. It will therefore be necessary to include the next level of complexity in the hierarchy of models, which is an n-layer (or n-mode) quasi-geostrophic model linearized about a mean flow, thereby adding the mechanisms of baroclinic and barotropic instability. From the superposition of sea level variability and the 3000-m bathymetric contour in the lower panel of Figure 1, the mesoscale variability, and hence (from the upper panel of Figure 1) the mean flow, appear to be channeled by the major topographic features on the ocean bottom. The model should therefore also be expanded to include bathymetry.

III. Anticipated Results

Previous in situ studies have revealed numerous interesting characteristics of variability in the Drake Passage region. Relatively little is known, however, about variability elsewhere in the Southern Ocean. Most of what is presently known is based on drifter trajectories during the First GARP Global Experiment (FGGE) in 1979. These data have been useful for mapping the distributions of mean and mesoscale variability in the Southern Ocean. The duration of the FGGE data set was too short, and the distribution and number of drifters were too sparse to obtain reliable estimates of the temporal variability of the large-scale circulation of the Southern Ocean. The TOPEX/POSEIDON sea level data will provide a descriptive picture of the variability of the surface circulation of the Southern Ocean with unprecedented accuracy and spatial and temporal resolutions.

The TOPEX/POSEIDON altimeter sea level variability data combined with modeling through data assimilation will significantly improve our understanding of the dynamics of the ACC. A particularly significant aspect of this application of altimeter data is that it will allow us to determine the relation between variability in Drake Passage and flow elsewhere in the ACC. A previous correlation between transport estimates from bottom pressure gauges in Drake Passage and circumpolar averaged winds suggests large-scale coherence of the ACC. These results must be considered tentative, however, because the winds over the Southern Ocean are known so poorly. The altimeter sea level variability data combined with wind estimates from operational meteorological analyses or satellite scatterometry will quantify this relation.

It should be emphasized that the technique for assimilation of altimeter sea level variability to be developed here represents a new approach for altimeter observations. Previous assimilation studies have focused on absolute sea level, which is rather difficult to obtain from altimeter observations because of the requirement that the marine geoid be known accurately. The scheme to be developed here is specifically designed to incorporate altimeter estimates of sea level variability about an unknown mean and therefore promises to enhance significantly the utility of altimeter data. The technique will be applicable not only to this study of the Southern Ocean, but also to altimeter studies elsewhere in the world ocean.

Finally, the results of this investigation will significantly improve our understanding of the geostrophic advection and eddy transports of heat and momentum in the Southern Ocean. When combined with meridional Ekman heat flux estimated from independently available wind data, the total oceanic meridional heat transport (including seasonal and year-to-year variations) will be known far more accurately than at present. This will contribute greatly to our understanding of the role of the Southern Ocean in the global heat balance. Similarly, the sea level fields generated from the TOPEX/POSEIDON data will provide fields of the surface geostrophic currents over a wide range of space and time scales. These velocity fields can be used to investigate the importance of horizontal eddy fluxes of momentum.

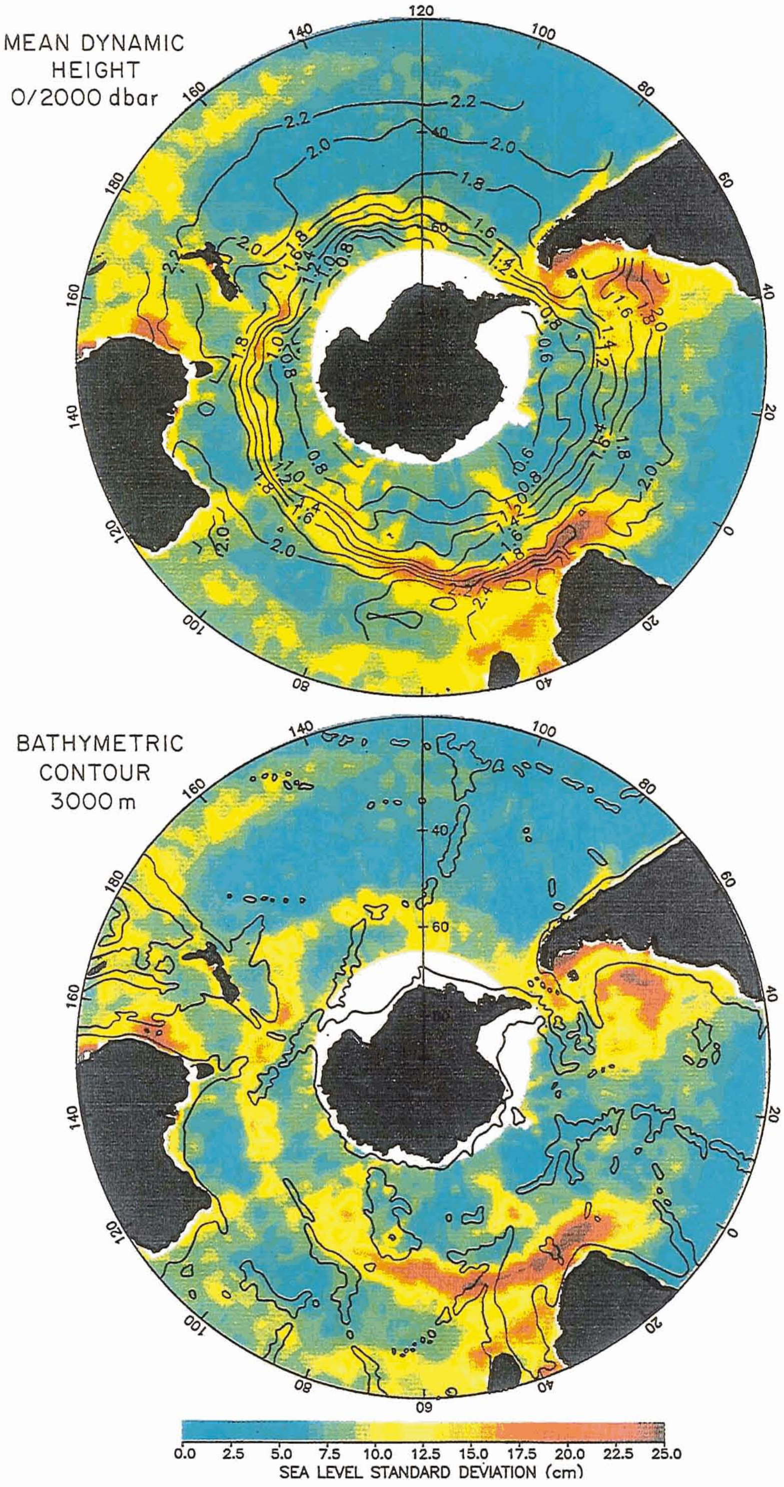

Figure 1. The standard deviation of sea level, according to the color scale at the bottom of the figure, computed from two years of Geosat data on a 2-deg-square grid. Superimposed on the standard-deviation maps are the historical mean dynamic height in meters of the sea surface relative to the 2000-m (upper) and the 3000-m (lower) bathymetric contours. Surface geostrophic current speed is proportional to the horizontal gradient of the dynamic height.

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Ocean Transport and Variability Studies of the South Pacific, Southern, and Indian Oceans

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I. Objectives

The objectives of this study are to analyse ocean dynamics in the western South Pacific and the adjacent Southern Ocean and the eastern Indian Ocean. Specifically, our objectives for these three regions are,

for the South Pacific Ocean,

(1) To estimate the volume transport of the East Australian Current (EAC) along the Australian coast and in the Tasman Front, and to estimate the time variability (on seasonal and interannual time scales) of this transport.

(2) To contribute to estimating the meridional heat and freshwater fluxes (and their variability) at about 30°S. Good estimates of the transport in the western boundary current are essential for accurate estimates of these fluxes.

(3) To determine how the EAC transport (and its extensions, the Tasman Front and the East Auckland Current) closes the subtropical gyre of the South Pacific and to better determine the structure at the confluence of this current and the Antarctic Circumpolar Current.

(4) To examine the structure and time variability of the circulation in the western South Pacific and the adjacent Southern Ocean, particularly at the Tasman Front.

for the Indian Ocean,

(5) To study the seasonal and interannual variations in the strength of the Leeuwin Current.

(6) To monitor the Pacific–Indian Ocean throughflow and the South Equatorial and the South Java Currents between northwest Australia and Indonesia.

(7) To study the processes that form the water of the permanent oceanic thermocline and, in particular, the way in which new thermocline water enters the permanent thermocline in late winter and early spring as the mixed layer restratifies.

for the Southern Ocean,

(8) To study the mesoscale and meridional structure of the Southern Ocean between 150°E and 170°E; in particular, to describe the Antarctic frontal system south of Tasmania and determine its interannual variability; to estimate the exchanges of heat, salt, and other properties between the Indian and Pacific Oceans; and to investigate the annual ventilation of the Antarctic Intermediate Water and Subantarctic Mode Water Masses.

II. Experiment Plan

To accomplish the objectives of this project, we plan to combine the TOPEX/POSEIDON altimeter data with traditional oceanographic data conductivity/temperature/depth (CTD) data, acoustic Doppler current-profiler data, moored-current-meter data, satellite-tracked drifter data, and thermal infrared imagery to get a far more complete time-variable, three-dimensional picture of the circulation in the region of interest. A number of the co-investigators are also investigators on a European Remote Sensing satellite (ERS-1) proposal, so there will be access to altimeter, SAR, and scatterometer data from the ERS-1 satellite.

Much of the in situ oceanographic data will be collected with the Commonwealth Scientific and Industrial Research Organization's (C.S.I.R.O.'s) oceanographic research vessel *RV Franklin*. Acoustic Doppler current-profiler data will be combined with GPS navigation data to give absolute velocities to a depth of about 300 m.

A. The South Pacific Ocean

During the prelaunch phase of TOPEX/POSEIDON, we are conducting a preliminary experiment in the Tasman Sea that is directly related to future plans for TOPEX/POSEIDON. This experiment is a forerunner of an experiment that will be conducted during the World Ocean Circulation Experiment (WOCE) TOPEX/POSEIDON period, and we plan to use the results from this experiment to plan our TOPEX/POSEIDON fieldwork.

The experiment involves two 43-day cruises on *RV Franklin* in the Tasman Sea during 1989 and 1990. On each cruise, a CTD/Doppler section will be completed from the east coast of southern Australia along 43°S to South Island of New Zealand. The ship will then return by completing a section north from the northern tip of New Zealand (at about 34°S) to 28°S and thence west to the east Australian coast. Both sections are the western end of Scorpio sections. The northern section will cut across the EAC as it flows down the east coast of Australia and will also cut across the outflow from the Tasman Front (the start of the East Auckland Current) as it rounds the northern tip of New Zealand. The southern section will cut across any southward continuation of the EAC and will also enclose the Tasman Sea, so that inverse techniques can be applied. Since the Tasman Sea is closed to the north at depth, the southern section will also indicate whether the circulation in the deep waters of the Tasman is clockwise.

On the continental slope at 30°S, current-meter moorings will be deployed for the period between the cruises to help estimate variations in the strength of the EAC. These moorings are essential components since, in the intense western boundary current, the satellite data have barely sufficient spatial and temporal resolution to measure fluctuations in the transport.

Between 28°S and 43°S, two further trans-Tasman sections will be completed on the first cruise, and further sections in the central Tasman Sea will be completed on the second cruise. Data from these sections would then be used in an inverse model to look for meridional variations in the EAC transport.

A separate element of the study will be two dynamic height moorings located in the central Tasman Sea; one well to the north of the Tasman Front and the other well to the south of the Tasman Front. Each mooring will consist of a bottom pressure gauge and enough instruments between the bottom and the surface to give a reasonable estimate of the temperature profile. The temperature profile will be converted to a density profile by using the tight temperature/salinity relationship for the Tasman Sea. The density profile will then be integrated from the bottom pressure gauge to the top of the mooring to give an estimate of the pressure anomaly throughout the water column. The variations in the differences in pressure between the two moorings is directly proportional (through the geostrophic relationship) to the variations in the currents perpendicular to the line joining the moorings. The location for the northern mooring is at the latitude of Norfolk Island (28°S), but farther to the west on the Lord Howe Rise. The low-passed mean sea level at Norfolk Island has only a very small range, indicating little variability in the oceanic conditions. In contrast, farther south at Lord Howe Island, the low-passed mean sea level has a bimodal histogram because the Tasman Front moves back and forth past the island. The southern mooring will be about 40°S in the central Tasman Sea. An independent estimate of the surface pressure gradient between the two moorings will be obtained from the altimeter data. Ideally, the moorings should be on the same ground track so that the various orbit errors are eliminated (because of the very long correlation scale of the orbit errors) when the altimeter heights at the locations of the two moorings are subtracted.

B. The Indian Ocean

The 1987 Leeuwin Current Interdisciplinary Experiment provides some background for future work in the eastern Indian Ocean, and we anticipate making significant contributions to the World Ocean Circulation Experiment.

The strong seasonal signals in the tropical Indian Ocean mean that satellite altimeter data would be particularly useful. We plan to measure variations in the strength (seasonal and interannual) of the Leeuwin Current and use altimeter data to help relate the Leeuwin Current to the wider scale Indian Ocean circulation (particularly the tropical circulation and the Indian–Pacific throughflow). The first steps toward this project have begun with the use of Geosat altimeter data and will be pursued with the more accurate TOPEX/POSEIDON altimeter data. The altimeter data should be particularly useful since there is an anomalously large poleward pressure gradient that is thought to drive the Leeuwin Current. Australia presently contributes to the Tropical Ocean Global Atmosphere (TOGA) expendable bathythermograph and tide gauge network in the Indian Ocean, and these data should be a useful complement to the altimeter data.

Australia has a continuing interest in the Pacific–Indian throughflow. We intend to complete a Java-to-Australia hydrographic section and hope to participate in a regional program to directly measure the throughflow and its effects by using moored instrumentation, tide gauges, research vessels, drifters, and altimeter data. The Java-to-Australia section should be completed twice in opposite seasons.

Because of the large heat fluxes into the ocean in the equatorial regions, the Indian Ocean carries a large poleward heat flux that reaches a maximum at about 20°S. We plan to participate in the completion of the 20°S repeat hydrographic section and complete direct measurements of the transport in the Leeuwin Current (at 20°S) by using current meters.

We expect to complete a subduction experiment in the southeast Indian Ocean, a region where thermocline water is formed and subducted into the main subtropical gyre. Two important factors contribute to the subduction process: (1) a downward Ekman pumping velocity and (2) a shoaling of the late-winter mixed layer in the direction of the mean circulation at this depth. Both requirements are satisfied in the eastern Indian Ocean, west of Cape Leeuwin. In concept, this experiment will involve two cruises in the area to collect hydrographic and turbulence data with the C.S.I.R.O.'s towed microstructure-profiling vehicle *Bunyip* and the acoustic Doppler current profiler that measures absolute lateral velocity as well as vertical shear. The first cruise will be conducted in the late winter/early spring (October) when water-mass formation occurs at a rate determined by the annual average Ekman pumping. The second cruise will be conducted about two months later in spring (December). Each cruise involves the detailed mapping of hydrographic variables over a region 100 nmi on a side and following a zigzag path with a horizontal spacing of 5 nmi between successive legs. The mapping takes two weeks of ship time. This patch of water must be tagged with autonomous pop-up floats on the first cruise; on the second cruise, samples along the same selected isopycnals (but deeper in the water column) will be centered on the updated positions of the floats.

C. The Southern Ocean

Integral to the WOCE are regularly occupied hydrographic sections across the Southern Ocean. Three key sections identified in the WOCE Implementation Plan are located in Drake Passage, south of South Africa, and south of Tasmania, where the circumpolar circulation is constrained by zonal boundaries (choke points). The choke-point fluxes will further our understanding of exchange between the ocean basins and the variability of the Antarctic Circumpolar Current. Planning is under way for the annual occupation of a transect between Hobart; Tasmania; and Commonwealth Bay, Antarctica, by using the marine science facilities of the Australia Antarctic Division. The primary objective is to monitor interannual variability of the Southern Ocean frontal systems and Antarctic Circumpolar Current transports.

In addition, the possibility of monitoring the zonal transport in the Southern Ocean south of Australia by long-term deployment of pressure gauges along the annual transect is being explored. The Antarctic Circumpolar Current generates a mesoscale structure that, in the analysis of altimetry data from Seasat, shows as a zonal band of high topographic variance. We plan to utilize synergistically the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer scanner data and TOPEX/POSEIDON altimeter data in conjunction with ship data and (possibly) ERS-1 Along Track Scanning Radiometer, altimeter, and SAR data to study the mesoscale structure in the Southern Ocean south of Australia. We plan to concentrate on the area between 150°E and 170°E, which was identified as a high-eddy-energy region deserving intensive study.

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Assimilation of Altimeter Topography Into Oceanic Models

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I. Introduction

The primary goals of the authors are to build an intuition for assimilation techniques and to investigate the impact of variable altimeter topography on simple or complex oceanic models. In particular, applying various techniques and sensitivity studies to model and data constraints plays a key role. We are starting to use quasi-geostrophic, semigeostrophic, and primitive-equation (PE) models and to test the schemes in regions of interest to the World Ocean Circulation Experiment (WOCE), as well as in the northeast Atlantic and the Mediterranean. The impact of scatterometer wind forcing on the results is also investigated. The use of Geosat, European Remote Sensing satellite (ERS-1), and TOPEX/POSEIDON altimetry data is crucial in fine tuning the models and schemes to the selected areas of interest.

II. Objectives and Problems of Altimeter Data Assimilation

The upcoming oceanographic satellites such as ERS-1 and TOPEX/POSEIDON will provide to a large community of scientists huge data sets of precise and adequate measurements of variables of interest in the ocean. Altimeter sampling is global and quasi-continuous both in space and time, making it possible to derive a representation of the ocean of the same essence as that from numerical model outputs. Both data and models are helpful in describing ocean phenomena. The idea of mixing these two ingredients is classic in dynamic meteorology where it bears the name of "data assimilation" (hereafter denoted DA, or "assimilation"). Its application to Oceanography has been evidenced much more recently. Assimilation can be achieved through various techniques and can be seen from either end as the dynamical adjustment of data or as a model being tuned to observations.

Assimilation is only one of two ways of making simultaneous use of data and models to obtain a better understanding of ongoing dynamics. The other way is direct modeling (hereafter denoted DM). In DM, a numerical model is run in free mode (i.e., without assimilation), and its outputs or diagnostics are compared with available observations or with interpretations of observations. According to the results of the comparison, some model parameters or the initial state can be changed, and the model run again. Ultimately, conclusions are drawn regarding the adequacy of the model to describe the (probably unknown) real system. A carefully designed DA scheme will take care of this feedback without the human intervention DM requires. Moreover, most DA schemes can explicitly take into account the fact that we probably do not know what the real system exactly is. Both techniques are complementary ways of improving our knowledge of the ocean, but DA is to be preferred when dealing with large quantities of data.

The variable surface topography of the ocean is a good candidate for assimilation. The satellite altimeters aboard GEOS-3, Seasat, and more recently Geosat have proven very helpful in providing maps of global sea height variability and eddy kinetic energy (e.g., Cheney et al., 1983; Douglas et al., 1983; Ménard, 1983). They have given access to previously unknown statistics such as wavenumber spectra of the surface topography. On the other hand, proof that altimeter heights can be helpful for intensive synoptic descriptions of limited-area domains is ubiquitous in the literature (Robinson et al., 1983; Cheney et al., 1984; Fu and Chelton, 1985; De Mey and Ménard, 1989; Malardé et al., 1987; Fu, Chelton, and

Zlotnicki, 1988; Fu and Zlotnicki, 1989; Gaspar and Wunsch, 1989). In regions of the world ocean where mean sea surfaces have been calculated or obtained by a priori assumptions, the need for collinear passes to derive the variability is no longer necessary. In midlatitudes, the interpretation of the residual height in terms of dynamic variables is straightforward if the flow is assumed to be quasi-geostrophic: It is a simple function of the Coriolis parameter and the quasi-geostrophic stream function. The techniques mentioned above are valid for limited-length arcs if residual orbit and tide errors are to be properly eliminated. However, a topographic "snapshot" of a basin can be obtained by dividing the basin into smaller domains.

The models to be used for the assimilation of variable topography data must contain the corresponding variability in their dynamics in addition to representing the general, time-independent circulation. The most commonly used, and the most promising, are built around quasi-geostrophic, semi-geostrophic, or primitive equations. However, since most processes on the oceanic meso- and synoptic scales have a baroclinic signature, the assimilation of surface data alone may prove especially challenging. For the most complex models, the topography constraint may even be too weak in some circumstances. Some studies (Marshall, 1985; Hurlburt, 1986) address this difficulty by using simple barotropic or two-layer models to incorporate surface topography. In this approach, most or all of the degrees of freedom of the model are saturated by the data. An alternative approach, as in De Mey and Robinson (1987) and Dombrowsky and De Mey (1991), is to prepare the topography for assimilation by using extension schemes on the vertical, thus allowing the assimilation to be performed in a realistic multilevel model.

One can make a rough estimate of the size of the altimeter data vector to be assimilated in a numerical model. Here we take the example of the Atlantic Ocean in both hemispheres, from ice edge to ice edge. Assuming the measurements refer to a seasonal mean surface, the number of statistically independent observations per day in the Atlantic Ocean is $O(10^4)$. This result is based on a horizontal decorrelation scale of O(R), where R is the Rossby radius for the first baroclinic mode. The assimilation of satellite altimeter data is thus a problem almost as big as numerical weather forecasting.

This fact has consequences, in particular in terms of practicability, cost, and choice of methods. To what extent should oceanographers take advantage of the experience accumulated over years by numerical weather forecasters? Some techniques used in operational meteorology may prove costly and impractical for oceanographic application. The use of predictive models in an assimilation mode is even more crucial in studies of the ocean than in studies of the atmosphere because of the specific features of the oceanic information that are accessible. First of all, these observations are (and will stay) sparse as far as the three-dimensional extent of the ocean is concerned. Secondly, the satellite measurements will provide only boundary (surface) conditions—the interior flow is inferred by models and other (mostly local) observations. This emphasizes the need to reach a concomitant reliability for the models and the data and to improve the model complexity and parameterization concurrently with assimilation techniques, each of which takes benefit from the other.

Some of the studies here concern data assimilation in limited-area quasi-geostrophic (hereafter denoted QG) models. The Harvard multilevel QG model has been described in Miller et al. (1983). It is used among other models by two of the authors (De Mey and Pinardi). A brief summary of the model characteristics and the assimilation methodology will be given here, since these elements are used as a starting point for investigations A1 and A2, described in subsection III.A.

The Harvard model integrates the quasi-geostrophic equations of motion on the β-plane. The dynamic vorticity is advanced in time by solving the prognostic vorticity equation, and the QG stream function is derived from the dynamic vorticity by solving a diagnostic Poisson equation. Along the open boundaries, stream function is specified everywhere, and vorticity is specified at inflow points. This provides a handy way of inserting data into the numerical model. However, some processing and interpolation has to take place before assimilation can be performed. To get a synoptic time series, the measurements are gridded onto a Cartesian coordinate system. Since their distribution is generally irregular in space and time, an optimal analysis method, such as Objective Analysis (Gandin, 1965; Bretherton et al., 1976) has to be used. Accurate estimates of the space-time statistical structure functions are needed for the signal as well as for the noise (measurement errors, unwanted processes). De Mey and Ménard (1989) give an example of this technique to analyze GEOS-3 and Seasat topography.

There is generally a discrepancy between the set of levels at which synoptic data are available and the depths at which the model discretization is desired. This is specially true when altimetric topography is used alone. Projection/extension schemes are interfaces between synoptic data and model requirements. They make use of vertical representations of buoyancy and horizontal motion in real or spectral space. An example of extension in the case of the Polymode Mark-2 dataset is given in Pinardi and Robinson (personal communication, 1986), and is based on a mixture of empiricism and dynamic hypotheses. An alternative, fully empirical approach is proposed in De Mey and Robinson (1987).

Methodology for assimilating sea surface temperature (SST) data has also been developed for the Harvard QG model (Spall, personal communication, 1986) as well as for its PE counterpart. It shows the predictive skills of the model when initialized with SST at the surface and conceptual models for the vertical structure of the subsurface Gulf Stream jet and rings. The combination of altimeter data with SST analyses (NOAA-9 and ERS-1 in particular) is expected to improve the forecast capabilities of the model, providing a more quantitative estimate of the Gulf Stream front and eddy field.

The authors' ambition here is not to design operational assimilation systems, but rather to (1) investigate the dynamic impact of data on numerical models and (2) test a few techniques that will be used to achieve WOCE and other goals. In this perspective, our intention is to deal with both (1) quasi-geostrophic and semigeostrophic (QG/SG) models and (2) PE models. Models other than limited-area QG are already used by the authors, such as the Holland QG model, the Alfred Wegener Institute QG model, the Haidvogel PE, the Cox and Bryan PE, and the Delécluse PE models. We are already testing schemes to assimilate variable altimetric topography into these models. Since this constraint is weaker for PE models than QG models, the assimilation of alternative, time-varying satellite-sensed fields such as the scatterometer wind field will be optionally considered. Investigations A3 and B2 (see subsections III.A and III.B) address this specific issue for evaluation purposes. To analyze the results of the assimilation runs and the impact of the data on the dynamics of the model, diagnostic and analysis routines will also be developed by the investigators.

III. Ongoing Investigations: Rationale, Results, and Prospects

A. Investigation A: Assimilation of Variable Altimeter Topography in Quasi-Geostrophic and Semigeostrophic Models of Ocean

1. **Investigation A1: Semicontinuous assimilation in limited-area models.** This investigation is an extension of the methodology described in De Mey and Robinson (1987) for the sequential reinitialization and boundary forcing of the Harvard model.

We perform the assimilation as a sequence of two operations: (1) the time stepping of the forecasting model and (2) the combination of the forecast (the "first guess") and new observations. Each time the combination is performed, new initial conditions are derived, and the numerical model can be run again, although on a modified trajectory. We call this data-controlled sequence of model trajectories "semicontinuous assimilation," since full-domain assimilation occurs only at discrete times.

The simplest technique to achieve the combination of a forecast and new observations is again some kind of objective analysis (OA) performed on the difference between the new data and the first guess. A slightly different procedure is to choose directly the weights of the linear combination of the first guess and the new data by minimizing the overall expected error variance. This last procedure, however, makes use of the error propagation characteristics of the numerical model, which consequently have to be available.

This technique is widely used in dynamic meteorology (e.g., Lorenc, 1981), where its results are generally regarded as satisfactory. One particular advantage is that it provides a conceptually simple and internally consistent procedure for processing large quantities of asynoptic data. Experience has also shown that objective analysis is extremely robust, in the sense that it can accept large temporal and spatial variations in the distribution of observations.

The extension techniques described in De Mey and Robinson (1987) are borrowed to simulate the conditions of an altimeter sampling the surface with no other simultaneous observations available. As mentioned earlier, the surface height is equal to the scaled quasi-geostrophic stream function.

A QG-consistent energy and vorticity analysis scheme (Pinardi and Robinson, 1986) is used to reach the proper dynamic interpretation of the behavior observed in the assimilation runs.

The following work has been performed to date. A first implementation of an intermittent assimilation scheme in the open ocean Harvard quasi-geostrophic model has been carried out and applied to simulated altimeter data assimilation. Three-dimensional synoptic observation fields and error-variance fields are derived from synoptic dynamic topography anomaly estimates using an empirical orthogonal mode (EOF) vertical extension technique. The three-dimensional estimates are optimally combined with the time-dependent part of the forecast fields. The resulting fields added to a mean model climatology are used as initial conditions for the model, which is integrated until a new dynamic topography anomaly estimate is available. The combination is optimal in the sense that it is based on the observational error variances, which reflect the measurement noise and the space-time distribution of data, and minimizes the error variance of the results. A similar combination scheme using past as well as future observations is used to update the boundaries during model integration. Simulated surface-topography anomaly maps, typical of the Northeast Atlantic, are assimilated every 20 days for a 300-day period, with different noise characteristics typical of altimetric sampling errors, in a three-level version of the model. The assimilation fields, especially the vorticity at deeper levels, converge towards the reference fields. The convergence is obtained after O(100 days) regardless of the observational noise levels tested (up to -2 dB). Using a relevant observational error model seems to matter; in particular, the error level should not be underestimated. In case of a 0(80-day) gap in the data inflow, the model predictability limits the reliability of the forecast beyond O(20 days). The scheme makes the model converge back as soon as new observations are entered, and with limited convergence loss due to the gap.

An alternate version of the scheme based on Newtonian relaxation has been tested, as well as a first implementation of these schemes in a semigeostrophic model.

Figure 1 shows a sequence of forecast Geosat surface stream function fields of 1000 × 500 km in the northeast Atlantic using the scheme described above. The AthenA-88 experiment (De Mey and the AthenA Group, 1991) occurred at the time of the plots. The Geosat coverage was sparse during the AthenA-88 experiment. However, the assimilation scheme restores the cyclone/anticyclone pair observed during the experiment at sea (De Mey and Dombrowsky, 1991).

2. **Investigation A2: Continuous assimilation in limited-area models.** Objective analysis (investigation A1) takes very indirectly into account the model's dynamics, since the time stepping and the combination with new data are performed almost independently of each other (the only possible link is the error propagation model used to describe the forecast error in such a way as to be acceptable by objective analysis). Numerical weather forecasters have also noticed at the beginning of numerous forecasts using OA the occurrence of a short spin-up time during which the model adjusts the analyzed fields to its own dynamics.

An alternative approach, which is the focus of this investigation, is to find the free trajectory of the model variables such that the model equations are satisfied exactly and the trajectory is as close, in some sense, as possible to the observations (Talagrand and Courtier, 1987). This is equivalent to globally adjusting one model solution to the complete set of observations. Let us define a scalar function that measures the distance between a given trajectory and the observations. We want to find the model trajectory that minimizes this distance. This is a constrained variational problem. This problem can become unconstrained if we notice that a solution of the model is uniquely defined by its boundary (and initial) conditions. Given proper initial conditions, for instance, the problem can be stated as follows: find the boundary conditions such that the model trajectory be as close as possible to the observations whenever and wherever they may be.

For this problem to be tractable, one has probably to reason in terms of perturbations to a first guess (e.g., the space-time optimally interpolated data). It is necessary to express in a practically useable form the relationship between the variations of the initial/boundary state and the corresponding variations of the distance function. This requires the ability to calculate the gradient of the distance function with respect to the parameters (or modes) defining the initial/boundary conditions.

Consequently, we are working in two directions: (1) find the best set of control variables for the limited-area QG model; (2) use the adjoint technique (Le Dimet and Talagrand, 1986) to calculate the gradient of the cost function.

Optimal control using the adjoint technique is a special variational method. From the differential equations describing the oceanic flow, a linearized perturbation equation is derived. The perturbation equation is integrated to study the variation of the model trajectory due to disturbances of the initial or boundary conditions. From the variation of the trajectory, the gradient of a general cost function (e.g., the data-model misfit) with respect to variations in the initial or boundary conditions can be calculated.

Once the gradient is calculated, by one method or the other, it is used in a descent algorithm to find the optimal values of the initial or boundary conditions for the problem considered. The method is equally well applicable to control variables other than initial or boundary conditions such as numerical constants in the model.

To test these techniques and to be able to compare the results with those of simpler techniques, we will use the same data and analysis tools used for Investigation A1.

To date, promising results have already been obtained in this investigation (e.g., Schröter, 1989; Seiler et al., 1990).

3. **Investigation A3: Assimilation experiments in basin-scale models.** A primary goal of this proposal is to test DA methods to find those that are the most reliable and adequate for use with regional and basin-scale prognostic models. The ultimate objective (investigations A4 and B3) is to describe and predict the general circulation of the ocean.

Investigations A1 and A2 focused on regional DA techniques. The next step is to test similar or new methods in basin-scale eddy-resolving QG models. The interactions between the eddy field and the general circulation have been evidenced in such models. Consequently, the description of high variability areas in the vicinity of western boundary currents is a major component of the description of the large-scale circulation. This variability should be readily accessed by the TOPEX/POSEIDON altimeter and should be dynamically adjusted on demand in regional QG models. It is expected in particular that optimum interpolation and numerical models have the ability to accommodate the undersampling of the mesoscale variability in the cross-track direction.

Using DA techniques of various sophistication (investigations A1 and A2), we aim at understanding the dynamical impact of assimilation in a prognostic model of the wind-driven QG oceanic circulation at basin-scale in midlatitudes. The resolution is fine enough to describe the mesoscale variability. The relative simplicity of QG physics and relative low costs of simulation make it possible to address the following fundamental questions:

(1) Can the model dynamically transfer altimetric data into subsurface information?

(2) Is the model sensitive to the adequation of the model physics, including wind forcing?

(3) Is the model sensitive to time and space sampling and errors, especially for the midlatitude jet-stream variability? Is there dynamic tuning of the different scales of the motion?

(4) Is the model sensitive to the lateral boundary conditions' adjustment and accuracy?

(5) Can the feedback effect on the tuning of a general circulation model minimize the disagreement between model and reality? Can we learn what is wrong in the model physics? Can QG physics coexist with the physics of the real ocean in the DA system?

(6) Can model studies of multivariate assimilation include

   (a) Altimeter data and other data types?

   (b) Global data and local data? (The local insertion—see Malanotte-Rizzoli and Holland, 1986—addresses the question of how information propagation is affected by the model's dynamics.)

Our starting point is the results that show the appropriateness of the Newtonian relaxation technique (Anthes, 1974; Verron and Holland, 1989; Holland and Malanotte-Rizzoli, 1989) for continuously or sequentially updating a multilayer basin-scale QG simulation. Simulated data are derived from other runs of equivalent QG models (identical twin experiments). During the first stage of the program, the investigation was performed in collaboration with W. Holland (National Center for Atmospheric Research) and P. Malanotte-Rizzoli (Massachusetts Institute of Technology).

The Newtonian relaxation technique, which is used here and for part of investigation A2, was shown to be a very robust and efficient way of adjusting the deep flow toward reality. In applications involving realistic datasets and sampling strategy, the relaxative time scale is a function of space and time, based on the expected error of the assimilated estimate.

The topic of the relative importance of altimeter and scatterometer data for assimilation/forcing of models is also very central to this section of the proposal and is explored by the authors and their collaborators (Barnier and Boukhtir, personal communication, 1990). As mentioned earlier, the topographic constraint may, in some circumstances, be too weak for models to adjust to local events in the dynamics. Additional constraints such as the variable wind field for the scatterometer may prove helpful.

B. Investigation B: Assimilation/Forcing of Variable Altimeter Topography and Optional Scatterometer Wind Products in Primitive-Equation Models of the Ocean

1. Investigation B1: Assimilation experiments in basin-scale models. The objectives of this investigation are linked to those of investigation A3. However, the present investigation concerns PE models, which are bigger and more complex than QG models, and for which little experience of DA schemes exists to date in oceanography.

The use of a model to study the large-scale variability and general circulation of the oceans with altimeter data is of primary necessity, firstly because the altimeter is not expected to resolve explicitly and accurately the larger scales of variability, and secondly because at these scales surface topography is a stronger constraint on the barotropic transport, whereas the baroclinic transport is mostly used to study the general circulation (Colin de Verdière, personal communication,1986).

There is a clear advantage in using the best possible physics in a numerical model. For instance, assimilating surface topography in a multilevel QG model can help deep currents to converge and surface currents to adjust (De Mey and Robinson, 1987). Also, the necessity of filtering the data to remove processes not represented in the model disappears. On the other hand, PE models are often very complex and contain more variables and parameters than QG models: The surface topography constraint is likely to be weaker here than in a QG environment, especially for the larger scales, which will be hardly represented by the altimeter.

We have started by using the Bryan and Cox primitive-equation model (Bryan, 1969a,b) which has been set up in the

Mediterranean by one of the investigators (Pinardi). It is routinely running with 16 levels in vertical and 0.25-deg resolution for the whole Mediterranean basin. Realistic topography, wind stresses, and heat fluxes are features of this model, which has been used for world ocean circulation studies. The time step is a few hours for climatological wind and heat fluxes. Data assimilation studies have now been undertaken in the model.

Only a few studies address the problem of assimilating altimeter data in PE models. Assuming the surface to be a rigid lid, the altimeter is able to provide the divergenceless part of the velocity field and corresponding temperature field to initialize and update the model fields at the surface, using schemes developed in this proposal. To get other levels, an extrapolation technique such as a set of EOFs derived from historial data could ultimately be used, so that a complete horizontal and vertical first-guessed velocity field would be available. Objective analysis could be used as a first approach to interpolate the measurements in the horizontal. The temperature field can be considered to be in thermal wind relationship with the velocity field, thus allowing a first-guessed temperature field to be derived.

A possible procedure to update the fields with the altimeter would be to separate the velocity field of the model forecast into divergent and nondivergent parts. The nondivergent part could be updated with the new data. Since there exists some form of nonlinear relationship between both components, the model could adjust the divergent part. This adjustment may be made more controllable provided that a variational assimilation scheme is used.

These work hypotheses are a starting point for this investigation, which is expected to lead the investigators to test and refine their first ideas against the results of experiments in the Mediterranean or in other basins.

2. Investigation B2: Application to the Mediterranean basin-scale circulation. The methodology and objectives in this investigation extend the objectives of investigation B1 by stating the willingness of the investigators to perform assimilation for dynamical studies in the Mediterranean, using a PE model. The work has just started as a joint effort with members of other proposals and of the international scientific community. It is supported by the MAST program of the European Economic Community.

IV. Applications

This section lists a few possible applications and outcomes of the work both performed and envisaged. Our ambition here is not to build operational assimilation schemes for oceanography. We want to build an intuition for assimilation techniques; the main and immediate application of this principle here is to investigate the impact of variable altimeter topography onto simple or complex oceanic models, preferably in the WOCE areas of interest, in the Northeast Atlantic, and in the Mediterranean.

In the selected areas, the mix of data and dynamics results in the best possible dynamic description of the variable circulation, and, through dynamic coupling with the help of conventional data, of the general circulation. For this last objective, the reliability of the assimilation model is linked to the knowledge of the deep circulation and of the global meridional and boundary fluxes. These critical elements are not directly accessed through altimetry; an independent validation (e.g., the WOCE field program and other field programs in the Northeast Atlantic such as AthenA-88 and Semaphore-93) have or will cast light on the validity and limits of the DA schemes and on the ability of satellite sensors to resolve through DA the desired oceanic degrees of freedom.

The horizontally and vertically interpolated model fields are specially adequate for dynamic analysis packages such as energy and vorticity budget analyses (e.g., Pinardi and Robinson, 1986; Robinson et al., 1986; and others). As shown in the aforementioned papers, DA acting as an interpolator allows the detection and estimation of dynamic processes such as frontogenesis, eddy–eddy interactions, and Gulf Stream ring detachment processes (Spall, personal communication, 1986). It is clear that such sophisticated analysis tools are necessary as a diagnostic for DA results, as well as for the dynamic interpretation and validation of results.

On the other hand, the development of models and DA techniques for the ocean circulation is of outstanding importance to medium- and long-range forecasting of the ocean and ocean–atmosphere coupled system (V. Cassé's ERS-1 AMERS program, De Mey, co-investigator).

Another major application is the possibility of "post-validation" of the TOPEX/POSEIDON data, algorithms, and data processing techniques through assimilation. Since most DA schemes are built around a feedback loop of some kind, they are able to detect bad input and sometimes correct for it, just as the data quality routines used in weather forecasting. To determine if the measurement was bad or if the processing was faulty, a solution would be to integrate all these elements together within the DA scheme. For instance, a mean surface could be checked internally for consistency with the ensemble of possible resulting oceanic circulations. Taking this further, it is expected to achieve "postoptimization" of the first steps leading from the sensor data records to the geophysical data records.

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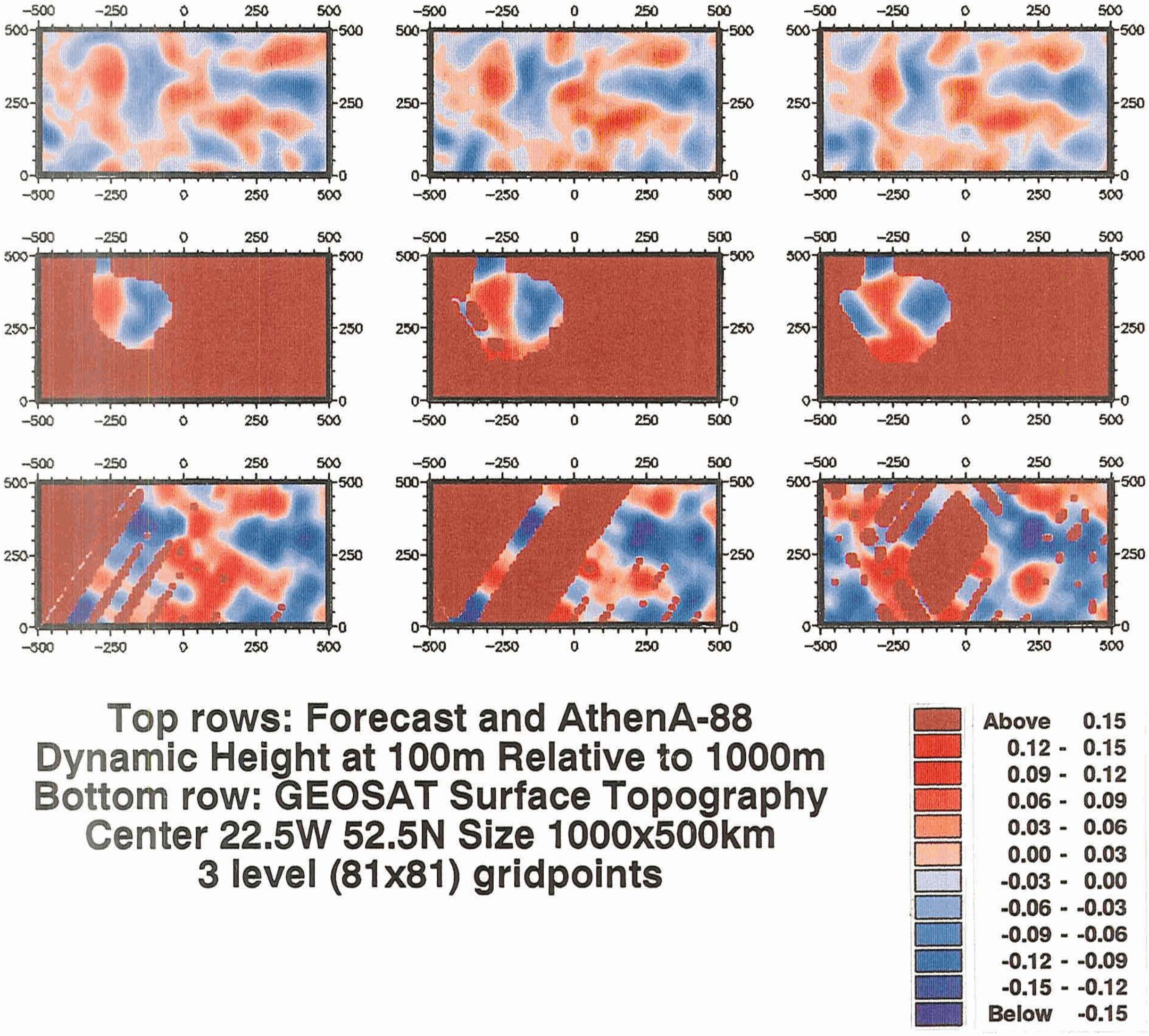

Figure 1. A sequence of estimations of 100-m dynamic height with 20-day intervals from different origins: (bottom) objective analysis of the Geosat altimeter data; (middle) objective analysis of the AthenA-88 conductivity/temperature/depth—expendable bathythermograph data; (top) assimilation of the bottom row (Geosat) data in the quasi-geostrophic model. The domain is 1000 × 500 km. The domain center is 22.5°W and 52.5°N. The assimilation run used three levels on the vertical and had been assimilating Geosat data for more than one year before these pictures were obtained. The assimilation scheme was of the intermittent type.

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Studies of the Intermediate and Deep Circulation in the Western Equatorial Atlantic

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This proposal concerns the preparation and design of an experiment, the objective of which is to improve our knowledge of the intermediate and deep circulation in the western equatorial Atlantic Ocean. We shall focus on the description of the western boundary currents, of their crossing with the equator, on the estimation of their mass and heat fluxes, and their seasonal and interannual variations. We will use satellite altimetric data, tomographic measurements, and in situ observations (current measurements, hydrology, and floaters). We propose a feasibility study and the definition of a strategy based on a high-resolution Geophysical Fluid Dynamics Laboratory (GFDL) numerical model to define which in situ measurements are necessary to optimally complete the altimetric observations.

The satellite altimeter measurements will provide a unique opportunity for repetitive global observations for many years. However, for the interpretation and the use of these observations, it will be necessary to have in situ measurements to determine, in particular, the current velocity inside the ocean and to improve the geoid. We propose to deploy a network of tomographic stations to provide density and velocity data. These data together with the altimetric data and the standard observations should provide a good representation of the general circulation and its seasonal and interannual variability.

The numerical models play a more and more important role in the simulation and prediction of oceanic flows. To run these models, we need measurements that provide initial states (or updates) and boundary conditions and that allow validation of prediction. These data have to fit the characteristics of the numerical model and of the simulated dynamics. We propose the use of a high-resolution GFDL numerical model to accomplish the following objectives: In a preliminary phase, we will simulate the physical conditions and design the optimal network; in an analysis phase, we will use the model with data assimilation to interpolate the observations to a space-time grid; in an application phase, we will evaluate the model and its underlying theory by taking into account observation errors.

The main scientific objective of this proposal is to describe and understand the intermediate and deep circulation (below 500 m, which will be referred to as deep circulation hereafter) in the western equatorial Atlantic, to determine mass and heat flux, and to understand the mechanisms responsible for the seasonal and interannual variations. This proposal is thus complementary to that of Merle et al., which focuses on the surface circulation with an objective of data assimilation using an operational general circulation model. On the technical aspect, our objective is to systematically use the techniques of optimal estimation, objective analyses, and inverse methods to conduct the tomographic experiment in conjunction with the TOPEX/POSEIDON mission and to analyze the results with the help of a numerical model with high resolution. The expected results are a better understanding of the dynamics of the equatorial Atlantic ocean, a better regional geoid, and the possibility of assimilating altimetric data to predict the intermediate and deep oceanic circulation.

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Application of TOPEX/POSEIDON Altimetry to Ocean Dynamics and Geophysics

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I. Scientific Objectives

We will analyze the TOPEX/POSEIDON data using techniques developed for Geosat, although the more accurate TOPEX/POSEIDON data will enable a wider range of problems to be addressed. Our proposed investigations will have five distinct areas.

A. A Description of Global Sea Level Variability

Variations of global sea level as a function of time will be determined from the TOPEX/POSEIDON data, and analyses will be performed to produce descriptions in terms of statistics, spectra, and time series. Data from other altimeter satellites operating during the TOPEX/POSEIDON mission will be used, where possible, to extract the maximum space–time resolution.

B. Tropical Ocean Dynamics

To improve understanding and the predictability of the tropical ocean/atmosphere system, TOPEX/POSEIDON data will be analyzed together with in situ observations to derive a time series of sea level in the tropical Pacific, Atlantic, and Indian Oceans. This information, combined with surface-wind observations, will improve knowledge of the mechanisms and processes associated with the ocean's role in the weather and climate variability. In addition, as part of the National Oceanic and Atmospheric Administration's (NOAA's) Tropical Ocean Global Atmosphere (TOGA) program, sea level in the three tropical oceans will be monitored in near-real time by using the TOPEX/POSEIDON interim geophysical data records (IGDRs). We will require within one week of observation IGDRs with quick-look laser orbits good to the 50-cm level.

C. Coupled Models for El Niño Prediction

Data from TOPEX/POSEIDON and other measurement systems will be regularly assimilated into primitive-equation ocean models. The resultant fields will be used for ocean-climate diagnoses as initial conditions for coupled ocean–atmosphere simulations that will be used for experimental, seasonal, and El Niño–Southern Oscillation (ENSO) forecasts.

D. Structure of the Lithosphere

The TOPEX/POSEIDON data set will be reduced to a digital data base consisting of along-track deflections of the vertical to facilitate investigations of fine-scale structure of the lithosphere. Analyses will include autospectra for determination of dominant wavelengths as well as comparisons of deflection profiles with seismics and bathymetry to define the mechanism and depth of regional compensation.

E. Global Tide Model Improvement

A unified geoid-ocean modeling technique will be applied to the TOPEX/POSEIDON sea level measurements to improve present tide models. This work is based on a new method that models simultaneously the geoid, tide, ocean current, and orbit error. The method will be developed prior to the launch of TOPEX/POSEIDON using Geosat data.

II. Anticipated Data Products

Our experience with Geosat has resulted in an extensive set of altimeter software, data-base management systems, and an archive of high-level oceanographic and geophysical products. We anticipate similar analysis procedures for TOPEX/POSEIDON, as outlined below.

(1) Raw altimeter data system. Geophysical data records (GDRs) are used to create compressed data records (CDRs). Depending on which fields are carried along, a compression of an order of magnitude can be achieved in terms of data volume. Pass headers and indexes based on equator crossings enable rapid search-and-access capabilities.

(2) Ephemeris data system. The satellite ephemeris is used to create a direct-access ground-track file, or ephemeris data record (EDR). Positions of the satellite are stored at 1-min intervals, enabling many years of data to be maintained on line. The EDR is particularly useful for crossover applications. Software has been developed to compute crossover differences from any combination of altimeter data sets. This capability will allow TOPEX/POSEIDON sea level data to be related to observations made previously by GEOS-3, Seasat, or Geosat. Interdecadal sea level changes can therefore be observed.

(3) Sea level time series. Using a combination of crossover and collinear difference methods, continuous sea level time series are computed for 2- × 1-deg regions. Such time series contain information about ocean dynamics from periods of weeks to years. A separate data base management system has been developed to enable rapid access to a global set of such records. This is the primary oceanographic data set on which other analyses are based (e.g., synoptic mapping of sea level anomaly, variability statistics, spectra, space–time diagrams, heat, and volume fluxes.)

(4) Model output. Sea level anomalies derived from altimeter data will be assimilated into a wind-driven-ocean general-circulation model. Various surface and subsurface outputs are obtained.

(5) Operational sea level monitoring. As has been done with data from Geosat, NOAA will use the TOPEX/POSEIDON data in near-real time (2-week delay) to monitor sea level in the three tropical oceans. Output will consist of monthly maps of sea level anomaly and other parameters useful for climate prediction. These products will be derived both from the altimeter alone and from the model output after altimeter data assimilation.

(6) Tide modeling. TOPEX/POSEIDON data will be analyzed to derive an improved global-ocean-tide model. Results will be expressed in terms of standard tidal constituents.

(7) Geophysical results. A digital data base consisting of along-track deflections of the vertical will be assembled from the TOPEX/POSEIDON data to facilitate investigations of the fine-scale structure of the lithosphere.

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p. 3

Circulation of the Gyres of the World Ocean: Observation and Modeling Using TOPEX/POSEIDON Altimeter Data

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I. Objectives

The overall objectives of the proposed investigation are to study the dynamics of the large-scale recirculating cells of water in the ocean, which are loosely defined as "gyres" in this study. A gyre is normally composed of a swift western boundary current (e.g., the Gulf Stream and the Kuroshio), a tight recirculating cell attached to the current, and a large-scale sluggish return flow. The water, of course, is not entirely recirculating within a gyre. The exchange of water among gyres is an important process in maintaining the meridional heat transport of the ocean. The gyres constitute a major mode of water movement in the ocean and play significant roles in the global climate system.

Our current knowledge about the ocean gyres has been obtained primarily from grossly undersampled observations. For instance, a hydrographic section across an ocean basin may provide a quasi-synoptic view of the large-scale density structure of a gyre, but gives no information on how the density structure changes with time. A moored current-meter array shows a coherent picture of the water movement in a small, fixed area, but gives no information on gyre-scale variabilities. This sampling problem will be significantly alleviated by the TOPEX/POSEIDON observations, which will be made along ground tracks that repeat themselves every 10 days with a spatial resolution on the order of 10 km along track and 200 to 300 km across track. Such a sampling scheme operating for a minimum of 3 years allows one to examine the gyre circulation in unprecedented detail in both the frequency and wave number domains.

We plan to investigate the gyre circulation using the TOPEX/POSEIDON altimeter data to address the following specific objectives:

(1) To achieve a spectral description (in terms of frequency–wave number spectra) of the variabilities of the ocean gyres.

(2) To achieve a synoptic description (in terms of sequential maps and empirical orthogonal function analysis) of the gyre-scale variabilities of the ocean.

(3) To estimate the time-averaged circulation of the gyres.

(4) To assimilate altimeter data into numerical models of the ocean in order to combine observations with ocean dynamics to
    (a) Achieve an eddy-resolving description of the surface motions of the gyre.
    (b) Infer subsurface motions.
    (c) Study the gyre dynamics.
    (d) Assess the prediction capability of ocean models.
    (e) Separate ocean circulation from geoid in altimeter measurement.

As an effort to improve the science results, we also plan to investigate methods for correcting two of the major errors in the altimeter measurement: orbit errors and sea state induced errors. The result of this investigation will have potential benefits to all the users of the altimeter data.

II. Approach

In our investigation, a strong link will be established between observational and modeling approaches. The optimized design of the TOPEX/POSEIDON altimeter system for ocean circulation studies makes the mission a unique opportunity to tackle the problem of merging observations with models in describing and predicting large-scale ocean circulation. The observational results will serve as a test ground for the very sophisticated, basinwide eddy-resolving general circulation models (EGCMs) to verify their ability to reproduce the observed ocean variability.

Shown in Figure 1 is a map of the global mesoscale variability obtained by using one year's worth of the Geosat altimeter data, demonstrating the type of results one would expect from an altimetry mission. The observations will also be assimilated into the models to assess the utility of altimetry observations in constraining models to generate realistic subsurface motions and forecast ocean variability. In the prelaunch phase of the research, investigations will be carried out by assimilating the Geosat altimeter data into EGCMs, with an aim toward improving assimilation techniques.

The approach to both observational analysis and data assimilation will be based on a variety of optimal estimation methods such as objective mapping, Kalman filter, and adjoint models. The proper application of these methods requires knowledge of the statistics of the errors of the measurement and/or models. Error analysis will thus constitute a major effort of the investigation.

III. Anticipated Results

The major results anticipated from the planned investigation can be summarized as follows. First, we will achieve a description of the circulation of the gyres of the World Ocean in both spectral and physical domains with unprecedented accuracy and coverage. Second, in a selected ocean basin (the North Atlantic Ocean), we will assimilate altimeter data into a specially designed EGCM to achieve an optimal description of the surface circulation that is not only dynamically sound but also realistic. We will also use the model/data system to compute subsurface motions and to forecast ocean variabilities to assess the utility of altimetry for ocean prediction. These observational and modeling results will not only significantly improve our knowledge of the gyre circulation, but also lay the groundwork for the design of future altimeter systems and ocean models to monitor and predict ocean variabilities.

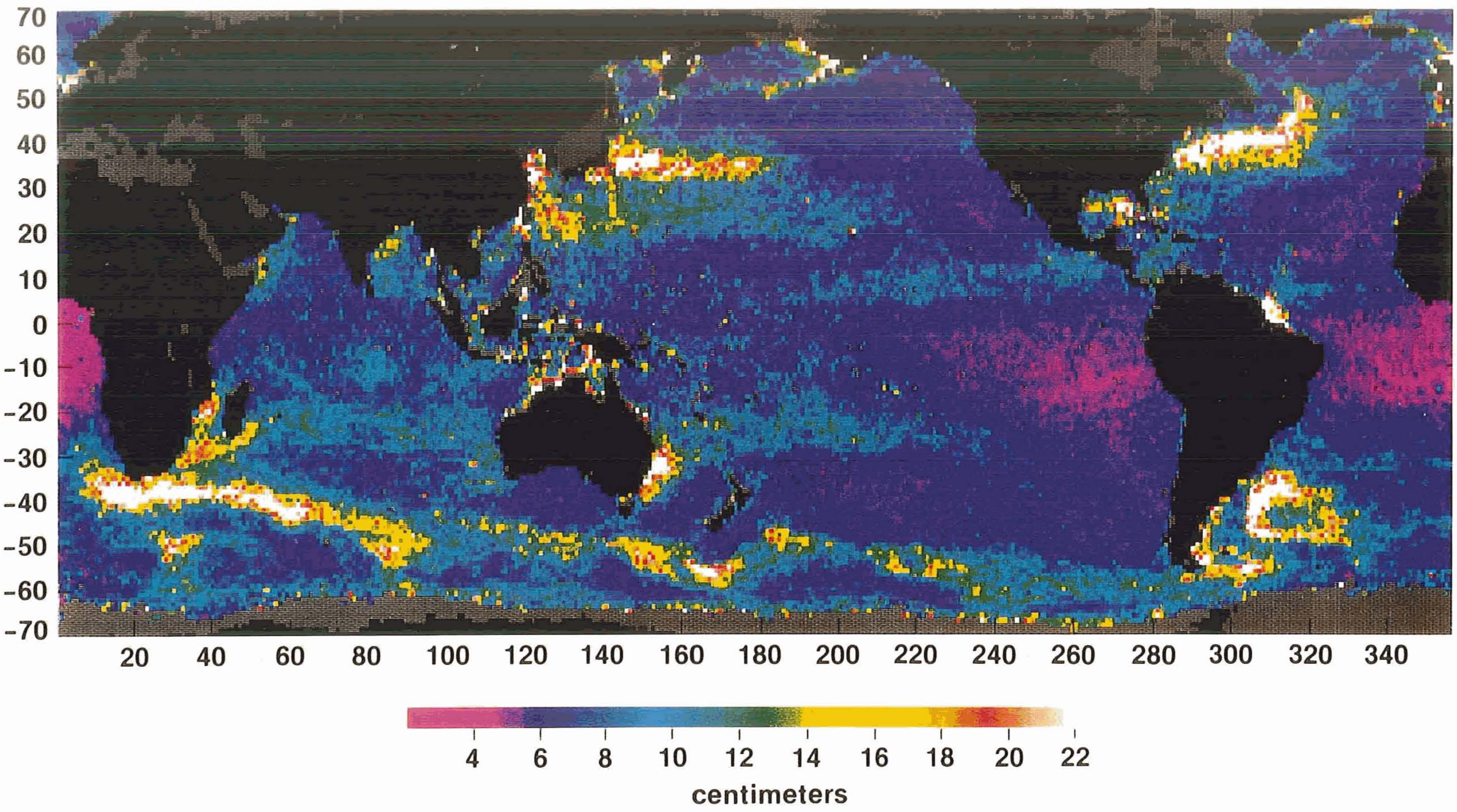

Figure 1. Global mesoscale variability from Geosat altimeter data.

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South African TOPEX/POSEIDON Altimeter Experiment

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I. Introduction

The area surrounding the southern tip of Africa contains a juxtaposition of a variety of interesting and climatically relevant features. On the Indian Ocean side, the Agulhas Current with its tributaries form a conduit through which much of the southern Indian Ocean surface flow is focused. South of the continent, this flow is fragmented and partially injected into the Atlantic Ocean and across the Subtropical Convergence into the Southern Ocean. To the west of the subcontinent, the circulation of the South Atlantic subtropical gyre in the Cape Basin interacts with the vigorous Benguela upwelling regime. The creation, transformation, and transport of water masses and the intra-annual and climatic importance of all these processes have been specifically recognised by the World Ocean Circulation Experiment (WOCE). The South African TOPEX/POSEIDON Altimeter Experiment addresses many of these issues through four mutually complementary and interrelated subprojects (Figure 1).

II. Agulhas Current System Topography

A. Rationale and Objective

The Agulhas Current is the major western boundary current of the southern Indian Ocean. As such, its behavior in terms of velocity, transport, and dimensions is of direct relevance to the local circulation as well the dynamics of the whole southern Indian Ocean. While the concept of semistationary flow in this region established through the International Indian Ocean Expedition is presently very contentious, quasi-seasonal (Gründlingh, 1980) and shorter term variations (eddies and meanders) have been shown to abound both in the Agulhas Current (Gründlingh and Pearce, 1984; Lutjeharms and Roberts, 1988), its tributaries (Saetre, 1985; Gründlingh, 1983), and the Agulhas Retroflection (Gordon et al., 1987). The Agulhas Current System has also been identified by the WOCE Core-1 and Core-2 projects as a major component of the Indian, Atlantic, and Southern Ocean circulation. The objective of this subproject is therefore to use altimetry to study the time and space variability of the Agulhas Current and its peripheral and tributary currents.

B. Approach

The first, or prelaunch phase, started in 1987 and encompasses the acquisition of computer hardware, the development of suitable software, and eventual testing and implementation of the system with Seasat and Geosat data. Establishment of the main hard- and software components has been concluded in 1989/90 and analysis of Geosat data will continue until the launch of TOPEX/POSEIDON. Collinear altimeter data originating from a collection of orbits that more or less coincided spatially and temporally with deep sea surveys in the southwestern Indian Ocean are correlated with eddy and current activity (from ship and buoy data).

The second or launch phase will involve the execution of hydrographic sections, the collection of other complementary data, and comparison of these with altimetric data. It is planned that the present level of deep sea data collection will continue over the satellite mission period. These in situ hydrographic surveys, as well as the altimeter data, will form an important component of the South African contribution to WOCE.

C. Anticipated Results

We hope that the altimeter data will identify areas of variability in the Agulhas Current System and enable any seasonal or intra-annual signal in the variability to be identified and quantified. Particular attention will be paid to the eddies and meanders of the Agulhas Current and Retroflection, Mozambique Current, East Madagascar Current, and Mozambique Ridge Current and thus determine their roles in the dynamics of the whole system.

III. Cape Basin Experiment

A. Rationale and Experiment Objectives

The South Atlantic is the only ocean in which the net transport of heat is equatorwards, and here the Cape Basin area provides the conduit for interocean exchange of thermocline water between the Indo-Pacific and the North Atlantic (Gordon, 1986; Gordon and Haxby, 1989). Consequently, the flux of heat, salt, and momentum through the area is important climatically. However, little is known about warm events occurring in the area (Shannon et al., 1986), the flow structure along the western boundary of the Benguela system (Nelson and Hutchings, 1983), or even the larger scale flow in the Cape Basin (Shannon and Van Rijswijck, 1969). This subproject will aim at documenting and describing the time-dependent flow field in the Cape Basin, over the Walvis Ridge and over the Benguela shelf, so as to provide information useful for heat- and salt-flux studies, for regional scenario modeling and, through WOCE, for global climate models. Through comparison of sea level and current-meter data (augmented by in situ hydrographic observations) with altimeter data, it is hoped that it will be possible to establish the extent of the Walvis Ridge's influence on the circulation in the Cape Basin and to discover how oceanic circulation influences flow over the Benguela shelf.

B. Approach

The altimeter data will be extracted and processed using the techniques currently under development in South Africa. Data from hydrographic surveys, drifters, and moored instruments will be used to provide a detailed description of the flow field in the Cape Basin and its variability. The characteristics (e.g., vertical structure and time dependence) of the features and processes will be related to their possible altimetric expressions, and variability will be quantified. The variability in the flow field in the Cape Basin will be compared with the variability in the shelf circulation in the Benguela region, and an attempt will be made to describe how the large-scale processes influence those on the shelf.

C. Anticipated Results

We are confident that the experiment will contribute substantially to the understanding of circulation in the southeast Atlantic, in particular with the quantification of the zonal and meridional flux of heat, water, and chemicals through the region. The utility of altimetry for monitoring variability in the region will be established. It is hoped that links between the large-scale and shelf processes will be found, with spinoffs for the dynamics and ecology of a major upwelling system. Finally, we shall be able to establish whether or not the time-dependent barotropic flow deduced from altimeter data is related to possible changes in the leakage of Antarctic Bottom Water into the Angola Basin. (If so, this may have important applications and implications for climate research and modeling and for regional circulation studies.)

IV. Indian-Atlantic Interaction

A. Rationale and Objective

It has been shown conclusively that the interaction between the waters of the Indian and Atlantic Oceans south of Africa influences the ventilation of the respective thermoclines and thus plays an important climatic role (Gordon et al., 1987). This geographical area has therefore been designated for particular research attention during the intensive observation period of WOCE. The exchange of water masses between the Indian and Atlantic Oceans takes place, for the greater part, in the Agulhas Current retroflection area and by means of ring shedding from this current. The incursions of these warm Agulhas rings into the southeast Atlantic Ocean have been documented (Lutjeharms and Gordon, 1987), but their full northward penetration and dispersion and their contribution to the meridional heat and salt flux is unknown. This ignorance is due to the lack of suitable data in the area and the fact that the loss of heat by these mesoscale features is very high, causing rapid deterioration of their distinctive sea surface temperature signature (which makes them identifiable in thermal infrared satellite imagery). It has been demonstrated, however, that altimetric data are highly suitable and appropriate in distinguishing and following Agulhas rings in this area (Colton and Chase, 1983; Gordon and Haxby, 1989).

The objective of this investigation is therefore to establish the heat and salt flux from Agulhas rings between the southwest Indian and southeast Atlantic Oceans through the concurrent and synchronised use of hydrographic cruises, drifting buoys, satellite thermal infrared data, and satellite altimetry.

B. Approach

Hydrographic data will be used to provide a detailed description of the vertical and kinematic characteristics of the features observed and to establish how representative the altimetric descriptions of these particular features are. During the prelaunch phase, one research cruise will be dedicated to the area, and Geosat altimetric data will be accessioned to investigate the nature and extent of Agulhas ring penetration into the South Atlantic Ocean. It will also establish in a preparatory fashion the possible correlations between hydrographic and altimetric data on mesoscale features in the area.

After launch, altimetry data from TOPEX/POSEIDON and data from dedicated cruises will be analysed on a regular basis to monitor the creation of rings, comparing these with concurrent thermal infrared imagery from NOAA to establish their coherency and to build a statistical information base on the phenomena. We intend to continue this investigation for the greater part of the Intensive Observation Period of WOCE, 1990 to 1995.

C. Anticipated Results

Upon establishing a suitably significant correlation between the average heat content and kinetic energy of specific rings and their surface topographic expression, long-term altimetry data series will facilitate the estimation of the rate of heat flux in this area as well as its possible seasonal and interannual variability. Other results will include the variability over shorter and longer terms of the mesoscale turbulence in the area, the preferred courses of Agulhas rings into the South Atlantic Ocean, their rates of progression, and the full geographic extent of their influence.

V. Meridional Heat Transport

A. Rationale and Objective

Historical hydrographic data (Lutjeharms and Baker, 1980), drifters, sea surface temperatures (Lutjeharms and Van Ballegooyen, 1986) and satellite altimetry data (Colton and Chase, 1983; Cheney et al., 1983) have demonstrated that the area where the Agulhas Current retroflexes and interacts with the Subtropical Convergence is an area of extreme mesoscale variability. The hypothesis that the heat flux into the Southern Ocean takes place preferentially where energetic mesoscale eddies are particularly evident has been put forward by the Scientific Committee on Ocean Research Working Group 74 as one needing urgent research attention for its verification.

About a decade of research data in the area south of Africa (Lutjeharms and Valentine, 1986) has given a solid hydrographic and kinematic basis on which to build. The manner in which warm eddies are spun off, cross the Subtropical Convergence, and lose their heat in the subantarctic region has been described (Gordon et al., 1987; Lutjeharms, 1988). The importance of establishing the total heat flux, monitoring this flux, and studying inter- and intra-annual variations has been recognised by the WOCE Core 1 and Core 2 meetings. Since altimetry data from Seasat have already been shown to be highly successful in identifying and following eddies in the area (Colton and Chase, 1983), such data may be ideal for this important investigation. The main objective is to determine the heat transferred by the eddies across the Subtropical Convergence and study its variability.

B. Approach

This will be the same approach used for the Indian-Atlantic interaction (Section IV).

C. Anticipated Results

The creation, drift pattern, possible rate of reabsorption, natural history, and frequency of spin-off eddies will be established, and a number of goals set by WOCE will be addressed. Altimetry data will be used in a way never attempted over such a long period. Furthermore, an attempt will be made to relate these altimetry measurements to the hydrographic measurements undertaken by dedicated research cruises in the area and to high-quality thermal infrared data from NOAA orbiting satellites.

VI. Acknowledgements

Apart from the principal and co-investigators listed above, the following coworkers will participate in the project: J. Taunton-Clark, G. Nelson, R. van Ballegooyen, and H. Valentine.

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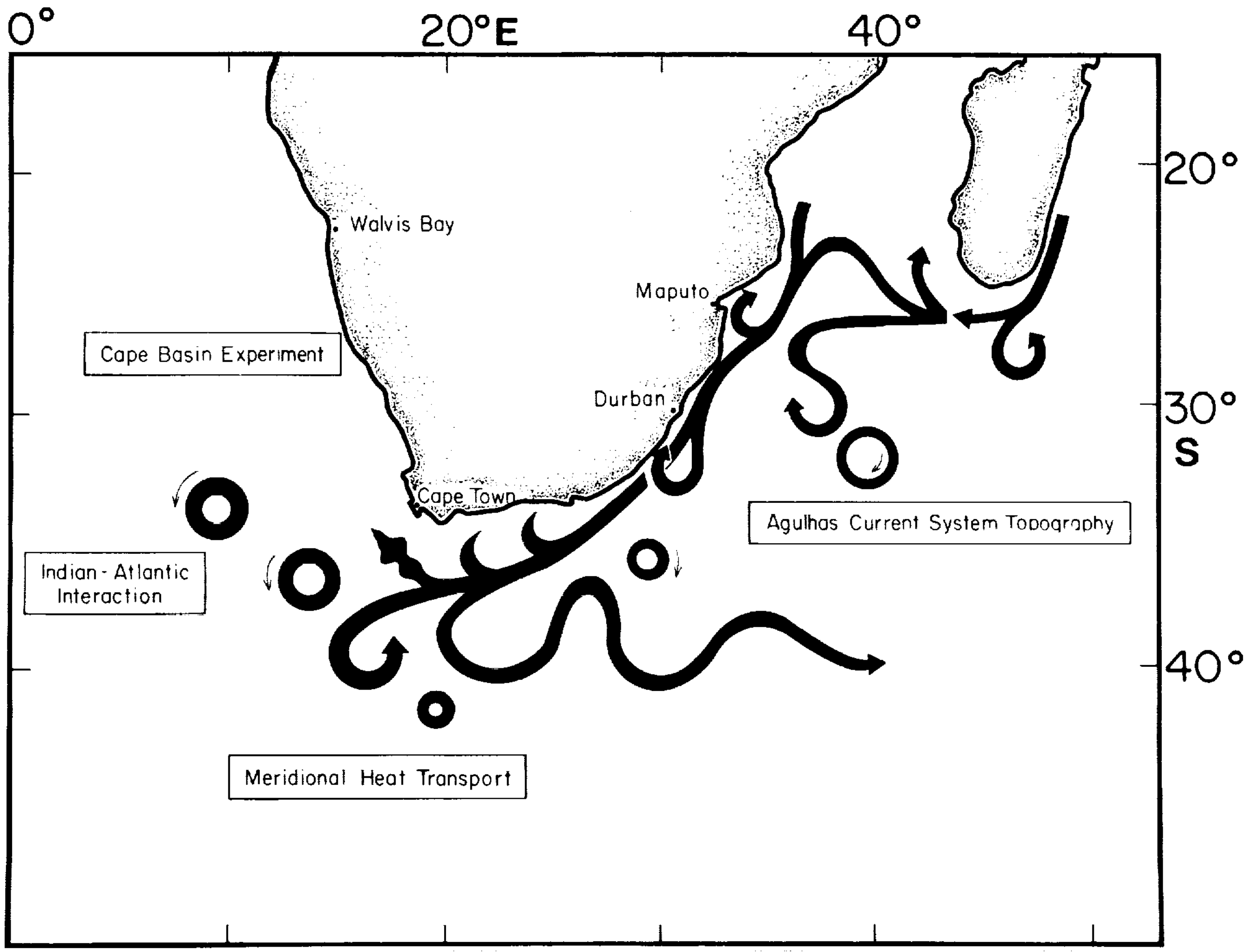

Figure 1. Representation of the circulation of the Agulhas Current System off southern Africa and an indication of the four subprojects of the South African Altimeter Experiment.

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p. 2

Sea Level Response to Wind Forcing in the Tropical Atlantic

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The circulation of the warm-water layer of the tropical Atlantic varies seasonally. This predominant signal is imposed by the annual migration of the Intertropical Covergence Zone separating two trade-wind regimes. As the migration varies interannually, so does the ocean circulation. A long-time objective of climate studies is to understand this interannual variability: to define its range, to fully explain the causal relationship between wind and ocean response, and eventually to understand how the resulting changes in sea surface temperature affect the wind field itself. Our initial objective is to observe and model the oceanic response.

The circulation patterns in the tropical oceans differ both spatially and temporally from the basinwide gyres to the north and south. Because of a vanishing Coriolis force as one approaches the equator, the ocean begins to respond to the wind more nearly as if Earth were not rotating. In particular, the response to the seasonally varying wind becomes very rapid and, for the most part, zonal. Interannual changes in the wind field, either stochastically expected variations or those associated with longer term climatic cycles, will be reflected in the upper ocean, and these changes will in turn affect the atmosphere. Perhaps not surprisingly, then, climatic conditions in regions bordering the tropical Atlantic are characterized by strong interannual variations (e.g., las Secas, or dry spells, in Northern Brazil and the Sahel droughts in Northwest Africa).

For the above and other reasons, the tropical Atlantic has been intensely studied by oceanographers for the last nearly 30 years. Nevertheless, progress has been hampered by the nature of the problem: To observe a rapid oceanic response, one that evolves over periods of a week to a month, requires both quasi-synoptic and time-series measurements that blanket the space and time scale of the response. That has been difficult to achieve in a field where observations are made from platforms (i.e., ships) that are both limited in number and slow to move. Information at appropriate sampling densities has been amassed only very slowly and with it our progress in understanding the dynamic response of the tropical Atlantic.

The twofold development of the satellite-borne scatterometer to measure surface winds and the altimeter to measure changes in surface height, in addition to an existing capability of sensing sea surface temperature from space, offers the possibility of obtaining the much needed synoptic observations. Our program has several components directed at developing methods to maximize the advantage to be accrued from these new data sets.

The first component is to evaluate and understand altimeter surface heights in terms of the more familiar in situ observations. We propose to do this by comparisons with time-scale measurements from tide gauges deployed on the few suitable islands in the region and by comparison with inverted echo sounders. The latter are placed on the sea floor for 1 to 2 years, and they indirectly record the changing height of the sea surface by measuring the travel time of a transmitted acoustic signal from the bottom to the surface. While still few in number, both tide gauges and sounders sample at least every hour and are therefore free of the high-frequency aliasing inherent in the semimonthly repeat cycle of the satellite. These comparisons are presently being made with Geosat data. Our objective is a quantitative evaluation of the importance of in situ measurements in the eventual analysis of TOPEX/POSEIDON data.

A second component is to develop monthly sea surface maps of sea surface height. Once again, this work has begun with Geosat data with the intent of developing the software for the TOPEX/POSEIDON mission. The goal is to design and evaluate methods of reconstructing dynamic sea level from sea level anomaly maps. In preparation for data assimilation studies using altimeter data, spatial and temporal statistics are being computed for the region based on multilevel simulations. These statistical estimates are required for data assimilation by optimal interpolation, the assimilation method most widely used in operational numerical weather prediction.

In the face of historically sparse observational data, there was an early recognition of the significant role to be played by models and data assimilation methods in studying the tropical oceans. The altimeter provides a powerful new observational field; a study of how best to exploit it is the third component of the program. Here we intend to construct flexible and efficient codes for assimilation of altimeter, as well as in situ, data; to devise and evaluate practical data assimilation schemes for eventual use with complex models; and to investigate error models using existing models and data bases. The latter is crucial, as reliable statistical error models determine the degree of success of any data assimilation method.

The absence of a sufficiently accurate geoid has been, and probably will remain, a major obstacle in directly applying altimeter data to physical oceanographic studies. To circumvent this difficulty, we have developed methods for assimilating altimetry differences into simulation studies using the Kalman filter. These same techniques can be easily adapted to optimal interpolation. Along with these techniques, we are studying the question of whether altimetry differences alone are sufficient to determine the model state uniquely. We hope to define the conditions for sufficiency in the context of particular models.

A fourth component of our study is to further understand the ocean models themselves. A hierarchy of simple to complex models of the wind-forced tropical motion already exist. All contain some level of simplification. By producing simulated data sets, we hope to isolate specific features of the predicted circulation that can be attributed to one or another modeling simplification. Sensitivity of model results to various boundary configurations and imposed boundary conditions is an important issue. The criticality of special regions, such as the western boundary and the intensive coastal currents generated there before subsequent bifurcation and/or separation, is especially significant because of the possible degradation of altimeter data near the continental margins of the ocean.

Driving all the ocean models is the wind field at sea level, and its quality imposes a limit on the validity of any subsequent model analysis. Our fifth component, then, is to understand how best to use available wind fields, data on which were either obtained from data assimilating forecast models or derived from satellite observations. One of the first objectives is to determine the appropriate temporal and spatial averaging needed for application to the data. After this is understood, numerical experiments will be performed to characterize the wind errors in a form sufficiently general to be applicable to any model. This will then be extended by numerical experiments to diagnose the propagation of errors in the wind field into the model-generated oceanic fields.

Our goal is to have in place at launch time a system that will produce a synoptic description of a wind-forced tropical Atlantic circulation, constrained by altimeter as well as in situ data. Over the life of the mission, each year will bring another realization of the atmosphere/ocean system that adds to the description of the range of natural variability, while providing contrasting data sets for further in-depth analysis. The full data set, aided by simulations on models honed with the data, will lead us to an understanding of the dynamics of interannual variability.

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Global Ocean Tides Through Assimilation of Oceanographic and Altimeter Satellite Data in a Hydrodynamic Model

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I. Introduction

Ocean tides must be considered in many scientific disciplines: astronomy, oceanography, geodesy, geophysics, meteorology, and space technologies. Progress in each of these disciplines leads to the need for greater knowledge and more precise predictions of the ocean tide contribution. This is particularly true of satellite altimetry. On one side, the present and future satellite altimetry missions provide and will supply new data that will contribute to the improvement of the present ocean tide solutions. On the other side, tidal corrections included in the Geophysical Data Records must be determined with the maximum possible accuracy. The valuable results obtained with satellite altimeter data thus far have not been penalized by the insufficiencies of the present ocean tide predictions included in the geophysical data records (GDRs) because the oceanic processes investigated have shorter wavelengths than the error field of the tidal predictions, so that the residual errors of the tidal corrections are absorbed in the empirical tilt and bias corrections of the satellite orbit. For future applications to large-scale oceanic phenomena, however, it will no longer be possible to ignore these insufficiencies.

II. Research Goals and Strategy

In the context of the European Remote Sensing satellite (ERS-1) and TOPEX/POSEIDON, our goals are

(1) To develop a method of processing all the existing and future altimeter and in situ data to improve our knowledge of mean sea level and tides.

(2) To use the method of (1) to establish new cotidal charts of the significant tidal constituents, over the ocean and the continental shelves, with centimetric accuracy.

(3) To develop on the basis of these results, and validate by checking with observations, a model of prediction of the tidal contribution to the sea surface variability under the altimeter satellite tracks.

The method, as formulated since the beginning of this program in 1987, is based on three components:

(1) A procedure to invert the altimeter (AD) and tide gauge data (MD).

(2) A hydrodynamic model (HM) of ocean tides.

(3) A variational method to assimilate in the HM the data coming from the inversion.

The stability and unicity of the inverse solution for the AD and MD are ensured with the use of all the available sources of information: altimeter data, coming from different satellites and with different orbit and instrumental precisions; equations that relate, theoretically, the parameters to be computed (mean sea level and harmonic tidal constituents); covariance models describing, a priori, the statistical properties of the data and parameter errors (computed from previous models of the geoid, of the dynamic heights of the general ocean circulation, and of the main tidal constituents).

The originality of the HM is based on two major characteristics:

(1) The formulation of the HM, which is spectral in time (as are models based on linear Laplace Tidal Equations), includes a nonlinear parameterization of bottom friction dissipation and allows wave–wave interactions within the spectrum to be taken into account.

(2) The numerical integration of the problem, expressed for each mode under a variational formulation, is realized with a Finite Element Method that allows meshes of several degrees over oceanic areas down to a 10-km resolution over the continental shelves and along the coasts.

Using a variational procedure, these two characteristics will be synthetized by assimilating the results from the inversion in the dynamic model. A posteriori standard deviations and error covariance will be produced for all the computed solutions.

III. Status of the Program

A. Inversion

The problem of the recovery of oceanic tide data from satellite altimetry has been formulated in the frame of the Inverse Problem Theory (Mazzega and Jourdin, 1991). By reference to the usual least-squares method, the total inverse is explicitly constructed from all the a priori available information on the tidal signals and the various errors embedded in the measurements. A set of auto- and cross-covariance functions a priori quantifies the spatial and spectral properties of the tides. The statistical properties of the other components of the altimeter data are also specified through covariances. The tidal solutions are obtained by an inversion of a positive, symmetric, and definite matrix dimensioned with the number of data. Presently, the dimension of the matrix is the only limitation to complete global tidal charts. The method has been tested by Mazzega and Jourdin with the 3 months of Seasat altimetry in the North Atlantic. From limited data subsets, the amplitude and phase of the eight leading tides have been estimated at the location of four deep-sea tide gauges. The inverse solution agrees well with in situ data for the semidiurnal constituents: within 5 cm in amplitude and 10 to 20 deg in phase; in the diurnal band, however, the heavy Seasat data-error budget allows, with similar accuracy, recovery of only the dominant K1 constituent.

It is essential to note that the inversion technique provides a description of the solution errors. An a posteriori error covariance tensor is computed and helps in measuring the ability to resolve the tidal waves in the frequency domain and the degree of spatial resolution of the restituted tidal maps.

This method has been generalized to the inversion of heterogeneous data sets. Tide gauge and gravity-loading data have been separately and jointly inverted to provide global charts of the M_2 wave (Francis and Mazzega, 1990; Jourdin et al., 1991). The results prove that tide gauge data can bring a major contribution to tidal mapping and suggest, on the other hand, that the gravity loading data introduce some distorted information in the present formulation, certainly due to nonmodeled geophysical phenomena and instrumental errors. The M_2 solution derived from tide gauge data and the standard deviations of the in-phase M_2 solution are presented on Figure 1. Tide gauge and Geosat satellite altimeter data have also been considered in both a separate and a joint inversion along geographical sections. These inversions have been performed especially to provide boundary conditions for our hydrodynamic tidal model. The results appear to be accurate enough for such applications. Our goal now is to extend the method for global mapping of the main tidal constituents over the world ocean.

B. Hydrodynamic Modeling

Ocean-tide models reached an impressive level of accuracy at the beginning of the 1980s. However, this accuracy is not ensured everywhere, because the quality of the solutions is closely linked to the quality and density of the dataset used to constrain their computation. One of the difficulties of these models is the lack of resolution over continental shelves. However, increasing the resolution is not sufficient: tides are strongly nonlinear over the shelves, and the interactions between the different tidal constituents play a significant role that is not taken into account in the usual way of computing separately the different tidal constituents. The model developed by Le Provost and Vincent (1986) better meets these constraints (see Section II). It has been tested over the northeast Atlantic: the solutions computed for the main semidiurnal constituents are accurate up to 2 cm in amplitude and 2 deg in phase (Vincent and Le Provost, 1988).

This model is now operational on a CRAY 2 supercomputer. It will allow computation of all the significant ocean tide components, at the basin scale and with the needed resolution everywhere (i.e., 1/15 of the local wavelength). This has been demonstrated for the semidiurnal M_2 wave over the North Atlantic (Le Provost and Vincent, 1991) and for the diurnal waves K1 and O1 over the northern part of the North Atlantic (Vincent, Dadou, and Le Provost, 1991). The high resolution used for the computation of the diurnal constituents has revealed the existence of quasi-nondivergent topographic features trapped along the continental shelf breaks: These waves have much smaller wavelengths than the open-ocean gravity wave and have never been resolved in the previous global ocean tide models. Solutions for the world ocean are presently under computation. The Atlantic Ocean, Indian Ocean, and Pacific Ocean have been triangulated with the necessary resolution. This network is presented in Figure 2. Because of the memory-core requirements, it will not be possible to compute each tidal component directly in a single step: These computations will be performed by basin: North Atlantic, South Atlantic, Indian Ocean, and Pacific Ocean.

C. Assimilation

The final goal of this program is assimilation of tide gauge and altimetric datasets in this numerical hydrodynamic spectral model of Ocean Tides. The method under consideration is based on the generalized linear least-squares theory. For each tidal wave, the problem is to minimize a cost function through perturbations on the forcing terms of the hydrodynamic equations, on the boundary conditions, and on the values of the datasets assimilated. In a first step, the friction and other terms in the dynamic equations are supposed to be exact. The problem is solved in the subspace defined by the nodes of the finite-element discretization and needs the resolution of a linear system sized by the number of nodes of the triangulation. The assimilation matrix is sparse and bandlike. The method is under validation of an analytical case based on the Kelvin wave solution by testing the sensitivity of the numerical solution to the a priori error levels of the forcing, the boundary conditions, and simulated tide gauge data.

IV. Conclusions

The three components of the program are developed simultaneously. A priority has been given in the past to the formulation of the inversion method and to the extension of the HM to the World Ocean. As shown in Section III, the inversion procedure is now operational and will soon be applied to the Geosat dataset. The large effort needed for hydrodynamic solutions of the different tidal constituents is going on, with the aim of completing this work before the end of 1991, as a potential alternative to the Schwiderski dataset. New efforts are now on the assimilation problem, with the goal of being operational for the start of the TOPEX/POSEIDON mission.

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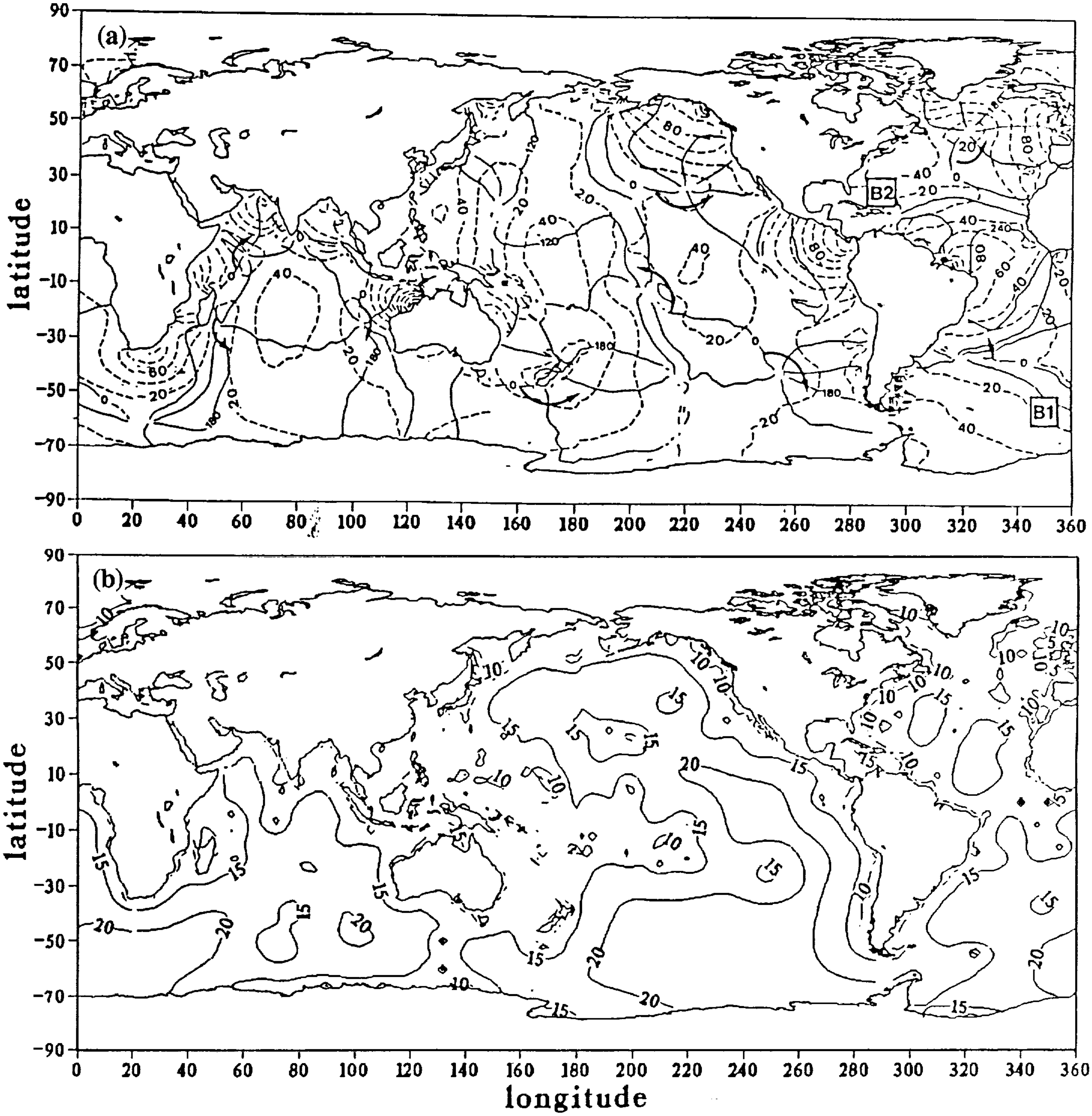

Figure 1. Inverse solution of the M_2 tide derived from tide gauge data: (a) amplitudes in centimeters and phases in degrees; (b) standard deviations in centimeters of the in-phase component (Jourdin et al., 1991).

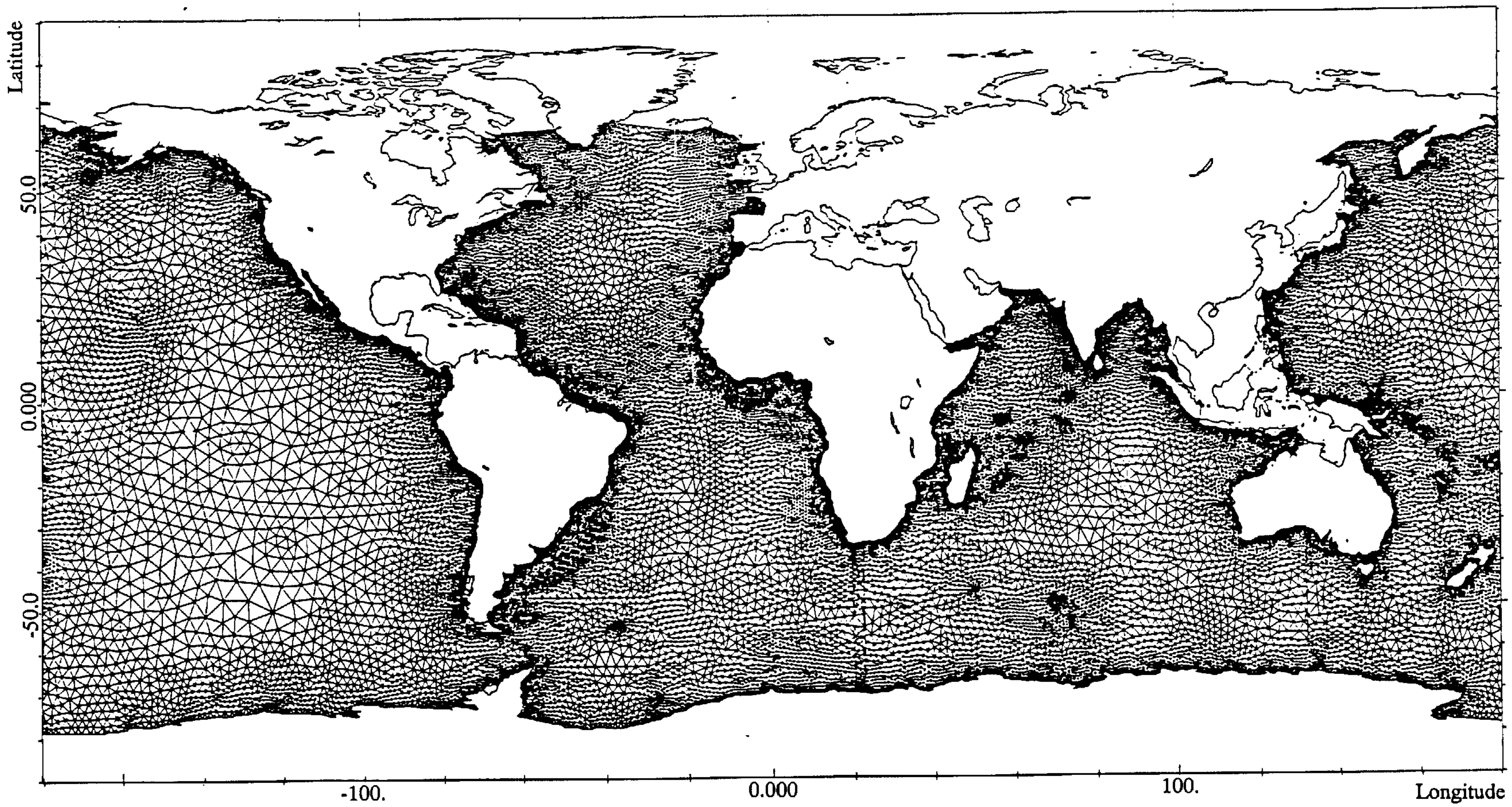

Figure 2. World Ocean triangulation of the Finite Element Hydrodynamic Tidal Model.

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Low-Frequency Variability of Sea Level as Related to the Heat Balance of Global Oceans

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I. Science Plan

A. Introduction

The major influences of the ocean on climate variability arise from the ocean's ability to store heat for many seasons and to redistribute it over large distances. Locally, the ocean absorbs heat in the summer and releases it in the winter; globally, heat accumulating in the tropics is transported poleward by ocean currents. This redistribution of heat significantly reduces the extreme temperature contrasts that would exist between the tropics and polar regions and, thus, moderates global climate.

Year-to-year changes in climate occur when the regular seasonal patterns of oceanic heat transport by currents or ocean atmosphere heat exchange are perturbed. Our current understanding of the variability of ocean heat storage, ocean heat transport, and ocean–atmosphere exchange is presently inadequate, primarily because of the undersampling of the oceanic conditions. The ocean is the main reservoir of water on Earth. The long-term change of global sea level reflects both the change in mass of water in the ocean and the change of thermal expansion due to global warming. The present in situ sea level network can monitor the change only at isolated stations. Spaceborne sensors planned for the 1990s could provide the repeated global observations required to compute the important ocean transports and the ocean–atmosphere exchanges that control climate variability. Unfortunately, these satellite sensors will not penetrate to the ocean depths, so that the variations of heat transport caused by deep current changes will be obscured from global scrutiny.

To solve this dilemma, it is our intention to use spaceborne observations to quantitatively determine the roles ocean surface circulation and ocean–atmosphere exchanges play in maintaining global energy balance and to diagnostically estimate the effect of the important deeper motions in this process. A variety of spaceborne sensors will be required for such a global study. Here we propose a study utilizing the data anticipated from the TOPEX/POSEIDON mission as the central component. It is an important part of our long-term objective of developing monitoring capability over the global ocean to understand the energy and hydrologic balances of the coupled ocean–atmosphere system and their effects on climate variability.

B. Objectives

The TOPEX/POSEIDON mission will determine global changes of sea level with unprecedented accuracy. Our main objective is to use TOPEX/POSEIDON data, concurrent in situ ocean measurements, and other satellite observations to document and diagnose physical processes by which heat is exchanged with the atmosphere, stored in the ocean, or transported by ocean circulation. During the prelaunch period, our objectives are to advise the project on an improved method of retrieving sea level data and prepare for the application of TOPEX/POSEIDON data by developing a diagnostic model using in situ measurements and altimeter observations from Geosat and the European Remote Sensing satellite.

C. The Approach

The designed accuracy of the TOPEX/POSEIDON data would enable the estimation of sea level slopes from which the temporal changes of surface geostrophic currents could be calculated. We intend to use these surface current changes to determine the variations in the surface geostrophic advection of thermal energy. Combining these geostrophic currents with the Ekman (wind-driven) component of the currents derived from wind stress, the effect of surface heat advection on the change of surface temperature will be examined. Moreover, since the local rate of change in sea level is the result of the change in the local mass distribution or thermal expansion (contraction) of the entire water column, we propose to map these steric changes as a diagnostic tool by which to estimate the deep, advective redistribution of heat and mass by the time-variable deep ocean circulation.

During the prelaunch phase, we will examine range correction due to atmospheric water vapor, making use of the large set of atmospheric temperature and humidity soundings we have collected. We will study the effect of atmospheric pressure on sea level change by analyzing the coincident atmospheric pressure and sea level time series. By combining Geosat data with in situ measurements during field experiments, we hope to model the role of atmospheric forcing and the steric change that affects ocean bottom pressure and deep currents. Historic hydrographic and expendable bathythermographic observations will be analyzed to understand oceanic steric changes and quantify their relationship with sea level changes as well as heat fluxes.

D. Anticipated Results

We expect to present our results in data reports and journal publications. We expect papers on atmospheric range correction, inverted barometric effects, the effect of atmospheric forcing on bottom pressure and deep currents, ocean steric changes, and geostrophic heat advection.

II. Data Plan

We do not have special requirements for data. We need all the along-track sea level measurements and their corrections. These will be combined with global sea surface wind stress, surface heat flux, expendable bathythermograph, and Lagrangian drifter data. The supporting data will be acquired from national and experiment archives.

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Studies of Tropical Ocean Dynamics Using the TOPEX/POSEIDON Altimeter-Derived Sea Surface Topography

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I. Objectives and Anticipated Results

Our primary objective is to carry out studies of tropical ocean dynamics using the TOPEX/POSEIDON altimeter-derived sea level data set in conjunction with the large in situ sea level data set available at the Tropical Ocean Global Atmosphere (TOGA) Sea Level Center. These studies will be supported by an interaction with numerical model simulations of tropical ocean variability. Five specific objectives can be identified.

A. Research Products

One specific objective is to use the altimeter data set to improve and expand the research products (e.g., monthly sea level anomaly maps and tropical current indices) put out by the TOGA Sea Level Center. The TOGA Sea Level Center routinely provides almost 300 users with maps of the monthly mean sea level anomalies in the Pacific Ocean each month. Work is progressing on the Indian Ocean network, and, by launch date, similar maps will be constructed for that ocean. Simultaneous monitoring of both the Pacific and Indian Oceans will be important for studies of El Niño–Southern Oscillation (ENSO) and the Indonesian throughflow, among others. The altimeter data set will help fill the large and obvious data-void region in the eastern Pacific where there are no islands for tide gauge installations. The altimeter data set will also be useful for interpolation between the in situ locations in general.

The Sea Level Center also provides the community with transport indices for the major zonal tropical Pacific currents and a time series of the upper layer volume anomaly of the tropical Pacific between 15°N and 15°S. These indices are distributed through the Climate Analysis Center. This time series has been used by Wyrtki (1985) to study the net mass flux from the tropical Pacific during ENSO. Producing this volume index requires the assumption that the monthly mean sea level field is in sufficiently large scale to be resolved by the in situ sea level network. The altimeter data set will be valuable for checking this assumption and for increasing the accuracy of the calculation. Given the increased spatial resolution of the altimeter data set, it should be possible not only to measure the total volume anomaly, but to determine specific regions in which fluid is gained or lost.

B. Short-Term Climate Variations

Another objective is to investigate the mass and heat fluxes from the tropics in order to understand short-term climate variations. Understanding these mass and heat fluxes is essential in meeting TOGA objectives, and it is important to the World Ocean Circulation Experiment (WOCE). The tropical ocean is closely linked to the atmosphere and is thus at the center of programs aimed at understanding short-term climate variability. Much of the emphasis here will be on the Pacific due to its importance to climate dynamics (Horel and Wallace, 1981) and the density of the Pacific in situ sea level data set. However, other oceans will be treated as well. In particular, the Indian Ocean sea level network will be greatly expanded by the launch data of the altimeter.

Wyrtki (1985) has shown that a large flux of mass and heat from the tropics occurs during ENSO events. Hastenrath (1980) and others have demonstrated that the tropical oceans play an important role in the integrated transport of heat from the tropics to the higher latitudes. These fluxes of heat and mass play a role in the dynamics of the general global circulation of climate scales. Thus there is a direct link to the objectives of WOCE. It is also important to note that the tropical zonal currents form the equatorward portion of the midlatitude gyre circulation and hence are important to WOCE in their own right. Meeting this objective of understanding short-term climate variations will greatly increase our understanding of the energy budget of the tropics and its region of midlatitude gyre fluctuations, as well as

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provide information on the process controlling the cycle time between ENSO events.

C. Tropical-Current Variations

A third objective is to understand variations of the tropical current system. The first current we will look at is the North Equatorial Countercurrent (NECC). This current is far enough from the equator (between about 5° to 10°N) that any geostrophic current fluctuations will be associated with larger sea level gradients than would be observed closer to the equator. This will provide a good starting point because, until we are able to deal with the larger signals, it is pointless to attempt an analysis of the smaller ones. This current has been shown to be important in the zonal heat transport during ENSO (Wyrtki, 1979), but its dynamics are not fully understood (Meyers, 1980; White, 1974; Spillane and Niiler, 1975).

We will construct and study the time series of transport indices for the NECC as a function of longitude. The NECC variability will then be studied as a function of space and time and in relation to the wind forcing. For example, we will compute correlations with wind stress, wind stress curl, and meridional and zonal pressure gradients. This work will result in a better understanding of the zonal heat transport in the tropics, a clarification of the NECC dynamics, and will be a clear test of the ability of the altimeter data set to resolve and monitor variations in tropical currents. If this study proceeds well, the analysis will be expanded to other currents in the tropical system.

D. Synoptic-Scale Variability

The fourth objective is to study the tropical "synoptic-scale" variability characterized by periods of about 20 to 90 days and length scales of 0(1000 km). Recent work by Legeckis (1977), Weisberg (1984), Hansen and Paul (1984), Lukas (1982, 1987), Philander et al. (1985) and others has highlighted the energetic oscillations that appear to be a result of instability of the strong zonal tropical currents in all three oceans. This synoptic variability is an important component of the dynamics of the mean currents (Cox, 1980; Semtner and Holland, 1980). Mitchum and Lukas (1987) have analyzed the synoptic band for the presently available Pacific sea level data and find that the lowest frequency variations are enhanced north of the equator, and that at the higher frequencies there is an energy minimum on both sides of the equator until atmospheric synoptic-scale fluctuations become important in higher latitudes.

A problem in studying the synoptic-scale variability is that the spatial scales that can presently be resolved are limited. We will determine whether the altimeter data set can be used to study these signals and, if these data are useful, we will pursue a more complete statistical analysis of their (frequency-dependent) zonal and meridional scales. We are particularly interested in the potential for relating variations of the energy levels within subsets of the synoptic band to wind variations and/or to low-frequency current variability. This work will result in a better understanding of the general wind-forced response of the tropical ocean and improved insight into the dynamics and energetics of the mean tropical circulation.

E. Model Simulations

A final aspect of our work is the use of numerical model simulations to complement all of these studies. For example, two-layer models will be particularly important for evaluating vertically integrated mass and heat transports. Prior to launch, sea level fields from wind-driven numerical-model simulations will be used to determine a priori estimates of the important spatial and temporal scales of variability with relevance to sampling concerns. During the postlaunch phase of the program, model calculations driven by observed wind stresses will be directly applied to the analysis of oceanic phenomena observed by the TOPEX/POSEIDON altimeter, e.g., the relation between observed NECC variability and the wind field. Of particular interest is the basin-scale closure of the system of equatorial currents on seasonal and interannual time scales, which will then be feasible because of the spatial coverage afforded by the TOPEX/POSEIDON data set.

To further investigate the vertical variability of the tropical ocean, we will also cooperate with other research groups. Tony Busalacchi is involved in another proposal that will study the TOPEX/POSEIDON altimeter data set in conjunction with subsurface thermal data from expendable bathythermographs. These projects and our own are highly complementary and linked by the modeling efforts described here.

II. Approach

Prior to the launch of the satellite, we will use the in situ sea level data and proxy sea level fields generated by numerical models to determine ways to make the best use of the altimeter sea level. We will evaluate the sampling and aliasing errors in the altimeter data set and use these results to test methods for combining the altimeter data with the in situ data. We will take advantage of the excellent temporal resolution of the in situ sea level data to determine the statistics of the tropical sea level signal. Spatial statistics will also be determined from the model data. We have addressed the sampling question by subsampling the in situ data at various repeat periods to determine the aliasing that may occur in the altimeter data set. We will be able to map aliasing errors over at least the tropical Pacific. Our next step involves adding the expected error terms from such factors as orbit determination and water vapor to the observed sea level signal. This will allow us to test methods of recovering the signal and is central to evaluating methods for producing a final data set that blends in situ and altimeter sea level fields. These sampling and aliasing studies will be complemented by similar studies carried out with numerical model output, which has better spatial resolution than the in situ data.

By launch time, we will have tested various methods for combining the in situ and altimeter data sets into a single research data set, and we will have determined what time and length scales we can reasonably expect, given the sampling constraints. The results of our work will include a combination of the altimeter and in situ data sets that will be used to achieve the objectives outlined above.

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Ocean Topography Mapping, Improvement of the Marine Geoid, and Global Permanent Ocean Circulation Studies From TOPEX/POSEIDON Altimeter Data

ORIGINAL CONTAINS
COLOR ILLUSTRATIONS

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I. Introduction

The TOPEX/POSEIDON altimeter measurements will be the first global observations of the sea surface with accuracy sufficient to make quantitative determinations of the ocean's general circulation and its variations. These measurements are an important step to understanding global change in the ocean and its impact on the climate. Our investigation will focus on the examination of features in the sea surface elevation at the largest spatial and temporal scales. TOPEX/POSEIDON altimeter measurements will be used in conjunction with observations from past satellite-altimeter missions, such as NASA's GEOS-3 and Seasat, the U.S. Navy's Geosat and SALT, and the European Remote Sensing satellite in order to address the following issues:

(1) Improve models of the marine geoid, especially at wavelengths needed to understand the basin-scale ocean dynamic topography.

(2) Measure directly from the altimeter data the expression of the mean global ocean circulation in the sea surface at the largest scales through a simultaneous solution for gravity, orbital, and oceanographic parameters.

(3) Examine the sea surface measurements for changes in global ocean mass or volume, interannual variations in the basin-scale ocean circulation, and annual changes in the heating and cooling of the upper ocean.

II. Geoid Improvement

Satellite altimeter measurements permit the global estimation of sea surface elevation relative to the Earth's center of mass. However, the undulations in the geopotential surface or geoid are two orders of magnitude larger than surface variations caused by the ocean circulation. Accurate determination of the geoid is prerequisite to an estimate of the dynamic sea surface. Estimation of the large-scale variations in the geoid is arrived at through the development of Earth gravity models based on both terrestrial and satellite observations. Short-scale variations in the geoid can be obtained using the mean sea surface data from satellite-altimeter measurements, but these estimates include the dynamic sea surface.

In our studies, improvement in geoid models will be based upon extending the present Goddard Space Flight Center (GSFC) TOPEX/POSEIDON gravity-model development activity to include the TOPEX/POSEIDON measurements. The gravity anomalies in milligals from the GSFC Earth Gravity Model (PGS-3337) created in this development effort are shown in Figure 1. The PGS-3337 model is based upon satellite tracking data from 17 satellites, a global set of surface gravity data, and Seasat altimeter data (Marsh et al., 1990). This model is the prototype for geoid models to be created by this investigation from TOPEX/POSEIDON altimeter data.

The geoid-improvement activities will also enable improved TOPEX/POSEIDON orbit computations. For the reference orbits to be used in the absolute definition of a mean surface with respect to a geocenter, highly precise orbits will be computed using the best available models and tracking data. Presently, these techniques are being used to estimate orbits for the Geosat satellite. A dramatic improvement in the precise determination of orbits for altimeter satellites has been accomplished in the past ten years. Orbit-determination accuracy for Seasat in 1979 was about 2 m rms for the radial position of the satellite, whereas our present computations for the Geosat orbit are approaching 20 cm rms. To precisely estimate the dynamic sea surface with TOPEX/POSEIDON, orbital accuracies will have to be on the order of 10 cm in radial position.

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[1] J. G. Marsh passed away on June 30, 1991. C. J. Koblinsky has assumed the role of Principal Investigator for this project.

III. Determination of the General Circulation

Traditionally, the mean dynamic surface of the ocean has been determined from composites of integrated vertical density profiles measured from ships. The surface is estimated relative to a reference level in the ocean, which is assumed to be a geopotential surface. A major goal of the TOPEX/POSEIDON mission will be to directly estimate the surface relative to the geocenter so that direct estimation of the deep ocean circulation can be made using hydrographic observations relative to the altimeter-derived surface. The lower part of Figure 2 shows a recent estimate of the dynamic sea surface relative to a pressure surface at 2250 db from climatological fields of shipboard measurements. This figure shows the classic picture of the ocean circulation patterns: The ocean circulation is perpendicular to the sea surface gradient because of the Coriolis effect. The circulation is clockwise around regions of high sea surface elevation in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. Regions of high sea surface are found in the western regions of each ocean basin, such as the North Atlantic. Strong western boundary currents (e.g., the Gulf Stream) provide the return flow for the broad circulation pattern in the eastern portion of the basin.

The advantage of satellite altimetry over shipboard observations is both a substantial increase in the number of observations and an ability to measure the surface relative to the geocenter. In our approach, the dynamic sea surface topography will be functionally modeled as a geometric surface uncoupled from, but relative to, the geoid, and the parameters of this surface will be simultaneously recovered along with the full gravity model and other geophysical parameters in the orbit-determination process. This technique has been used to examine the mean dynamic topography in both the Geosat and Seasat altimeter measurements (Marsh et al., 1990; Koblinsky et al., 1991). In the upper part of Figure 2 are the results from Seasat. This part of the figure can be compared with the climatological version of the sea surface shown in the lower part.

The altimeter observations from the 3-month Seasat mission already suggest the basic patterns and magnitudes of the general circulation that have been estimated from composites of 70 years of ship observations. The causes of the strong discrepancy between the two estimates in the eastern Pacific and South Atlantic are presently unknown. They could be the result of poor orbit determination or errors in the geoid, or they could be the result of unknown circulation processes. The measurements from TOPEX/POSEIDON will revolutionize the information in Figure 2. The TOPEX/POSEIDON measurements will significantly improve the horizontal and vertical resolution of this technique and permit a direct estimation of the error in the surface.

IV. Large-Scale Sea Surface Variations

Large-scale fluctuations in sea surface topography are important indications of global change. Such variations include secular trends in the total mass or volume of the oceans; large-scale interannual variations of the surface, such as those created by the anomalous wind-forced undulations of the thermocline during the occurrence of the El Niño–Southern Oscillation (ENSO); and the annual expansion and contraction of the upper ocean in midlatitudes that result from the seasonal heating cycle. These fluctuations occur at very large scales and are severely contaminated by orbit-determination errors in the present satellite-altimeter systems. For TOPEX/POSEIDON, the improved orbital accuracy and geoid determination will substantially enhance our ability to resolve these important signals.

This investigation will examine the large spatial and temporal variations of the sea surface. Our approach will be to utilize the simultaneous solution mentioned above to solve for the mean dynamic topography on a monthly basis. Initial computations with this technique on the Geosat and Seasat data have been quite encouraging. An estimate of the global annual cycle of sea level from the Geosat data for 1986 and 1987 compares quite well with a climatology from in situ measurements and suggests that our technique has a resolution of at least 3 cm rms (Koblinsky et al., 1991). We have also examined the difference in a mean dynamic topography surface from the Geosat data for the summer of 1987 with a similar surface from Seasat data for the summer of 1978 (see Figure 2).

The change in the global sea surface between 1978 and 1987 as estimated from these altimeter measurements is shown in Figure 3. The lower part of this figure shows the altimeter estimate of the 9-year change in sea level. The upper part shows an estimate created by interpolating island and coastal tide gauge measurements; the error in this method is especially severe in the eastern Pacific where observations are quite sparse. The most obvious consistency in these surfaces is the high and low elevations in the eastern and western tropical Pacific, respectively. This change relative to 1978 was caused by the ENSO event in 1986 and 1987. It reflects the depression of the themocline in the eastern tropical Pacific. In other regions, for example the western subtropical North Pacific, the comparison is not good. In the western subtropical North Pacific, there are a substantial number of tide gauges, so that the difficulty in the comparison is probably the result of problems in the altimeter observations. The most likely cause for this discrepancy is the poor correction for the radar range delay through the troposphere in the Geosat data. The TOPEX/POSEIDON mission will make simultaneous measurements of surface height and atmospheric water-vapor content to accurately determine this important correction factor.

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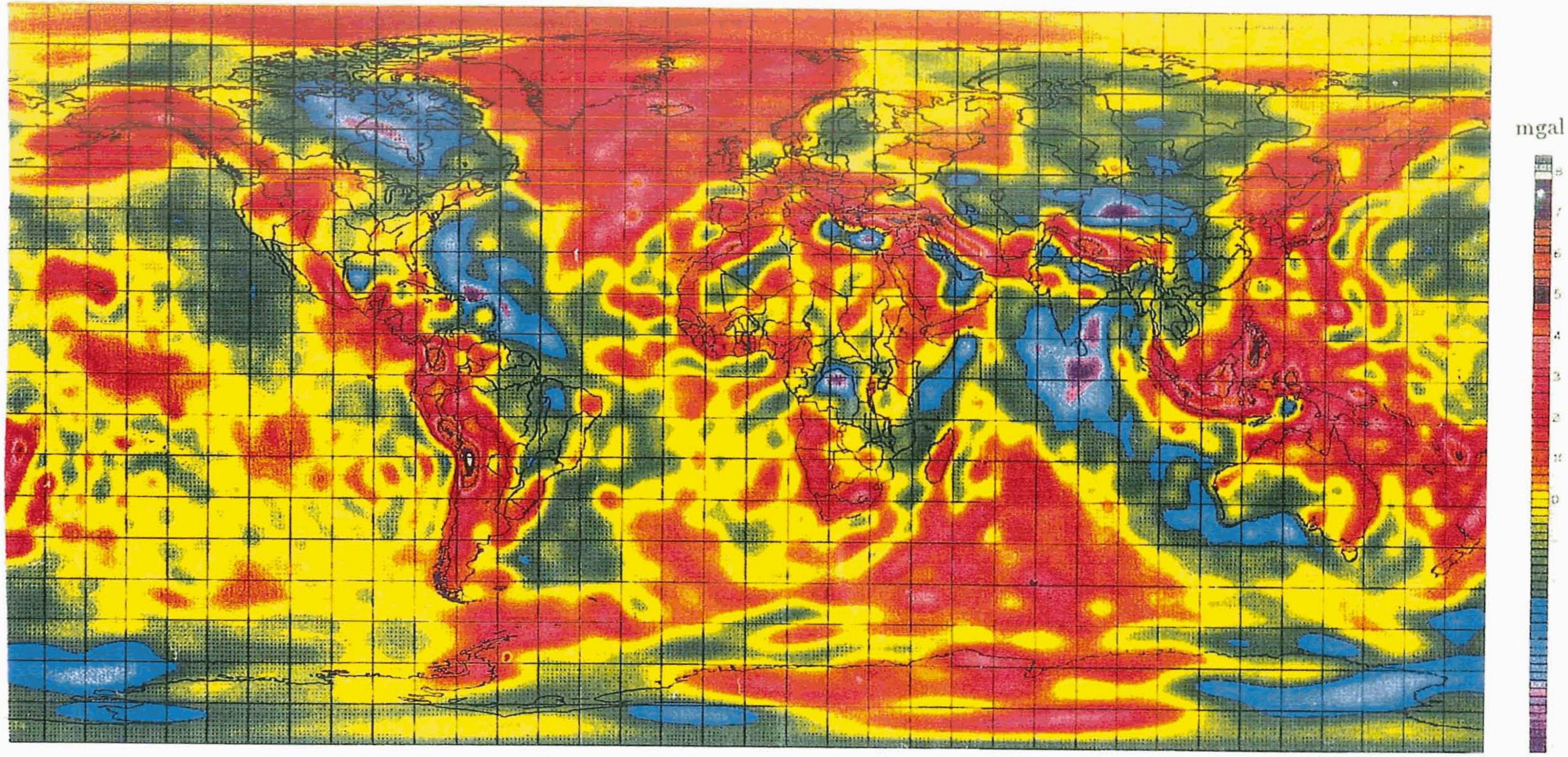

Figure 1. Gravity anomalies determined from PGS-3337.

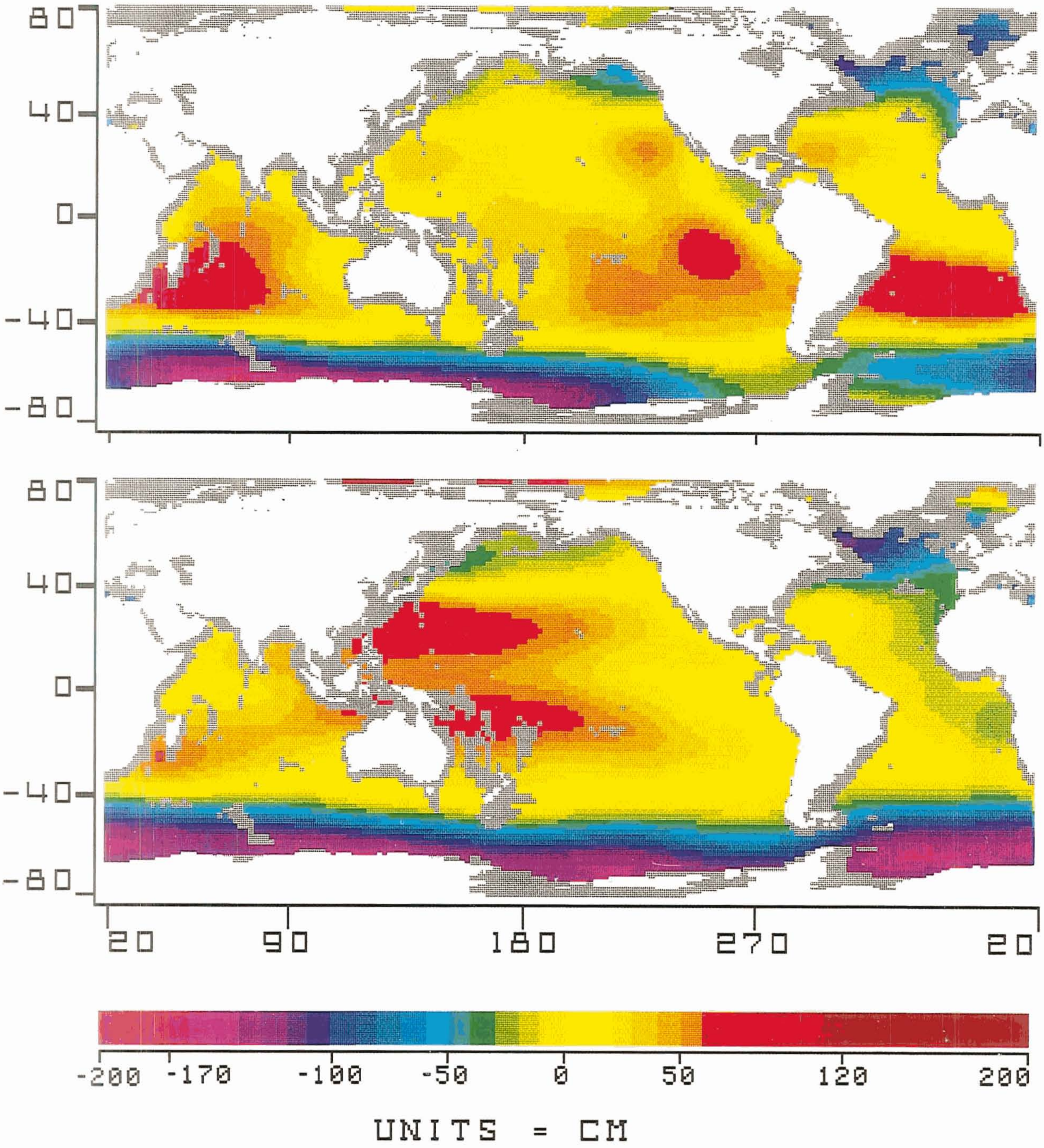

Figure 2. The upper image shows the mean dynamic topography of the ocean surface from NASA's Seasat altimeter measurements between July and October 1978. The lower image shows the dynamic topography of the ocean surface relative to a surface at 2250-db pressure from climatological in-the-water measurements of vertical density profiles. Both figures have been constructed from spherical harmonic representations of the data for the degree and orders 1 through 10.

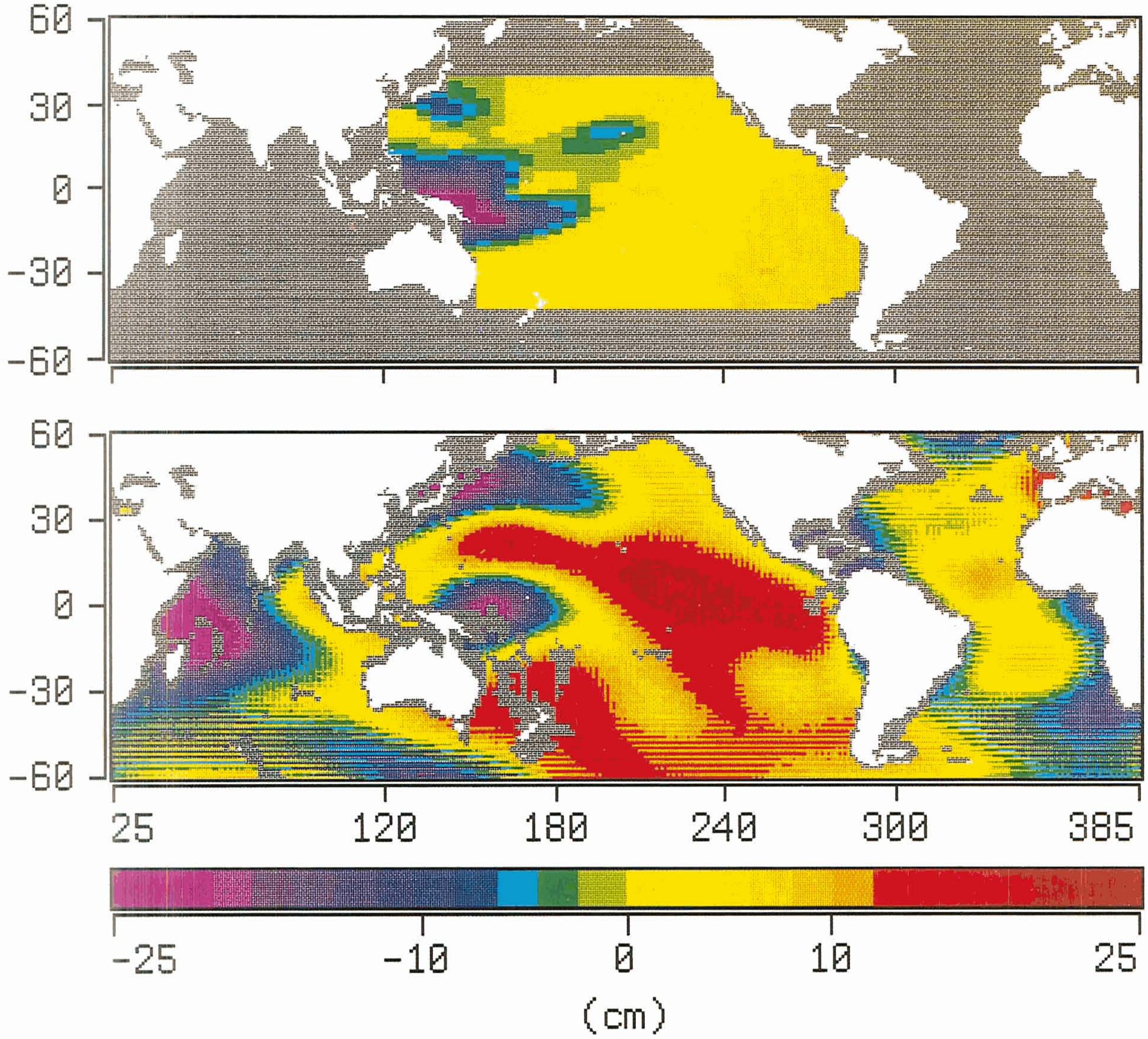

Figure 3. The upper image shows the change in sea level between August 1987 and August 1978 that has been determined from tide gauge stations in the tropical Pacific. The lower image shows the difference in absolute dynamic topography between summer 1987 determined from the Geosat altimeter measurements and summer 1978 determined from the Seasat altimeter data (see Figure 2). The altimeter data have been constructed from spherical harmonic representations of the dynamic topography for degree and orders 1 through 10.

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Geophysical Validation of TOPEX/POSEIDON Altimetry Products

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I. Background

Local calibration experiments are already planned to perform the engineering verification of the TOPEX/POSEIDON altimeters during the first 6 months of the mission. Two sites, Lampedusa Island and the Harvest Platform, will be equipped with appropriate instruments to compare, with the required accuracy, the sea level as measured by the altimeters to the sea level deduced from tide gages and laser measurements. These campaigns will be dedicated primarily to the determination of the instrumental bias and to the quality control of the instruments. These on-site studies provide a way to locally control the entire altimeter system, which is appropriate for the engineering verification, but the studies are representative of local conditions only. The altimeter system must be qualified also on a global scale, in different environmental conditions, and for a wide range of oceanic signals. This will be done through regional validation opportunities. Each of these validation studies can be associated with specific objectives depending on the environmental characteristics of the area investigated and on the altimetry product to be evaluated.

This study will focus on the validation of the dynamic topography and sea state products as deduced from altimetry. The validation includes a verification of the results' coherence, an estimation of the errors, and an evaluation of the correction models applied to altimeter data. These objectives will be met in regions well monitored by a dense network of in situ measurements and whose ocean dynamic is already well understood and accurately modeled.

The tropical Atlantic is one of the most appropriate regions for validation of the large-scale dynamic topography signal. It has been observed during various in situ campaigns, especially the Programme Français Océan et Climat dans l'Atlantique Equatorial (FOCAL)–Seasonal Response of the Equatorial Atlantic (SEQUAL) experiment, and it is still the object of an intense survey through the Tropical Ocean and Global Atmosphere Programme (TOGA) and will be the object of the next World Ocean Circulation Experiment (WOCE) program. A tide-gage network is being developed (Figure 1) all around the tropical basin, allowing a future direct adjustment of the altimeter observations by the gage observations. Finally, the modeling effort is quite advanced with basic two-layer models (Du Penhoat and Gouriou, 1987) and more complete three-dimensional models (Philander and Pacanowski, 1986), in which altimeter data will be soon assimilated. In terms of the altimeter operating in the tropics, atmospheric effects (e.g., tropospheric and ionospheric delays and rain perturbations) on the measurements are the most important consideration and must be carefully evaluated. This is a required preliminary step taken before the assimilation of altimeter data in oceanic models.

The North Atlantic is subject to medium and extreme (at high latitudes) sea state situations. These highly variable conditions are favorable to an estimate and better understanding of the sea state bias affecting the altimeter measurements and the calibration and validation of the wave height and wind speed altimetry algorithms. The North Atlantic is relatively well observed by the conventional meteorological network. Global meteorological models that already exist are being improved by high-resolution regional models (Bougeaut and Bret, 1986) soon controlled by satellite data.

More specific campaigns, especially dedicated to altimetry sea state validation, are planned in such northern regions as the northeast Atlantic or the Norwegian Sea. Pre- and post-launch validation experiments are already planned for the European Remote Sensing satellite (ERS-1) in the Norwegian Sea. The same region should serve the TOPEX/POSEIDON validation campaigns. Winds reaching 30 m/s or more and wave heights of 10 m are frequently recorded in this area. An altimeter-data assimilation scheme will be performed through the Norwegian Meteorological Institute (DNMI) and the French Meteorology Office (Meteo France) numerical wave models.

II. Objectives

The objectives of this study are the following:

(1) To assess the quality of the sea level observed by altimetry on a global scale, especially in tropical regions where the atmospheric effects are the most critical, and to prepare the altimeter data for their assimilation into tropical Oceanic General Circulation Models. These efforts include

  (a) Evaluation and determination of the frequency–wave number structure of the water-vapor content and its variability; validation of the altimeter tropospheric correction obtained from models or radiometer measurements; sensibility studies about the propagation of the tropospheric errors in the altimeter fields; and evaluation of the rain-cell effects on the altimeter measurements.

  (b) Evaluation and determination of the frequency–wave number structure of the total electronic content in the ionosphere; validation of the altimeter's ionospheric correction obtained from models; characterization of the propagation of the ionospheric errors in the altimeter fields.

  (c) Participation in the development of methods of assimilation in the oceanic circulation models.

(2) To validate and calibrate the altimeter-derived sea state parameters, to assimilate these parameters into numerical models, and to estimate the altimeter's sea state and electromagnetic biases. These objectives especially include

  (a) Calibration and validation of the altimeter's significant wave height and wind speed measurements.

  (b) Validation of the altimeter-derived significant swell height, peak period, direction, and arrival time; validation of altimeter-derived wind–wave period and energy.

  (c) An estimate of the electromagnetic bias and sea state biases on the sea level altimeter measurement.

  (d) Comparison and assimilation of the altimeter-derived sea state parameters into the numerical meteorological models.

III. Approach

These issues will be addressed by using, simultaneously, in situ data, modeling, and satellite data.

Validation of the large-scale altimeter signal in the tropical Atlantic (20°S to 20°N) first requires analysis of the available in situ data to determine the principal characteristics of the tropical signal. These specifications are useful in verifying the internal coherence of the altimetry results. This work is already well advanced thanks to the profusion of data from previous experiments like the FOCAL–SEQUAL and the TOGA, and the Geosat altimeter data (Arnault et al., 1990). During the TOPEX/POSEIDON mission, new conventional in situ data will be collected, especially through the WOCE program, in association with additional satellite data (e.g., ERS-1). The methods developed for the altimeter validation are usually based on comparisons between conventional hydrographic data and altimeter sea level fields. Oceanographic data like expendable bathythermograph (XBT) and conductivity/temperature/depth (CTD) measurements allow measure of the depth of the thermocline, which, in the tropics, is closely related to the sea level as observed by altimetry (Figure 2).

Tide gages are even more comparable to altimetry, as they measure the same sea level parameter. A new network is being developed in the tropical Atlantic that will be fully operational by the time TOPEX/POSEIDON is launched (Figure 1). This network, whose tide gage sites will be collocated by GPS, covers all of the basin and can meet the altimetry validation requirements (especially those that reduce the large-scale orbit errors). The atmospheric models that provide corrections of the altimeter measurements (water-vapor content, atmospheric pressure, rain, and ionospheric total electronic content) will be evaluated in terms of accuracy and resolution. They will be cross-compared with external measurements. The troposphere effect and its variability are especially critical in the tropical regions; onboard satellite radiometer measurements, available radiosoundings or airborne radiometer measurements, and meteorological-model correction will be used. Propagation of the corresponding errors in the results and the artifacts they create will be characterized. Finally, the comparison with two-layer or even three-dimensional models will constitute another way to control the quality of altimeter guess fields before their assimilation (cf Merle's TOPEX/POSEIDON proposal in this publication).

Validation of the altimeter sea state measurements (significant wave height and wind speed) and of the derived sea state estimates (swell and wind–wave characteristic parameters) has started with the acquisition, processing, and analysis of the Geosat data set collected during the prelaunch ERS-1 experiment—the Norwegian Continental Shelf Experiment (NORCSEX'88)—which took place in March of 1988 in the Haltenbanken region. Direct comparisons of Geosat data with wave scan buoys, with the DNMI model hindcasts output, and with simultaneous aircraft synthetic-aperture radar (SAR) measurements have been performed (NORCSEX'88 Group, 1989; Olsen and Barstow, 1988; Barstow and Bjerken, 1988; Mognard et al., 1988a,b). Very encouraging results have been obtained, especially those concerning the Geosat-deduced swell propagation patterns and wind–wave characteristics in the midst of storms (Figure 3).

The algorithms used to infer swell and wind–wave parameters from the Geosat altimeter will be used and tested in the same ways for TOPEX/POSEIDON. Statistics will be performed in the regions (Norwegian Sea and North Atlantic) specially dedicated to the sea state parameter validation in order to determine their time–space characteristics. Fields from numerical forecasting models, wave models (e.g., the VAG model, Guillaume, 1987), regional high-regional models (e.g., the PERIDOT model, Bougeaut and Bret, 1986), and other satellite measurements (e.g., altimeter and scatterometer ERS-1 data) will be cross-compared with TOPEX/POSEIDON sea state fields. Then the altimetric data will be assimilated into a numerical wave model (a Guillaume and Mognard analysis is in progress). In the same way, the altimetry wind fields will be compared with external data and assimilated into the French operational, numerical, weather-prediction model.

For the electromagnetic bias estimation, three approaches are currently being investigated: one is based on the modeling of the altimeter-return waveforms and the extraction of order-3 momentums (taking into account the non-Gaussian distribution of wave height and slope) from these waveforms. Another approach is to better understand the dynamics and the distribution of this electromagnetic bias through experiments in wave tanks (at Institut de Mécanique Statistique de la Turbulence (IMST), Marseille) associated with numerical modeling. Finally, statistical methods based on the simultaneous use of sea state models and altimetric wave height and sea level topography fields can be helpful in better understanding the respective effects on the altimetric measurements.

IV. Expected Results

The prime expected result is to qualify on a global scale the altimetry system for large-scale dynamic topography-signal and sea state parameters. The calibration (tuning of the algorithms), validation (accuracy estimation of the algorithms), interpretation, and understanding of altimetry products are among the objectives of this study. Preliminary results, based on data available today (mainly Geosat data) will allow us to optimize specific regional validation experiments for the TOPEX/POSEIDON mission (Menard et al., 1990).

In addition, other opportunities for regional or global validation will be used to cover a wide range of environmental conditions. The eventual defaults of the system and their possible origin will be identified. The long-term monitoring of the tropical and North Atlantic, which is planned for many years through different programs (e.g., TOGA and WOCE), will provide an opportunity to have a quasi-continuous verification of the internal coherence and stability of the altimetric system. This is a necessary task for future operational assimilation of altimetric data in three-dimensional oceanic models and meteorological models.

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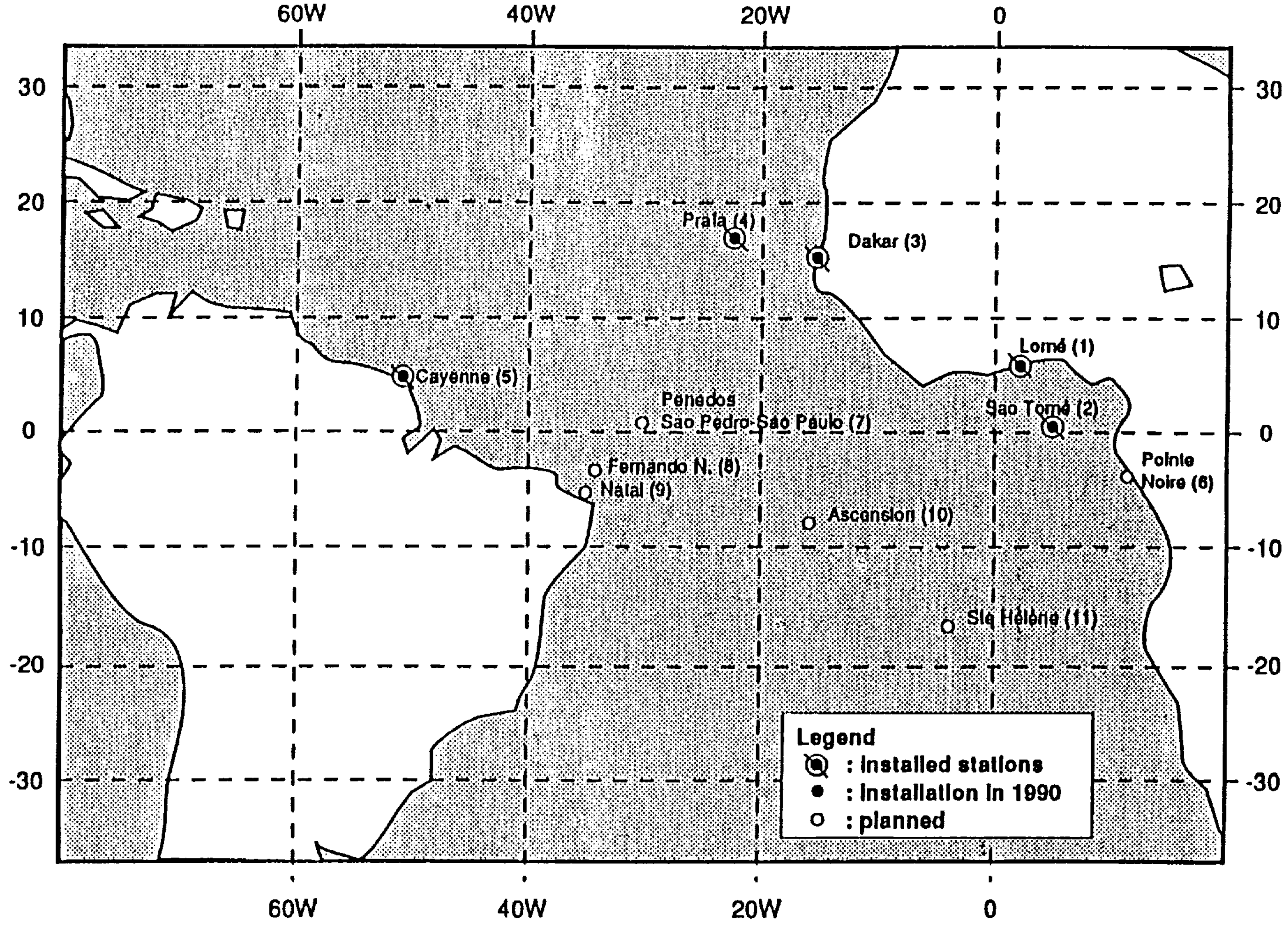

Figure 1. South Atlantic tide gauge network. Togamar, one of the main components of the French contribution to TOGA, should be implemented over an 18-month period starting in May 1989 when the first station in the series will be tested at Lomé (Togo). Four stations will then be established before the end of the year. Five to 10 further stations are planned for 1990, the objective being an operational network of 10 to 15 stations for the South Atlantic.

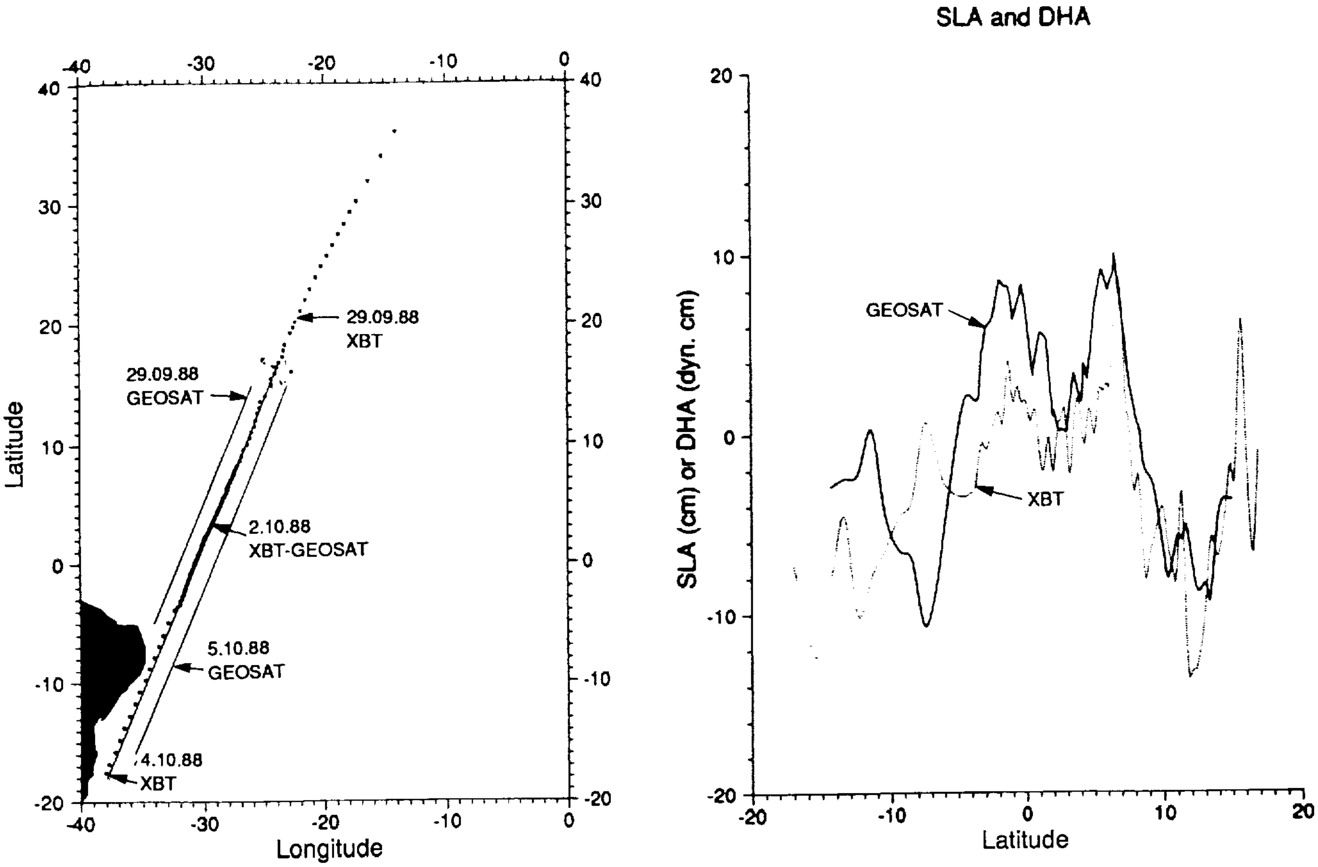

Figure 2. Cross-comparison between XBT section and Geosat altimetry in the Tropical Atlantic (Gourdeau, 1989).

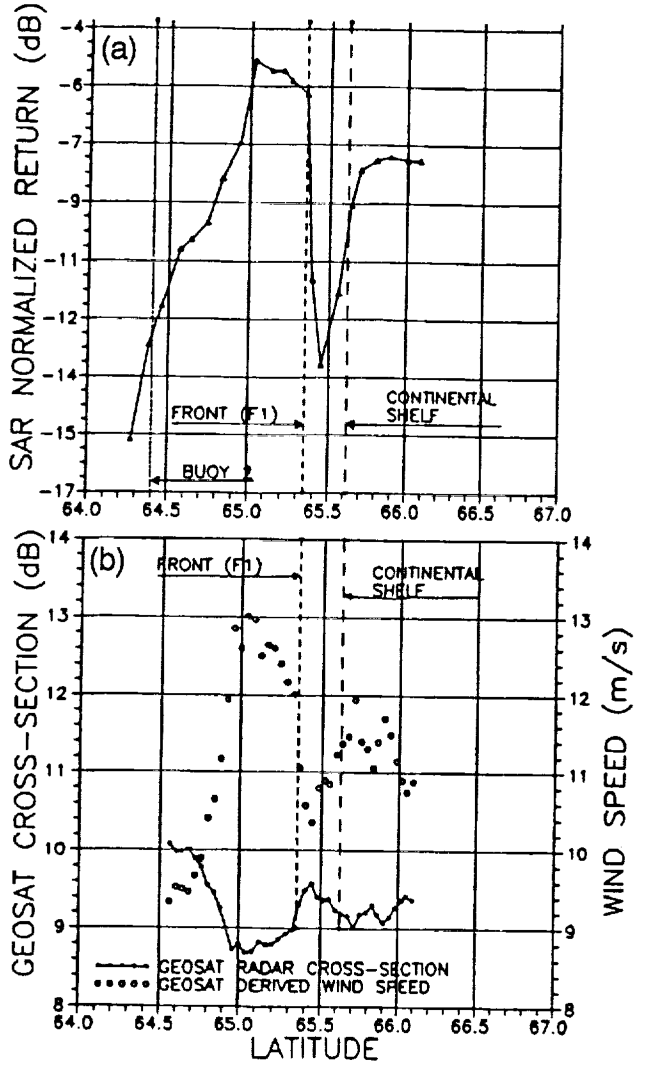

Figure 3. Geosat-deduced swell propagation patterns and wind–wave characteristics in the midst of storms: (a) variations of the SAR normalized return along flight line 1 at buoy 2, of the frontal feature (F1), and of the edge of the continental shelf; (b) quasi-simultaneous variations of the Geosat altimeter cross section and of the derived wind speed (Mognard et al., 1989a,b).

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p. 4

Study of Mass and Heat Transport of the Tropical Atlantic Ocean Using Models and Altimeter Data

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I. Scientific Background

There is recent interest in studies of tropical ocean climates because (1) the changes of sea surface temperature (SST) in the tropics have an influence on the circulation of the global atmosphere; (2) the tropical oceans play a major role in meridional heat transport (Oort and Vonder Haar, 1976) and have an additional important influence on climate at time scales of the order of a decade; (3) in the vicinity of the equator, the vanishing of the Coriollis parameter implies that a stratified ocean can respond strongly and rapidly to basinwide wind fluctuations and adjust its thermal structure on seasonal and interannual time scales.

The Atlantic Ocean contributes enormously to the heat budget of the Northern Hemisphere (Stommel, 1980), and the tropical region plays a key role in the meridional transport of heat. The annual mean meridional heat flux in the Atlantic is northward in both hemispheres and reaches a high maximum in the tropics (Oort and Vonder Haar, 1976; Hastenrath, 1977). However, little is known about the pathways and rates of these interhemispheric exchanges and their seasonal and interannual variations. This is a major objective of the World Ocean Circulation Experiment (WOCE) program.

Important progress has been achieved during the last decade in modeling the tropical oceans, which suggests that models can be used as tools for understanding and possibly forecasting the upper-ocean changes in the tropics. One ultimate goal of the Tropical Ocean and Global Atmosphere (TOGA) program, achieved before demonstrating the possibility of a complete simulation of the coupled air–sea interaction system, is to implement an operating monitoring and modeling of the tropical oceans with the assimilation of data. Such a now-casting/ forecasting operational simulation of the three-dimensional tropical Altantic Ocean is now in development. Altimeter observations have particular importance in the tropics because the structure of the ocean could be considered a two-layer system. A sharp and thin thermocline separates a warm and well-mixed superficial layer from deeper cold waters. In such a simplified system, sea level, dynamic height, and heat content are directly related to the thermocline depth. With such a system, it is possible to derive the depth of the thermocline and the heat content changes from sea level observations. Nevertheless, to determine more accurately these budgets and to compute the global mass and heat transport with the full dynamic and thermodynamic constraints, three-dimensional model simulations are necessary, as clearly shown recently by Philander and Pacanowsli (1986).

The validity of the model simulations, however, should be checked by comparison with observed data. And the model simulations will be greatly improved if controlled by assimilation of both conventional in situ data and altimeter data. The TOPEX/POSEIDON project is a unique opportunity to provide on a large-scale basin a global and long-term coverage of the sea level, a coverage that could allow constraint of these models for a realistic simulation of the circulation fields and computation of the heat transport and depth of the thermocline over a 3- to 5-year period.

II. Objectives

The specific objectives of this proposal are

(1) To assess the quality of the TOPEX/POSEIDON surface altimeter data in regard to its use for a large, low-frequency monitoring of the surface topography of the tropical Atlantic Ocean (from 25°N to 25°S).

(2) To develop a method, on a demonstration basis, to derive from the tropical Atlantic the depth of the

thermocline and the heat content changes from the surface altimeter data field.

(3) To develop a method of assimilation of altimeter data into Oceanic General Circulation Models (OGCMs) for the purpose of preparing an operational, permanent, three-dimensional now casting of the tropical Atlantic Ocean (a TOGA objective).

(4) To derive from these models global circulation fields and a time series of mass and meridional heat transports across the tropical Atlantic region (a WOCE objective).

III. Approach

These objectives will be approached with a strategy that intimately combines conventional in situ observation, altimeter observation, and models.

The altimeter data and other conventional oceanographic data will first allow us to derive a two-layered tropical-ocean concept, the depth of the thermocline change, the heat content change, and the heat divergence. The assimilation of these altimeter data with the other oceanographic data in an OGCM will then allow us to perform a three-dimensional now casting of the thermal structure and current fields (a TOGA objective). From these simulations, more complete and accurate computations of heat-budget parameters will be performed. The model simulations will be used for the computation of global mass and heat transports (a WOCE objective).

The following sequence of operations is proposed:

(1) Acquisition and analysis of altimeter TOPEX/POSEIDON data on the tropical Atlantic Ocean (from 20°N to 20°S), with a possible extension to 35°S. A repetitive orbit of 7 to 10 days is required.

(2) Acquisition and analysis of conventional in situ oceanic data, including expendable bathythermograph (XBT), tide gauge, and conductivity/temperature/depth (CTD) data.

(3) Long-term calibration of the satellite sea level data in reference to the in situ conventional data.

(4) A run of the three-dimensional primitive-equation model on an operational basis, forced by surface wind and thermodynamic air–sea fluxes.

(5) Assimilation of altimeter data and in situ ocean data in the model.

(6) Analyses of the model simulations and computations of time series of global mass and heat transports over the whole tropical Atlantic basin for the total life of the satellite (3 to 5 years).

IV. Anticipated Results

The main anticipated result of this investigation is an improved understanding of altimeter measurements and a demonstration of their usefulness for climate studies in tropical oceanography. Large-scale, low-frequency, sea level changes in the tropics are intimately associated with climatological events like the El Niño Southern Oscillation (ENSO) in the Pacific Ocean and similar warm events in the Atlantic. The mean sea surface dynamic topography in the tropical Atlantic is characterized by the superposition of an east-to-west rise and a series of zonal ridges and troughs. The total variability of the altimeter signal is maximum and reaches 10 cm in an area situated along the equator and between 10°W and west of 30°W. This is consistent with what has been observed with hydrographic observations (Figures 1 and 2). Furthermore, it has been recently demonstrated that altimeter observations are able to restitute the main aspects of the sea level seasonal-variability data from the tropical Atlantic (Menard, 1988; Arnault et al., 1989). Sea level in the tropics is the most pertinent indicator of the baroclinic response of the ocean to atmospheric forcing. This is due to the near two-layer structure of the upper tropical ocean that places heat content, depth of the thermocline, and dynamic height in close relationships with sea level. Such monitoring of the thermal and dynamic variability of the upper tropical oceans is a central objective of the TOGA program.

Another anticipated result of this investigation is the demonstration of the feasibility of a permanent three-dimensional model simulation using assimilation for altimeter sea level observations. The operational assimilation of the altimeter data will be made tentatively in real time if the ephemerides of TOPEX/POSEIDON are available in real time. Up to now, Ocean General Circulation Models (OGCM) have been used primarily in idealized studies to improve our understanding of the oceanic response to different wind and thermal forcings. This will change very soon when OGCM are run operationally to provide real-time and synoptic descriptions of phenomena, such as El Niño in the Pacific Ocean and similar warm events in the Atlantic. These models will assimilate the available data and, in particular, satellite altimeter data, and will provide coherent pictures of large-scale conditions in tropical oceans—the analogs of weather maps. The gridded data sets produced by the models will make possible computation of the oceanic mass and heat transports, a computation that cannot be obtained from the measurements only. These heat and mass transports in the Atlantic Ocean are of crucial importance and represent one of the central objectives of WOCE.

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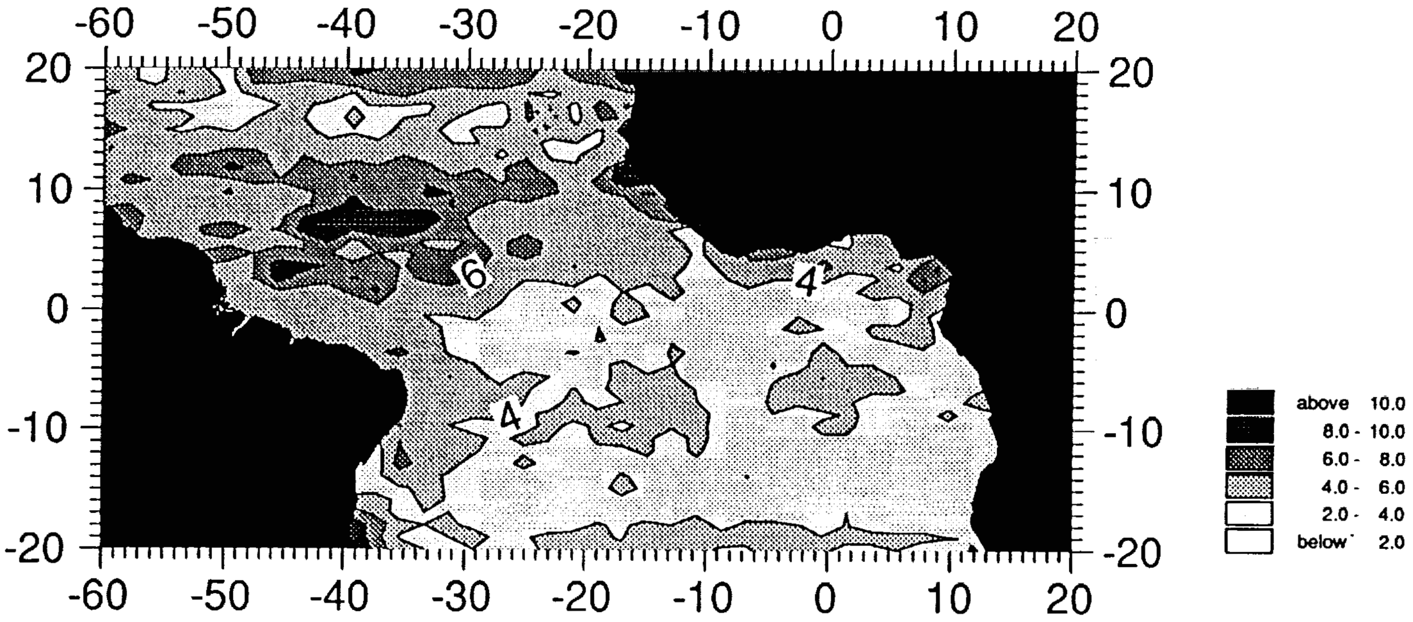

Figure 1. Variability over the tropical Atlantic obtained through altimeter Geosat data from November 1986 until November 1987.

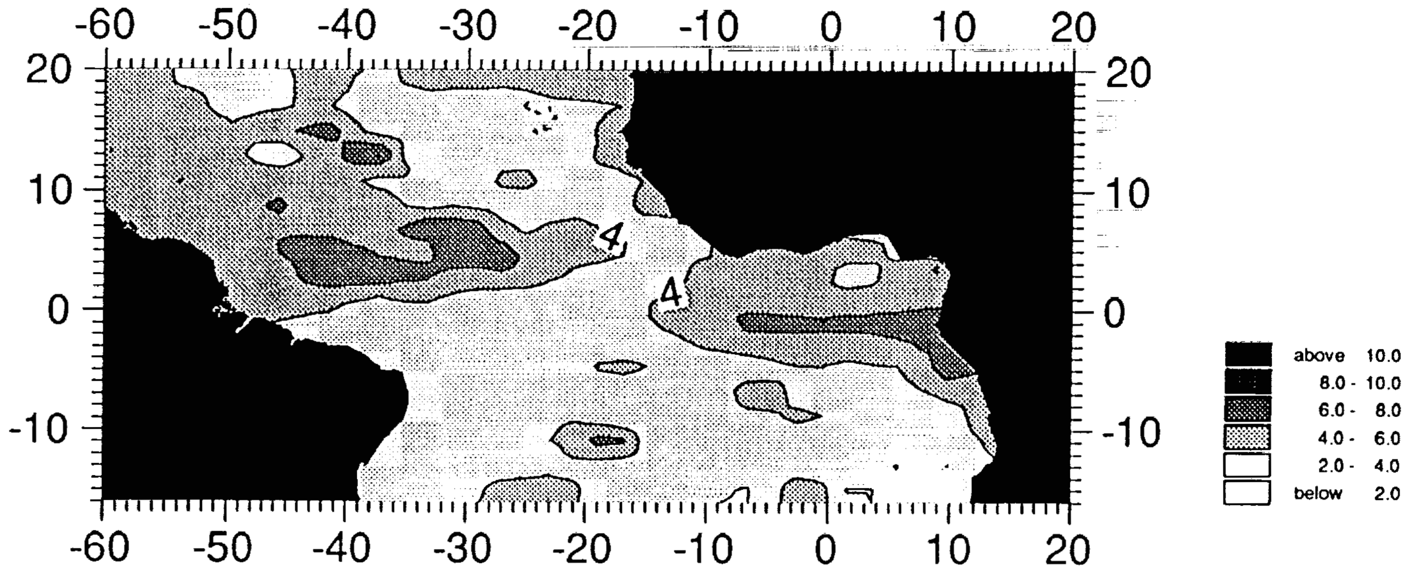

Figure 2. Variability of dynamic height over the tropical Atlantic obtained through hydrographic data.

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Ocean Circulation Using Altimetry

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I. Introduction

Our group has been very actively involved in promoting satellite altimetry as a unique tool for observing ocean circulation and its variability. TOPEX/POSEIDON is particulary interesting as it is optimized for this purpose. It will probably be the first instrument really capable of observing the seasonal and interannual variability of subtropical and polar gyres and the first to eventually document the corresponding variability of their heat flux transport.

The studies of these phenomena require data of the best quality, unbiased extraction of the signal, mixing of these satellite data with in situ measurements, and assimilation of the whole set into a dynamic description of ocean circulation. Our group intends to develop responses to all these requirements. We will concentrate mostly on the circulation of the South Atlantic and Indian Oceans: This will be done in close connection with other groups involved in the study of circulation of the tropical Atlantic Ocean, in the altimetry measurements (in particular, those of the tidal issue), and in the techniques of data assimilation in ocean circulation models.

II. Data Evaluation

The actual quantitative observation of large-scale ocean variability is very demanding on data quality. Large efforts will thus be devoted to assess this quality. These efforts will include the detection of spurious values. A number of tests have been developed for Seasat and Geosat data. They include essentially the detection of isolated points that are at some distance from an altimetric mean sea surface and extreme values of the geophysical corrections and parameters. These tests will be adapted to the TOPEX/POSEIDON data and analyzed. In addition, along-track wave number analysis of the data will be performed: This is a very sensitive tool for detecting noise levels and their variations.

The most difficult source of error is the long-term variability of the orbit error and corrections. The former will be quantified by spectral analysis of the altimetric profiles on various time scales from the "arc length" of 10 days to the pluriannual scale. For the former, spectral analysis will be performed during different seasons of the year throughout the lifetime of the satellite.

Particular attention will be paid to intercomparing the values of the POSEIDON altimeter with those of the TOPEX altimeter. This intercomparison will be supported by the validation experiments deployed by the project teams during the validation phase. However, it will also be necessary to achieve statistical intercomparison on a longer time scale. In particular, it will be necessary to intercompare the different geophysical corrections.

Finally, the European Remote Sensing satellite (ERS-1 and ERS-2) altimeter data should provide a complementary data set; in particular, their simultaneous use should allow the separation of ocean mesoscale noise (e.g., eddies and meanders of strong currents) from large-scale signals. The two data sets will be intercompared and their difference statistically described.

III. Ocean-Signal Extraction

Extraction of the ocean signal can be achieved on the mesoscale by the classical along-track technique. The technique should be all the more valid because the TOPEX/POSEIDON orbit error should be small. Note, however, that this approach, whereby residual orbit error is reduced by a bias and tilt correction to each altimetric pass, should be handled with care: Data used for the bias and tilt estimations must be weighted according to their local mesoscale variability signal in order not to alias the latter into the correction. Through objective analysis, these signals can then be used for synoptic maps.

On larger scales (mean signal and variability), direct mapping is required to separate objectively the signal from the orbit error; this error is comparable to the ocean signal in terms of space scales. As such, the technique is computationally heavy and appropriate subsampling of the data will be applied; this subsampling should be compatible with the signal and the measurement errors. More constraining extractions will also be used to analyze specific signals (e.g., Rossby waves using Kalman filters).

In any case, these approaches will require realistic estimations of the data errors such as those described in the previous section. The most serious difficulty is that actual statistics are accessible only from the data themselves: Thus great care is needed in the iterative analysis of the data to produce robust results.

The extracted signals will then be analyzed in terms of statistics (variability and space–time spectra) and their evolution (eddy displacement, front evolution, and seasonal and interannual variations of strong western boundary currents of the return flows).

The focus here is on the climatological variation of the ocean dynamic topography in the area of interest, and its relation to local and regional wind forcing and to variations in other ocean domains (the tropical and Antarctic regions).

IV. Diagnostic Studies and Assimilation Into a Dynamic Model

The altimetric data provide only the surface dynamic topography (particularly the long-wavelength mean value and the variable signal on all scales). Moreover, the signals are aliased by a complex space–time observation pattern.

Our objectives, however, concern a nearly continuous (or at least periodic) analysis of the three-dimensional field of ocean currents and transport. To achieve this analysis, it will be necessary to mix the altimetric observations with others, which are being accumulated by the World Ocean Circulation Experiment (WOCE) program (surface and subsurface float velocities, current-meter measurements, and hydrographic and tracer data).

In addition, the dynamic description of the ocean circulation is a powerful constraint that relates various measurements from different places and times.

The general approach will thus be to develop further the necessary diagnostic and assimilation techniques required for mixing all these data. Our group, in collaboration with others, has developed some experience in the inverse techniques as well as on nudging and periodic assimilation in quasi-geostrophic models. Work is under way on the Kalman filters and on the adjoint assimilation technique. Further studies will be devoted to the primitive-equation dynamic models.

V. Conclusion

Our expectation is that this overall approach will provide a three-dimensional description of the ocean circulation in the areas of interest, and a similar description of the heat and salt transports. This is the goal of WOCE and the World Climate Research Programme (WCRP). In this respect, TOPEX/POSEIDON will provide a unique observational set in terms of coverage, continuity, and duration, as compared with in situ data. We believe that the TOPEX/POSEIDON system has indeed been optimized in this regard. This data set will be completed in particular by altimetric and scatterometric measurements by ERS-1 aand ERS-2. Our group is also involved in this analysis.

A longer term goal will be the monitoring of the mean sea level. This requires a coherent reanalysis of all existing data (Seasat, Geosat, TOPEX/POSEIDON, ERS-1, and ERS-2) and those of future missions: Indeed the signal to be expected is of a few centimeters per decade, which is at the limit of precision of the measurements. Thus all systematic errors must be pursued. We have the capacity and the ambition to attempt such an analysis, in relation with other studies in geodesy (variations of the Earth's rotation and J2—the Earth's gravity) and glaciology (variation of the polar-cap topography).

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The Dynamics and Energetics of Midlatitude Western Boundary Currents: A Comparison of the Kuroshio Extension and the Gulf Stream

p, 8

ORIGINAL CONTAINS
COLOR ILLUSTRATIONS

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I. Introduction

We will use TOPEX/POSEIDON altimetry in combination with ongoing and planned efforts, including data from the European Remote Sensing satellite (ERS-1), in situ measurements designed specifically to complement satellite altimetry, and assimilation of these several data types into eddy-resolving numerical models in order to understand the dynamics and energetics of midlatitude western boundary currents (specifically, the Gulf Stream and the Kuroshio Extension). A better understanding of the recirculation of midlatitude gyres can best be undertaken in the format of such regional, eddy-resolving experiments. Such regional programs will enhance and be enhanced by the larger scale circulation studies of the World Ocean Circulation Experiment (WOCE) as well as by global-scale eddy-resolving models that we will develop prior to the TOPEX/POSEIDON mission. This effort includes participation on the TOPEX/POSEIDON Science Team.

The dynamic and kinematic interaction between the time-mean western boundary current, its time-dependent meanders and rings, and the gyre-scale circulation is a fundamental problem in modern physical oceanography. The relationship between the highly energetic and relatively short space-and-time scale variability in western boundary currents and the large-scale circulation is presently only partially understood. This problem is particularly important to the WOCE in light of the substantial fluxes of heat and other conservative and nonconservative tracers accompanying the western boundary current in the upper ocean. Although a principal focus of the TOPEX/POSEIDON Mission is the basin-scale circulation, both its mean and time-varying components, we must also ensure that an accurate accounting of the narrow western boundary currents closes the problem. Presently, our most complete knowledge of western boundary currents relates to the Gulf Stream and Kuroshio. These current systems are comparable in many respects, but they differ in wind-stress distribution, bathymetry, boundary interaction, basin dimension, and stratification. These differences offer opportunities to examine the physics of the important western boundary flows and to verify our understanding with regional and basin-scale models.

The study of mesoscale dynamics and energetics in the Gulf Stream using satellite altimetry is presently the focus of the northwest Atlantic Regional Energetics Experiment (REX), a major research initiative sponsored by the Office of Naval Research (ONR). The REX combines the emerging technologies of satellite altimetry (from the Geosat and Geosat–Exact Repeat Missions (ERMs)), eddy-resolving numerical modeling of the Gulf Stream circulation, and the collection of complementary in situ data from bottom-moored arrays of inverted echo sounders with pressure gauges (IES/PGs) and from extensive periodic aircraft surveys deploying deep airborne expendable bathythermographs (AXBTs). These technologies are directed toward an understanding of the balances and exchanges of energy between mean and eddy fields in the Gulf Stream in the presence of the New England Seamount Chain (NESC). Meeting the scientific goals of REX has required of us a focus on several critical problems in the assimilation of multiple data types into eddy-resolving numerical models including: (1) space–time aliasing by a single-beam altimeter, (2) deducing interior information from surface data, and (3) eliminating large geoid error and radial-orbit error from the altimetry.

II. REX and the Kuroshio Extension Regional Experiment

While the northwest Atlantic REX is an ongoing project (i.e., the field-data collection program, the Geosat–ERM, and the model development effort are still under way), we are in the planning stages for a similar experiment to be carried out in the Kuroshio Extension region during the time frame of TOPEX/POSEIDON. While the major objectives of this Kuroshio Extension Regional Experiment (KERE) will be analogous to the northwest Atlantic REX, the combination of the KERE with the earlier REX will, for the first time, allow the direct comparison of similar data and data analysis techniques (including numerical modeling) in the two major western boundary regimes of the northern hemisphere. Further, most of the limitations of the Geosat altimeter system will be overcome in the KERE by the highly accurate TOPEX/POSEIDON altimetry coupled with the enhanced space–time sampling provided by the concurrently flying altimeter system on board the ERS-1. As well, additional altimetry data for subsequent analysis will be provided in the Gulf Stream area by these two altimeter systems. TOPEX/POSEIDON altimetry will be used in regional and global model studies through the assimilation of altimeter data into these models to provide more realistic surface and subsurface representations of the ocean circulation. Finally, the REX and the KERE will greatly enhance our understanding of the physics of the midlatitude recirculation gyres in the context of the WOCE. As part of our WOCE participation, the results from the KERE and REX will be used in the analysis and evaluation of an eddy-resolving world-ocean model that will be implemented on the Navy's Class VII supercomputer scheduled for installation at the National Space Technology Laboratories (NSTL) in 1989. This global-ocean model, constrained by TOPEX/POSEIDON altimetry, will be extremely useful in providing boundary information for regional- and basin-scale models.

Because the KERE will be a major focus of our effort during the TOPEX/POSEIDON time frame, a more detailed description of our plans for this experiment and its relation with our other TOPEX/POSEIDON research activities is given below.

III. Plans for the Kuroshio Extension Regional Experiment

A. Objectives

During the mid-1990s, the KERE will examine the critical issues governing the dynamics and energetics of the Kuroshio Extension Current System. Specific scientific issues to be addressed are

(1) The presence (?) and impact of a Deep Western Boundary Current (DWBC) on the Kuroshio Extension.

(2) The ratio of internal (gravest baroclinic) mode to barotropic mode and its effects on Kuroshio Extension mesoscale dynamics (particularly in the Oyashio Intrusion area).

(3) The relationship between surface wind stress forcing and gyre circulation of the northwest Pacific.

Additionally, the effect of coastlines and bottom topography on Kuroshio separation and eastward penetration will be studied.

Focused on these issues will be several major new technologies (as most recently demonstrated during the northwest Atlantic REX). These will include

(1) Satellite altimetry (from TOPEX/POSEIDON, ERS-1, and the U. S. Navy's Geosat-follow-on altimeters).

(2) Satellite scatterometry (from ERS-1).

(3) Satellite infrared imagery (IR).

(4) Numerical model experiments.

(5) A complementary field program.

B. Approach

The KERE represents a coordinated project involving the major techniques of remote sensing, field experiment, and ocean numerical modeling. Key data types supporting the KERE are satellite altimetry and scatterometry from TOPEX/POSEIDON and ERS-1. In situ data will come from inverted echo sounders with bottom pressure gauges (IES/PGs), current meters, and AXBT/XBT surveys. Data synthesis and analysis will proceed through the use of regional, eddy-resolving numerical models of the ocean circulation. Field-experiment design will be largely motivated by (and its strategy planned) using numerical model simulations. Efficient and complementary field measurements will be emphasized. The vast quantities of altimeter-measured sea surface topography available from the altimetric satellites will allow improved analysis using model-data assimilation schemes. Scatterometer-derived winds from ERS-1 will allow a detailed examination of the role of surface wind forcing in modulating a western boundary current, particularly over the larger North Pacific Basin (where the wind stress curl may play an even more dominant role than in the smaller North Atlantic). Analysis of these satellite data will proceed in both the Kuroshio Extension and Gulf Stream systems, while the collection of in situ data during the KERE will take place in the Kuroshio Extension only.

1. Northwest Atlantic Regional Energetics Experiment (REX). The KERE is designed as a follow-on experiment to the presently concluding northwest Atlantic REX. Some of the most notable preliminary REX results include

(1) Consistent sea level variability amplitudes observed from Geosat altimetry data (see Figure 1), IES/PG array data, and model simulations incorporating a DWBC.

(2) Two-gyre structure in the recirculation south of the Gulf Stream (see Figure 1) indicated from Geosat–ERM analysis.

(3) One-third of mesoscale rms variability in sea level of the Gulf Stream is the result of barotropic mode.

(4) The first detailed maps of both the mean and variable topography over the northwest Atlantic (see Figure 1) made from precise along-track geoid profiles (computed from collinear altimetry and complementary AXBT sections) and/or IR images.

(5) Highly realistic "synthetic" thermal, salinity, and sound-speed sections from collinear altimetry data taken over the northwest Atlantic can be generated using climatology-based regressions.

Through the comparative effort mounted in KERE, some general conclusions regarding the basic nature of western boundary currents will be possible. KERE, in combination with REX, will represent a thorough study in comparative anatomy of western boundary currents.

2. Satellite analysis plans for KERE. As already noted, a major component of the KERE will be the analysis of satellite-altimetry, IR, and scatterometry data in both the northwest Pacific and Atlantic. Analyses of both the mean and variable surface topography (such as those depicted for the northwest Atlantic in Figure 1) from satellite altimetry data will play a major role in the KERE. Such analyses are useful for

(1) Examining the impact of depth on the western boundary current (for example, the two-gyre recirculation structure seen in Figure 1 is clearly associated with the presence of the New England Seamount Chain (NESC) in the northwest Atlantic).

(2) Tuning and adjusting numerical model simulations to obtain results in agreement with the altimetry data (e.g., this is the way in which the importance of a DWBC in the northwest Atlantic was first recognized during the REX; see Thompson and Schmitz, 1989).

(3) Studying the regional distributions of both mean kinetic and available potential energies from eddies (e.g., see Figure 2).

We will continue altimetric analyses of the northwest Atlantic and extend these analyses to the northwest Pacific during the KERE. Additionally, the statistics of mesoscale variability derived from satellite IR data will play an important role in the KERE. Finally, surface-wind stress fields observed by ESA's ERS-1 will provide important (and long-awaited) input for the ocean circulation models.

3. Numerical model experiments in KERE. Work is already under way at the U.S. Naval Oceanographic and Atmospheric Research Laboratory (NOARL) on the development of realistic, primitive-equation (PE), layered models of the North Pacific Basin (including the Kuroshio and Kuroshio Extension). Use of these layered PE models has had remarkable success in simulating and providing meaningful forecasts of Gulf Stream evolution. Using realistic bathymetry and coastline geometry, our 1/8-deg-resolution PE models are now able to successfully simulate many salient features of the North Pacific, including the Subartic Front and the Kuroshio Extension (see Figure 3). Comparison between model simulations, satellite analyses, and field data will serve as the basis for model improvements.

4. Field experiments in KERE. During 1992 through 1994, field experiment components of the KERE will be under way. These components include

(1) The deployment and subsequent recovery of a line of acoustic current meters (ACMs) and IES/PGs. There instruments are arrayed along the section depicted in Figure 4. A major objective of these measurements will be monitoring of any northwest Pacific DWBC. As this line will coincide with the TOPEX/POSEIDON altimeter groundtrack, comparison between the altimeter and in situ data will provide analyses of both the time series and spectral nature of the mesoscale variability in this region as well as an assessment of the relative importance of the barotropic and gravest baroclinic modes of this variability (see Hallock, Mitchell, and Thompson, 1989).

(2) Drops of AXBTs along TOPEX/POSEIDON groundtracks over the Kuroshio Extension region. Data from these instruments will be used in conjunction with the satellite altimetry to provide precise estimates of the along-track geoid profile (see Mitchell et al., 1991), which are necessary for subsequent inferences about the temporal surface topography from the altimetry data (see example, Figure 1b) and to provide an error analysis of the climatology-based inferences about the deeper density structure from the altimeter alone.

(3) Other field work in the KERE will most likely focus on the use of deep floats for defining the current structure of the Kuroshio Extension, particularly near its separation from the Honshu coastline.

(4) Additionally, the feasibility of carrying out a regional, mesoscale-resolving acoustic tomography experiment is presently being examined as part of the planning for the KERE.

C. Summary

The KERE will culminate in a comparison of the dynamics and energetics of the Northern Hemisphere's two major western boundary currents. Following the northwest Atlantic REX, the KERE will extend results and hypotheses derived from Gulf Stream studies to the Kuroshio Extension. Additionally, the collection and analyses of common data types in both the northwest Atlantic and the northwest Pacific, made possible by REX and KERE (i.e., through satellite-altimetry data, model simulations, and IES/PG data), will serve to enhance our understanding of the fundamental dynamics and energetics of western boundary currents in general.

An approximate timetable for the KERE follows:

Event	Period
Detailed planning for the KERE	Through 1991
Model development (Pacific) and simulations	1990–95
ERS-1 altimeter/scatterometer data acquisition/ analysis	1991–94
TOPEX/POSEIDON altimeter data acquisiton/ analysis	1992–95
KERE field activities in the NW Pacific	1992–94
Analysis of NW Pacific field data	1993–95
Model/Data intercomparisons	1992–95
Kuroshio Extension/Gulf Stream comparisons	1993–95

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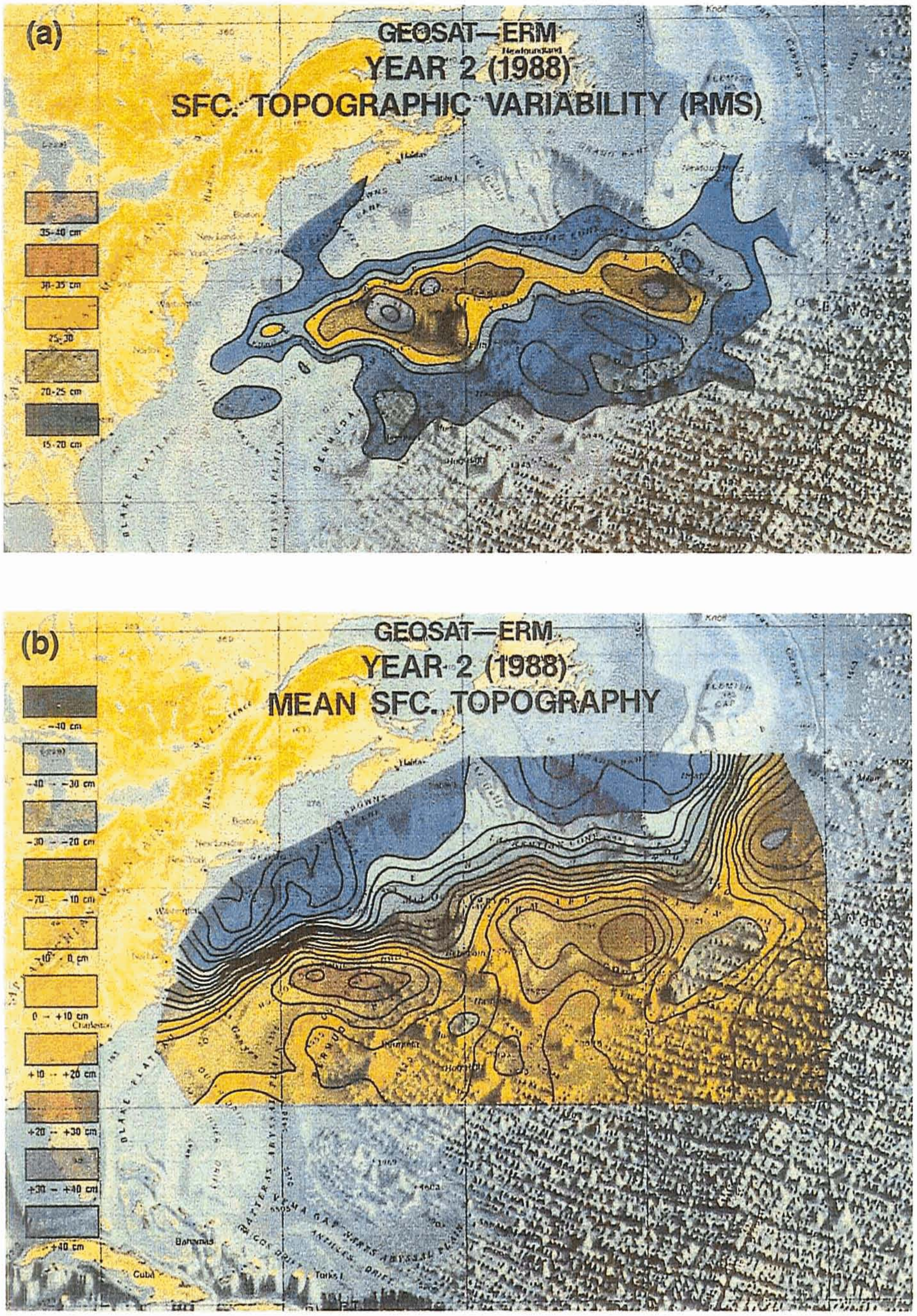

Figure 1. The northwest Atlantic Gulf Stream region. (a) Sea level variability (rms in cm; highs are shown in red/pink and lows in blue with a range of 15 to >35 cm) as observed during 1988 with Geosat–ERM altimetry. (b) Annual mean sea surface topography (relative topography in cm; highs are shown in red and lows in blue with a range of –40 to +40 cm) as observed during 1988 with Geosat-ERM altimetry. Note the prominence of two local recirculation gyres south of the Gulf Stream.

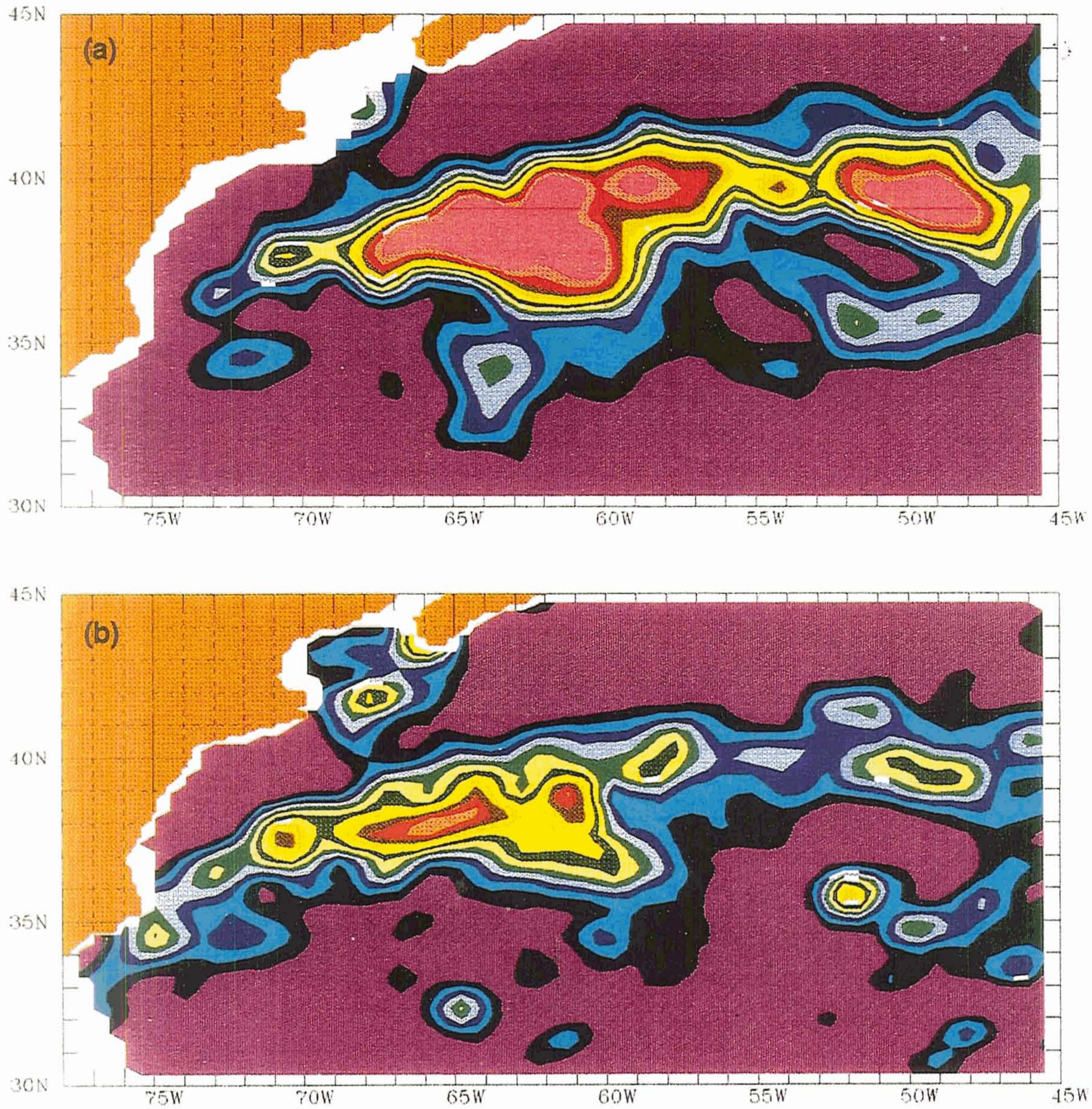

Figure 2. Eddy energy of the Gulf Stream computed from Geosat–ERM altimetry. (a) Eddy available potential energy (EAPE) in cm^2/sec^2 (highs are shown in red and lows in blue with a range of 500 to >4000 cm^2/sec^2); distribution and magnitudes depicted are in excellent agreement with other estimates of EAPE based on in situ hydrography. (b) Eddy kinetic energy (EKE) in cm^2/sec^2 (highs are shown in red and lows in blue with a range of 500 to >2500 cm^2/sec^2); distribution and magnitudes depicted agree well with other estimates of EKE based on drifter data.

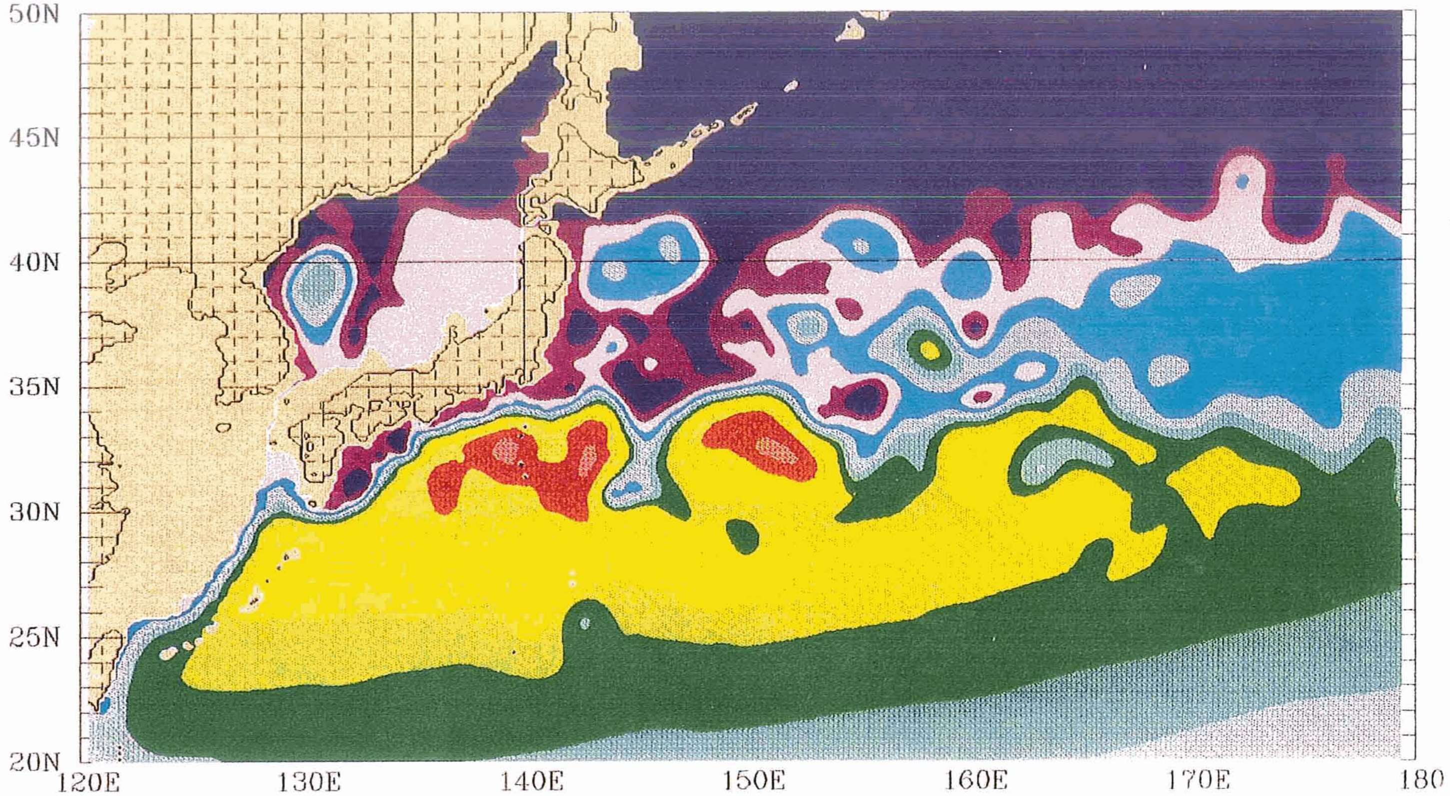

Figure 3. A synoptic view of the Kuroshio Extension region from numerical model simulation. Depicted is sea surface topography during a 1/8-deg resolution, two-active layer, wind-forced primitive-equation model experiment for the North Pacific (courtesy of H. Hurlburt). Relative topographic range is –47 to +115 cm (highs are shown in red and lows in blue).

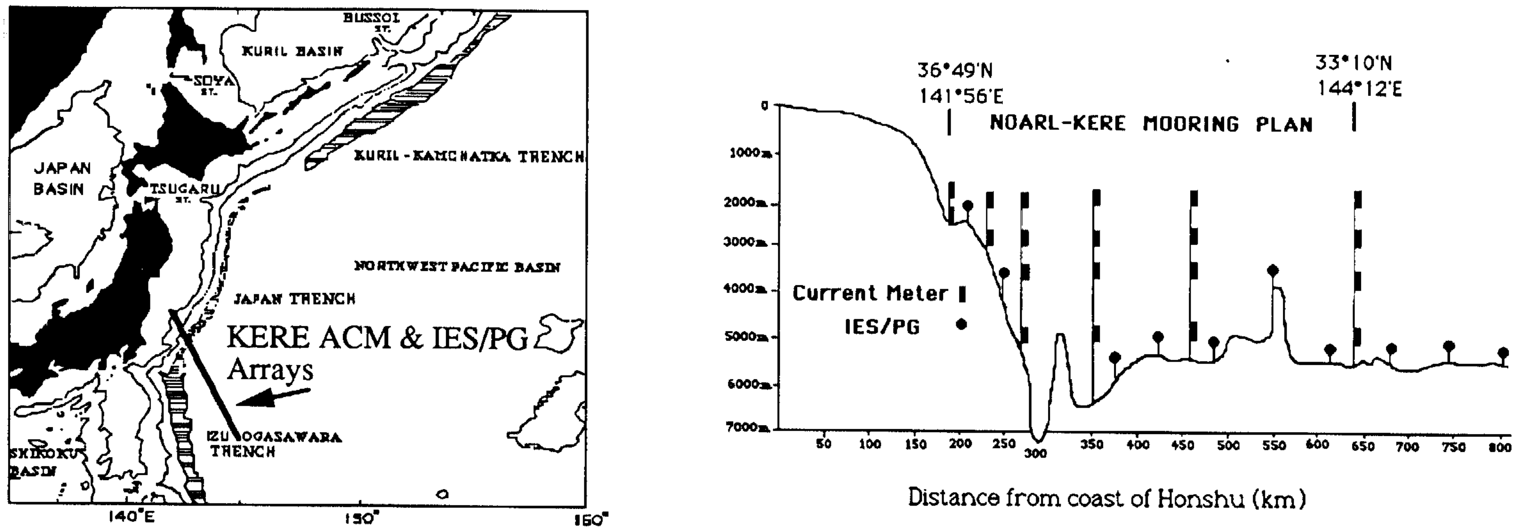

Figure 4. Location and vertical cross section of NOARL arrays of acoustic current meters and inverted echo sounders with pressure gauges. The line runs across the Japan Trench and coincides with a TOPEX/POSEIDON groundtrack (courtesy of Z. Hallock).

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p. 2

Ocean Circulation Modeling by Use of Radar Altimeter Data

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I. Summary

The project will investigate the use of radar altimetry (RA) data in the determination of the ocean circulation models. RA data will be used to verify prognostic experiments of the steady state and seasonal cycle of large-scale circulation models and the statistical steady state of eddy-resolving models. The data will serve as initial and update conditions in data assimilation experiments and as constraints in inverse calculations. The aim of the project is a better understanding of ocean physics, the determination and mapping of ocean currents, and a contribution to the establishment of ocean circulation models for climate studies.

The project is part of a national research program of ocean modeling and climate research as a contribution to the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean and Global Atmosphere Programme (TOGA). The research group has applied for RA data from the ERS-1 mission and will use them in a similar way.

The goal of the project is to use satellite radar altimetry data for improving our knowledge of ocean circulation both in a descriptive sense and through the physics that govern the circulation state. The basic tool is a series of ocean circulation models. Depending on the model, different techniques will be applied to incorporate the RA data.

II. Objectives

A. Estimation of the Actual State of the Surface Topography and the Surface Circulation in Limited Areas of the Ocean

The work will concentrate on oceanic regions in which a clear altimetric signal can be expected and in which suitable in situ measurements will be available. This is the case for western boundary currents in the North and South Atlantic as well as other regions with a high variability and eddy activity.

The aims are

(1) To verify the objective analysis of satellite sea surface height with in situ observations.

(2) To include measurements by drifting buoys and current meters into the objective analysis algorithm in order to increase the accuracy of the estimates of the sea surface topography.

B. Description of the Variability of the Circulation as a Function of Space and Time

We want to increase our knowledge of which mechanisms govern the variability of the large-scale oceanic transports of momentum (vorticity), heat, and salt.

To give an oceanographic interpretation of these processes, eddy-resolving ocean models that describe the full variability on all scales are necessary. Two regions have been chosen for analysis: the North Atlantic and the Southern Ocean. Both regions are focal points of WOCE modeling activities with eddy resolving models. In the North Atlantic there exists already a comparatively large data base, while for the Southern Ocean the variability plays an important role in the dynamics of the circumpolar as well as the meridional transports.

C. Use of Altimetric Data in Circulation Models

Methods have to be developed that introduce observations into ocean models by means of inverse modeling. The optimal method seems to be assimilation with an adjoint model. It remains to be seen, however, if, for complex models, other techniques, such as those used in numerical weather prediction, turn out to be more practical. We plan to replace the optimal-estimation techniques that are based on statistical information about the data by a dynamic interpolation technique in which, additionally, the space–time variability of the analyzed fields has to obey the model dynamics.

Critical model parameters have to be adjusted to the data to ensure compatibility with altimetric measurements. As there is a strong dynamic connection between mean circulation and variability, it is, in principle, possible to estimate the mean circulation by assimilation of variance alone, even without a good knowledge of the geoid.

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P_ 3

General Circulation of the South Atlantic Between 5°N and 35°S

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I. Objectives

A good description of the general circulation of the South Atlantic Ocean as well as an understanding of its dynamics is lacking at present. By general circulation is meant movements occurring at large spatial and temporal scales (say greater than 500 km and greater than 5 years).

At these large scales, the incoming solar radiation in the equatorial band is normally redistributed by the oceans and the atmosphere to higher latitudes.

The South Atlantic Ocean has, in fact, a strange behavior since present estimations give a global meridional (integrated on a latitude circle from South America to Africa) heat flux directed to the North Pole! This is established beyond doubt even if the numerical value ($\sim 10^{15}$ W) must be confirmed. Furthermore, the contribution to this flux of the different water masses encountered in the South Atlantic is only schematic. It is thought that surface waters flowing northward from the tip of South Africa contribute mostly to that flux (Gordon, 1986). But Antarctic intermediate water, whose circulation near 800 m in depth is poorly known, may also contribute.

Beginning in 1992, Lagrangian floats will be launched below the core of this Antarctic intermediate water at a depth of about 1000 m, and at greater depths in the North Atlantic deep water near 2500 m, and in the Antarctic bottom water near 4000 m. They will follow the movements of the water for several years and permit us to obtain the general circulation (as defined above) at these depths. During the same time (between 1991 and 1995), hydrographic sections will reveal the vertical shear of the circulation on almost the same scales. This experimental effort is shared by France, Germany, and the United States of America and is a contribution to the WOCE (World Ocean Circulation Experiment).

This investigation proposes first to combine float and hydrographic data to estimate the absolute sea-surface dynamic topography (in the general circulation sense).

The TOPEX/POSEIDON altimeter will provide the temporal mean sea level. So, secondly, we propose to compute the difference between these two surfaces (mean sea level minus general circulation dynamic topography). The result will be an estimate of the marine geoid, which is time invariant for the 5-year period under consideration. If this geoid is precise enough, it will permit a description of seasonal variability of the large-scale surface circulation. If there happens to be enough float data, it may be possible to infer the first vertical modes of this variability.

Thus the main goal of our investigation is to determine the 3-D general circulation of the South Atlantic and the large-scale seasonal fluctuations. This last objective, however, may be restricted to the western part of the South Atlantic because float deployments have been scheduled only in the Brasil basin.

II. The Approach

Preceding the experimental phase of our investigation and the launch of TOPEX/POSEIDON, the method tailored towards obtaining the general circulation is being developed step by step.

Roughly speaking, the first step consists of using only in situ measured data (i.e., hydrographic density profiles and Lagrangian float velocities) but jointly with known ocean physics: geostrophy in the ocean interior and conservation of mass, heat, and salt. This is done within the framework of an inverse model.

More precisely, all data are first interpolated at the crossing points of a regular grid of 2 deg in latitude and 2.5 deg in longitude over the full ocean portion considered. This interpolation process using empirical orthogonal function decomposition and objective analysis is delicate work since it must preserve the essential general-circulation features of the original data and because the interpolation error also has to be estimated. The inverse model then looks for the ocean-circulation solution that minimizes the weighted sum of the squared distance to an a priori estimate of the circulation, the squared distance to the data, and the squared residuals of the dynamical constraints. The weights are approximatiely inversely proportional to the associated error variances.

This model has already been applied to the North Atlantic between 20°N and 50°N. The result of the inversion for the surface geostrophic currents using only hydrographic data is shown in the upper panel of Figure 1. This circulation scheme is consistent with the available float data (surface-drifter mean velocities are pictured in the lower panel of Figure 1) and shows known features of the general circulation. However, it is the combination of the two data sets that decreases the a posteriori errors on the reconstructed surface velocity field, also a product of the model, from a few cm/s to the order of 1 cm/s.

To prevent any misunderstanding, it must be stressed that Ekman pumping is imposed at the base of the surface layer from climatological winds, and that the surface mean velocity given by the model includes the Ekman drift. In Figure 1, only the geostrophic part is shown for comparison purposes, since the drifters used were drogued normally under the Ekman layer. Lateral and bottom boundary conditions are of no normal flux for the 3-D velocity.

Now the same least-square inverse model formulation will permit us to estimate a geoid by using jointly the surface dynamic topography already obtained, Geosat altimetric data, a first-guess geoid, and their associated errors. Actually, when we say errors, the reader should understand error covariance matrix. The error covariance matrix for altimeter data comprises altimeter noise proper, long wavelength radial orbit error, and ionospheric, tropospheric, and electromagnetic bias correction errors, but includes also mesoscale oceanic variability, which is noise at this stage. The needed statistical description of this oceanic variability will be obtained from classical repeat-track analysis. This second step of the work may give a slightly different and, we hope, better geoid than the one obtained from the simple difference between the mean sea level and dynamic topography.

III. Anticipated Results

During the mission of TOPEX/POSEIDON, we hope that in situ WOCE data collection will provide in the South Atlantic an amount of data at least as important as the existing North Atlantic data, thus lending confidence to the anticipated results.

To date, the general circulation has been obtained only with in situ oceanographic data (Fu, 1981). However, with the TOPEX/POSEIDON and other available altimetric data (Geosat and the European Remote Sensing satellite (ERS-1)), it seems possible to obtain a precise-enough geoid with the approach sketched above; seasonal fluctuations of the large-scale circulation, then, could be monitored at least at the ocean surface. More elaborate modeling and the use of floats may even allow penetration of the interior.

Only an important and high-quality in situ data collection such as the one programmed for WOCE can permit calibration of the altimeter and calculation of the geoid at the scales relevant to the oceanic general circulation. This is why the focus of our investigation is first on the obtention of good data at sea. It is only after a careful check of the dynamic assumptions of our model using these data that the assimilation of altimetric heights takes place.

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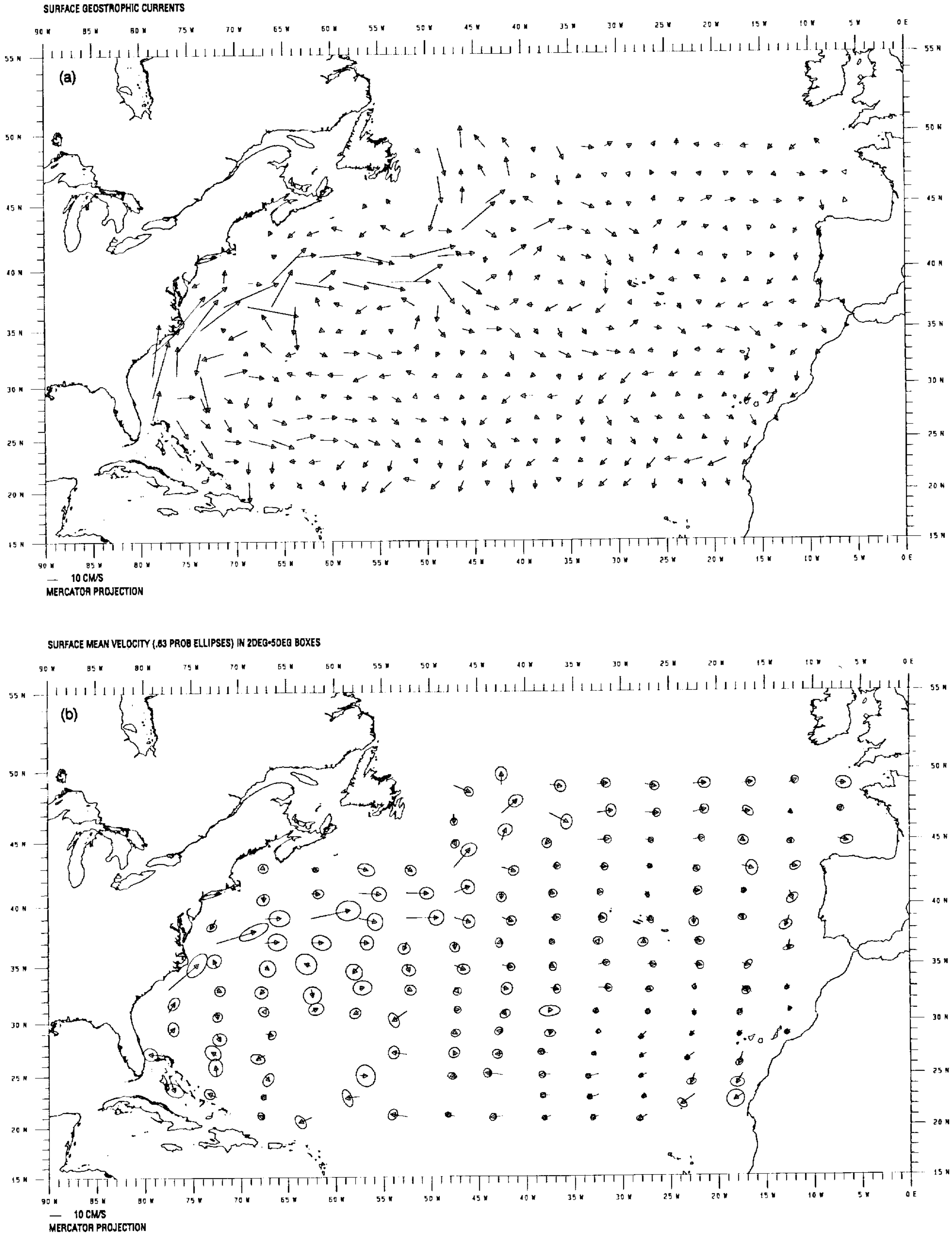

Figure 1. Surface geostrophic currents (a) resulting from the "inversion" on hydrographic data only and (b) given by surface drifters only.

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P 6

Ocean Dynamics in the Nordic Seas Using Satellite Altimetry

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I. Objective

The inflow of warm water with the North Atlantic Current (NAC) through the Faeroe–Shetland Channel is of fundamental importance to the oceanic conditions in the Greenland, Iceland, and Norwegian (GIN) Seas and the Barents Sea (Figure 1). This warm and high-energy branch of the NAC is the major reason for the relatively mild climate along the coast of Norway during winter. North of the Faeroe–Shetland Channel, the NAC extends into the Norwegian North Atlantic Current (NNAC) and meanders with wavelengths and eddy scales of 50 to 100 km. These phenomena are clearly documented in National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) images (Figure 2) and in the sea surface topography data from the Geosat altimeter (Figure 3), as well as in situ ship and mooring measurements. The NAC is also interacting with the Norwegian Coastal Current (NCC), and this interaction contributes to the generation of meanders and mesoscale eddies in the coastal current. The NCC flows northward along the continental shelf area from Skagerrak in the southern part of Norway to the Barents Sea. The shelf area has always been of great importance to the Norwegian coastal trade and fisheries, as well as the growing sea-farm industry. Due to the increased oil exploration activities on the Norwegian Continental Shelf during the last decades, extensive effort has been made to improve the knowledge and capability of modeling and forecasting the oceanic and meteorological conditions in this region.

Since the approval of this TOPEX/POSEIDON project, an initiative to extend the World Ocean Circulation Experiment (WOCE) to the Nordic Seas has been suggested from the countries in this region. The Nordic WOCE is now an approved part of the global WOCE project. Fortunately for this TOPEX/POSEIDON project, the objectives of the Nordic WOCE are complementary, and the remote sensing and in situ data collection program will be coordinated. The goal of Nordic WOCE is to establish a multidisciplinary oceanographic data base combining extensive in situ and remotely sensed data in order to

(1) Improve the estimates of the fluxes of the different water masses across the submarine ridges between Greenland and Scotland, including the flux and distribution of CO_2 in the deep water overflow of the Denmark Strait.

(2) Improve knowledge of those processes that determine these fluxes and their spatial and temporal variation.

The ultimate goal of the Nordic WOCE is to use these data in combination with realistic numerical ocean models to improve the quantitative understanding of how the climate and climatic variations at high latitudes of the Northern Hemisphere are related to these fluxes.

The main objective of this TOPEX/POSEIDON project is to integrate the accurately measured sea surface topography, as resolved by both TOPEX/POSEIDON radar altimeters, into the above-mentioned quantitative studies of the short- and long-term variations in the mesoscale ocean dynamics of the Nordic Seas south of 66°N. This implies

(1) Comparison and validation of the capability to resolve the general basin-scale circulation and the mesoscale variability by, respectively, radar altimeters and numerical ocean circulation models.

(2) Calibration and validation of the altimeter-derived sea surface topography against in situ measurements from research vessels and moorings, particularly under extreme wind and wave conditions.

(3) Improved monitoring and understanding of the flux variations between the North Atlantic and the Nordic Seas, both on the short and seasonal time scales.

II. Approach

Two major areas are to be investigated in the frame of this project:

1. The sill and trenches between Norway, Scotland, Faeroe Island, Iceland, and Greenland—the northeastern Atlantic boundary to the Nordic Seas.
2. The Norwegian Coastal Current region and Continental Shelf areas.

Previous studies of the Seasat and Geosat altimeter height data from the Nordic Seas—including the region between Norway, Faeroe, Shetland, Iceland, and Greenland—have demonstrated the usefulness of altimetry in monitoring oceanic mesoscale variability (Figure 3). It is also expected that more than 1 year of European Remote Sensing satellite (ERS-1) altimeter data with improved accuracy of the orbit determination by use of the Precise Range And Range-rate Equipment (PRARE) System will provide a better altimetric data set for studies of the mesoscale oceanic variability.

The national Norwegian ERS-1 project—the Norwegian Continental Shelf Experiment (NORCSEX) centered on Haltenbanken (65°N, 8°E)— includes both a prelaunch (1988) and a postlaunch (1991) experiment. The latter may serve as a prelaunch TOPEX/POSEIDON campaign.

During a 4-week period in March 1988, an extensive set of remote sensing data, including data from the airborne synthetic-aperture radar (SAR), Geosat altimeter, and shipborne scatterometer, was gathered. In addition, a dense network of oceanographic and meteorological measurements was obtained simultaneously from two research vessels and six moorings in the investigation region. The postlaunch ERS-1 experiment will involve two experimental periods scheduled for July (one week) and November (four weeks) in 1991. Studies related to geophysical validation and applications of the ERS-1 altimeter data will be conducted within this project.

As a part of the Nordic WOCE, seasonal cruises between Norway, Scotland, Iceland, and Greenland during both winter and summer conditions are scheduled, beginning in 1992. Data from these cruises will provide a data set optimal for comparing the altimeter-derived sea surface slopes with in situ current and hydrographic measurements. Several fixed current-meter moorings and tide gauges are also scheduled for deployment in the Nordic WOCE investigation area.

The above field activities will use the R/V H. Mosby of the University of Bergen. This vessel is equipped with an Acoustic Doppler Current Profiler (ADCP) that measures the horizontal velocities between 8- and 500-m depths with typical averages of 150 s (equivalent to a distance of 500 m). These measurements, integrated with exact navigation by the onboard Global Positioning System (GPS), will provide information on the absolute current velocity profile in the upper 400 m of the ocean. Hydrographic measurements (conductivity/temperature /depth) from the surface to the bottom and fixed moorings that resolve the time variance of the ocean dynamics combine to provide the information necessary to estimate the actual sea surface slopes to validate the altimeter measurements. Simultaneous observations of meteorological parameters and the boundary layer stability conditions are important for interpretation and correction of the radar signal's interaction with the sea surface. A ship-mounted scatterometer provides information on the surface capillary wave field and the backscatter coefficients.

Information on the variability of the mesoscale ocean dynamics is an important input for boundary conditions and for assimilation in the numerical modeling of the ocean dynamics. The Nansen Environmental and Remote Sensing Center has available an isopycnal numerical model for the northeast Atlantic and Nordic Seas capable of resolving the sea level variability at a 30-km resolution. The variability of the sea surface topography as resolved by this model will be used in a comparison of the variability of the ocean dynamics as resolved by radar altimeter data.

III. Anticipated Results

The anticipated results are an improved understanding of the general circulation in the northeast Atlantic and Nordic Seas, particularly the changes in and effects of the variation in the fluxes of the inflow from the northeast Atlantic. Improved mapping of the mesoscale variations, which are difficult to observe by traditional in situ observations, will result from the accurate TOPEX/POSEIDON altimeters. This kind of knowledge will be important in the prediction models and forecasts of the ocean currents.

Better quantitative estimates of the volume transports through the sill and trenches between Scotland and Greenland will be important in gaining knowledge of the dynamic processes for the bottom water formations further north in the Greenland Sea and Fram Strait. Further, this detailed information may be used as a southern boundary condition for modeling of the entire Nordic Seas.

Reliable altimeter measurements of the sea surface topography, and hence the surface current speed, together with estimates of wave height and wind speed will be important for studies of the interaction between waves and currents on the continental shelf. The long-term goal is to combine these environmental parameters with other remotely sensed information (e.g., SAR, AVHRR, and ATSR images) in a multisensor analysis to support smaller scale, detailed observations of the oceans.

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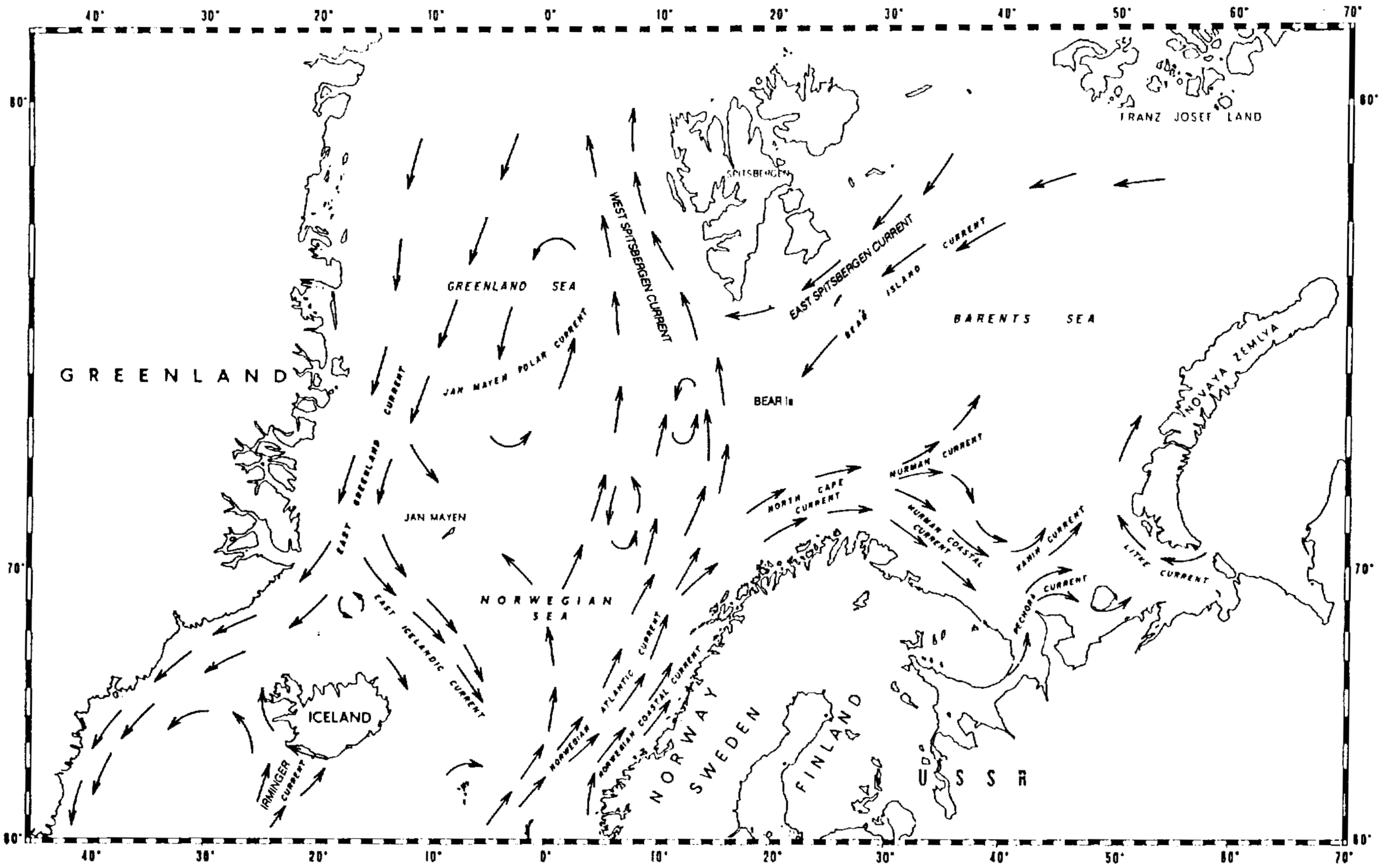

Figure 1. The major surface currents in the Nordic Seas, of which the southern region will be the study area of this TOPEX/POSEIDON project.

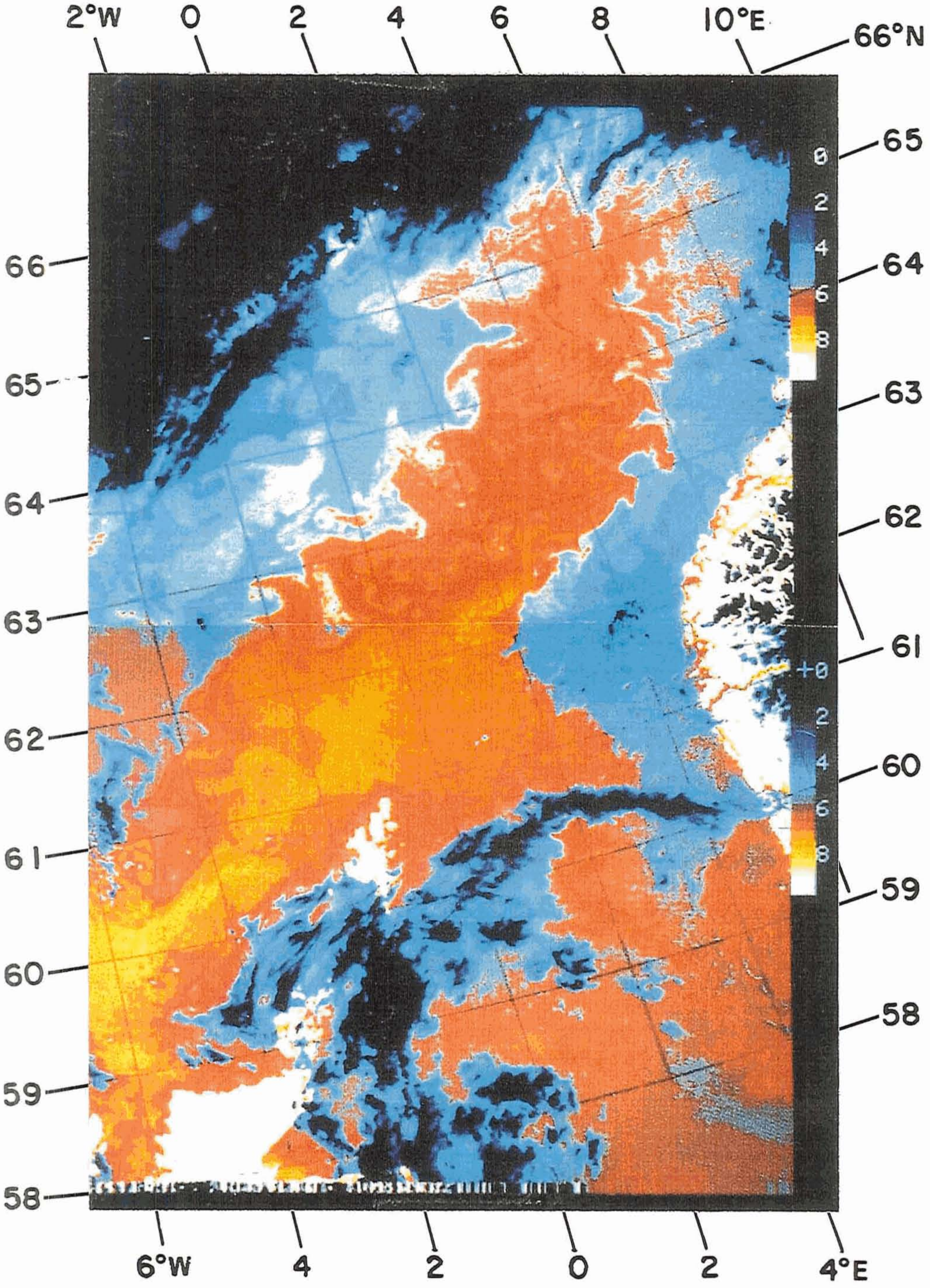

Figure 2. A NOAA AVHRR image of May 14, 1980, resolving the sea surface temperature in the region west of southern Norway. The extensive mesoscale variability of the surface currents are observed in the Faeroe–Shetland Channel and in the interaction between the North Atlantic Current and the Norwegian Coastal Current. Ocean variabilities at these scales are also expected to be resolved by the highly accurate TOPEX/POSEIDON radar altimeters under all weather conditions (after O. M. Johannessen, 1986).

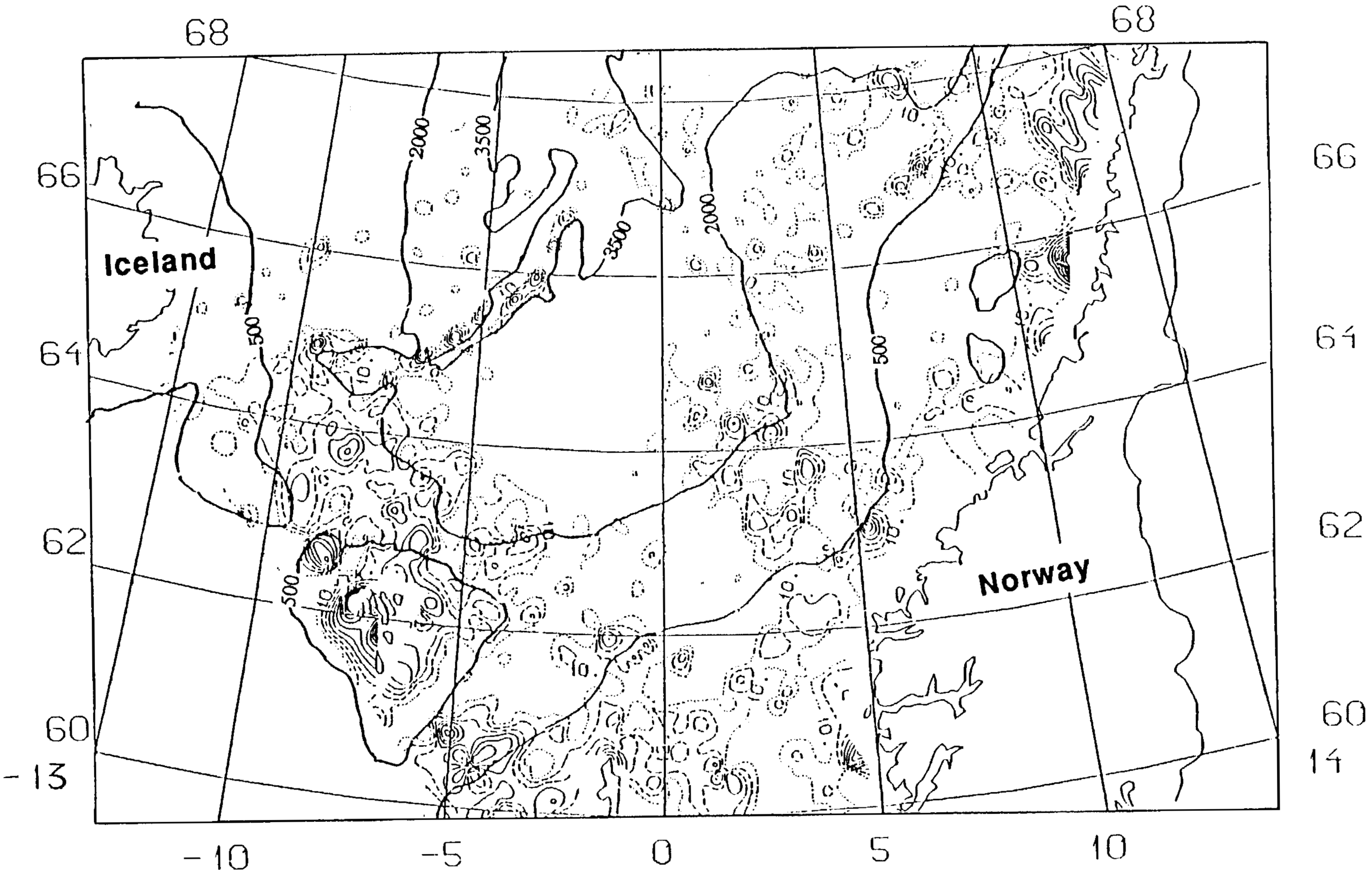

Figure 3. The rms variability as resolved by the Geosat altimeter heights in the region between Norway and Iceland (after P. Samuel—NERSC Thesis, 1990).

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Application of TOPEX/POSEIDON Altimetry Measurements to Observational and Modeling Studies of the Low-Frequency Upper Ocean Mass and Heat Circulation in the Tropical Pacific

p. 4

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I. Introduction

The importance of the El Niño/Southern Oscillation (ENSO) phenomenon in year-to-year variations of the Earth's climate is now recognized. This phenomenon is characterized by the huge transport of mass and heat over the tropical Pacific basin; this transport drastically modifies ocean-atmosphere interactions. Despite the concentration of in situ measurements in the tropical Pacific Ocean during the first five years of the Tropical Ocean and Global Atmosphere (TOGA) international program, synoptic measurements of currents over the whole ocean are still lacking. Since these currents are in quasi-geostrophic equilibrium at low frequency, their intensity and corresponding variation could be monitored from dynamic height topography and hence from satellite altimetry. In turn, accumulation of measurements during TOGA and the ongoing TOGA–Coupled Ocean-Atmosphere Experiment (COARE) in the western Pacific, will help tremendously in calibrating altimetry measurements.

The main purpose of the proposed work is to describe the seasonal and interannual variability of the upper ocean mass and heat transport in the tropical Pacific and to understand the mechanisms responsible for these transports. This will be done through a combination of experimental and modeling approaches. Remotely sensed sea level and derived currents, observed on the basin scale, will be compared, analyzed, and combined with routine and enhanced in situ measurements of thermal and current fields, as well as with model solutions forced by satellite-derived estimates of momentum and heat fluxes. The practical scientific rationale for this work stems from the unique data sets collected by (or easily available to) the investigator's team, and from the team members' complementary backgrounds (physical oceanography and meteorology) and expertise (in situ and satellite-observation analysis and numerical ocean modeling).

II. Research Plan

Our investigation will first evaluate and, we hope, improve sea level and surface current data derived from TOPEX/POSEIDON measurements. As part of the prelaunch studies, preliminary calculations were performed using data from the first 22 cycles of the Geostat Exact Repeat Mission (November 1986 through November 1987). The corresponding altimetry sea level has been compared with various in situ estimates of sea level in the western equatorial Pacific (Deleroix et al., 1991). These sea level estimates were dynamic heights calculated from thermistor-chain mooring measurements, conductivity/temperature/depth (CTD) cruise measurements, and expendable bathythermograph (XBT) measurements taken as part of the tropical Pacific Ship-of-Opportunity Programme (SOP). Furthermore, a comparison between in situ currents, measured from moorings and drifting buoys (Figure 1), and altimetry-derived surface currents demonstrates that a reasonable estimate of zonal current at the equator can be obtained from altimeter data (Picaut et al., 1990).

The previous intercomparison will be extended to the complete data set of the Geosat altimeter (up to January 1989) and later to the improved TOPEX/POSEIDON altimeter.

Since 1987, the number of in situ measurements in the tropical Pacific Ocean has increased. As part of the TOGA–TAO (Tropical Ocean Atmosphere) array, there are presently 19 Autonomous Line Acquisition System (ATLAS) thermistor-chain moorings in the tropical Pacific (Hayes et al., 1991). The TOGA current-meter mooring array now includes five equatorial moorings (World Climate Research Programme (WCRP), 1990a), and more TOGA cruises have been conducted recently in the tropical Pacific. The launch of TOPEX/POSEIDON in mid-1992 will greatly benefit from the TOGA–COARE in the Western Pacific (WRCP, 1990b). The COARE Intensive Observation Period (IOP, November 1992 through February 1993), embedded in a period of enhanced monitoring, will provide the best ocean and atmosphere data set for altimeter calibration in the tropics. The present investigators are involved in this international experiment. The ATLAS–TAO and current-meter arrays will be augmented in the COARE domain (10°N to 10°S, 140°E to 180°); CTD and current profiler cruises will be conducted during the IOP. Drifting buoys will be launched in the COARE domain. Thermosalinographs, added on the corresponding moorings and on the XBT-SOP, will enable a better estimate of dynamic height from temperature profiles. In addition, the expected continuation of the TOGA moored current-observing array and the anticipated deployment of 65 ATLAS moorings within the equatorial Pacific wave guide to complete the TOGA–TAO array will provide an excellent in situ verification data set for TOPEX/POSEIDON until the termination of TOGA (December 1994).

After being evaluated and improved, the altimetery estimates of sea level and derived surface current will be used to describe and understand the four-dimensional variability of mass and heat transport in the tropical Pacific Ocean. Various fields of oceanic parameters and ocean-forcing functions will be first produced over the whole tropical Pacific on similar grid size. When possible, these fields will be conducted on a finer grid over the COARE domain. Filtering in space and time of the original altimeter data and an objective analysis procedure will be improved according to results of previous evaluations. Sea level and surface geostrophic current fields will be produced over the tropical Pacific basin, probably on a weekly basis. The method developed by Delcroix and Gautier (1986) will be corrected from salinity variation in the surface layer to derive the heat content field from the sea level field. Salinity fields will thus be constructed from all available sources (at the surface from SOP measurements and, if feasible, from the satellite estimate of precipitation, and near the surface from CTD cruises and moorings). The satellite surface heat flux field will be provided, following the procedure developed by Gautier (1984) and improved in the ongoing Tropical Heat Exchange Programme (THEP). Finally, as a major atmosphere tropical ocean forcing function, gridded wind stress fields derived from various data sets (e.g., ship measurements, moorings, and satellite estimates) and operational analyses will be generated and/or assembled by the present investigators.

Descriptive and statistical studies of the aforementioned fields will be a first step toward a better comprehension of the seasonal and interannual variation of mass and heat transport in the tropical Pacific. Following a prelaunch study (Delcroix et al., 1991), special emphasis will be placed upon the importance of Kelvin and Rossby waves on the redistribution of mass and heat in the tropical Pacific. Besides, modeling experiments will be conducted to gain a more rigorous mechanistic interpretation of these variations and to construct, on a global grid, subsurface temperature and current information that could not be provided from satellite and sparse in situ measurements alone. The availability of such subsurface information, especially for currents, would greatly improve the potential of the TOPEX/POSEIDON satellite measurements.

To address this last goal, we will start by calculating the low-order vertical model structure from sea level and a few subsurface temperatures demonstrated by Hayes et al. (1985). The structure will be tested at sites with sufficient relevant observations (e.g., sea level, CTD, and mooring data); if successful, the results will be applied to the whole tropical Pacific. The modeling component of this proposition will use two ocean models. Busalacchi and O'Brien (1981) were the first to demonstrate that wind-driven linear model results can account for a significant portion of the El Niño variations in dynamic topography and sea level. An updated multivertical mode version of this model (Busalacchi et al., 1990) will be used to describe and interpret the strictly dynamic response to the tropical Pacific Ocean.

The hydro- and thermodynamic response will be inferred from a reduced gravity primitive-equation model consisting of several layers in the vertical and a surface mixed layer with active thermodynamics. This model will be forced by surfacing fluxes of momentum and heat. Comparison will be made with direct current measurements and altimeter-derived surface currents to identify and quantify where and when geostrophic contributions are important, and, by so doing, provide a determination of where altimeter-derived geotrophic currents can be used with confidence to describe the ocean circulation. Given sea level altimetry and our numerous in situ observations, model data assimilation is probably the best way to extend the satellite information in the subsurface layer.

Thus, prior to launch, assimilation schemes for sea level and sea surface temperature will be implemented and tested. Error analysis would be an important aspect of this task since it would determine the accuracy of such extrapolation. Finally, and given the near real-time availability of many of our in situ and satellite data, forecast studies would be attempted with both ocean models.

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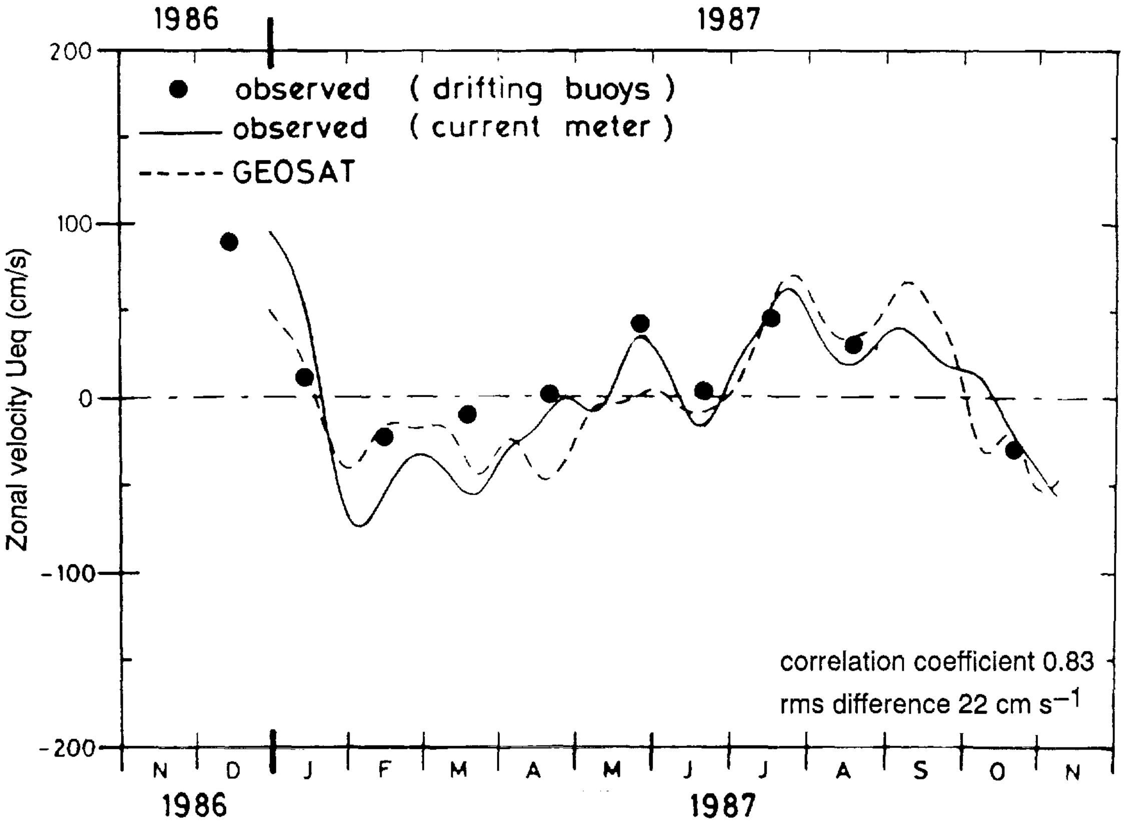

Figure 1. Low-pass-filtered geostrophic zonal flow estimated from Geosat altimeter data (dashed) and near-surface zonal flow measured directly from an equatorial mooring at 165°E (solid line). The dot represents the monthly mean surface current derived from drifting buoys within a 162°E to 167°E, 1°N to 1°S box.

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Mean Sea Surface and Gravity Investigations Using TOPEX/POSEIDON Altimeter Data

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I. Background

The shape of the oceans is determined by numerous factors. The first and most important is the Earth's gravity field; the second is the circulation of water as reflected by ocean currents; the third is tidal variations caused by the rotation of the Earth in the presence of external masses such as the Sun and Moon; a fourth factor is wind. All these factors interact in a complex way to produce an ocean surface that varies in time and geographic location. These variations interact with the atmosphere to produce climate variations both in the oceans and on land.

If the Earth were uniform in density and topography and if tidal variations were ignored, the ocean surface would be very close to an ellipsoid in shape. However, in reality, we do have significant topography (both on land and in the oceans), and the density of the upper layers of the Earth can vary. These variations give rise to a complex gravity field. This gravity field, in turn, causes variations in the ocean surface so that the surface can be quite irregular when compared to the shape of an ellipsoid of revolution. In fact, the variations from the ellipsoid can reach 102 m. An idealized ocean surface on which no currents flow is called the geoid. The determination of the geoid has been a major task of the geodetic community for more than 100 years. It has been only in the past 20 years that substantial progress has been made. This progress took a great step forward with the advent of satellite altimeters that can measure the distance from a satellite to the ocean surface. Knowing the satellite orbit (from which the height of the satellite can be computed) and the altimeter measurement, the height of the ocean surface can be determined along the path of the satellite. Satellite missions such as Seasat and Geosat have enabled a large portion of the ocean surface to be measured to an accuracy of approximately 1 m. Because variations of the ocean surface reflect bathymetric and density information, studies of the ocean surface have revealed significant information on the Earth's gravity field in the oceans and the implications of such variations on the Earth's structure.

In reality, the ocean surface is not the geoid because currents exist in the ocean. These currents imply that the gravity potential is not constant on the ocean surface while the potential on the geoid, by definition, is. The separation between the ocean surface and the geoid is called sea surface topography. Sea surface topography can be defined in an instantaneous (with respect to time) manner or, by averaging with respect to time, a mean form. The study of both forms of sea surface topography can yield important information in studying ocean circulation.

To determine sea surface topography, it is first necessary to determine the ocean surface after excluding tidal effects. This can be done using satellite altimetry where these measurements to the ocean surface, in conjunction with a precise satellite orbit, can yield the position of the ocean surface (along the satellite track) in an instantaneous sense or, by averaging, in a mean sense. These ocean surfaces defined on a spatial grid can be used with geoid undulation information to define sea surface topography.

The above information identifies several key elements in the use of satellite altimeter data. These are the altimeter measurements, the orbit determination, the determination of the ocean surface, the determination of the geoid, the determination of gravity field information implied by the altimeter data, the determination of variations of the ocean surface, the determination of sea surface topography and ocean circulation from the ocean surface, and geoid undulation information. The research that we will carry out for the TOPEX/POSEIDON project involves aspects of each of the topics mentioned.

II. Research Objectives

The previous discussion describes the general problem of interest to us in our analysis of the TOPEX/POSEIDON satellite altimeter data and related information. From a broad point of view, we will be concerned with studying global ocean circulation patterns on the basis of ocean surface determinations with geoid undulation information. In addition, we will study local variations of the gravity field implied by the altimeter data. These general goals are reflected in the title of our investigation. To meet our general goal, we have defined a number of specific objectives:

(1) *Sea Surface Topography Representation.* We will study the appropriate mathematical representation of sea surface topography for use in gravity field/orbit improvement studies and for use in ocean circulation research. Legitimate concerns on existing global representations suggest that alternative techniques need to be developed and tested.

(2) *Mean Sea Surface Determination.* From the TOPEX/POSEIDON altimeter data and, perhaps, other altimeter data, we will develop optimum procedures to define a mean ocean surface on a geographic grid. The development of this surface will consider orbit improvement possibilities, but will concentrate on the interpolation of data from the most precise orbits.

(3) *Development of Local Geoid Models.* We will develop precise geoid models for selected geographic regions using global gravity fields and local gravity data acquired by ships.

(4) *Mean Sea Surface Comparisons.* Various groups will prepare mean sea surfaces using different techniques from the TOPEX/POSEIDON data. We wish to compare the various surfaces to understand the differences caused by the different processing techniques.

(5) *Sea Surface Topographic Files.* We will create files of sea surface topography for long wavelengths on an ocean scale and for short wavelengths on a local scale.

(6) *Gravity Anomaly Determination.* We plan to use the ocean surface information to determine the gravity anomalies for use in geodetic and geophysical studies of the Earth.

III. Scientific Approach

Each of the objectives outlined in Section II will require the development of mathematical models and numerical techniques for the processing of numerous data types including the TOPEX/POSEIDON altimeter data, other altimeter data (from Geosat and the European Remote Sensing satellite (ERS-1)), and terrestrial gravity data. The approach now planned for each objective is described below.

A. Sea Surface Topography Representation

Current procedures for the representation of global sea surface topography involve the use of spherical harmonic functions. These functions are convenient as they are simply defined with knowledge of coefficients and the latitude and longitude of a point. These functions are orthogonal over the sphere, but we use the representation over only the oceans. This means spurious results may be obtained over the land.

We will explore alternative representations that will be designed for the oceans alone. Ideally, we would like to examine a class of functions that are orthogonal over an irregular boundary (i.e., the shorelines of the oceans). After the function has been chosen, we will use the new model in our orbital analysis/parameter recovery program where the parameters of the sea surface topography will be determined and used for ocean circulation determination.

B. Mean Sea Surface Determination

To prepare a mean sea surface, we will carry out computations to obtain adjusted altimeter data with orbits improved through the use of first Geosat (prelaunch) data and then TOPEX/POSEIDON (postlaunch) data. Tests carried out so far (Engelis and Knudsen, 1989; Denker and Rapp, 1990) indicate a successful modeling effort. With the adjusted track data, we will use various interpolation methods to calculate the mean sea surface at a selected grid interval. Past experience (Rapp, 1986) will lead us to consider first optimum prediction techniques involving some statistical assumptions. We will also study the incorporation of several different types of satellite data (specifically that of Geosat and ERS-1) to assume the most representative sea surface.

C. Development of Geoid Models

We will build on our extensive experience in the development of geoid models (Despotakis, 1987; Rapp and Kadir, 1988). We are collecting ship gravity data in several areas that will be used with new geopotential models to calculate a geoid at an interval consistent with that used in the mean sea surface computations. Two areas tentatively selected for these computations are the North Atlantic and the Agulhas Basin off the southern tip of Africa. Accuracy assessment of the geoid will be carried out to understand the accuracy of the computed geoid by geographic location and by wavelength.

D. Mean Sea Surface Comparisons

A key product of the TOPEX/POSEIDON project will be the mean sea surface. This sea surface will be defined over different averaging intervals such as 2 months, 6 months, 1 year, and longer. Various investigations (including this one) will develop techniques for the extraction of the mean sea surface from the altimeter data. As much of the analysis will depend on these surfaces, we intend to compare the surfaces created by the various groups. We will examine the differences both geographically and by wavelength.

E.. Sea Surface Topography Determination

We will determine sea surface topography in two ways. The first method will use the orbit improvement/parameter estimation process discussed in Subsection B. This will yield determinations of sea surface topography on a long-wavelength basis. To recover sea surface topography on a more local basis (500 km x 500 km areas), we will use the mean sea surface developed as described in Subsection B with the geoid models developed as described in Subsection C. The results in both cases will be sea surface topography models for selected time periods varying from 2 months to 2 years.

F. Gravity Anomaly Determination

Gravity information can be precisely derived along the track of the altimeter. Although the spacing of TOPEX/POSEIDON will not permit detailed studies between the tracks (the spacing between the tracks will be about 150 km), the altimeter data can be combined with other altimeter data to achieve an improved determination of the ocean gravity field at various wavelengths. We have extensively applied processing tools to carry out these determinations (Rapp, 1986; Hwang, 1989), and we intend to use them for their computations.

IV. Anticipated Results

The analysis that we will carry out in response to the objectives given in Section II will yield results in several different areas. These results will be based on the processing of the satellite altimeter data from the project as well as related information, such as other altimeter data, terrestrial gravity data, and oceanographic data. More specifically, we anticipate the following results will be available at the completion of the project:

(1) An improved mathematical model for the representation of sea surface topography.

(2) A mean sea surface, at suitable time-interval averages, defined on a detailed geographic grid.

(3) A comparison of gridded ocean surfaces developed by various groups.

(4) A set of geoid models for selected areas of significant oceanographic interactions with accuracy estimates.

(5) A global and local set of gridded sea surface topography values with associated computations of ocean currents.

(6) A set of gridded gravity anomalies along the altimeter tracks or on a complete geographic grid, if sufficient data are available.

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Global Ocean Tide Mapping Using TOPEX/POSEIDON Altimetry

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I. Summary

The investigation's main goals are to produce accurate tidal maps of the main diurnal, semidiurnal, and long-period tidal components in the world's deep oceans. This will be done by the application of statistical estimation techniques to long time series of altimeter data provided by the TOPEX/POSEIDON mission, with additional information provided by satellite tracking data.

In the prelaunch phase, we will use in our simulations and preliminary work data supplied by previous oceanographic missions, such as Seasat and Geosat. These results will be of scientific interest in themselves. The investigation will also be concerned with the estimation of new values, and their uncertainties, for tidal currents and for the physical parameters appearing in the Laplace tidal equations, such as bottom friction coefficients and eddy viscosity coefficients. This will be done by incorporating the altimetry-derived charts of vertical tides as boundary conditions in the integration of those equations. The methodology of the tidal representation will include the use of appropriate series expansions such as ocean-basin normal modes and spherical harmonics. The results of the investigation will be space-determined tidal models of coverage and accuracy superior to that of the present numerical models of the ocean tides, with the concomitant benefits to oceanography and associated disciplinary fields.

II. Approach

The goal of the proposed investigation is to obtain better representations of the main tidal components on a global basis by developing statistical estimation techniques suited to the analysis of long time series of data from highly accurate state-of-the-art spaceborne altimeters. In particular, the TOPEX/POSEIDON mission has been designed to provide the observations necessary to calculate for the first time all the dominant deep sea tides with useful accuracy.

There are two major approaches for accomplishing these objectives. The first is with the use of spaceborne altimeters, which directly map the instantaneous shape of the ocean surface. Changes in the observed height of this surface, especially at diurnal and semidiurnal frequencies, give a strong measurement of global ocean tidal processes. The second uses the observed evolution of well-tracked near-Earth satellites, where the time-varying change in the Earth's external gravitational potential due to the mass redistribution of the tides is clearly observable because of the resulting orbital perturbations they induce.

The direct observation of tidal perturbations on near-Earth satellites is capable of resolving only the longest spatial wavelength components of the major tides, this because of attenuation with height. However, on the ocean's surface, these components make a substantial contribution to the total tidal amplitude, and, if poorly modeled, are the most likely to inhibit the recovery of the nontidal dynamic slope of basinwide ocean circulation patterns. In contrast with satellite tracking, altimetry directly samples the height above the sea surface, thus providing a full oceanographic signal, including the tides at all wavelengths.

Therefore, the ultimate objective of this proposal is to develop global ocean tidal models from all available, high-quality satellite altimetry data sets (especially those from Geosat) and calibrate and enhance them, as far as practical, with the tidal information obtained from spacecraft tracking data.

III. General Objectives

The accurate modeling of oceanic tides is very important for the interpretation of oceanic measurements from spaceborne altimeters. The tides not only introduce errors into the dynamic topography at nontidal frequencies and interfere with very precise geodetic and geophysical calculations, particularly those depending on accurately determined spacecraft orbits, but they are of considerable interest in their own right.

Ocean tidal studies have a long history. Several comprehensive reviews can be found in the literature: Cartwright (1977), Hendershott (1981), and Schwiderski (1980).

The extraction of ocean tidal components from the analysis of satellite altimetry data could become an alternative and complement to the numerical integration of the Laplace tidal equations. The tidal analysis of long time series of data from satellite altimetry in a repeated Earth-track orbit should provide better knowledge about the ocean and Earth tides than we shall ever get from surface-based measurements. With one or two years of altimetry of uniformly high precision, we should be able to resolve both the semidiurnal and diurnal tides more reliably than has been possible so far.

The feasibility of mapping the tidal components by means of altimetry data has been demonstrated by an increasing number of investigations. Studies by Estes (1980), Colombo (1984), Mazzega (1985), Woodworth and Cartwright (1986), Sanchez and Cartwright (1988), and Cartwright and Ray (1990a) are a few of the increasing number of contributions in this field.

Figures 1 and 2 are examples of our current state of the art in defining the global tidal field from the altimetry data of Geosat. They show contours of the Real (X') and Imaginary (Y') admittance of the M_2 constituent relative to local transits of the generating potential, for all oceans and tidal seas between 68°N and S. The originating digital array for X' and Y' is at a resolution of 1 deg latitude × 1.46 deg longitude, and may be simply transformed into amplitude H and phase lag κ (from Cartwright and Ray, 1990b).

Regarding the value of tidal analysis based on tracking data, Williamson and Marsh (1985) and Christodoulidis et al. (1987) have shown that such an analysis can yield highly accurate estimates of the long-wavelength spatial features of the major tides. In the new GEM-T1 gravity solution (Marsh et al., 1988), 66 terms containing information on 12 major tides were simultaneously estimated with the gravity solution. This information can play an important role in our altimeter analysis.

The objectives proposed by this investigation are the following:

(1) To produce global deep ocean tidal maps of the main diurnal and semidiurnal tidal components that are more reliable than the present numerical models. These maps will be based mainly on the analysis of long time series of altimeter data provided by the TOPEX/POSEIDON mission.

(2) To obtain accurate global tidal maps of the main long-period tidal components by means of analysis of the altimeter data provided by TOPEX/POSEIDON and by the analysis of the perturbations produced by such tides on spacecraft orbits.

(3) To compute estimates for such physical quasi-empirical parameters appearing in the tidal differential equations as bottom friction coefficients and lateral turbulent-eddy viscosity coefficients. Other parameters appearing in the equations will be estimated also, parameters such as Love numbers, tidal loading, and tidal self-attraction parameters.

During the prelaunch phase, the major effort will be directed at making ready the tools to be used to map the tides as well as the testing of those tools, both by way of extensive simulations and their use with actual altimetry data available during this period. This activity should produce the required analysis software, as well as preliminary tidal maps of scientific interest. The postlaunch phase will concentrate on the use of the TOPEX/POSEIDON altimetry to produce the final tidal models and to complete all related tidal studies.

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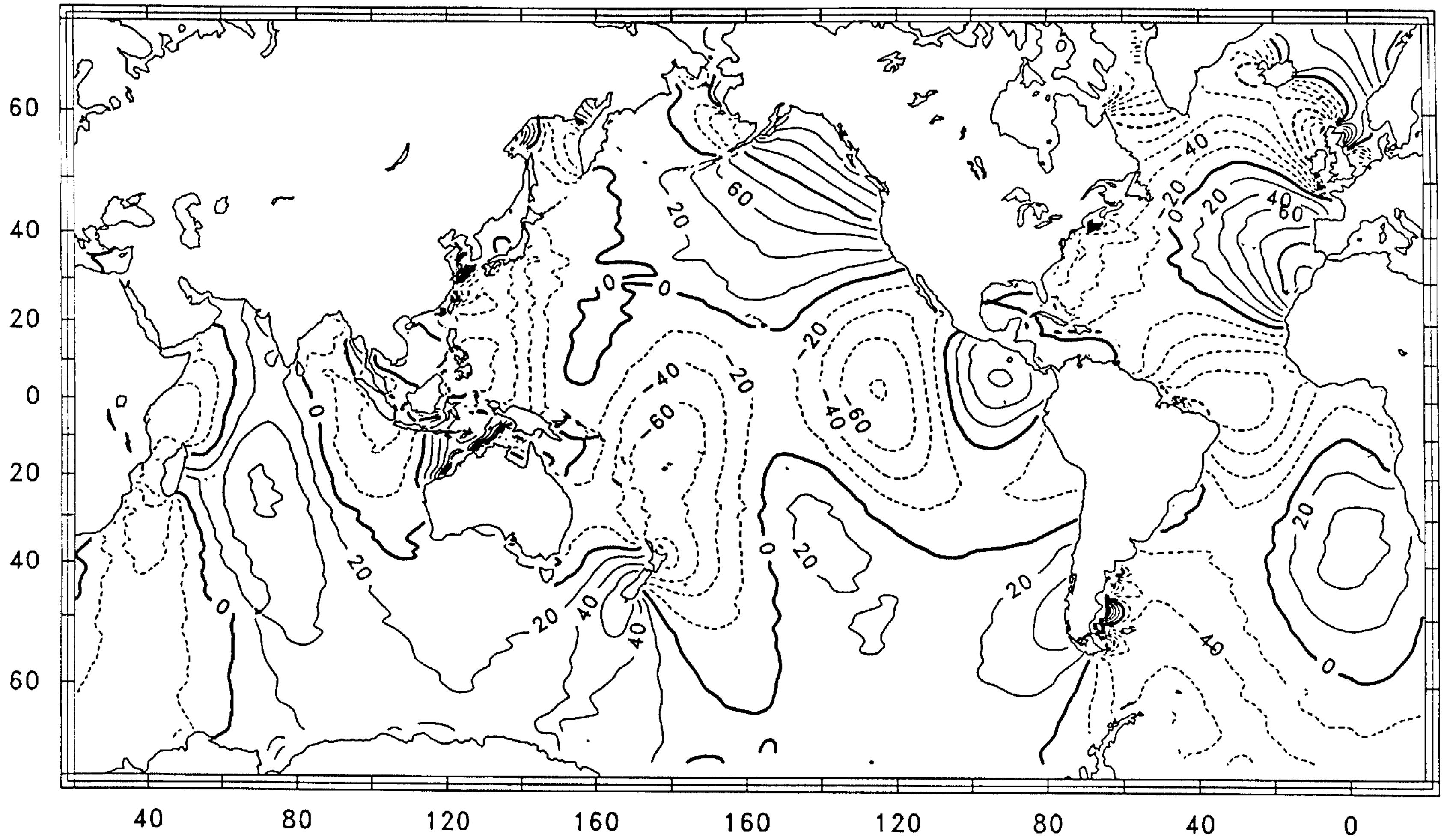

Figure 1. Contours of the X' component of admittance of the M_2 constituent of the (ocean + load) tide in phase with the local transit of the generating potential, as derived from Geosat altimetry. Labels are in percentage units, i.e., they give $100X'$ at intervals of 20. Nodes (or amphidromes) occur at intersections of zero contours of X' and of Y' (Figure 2). Amplitudes H (meters) and local phase lags k are given by $0.632\,|X' - iY'|$ and $\arg(X' - iY')$, respectively.

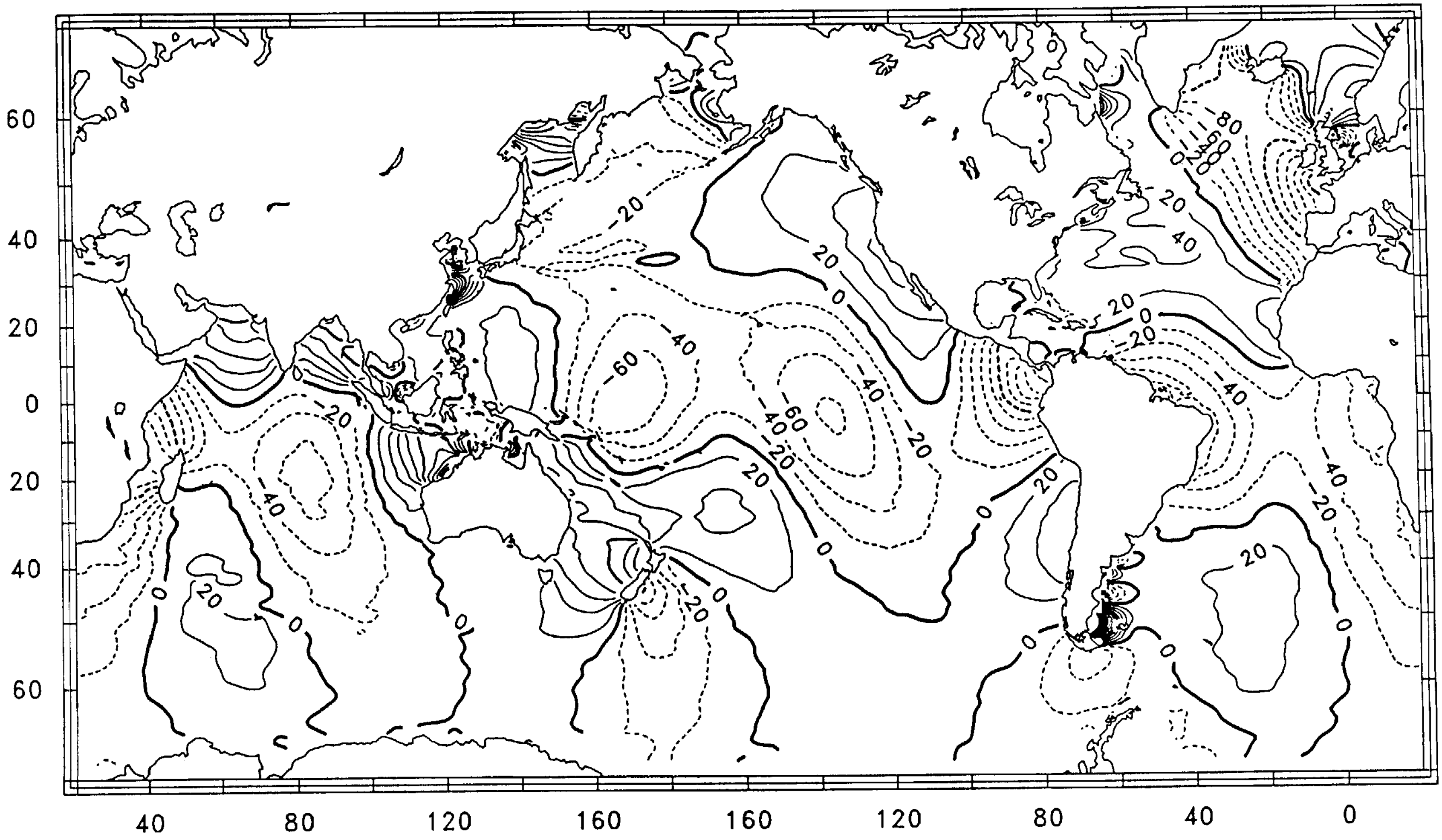

Figure 2. Contours of the Y' component of admittance of the M_2 constituent of the (ocean + load) tide with a 90-deg phase advance on local transit of the generating potential, as derived from Geosat altimetry. See Figure 1 for the definition of nodes, amplitude, and phase lag. The rate of working per unit area is proportional to $-Y'\cos^2$(latitude).

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5 P

Application of Precise Altimetry to the Study of Precise Leveling of the Sea Surface, the Earth's Gravity Field, and the Rotation of the Earth

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I. Summary

Our program includes five research items:

(1) Determination of a precision geoid and gravity anomaly field.

(2) Precise leveling and detection of tidal changes of the sea surface and study of the role of the tide in the global energy exchange.

(3) Oceanic effect on the Earth's rotation and polar motion.

(4) Geological and geophysical interpretation of the altimetry gravity field.

(5) Evaluation of the effectiveness of local tracking of TOPEX/POSEIDON by use of a laser tracker.

II. Prelaunch Scientific Activities in Individual Research

One of our investigations is a prelaunch study on the redetermination of the geoid and gravity anomaly in and around the Japanese Islands using GEOS-3, Seasat-1, and Geosat altimeter data together with updated land/sea measurements. The area covers the Japanese Islands, the Sea of Japan, the western part of the North Pacific, the Philippine Sea, and the East China Sea. Data processings include data adjustment at crossover points, converting altimeter data to gravity anomalies, combining land and sea data with the altimeter data, and bias adjustment with reference to a global gravity model. All of these processings were conducted using the method of least-squares collocation.

As a result, we have obtained new reliable models of the geoid, free-air gravity, and Bouguer gravity anomalies with an error estimated to be ±12 cm for the geoid and ±8 mgal for the free-air anomaly (Figure 1).

Since there are gaps in the measurements where both land/sea truth and satellite altimeter data are lacking, the error estimation varies from place to place. To demonstrate this situation clearly, error maps have been compiled also using the least-squares collocation method, which will be useful for planning a gravimetric survey in the future (Figure 2).

The error maps show that, even within the area surrounding Japan, the errors in the geoidal height/gravity anomaly are, in places, too large to be ignored. We hope that, with the new TOPEX/ POSEIDON data, these errors can be further reduced.

Another of our investigations relative to TOPEX/ POSEIDON is the evaluation of the performance of satellite laser ranging (SLR) devices developed in Japan. We have two sets of the SLR system: one is fixed at Shimosato in Wakayama prefecture and the other is a mobile system. We have used Lageos and Ajisai as targets, from which we received range measurements with an accuracy better than 9 cm. With these SLR systems, we have so far obtained beautiful results of polar motion, plate movement, and irregularities in the Earth's rotation. Since Lageos is more stable than Ajisai as a target, the ranging to Lageos gave a better result with the accuracy of 3 cm (Figure 3).

Considering the importance of exact orbit determination for TOPEX/POSEIDON in the far-east zone, the Japanese SLR systems should fully contribute to the present program. In connection with this, we strongly suggest that the NASA/CNES coordinators of this program take into account the incorporation of the Japanese systems in order to reenforce the tracking capability in the world.

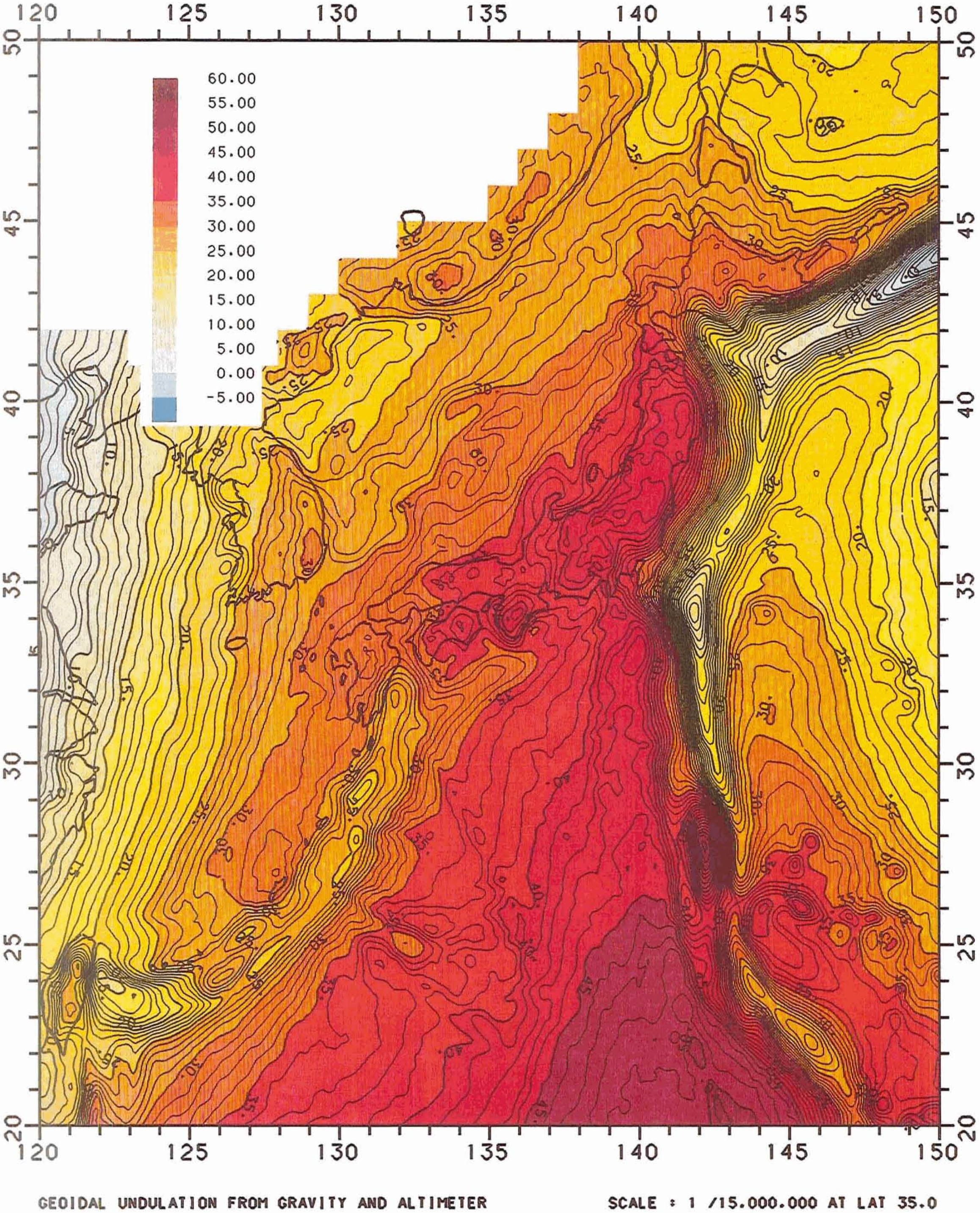

Figure 1. Best-fit geoid in and around the Japanese Islands between 20°N and 50°N, 120°E and 150°E. The altimeter data used are from GEOS-3, Seasat-1, and Geosat; the land/sea gravity data were obtained from 1970 to 1987. Data adjustment, filtering, interpolation, and conversion between gravity and altimeter data are based on the least-squares collocation. The long wavelength trend of the geoid in the area of concern is based on the OSU86F model developed by R. H. Rapp, with which the bias of the processed data has been adjusted to coincide. The contour interval is 1 m. Color displays are from –5 m (blue) to 60 m (dark red). (Reproduced from Y. Fukuda , Ocean Research Institute, University of Tokyo.)

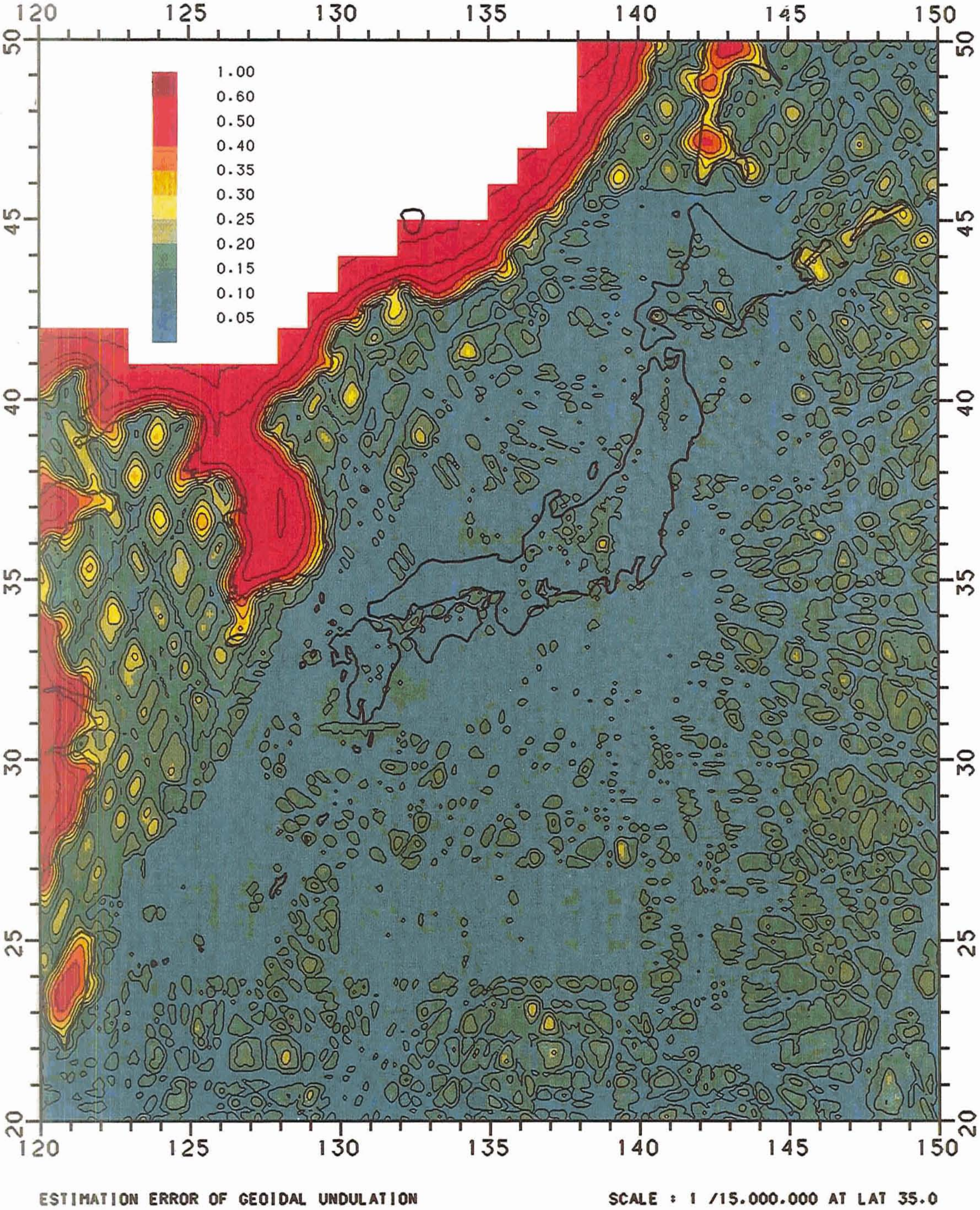

Figure 2. Error estimation of the geoid shown in Figure 1. The estimation is based on the evaluation of reliability obtained from the least-squares collocation. This error depends on the intrinsic error of measurements of gravity and altitude as well as nonuniform data distribution. The error of the geoidal height in the area close to the Japanese islands falls mostly within 10 cm, except for patched zones where either gravity or altitude measurement is lacking. Even in these zones, the error is less than 20 cm. In the western Pacific Zone east of 145°E, the northwestern part of the sea of Japan, the East China Sea, and the Philippine Sea south of 25°N are found the zones of large-error estimation. This is because there are few gravity data available in the zones, so the geoid evaluation is based mostly on altimeter data. (Reproduced from Y. Fukuda, Ocean Research Institute, University of Tokyo.)

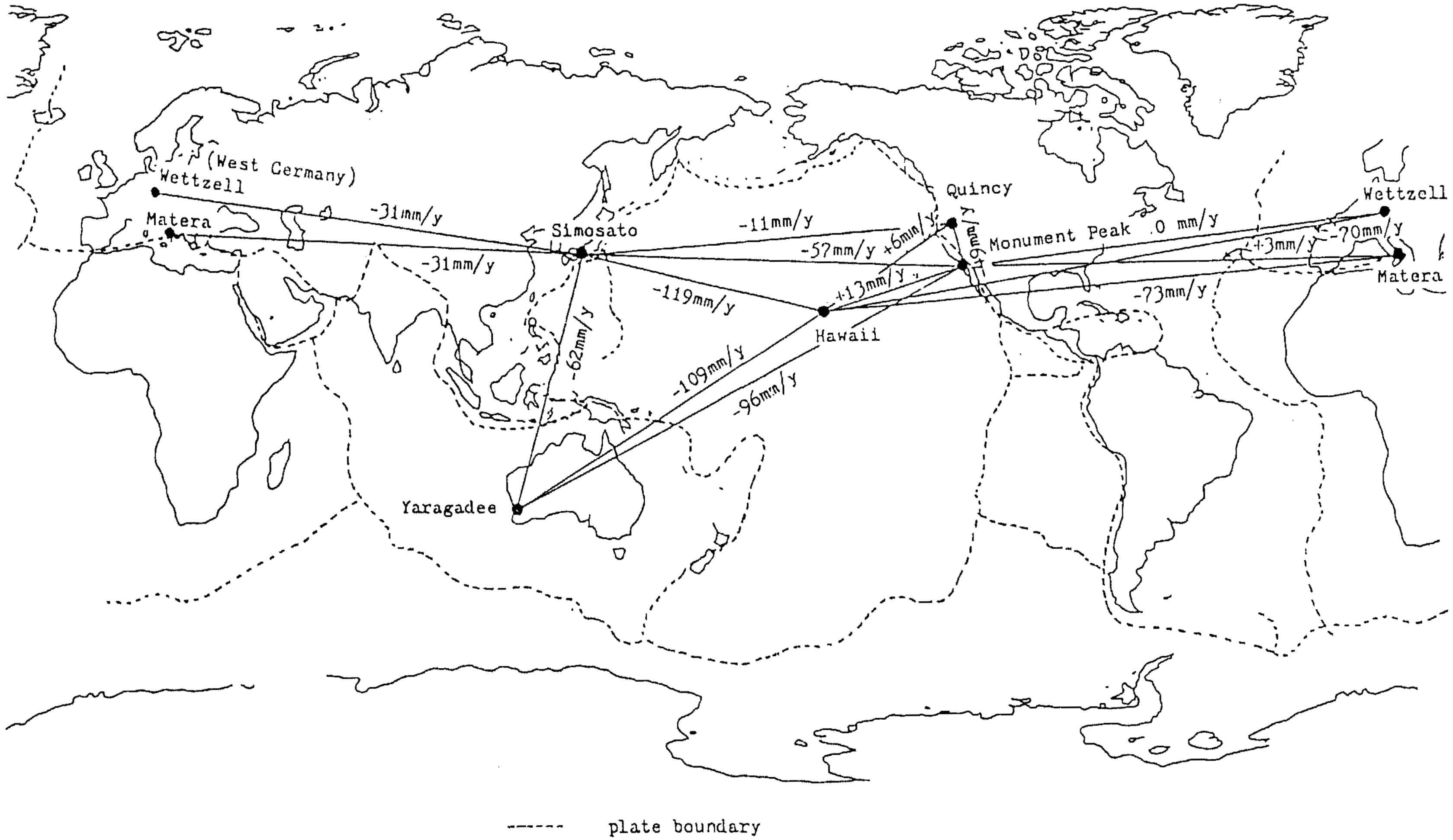

Figure 3. Baseline length changes between worldwide SLR stations. Calculation is based on ranging by the Japanese SLR systems installed at Shimosato in relation to that by the worldwide stations: Hawaii, Quincy, Monument Peak, Wettzel, Matera, and Yaragadee. The baseline length changes obtained have been correlated with the plate movement. The results show that the yearly movements of the plate coincide mostly with the estimation by Minster/Jordan, except for the case of Japan and Europe. Contrary to the Minster/Jordan theory, which claims the identity of the plates to which Europe and Japan belong, there is a definite relative movement of plates between Europe and Japan in the amount of 31 mm/year (contraction). This phenomenon is, at present, considered to be the result of the Philippine Sea Plate, which is underthrusting the Japanese Islands. (Reproduced from M. Sasaki, Hydrographic Department, Maritime Safety Agency.)

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P 6

Present-Day Plate Motions: Retrieval From The TOPEX/POSEIDON Orbitography Network (DORIS System)

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I. Research Goals

The goal of the proposal is to determine the present motion of the main tectonic plates from the Doppler data of the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) orbitography system, which includes in its final configuration about 50 tracking stations with a worldwide distribution.

The surface of the Earth is covered by 11 major plates, whose relative motions have been determined at the geological time scale from paleomagnetic, geographic, and seismic data (Minster and Jordan, 1978; De Mets et al., 1990). Present-day relative plate motions have been determined for some couples of plates from terrestrial geodesy (e.g. Ruegg and Kasser, 1987), from laser measurements (Christodoulidis et al., 1985; Biancale et al., 1991), and from very long baseline interferometry (VLBI) data (Herring et al., 1986). However, laser and VLBI stations have an uneven distribution on the various plates, in particular in the Southern Hemisphere. On the other hand, a model of rigid plates with smooth, regular motions is criticizable. Questions of particular interest are intraplate deformations, mechanisms of spreading at ridges and convergence at subduction zones, continental collisions, and possible relations of plate motions with earthquake occurrence and seismic gaps.

The DORIS system is a Doppler system for orbitography and station positioning using the Doppler shift of two frequencies emitted by the stations and received by the satellite. This system was launched in February 1990 on the SPOT2 satellite, with a tracking network of about 35 stations sampling almost all the tectonic plates (Figure 1). The French tracking system on TOPEX/POSEIDON will use 50 tracking stations and fly on SPOT3–4 experiments. The availability of data over a period of about 10 years offers the possibility of studying present plate motions and intraplate deformations from a global point of view and relating them to major tectonic and seismic events. Intercomparisons with results from other space techniques will also be performed.

II. Preliminary Studies of Positioning With the DORIS System

Doppler data from the DORIS tracking stations have been available since February 1990 (DORIS on the SPOT2 satellite). Besides, several field experiments were planned for the SPOT2 life, with the setup of field beacons in regions of particular interest:

(1) At Djibouti, to monitor tectonic motions. Intercomparison with terrestrial geodesy and Global Positioning Satellite (GPS) measurements.

(2) At Hawaii, to monitor deformations in relation to volcanic activity.

(3) At Saint-Étienne-de-Tinée, France—a ground sliding survey.

A. Method

Three methods have been used for the retrieval of station positions:

(1) Dynamic approach: parameters are the geoid coefficients, the orbit parameters, and the station coordinates.

(2) Hybrid semidynamic approach: the Earth gravity potential is assumed to be known; a first step performs orbit computation and a second step uses this orbit for the retrieval of station coordinates.

(3) Geometric approach: the orbits are assumed to be known and the station positions are computed with respect to these orbits.

B. Results

1. Coordinates of the stations of the orbitography network. Method 1 has been applied to 3 months of Doppler data, leading to a new model of geopotential (GRIM 4) and to a new set of station coordinates (Biancale et al., 1991).

The computation of the new gravity field model GRIM 4 (carried out by a Groupe de Recherche de Géodésie Spatiale/Deutsches Geodätisches Forschungsinstitut (DGFI) team) from about 2-million tracking observations on 30 satellites including DORIS/SPOT2 is an asset in dynamic station positioning. A set of 35 DORIS stations was jointly located with the whole laser network, a few of them linked to laser stations. This effort has, among other things, reduced the DORIS doppler residuals from 5 mm/s to 1.8 mm/s in dynamic orbit computation and provided an homogeneous DORIS global network, which is estimated to have an absolute decimeter precision. DORIS beacons deployed worldwide on each tectonic plate could help, in a few years, quantify the actual global motion.

Method 2 has been applied to 6 months of data. A global solution over 6 months as well as individual monthly solutions have been derived for station coordinates. Absolute positions are stable at the decimeter level over a monthly basis. The 6-month solution shows differences in absolute and relative positions ranging from a few cm to 10 to 20 cm with the International Earth Rotation Service (IERS) positions of laser and VLBI stations. Relative positions derived by method 2 for the three Djibouti stations, as well as for the two Toulouse stations, are in excellent agreement with those derived by method 3 and those measured by ground geodesy (Tables 1 and 2).

2. Positioning experiments in the Republic of Djibouti. The rift system of Djibouti is well documented from studies of the tectonic features (faulting with graben and volcanic activity), the seismic activity, and deformations. Geodetic surveys (Figure 2) are carried out each year; they have revealed an opening of the rift at a nearly constant rate of 6 cm per year and vertical deformations at the border of the rift, possibly related to the seismic activity. Large-scale deformations are also studied from terrestrial geodesy and GPS experiments (Ruegg and Kasser, 1987).

Two DORIS field beacons have been set up on both sides of the Asal graben in addition to the orbitography beacon at the Arta Observatory (Figure 2). Table 2 gives an intercomparison of the baseline lengths obtained from the DORIS experiment (with preliminary orbits) and from direct geodetic measurements. The agreement is within 2 cm for baseline lengths ranging from 15 to 44 km. We expect very good accuracy (below 1 cm) when good-quality orbits are routinely available.

III. Future Studies

The DORIS system appears to be a very accurate positioning system for the study of global plate motions as well as for monitoring regional deformations.

A. Global Studies

Data collected during the SPOT2 experiment, the TOPEX/POSEIDON experiment, and forthcoming experiments will be processed routinely, at least for selected baselines. The availability of a long time series will make it possible to introduce plate velocities as an additional parameter in the data processing, at least for the profiles with the highest deformation rates (Figure 3).

Various tests and processing experiments have still to be carried out. In particular, the stability of the results and their consistency with those obtained from other space technics (laser an VLBI) will have to be checked.

A global interpretation will probably require both a tectonic plate model and an account of intraplate deformations. Because many DORIS sites are close to plate boundaries (midoceanic islands and the proximity of subduction zones), a careful analysis of the positioning results together with the earthquake occurrences and focal solutions will probably be interesting.

B. Regional Studies

Several studies of regional deformations are already planned with both DORIS and GPS positioning (e.g., an experiment along the seismic gap in Chile in 1991). In regional experiments, the main goal of the DORIS system will be to provide a large-scale survey continuous in time.

IV. Conclusion

Preliminary results from 6 months of DORIS data have shown that an accuracy of the order of a few centimeters is easily obtained for baselines of several tens of kilometers. We hope a similar accuracy will be obtained with improved orbits on baselines of the order of a thousand kilometers. The relative motion of tectonic plates and the intraplate deformation, which are of the order of a few centimeters per year, could then be monitored if several years of DORIS doppler data are available. The DORIS data obtained during the TOPEX/POSEIDON experiment, added to those obtained during the SPOT2 experiment, will allow us to reach this goal.

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Table 1. Preliminary results of the DORIS positioning experiment at Djibouti: Monthly results for three baselines (see Figure 2) obtained with the semidynamic method.

Parameter	Mean Value July 1990	Aug. 1990	Sept. 1990	Apr.–Sept. 1990
Arta—C, m	43795.78	43795.84	43795.88	43795.90
Arta—M, m	33273.49	33273.50	33273.52	33273.55
C—M, m	15125.75	15125.86	15125.85	15125.83

Table 2. Preliminary results of the DORIS positioning experiment at Djibouti: Comparison of the baseline length C—M obtained with the DORIS experiment and with terrestrial geodetic measurements.

Parameter	Value
DORIS: dynamical method (1-week data), m	15126.09
DORIS: geometric method (1-month data), m	15125.85
DORIS: semidynamical method (3-month data), m	15125.83
Terrestrial geodetic measurements, m	15125.83 ±0.02

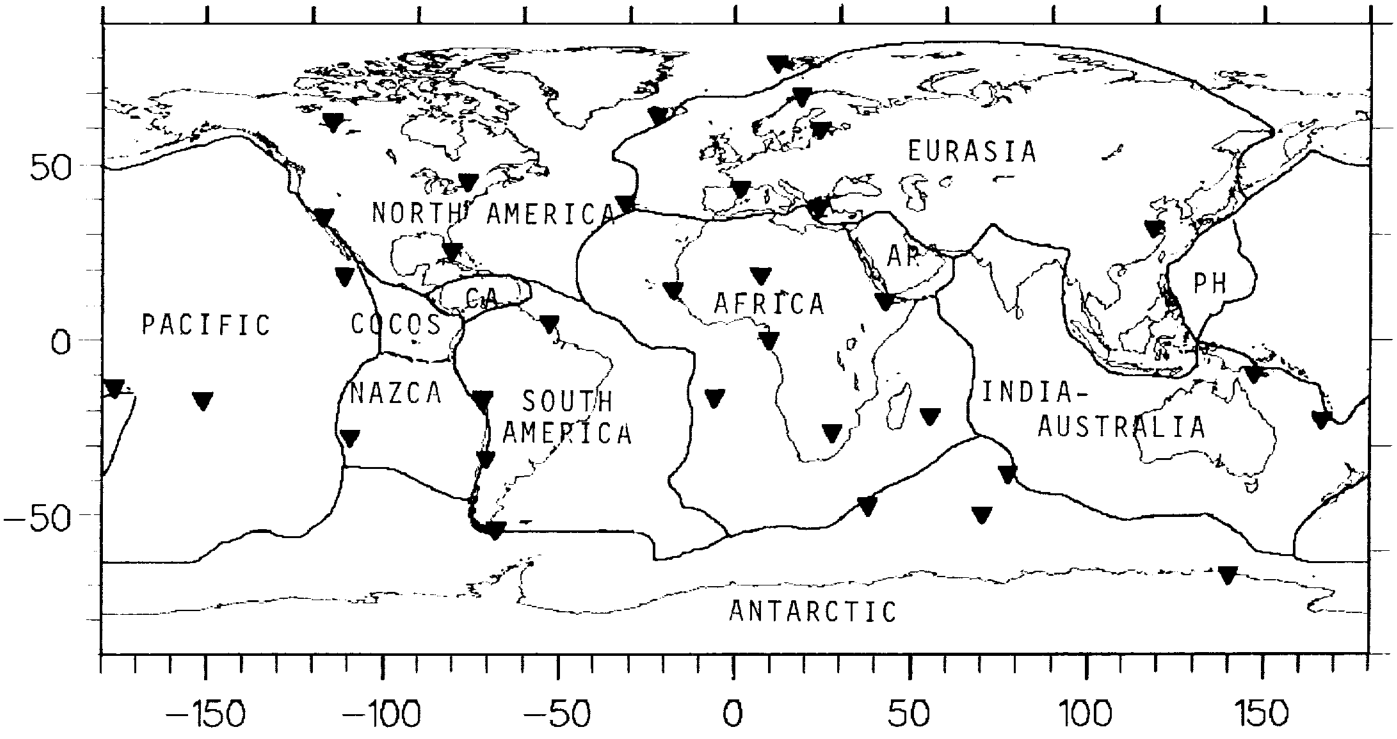

Figure 1. The DORIS orbitography network (April 1990) and the major tectonic plates.

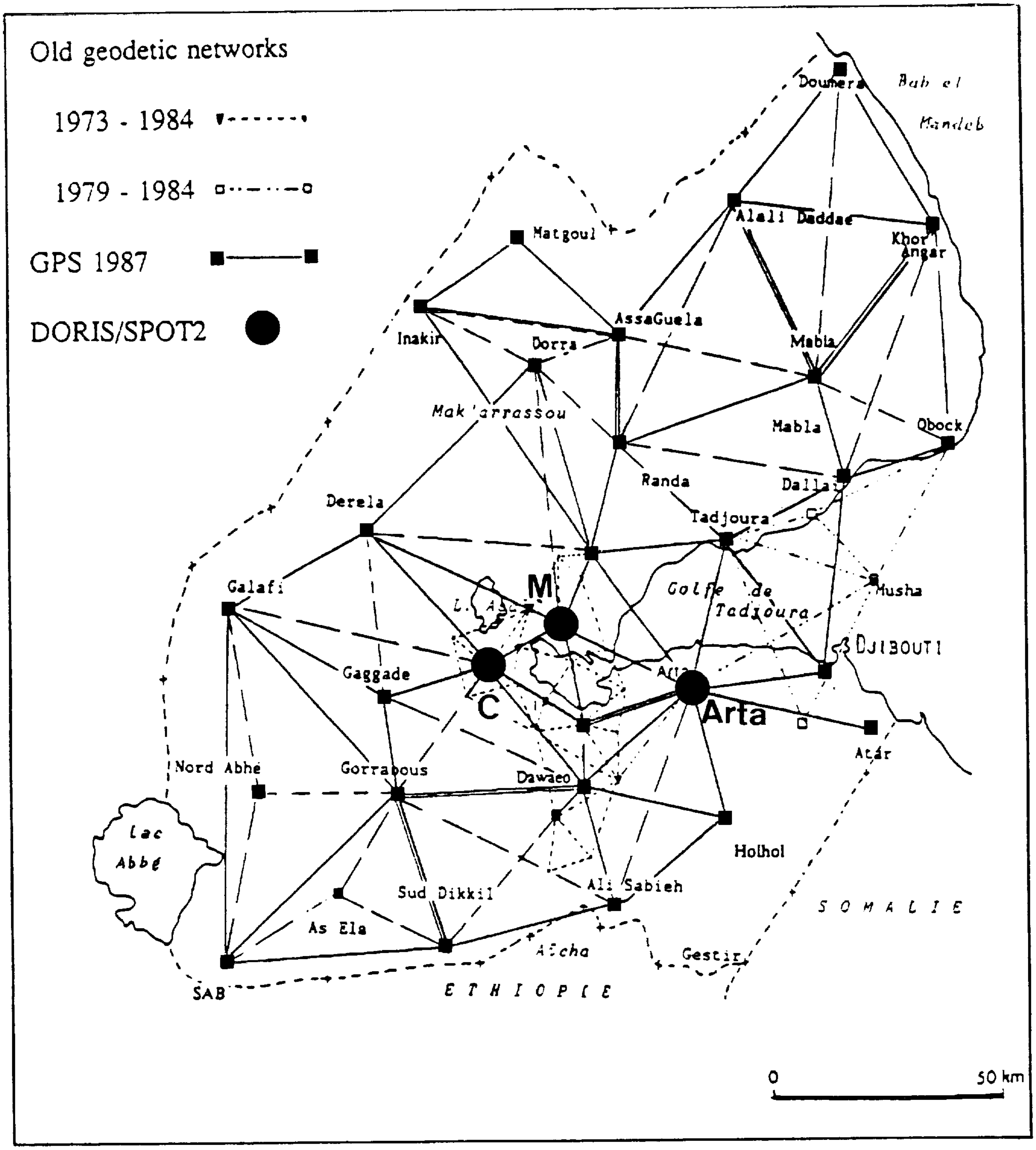

Figure 2. The DORIS experiment in the Republic of Djibouti.

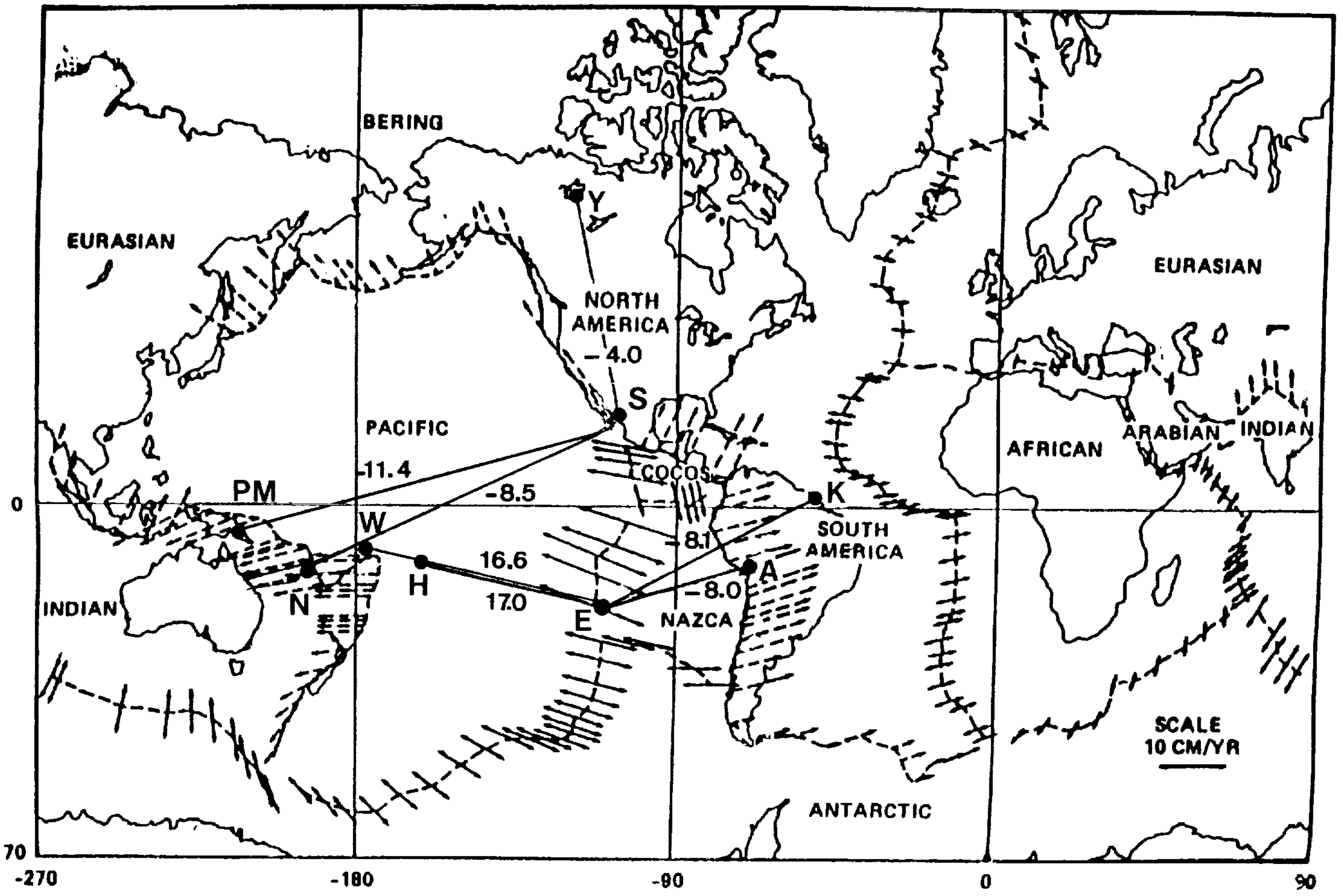

Figure 3. Selected profiles with high deformation rates. Values are predicted rates (in cm/yr) for the AMO2 model by Minster and Jordan (1978).

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Equatorial and Eastern Boundary Current Variability in the North and South Pacific Oceans

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The overall objective of our investigation within the TOPEX/ POSEIDON project is to describe the large-scale and mesoscale circulation of the upper ocean in the eastern North and South Pacific Oceans. We also wish to understand the relation between these currents and local and distant wind forcing. In this context, "large scale" refers to basin-scale fluctuations at annual and interannual time scales; "mesoscale" refers to variability with periods less than 60 days, regardless of the spatial scale.

Emphasis is on the Eastern Boundary Currents (EBCs) in each hemisphere, i.e., the California Current System (CCS) off North America and the Peru Current System (PCS) off South America (Figure 1). These currents provide the connection between the eastward flowing West Wind Drift (WWD) currents at higher latitudes (~50°N) and the Equatorial Current System (ECS) at low latitudes. The EBCs are regions of high productivity because of increased surface-nutrient concentrations resulting from upwelling and increased vertical mixing over the shelf. This productivity has a large degree of interannual variability (Thomas and Strub, 1989). They are also regions of net surface heating due to lower surface temperatures, which reduce the rate of surface cooling (Hsiung, 1986). The fate of the heat and organic carbon gained by the upper ocean in these regions is not well understood at present. In addition to the EBCs, surface currents in the eastern parts of the WWD and ECS will be studied, since they comprise distant sources and sinks of variability in the EBCs (Enfield, 1987; Spillane et al., 1987).

The specific goals of the large-scale study are

(1) To quantify the horizontal structure and annual/ interannual variability of the upper-ocean geostrophic transports in each region.

(2) To determine the covariability between the EBC and the eastern extents of the WWD and ECS in each hemisphere and to estimate the coherence of these currents with the wind field.

(3) To examine the variability of the total mass and heat transports in the upper ocean using Ekman wind drift and surface temperature along with geostrophic currents.

The specific goals of the mesoscale study are

(1) To quantify the annual/interannual variability of the mesoscale energy in each region and to determine the relation between the mesoscale variability and wind forcing.

(2) To examine the fluctuations that have periods of around 50 days and that are observed to propagate eastward along the equator and to continue poleward next to North and South America.

(3) To track selected mesoscale features with a combination of altimeter and satellite surface temperature fields from the Advanced Very High Resolution Radiometer (AVHRR) sensor on the NOAA polar-orbiting satellites.

Our approach during the prelaunch period will be to evaluate the ability of the altimeter to resolve the oceanic signals of interest. The expected error of fields derived from the altimeter data depends on both altimeter measurement error and the analysis method and varies with the desired resolution in time and space. The objective of this work is to determine which analysis methods are optimum for the different resolutions desired. Data from the Geosat altimeter and from simulated TOPEX/POSEIDON observations will be used to verify the error modeling. We will also identify and collect historical hydrographic and sea level data for the purpose of estimating whether the expected signal is large enough to be resolved by the TOPEX/POSEIDON altimeter.

In addition to the error analysis, we will develop techniques for incorporating auxiliary data into the altimeter analysis. We plan to use AVHRR data with altimeter observations to track mesoscale features. Methods of using sequences of AVHRR fields to estimate horizontal displacements of temperature features (Emery et al., 1986) are presently being tested. Methods of combining surface velocity fields estimated from the altimeter and AVHRR data will be evaluated. Other types of auxiliary data include coastal and island tide gauge data, which will be used to calculate geostrophic surface currents with high temporal resolution; these will be compared with the 10- to 30-day estimates from the altimeter. This is especially promising in the eastern South Pacific Ocean where there is a network of tide stations recently augmented by the Tropical Ocean Global Atmosphere (TOGA) project. In this region, methods of combining tide gauge and altimeter data to form fields of absolute surface topography will be explored.

In the postlaunch period, short-period variations will initially be examined and a comparison between the current systems of the eastern North and South Pacific will be made. By the middle of the postlaunch period, the altimeter observations will be combined with auxiliary data, such as sea level data from tide gauges, wind data from weather centers or scatterometers, density data from conductivity/temperature/depth surveys, and surface temperature fields from the AVHRR. By the end of the postlaunch phase, the TOPEX/POSEIDON and historical Geosat data should be adequate to quantify the annual cycle and interannual variability in surface geostrophic currents as well as to estimate the covariability of the currents with the wind forcing. The analysis of total surface-mass and heat transports (our third large-scale goal) will be accomplished by the combination of geostrophic and wind-driven (Ekman) surface transports.

On the larger scales, the most important result anticipated from this work is an increased understanding of upper ocean-mass and heat transport in the eastern Pacific Ocean. The regions chosen for the study comprise most of the areas of the Pacific Ocean where the ocean gains heat from the atmosphere on an annual average (Hsiung, 1986). An understanding of the heat transport within these regions is critical for our understanding of the role of the ocean in climate fluctuations. If no major El Niño occurs, the normal annual and interannual variability should be well defined over the Geosat and TOPEX/POSEIDON periods. If a major El Niño occurs, the normal annual cycles will be less well resolved, but the evolution of winds, currents, and temperatures will be well documented during this event. In either case, the significance will be great if we can trace the evolution of annual or interannual changes in ocean currents from one region to another and identify critical regions of wind forcing. This is important not only for the tropics, but also for regions such as the CCS, where the strength of the southward transport has been correlated to biological productivity (Chelton et al., 1982). The connection between the strength of the CCS and the strength of the upsteam WWD is thus important. This may also be true of the PCS and the WWD in the Southern Hemisphere. The description of the normal variability of the currents in the Southern Hemisphere will fill important gaps in our knowledge of the world oceans.

On the mesoscale, we expect to quantify the large-scale patterns of annual and interannual variability of mesoscale features and their relation to wind forcing. This relationship is presently unknown and represents a gap in our understanding of ocean energetics. The role of mesoscale features in heat transport is also unclear. Bryan (1986) argues that compensating flows in midlatitude eddies result in little net meridional buoyancy flux, though a small amount of heat flux is still possible. This may not be true for mesoscale features in the EBCs, which are thought to be important for offshore transport (Kosro and Huyer, 1986); it also may not be true for mesoscale features in the ECS (Cox, 1980; Hansen and Paul, 1984; Enfield, 1987). Other results of the mesoscale study will be the definition of the forcing and propagation characteristics of the 40- to 50-day waves in the ECS, which should be possible given a long enough record. The construction of surface topography from combined altimeter and AVHRR fields is an important goal, since it would extend the construction of synoptic 2-D surface height maps to scales smaller than those attainable by altimetry alone.

Our study derives some of its significance from its relevance to the objectives of the TOGA and World Ocean Circulation Experiment (WOCE) programs and from its contribution to the increase of basic scientific knowledge of equatorial dynamics and EBC systems. The spirit of the TOGA and WOCE programs is to improve our understanding of the ocean climate system through a blend of observations and modeling, so as to better serve the needs of society (e.g., through environmental prediction). Another theme is the implementation of satellite applications within these programs. The three areas—observations, modeling, and satellite technology—form an interactive triangle in which each element contributes significantly to the other two. Our own study concentrates primarily on exploring the interactions between observations and satellites, two areas that complement each other extremely well. Together they can yield much more effective results than either alone. They also form the feedback and verification framework necessary for the modeling effort.

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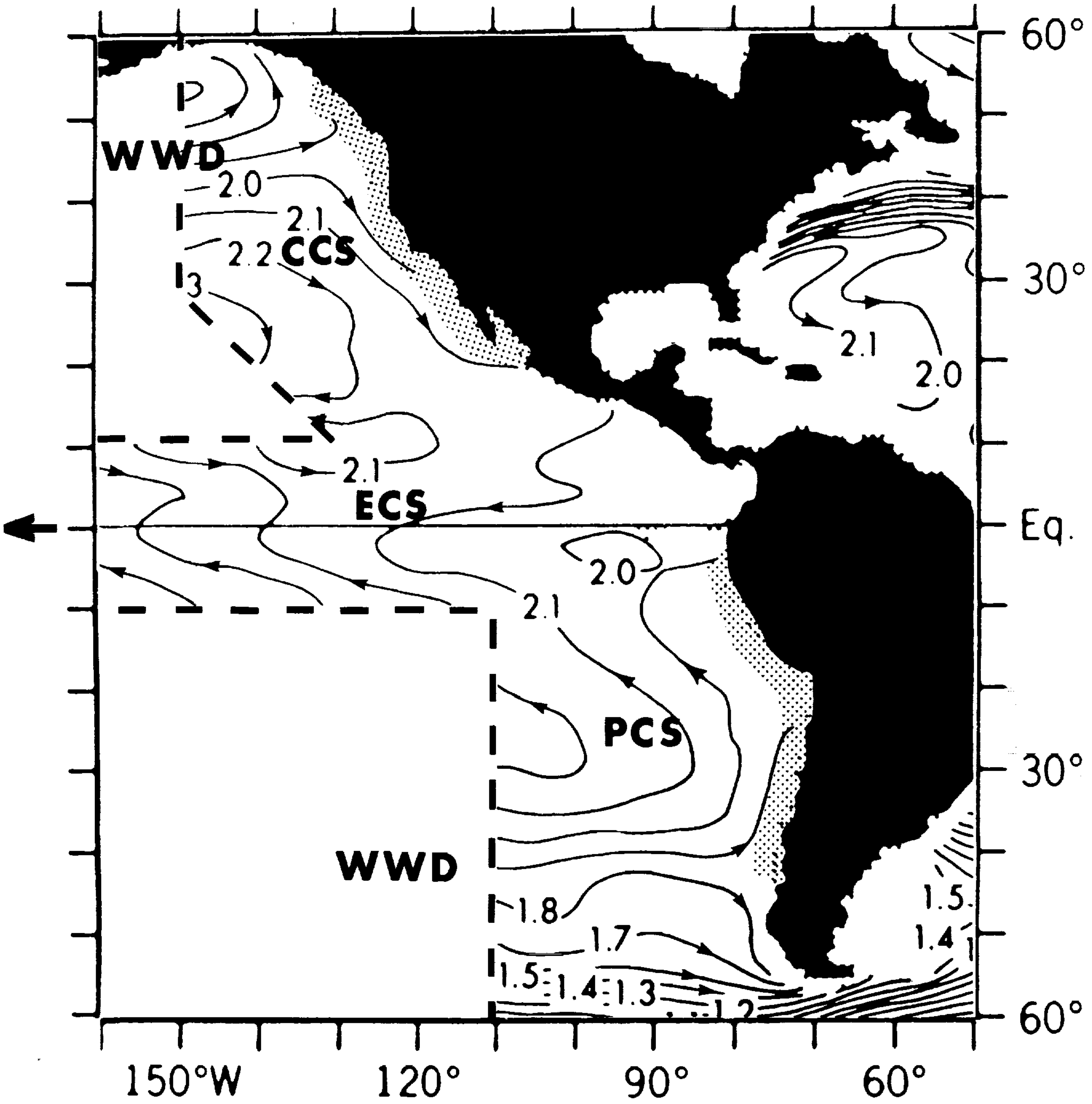

Figure 1. Oceanic regions described in the text (bordered by heavy dashed lines) contain contours of dynamic topography relative to 2000 db. The equatorial strip between 10°N and 10°S (eastern terminus only is shown) will be used for studies of the 40- to 50-day intraseasonal oscillation. The seasonal and interannual variability of the large-scale circulation will be studied over the large eastern boundary regions (EBCs) west of North and South America. The mesoscale variability of jets and eddies will be studied within the stippled regions 300 to 400 km off the North and South American coasts.

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An Integrated Research Program for TOPEX/POSEIDON With Emphasis on the Pacific Ocean

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There are four distinct but related tasks in this investigation. First, we want to combine estimates of the surface dynamic topography derived independently from altimetry and from hydrography in an optimal way (weighted least squares with a priori estimates) to produce an optimal estimate (with error bounds) of the large-scale circulation (e.g., Tai, 1988a). The weighted least-squares methodology requires that error bounds for the a priori estimates be given. Thus, extensive analyses are needed to establish the uncertainties of the dynamic-topography estimate based solely on hydrography and of that based solely on altimetry. We will try to provide the uncertainties both in the spatial domain and in the wavenumber domain (i.e., in terms of spherical harmonics). Even the optimal estimate (combining independent estimates from altimetry and hydrography) would not satisfy many physical constraints, such as mass conservation and tracer conservation. Hence, a final adjustment using the inverse method will be executed to ensure consistency with these physical constraints.

Second, we want to study the large-scale (as opposed to the mesoscale) variability using crossover differences as well as exact repeat tracks (e.g., Tai, 1988b; Tai, 1989a; Tai et al., 1989). The method is a combination of a modified crossover adjustment to preserve the large-scale oceanic variability (while removing the orbit error) and a technique of putting irregular sea level time series on a regular grid in space and time (e.g., Tai, 1988c; Tai, 1989b). The geographical extent of this task is initially the tropical Pacific (e.g., White *et al.*, 1990a), but it will be extended to the entire Pacific and eventually to the whole globe, if possible. We intend to preserve the large-scale oceanic variability from two fronts. First, the crossover adjustment process (which is used to remove the orbit error) will be limited to between those tracks that are less than a certain short time apart so as to preserve the large-scale (and often long-period) ocean variability. Second, large-scale dynamic topography will be constructed every two months from expendable bathythermograph data (with the aid of historical hydrographic data) concurrent with the TOPEX/POSEIDON Mission to see how large-scale variability can be preserved in the altimeter data. The regular grid in space and time will be adapted to the repeat ground-track pattern and satellite-passage time for some usage and will be interpolated to an equally spaced latitude, longitude, and time grid for other usage. This effort has already borne fruit in the tropical Pacific. A clear annual signal is detected using Geosat crossover differences (Tai *et al.*, 1989), and the same data set shows clear evidence of Rossby wave reflection at the maritime western boundary of the tropical Pacific (White *et al.*, 1990a).

The third task involves the study of mesoscale variability in the Kuroshio Extension (e.g., Tai and White, 1990), the California Current (e.g., White *et al.*, 1990b), and eventually the Pacific Ocean and the whole globe (e.g., Tai, 1990, wherein surface transport estimates are provided for both the Kuroshio Extension and the Gulf Stream). The mesoscale eddy study in the Kuroshio Extension gives indication of westward and outward energy propagation from the jet. The physical mechanism for the instability process (i.e., meandering) has been clarified. A similar seasonal cycle in both the eddy field and the surface transport of the jet can be detected. The California Current region study has revealed clear evidence of Rossby waves generated at the eastern boundary and propagating westwards. The surface-transport study of the Gulf Stream and Kuroshio Extension has yielded a reasonably smooth circulation pattern for both currents (as opposed to the widely varying direct-transport estimates). The surface-transport estimates compare well with Richardson's surface-drifter observations. The mean positions of the jet also compare well with the long-term average derived from IR imagery.

The final task is a study of how altimeter data and other data can be assimilated into numerical models (e.g., White *et al.*, 1990c and 1990d). We have attempted to assimilate a simulated altimeter data set (with Geosat sampling characteristics) into a three-layer, eddy-resolving, quasi-geostrophic numerical model using a variety of schemes and have settled on Lorenc's optimal interpolation scheme and an improved version of this scheme. We have managed to improve the assimilated results to the point where they are superior to results produced by statistical interpolation in the surface layer. The information set in the surface layer does transfer to the lower layers. The major stumbling block has been Geosat's inability to sample the eddy field properly (i.e., the space–time aliasing problem).

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Oceanic Transports of Mass, Heat, and Salt in the Western North Pacific

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Because the Pacific is the largest ocean in the world, fluctuations in air–sea interactions there sometimes cause a severe change in worldwide climate. Understanding the physical mechanism for this climate change is most urgent. Estimates of oceanic transports of mass, heat, and salt are clues to the physical processes. The vastness of the Pacific has prevented accurate estimates of them. The altimeter of TOPEX/POSEIDON will measure surface topography of the world oceans, and the geostrophic velocity will be estimated from the measurements. The mass transport in the surface layer can also be estimated from the altimeter measurements. When sea surface temperature is measured by ship observations and thermal imageries from satellites, the heat flux in the surface layer can also be estimated.

Estimation of the oceanic transports through the whole water column requires vertical profiles of velocity, temperature, and salinity. Japanese oceanic agencies have been engaged in routine hydrographic surveys in the seas around Japan and in the western North Pacific. Baroclinic velocities are estimated with the hydrographic data by assuming a no-motion layer at an appropriate depth. The assumption of a no-motion layer gives a large ambiguity in the estimates of absolute volume transport. Several attempts at direct measurements of volume transport have been made in the Kuroshio current. However, time series of the Kuroshio are not yet available. When we use the surface velocity determined through satellite altimeter data as the reference velocity, the baroclinic velocity from the hydrographic data can be treated as absolute. The main research objective of this proposal is an estimate of oceanic transports of mass, heat, and salt of the Kuroshio in the seas around Japan and those of the tropical and subtropical circulations in the western North Pacific.

The integration of the subsurface geostrophic velocities determined by the hydrographic data with the surface geostrophic velocity derived from satellite altimetry is rather straightforward provided the satellite measurements and hydrographic surveys are made simultaneously, and that the surface topography represents only the geostrophic relation with the ocean current. The measurement by satellite altimetry will be made with a time interval of 3 to 20 days for a fixed point on the earth. On the other hand, each hydrographic section is usually reoccupied every couple of months. An interpolation is necessary, and variations of the circulations should be considered in order to diminish interpolation errors. Long-term records of current meters have shown that fluctuations of 30-day and 100-day durations are dominate in the Kuroshio. The variability of the circulations in the western North Pacific will be examined through the existing records of moored current meters and the sea level at islands. The hydrographic lines are not always coincident with the swaths of the altimeter, and a spatial interpolation is also requisite. Sea level variations due to ocean tides are significant, and they must be subtracted from the altimeter data before estimation of the surface geostrophic velocity. Offshore tides south of Japan are being investigated by the co-investigators of this research proposal. The tentative results of this investigation show that the tides in the Philippine Sea are described by Schwiderski's model with an accuracy sufficient for the altimeter measurement. The tides in Japan Sea, however, are not treated in the model. The development of a model is required for the tides in the Japan Sea.

The problems described above are to be studied in Phase I (i.e., the prelaunch phase). An optimum orbit of the satellite will be presented for confirmation of estimates of tides and interpolation errors. Hydrographic surveys complementary to the routine surveys will be planned in Phase I by using research vessels belonging to Japanese universities. Direct measurements of oceanic transports with moored current meters and shipborne acoustic Doppler velocimeters will be planned for selected sections as an activity of the Japan-WOCE (World Ocean Circulation Experiment) Project.

In the operational phase of TOPEX/POSEIDON, the delivered altimeter data will be used for the computation of surface geostrophic velocities to be applied in the hydrographic sections of the Japan Meteorological Agency, Hydrographic Department, Japan Fisheries Agency, and the universities. The estimates of transports are made by the co-investigators of each agency. The composite of the transports in the circulations will be made at the Japan Oceanographic Data Center. The direct measurements of current velocity and transports will be made mainly by the principal investigator.

The anticipated results of the research are

(1) Monthly estimates of volume transport of the Kuroshio; these estimates will reveal whether the Kuroshio path south of Japan is determined by the volume transport. The monthly estimates also clarify the partition of Tsushima Current in the Japan Sea and recirculations in Shikoku Basin.

(2) Volume transports will be estimated for the Equatorial Countercurrent, the North Equatorial Current, the Subtropical Countercurrent, the Kuroshio Countercurrent, and the Kuroshio, in both summer and winter. This will clarify the seasonal variation in the volume transport of the North Equatorial Current, which is expected from the seasonal variation of the Trade Wind, but has not been observed.

(3) The role of the oceans on the climate will be studied through the oceanic transports of mass, heat, and salt in the western North Pacific. The study area will cover an ocean with a width of about 40 deg in longitude, which is nearly 60% as large as the North Atlantic.

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The Determination and Interpretation of Ocean Surface Topography Using TOPEX/POSEIDON Altimeter Data

ORIGINAL CONTAINS COLOR ILLUSTRATIONS

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I. Introduction

Recent investigations have demonstrated that the separation of the geoid and ocean circulation signatures in a solution that uses altimeter data from a single satellite altimeter is possible, provided that a priori gravity information or tracking data from multiple additional satellites can be used as a constraint on the gravity field solution. Consequently, the use of TOPEX/POSEIDON altimeter and tracking data in combination with tracking and altimeter data from other satellites holds the potential for obtaining a substantial improvement in the knowledge of the basin-scale ocean circulation and long-wavelength components of the marine geoid. The complete set of TOPEX/POSEIDON altimeter and tracking data, in combination with altimeter and tracking data from the European Remote Sensing satellite (ERS-1) and other satellites, will be used to perform scientific research in the areas of oceanography, geodynamics, and geophysics.

This investigation will attempt to separate and determine improved models or representations for each of the following effects:

(1) The global marine geoid.

(2) The ocean tides.

(3) The quasi-stationary sea surface topography.

These three topics will be treated in dynamically consistent fashion, so that the quasi-stationary sea surface topography and the ocean tide solutions will be referred to a single geopotential model and hence a consistent marine geoid.

A fundamental issue to be treated in the investigation is the inherent separability of the geoid, sea surface topography, and ocean tides in a simultaneous solution with the data obtained by the TOPEX/POSEIDON satellite. The concurrent determinations of the ocean surface topography and tides will provide products of direct relevance to the TOPEX/POSEIDON mission, and the successful completion of this investigation will yield a significant improvement in the model for the marine geoid as a contribution to other oceanographic and geophysical investigations. The covariance matrix from the solution will provide significant information for analysis and for interpreting the correlations between the quasi-stationary sea surface topography and the associated marine geoid.

II. Objectives

The objectives of this investigation are to use the complete set of TOPEX/POSEIDON altimeter and tracking data, in combination with altimeter and tracking data from ERS-1 and other satellites, to perform scientific research in the areas of oceanography, geodynamics, and geophysics. The following specific objectives will be addressed:

(1) *Oceanography.* To create a dynamically consistent global mean sea surface and to separate and study the constant and time-varying components of the ocean surface topography.

(2) *Geodynamics.* To improve the global marine geoid and the global ocean tide model to support studies in basin-scale ocean circulation.

(3) *Geophysics.* To improve the detail and accuracy of the global sea surface topography to support marine geophysical studies, to use the improved surface to obtain further understanding of the remote ocean basins, and to study thermal and mechanical features

such as spreading ridges, fracture zones, and trenches.

The investigation will employ new techniques that involve processing, in a dynamically consistent solution, crossover measurements from both single and dual satellites (TOPEX/POSEIDON and ERS-1) to improve the marine geoid and the ocean tide model.

III. Approach and Experimental Plan

Research in the areas of oceanography, geodynamics, and geophysics will be undertaken utilizing altimeter and tracking data from TOPEX/POSEIDON, ERS-1, and other satellites. A fundamental issue to be treated in the investigation is the inherent separability of the geoid, sea surface topography, and ocean tides using a dynamically consistent parameter estimation technique.

The approach and experimental plan for the three areas of research are discussed in the following sections. The determinations of the quasi-stationary sea surface topography and ocean surface variability are discussed under Oceanography, the marine geoid and tide investigations are discussed under Geodynamics, and the geophysical interpretations of the marine surface determinations are discussed under Geophysics.

A. Oceanography

The oceanographic effort can be separated into two basic areas: (1) the determination and analysis of the absolute height of the ocean surface and (2) the analysis of the variability of these ocean heights with time. Each of these studies requires accurate altimeter measurements from the TOPEX/POSEIDON mission. For a repeating ground-track orbit, ocean variability may be studied without the use of an accurate geoid, whereas an accurate geoid is needed to detect ocean currents using sea surface height measurements. By differencing the sea surface heights from an appropriate geoid, the mean large-scale ocean circulation may be determined. Repeating this process for each season will allow ocean current maps to be generated on a seasonal basis. By differencing these maps, annual and seasonal changes in the circulation patterns can be studied. By examining the variability of these sea surface heights about their mean, inferences may be made about the variability of the ocean currents. Hence, both types of analyses are important for studying ocean circulation. Finally, the specific objective of the research will be the simultaneous estimation of the 3-year average dynamic ocean surface topography and the marine geoid, thereby providing an improved marine geoid to support other investigations. The covariance matrix from this solution will allow assessment of the accuracy of the determinations.

The oceanographic research employs two very different techniques to determine the sea surface topography—a "dynamic" approach and a "geometric" approach. The dynamic approach involves the simultaneous estimation of the sea surface topography and the geoid using TOPEX/POSEIDON satellite tracking and altimeter data and the orbit determination program UTOPIA. This activity involves a new data analysis technique, and it is the underlying thrust of this investigation. The geometric approach has been used by most previous investigations. However, particular attention will be given to using the along-track sea surface slope generated from the altimeter height measurements as the data type. By using both approaches, the advantages of each technique will be more fully exploited, and the complementary results can be interpreted more easily than if only a single technique were employed.

Using the dynamic approach, Seasat and Geosat altimeter data have been used to estimate a sea surface topography model. The solution was based on ground-based tracking observations from a dozen different satellites. The resulting map is shown in Figure 1(a). For comparison, Figure 1(b) shows the same map, but determined using the historical hydrographic data collected by ships.

A global time-averaged map of the height of the ocean surface will be computed utilizing altimeter data. This map will serve as a reference for ocean variability studies, as an investigative tool for geophysical studies, and as an additional means of computing the mean large-scale ocean circulation. An example sea surface height image computed at the University of Texas Center for Space Research using Seasat data is shown in Figure 2(a). For comparison, an image of the ocean bathymetry is shown in Figure 2(b). Figure 3 is a color map of the global mesoscale variabilities inferred by along-track slope measurements generated from 1 year of Geosat data.

B. Geodynamics

1. **Marine Geoid.** The ability of a spaceborne altimeter to map the global ocean surface with high accuracy and detailed spatial resolution constitutes a powerful tool for the determination of a precise marine geoid. TOPEX/POSEIDON altimeter data, tracking data from doppler and laser ground stations, and global positioning system (GPS) data, when available, are expected to form a valuable data set for the improvement of the global geoid model. The improved global geoid model will enable improved estimates of basin-scale dynamic ocean topography and improved separation of long-wavelength, ocean tide, and gravity signals. With the

simultaneous analysis of data from TOPEX/POSEIDON and ERS-1 and historic data collected from GEOS-3, Seasat, and Geosat, enhanced resolution of the altimetry sea surface, both spatially and temporally, is expected. Altimeter data have been used successfully for obtaining an improved solution of the model of the Earth's gravity field as a part of the prelaunch TOPEX/POSEIDON gravity model development effort. The short-wavelength components of the gravity field influence the altimeter measurement through their effect on the marine geoid. The long-wavelength components have a direct influence through their effect on the satellite orbit. The long-wavelength component of the ocean surface topgraphy has a geometric effect on the altimeter measurement, but no effect on the satellite. Hence, the use of altimeter data and tracking data from other satellites will allow separation of the Earth's gravity field, its tides, and the sea surface topography.

2. **Ocean Tides.** With the availability of altimeter measurements over a lengthy period of time and with the abundance of spatial coverage, the direct measurement of tidal heights and the construction of global, high-resolution tide charts are possible. The gravity and tide information equations, compressed from the tracking observations of 20 different satellites, as well as historic satellite altimeter and satellite-to-satellite data, will provide an excellent a priori data base with TOPEX/POSEIDON tracking data for the improvement of the ocean tide model. These data sets include accurate information provided by precise orbits computed from satellite laser tracking of satellites such as the Laser Geodynamics Satellite (LAGEOS) and the Starlette Satellite. The laser and ground-based tracking systems and the GPS satellite-to-satellite tracking will further enhance precise mapping of the Earth's tidal response.

The investigation will use TOPEX/POSEIDON, ERS-1, and other historic altimeter data to perform a simultaneous solution of the marine geoid, tides, and the quasi-stationary sea surface topography.

C. Geophysics

The investigation will use TOPEX/POSEIDON data along with data from other satellite altimeters (i.e., GEOS-3, Seasat, Geosat, and ERS-1) for two types of marine geophysical studies. First, attempts will be made to improve the resolution and the accuracy of global sea surface topography maps. These maps will be used to improve the understanding of the remote ocean basins. Second, the highly accurate TOPEX/POSEIDON altimeter data will be used to study the thermal and mechanical structure of linear features such as spreading ridges, fracture zones, and trenches. Examples of recent determinations are shown in Figure 4.

While Seasat has greatly improved knowledge of the poorly charted southern ocean basins, it did not complete its task. The resolution of the marine geoid could be improved by nearly an order of magnitude. This increased resolution would lead to many important discoveries in marine geophysics. For example, detailed geoid maps can be used to locate new features in poorly surveyed basins. Features that may be observable with these more detailed maps include areas of extended and compressed oceanic lithosphere, the fine-scale fabric of the seafloor associated with seafloor spreading, and the global distribution of seamounts. The higher accuracy of the TOPEX/POSEIDON data will enable us to model the thermal and mechanical structure of the lithosphere in greater detail.

IV. Anticipated Results

The successful completion of this investigation will yield a significant improvement in the model for the marine geoid as a contribution to other oceanographic and geophysical investigations. The concurrent determinations of the ocean surface topography and tides will provide products of direct relevance to the TOPEX/POSEIDON mission. The anticipated results in each of the three areas of the investigation are as follow:

(1) Oceanography.
  (a) Estimates of quasi-stationary sea surface topography and surface manifestations of large-scale ocean circulation at seasonal intervals.
  (b) The variation in the large-scale sea surface topography from the average, quantified in seasonal increments.
  (c) Mesoscale variability maps at seasonal intervals.
  (d) Global TOPEX/POSEIDON and ERS-1 mean sea surfaces at timely intervals.

(2) Geodynamics.
  (a) An improved long-wavelength (3500-km) component of the gravity field and the marine geoid.
  (b) Better definition of Earth's center of mass and improved positioning of tracking stations in the definition of the Conventional Terrestrial Reference System.
  (c) Improved global ocean tide model.
  (d) Improved long-period tide model for the improvement of TOPEX/POSEIDON and ERS1 ephemerides.

(3) Geophysics.

   (a) Improved marine geoid and the attendant definition of new features in poorly surveyed ocean basins.

   (b) Detailed charting of new features including areas of extended and compressed oceanic lithosphere, the fine-scale fabric of seafloor spreading, and the global distribution of seamounts.

The anticipated results and data products will be available to other TOPEX/POSEIDON science investigators for purposes of intercomparison, independent interpretation of scientific results, and as input to numerical ocean circulation modeling investigations.

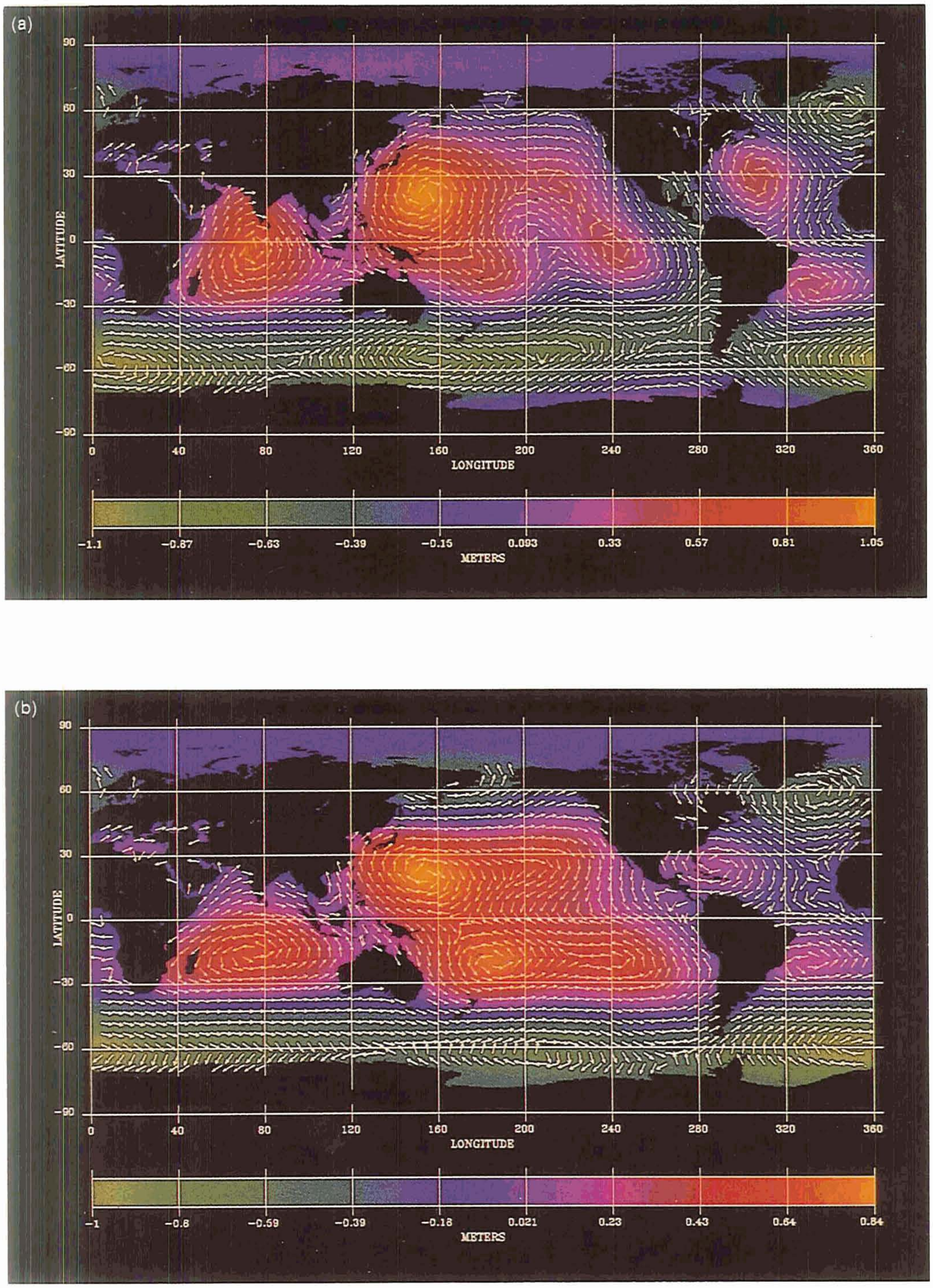

Figure 1. Large-scale ocean circulation (6×6) determined from (a) a joint solution for the Earth's gravity field and (b) hydrographic data.

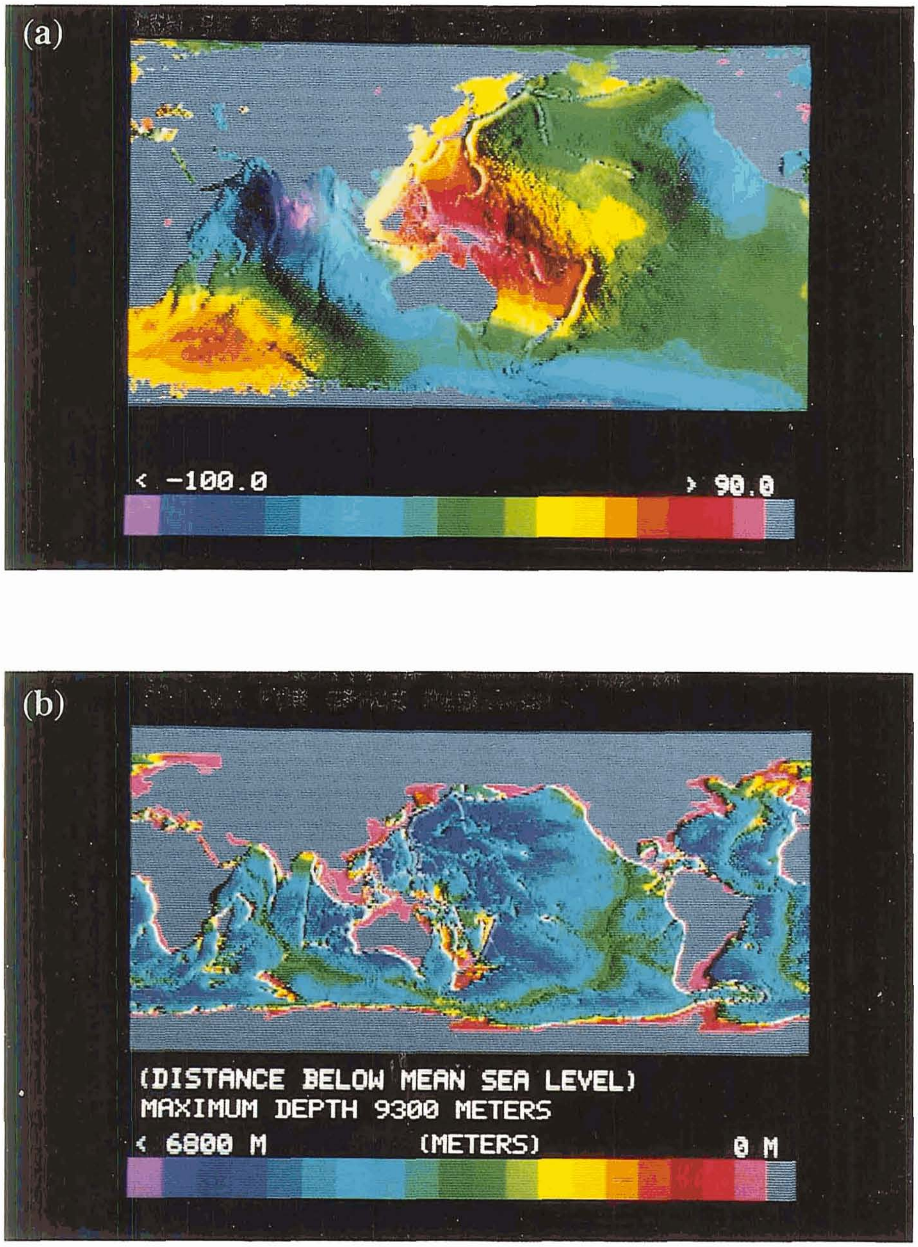

Figure 2. Shaded relief maps: (a) color-contoured map of a mean sea surface derived from Seasat data for the Pacific and Indian Oceans; (b) the SYNBAPS II digital bathymetry for the world.

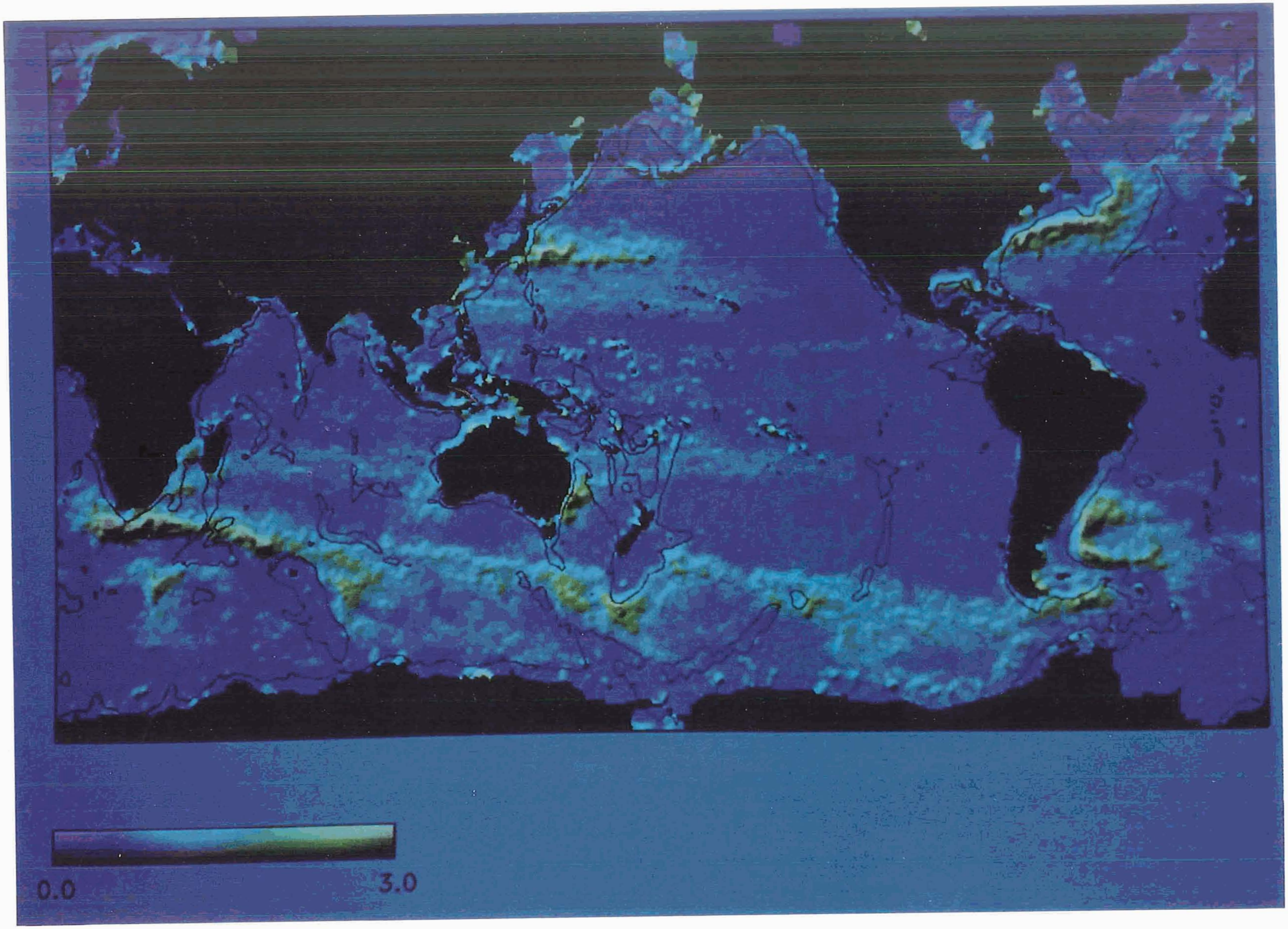

Figure 3. Sea surface slope variability derived from 20 repeat cycles (1 year) of Geosat data. Over most ocean areas, sea surface slope has a low variability (purple). Areas of high variability are in green to yellow.

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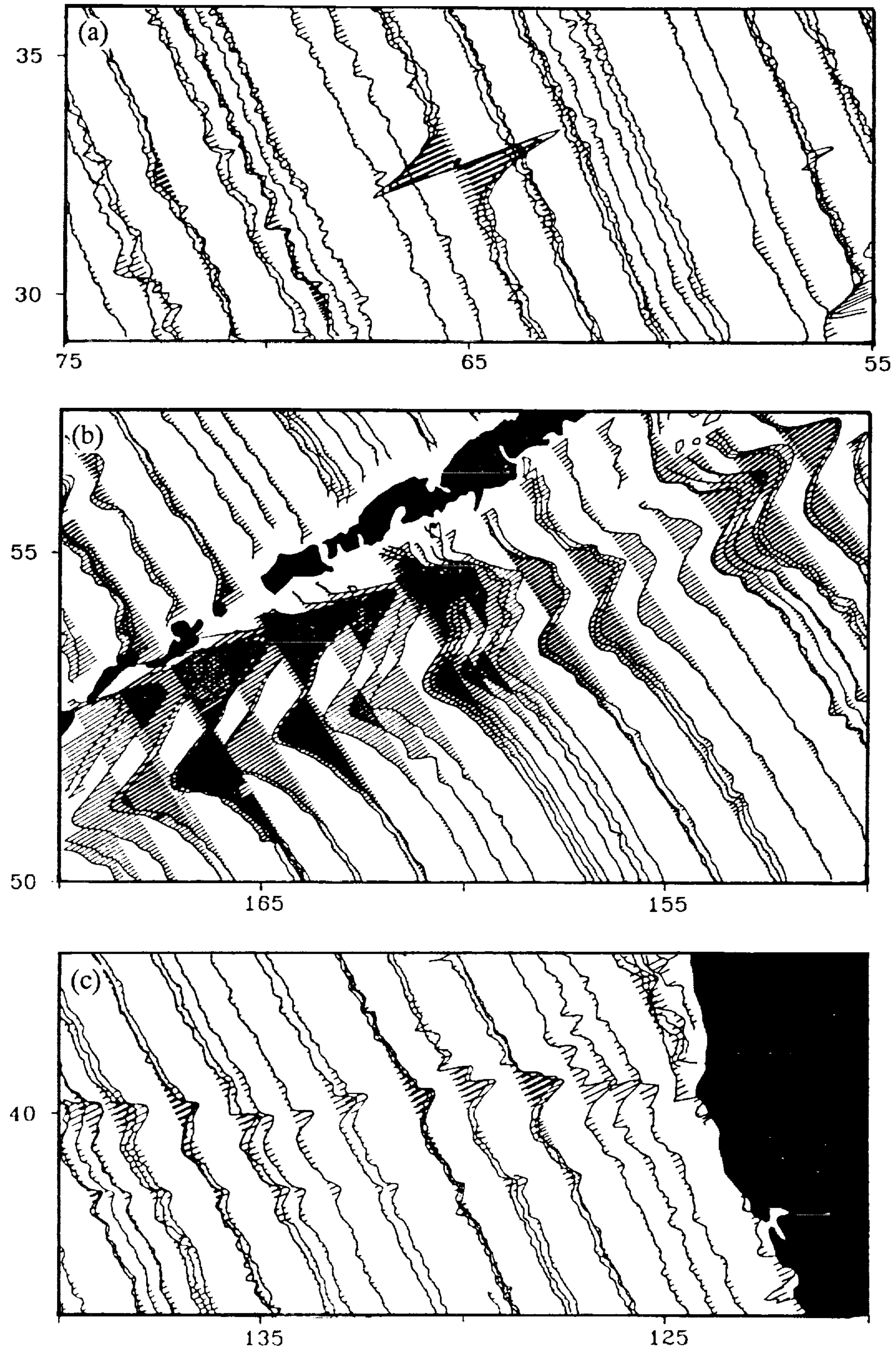

Figure 4. Examples of deflection of the vertical profiles over (a) Bermuda, (b) the Aleutian Trench, and (c) the Mendocino Fracture Zone.

Analysis of Altimeter Data Jointly With Seafloor Electric Data (Vertically Integrated Velocity) and VCTD-Yoyo Data (Detailed Profiles of VCTD)

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I. Scientific Objectives

We propose simultaneous analyses of the TOPEX/POSEIDON altimetry data, in situ data—mainly permanent seafloor electric recordings—and velocity, conductivity, temperature, density (VCTD)-yoyo data at several stations in areas of scientific interest.

At a subinertial period, the horizontal seafloor electric-field data provide a measurement of the vertically integrated (over the ocean thickness) velocity weighted by the electrical conductivity of sea water. The measurement is predominantly a determination of the barotropic component of the water flow. The electrometer is a free-fall instrument and will record continuously the electric field on the seafloor.

The VCTD-yoyos will be moored and will record daily detailed profiles of horizontal velocity, temperature, and salinity. The association of an electrometer and a VCTD-yoyo is called the Barotropic and Baroclinic Measuring Station (BABAS).

The combination of seafloor electric and VCTD-yoyo data with altimetric data and with more classical tools (e.g., hydrography and moorings) will help to better characterize numerous oceanographic problems as, for instance, short- and long-term variability of barotropic, near-surface, and baroclinic water velocities; the distribution of the barotropic flow and its wave number structure; the characterization of small-scale processes; and the determination of the barotropic and baroclinic fluxes. In addition, independent data, such as seafloor electric data, are very important constraints for data assimilation in models.

We are planning experiments in various areas of low and high energy levels. Several complementary and redundant methods will be used to characterize the ocean circulation and its short- and long-term variability. We shall emphasize long-term measurement using permanent stations. Our major initial objectives with the TOPEX/POSEIDON mission are the Confluence area in the Argentine Basin and the Circumpolar Antarctic Current. An early experiment was carried out in the Confluence zone in 1988 and 1990 (Confluence Principal Investigators, 1990) to prepare for an intensive phase later on. This intensive phase will include new types of instrumentation (see below). Preliminary experiments will be carried out in the Mediterranean Sea (in 1991) and in the North Atlantic Ocean (in 1992, north of the Canary Islands) to test the new instrumentation.

II. Practical and Theoretical Approach

The preparation of our scientific programs is organized along the following guidelines:

(1) The development of new instrumentation.

(2) The analysis of existing data.

(3) Tests for the assimilation of seafloor electric data in models of circulation.

A. Instrumentation

Seafloor electric data have been used for oceanographic investigation for some years (e.g., Filloux, 1987; Luther et al., 1990). The seafloor horizontal electric field is recorded on the seafloor with a free-fall acoustically realized instrument. The natural electric-potential differences along two perpendicular directions are measured by means of two pairs of nonpolarizable electrodes. The electrode-switching device developed by Filloux (1973) removes the electrode drift and provides a precise determination of the electric field.

In 1986, the Institut de Physique du Globe de Paris (France) began the scientific program MAGELLAN (developed by P. Tarits) to study the Earth and the Ocean using seafloor electric and magnetic data. In the frame of this program, we are developing seafloor electric instruments suitable for our TOPEX/POSEIDON proposal (Figure 1).

In 1990, the new program BABAS (developed by P. Tarits and C. Le Provost, with cooperation from Italian and Spanish institutions) was funded by the MAST program of the European Community Commission. The station (Figure 2) combines a moored VCTD-yoyo and a seafloor electric instrument connected acoustically to a surface buoy for real-time transmission. Such a station will observe simultaneously both the barotropic and the baroclinic components of the flow. The data set consists of permanent recordings of the seafloor electric field (i.e., the vertically integrated velocity) and daily detailed profiles of horizontal velocity, temperature, and salinity.

B. Validation of Seafloor Electric Data

At subinertial frequencies and in the limit where the horizontal length scale of the flow is much larger than the vertical scale, the horizontal electric field is related to the vertically integrated product of water velocity and the water's electric conductivity. This has been proven using motional electromagnetic theory (e.g., Sanford, 1971; Chave and Luther, 1990). In most cases, this physical quantity divided by the mean conductivity is an excellent approximation of barotropic velocity. In some cases, baroclinicity may leak in the vertically integrated velocity, when, for instance, the conductivity becomes substantially baroclinic.

Several experiments have confirmed those theoretical results (e.g., Cox et al., 1980; Sanford, 1982; Filloux et al., 1989; Tarits, 1989). A very good example is given in Luther et al. (1990). Those authors described the results from the Barotropic Electromagnetic and Pressure Experiment (BEMPE) (see Luther et al., 1987 for details).

The conductivity-weighted, vertically integrated velocity was computed with six current meters from a conventional mooring and compared with the vertically integrated velocity deduced from the seafloor electric data from seafloor electric stations a few kilometres apart (Figure 3, from Luther et al., 1990). The agreement between these stations is remarkable.

C. Comparison Between the Seafloor Electric Field and Altimetry Data

Geosat altimetric data were available for 9 months during the BEMPE experiment (November 1986 to July 1987). Time series were extracted along ascending and descending tracks in the BEMPE areas. Various processes are applied to compare the barotropic variability from the seafloor electric data to the surface variability from the Geosat altimetric data. The preliminary results will be published.

Future work will include the analysis of the seafloor electric data and the sea bottom pressure recorded during the MAGELLAN-TEAHITIA experiment carried out in 1989 in French Polynesia.

D. Seafloor Electric-Data Integration in Quasi-Geostrophic Models

The integration of vertically integrated, conductivity-weighted velocities has been studied using the outputs of numerical tridimensional models of the Institut Français de Recherche pour l'Exploration de la Mer Centre de Brest (developed by L. Hua) and Institut de Mécanique de Grenoble (developed by B. Barnier) (Provost and Tarits, 1989). Data from seafloor electrometers and VCTD-yoyos are simulated and then inverted in an attempt to recover vertical structures and velocities. Further tests with random topography are more encouraging and are progressing.

III. Future Work

Preparation will continue along the paths we have described. Preliminary results obtained with the Geosat data are encouraging. Further work is necessary to analyze the seafloor electric data from such energetic areas as the Confluence zone.

A first experiment with a BABAS station (electromagnetic and VCTD-yoyo) and conventional moorings will be conducted late in 1991 in the Mediterranean Sea. A long-term experiment north of the Canary islands will begin in 1992. Long-term tests of the BABAS stations and a seafloor electrometer array will be performed during this experiment. The objective is to establish a permanent European station along the line of the Bermuda or Hawaii stations. A major experiment in the Confluence area is planned in 1994.

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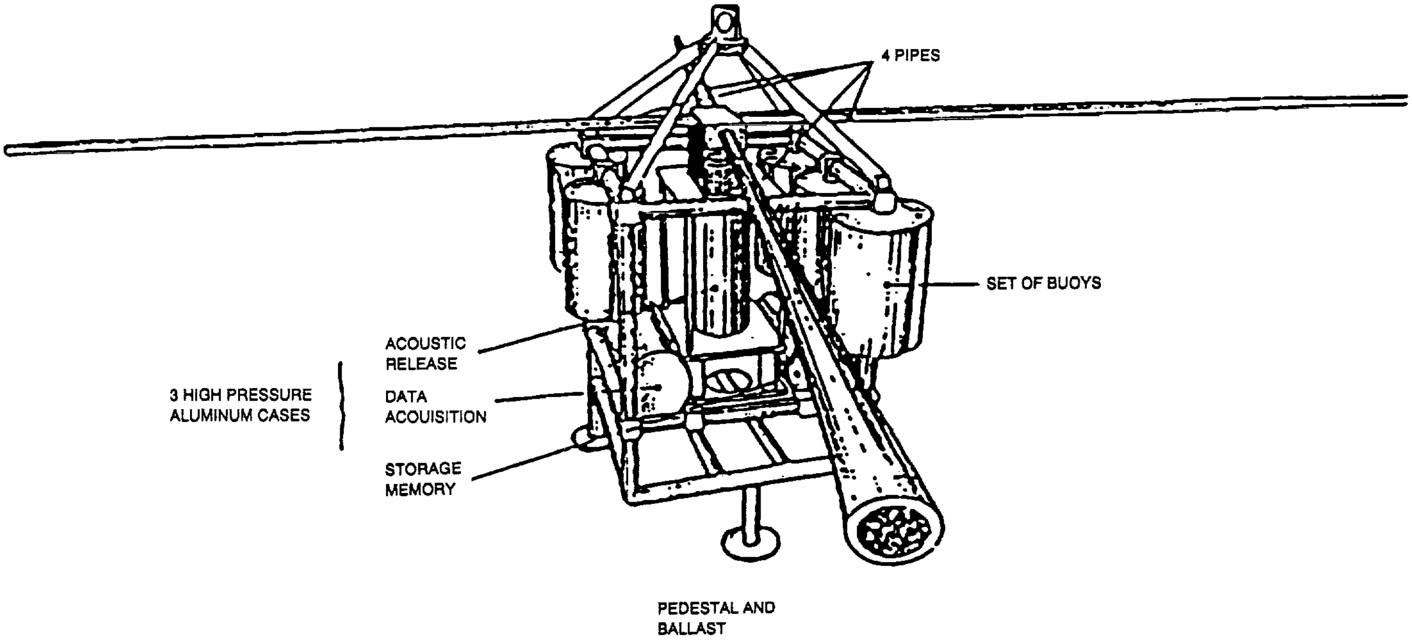

Figure 1. Sea-floor electrometer.

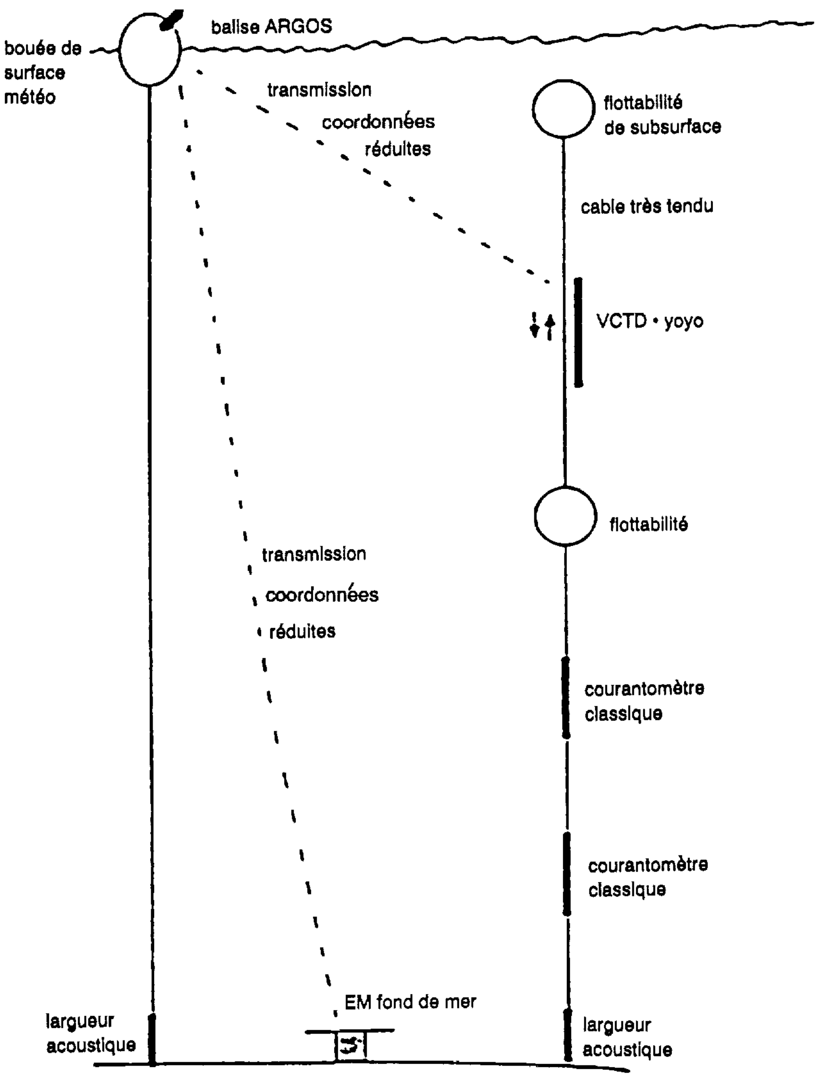

Figure 2. BABAS barotropic and baroclinic measuring stations.

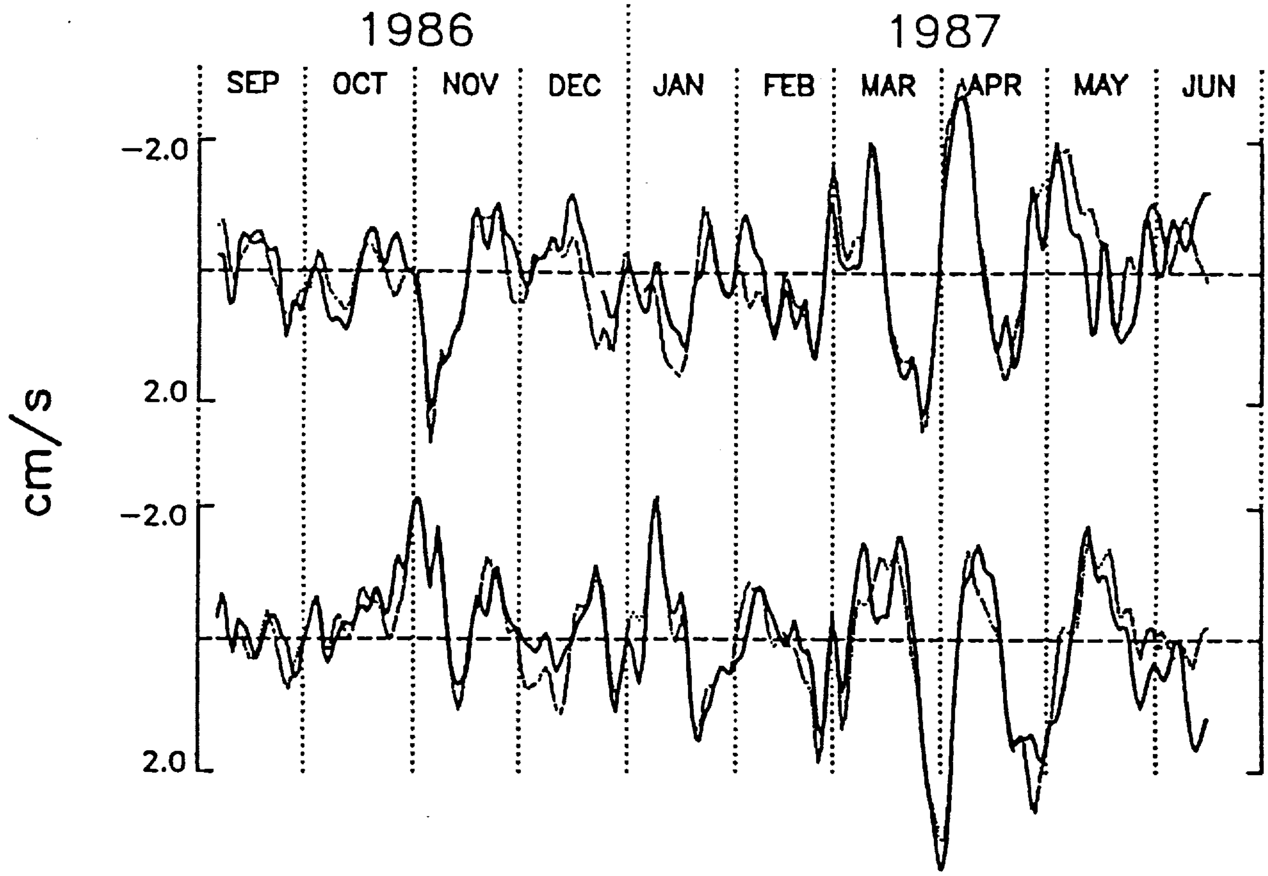

Figure 3. A time series of low-pass-filtered (3 dB at 2.7 d, 20 dB at 1.6 d), vertically integrated, conductivity-weighted velocity that was computed from the BEMPE mooring where the horizontal electric field is converted to velocity. The top traces show the zonal component, while the bottom traces are the meridional component. (Taken from Luther et al., 1990.)

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A TOPEX/POSEIDON Study of Oceanic Effects on Observations of the Earth's Interior

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I. Introduction

The primary objective of our research program is the application of TOPEX/POSEIDON oceanic data to the study of various geophysical observations, thereby improving our knowledge of the Earth's interior. Observations of the Earth's solid tides, rotation, time-dependent gravity, and crustal deformation provide potentially useful constraints on properties of the solid Earth and its liquid core, but all these parameters are also sensitive to oceanic effects. Depending on the type of observation, those effects are usually either removed by modeling (often using particularly simple assumptions about the dynamics of the ocean) or ignored entirely. Useful oceanic data are rarely available. In many cases, the uncertainty in the oceanic correction is the main source of error in the geophysical interpretation of the results. We describe, below, several of these geophysical observations, how their interpretation in terms of the Earth's interior is affected by the oceans, and how data from the TOPEX/POSEIDON mission can be used to improve this situation.

II. Earth Tides

The Sun and Moon cause tides in the solid Earth, just as they do in the ocean. The solid-Earth tides can be detected in observations of gravity (both from satellites and from the ground), of tilting and deformation of the Earth's surface and of changes in the Earth's rotation rate. The amplitude of the solid-Earth tide depends on certain interesting, but poorly known, geophysical parameters, including friction coefficients in the Earth's mantle and the shape of the interface between the Earth's fluid core and mantle. This suggests that tidal observations might be used to put bounds on these parameters.

However, this has not proven to be an easy task, and part of the reason is the ocean tide. Ocean tides cause the solid Earth to deform, mainly through the additional pressure on the seafloor caused by the extra weight of the tide. That deformation affects all solid-Earth tide observations, and it makes it more difficult to use those observations to learn about the solid Earth.

Good numerical ocean-tide models exist, but those models are not accurate enough for all applications, particularly for the long-period tides. We will use TOPEX/POSEIDON data to try to improve the models. We will concentrate, particularly, on extracting the spatial components of the tides that have the largest effects on specific, solid-Earth tide observations. Those components, along with other long-wavelength, orthogonal terms, will be fit to the altimeter data.

III. The Earth's Rotation

Both the Earth's rotation rate and the position of the rotation axis vary with time. The variabilities are caused by many processes, including atmospheric winds and variations in surface pressure, changes in ground-water storage and the global ice balance, fluid motions in the Earth's core, ongoing mantle deformation related to the melting ice from the last ice age (postglacial rebound), the gravitational attraction of the Sun and Moon, and (possibly) earthquakes.

The role of the ocean in all this is not yet well understood. There are some indications that fluctuations in the Antarctic circumpolar current might have observable effects on the rotation. Most studies suggest that fluctuations in other current systems are not important, but all of those results are based on models rather than oceanographic data.

The ocean can cause changes in the Earth's rotation not only through fluctuations in ocean currents, as described above, but also through changes in sea level (changes in sea level can lead to changes in the Earth's inertia tensor). One of the important sources of sea-level fluctuations is atmospheric pressure. Most Earth-rotation studies assume that the ocean responds to pressure as an inverted barometer: when pressure goes up by 1 mbar, the sea surface goes down by 1 cm, so there is no change in pressure at the seafloor.

We will use the TOPEX/POSEIDON data to study these oceanic effects. We will use the data in a global fit, to solve for the appropriate fluctuations both in currents and in sea level. We are interested in finding the oceanic effects on the Earth's rotation both because it is an interesting problem in its own right and because the oceanic effects can be removed sufficiently to allow study of other excitation processes. We will pay special attention to the inverted-barometer hypothesis, particularly at short periods where it is most likely to fail. This hypothesis is also used by virtually everyone who analyzes altimeter data: Once the effects of pressure-driven sea level are removed from the data, the effects of wind forcing are easier to observe. Thus, this problem has important oceanographic consequences, as well.

IV. Satellite Gravity and Crustal Deformation

Satellite ranging data have been used to infer secular and seasonal trends in the Earth's gravity field. These trends have been interpreted in terms of postglacial rebound and solid-Earth tides and have been used to explain the constraint in the long-term viscosity and short-term friction of the mantle. To improve these bounds, it is useful to look also at the possible gravitational effects of the ocean and of global ice melting and accumulation. Changes in ice volume should lead to corresponding changes in sea level, and so the contribution from ice can be addressed (albeit indirectly) by considering sea-level data. We will use the TOPEX/ POSEIDON data to look for evidence of the effects of the ocean and of changes in ice balance on gravity.

One of the important on-going efforts in geophysics is the use of space geodetic techniques to detect tectonic motions: both the rigid motion of the plates and the aseismic and coseismic deformation within the plates. A useful interpretation of the observations in terms of these tectonic processes requires that all significant nontectonic deformation first be removed from the data. Changes in sea level can cause deformation of the crust, with possible amplitudes in excess of 1 cm in certain cases. A study of sea level changes using TOPEX/POSEIDON data will give some insight into how frequently such large deformations occur and how well their effects can be removed from the crustal deformation data.

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Precise Orbit Computation and Sea Surface Modeling

ORIGINAL CONTAINS
COLOR ILLUSTRATIONS

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I. Research Goals

The research project described below is part of a long-term program at Delft University of Technology aiming at the application of European Remote Sensing satellite (ERS-1) and TOPEX/POSEIDON altimeter measurements for geophysical purposes. This program started in 1980 with the processing of Seasat laser range and altimeter height measurements and concentrates today on the analysis of Geosat altimeter data. The objectives of the TOPEX/POSEIDON research project are the tracking of the satellite by the Dutch mobile laser tracking system MTLRS-2, the computation of precise TOPEX/POSEIDON orbits, the analysis of the spatial and temporal distribution of the orbit errors, the improvement of ERS-1 orbits through the information obtained from the altimeter crossover difference residuals for crossing ERS-1 and TOPEX/POSEIDON tracks, the combination of ERS-1 and TOPEX/POSEIDON altimeter data into a single high-precision data set, and the application of this data set to model the sea surface. The latter application will focus on the determination of detailed regional mean sea surfaces, sea surface variability, ocean topography, and ocean currents in the North Atlantic, the North Sea, the seas around Indonesia, the West Pacific, and the oceans around South Africa.

II. Application of Altimeter Data

In a simplified form, the altimetry concept is depicted in Figure 1. In this figure, H is the height of the satellite above a reference surface, conventionally an ellipsoid of revolution. This height is deducible from a precise orbit computation of the satellite. After correction for several effects (Marsh, 1983; Chelton, 1988), the corrected altimeter measurement, h, is referenced to the local geometric instantaneous sea level. The difference between the instantaneous sea level and the reference ellipsoid can be expressed by a parameter η, which accounts for the geoid undulations, atmospheric loading correction, tides, and dynamic ocean topography.

From a global set of these corrected height measurements, a model of the global mean sea surface may be derived. This surface approximates to within 1 m the marine geoid, which is a representation of the Earth's gravity field. These data are therefore very valuable in mapping the marine gravity field and sea bottom features. Examples of the results that may be obtained are shown in Figures 2 and 3. Figure 2 shows a mean sea surface model for a region of the South Atlantic derived from all-Seasat altimeter data, while Figure 3 shows a mean sea surface model for the oceans around South Africa derived from one year of Geosat altimeter measurements (Wakker et al., 1990a).

For oceanographic investigations, one is particularly interested in the differences between the mean sea surface and the true geoid. This dynamic sea surface topography is primarily the net result of all kinds of currents in the oceans. Superimposed on the time-averaged flows are a variety of time-dependent current systems. A major goal of satellite altimetry missions is to measure the surface signature of these phenomena with sufficient accuracy, precision, and resolution in time and space. Figure 4 shows both the mean sea surface and the sea surface variability for the South Atlantic and the South Indian Ocean, determined from one year of Geosat altimeter data. From this data set, the trajectories of a number of eddies in the South Atlantic also have been determined. As an example, Figure 5 shows the trajectories of six large anticyclonic eddies (Wakker et al., 1990b).

The application of altimeter measurements for modeling the global mean sea surface requires accurately determined satellite orbits, while the application of the altimeter data for modeling the dynamic ocean topography requires, in addition, the availability of detailed geoids or the separation of the geoid from the ocean topography during the altimeter data processing. To eliminate residual radial orbit errors, most altimeter data processing schemes require a model for the variation of the radial orbit error along the satellite tracks. It is well known that the major orbit errors have frequencies of less than 3 cycles per revolution, so that these may be modeled by long-wavelength analytic functions.

Apart from the application of the altimeter measurements to oceanographic investigations, these measurements can also be used as tracking data (Wakker et al., 1987). Referring to Figure 1, it may be stated that in this case $h + \eta$ is used as a data type to control H, i.e., the vertical position of the satellite. Depending on the strategy adopted, both the actual altimeter measurements and the altimeter crossover differences can be used as tracking information. For this application, of course, information on η is needed and this has to be derived from existing models. This application of the altimeter measurements is particularly attractive in the ERS-1 mission. This satellite will fly in about the same period as TOPEX/POSEIDON, but its tracking network will probably be less dense than that of TOPEX/POSEIDON.

When the orbit has been computed, the altimeter height residuals and the altimeter crossover difference residuals are a good measure of the radial orbit errors. The crossover difference residuals provide information about the uncorrelated part of the local radial orbit errors at a crossover point (Wakker et al., 1987, 1991). The low-frequency part of the altimeter height residual profiles is primarily a representation of the orbit errors. This orbit error information can be used to correct the computed orbit in a nondynamic way.

When using the ERS-1 altimeter measurements, the satellite's radial position component will probably not be known with an accuracy of better than 0.5 m. Because the orbit accuracy of TOPEX/POSEIDON will be significantly higher, the altimeter crossover difference residuals from combinations of TOPEX/POSEIDON and ERS-1 tracks can be applied to determine the local radial errors of the ERS-1 orbit up to an accuracy of about 0.2 m. Consequently, the TOPEX/POSEIDON mission provides the opportunity to study in detail the spatial and temporal distribution of the ERS-1 orbit errors and to generate in retrospect more accurate ERS-1 orbits. This technique also allows the improvement of ERS-1 orbits at latitudes higher than the maximum latitude of 63 deg reached by TOPEX/POSEIDON. This means that the ERS-1 altimeter may add important information over regions that cannot be measured by TOPEX/POSEIDON. Between 60°N and 60°S, the combination of the altimeter measurements of both satellites will provide a much denser surface coverage for determining the mean sea surface and mapping the mesoscale currents.

III. Research Plan

Major topics of the research project are the tracking of TOPEX/POSEIDON by the Dutch laser system MTLRS-2 and the computation of precise orbits from laser, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), GPS, and altimeter measurements. It is believed that a proper combination of the different types of tracking data will contribute to the strength, accuracy, and reliability of the orbit determination process. The selection of optimal arc lengths and the appropriate relative weighting of the different types of tracking data will be addressed. Various techniques will be applied to assess the accuracy of the computed orbits. These techniques include the analysis of orbit differences for overlapping arcs, the analysis of patterns of tracking measurement residuals per pass over a tracking system, and the application of altimeter measurement residuals and crossover difference residuals to monitor the satellite's radial position errors. Special attention will be paid to the separation of orbit errors from the geoid and tide model errors, as well as to the determination of the temporal and spatial distribution of the orbit errors. All orbit error information will be used to improve the orbits in a dynamic or nondynamic mode. ERS-1 orbits computed from laser and Precise Range And Range-rate Equipmenmt (PRARE) tracking data will be improved using the information provided by the crossover difference residuals for crossing ERS-1 and TOPEX/POSEIDON arcs.

The TOPEX/POSEIDON and ERS-1 altimetry data sets will be merged and a data set of all crossover points and crossover differences will be constructed. In this way, dense data sets covering latitudes of up to 80 deg north and south will be obtained. It is believed that the proper combination of ERS-1 and TOPEX/POSEIDON altimeter measurements obtained from different repeat orbits will yield mean sea surface maps of both high precision and high resolution and will provide detailed information about mesoscale ocean currents. In computing mean sea surfaces and analyzing sea surface variability and ocean currents, special attention will be paid to the proper elimination of residual orbit errors. In addition, special processing techniques will be applied to model the semipermanent ocean currents.

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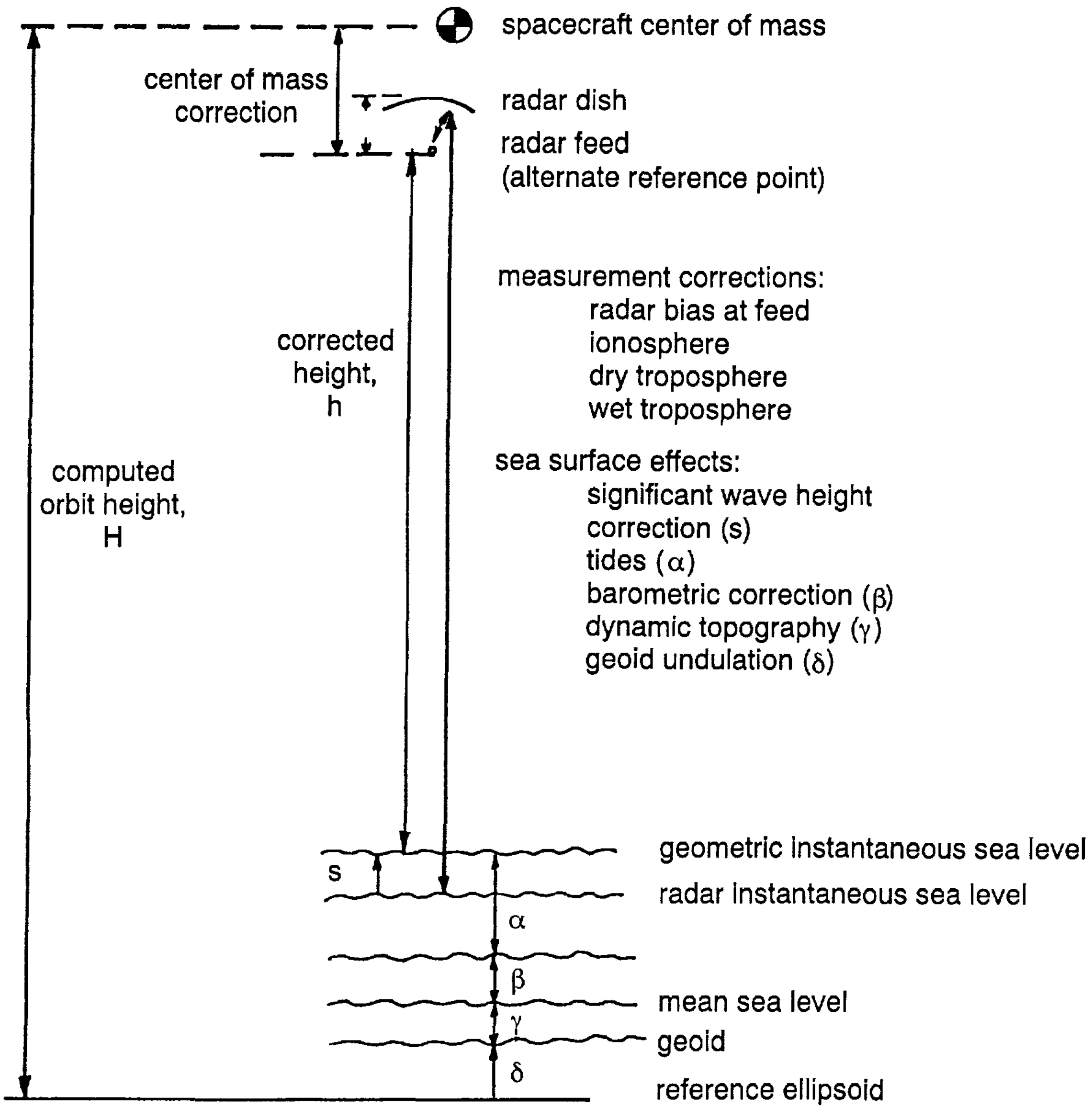

Figure 1. General altimeter measurement concept.

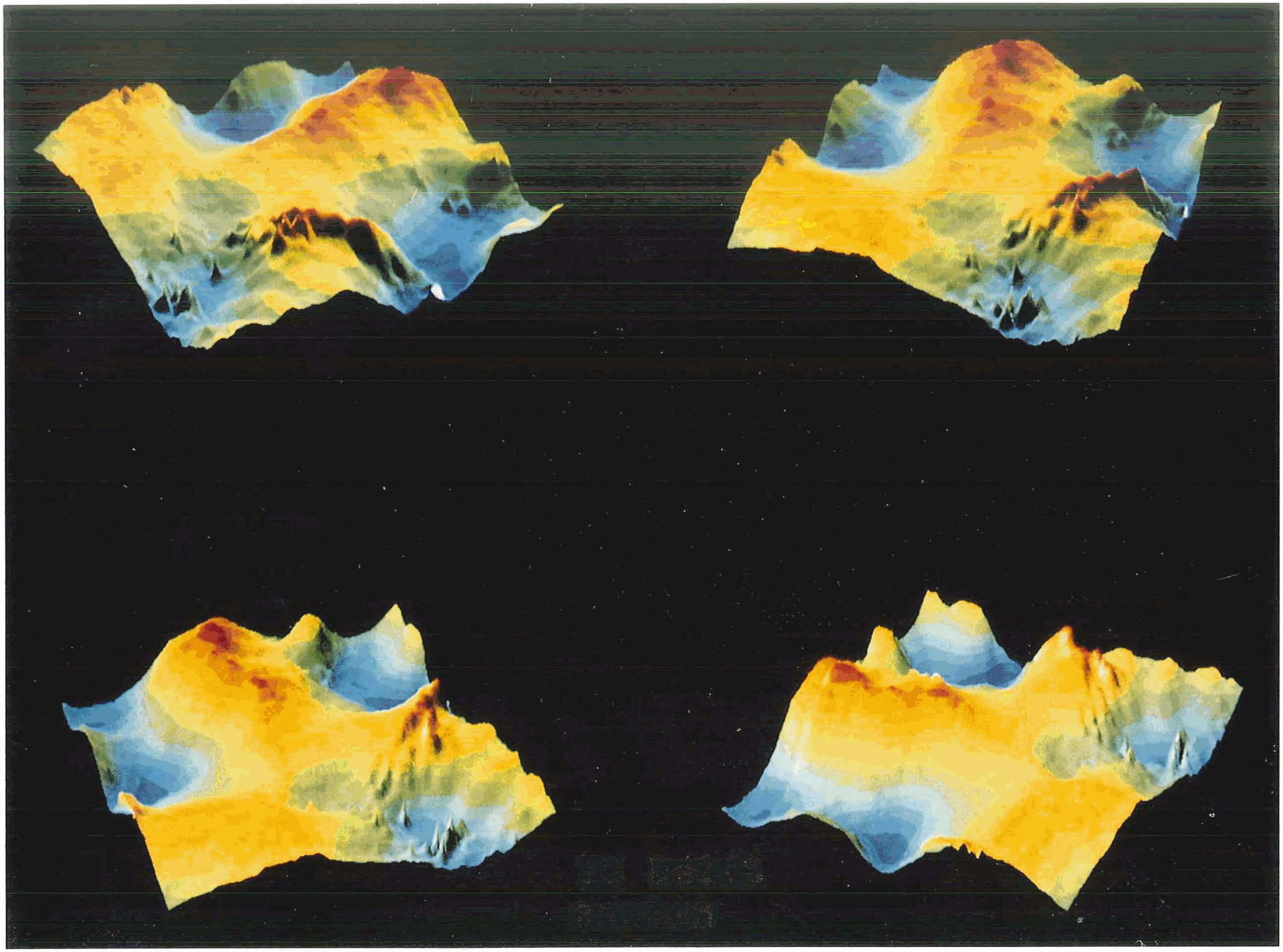

Figure 2. Three-dimensional representations of a Seasat mean sea surface model for a region of the South Atlantic. The area is viewed from four different directions and the picture clearly shows the sea surface signals produced by the Mid-Atlantic Ridge and the Walvis Ridge.

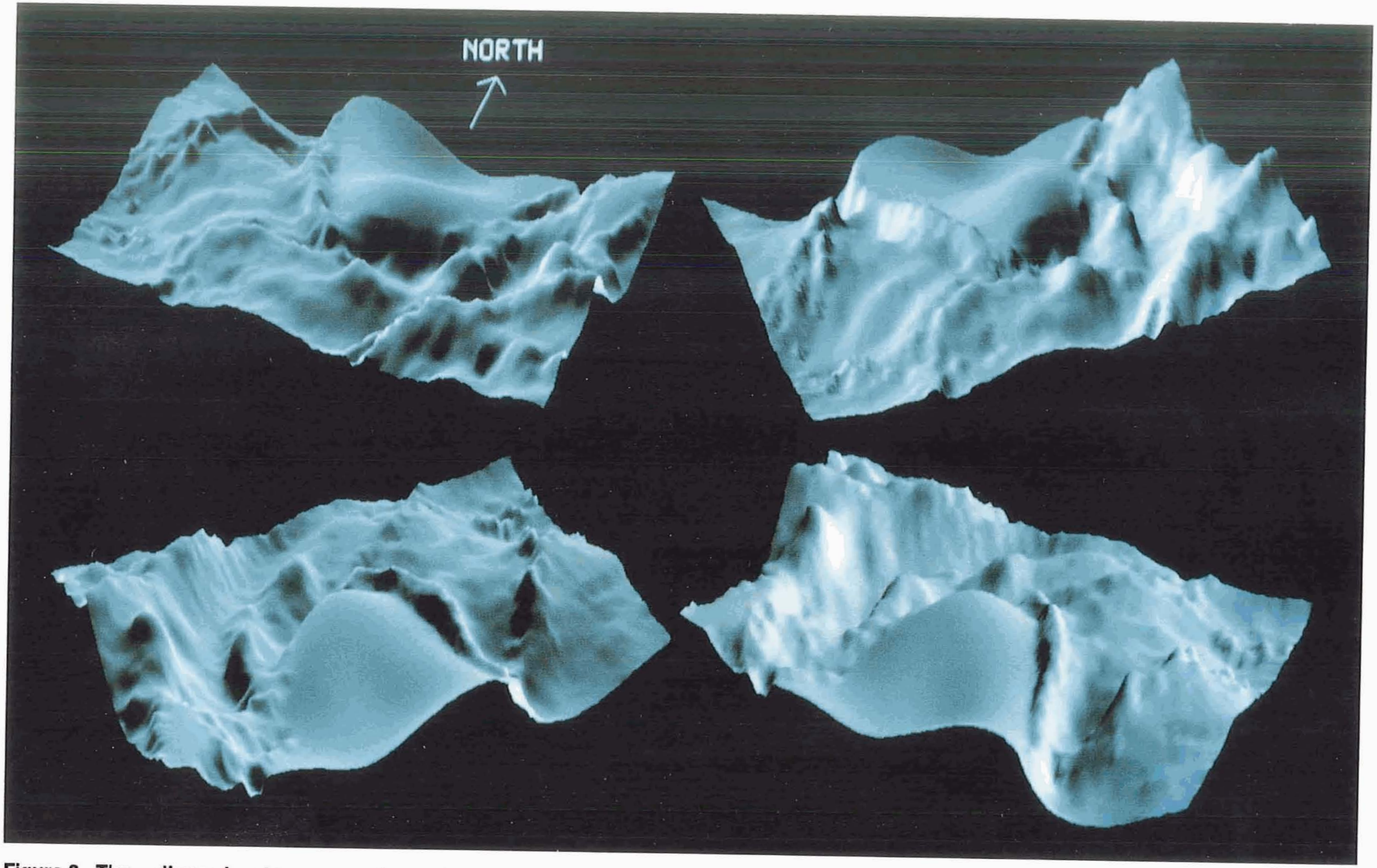

Figure 3. Three-dimensional representations of a Geosat annual mean sea surface model for the oceans around South Africa. The area is viewed from four different directions and the pictures show in detail many ridges and small-scale ocean bottom features.

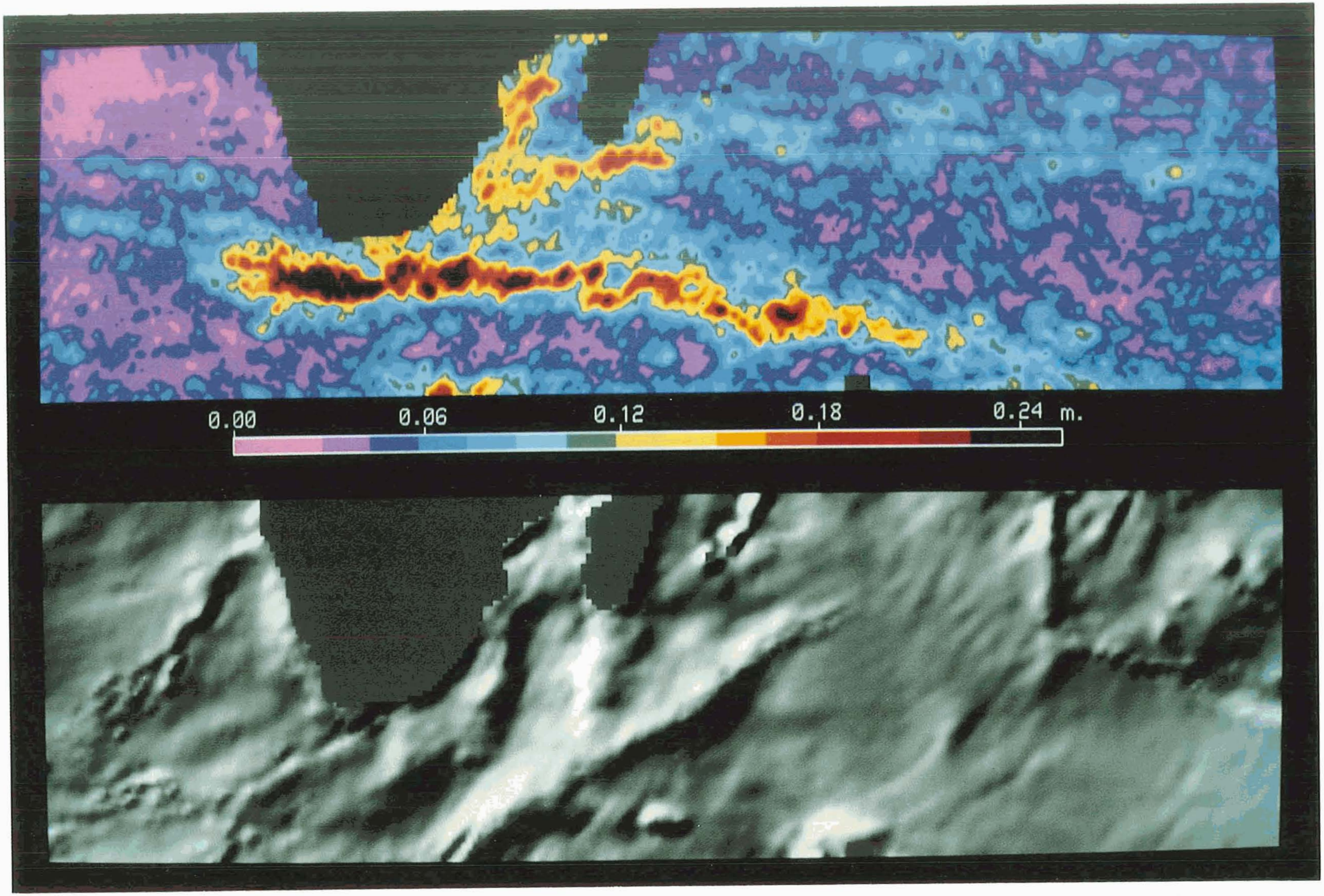

Figure 4. The mean sea surface and the mesoscale sea surface variability computed from an entire year of Geosat altimeter data. Main areas of variability coincide with the Agulhas Current, the Madagascar Current, and in particular with the Agulhas Return Current. Very low variabilities are observed in the South Atlantic north of the Walvis Ridge.

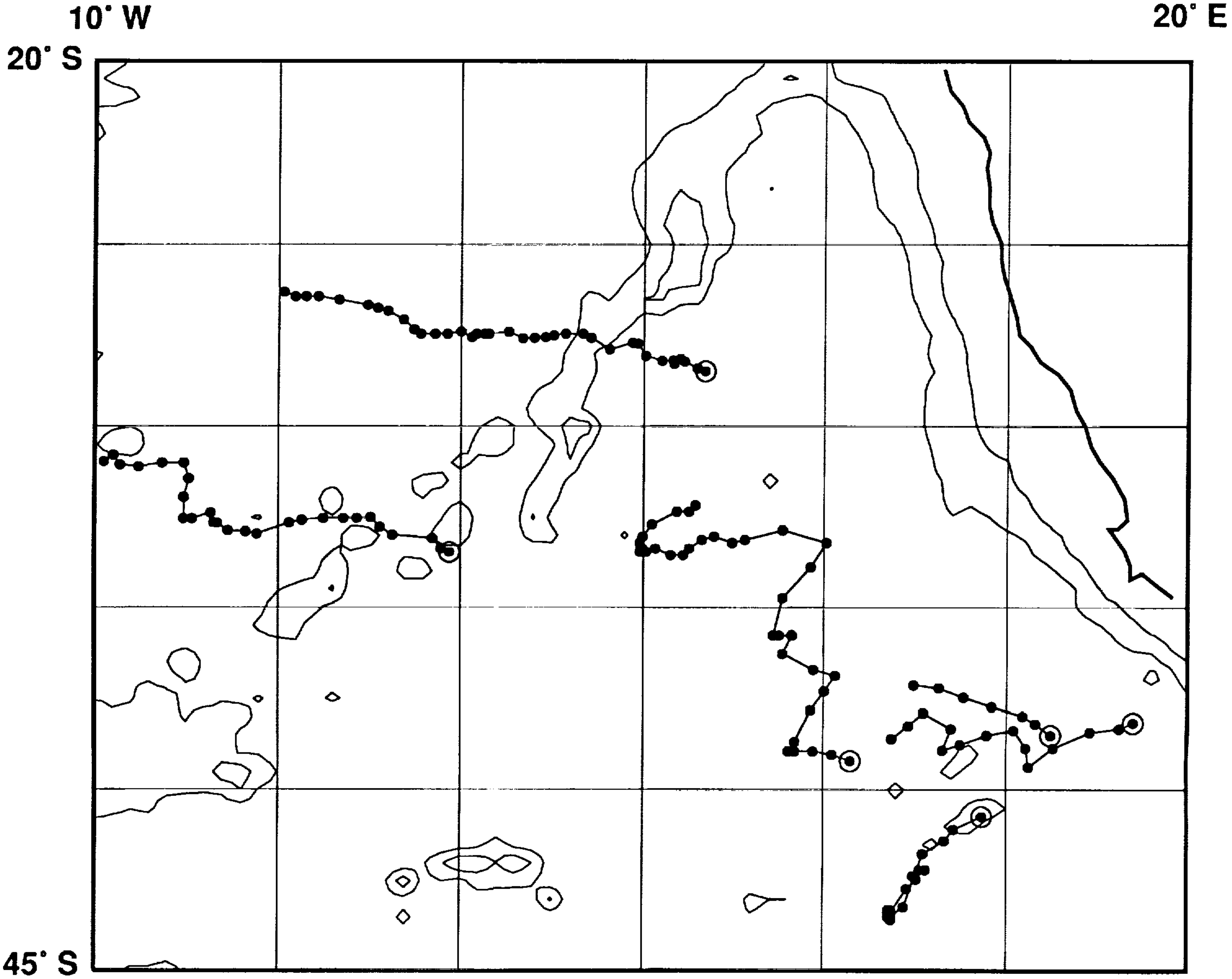

Figure 5. The trajectories of six large anticyclonic eddies detected in the Cape Basin, together with the 2-km and 3.5-km isodepth contours. The larger dot indicates the starting point of each trajectory; the smaller dots indicate the position of the eddy at 10-day intervals.

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Marine Research Using Data From TOPEX/POSEIDON

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I. Introduction

The Proudman Oceanographic Laboratory (POL), the Institute of Oceanographic Sciences Deacon Laboratory (IOSDL), and the British National Space Centre (BNSC) plan to use radar altimeter data from the TOPEX/POSEIDON mission in five main areas of research. These are

(1) Investigation of variations in Southern Ocean sea levels and circulation.

(2) Related numerical modeling and data assimilation.

(3) Global and regional ocean tides.

(4) North Sea and northeast Atlantic studies.

(5) Winds and waves.

Each one of these topics is described briefly below while more information can be extracted from the United Kingdom response to the TOPEX/POSEIDON Announcement of Opportunity (Allan, 1986).

II. Investigation of Variations in Southern Ocean Sea Levels and Circulation

The aims and likely results of this part of the Mission Science Plan are inseparable from those of the World Ocean Circulation Experiment (WOCE). It is to be hoped that as a result of these activities, adequate ocean models will eventually provide a proper description of current climate and potential climate change. The geographical area of interest is the Southern Ocean, which is recognized as being of special importance to ocean circulation and which is to be studied in detail in WOCE Core Project 2.

Our intention is to investigate the spatial and temporal variations of sea surface topography in the South Atlantic and southern Indian Oceans with particular regard to the study of the variability of the Antarctic Circumpolar Current (ACC). Distributions of altimeter sea surface height anomalies will be analyzed in combination with tide gauge measurements. In addition, anomalies of geostrophic surface currents obtained from altimetry will be compared to those determined from sea level differences between tide gauge pairs, including those across the three interocean basin choke points of the ACC. Oceanographic interpretation will be made in combination with other measurements from Core Project 2 and with model studies, in particular those of the United Kingdom (U.K.) Fine Resolution Antarctic Model (FRAM) (see Section III below).

Over the past few years, POL and the British Antarctic Survey (BAS) have installed tide gauges throughout the South Atlantic at Ascension, Tristan da Cunha, St. Helena, Signy (South Orkney), Port Stanley (Falklands), and Faraday (Antarctic Peninsula) and will install others in the near future at South Georgia and, possibly, the Drake Passage (Figure 1). Pelagic sea level recorders have been operated at Kerguelen and Amsterdam Island in the Indian Ocean and at several South Atlantic locations; more deployments are in progress and planned. Several islands with gauges are already, or will be, linked into the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) geodetic network with equipment supplied by Institut Géographique National (IGN) (Paris). Measurements by inverted echo sounders and current-meter moorings will further complement the Southern Ocean sea level network and will provide an important parallel data set of measurements for comparison to the altimeter data.

III. Related Numerical Modeling and Data Assimilation

This section of the Plan has two main objectives:

(1) To use a combination of the FRAM model and altimeter data sets to study the physics of the Antarctic Circumpolar Current.

(2) To develop schemes for the assimilation of TOPEX/ POSEIDON altimetry into ocean models including the FRAM model.

Two large modeling and data assimilation studies that will make use of TOPEX/POSEIDON data have commenced. The first of these, the FRAM model, is being developed as a joint U.K. oceanographic community project and will enable studies of the dynamics of the Southern Ocean and its response to atmospheric forcing. Its grid size is such that it will resolve mesoscale eddies and represent the interaction of the flow with bottom topography. One test of such a model is its ability to produce correct mesoscale eddy statistics. We intend to compare the model results with those derived from TOPEX/ POSEIDON, particularly in regard to the position of the ACC and the energetics of the mesoscale eddies. Such analyses should enable systematic errors in the model to be identified and hopefully to be eliminated by improvements to the model.

The second of these studies will further develop methods for assimilating satellite data into numerical models of the ocean (Webb and Moore, 1986) and to use these methods and models to assimilate TOPEX/POSEIDON, European Remote Sensing satellite (ERS-1), and other altimetry together with scatterometry and other remotely sensed data. The FRAM model, for example, running on the assimilated data, could then be used to further study the detailed physics of the region. This work is being carried out by colleagues at the above named laboratories, at the Hooke Institute (Oxford) and at several other U.K. laboratories.

IV. Global and Regional Ocean Tides

This part of the Plan is a proposal to use TOPEX/ POSEIDON and ERS-1 data to produce regional and possibly global distributions of the major lunar and solar tidal constituents. Geographical regions will include the northeast Atlantic, with the northwest European continental shelf, and the Southern Ocean. There is a long history of U.K. interest in altimetry tidal research; it commenced with the analysis of Seasat data (Cartwright and Alcock, 1983; Woodworth and Cartwright, 1986), continues with Geosat measurements (Woodworth and Thomas, 1990), and will be further developed with future altimetry. ERS-1, being almost perfectly sun synchronous, provides an ideal lunar tidal analyzer while TOPEX/ POSEIDON will provide a rich spectrum of both lunar and solar tides; distributions of the major constituents should be extractable if the data from all satellites are analyzed in combination. The algorithms expected to be employed for this work will be adaptations of methods developed for Seasat and Geosat analysis. Comparison will be made to existing tidal models and disagreements resolved. In areas such as the northwest European continental shelf, it may also be possible to assimilate the altimeter tidal measurements into existing numerical models of the area. The objective will be the production of new models of an accuracy sufficient for other U.K. oceanographic research purposes during WOCE and beyond.

V. North Sea and Northeast Atlantic Studies

The North Sea was successfully used as a validation area for Seasat in a study in which several European laboratories collaborated (Alcock and Cartwright, 1982). The in situ techniques required for such a validation (for example, tide gauges and tide surge models) have since been maintained and developed and will once again be employed in this role in the validation of Geosat, ERS-1, and TOPEX/POSEIDON data.

Investigations will also be made of deep ocean areas bordering the northwest European continental shelf. These studies will include the transfer of sea surface gradients across the continental shelf and slope as a function of long-shore scale and frequency (Huthnance, 1987). Previous measurements suggest that a direct transfer from ocean to shelf occurs for some scales and frequencies, that extra variability on the shelf can prevent the reverse inference of oceanic levels from coastal values, and that determination of scale-dependent behavior requires the spatial coverage of satellite altimetry. The northeast Atlantic studies will also include an investigation of the complex water masses of the U.K.–Iceland–Greenland gap, which will form part of U.K. WOCE activities.

VI. Winds and Waves

The objectives of this part of the Plan are

(1) To provide a sounder basis for wind speed retrieval from altimeter data by relating radar backscatter measurements to the sea surface geometry. This is especially relevant to assimilation of altimeter data

in wave models where coincident observations of wind speed and wave parameters are required. It will also benefit the computation of the wet tropospheric range correction by enabling surface emissivity to be obtained for the microwave radiometer.

(2) To assess the effect of atmospheric liquid water on altimeter returns and, if possible, to provide an effective means of flagging and correcting data.

(3) To develop and test a method of determining nonlinear wave parameters and the sea state bias correction from TOPEX/ POSEIDON data.

Wind speed retrieval from altimeter data has been hampered by the empirical nature of the relationship between backscatter (sigma-0) and wind at nadir and by the sensitivity of the radar return to atmospheric water, especially rain. Our approach to the former is to measure the surface geometry down to centimetric scales using stereophotogrammetry and to relate these observations to surface meteorological conditions, principally the wind speed as determined from IOSDL surface meteorological packages. Development of the camera system is under way and initial deployment will be on a reservoir. During the TOPEX/POSEIDON mission, coincident in situ and satellite sigma-0 measurements will be obtained at open-ocean sites. Plans for camera deployment at sea are still being developed.

In the retrieval of wind speed from altimeter data, it is usual to assume that the measured sigma-0 is a function of surface wind speed alone. However, atmospheric liquid water, particularly in the form of rain, can produce sigma-0 changes that result in large errors in wind speed. By using data from microwave radiometers (including the radiometer on board TOPEX/POSEIDON), ships, and atmospheric models, occasions of high rain probability will be identified and the waveforms and sigma-0 values of the altimeters will be examined to quantify the effects. Particular attention will be paid to the effect of radar frequency.

The primary role of the altimeters is to make sea level measurements. In nonlinear wave conditions, the altimeter no longer tracks mean sea level, but is offset by the sea state bias. Hitherto it has been necessary to apply an empirical correction for this effect. In addition to pursuing a modified form of such techniques (Guymer and Srokosz, 1986), we intend to estimate the bias by using Maximum Likelihood Estimation to fit a model for an altimeter return from a nonlinear sea surface. Two nonlinear parameters, sea surface skewness and a so-called "cross skewness," need to be included. These nonlinear parameters will also be estimated from coincident stereophotography and the two sets of estimates compared. It may also prove possible to extract sea state bias directly from the photographs. Again, differences due to radar frequency will be assessed.

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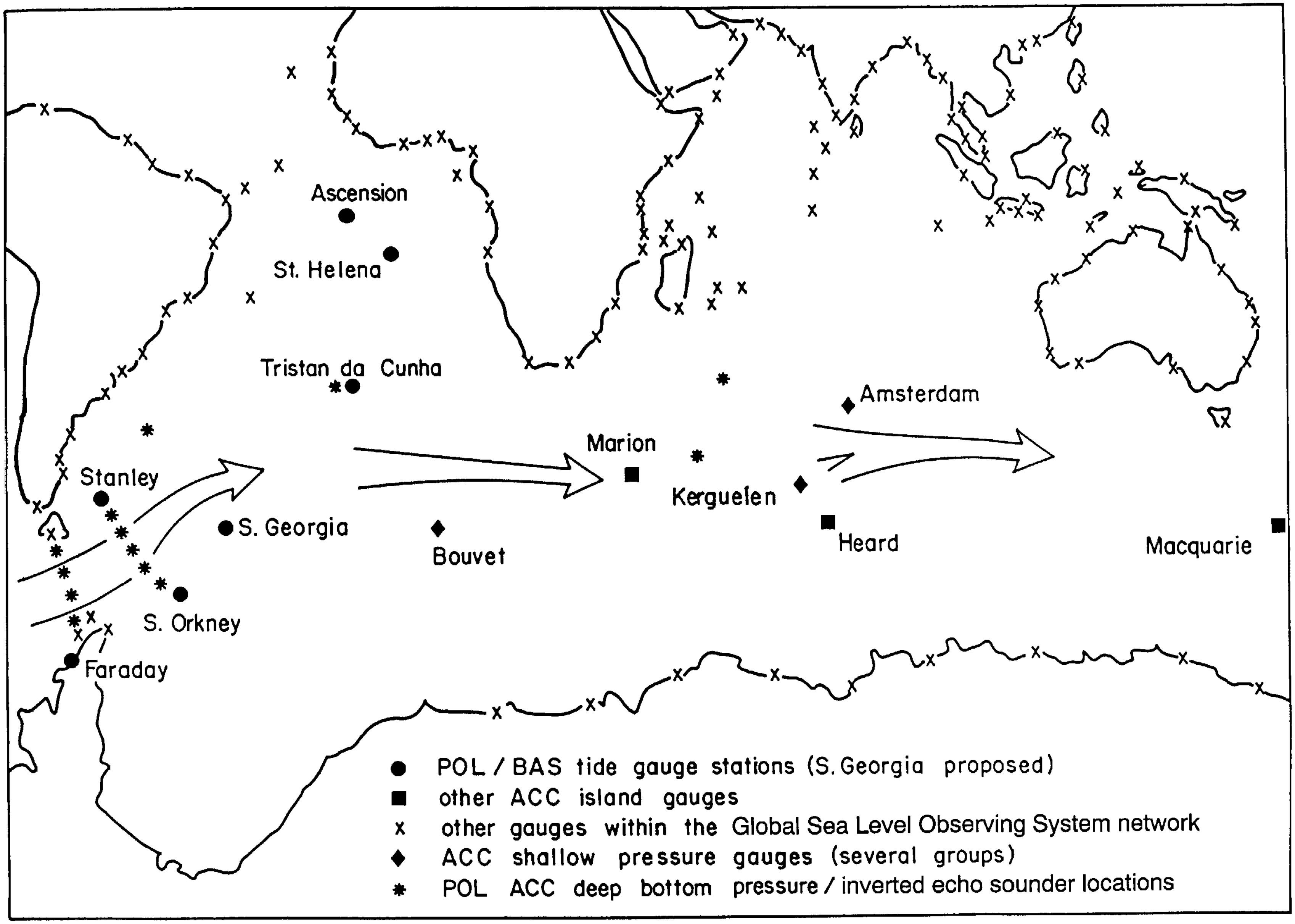

Figure 1. Location of tide gauges.

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Global Ocean Circulation By Altimetry

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I. Objectives

The overall objectives of this project are to determine the general circulation of the oceans and many of its climate and biochemical consequences through the optimum use of altimetry data from TOPEX/POSEIDON and related missions. Emphasis is on the global-scale circulation, as opposed to the regional scale, but some more local studies will be carried out. Because of funding limitations, the primary initial focus will be on the time-dependent global-scale circulation rather than the mean; eventually, the mean circulation must be dealt with as well.

II. Methodology

We intend to combine altimetry with in situ data and large-scale dynamical models to determine what the nature of the circulation and its variability is and to understand its physics. Figure 1 is an example of what is intended: It shows an estimate of the deviation of the sea surface from its long-term mean (2 years) of the Geosat data set; this mean is determined by combining the altimetry in an optimal-estimation procedure with the tide gauge network in the World Ocean. These estimates are being improved in several ways:

(1) The interval of 3 months will be reduced, using TOPEX/POSEIDON, to a more oceanographically sensible 10 days (of that order).

(2) Corrections will be made for such parameters as barometric effects (dynamical effects, not simply static ones), wave height, and electromechanical bias, most of which are not reliable in the Geosat data.

(3) A dynamical model to both test the data and dynamically interpolate them will be introduced (for an implementation of such a methodology on a regional scale, see Gaspar and Wunsch, 1989).

(4) Improved estimates of the field error covariances will be made from the data themselves rather than assumed a priori.

(5) Direct in situ observations derived from the World Ocean Circulation Experiment (WOCE) will be used to help constrain the model in terms of velocity and density.

Model making is proceeding in parallel with the data reduction. Dale Haidvogel of Johns Hopkins University is developing a primitive equation model that will be used (eventually) to produce our best estimate of the dynamics involved in sea surface physics (see Haidvogel, et al., 1991). In the shorter term, we are using a simplified regional dynamic version.

The approach to the absolute (as opposed to time-varying) circulation is through construction of tightly constrained, a priori general-circulation models based upon hydrography, chemistry, in situ velocity measurements, and "inverse" methods (e.g., Rintoul and Wunsch, 1990). These are then combined with the best extant geoids at any given time with the resulting changes in the a priori circulation model forced to remain consistent with known physics. Under the WOCE program, we are developing both a regional North Atlantic 1-deg and a global 1-deg inverse model. WOCE should also gather data to greatly improve these models by the time the TOPEX/POSEIDON data are fully available.

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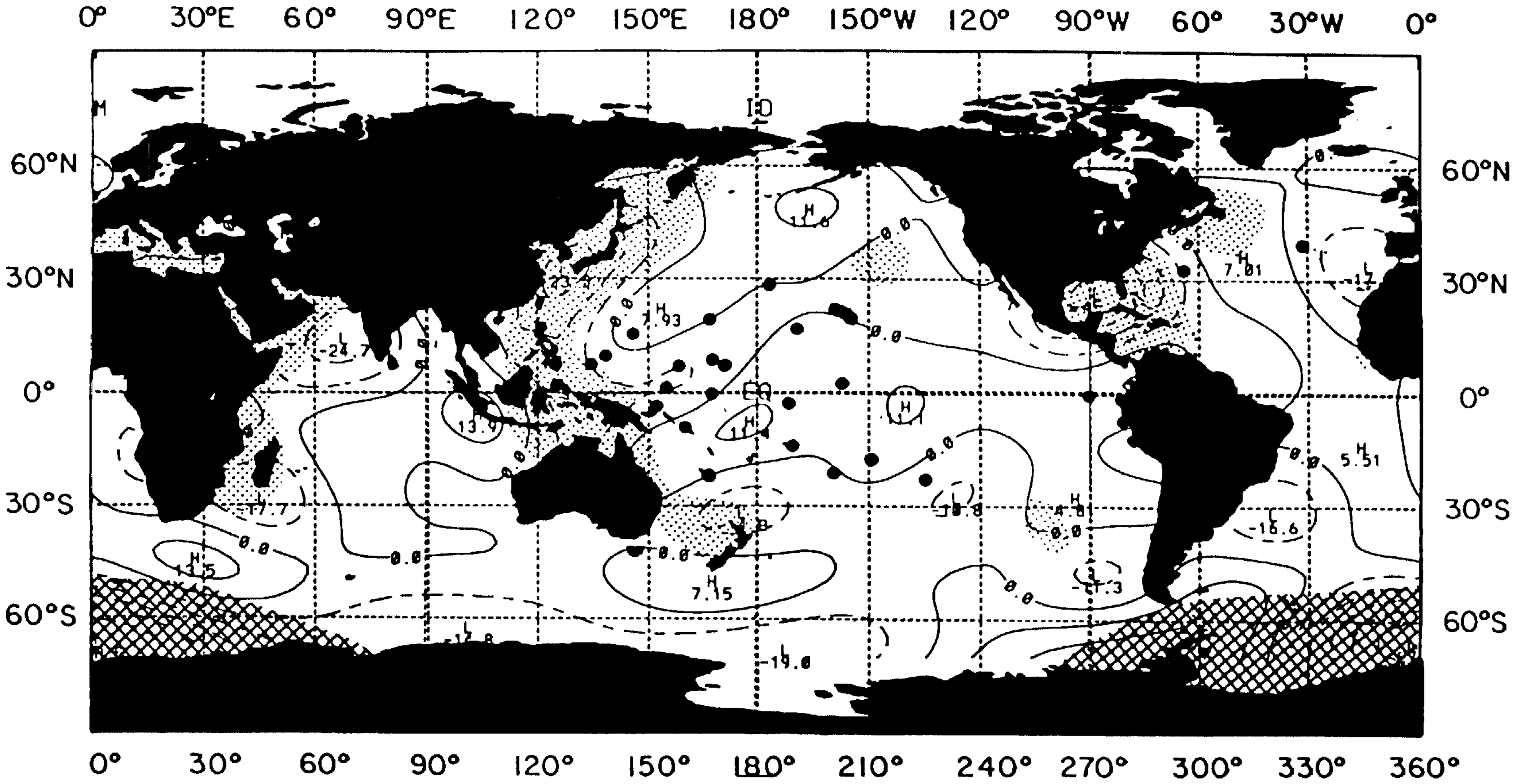

Figure 1. Contours of estimated sea surface variation relative to a long-term average as determined from a combination of Geosat altimetry and in situ tide gauges. The contour interval is 10 cm. Stippled areas show regions of high estimated error. This preliminary figure is intended to display only the type of result anticipated from TOPEX/POSEIDON, which will provide much higher quality results.

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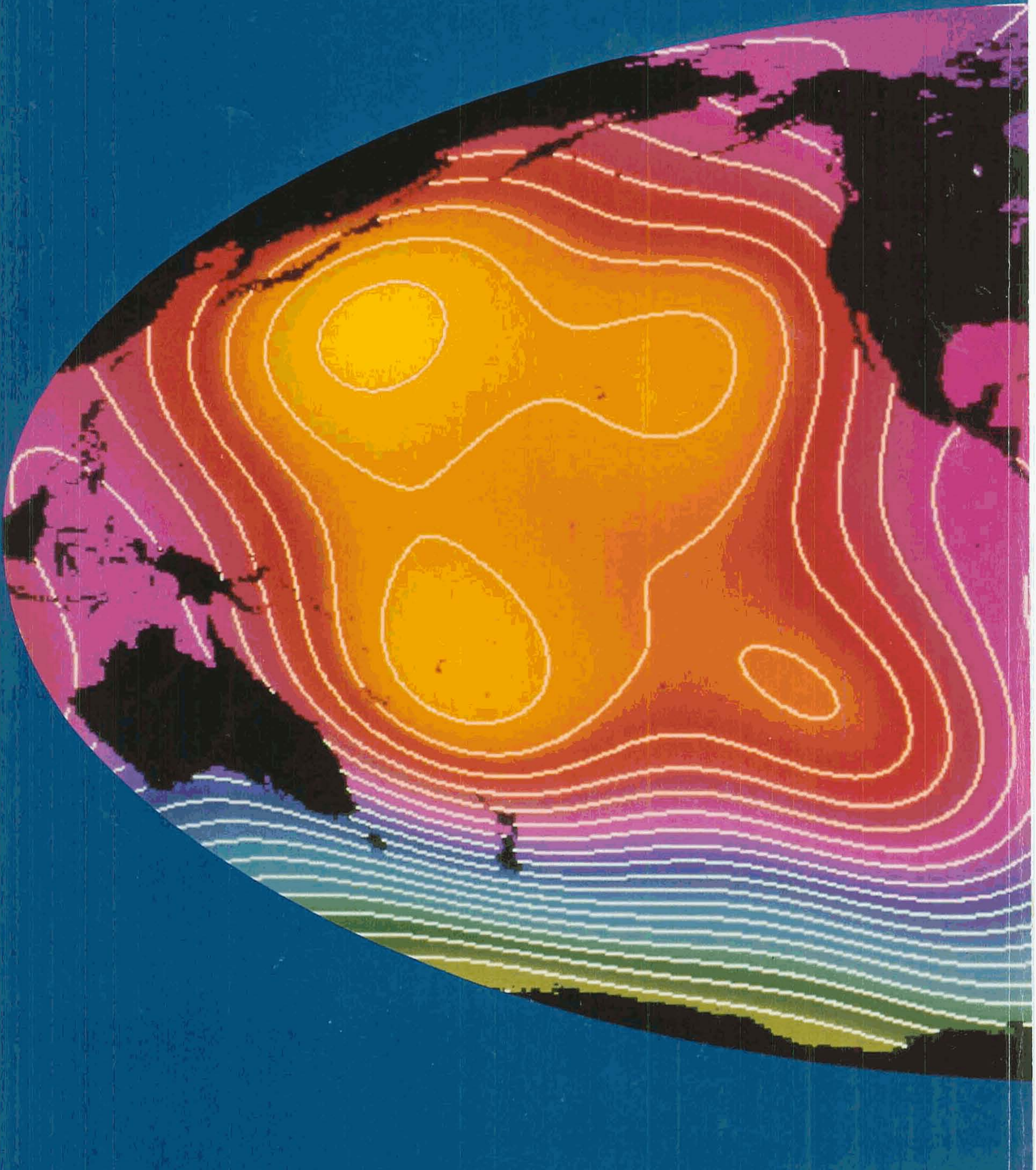

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