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# The Oceans and Climate: A Guide to Present Needs

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# PREFACE

The threat of global climate change due to increasing concentrations of greenhouse gases has focussed governmental attention on the global environment and the impact of human actions on this environment. The ocean plays a fundamental role in the climate system which must be understood in order to predict as accurately as possible how the climate will change. At the Sixteenth Session of the IOC Assembly in March 1991, the Delegate of Malta, suggested that IOC be given the task of elucidating the role of the ocean in climate change and assisting governments in promoting necessary elements through the work of the Intergovernmental Negotiating Committee on a Framework Convention on Climate Change (INC). Malta expressed a willingness to host a meeting of scientific and technical experts to review the role of oceans in relation to climate change and variability. Subsequent to ad hoc consultations with IOC and WMO representatives, invitations to a meeting of Scientific and Technical Experts were extended by the Government of Malta to all Heads of Delegations at the Second Session of Intergovernmental Negotiating Committee for a Framework Convention on Climate Change, Geneva, 19-28 June 1991.

An International Meeting of Scientific and Technical Experts on Climate Change and Oceans, Valetta, 19-21 July was hosted by Malta with the participation of an international group of ocean climate experts and representatives from the IOC, WMO, and UNEP.

This publication consists of (I) a report produced at the meeting which summarizes what is known, what is not known, what is currently being done and what needs to be done in order to improve our current understanding of the role of the oceans in the climate system and to reduce the uncertainties in predicting climate and (II) a scientific background document (The Ocean and Climate Change), prepared by the IOC Secretariat with inputs from WMO and UN (OALOS) which assesses the current state of understanding of the ocean's role in climate change as well as our present capability to detect, monitor and predict changes.

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## INTRODUCTION

The problems of climate change are closely interrelated and need to be considered as a whole, if the current efforts by the INC are to succeed effectively. This approach should be reflected in the proposed Framework Convention on Climate Change. The oceans play a key role in determining the earth's climate. Any possibility of predicting the evolution of climate beyond a few weeks demands that ocean behaviour be taken into account. There is great promise that it may become possible to describe and predict many aspects of upper ocean behaviour with enough accuracy to improve long range weather, sea-surface layer conditions, storm surges and fisheries forecasts usefully. This promise can only be realized if appropriate data are collected regularly and disseminated promptly, and relevant studies are undertaken to ensure early realization of the applications which are of benefit to nations.

There is every reason to believe that the ocean is now changing in response to climate changes over the past few hundred years (the Little Ice Age). It can be expected to change further as anthropogenic influences become increasingly marked.

To determine how the ocean is changing now we must have systematic and repeated measurements at all depths throughout the ocean. To predict its future evolution will require models supported by a regular influx of new data.

New structures both internationally and in many countries nationally will have to be established to meet the needs. Climate change will have an impact on oceanic processes which have implications e.g. for fisheries, coastal zone developments, human settlements and fresh water resources.

There is a requirement therefore to meet the following:

(i) the need to follow-up the acknowledgement by the Second World Climate Conference (SWCC) of the role of the oceans in the climate system by commitment to implementation of on-going global-regional research programmes (e.g., the Tropical Ocean and Global Atmosphere [TOGA] programme, the World Ocean Circulation Experiment [WOCE], and the Joint Global Ocean Flux Study [JGOFS]) and related research to reduce uncertainties in predictions; the related data and process studies are definitely needed for improving the models. Specific scientific activities relating to the oceans which should be enhanced due to the implications for many nations and regions of the related phenomena include:
   - El Niño and its influence on world-wide weather anomalies,
   - Relationship of sea surface temperatures in the Atlantic and rainfall in the Sahel, and
   - Changes in air-sea interaction and sea surface temperatures which could affect frequency, intensity and distribution of tropical and extratropical cyclones in the event of global warming.

(ii) the need to ensure timely exchange of data and related products on the international level, of material obtained both through research and routine observation programmes;

(iii) the need for a gradual establishment of an adequate Global Ocean Observing System that includes the mechanism for data acquisition and products exchange as part of a Global Climate Observing System;

(iv) the need for transfer of appropriate technology to help ensure building of capacity, including infrastructure, financial and human resources, to help ensure adequate involvement and participation in global-regional programmes and observing system(s), and ability to independently interpret and use related data and products, including those obtained from exchange;

(v) the need to ensure adequate consideration of ocean processes and resources in socio-economic national planning and development.

The major subject areas of the ocean and climate change are (1) Role of the Oceans as a Source and a Sink for Greenhouse Gases, (2) Sea-Level Rise and Climate Change, (3) Impacts of Climate Change on Marine Living and Non-Living Resources and (4) Climate Change and Variability. Each of these topics is discussed below in general terms of what is known and what needs to be done:

# ROLE OF THE OCEANS AS A SOURCE AND A SINK FOR GREENHOUSE GASES

### What Is Known?

* On time scales of less than 1000 years the oceans are the major reservoir of the two most abundant greenhouse gases: water vapor and carbon dioxide.
* Oceanic studies using tracers such as anthropogenic tritium, carbon-14, and chlorofluorocarbons reveal the importance of the deep ocean in taking up greenhouse gases during the past several decades.
* In the simplest terms, three aspects of the oceans must be considered in assessing their uptake of greenhouse gases: solubility in surface waters (the upper 150 m); the amounts of deep waters formed each year; the amounts of intermediate waters formed each year.
* Increased open-water in the Arctic such as leads, polynya, and reduced sea-ice cover will increase the evaporative flux of water to the polar atmosphere.
* A significant fraction (35 + or - 10 %) of the anthropogenic carbon dioxide emissions of the past 100 years that does not appear in atmospheric measurements probably has been taken up by the oceans.
* As the oceans take up carbon dioxide their pH decreases and their capacity to take up further carbon dioxide is reduced.
* As the temperature of surface ocean waters increases they release carbon dioxide to the atmosphere.
* During photosynthesis, phytoplankton convert carbon dioxide to organic carbon thereby enhancing the uptake of carbon dioxide by the oceans.
* The gravitational settling of biological particles in the ocean and the vertical circulation of the ocean are significant factors in the global carbon cycle.
* The marine environment plays a significant role in the global cycle of methane.
* Marine phytoplankton produce dimethyl sulfide that can be a source of atmospheric aerosols and thereby influence the formation of water droplets in the atmosphere.
* Anoxic marine sediments with rapid accumulation rates provide a record of ocean variability on the time scales of years, decades and centuries.

### What Is Presently Being Done?

* Information on the transport of carbon and other elements from surface waters to depth in the ocean by biological processes is being obtained by the Joint Global Ocean Flux Study (JGOFS).
* Oceanic time-series of selected chemical and biological parameters has been initiated by JGOFS at locations near Hawaii and near Bermuda to document the changes that occur in the ocean.
* Measurements of the carbon dioxide system in the global ocean are being made by JGOFS in co-operation with the World Ocean Circulation Experiment (WOCE) in order to provide improved assessment of this major carbon reservoir in the 1990s.
* Investigations are underway of oceanic processes involving greenhouse gases that will lead to improved chemical and biological models of their behaviour in the ocean.
* Certain historical and on-going time-series data sets have become increasingly valuable due to our concern about global climate change; examples include the California Cooperative Fisheries Investigations (CalCOFI) and the North Atlantic Continuous Plankton Recorder (CPR) work.
* Geochemical studies of ice cores, of Pleistocene coral reef deposits, and of oceanic sediments are providing invaluable information about past climate variations.
* Analytical methods are being standardized and intercalibrated to provide global consistency in ocean chemical measurements.

### What Needs To Be Done?

* We need to improve the reliability of our estimates of the amount of anthropogenic carbon dioxide being taken up by the oceans, and then we need to monitor this uptake on a regular basis.
* We need to determine the importance of coastal ecosystems in the global cycles of carbon and methane. In the case of methane the importance and variability of clathrate[1] deposits in coastal sediments needs to be determined.
* We need to determine the retention times of Greenhouse Gases in the oceans.
* We need to establish national, regional, and global programmes for long-term systematic monitoring of selected Greenhouse gas parameters such as their emissions to the atmosphere, their concentrations in coastal and oceanic waters, and their deposition in marine sediments.

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[1] Methane clathrates are formed by methane and water at low temperature and elevated pressure. They are a solid phase formed within sediments and soils. They are similar to ice in that if the temperature increases or the pressure decreases, they "melt or sublime" releasing the methane as a gas and the water as a liquid.

* A global evaluation should be made of the calcium carbonate compensation depth[2] (both past and present) and its variation with climatic conditions in order to determine the time-scales over which this portion of the carbon cycle interacts with atmospheric carbon dioxide.
* We need to improve our recognition of non-linear, episodic changes in oceanic Greenhouse gases, rather than assuming gradual, linear changes.

## SEA-LEVEL RISE AND CLIMATE CHANGE

Noting UN General Assembly Resolution 44/206 of December 1989, on possible adverse effects of sea-level rise on islands and coastal areas:

### What Is Known?

* Global sea-levels have risen by the order of 15 cm in the past 100 years.
* Locally, sea-level changes are strongly affected by land movements and local oceanography and meteorology in addition to the global sea-level changes.

### What Is Not Known?

* Exactly how increased global temperatures will influence future sea-levels. The IPCC, under its severe scenario, the Business-as-usual[3] emissions scenario, "... estimates an average rate of global mean sea-level rise of about 6 cm per decade over the next century (with an uncertainty range of 3-10 cm per decade), mainly due to thermal expansion of the oceans and the melting of some land ice."
* The relative vulnerability of areas, regions and countries to anthropogenically induced sea-level changes, due to a lack of full understanding of natural processes affecting sea level, e.g. tectonically induced sea-level changes may reverse or enhance those due to global temperature rise at the local level.
* How local changes in weather patterns will affect probabilities of flooding through changed frequencies and intensities of storms.
* The implication of sea-level rise on species diversity in coastal zones is not known.

### What Needs To Be Acquired?

* Reliable estimates of local changes in sea-level and patterns of flooding, over at least 50 year periods, to use an manage coastal areas in a sustainable manner, ant to plan for and adapt to climate induced sea level variations.
* Reliable estimates of global changes in sea level, to analyze and predict climate change and the impacts of climate change.

### What Needs To Be Done?

* Develop and fully implement the GLOSS global sea-level measuring system and related satellite based remote sensing systems for sea-level, tectonic movements and the geoid.
* Analyze for trends by removing local ocean variability.
* Develop a full scientific understanding of the mechanisms of long-term sea-level change.
* Ensure that all maritime nations have the capability to measure and interpret their local sea-level variations, in the context of national needs and global climate processes.

## IMPACTS OF CLIMATE CHANGE ON MARINE LIVING AND NON-LIVING RESOURCES

### What Is Known?

* Coastal zones represent the interface between atmospheric, terrestrial and oceanic systems resulting in poorly understood, complex ecosystem processes.
* The impacts of climate change and sea-level rise in coastal areas will be diverse and extensive. The IPCC reports indicate the nature and wide variety of these impacts.
* Recent studies indicate the existence of biological "switch mechanisms" which result in abrupt non-linear responses to various physical climatic and oceanic factors, such as the bleaching and mass mortality of corals in response to raised temperatures; the regression of mangrove systems in response to reduced land-based sediment inputs; changes in planktonic community composition in response

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[2] The calcium carbonate compensation depth (CCD) is a level in the ocean (presently at about 4000 m) above which calcium carbonate particles tend to accumulate in the seafloor sediments, and below which these particles tend not to accumulate due to the dissolution of the calcium carbonate. The CCD reflects a balance between calcium carbonate deposition and dissolution which can be a sensitive indicator of changes in oceanic conditions.

[3] Under the IPCC Business-as-Usual scenario, i.e., little or no control imposed on emissions of greenhouse gases, the average rate of increase of global mean temperature during the next century is expected to be about 0.3°C per decade (with an uncertainty range of 0.2°C to 0.5°C per decade).

to changed nutrient levels and water temperature.

* Low-lying coastal and archipelagic areas are among the most vulnerable areas of the worlds surface to the impacts of climate change and sea-level rise. This sensitivity reflects the combined effects of changes to oceanic, terrestrial and atmospheric parameters most of which are anticipated to have adverse socio-economic consequences.

### What Is Not Known?

* We cannot accurately predict the scale and direction of many changes at a local level. For example changes to local rainfall patterns, run-off volumes and coastal salinity or changes in which coastal circulation may be altered by larger scale changes in ocean circulation.
* Due to our present inadequate understanding of many ocean processes and their relationship to biological processes in marine and coastal areas unsuspected impacts and abrupt changes must be considered as a very real possibility, for example, the existence of threshold responses or biological switch mechanisms other that those which have already been identified.
* Until these uncertainties are reduced our ability to predict the magnitude of potential impacts on a local , national and regional level is severely constrained leading to problems of long-term planning and impact mitigation.

### What Needs To Be Done?

* Management of the impacts of climate change and of sea-level rise in coastal zones requires regional based predictions of future oceanic and atmospheric conditions as they effect sea-level, storm frequency and intensity; wave set up, currents, rainfall pattern and freshwater run-off, sediments, water chemistry and living marine resource distribution and abundance amongst others.
* Such predictions are required to determine the scale of identified impacts on coastal population and societies, and in extreme cases to determine their long-term viability and vulnerability.
* Locally, nationally, and regionally applicable models of physical, chemical and biological processes in the ocean are required to provide the predictive capability needed for sustainable management and use of oceans and coastal areas.
* Improved methodologies for impact identification and assessment are required and assistance needs to be provided to developing countries in identifying response options and estimating the costs of their application and implementation.
* Improved education, training, public awareness and information flow are needed to sensitize governments to the risks of climate change and sea-level rise and for facilitation of collaborative efforts to address the climate change issue. In particular, impact studies on the sovereign rights of the coastal states to benefit from the economic exploitation in the exclusive economic zone need to be done.

### How To Get There

* Strengthen large scale global monitoring and research of ocean and atmospheric processes to reduce as a contribution to reducing uncertainties at regional and local levels.
* Enhanced local and national level capabilities and capacities in marine science and coastal environmental management.
* Adoption of integrated approaches to programmes of research, monitoring and management at national, regional and international levels.
* Enhanced commitment at all levels to climatic change impact assessment and its co-ordination with the World Climate Impact Assessment and Response Strategies Programme within the World Climate Programme.

## CLIMATE CHANGE AND VARIABILITY

The ocean covers over 70 percent of the Planet Earth. It has great inertia and heat content which has profound effects on climate variability. These variations occur on many scales. We are already aware of the moderating effect of the ocean on the daily and seasonal time scales.

It is now being recognized that the ocean moderates climate variability on many time scales. There is interannual (year to year) variability, such as El Niño Southern Oscillation (ENSO) events, and interdecadal variability in addition to long term climate change.

### What Is Known?

* The oceans are a moderator of extreme climate variability on seasonal to interdecadal time scales.
* The oceans store and redistribute large amounts of heat causing long term variability such as El Niño events; monsoon variations, droughts, floods, etc. Besides atmospheric variability, the variation in oceanic processes has impact on such areas as fisheries, coastal zone development, human resources and freshwater management.

* The ability to forecast interannual and interdecadal climatic variability has significant economic benefits to all countries.
* Recent understanding of oceanic temperature variations are being used to forecast climatic events in all tropical and semi-tropical regions. It is anticipated that knowledge of oceanic variations will improve the prediction of tropical storm frequency, intensity and paths, related surface wave climates and other climatic variations.

**What Is Presently Being Done?**

* The Tropical Ocean and Global Atmosphere (TOGA) programme is a major project of the World Climate Research Programme (WCRP). The major objectives of TOGA are: (1) to gain a description of the tropical oceans and the global atmosphere as a time dependent system, in order to determine the extent to which this system is predictable on time scales of months to years, and to understand the mechanisms and processes underlying its predictability; (2) to study the feasibility of modelling the coupled ocean-atmosphere system for the purpose of predicting its variations on time scales of months to years; and (3) to provide the scientific background for designing an observing and data transmission system for operational prediction if this capability is demonstrated by coupled ocean-atmosphere models. TOGA implementation was initiated in 1985 and is scheduled for completion in 1995. TOGA has been highly successful in beginning to provide forecasting skill in seasonal and annual time scales.
* The World Ocean Circulation Experiment (WOCE) is a major project of the WCRP and the largest scientific study of the ocean ever attempted. Using satellites, dozens of ships and thousands of instruments it will take a comprehensive global "snapshot" of the physical properties of the ocean for use in developing numerical models of ocean circulation and physical processes. WOCE implementation began in 1990 and is scheduled to be completed by 1997. Additional national commitments are needed to accomplish all its objectives.
* The Joint Global Ocean Flux Study (JGOFS) is an established Core Project of the International Geosphere Biosphere Programme (IGBP). The objectives of JGOFS are (1) To determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor, and continental boundaries; and (2) To develop a capability to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climate change.
* The Global Energy and Water Cycle Experiment (GEWEX) is a major project of the World Climate Research Programme with the objective of observing and modelling the global hydrological cycle and interactions of the atmosphere with the underlying land and ocean surfaces. It currently lacks a significant oceanic component.
* The Global Ocean Euphotic Zone Study (GOEZS) is an important newly proposed study and a potential Core Project of the IGBP. GOEZS is at an early stage in the detailed planning development.
* The World Climate Programme (WCP) consists of four components: (1) Data - to monitor the climate system, detecting climate change and assisting developing countries in climate measurements and data management; (2) Applications - to develop and exchange methods for using information on climate and climate changes to improve efficiency and safety of many human activities; (3) Impacts - to assess effects of global warming on major economic sectors; and (4) Research - to provide better understanding of the processes in the climate system to better predict global warming due to greenhouse gases, and make seasonal predictions of climate for drought warnings and other purposes.
* The Arctic Climate System Study is a newly proposed project of the WCRP to study the circulation of the Arctic ocean; including the sea-ice, energy and fresh water budgets of the region encompassing the Arctic Ocean.
* SECTIONS is an on-going project of the USSR initiated in 1981 with the objective to investigate the role of the ocean in short-term climate change and variability. The programme includes systematic seasonal oceanographic and meteorological observations from research vessels, in some key oceanic areas, called energetically active zones of the ocean (EAZOs) in the tropical and north Atlantic and the north Pacific Oceans. It also includes development and improvement of ocean and ocean-atmosphere models and methods for four-dimensional analysis of oceanographic data.

**What Needs To Be Done?**

* Establish an ability to predict interannual and interdecadal ocean variability, and its interaction with changes in the other components of the climate system.

* Enhance regional, national and international programmes to observe systematically, ocean temperature, salinity and winds over the ocean to create long-term time series to be integrated into comprehensive data sets; i.e., implement the Global Ocean Observing System (GOOS) as part of the Global Climate Observing System (GCOS). This should include the development of low-cost automated salinity measurement systems so as to permit an order of magnitude increase in the number of salinity observations per year and the expansion of the surface- layer heat-monitoring programme through augmentation of available expendable bathythermographs (XBTs).
* Implement a global 4 dimensional data assimilation system for the ocean in order to organize the oceanic data into global and regional grided data fields.
* Expand the study of the global fresh-water budget to include the role of the ocean.
* Implement operational forecasting of climate variability associated with ENSO and longer time scales as possible.

The foregoing should be seen in the context of the Global Climate Observing System (GCOS), the need for which was highlighted by the SWCC. The goals of GCOS include:

- climate system monitoring, climate change detection and response monitoring, and ultimately a comprehensive observing system for climate forecasting; and
- provision of data for application to national economic development and for research directed towards improved understanding, modelling and prediction of the climate system.

Present observing systems for monitoring the atmosphere, land surface and oceans all fail to meet these goals. For the oceans, observations are available from a variety of established sources such as the Integrated Global Ocean Services System (IGOSS) of IOC and WMO, the Global Sea-level Observing System (GLOSS) of IOC as well as from national and international research programmes, but none currently provide for the global coverage and continuing long-term time series required. The acquisition of a long-term systematic observing system to monitor, describe and understand the physical and biogeochemical properties that determine ocean circulation and the seasonal to decadal climatic changes in the ocean, as well as to provide the observations needed for climate prediction, is an established goal of the Global Ocean Observing System (GOOS), a fundamental component of GCOS.

# II. THE OCEANS AND CLIMATE CHANGE: A BACKGROUND

## FOREWORD

This document examines the current state of knowledge of the ocean's role in climate as well as our present capability to monitor, predict and detect changes. It was prepared as background for a scientific and technical meeting hosted by the Government of Malta whose purpose was to prepare a brief authoritative guide of the ocean's role in climate variability and change, including what is known, questions currently being addressed and questions not receiving sufficient attention.

It was developed in large part by excerpting text from a number of publications and special reports prepared by or for the IOC of UNESCO on ocean climate-related subjects. Every effort has been made to properly reference these reports. However, particular recognition is due to the authors of the following papers whose contributions were most heavily drawn upon in preparing this document:

- The Ocean and Climate. Principal author: R.W. Stewart, IOC of UNESCO (1990).
- Relative Sea Level Change: A Critical Evaluation. Principle authors: R.W. Stewart, B. Kjerfve, J. Milliman and S.N. Dwivedi, UNESCO (1990).
- Mysteries of the Ocean Water Budget. Unpublished manuscript by R. Schmitt and K. Bryan (1991).
- Impacts of Climatic Change and Implications for Future Ocean Management, for Sustainable Development. Unpublished UNCED document, prepared by IOC. Principal author: J. Pernetta (1991).

## INTRODUCTION

The oceans play a key, but frequently understated, role in determining the earth's climate. Indeed, any possibility of predicting the evolution of weather systems beyond a few weeks demands that ocean behaviour be taken into account. There is great promise that it may become possible to describe and predict many aspects of upper ocean behaviour with enough accuracy to improve long range weather and fisheries forecasts usefully. This promise can only be realized if appropriate data are collected regularly and disseminated promptly.

With respect to sensitivity to, and contribution to, long term climate change, there is every reason to believe that the ocean is now changing in response to climate changes over the past few hundred years (the Little Ice Age). It can be expected to change further as anthropogenic influences become increasingly marked. The effect of the ocean on the atmosphere could be either to moderate or to intensify these changes. It will certainly modify them.

To determine how the ocean is changing now will require much more in the way of systematic and repeated measurements at all depths throughout the ocean. To predict its future evolution will require superior models supported by a regular influx of new data.

These needs will require new structures both internationally and in many countries nationally, for oceanography is rapidly becoming an operational science like meteorology, not just a research science. Experience has shown that structures designed to manage research are not usually well suited to manage operations.

## THE OCEAN CLIMATE SYSTEM

It is sometimes referred to as "the flywheel of the climate system", although that notion inadequately describes the contribution of the ocean to the system. Like a flywheel, the ocean stores energy, in this case thermal energy, when it is in large supply during the day or summer, and releases it when the energy supply is reduced or reversed during night or winter.

When it is heated the ocean responds by storing some of the heat and by increased evaporation. Because the heat is mixed down for some meters by the wind, temperature rises much less than it does on dry land under the same heating conditions. The evaporation has profound effects on the atmosphere and on climate. Water vapour released into the atmosphere importantly increases the greenhouse effect in the atmosphere. When it recondenses (sometimes far from where it evaporated) the resulting heating of the air is a major source of energy for atmospheric motion.

When the ocean is cooled, it responds by generating vertical convective motions, which bring heat to the surface, so that the cooling is spread over considerable depth -- sometimes to the bottom. Thus the temperature fall is much less than over land under the same cooling conditions.

The overall result is that for the two thirds of the earth's surface covered by ice-free ocean, the temperature over the whole ocean ranges only from -2°C ( the freezing point of salt water) to 30°C, and at any one place by hardly more than 1°C during the course of a day and 10°C during the course of a year. This range might be compared with that over dry mid-continental areas, where the variation from place to place can be about 100°C, and during the course of the year in particular places about 80°C. Further, the relatively slow response of the ocean to heating and cooling results in the oceanic annual cycle being retarded relative to that in continental regions. Temperature contrasts between the land and adjacent sea surfaces give rise to a variety of atmospheric responses from the daily generation of coastal land and sea breezes through to the great seasonal monsoonal circulations.

Such effects would be experienced even if the ocean were little more than a deep swamp -- as indeed it is assumed to be in many numerical models of the climate system. However the ocean is much more complex than that. It moves, both horizontally and vertically, under the influence of wind forcing and density differences generated by heating and cooling, evaporation, precipitation and runoff. In moving, it redistributes heat (and salt) in ways that are of central importance in determining the details of the earth's climate. The North Atlantic provides a particularly notable example. In the tropical Atlantic, solar heating and excess evaporation over precipitation and runoff creates an upper layer of relatively warm, saline water. Some of this water flows north, through the passages between Iceland and Britain. On the way it gives up heat to the atmosphere, particularly in the winter. Since winds at these latitudes are generally westward, the heat is carried over Europe, producing the mild winters which are so characteristic of that region relative to others at similar latitudes.

So much heat is withdrawn that the temperature drops close to the freezing point. Unlike fresh water, sea water has no temperature of maximum density higher than the freezing point, so cooling always increases density. This water, now in the Greenland Sea, remains relatively saline, and the combination of low temperature and high salinity makes the water more dense than deeper water below it. Convection sets in and the water sinks -- occasionally and locally right to the bottom. There it slides under, and mixes with, other water already close to the bottom. It spreads out and flows southward, deep and cold.

This thermohaline circulation: surface warm water flowing north, cooling, sinking and then flowing south provides an enormous northward heat flux. It amounts to about 1 PW, fully comparable with that transported poleward by the atmosphere. This is the part of the climate system which has been most clearly identified as one which might be dramatically modified by quite small changes. Thus if the surface salinity in the northern parts of the North Atlantic should be reduced for some reason, then cooling might not be able to produce water dense enough to sink to great depths, let alone the bottom. Such is the present situation in the Arctic Ocean and in the North Pacific, so it is clearly physically possible. Should that occur, the winter North Atlantic would be covered by a layer of water which would quickly cool, freeze in some areas and would be unable to provide the heat source which now warms Europe. Lowered surface salinity could be brought about by increased precipitation, melting of the Greenland ice cap and/or changes in the way relatively low salinity water of the Arctic Ocean passes into the Atlantic. Any or all of these changes are possible, and modelling studies indicate that the resulting climate change could be quite persistent. There is evidence that such a change in conditions occurred toward the end of the most recent ice age, some 12,000 years ago, perhaps because of the rapid unleashing into the North Atlantic of fresh water derived from melting the Laurentian ice sheet.

Even larger quantities of deep water are generated near the Antarctic Continent. If for some reason, like increased precipitation or increased melting of Antarctic ice, the surface salinity in this region were substantially lowered, this source also could be cut off.

Deep water from these two sources spreads throughout all the world's oceans. There it is slowly warmed by mixing with slightly warmer water above, and new supplies of cold water push under it. Over the course of centuries the water gradually rises, warmed by mixing from above and pushed up by newly produced cold water below. Eventually it rises enough to participate in the wind-driven circulations of the upper parts of the ocean and then to become part of the thin upper layer which is directly heated by the sun. From there it can again move into higher latitudes and again be cooled to the point of convection. Water which moved into the most distant parts of the ocean, in the North Pacific, can take about one thousand years for this cycle.

Other surface water, which does not reach very high latitudes, also experiences cooling and convection, in this case only to some intermediate depth. It also spreads out, mixing laterally with other water of about its own density, pushes up water above it and is in turn pushed up by other water sliding in below it. This shallower circulation can be completed in a few years or decades.

During the highly turbulent convective process, water is in repeated contact with the surface and comes into approximate equilibrium with atmospheric concentrations of gases, including notably $O_2$, $CO_2$ and freons. The freons are inert, and provide a valuable passive tracer for ocean movement. $O_2$ and $CO_2$, on the other hand, are strongly affected by biological activity. The surface layers of the ocean contain planktonic plants which, in the presence of sunlight, convert dissolved $CO_2$ into organic carbon. The plants are eaten by animals, which are in turn consumed by other organisms. Debris from these organisms falls out of the surface layers into the deeper water. On the way down, bacteria decompose some of the material, releasing $CO_2$ and nutrients in dissolved form in the process and absorbing $O_2$. As a result the deeper water is enriched in $CO_2$ and nutrients and depleted in $O_2$.

Deep ocean mixing is inefficient and slow, so while the deep water is warmed somewhat as it rises, the great majority of ocean water is much closer in temperature to bottom water than to surface water. (At 1km depth the temperature of most of the ocean is about 5°C.) The depth of the warm surface layer varies considerably, depending upon ocean circulation, but typically the main thermocline, in which winter temperature decreases from values close to those of the surface to values close to those of the deep water lies between about 100m and 1000m. (In summer a temporary upper layer develops,which may be up to about 100 m deep and up to 10°C warmer.) The main thermocline is particularly shallow in tropical areas.

In certain areas, notably on some coastlines and near the equator, wind driven currents drive surface water away, so that it is replaced by the upwelling of deeper water from within the main thermocline. The upwelled water is rich in both nutrients and $CO_2$. If other conditions are suitable, the nutrient supply greatly enhances biological activity and most of the richest fisheries in the world are located in these upwelling areas. Some of the excess $CO_2$ is absorbed by the marine plants, and the rest is exuded to the atmosphere. It should be noted that a part of the $CO_2$ released was absorbed from the atmosphere in convective regions, perhaps thousands of kilometers away and hundreds of years earlier. The atmospheric $CO_2$ was then in lower concentration than today, so the concentration of $CO_2$ in the water is correspondingly lower and so is the amount of the gas exuded to the atmosphere. This is one of the ways in which the ocean can absorb $CO_2$: enhanced absorption in high latitude convective regions and reduced transfer to the atmosphere in upwelling regions.

The eastern equatorial Pacific provides an outstanding example. The most frequent wind pattern in the Pacific leads to upwelling off the coast of South America and cool thermocline water coming to the surface there and in an equatorial tongue which extends far into the Pacific. The western equatorial Pacific, on the other hand contains a deep pool of the warmest water in the world, usually above 29°C. From time to time the eastern region becomes flooded with this warm water. This is the el Niño phenomenon, which has profound effects upon the climate and marine life of all kinds.

This phenomenon has been subject to intense study, particularly during the decade of the 80's, within the TOGA programme, and substantial progress has been made in understanding and attempting to predict it. Behaviour of the equatorial Atlantic and Indian oceans is also quite variable, with climatological consequences on areas which contain a large fraction of the world's population. These regions remain less thoroughly studied and less well understood than is the Pacific.

## OCEAN OBSERVATIONS AND MODELS

The behaviour of the ocean will only be understood through an interplay between modelling and observation. Understanding of the nature of important phenomena is far too incomplete to enable modelling alone to deal with the problems effectively. Models must be constrained and modellers must be guided by comprehensive data sets. With respect to the deep ocean, it is not even clear what a model should be expected to reproduce. For example it may well be that the deep water in the North Pacific is a relic of a previous climate and should not be reproduced by a steady state ocean model based on today's climate.

The upper layers are better observed and it is much clearer what the models should be designed to reproduce. However it is known that the most energetic motions in the ocean are only about 100km in size, and it is also known that unless a model is able to deal with these small scales it cannot closely reproduce the larger scale motions. Comprehensive ocean models are therefore very demanding of computer capability. Indeed even the largest available computer is unable to handle an appropriate global ocean model for even a steady-state solution, let alone for the transient behaviour one would like to study in order to understand the effects of greenhouse-gas induced warming. Suitable computers are expected to be available within about a decade. In the meantime it is necessary to refine techniques for handling many important phenomena, including heat transport by ocean currents, deep convection and other aspects of the annual cycle, and various mixing phenomena. This work must be supported by appropriate data since for a very long time to come modelling will require the inclusion of a great many factors which can be obtained only from observation.

On the other hand, observations alone will remain insufficient. They will continue to be too sparse in both space and time to provide an adequate description. Models can tie the observations together and put them in appropriate context. They can also help identify the nature and location of the most crucial observations. Only through modelling is it possible to make quantitative statements about the way the system may evolve in the future.

The ultimate objective is, of course, prediction. This is of two kinds: (1) detailed prediction of the weather forecast type and (2) sensitivity to external changes, in particular those associated with global warming. The only kind of detailed prediction which seems possible in the relatively short term is that associated with the tropical oceans. There, the progress made with attempting to predict el Niño shows great promise. To some extent it is limited by the inaccuracy of long range atmospheric forecasts, but predictions of the evolution of the ocean behaviour are an essential input to predicting that of the atmosphere. The ocean and the atmosphere are particularly tightly coupled in this part of the world. Oceanography and meteorology must be equally tightly coupled to deal with it. Predictions will depend crucially upon the timely acquisition and distribution of ocean data, of the kind now being undertaken within TOGA.

The behaviour of the ocean depends on driving forces through the surface: wind stress, precipitation, heat flux and evaporation. None of these is now adequately determined. This weakness arises partly because these quantities cannot be routinely measured, and their relationship to other quantities which are measurable has not been established with sufficient accuracy. It is also partly because there is inadequate atmospheric data on surface wind, temperature and humidity. In principle the surface fluxes should be obtainable from weather forecasting models provided sea surface temperature is known. However much work remains to be done before that becomes routinely possible.

Accurate determination of sensitivity demands accurate models. These can only be developed and checked by accurate and comprehensive data. The goal must be to develop models able to predict the evolution of ocean properties subject to changing driving forces. The way in which ocean properties are now evolving, and the way in which the ocean responds to changes in driving as they are observed will be an essential input into the development of such models. Thus there is a requirement for ongoing time series of ocean data, to determine the way in which the ocean is changing.

An essential requirement for improved models of the ocean is much better and more complete knowledge of what the ocean is actually like now. This information is also needed in order to determine how it is changing. One of the major objectives of the World Ocean Circulation Experiment (WOCE) is to satisfy this need. The data obtained in WOCE will enable use of basic conservation laws and the powerful mathematical tools of inverse modelling in order to obtain crucial knowledge on the way our contemporary ocean is transporting heat and salt about the earth. They will also provide a firm base upon which to build time series of the evolution of ocean behaviour in a changing world. Even before these future data are collected, the data from WOCE will be closely compared with data gathered in past, piecemeal efforts in order to detect and try to understand changes now taking place.

WOCE will also include a comprehensive study of the Southern Ocean, to improve understanding of that important area where most of the deep water of the ocean is formed, and where the different oceans are linked and thus enabled to influence one another.

## AN OCEAN OBSERVING SYSTEM: BASIC INGREDIENTS

The detailed nature of a future ocean observing system for research, monitoring and prediction of long-term climate variability may only be known after the results of TOGA, WOCE, JGOFS and GEWEX have been fully and carefully assessed. However enough can be seen already to permit planning and initial implementation to go ahead, with a view to refining the system as more information becomes available. The system will have several components:

(i) Satellites.
(ii) Ships of opportunity.
(iii) Tide gauges.
(iv) Buoys, both drifting and moored.
(v) Specialized vessels (usually research ships).
(vi) New techniques.

(i) Satellites provide the only feasible way of giving truly global coverage. Measurement can and should be taken of sea-surface temperature, ocean colour which can be related to plankton activity, wave characteristics from scatterometer measurements which can be related to wind stress, surface elevation which can be related to surface currents, sea-ice cover and sea-ice character.

(ii) Ships of opportunity permit relatively inexpensive measurement of near surface wind speed, air temperature and humidity, salinity of water and perhaps partial pressure of $CO_2$ near the surface and temperature structure of the upper layers of the ocean. Efforts are being made to perfect an expendable instrument capable of measuring upper layer salinity with sufficient precision.

(iii) Tide gauges provide an inexpensive way of determining changes in sea level, which can be interpreted in terms of ocean heat content and currents, as well as long-term trends in sea level -- an important parameter in itself.

(iv) Buoys can provide information from areas rarely travelled by ships of opportunity. They give very accurate sea-surface temperatures which can be used to calibrate satellite data. They can also provide information on upper ocean temperature structure. Buoys can also provide information about ocean currents. It would be desirable to develop buoy instrumentation capable of measuring upper ocean salinity reliably, although there are severe technical difficulties in achieving such a capability.

(v) Specialized vessels are very expensive. However, they remain the only vehicle suited for obtaining essential information on deep temperature, salinity, geochemical constituents of sea water and such tracers as freons, with the required accuracy. For most parameters, the deep water varies so little that great accuracy is required. It would be desirable to have instruments suitable for deep ocean measurements which would be less demanding than is presently the case on the capabilities of both vessels and personnel in order to make acceptable measurements.

(vi) Oceanographers have always been very inventive of new instruments for measuring ocean parameters. At the present time there is a large array of new and proposed instruments. Some have been deployed in small numbers, others have been built in prototype and still others are being designed. These include a variety of acoustic instruments and arrays, "pop-up" buoys and unmanned powered vehicles. There will be more as human ingenuity comes to grips with the difficult problems of long term monitoring of the ocean. Institutional structures put in place to deal with monitoring must be responsive to such new ideas as they become cost effective.

Important elements of a comprehensive long-term ocean monitoring and data management system are already in place, in particular within IGOSS, the WMO World Weather Watch and GLOSS, together with their associated data exchange and processing components. It is essential that the future Global Ocean Observing System should build on and strengthen these existing operational systems, to make use of the procedures, mechanisms, techniques and expertise which already exist, and to make the most cost-effective use of available resources. In view of the dependence of global climate on interactive, interdependent atmosphere, ocean, land, cryosphere processes, it is also essential that the Global Ocean Observing System be integrated as the ocean component of the Global Climate Observing System, to form a fully co-ordinated global climate monitoring system.

## TIME AND SPACE SCALES

The time and space scales required for monitoring a system are usually different from those needed to describe and explain it. In this section we deal with the former, leaving the latter to specialized research programmes, in particular WOCE and JGOFS.

Surface temperature data are used in routine weather forecasting and need to be available within a few hours globally. A combination of satellite data and data received from buoys by satellite can meet this need. For meteorological use a spatial scale of a few hundred kilometers is sufficient, but oceanographers can make use of data down to a scale of about ten kilometers.

The upper layer data must be monitored through the annual cycle in order to identify interannual anomalies. Thus a time interval of about two months is appropriate. More frequent sampling will be required in some specific areas, e.g., the tropical Pacific, for operational purposes, in order to provide data for assimilation into the upper ocean component of models.

The space scales need to be site specific and can range from tens of kilometers to several hundred kilometers depending on the location relative to coastlines and the equator.

Deep ocean measurements are more difficult and expensive. Fortunately changes are slower. Provided the area is repeatedly sampled on those occasions when it is examined, in order to reduce data distortion through short term, small scale phenomena such as internal waves, a time interval of about five years is suitable. Spatial scales are again site specific. The requirements for deep ocean measurements, in particular, will be much refined in the light of WOCE and of JGOFS.

## OCEAN FRESHWATER AND SALT TRANSPORT

The oceans harbor over 97% of the world's water and are the source of most of the water that rains onto land. The atmosphere holds only 0.001%. Similarly, the transport of water by major ocean currents within and between ocean basins exceeds water transport in the atmosphere by several orders of magnitude. While we have decades of data on river flows and global estimates of atmospheric water transport from rawinsodes and models, we remain remarkably ignorant about oceanic freshwater transports. The fault lies with the general paucity of ocean observations and, in particular, the problems of making precipitation measurements at sea. Unfortunately, this had led to intellectual neglect of the problem, to the extent that fundamental misconceptions about the oceanic water budget persist. Since the oceans have such a dominant role in the world water budget there is a strong need to improve our understanding of its hydrologic forcing. Further, because freshwater inputs to the high latitude ocean play a key role in controlling the thermohaline circulation, which has a significant influence on climate, the ocean measurement problem has direct relevance to global change studies. In the following, major issues and possible approaches to the problem of assessing the ocean freshwater budget are discussed, many of which are salient in the Global

Energy and Water Cycle Experiment (GEWEX).

As a way of introducing the uncertainties, let us focus attention on one particular ocean basin, the North Atlantic. Schmitt, Bodgen and Dorman (1989) (SBD) have produced an updated estimate of evaporation minus precipitation (E-P) for that basin (Figure 1), derived from the latent heat flux data of Bunker (1975) and the rainfall data of Dorman and Bourke (1981). Their estimates have more detail than those of Baumgartner and Reichel (1975) (B & R) (Figure 2) and differ significantly in areal averages as well. When summed over the North Atlantic the SBD numbers yield $10^5$ $m^3$ $s^{-1}$ more evaporation than the B & R summation. This is over half the flow of the Amazon. Even greater discrepancies arise when more recent climatologies are considered for the evaporation field. For instance, Isemer and Hasse (1987) have revised the Bunker estimates for the North Atlantic. While they adjust the exchange coefficients in the bulk formulae downward, their revision of the Beaufort wind scale leads to higher trade winds and increased evaporation in the tropics and subtropics. Their estimate of 20 to 40 cm/yr. more evaporation south of 40°N suggests that an additional freshwater loss of nearly 4 x $10^5$ $m^3$ $s^{-1}$ occurs over the North Atlantic. Thus, current estimates of net E-P over the basin differ by several times the flow of the Amazon (1.9 x $10^5$ $m^3$ $s^{-1}$). Since the North Atlantic is a small, relatively well sampled basin, we can only conclude that the uncertainties for the other ocean basins are even larger.

Additional surprises arise in the SBD data when their estimates of thermal and salt density are considered. In particular, the haline contribution to the density flux is found to be most important in the tropics and subtropics and relatively less significant in the open ocean of the subpolar gyre. Run-off and ice melt appear to be more important high latitude buoyancy sources. One way of considering this is to examine the absolute value of the thermal/haline density flux ratio (Figure 3). Values of the flux ratio near 1.0 indicate that heat and freshwater fluxes make nearly equal contributions to the buoyancy fluxes. We see that the heat flux dominates near the equator and at high latitudes, the heat and salt fluxes are of comparable importance throughout much of the mid-latitude Atlantic and that the salt flux dominates over several large areas. The salt flux would assume even more importance if the elevated evaporation rates of Isemer and Hasse were used instead. We can only conclude that over significant portions of the North Atlantic we do not know the sign of the mean annual buoyancy flux.

Consideration of the zonally integrated E-P has also led to revisions in the estimates of the Northward freshwater flux carried by the oceans. That is, B & R assumed that the cross equatorial freshwater flux in the Atlantic was zero, and achieved this by allocation of 2/3 of the Amazon flow to the South Atlantic. Oceanographically, this makes little sense, because the North Atlantic is expected to be a strong evaporation basin. Also, the North Brazil Current is known to sweep all of the Amazon discharge into the North Atlantic. Wijffels, Schmitt, Bryden, and Stigebrandt (1991) have used the measured transports through Bering Strait as a reference for establishing the freshwater fluxes in the Atlantic and North Pacific (Figure 4). Their picture of the global ocean water budget is radically different from that presented by B & R (Figure 5) and others, who have misinterpreted the Arctic freshwater flux divergence as the Bering Straits flux. The major feature is that the North Pacific precipitation excess is largely transported through Bering Straits into the Atlantic rather than into the South Pacific. This means that the Atlantic exports freshwater (and salt) to the Antarctic Circumpolar sector. That such a fundamental revision of the ocean water budget can be made at this time indicates how little attention has been paid to the problem in the past. The increased importance of the Bering Straits suggested by Wijffels *et al.* raises interesting climatological questions. Due to the shallowness of Bering Strait (50 m), the transport from Pacific to Atlantic must be very sensitive to sea level fluctuations; this raises the possibility of modulation of surface salinities in the Arctic, which can influence deep water formation on climatic time scales.

There is strong evidence that salinity fluctuations in the high latitude North Atlantic do modulate the thermohaline circulation by decreasing deep water formation. A cap of fresher water can strongly limit the depth of convective cooling, insulating the deeper waters from surface influence. The existence of a halocline in the northern North Pacific prevents that ocean from generating deep water. Apparently, deep water formation in the North Atlantic was interrupted many times, especially at the end of each ice age, when large amounts of glacier melt water flooded the basin. Evidence for similar effects in recent times has been noted by Lazier (1980) (Figure 6), Dickson *et al.* (1988), Mysak and Power (1991) and others. Dickson *et al.* describe a several year shut-off of deep convection by a large scale, low-salinity anomaly which could be tracked around the sub-polar gyre. Shutdown of deep water renewal limits the northward penetration of warm surface waters which are a significant high latitude heat source. This particular salinity anomaly appeared to originate in the Arctic, probably from ice melt.

Large positive sea-ice and negative salinity anomalies observed in the Greenland Sea during the late 1960s were preceded by above-average runoffs from North America into the western Arctic during the mid 1960s. Such strong freshets produced large positive sea-ice anomalies in the latter region, which Mysak and Power (1991) argue, then drifted out of the Arctic into the Greenland Sea via the Beaufort Gyre and Transpolar Drift Stream about three to four years later. During the melt season such ice anomalies would have contributed to the production of an extensive cool, relatively fresh

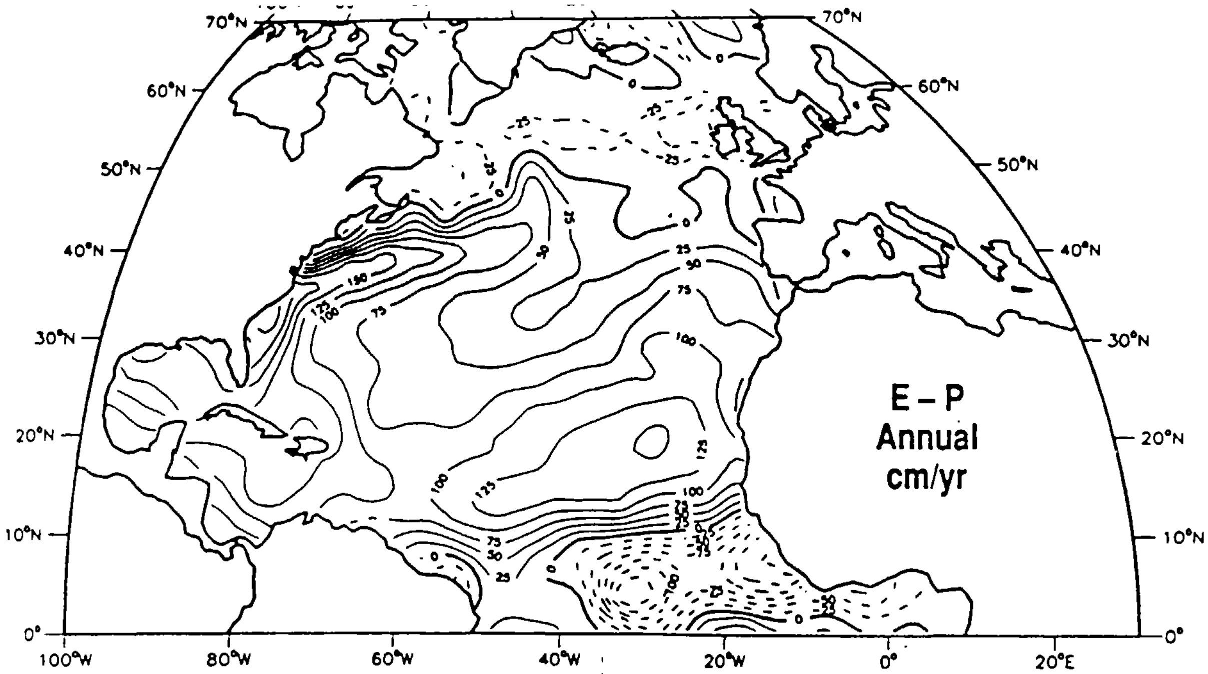


Figure 1. E-P estimate for the North Atlantic (cm/yr) from Schmitt, Bogden and Dorman (1989. Evaporation estimates were obtained from data of Bunker (1976); precipitation estimates from Dorman and Bourke (1981).

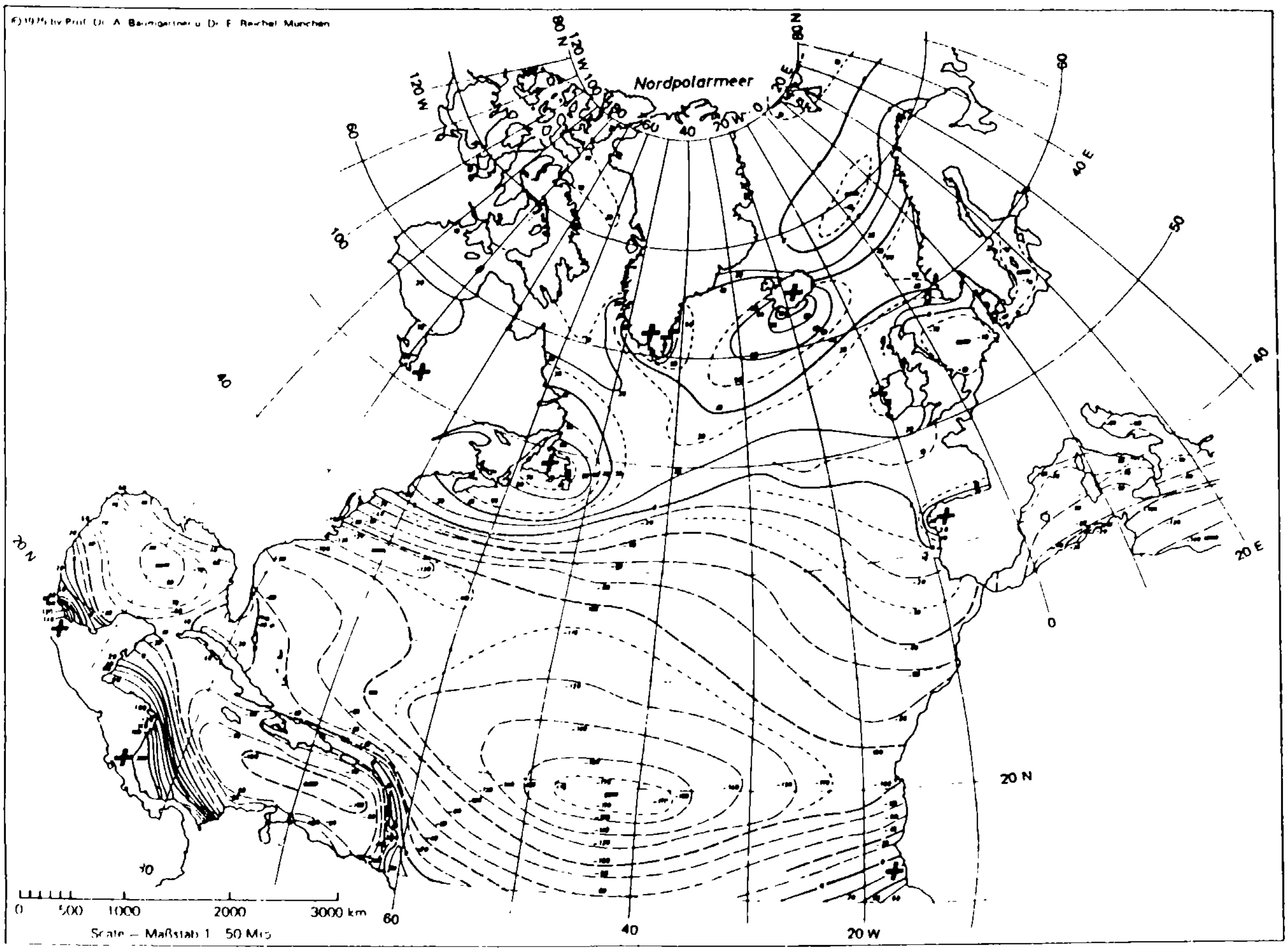


Figure 2. E-P estimate for the North Atlantic cm/yr by Baumgartner and Reichel (1975).

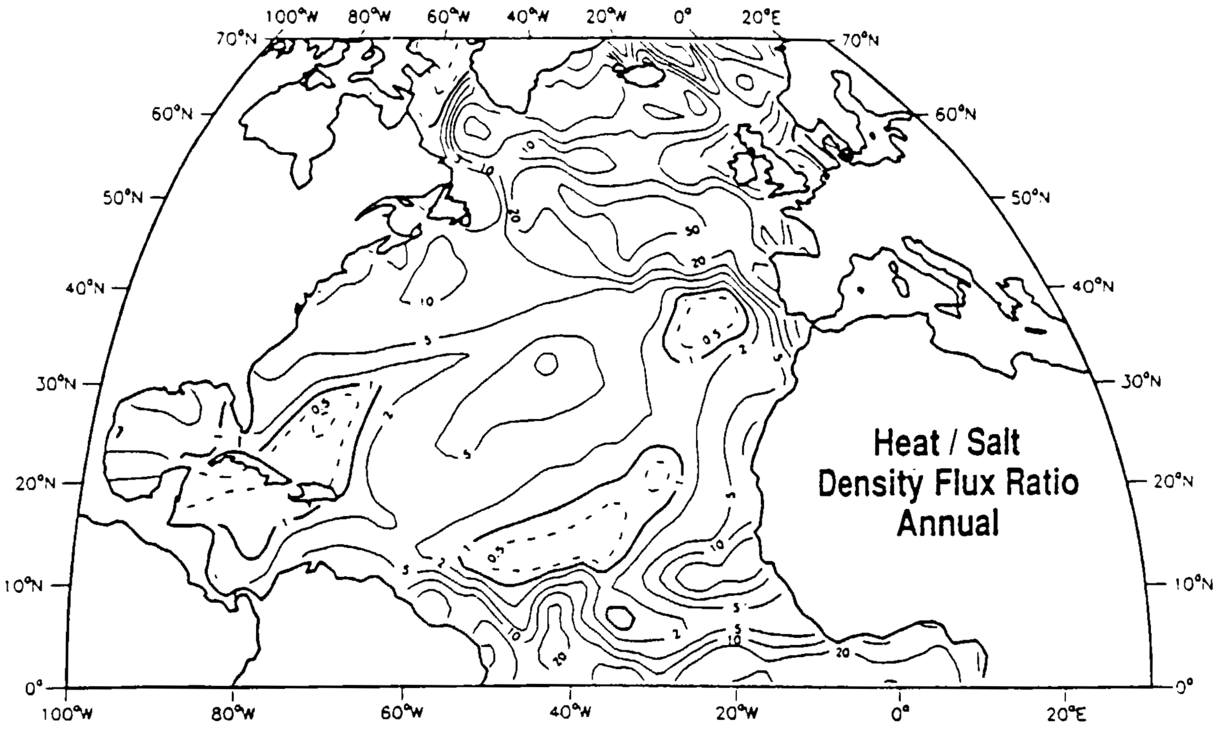


Figure 3. Absolute value of the ratio of the annual heat and salt density fluxes from Schmitt, Bogden and Dorman (1989).

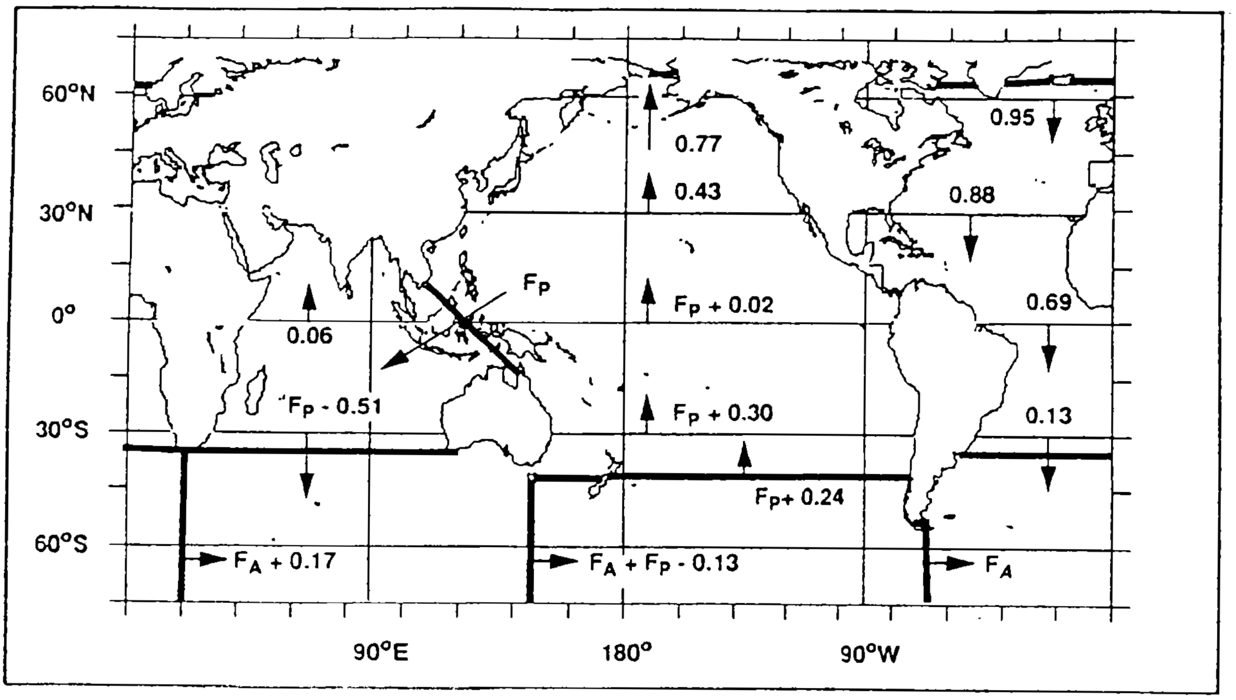


Figure 4. Freshwater transport by the oceans according to Wijffels et al. (1991) in $10^9$ Kg/s

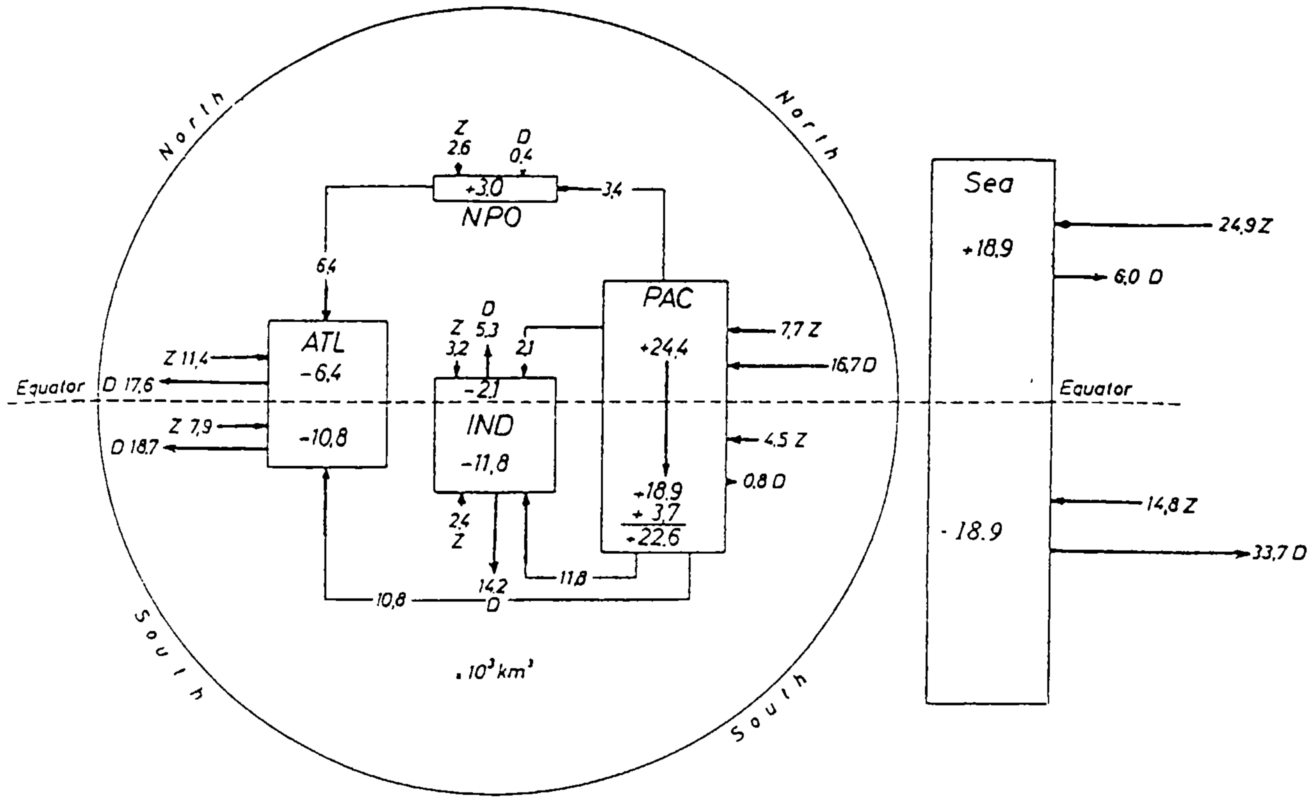


Figure 5. Freshwater transport by the ocean according to Baumgartner and Reichel (1975) in $10^3$ $Km^3$/yr ($10^3$ Km/yr = 0.032 x $10^9$ kg/s)

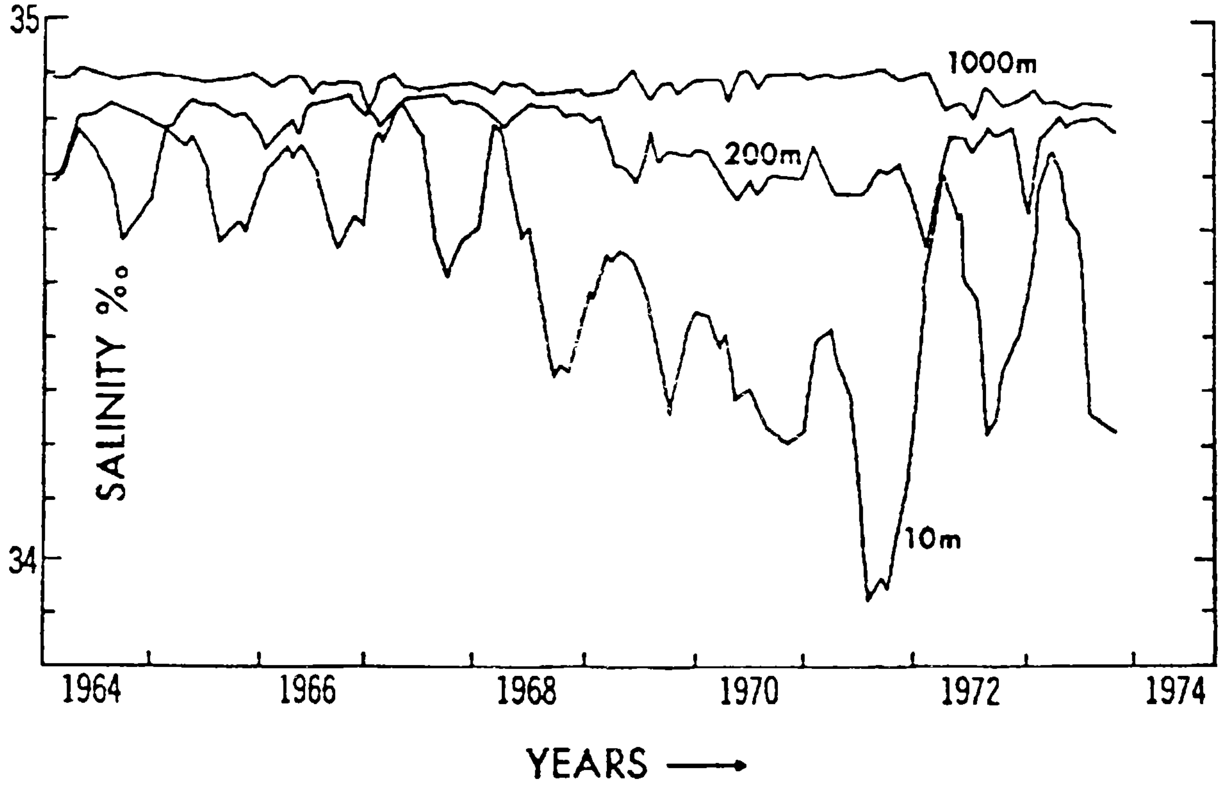


Figure 6. Salinity as a function of time at 10, 100 and 1000 m depth at OWS Bravo in the Labrador Sea (Lazier, 1980)

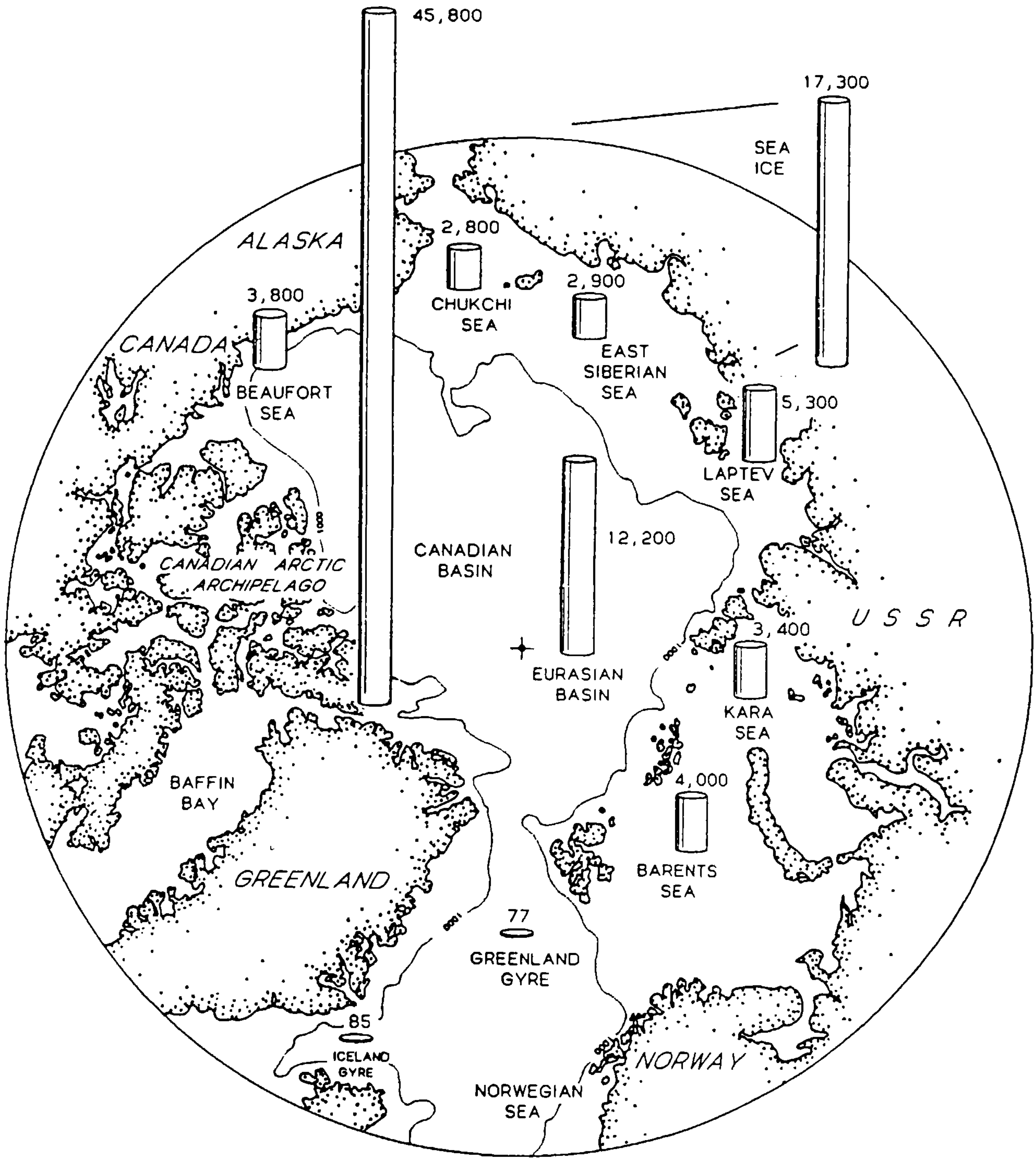


Figure 7. Fresh water storage in the Arctic Ocean and GIN Sea, according to Aagaard and Carmack (1989). The freshwater anomaly in the ocean basins is calculated relative to a mean salinity of 34.93.

surface layer in the Greenland Sea which suppressed convective overturning during winter. The latter, stably-stratified oceanic state appeared to have subsequently reduced high-latitude cyclonic activity and precipitation over northern Canada. Mysak and Power hypothesize that this sequence of hydrological, sea-ice, oceanic and atmospheric events can be described in terms of a negative feedback loop which suggests the existence of self-sustained climatic oscillations in the Arctic with a period of about 20 years. Remarkably, during the late 1980s another large positive sea-ice anomaly occurred in the Greenland Sea, in agreement with the interdecadal climate cycle hypothesis. Clearly such natural variability should be taken into account as baseline information when searching for "evidence" of greenhouse warming in long-term sea-ice thickness and areal extent records.

Ice represents a sizeable portion of the storage of freshwater anomaly in the Arctic according to Aagaard and Carmack (1989) (Figure 7). If significant variations in ice volume occur, there would be direct impacts on net discharge from the Arctic. These could easily generate the observed salinity anomalies. For instance, we calculate that only a 20-30% variation in annual discharge could have created the anomaly observed by Dickson *et al.* (1988). Thus, improving our understanding of the relative contributions of precipitation, run-off, ice melt, and transport through Bering Strait to the Arctic freshwater budget is a key climatological issue.

It is also important to improve knowledge of the hydrologic forcing in middle and low latitudes. Strong local gradients in E-P and large seasonal cycles may force a variety of oceanic responses. Regions such as the Gulf Stream and the Intertropical Convergence Zone show particularly strong variations. In the annual mean the strong evaporation regions in the subtropics suggest that we have to develop a better understanding of the salt flux. For instance, are salt fingers important in stabilizing the main thermocline by virtue of their greater transport of salt than heat? It has been argued that fingers are responsible for the structure of the temperature-salinity relationship in the Central Waters (Schmitt, 1981). However, Stommel (in preparation) has proposed a mechanism whereby lateral exchange processes in the surface mixed layer establish a positive temperature-salinity correlation when forced with a sufficiently large variance in precipitation. Such internal mixing processes of the sea are completely unaccounted for in present models, yet must have first order effects on the thermohaline circulation. Developing a better understanding of the surface hydrologic forcing on a variety of space and time scales is vital to the development of models of the thermodynamics of the ocean.

To summarize, our ignorance of the ocean water cycle is such that:

- estimates of net E-P over the best measured ocean basin (N. Atlantic) differ by amounts several times the flow of the Amazon,
- we are unsure of the sign of the buoyancy flux over significant portions of the sub-tropical gyre,
- popular conceptions of the mean oceanic water budget are in error by an order of magnitude in the treatment of Pacific to Atlantic through-flow,
- along with little confidence in mean estimates, we have virtually no understanding of seasonal or interannual variability of ocean freshwater transports, a variable which has important dynamic and climatic influences.

Thus a serious effort must be mounted to improve our understanding of one of the ocean's most basic forcing functions. One approach is to model the oceanic response to a variety of plausible freshwater forcings and compare the results with known features of the ocean. Assimilative models must be developed and supplied with the best available data. However, fundamental issues such as the parameterization of mixing processes within the ocean remain unsolved. Certainly, we cannot begin to develop credible answers to the issues raised above without markedly better data on the space and time scales of ocean hydrologic forcing and improved understanding of the relevant ocean physics. A variety of approaches will be necessary to advance our knowledge of the marine hydrologic cycle, including:

- Incorporation of best available salinity and precipitation measurement techniques into air-sea interaction experiments and control volume surveys. The projects planned as a part of WOCE Core 3 activities in the North Atlantic offer new opportunities to advance fresh water budgeting techniques in a variety of E-P forcing conditions and to increase our understanding of ocean physics. Oceanographic field programmes should also be developed in the tropics to take advantage of the TRMM mission to occur in the mid-90s.
- Development and deployment of at-sea precipitation sensors (such as subsurface ambient noise measurements and surface buoy rain gauges). These are needed for ground truthing satellite estimates to determine sampling biases and sensor drift and along term monitoring in key climatological areas. R. Weller of Woods Hole is employing capacitive rain gauges on the WOCE sponsored IMET meteorology buoys to be deployed in the Core 3 Subduction experiment in the North Atlantic and the TOGA COARE programme in the tropical Pacific. He is also investigating the performance of optical rain gauges, piezoelectric

impact sensors and ambient noise measurements for rainfall.

- Improvement and deployment of stable, long-life salinity sensors for moorings, drifters and volunteer observing ships. Recent success in moored salinity measurements in the Pacific has been reported. Also, development of a very low power, self calibrating CTD has been proposed by N. Brown at Woods Hole. A long term goal should be the development of a synoptic salinity monitoring network as part of the World Ocean Observing System. A significant component of such a system may be the Slocum vehicle (Stommel, 1989) currently under development by D. Webb.
- Exploration of simple water mass formation models such as that of Huang, Luyten and Stommel (1991), as well as full GCMs, under plausible forcings and different ocean mixing parameterizations including double-diffusion (Huang and Stommel, in preparation).
- Re-examination of existing estimates of ocean hydrologic forcing to develop an understanding of the uncertainty in such data and to establish plausible forcing functions for models.
- Evaluation of the freshwater budgets of the ocean basins by repeated zonal sections, monitoring strait throughflows and ice volumes and use of best available E-P estimates from observations and models.
- Monitoring of transport and salinity of important straits (Bering, Gibraltar, Indonesian through-flow, Greenland, Iceland and Norwegian Sea overflows).

## OCEAN HEAT TRANSPORT

The continents and the mid-ocean ridges greatly influence the ocean circulation. Despite this, the circulations in the different ocean basins (Pacific, Atlantic and Indian) are linked through the Antarctic Circumpolar current and the Agulhas current. This gives a global coherence to the circulation of heat, freshwater and dissolved chemicals. Only of the order of one percent of the power supplied to the climate system ($100 \times 10^{15}$ W from the sun) is circulated around the globe by the ocean circulation, and nearly an equal amount by the winds.

A most important feature of the heat circulation by the ocean currents is the northward heat flux in the Atlantic Ocean, with the flow past Florida being estimated at $1.2 \times 10^{15}$ W. On the track northwards this flow loses about three-quarters of this amount to the atmosphere over the northern North Atlantic. This leaves one-quarter for the Greenland-Norwegian Sea, where the ocean carried heat keeps the sea ice-free in winter. The heat flux from the ocean into the Westerlies is about 100 megawatts/km$^2$ (Woods, 1984). This is one of the principle heat sources for the atmosphere. Natural fluctuations of only a few per cent of that heat exceed the anticipated greenhouse effect on the ocean during the next 50 years (about 6.5 megawatts/km$^2$ according to the "business as usual" scenario of the IPCC Report). These estimates provide a basis for judging the experiments of a global ocean observing system as far as information about this heat flux.

The ocean heat transport across 24°N in the Pacific has recently been re-evaluated by Bryden *et al.* (1991) on the basis of new data from the 1985 North Pacific hydrographic section, supplementing the data from the corresponding North Atlantic section. The Pacific and Atlantic sections at 24°N close off the world ocean since there is essentially no Indian Ocean north of 24°N. To reconcile the recent satellite measurements for the radiation budget at the top of the atmosphere, the ocean and atmosphere must together transport $5.3 \times 10^{15}$ W of heat poleward across 25°N.

The new direct estimates by Bryden *et al.* (1991) of the North Pacific heat transport give a northward transport across 24°N of $0.76 \times 10^{15}$ W with an error of approximately $0.3 \times 10^{15}$ W. The total ocean (Atlantic and Pacific) heat transport across 24°N is estimated to be $2.0 \times 10^{15}$ W northward. This is larger than the accepted value of northward atmospheric transport of $1.7 \times 10^{15}$ W. The ocean and atmosphere thus together transport $3.7 \times 10^{15}$ W northward. This value, however, is considerably less than the $5.3 \times 10^{15}$ W required by the recent satellite determinations of the Earth's radiation budget. We thus still have a "mystery" here in the heat balance of the climate system.

Lately, increasing attention has been given to how changes in the ocean circulation can significantly affect the climate irrespective of greenhouse forcing. Watts and Morantine (1991) examine the proposition that changes in the strength of the thermohaline circulation can result in surprisingly large variations in the ocean surface temperature. The physical mechanism is quite easy to understand. If basin-wide upwelling is decreased, the upward flow of heat due to upwelling would no longer balance the downward diffusive transport. Heat would therefore flow from the warmer upper ocean into the deeper ocean, temporarily cooling the surface layer while warming the water at intermediate depths. Watts and Morantine (1990), with a two-dimensional (depth-latitude) upwelling-diffusion model, showed that these conditions could result in a poleward amplification of the temperature fluctuation with a maximum near 60°N. With this model, a complete shut-down of upwelling in the world ocean leads to a 6°C drop at 60°N within 30 years followed by a slow recovery. It is just such a decrease that is suggested by Broecker *et al.* (1985) as leading to the dramatic cooling of the North Atlantic marking the Younger Dryas event. If indeed this phenomenon was caused by a cessation of North Atlantic upwelling, it is important to note it was fundamentally transient in nature.

Several investigators have found supporting evidence to suggest that a temporary interruption of upwelling may be the explanation for the absence of the expected greenhouse-induced temperature increase during the period between 1940-1970. Roemmich and Wunsch (1984) and Levitus (1989) assembled data sets that show a warming of .05°C near 1000 meters and a cooling above 500m during the 1955-59 time period as compared with the 1970-74 interval. Jones *et al.* (1987) used a simple energy balance model to show how an interruption of upwelling in the world ocean could cause surface temperature to temporarily decrease on average during greenhouse warming.

Rind and Chandler (1991) demonstrate with an atmospheric GCM that, without altering greenhouse gases, the entire range of temperatures experienced on Earth since the Jurassic (180 million years ago) could have been generated by a factor-of-two variation in ocean heat transport. Thus, although geological evidence, such as from the Vostok ice cores, shows $CO_2$ concentrations to be correlated with past global temperatures, the changing concentrations could be more the result of an altered ocean circulation than a primary cause of climatic variations. Covey (1991) compared the Rind and Chandler results with that of a complementary simulation by Covey and Thompson (1989). He finds it significant, despite their differing assumptions, that both studies conclude the climate resulting from enhanced oceanic heat transport is quite different from that resulting from the greenhouse effect, with much more warming at the poles and much less warming (even cooling in the Covey and Thompson simulation) in the tropics. If variations in ocean heat transport are responsible for the Earth's climate history, then using direct analogy with past climates to estimate global warming due to increasing greenhouse gases is a questionable exercise. This means more dependence will have to be placed on computer models than ever before. The eventual construction of validated, fully coupled models of the ocean, atmosphere, biosphere and cryosphere is a daunting goal requiring computer power not yet at hand. Until that goal comes closer to realization, oceanographers will have to be increasingly clever in designing experiments that are currently feasible that, step by step, put bounds on the range of possible cause-and-effect climate scenarios.

All these ocean heat transport studies pose difficult questions that need answers. The importance of the answers in developing a climate prediction capability underscores the need for future increased attention to the ocean's impact on climate.

## OCEAN CARBON CYCLE

Greenhouse gases in the atmosphere, such as carbon dioxide are part of vast natural cycles. For some greenhouse gases, the current rates of release which are directly attributable to human activities are small percentages of large natural fluxes between the atmosphere, the ocean and terrestrial ecosystems while for others, human activities result in dominant emissions. The atmospheric carbon content is a very small fraction of existing reservoirs of carbon in ocean waters and sediments. Relatively minor adjustments in the world ocean circulation and chemistry, or in the life cycle of terrestrial vegetation, could significantly affect the amount of $CO_2$ in the atmosphere, even were anthropogenic emissions to be stabilized. In particular, global warming is likely to decrease the absorption of carbon dioxide by sea water. Conversely, positive changes in the biogenic storage of carbon in the ocean could increase the oceanic $CO_2$ uptake and ameliorate the greenhouse effect.

Current knowledge of oceanic and terrestrial biogeochemical processes is not yet sufficient to account quantitatively for exchanges between the atmosphere, ocean and land vegetation. Investigations are currently underway to investigate the oceanic biogeochemical processes relating the cycle of carbon in the ocean and to assess the capacity of the ocean for absorbing $CO_2$. A central question being addressed relates to the role of the ocean and its circulation in the uptake of $CO_2$ produced from the burning of fossil fuels. This uptake occurs via both physical and biological processes. Neither is well quantified on a global scale, and the regulation of the biological processes is at present only poorly understood. In particular, the biogeochemical processes responsible for the long-term storage of a portion of the total primary production cannot at this time be resolved sufficiently in time and space to say how they might be affected by climate change. Current $CO_2$ issues which are being addressed are centered on the following four topics:

(i) **Recognition of the Oceanic Anthropogenic $CO_2$ Signal** -- The fossil fuel $CO_2$ increment which has entered the ocean is a modest addition to that present from the natural carbon cycle (e.g. in the upper few hundred meters, on the order of a 25% increase in $pCO_2$ (an index of gaseous $CO_2$ in seawater) over pre-industrial values). In addition, it is difficult to describe due to the biological cycling of carbon. Nevertheless, the accuracy of today's measurement techniques ($\pm$ 1 micromol/kg for $TCO_2$) makes it possible to estimate and subtract the contributions to $TCO_2$ and alkalinity due to biological activity, i.e., from respiration and $CaCO_3$ dissolution. Several approaches to this problem are being reviewed and also the perturbations likely to affect the kinetics of key processes in response to a small increase in global ocean temperature.

(ii) **Remote Sensing** -- Satellite observations of ocean color, winds and sea-surface temperature in association with models can be used to describe and define the surface ocean $pCO_2$ globally. Sinks and sources and their change over time can be recognized. Increased attention and effort should be devoted to international exchange and access to such data. Data sets, including information on the validation of the algorithms used to derive them, should be made easily available to every interested scientist.

(iii) **Measuring Ocean $CO_2$** -- Data needed to describe the oceanic $CO_2$ system completely, could never be collected using conventional sampling and be measured from surface ships. Time and space scales demand technologies providing continuous data streams from many places. There are promising prospects for moored sensors for pH and $pCO_2$ measurement that have prospects for use on unattended buoys and on ships of opportunity. Currently, there seems to be little hope, however, that such ships could measure total $CO_2$. The Joint Global Ocean Flux Study (JGOFS) in collaboration with the World Ocean Circulation Experiment (WOCE) Hydrographic Programme, are providing a once-in-a-lifetime opportunity to assemble a high-quality, 3-D, global $CO_2$ data set with all the accompanying data to be acquired by WOCE. All potential participating countries should reexamine their $CO_2$ programme plans and make every effort to make the most of this opportunity. Data to be collected should include global scale survey measurements of surface carbon properties to define the size of the present ocean sink and time series measurements for process studies and model development to obtain a deeper understanding of the nature of the carbon cycle.

(iv) **Modelling/Data Analysis/Algorithms** -- The complexities of the ocean carbon system and the necessity for making forward predictions lead to the central role of modelling. Current activities in modelling the atmospheric and ocean transport of $CO_2$ and associated data needs are being reviewed. So, in like fashion, are computational techniques to relate remotely sensed and *in situ* data to descriptors of oceanic $CO_2$ and biological productivity.

For improving the existing models of the carbon cycle in the ocean and atmosphere, a high-precision 3-D global set of observations of the oceanic $CO_2$ system is required. A unique possibility to obtain such observations, accompanied by hydrographic and nutrient data of unprecedented quality, is provided through the co-ordinated efforts of JGOFS and the WOCE Hydrographic Programme described in section (iii).

Atmospheric models offer the potential to provide constraints or methods for validation on models of the ocean carbon system. Increased interdisciplinary interaction between the atmospheric and marine physical/chemistry/biology communities is needed to exploit this potential.

## SEA LEVEL CHANGE

The actual determination of changes in relative sea level is an extremely complex and time-consuming task. It involves the consideration of many factors, and requires decades of high-quality observations, data analysis and modelling. A large number of effects are now thought to be at least as important as melting of ice sheets. Most of these other factors are site-specific rather than global. In fact, in many parts of the world, relative mean sea level is falling rather than rising, and may continue to do so despite greenhouse warming. Thus, one should speak of sea level change rather than sea level rise. Because the sea level change that concerns us reflects both movement of the sea level and the level of adjacent land, we don't measure absolute sea level, but rather relative sea level. In general terms we can identify the sources of sea level change affecting relative mean sea level (RMSL) as originating from the following four categories:

These may be subdivided as follows:

**A. Those which determine water volume**

(1) Change in the mass of the ocean as a result of melting or accumulation of land-supported ice in the great ice sheets of Antarctica and Greenland, and in the smaller ice sheets and mountain glaciers.

(2) Change in the volume of water in the ocean by heating or cooling, leading to expansion or contraction, and thus to a steric rise or fall of sea level.

**B. Those which determine sea surface shape**

(1) Change in the way in which water is piled up against, or pushed away from coasts by the local wind field.

(2) Changes in the atmospheric surface pressure field.

(3) Changes in river run-off regimes.

(4) Changes in ocean currents caused by changes in the wind field over the ocean basin.

## C. Coastal subsidence

(1) Changes in the thickness of coastal unconsolidated sediments, caused by sediment deposit, erosion, compaction or consolidation of sediments, or the withdrawal of fluids from the sediments.

(2) Crustal movements of coastal areas, relative to the geoid.

## D. Large scale crustal and subcrustal movements

(1) Changes in the depth of the ocean basins.

(2) Changes in the geoid, mainly due to change in the volume of ice and to flows in the earth's mantle.

With the conclusion that very rapid melting of the great ice sheets is unlikely, none of these influences can be neglected relative to the others. It is common experience that smaller ice sheets and glaciers have lost mass during the past century. Meier (1984) concludes that this effect has contributed about 0.4 mm/a to sea level rise. There remains the equivalent of about 50 cm of sea level rise in such bodies of ice, should they all be melted. It is noteworthy that with the exception of numbers A(1) and D(1) above, and some possible aspects of A(2), these influences are local or regional, rather than global. Thus, changes in relative mean sea level differ substantially from place to place and from region to region. These differences can be expected to continue into the next century although there may well be a bias towards accelerated sea-level rise everywhere.

Almost all relative mean sea level change over the past century, apart from that caused by small ice field melting (Meier, 1984), has been the result of earth movements. We are living in a geologically unusual time (Rice and Fairbridge, 1975), since it is only about 10,000 years since the end of the most recent northern hemisphere glaciation and the earth is still recovering (rapidly on a geological time scale) from this event.

The nature of this recovery is such that it is still producing very significant effects upon sea levels (e.g. Peltier and Tushingham, 1989, 1990). Over a few thousand years, as the glaciers receded, something like $5 \times 10^{19}$ kg of water was added to the ocean, mostly from the northern hemisphere although with some Antarctic contribution (Nakada and Lambeck, 1989, Peltier and Tushingham, 1990). The ocean is mostly in the southern hemisphere, so the centre of mass of this water moved several thousand kilometers south. In response, the centre of mass of the solid parts of the earth moved north some tens of meters. This rearrangement of mass led to increased pressure on the bottom of the oceans, with no corresponding change on land except on the land which had been bearing the load of ice, which now experienced a great reduction in pressure. The resulting stress field in the earth led to flows in the earth's mantle. These continue to the present day, although since this is a relaxation process, the rate of change has decreased. Mantle material is flowing in under the areas formerly glaciated, causing them to rise relative to the geoid and to sea level (e.g. Stewart, 1989c). These flows are causing the geoid itself to change. To a lesser extent the same is occurring under other land masses, which can be pictured as floating up because of the deeper ocean. Mantle material is flowing out from under the ocean basins, causing them to sink, taking the ocean down with them.

There are other causes for substantial vertical movement of the land. For example, along many active margins, where subduction of one plate under another is taking place, the crust may crumple under compression, leading to uplift in some areas and sinking in others, perhaps within only about 100 km of each other. Such motions can be of as fast as 2 mm/a. They are probably shortlived on a geological time scale, but persistent on a human scale (e.g. Riddihough, 1982).

Other processes, some of which are influenced or induced by human activity, can substantially affect the level of the land surface, without much changing the level of the underlying rock. In the normal course of events, loose unconsolidated near-surface sediments become more compact with time. Water is squeezed out, pores become smaller and grains become cemented together. The density increases and the surface level sinks. This is a natural process, gradually giving rise to semi-consolidated sediments and ultimately to sedimentary rock. However, the withdrawal of fluids, usually water but also oil and natural gas, from near-surface sediments can hasten the compaction of these sediments and lead to a drop in the land level and therefore to a relative sea-level rise. This influence is observed in such places as Venice and Bangkok (Milliman *et al.*, 1989). In recent years, Bangkok has been sinking at a rate greater than any other major city, indeed at a rate greater than almost all estimates for greenhouse-gas induced sea-level rise.

Other human activities have influenced relative sea level. The natural sediment flow has been altered in many ways. For example, rivers have been dammed and/or diverted to irrigation projects, so that the sediment load never reaches the coastline. The situation at the mouth of the Nile is an outstanding example, where the construction of the high Aswan dam has largely eliminated the flow of sediment to the coast, which is now experiencing very rapid change (Milliman *et al.*, 1989). Levees and dykes have been constructed, and river channels are dredged, so that floods are inhibited; water and sediment flow out through defined channels rather than spreading over the deltas. Sinking and compacting sediments are then not renewed by additional layers, elevation of the surface relative to sea level drops, and the area becomes increasingly vulnerable to inundation from the sea. This effect can be seen clearly in the area of the Mississippi delta (Wells and Coleman, 1987, Coleman, 1976).

Expansion of the ocean by heating, and sea-level changes associated with changes in ocean currents show up in measurements as a change in the steric effect[4]. Modern techniques permit determination of steric effects on sea level with an accuracy of about 1 cm, although fluctuations associated with internal waves mean that such accuracies are attainable in the mean only if a great deal of averaging is possible.

Salinity also influences the steric effect on sea level. Thus the difference between evaporation and precipitation in any area changes sea level. Perhaps more importantly, the addition of large volumes of river water in a relatively localized region causes very significant dilution with an accompanying halosteric rise of sea level. Since river flow is usually quite variable on all time scales, in many estuarine regions halosteric effects contribute importantly to the fluctuations of sea level. For example, due to monsoon runoff, the upper Bay of Bengal experiences a seasonal halosteric effect approximating 1 meter (Pattullo *et al.*, 1955).

Even at depths of hundreds of meters in deep water, time-dependent halosteric effects of unknown origin have been observed to amount to several centimeters (e.g. Thomson and Tabata, 1989, Levitus 1989.)

It is difficult to see any mechanism that would lead to a significant thermosteric rise of more than a few centimeters within a century, before there is a greater rise of sea surface temperature than the half degree which seems to have occurred. Thus thermosteric effects are unlikely to be playing a very important role at the present time. However the nature of ocean circulation is sufficiently poorly understood that it may yet hold surprises, and monitoring for any possible steric rise should be an integral part of sea-level rise study.

It is clear that relative mean sea level can either rise or fall locally as a result of a combination of factors. As most lesser developed countries are located in low latitudes more likely to experience a relative rise rather than fall of sea level, it is important to address some probable consequences of relative mean sea level rise. There is no reason to suspect that there will be any particular exacerbation of problems associated with dropping relative sea level, although they will continue to occur in some areas, particularly at high latitudes.

It is important to recognize that relative mean sea level changes which may take place in a few decades are in fact rather small compared with changes in sea level which take place on much shorter time frames. There are few places in the world where the tidal range is much less than a meter, and a tidal range of five meters is far from unusual. It is quite normal for the difference between high neap tides and high spring tides to be more than a meter. Storm surges of elevation 50 cm are very common everywhere, and in regions subject to tropical storms such surges may be an order of magnitude larger. Ordinary weather changes, with corresponding changes in wind fields, can result in changes in sea level of around 20 cm, and the annual heating-cooling and runoff cycles, together with associated wind field changes, lead to seasonal sea level cycles of the same magnitude but up to 1 m in exceptional cases like the Bay of Bengal. Sea-level records typically show interannual fluctuations of the order of 10 cm, which sometimes persist for a few years before being reversed (Pugh, 1987; Thompson and Tabata, 1989). Some such changes are the result of causes which are not clearly identifiable.

A higher relative mean sea level will cause flooding associated with some combination of these events to occur more frequently. However, one is dealing with the statistics of small numbers and it will be difficult for the public to interpret such an increase in the frequency of occasional events, even if it is noticed at all.

Thus a higher relative mean sea level most usually will not be noticed by the general public as an insidious, gradual rise but by some extraordinary event. If sea level has risen significantly, and if chance produces a coincidence among, for example, a high spring tide, the seasonal sea-level high and a strong storm surge, the combination may raise the sea to unprecedented levels, inundating areas which had not before been flooded. Since the storm surge will most usually be accompanied by strong wave action, damage will be done to areas which had heretofore been considered too high or too far inland to be affected.

These formerly untouched areas are likely to have some properties making them very vulnerable, including vegetation with low tolerance to salt water and unconsolidated sediments and soils which could be dramatically rearranged by the water. Some of these effects can in fact be assessed now, since river diversion and dam-building often alters river environments into brackish and saline estuarine waters. As the soil salinity increases, the original vegetation can die off on time scales from months to years if the marine inundation persists for any length of time (Kjerfve, 1976; Bradley *et al.*, 1990). These affected areas are then frequently recolonized by salt marsh or mangrove vegetation, as long as they continue to experience marine tidal flooding, although the time-scale of recolonization is measured in years.

Closer to the ocean, areas which had in the past occasionally been inundated only very rarely might find themselves covered with enough water to sustain appreciable waves, leading to significant changes on the bottom. Also structures not designed to resist wave

[4]The steric effect describes the effect of the difference in the volume of a mass of water relative to the volume at a standard salinity and temperature (e.g. Pattullo et al., 1955). If water has higher temperature and/or lower salinity than the standard, then for a given pressure at the bottom the surface will stand higher than would be the case for water at standard salinity and temperature. Thus heating or diluting sea water, at any depth, leads to a steric rise of the surface. Steric effects due to temperature differences are referred to as thermosteric, while those due to salinity differences are halosteric.

action could be damaged or destroyed.

The particular condition of the river at the time of the unusually high sea level can also influence the degree of flooding. The details of the coastline can interact with the details of the trajectory of a storm in ways that can either exacerbate or ameliorate the situation. Thus, areas which relative mean sea-level rise had made much more vulnerable might escape unscathed for long periods of time, while other areas, in principle less subject to damage might be devastated by some freak combination of events. Chance plays a significant role in these events. Wave set-up, for example, can add tens of centimeters to the sea level at some locations along the shore (Longuet-Higgins and Stewart, 1964; Tait, 1972), perhaps without affecting an adjacent tide gauge, which might even experience wave set-down.

One likely local effect of increasing relative mean sea level is accelerated coastal erosion. An increase in sea level would result in more severe wave erosion of dunes and beaches and a resultant offshore sediment transport to create a flatter offshore beach profile (Bruun, 1962; National Research Council, 1987). Although this would occur episodically in response to storm wave events, the result would be a diminishment of local beach environments as sand sediments are transported offshore beyond the depth at which they participate in seasonal onshore-offshore sediment cycles.

Of course the more insidious effects will also take place if a location experiences relative mean sea level rise. The boundary between fresh and brackish water in aquifers will retreat upward and landward. The resulting contamination of freshwater aquifers will, no doubt, have major adverse impact on coastal population centres, which often rely on groundwater for drinking water. Also, a salt water wedge of bottom marine water will intrude a greater distance upstream in stratified estuaries, and tidal mixing will extend the estuarine zone further upstream in partially and well mixed estuaries. The end result, in both cases, will be an inland intrusion of the marine or brackish water zone.

As the estuarine salinity zone moves further inland, in areas experiencing relative mean sea level rise, there are likely to be dramatic effects not only on the adjacent bank and wetland vegetation, but also on coastal primary and secondary productivity. Undoubtedly the coastal terrestrial vegetation will be stunted or destroyed. Whether the long-term effect will cause increased or decreased marine primary production is highly speculative.

On time-scales of a century, however, it seems reasonable to expect increased production by salt marshes, mangroves, benthic algae, and coastal phytoplankton production as a result of inland erosion induced by a relative sea level rise. For example, a significant increase in production of *Spartina alterniflora* cord grass in South Carolina salt marshes is positively correlated with years of detrended, anomalously high mean sea levels during the growing season (Morris *et al.*, 1990). One explanation for this is that the anomalously high mean sea level implies a greater likelihood that nutrient exchange can take place between estuarine waters and the adjacent marsh.

Morris *et al.* (1990) also found a significant positive correlation between the years of anomalously high mean sea level and commercial landings of *Peneaus* shrimp and menhaden (*Brevoortia* spp.) for years from the Southeastern and Gulf coasts of the USA. Since these species utilize the *Spartina* marshes as juveniles, both increased habitat area and available food sources can be used to suggest the role of high sea level anomalies in explaining increased secondary coastal production. These results are also consistent with positive correlations between shrimp landings and size of adjacent intertidal wetlands for salt marsh (Turner, 1977; Turner and Boesch, 1988) and mangrove (Martusubroto and Maamin, 1977) environments.

Since both relative sea-level change and the nature of the areas under threat are site specific, any international programme designed to deal with the situation should also have strong site-specific features (e.g. van de Plassche, 1986). An important characteristic of such a programme is that it should stress learning-from-each-other, and the sharing of such equipment as is both expensive and only occasionally used.

The first, and *sine qua non*, requirement is a suitable tide gauge network, carefully maintained, and subject to careful data analysis and regular careful vertical control. Because of the site-specific character of the task at hand, the need cannot be met by the sparse Sea Level Observing System (GLOSS) network (Pugh, 1987), valuable as that network is for determining ocean-scale variations in sea level. Each stretch of coast threatened by inundation in the event of abnormally high sea level (say 1 meter above the highest astronomical tides) should have a well-sited tide gauge. To the extent possible tide gauges should be sited in locations particularly suitable for determining long term changes in RMSL. Such locations will frequently not be in ports or at military installations, where most existing gauges are sited.

Dealing with relative mean sea level change involves the responsibilities of many agencies and jurisdictions, and many levels of government. Some aspects are global; others are very local. Some aspects require a research emphasis, best met by involving university and research institute personnel. Monitoring over long periods of time is best undertaken by government agencies with personnel and terms of reference attuned to this task, which is closely analogous to that undertaken by weather services. However, there should be close association, which may or may not be reinforced by institutional arrangements, between those responsible for the research and those responsible for the monitoring. Such association strengthens the motivation of those undertaking the monitoring, and thereby improves the quality of the data. At the same time, it gives those undertaking the research a realistic understanding of the nature and limitations of the data set. It also permits improvements and modifications to be made in the way in which data is collected and archived, without destroying the continuity and comparability needed for valid interpretation.

## LIVING MARINE RESOURCES

Cushing (unpublished, 1990) in a recent review, and Crawford *et al.* (1990) brought out several examples from the world's oceans showing strong influence of climatic conditions on recruitment and fisheries. Cushing considers that strong evidence has emerged of the link between recruitment and climatic factors, drawing an example from the northeast Atlantic; the ocean off Alaska and California; the Indian Ocean and the Pacific Ocean. The climatic factors involved are diverse: wind patterns and their changes; convergences and divergences, in some cases across the ocean basin; changes in upwelling distribution/intensity; changes in seasonality (spring heating-stratification); atmospheric depressions; changes (slowdown) in production of cool water.

According to Cushing it is more difficult to demonstrate the effect of climatic change on fisheries, despite the fact that the change is a consequence of the play of climatic factors. High negative and positive correlations are found between trends in temperature and catches of herring and sardines (Kawasaki, 1983; 1991). Good sardine and poor herring catches occurred when the global temperature was high (1940 and mid 1980s). Conversely, poor sardine and good herring catches were experienced when the global temperature was low (mid 1880s and 1960s). Cushing states that "we may speculate that the enormous changes in catches since the twenties were driven by long-term, pan-oceanic changes in the wind distributions".

On the basis of the review, three requirements from marine research are identified:

(i) study of growth and mortality of fish larvae from spawning ground to nursery ground to the time of metamorphosis or just after;

(ii) studies of the effects of the physical processes on the drift of larvae and juveniles, as these processes affect the estimates of growth and mortality; and

(iii) examination of past events in climate change (or climate variability) and the results of such changes; examples include the North Sea case in changes in northerly winds; the El Niño/Southern Oscillation; the North Atlantic Oscillation; the Quasi-Biennial Oscillation.

Climatic change, being an effect of the interaction of climatic factors in time -- a broad array of investigations is needed to elucidate in more detail the effects of various climatic factors.

There is an essential need for active co-operation between physical oceanographers and atmospheric scientists on the one hand and fisheries biologists and biological oceanographers on the other. The co-operation should be continuous. The dialogue and mutual understanding must increase.

## IMPACTS OF CLIMATE CHANGE: ISLAND AND ARCHIPELAGIC STATES

Recent assessments of climate change impacts on small islands include those conducted through the UNEP-IOC Regional Task Teams on climate-change implications. The most comprehensive include studies of the Maldives and of various Pacific and Caribbean Islands. For most small archipelagic states the entire land area may be considered "coastal" in that it is directly influenced by and influences the inshore waters. Few studies to date appear to have attempted a comparative ranking of the vulnerability of areas, regions or countries. One comparative algorithm for the islands of the Pacific Basin has been developed and used to identify priority countries within the region.

Small archipelagic states are among the most vulnerable in the world to the potential impacts of climatic change and sea-level rise. Delegates from small states to the Second Preparatory Committee Meeting of UNCED stressed the need to take immediate and effective action. The Ministerial Level Meeting of 14 small states, in Malè in 1989 amplified their needs and called on the UN and other international bodies to assist. To date, the response has been limited.

Whilst the potential impacts identified for coastal zones in general are equally applicable to small island nations, such countries are also subject to constraints and potential impacts in coastal states having higher altitudes and more extensive inland areas. The distinctions between such "archipelagic" and "coastal" states are already drawn within the UN Convention on the Law of the Sea (UNCLOS) and such states may merit particular consideration within the framework of future attempts at managing the global marine environment.

One critical and frequently limiting factor on small islands is the freshwater supply which is derived from rainfall stored in underground aquifers. Aquifers are small freshwater lenses floating on the seawater. Aquifer volumes reflect island area and the underlying geology. On many islands current supplies are already limiting development and agriculture. Higher sea level will ultimately reduce aquifer volumes, thus reducing the carrying capacity of the island. For island communities, desalination is prohibitively expensive, increasing the dependence of the country on imported fossil fuels.

Small archipelagic states have limited land areas that are close to sea-level. In atoll states such as Kiribati, the Marshall Islands, Maldives and Tuvalu, up to 80% of land is less than 1m above sea level. In high islands most agricultural land is at or close to sea-level. Most infrastructure development, including roads, airports and communication networks, are coastal in location, often flooded by spring high tides. A small rise in sea level may result in substantial losses in total land area. Changes in stability pose threats to the continued existence of such islands. Coastal erosion is already a problem for many Pacific islands which will be accentuated by sea-level rise and which threaten their economy.

It has been suggested by the IPCC that since atolls survived past conditions of rising sea level they will keep pace with rising sea level. Such perceived "truth" is open to serious questions given the lack of present knowledge concerning various biological and physical processes in atoll systems. It is well known amongst coral reef biologists that not all coral reefs "kept-up" with past rising sea levels, some "gave-up" and some "caught-up" following initial inundation. The reasons why individual reefs responded in these different ways are unknown at the present time.

A number of researchers have drawn attention to the increasing frequency of coral bleaching and mortality, apparently as a consequence of high temperature anomalies. Changes in corallivore populations apparently as a response to small scale changes in ocean circulation and higher water temperatures are known to have occurred in a number of reef systems. Studies and reviews have clearly shown that coral reef systems are already stressed in many areas of the world as a consequence of human activity. Current and predicted changes will affect the ability of reef systems to respond to rising sea level and this seriously undermines the view that all atoll islands will survive climatic changes and sea-level rise.

Similar statements relating to the ability of marshes and mangroves to respond without significant change have also been made. Various studies suggest, however, that mangroves will be unable to keep pace with rising sea levels unless allochthonous sediment inputs are increased; that wetlands soil chemistry may change such that peat reserves are depleted; and that certain ecotones of marsh communities may be disproportionately reduced in extent.

Any changes in that frequency, intensity or distribution of tropical cycles or hurricanes could potentially have devastating effects on small island communities particularly where urbanization has formed aggregations of people on islands with restricted land areas and little or no high ground.

The diversity of the terrestrial flora and fauna of islands is limited, although islands contain a disproportionate number of endemic species and species with restricted distributions. The high salinity, alkalinity, pH and low fertility of many island soils, and the limited freshwater limit agricultural potential. Any changes in rainfall and temperature as a consequence of climatic change will further limit this potential. The eco-physiological tolerances of many tropical crops restrict the range of potential introductions which might be made.

Islands are home to a disproportionately large section of the world's cultural and linguistic diversity with each island community having its own cultural traditions, scientific and traditional knowledge base. Over a third of the world's languages are spoken in the archipelagic countries of Melanesia. Maintaining such cultural integrity would be impossible if such communities were relocated.

Island communities are highly dependent on the marine environment and resources both for subsistence and commercial productions. Their store of knowledge concerning the marine environment and its resources is more detailed and sophisticated than that of western science. Any change to biological productivity within the areas of their Exclusive Economic Zones would have dramatic impacts on the capacity of such countries to achieve sustainable development. The ability of such fragile economies to respond to the constraints imposed by the need to adopt mitigation measures for climatic change impacts is severely limited.

Many similar island countries in the tropics and sub-tropics are dependent upon tuna as a major source of export earnings. Climate-change impacts on the distribution of such stocks may not be great although this is uncertain. In contrast, the potential impacts on reef fish stocks are likely to be greater, given predicted changes to coral reefs, threatening the basis of the subsistence economy. A major source of income for island countries is tourism, particularly associated with coral reefs. Any decline in the amenity value of reefs, beaches and climate following climatic change and sea-level rise could reduce tourist related income.

A high proportion of the Least Developed Countries identified by the UN are small island countries. The fragility of insular economies is well illustrated by that of the Maldives which has received a number of setbacks during the last two decades. Seventy percent of government revenue in the Maldives is directly derived from tourism and fisheries. Both are subject to external influence.

A further constraint to response on the part of small island states to potential impacts is the limited pool of scientific and technical expertise available to respond to the need for integrated coastal zone management and mitigation measures for potential future impacts. The Maldives, for example, have, out of a population of 214,000 people, only 219 first degree holders in all disciplines, a few Masters degrees and one Ph.D.

The constraints imposed by small land areas, huge exclusive economic zones (land areas are generally less than 0.001% of the EEZ) and consequently large maritime distances separating population centers; the small, narrow, marine-based economies; and the lack of skilled manpower and expertise, all render the achievement of sustainable development in such states a monumental if not impossible task. The imposition of the added burden, of planning for and taking measures to mitigate the impacts of climatic change and sea level rise may place the achievement of sustainable development beyond the reach of many small island states.

Although the small island states have contributed little to the problem of global climatic change they are, nevertheless, the countries which are likely to feel the impacts first and potentially might be the worst affected. It cannot be stated categorically that any small state will cease to exist as a consequence of global climatic change and sea-level rise, but the possibility that several states may become uninhabitable or completely unviable economically must be accepted.

In the case of small islands, two of the three response strategies advocated by the IPCC subgroup on coastal zone management, namely retreat and protection, are not possible whilst the third, accommodation, may not be possible within the existing economic and environmental conditions. Transferring solutions and models from larger coastal countries to small islands will not work. Holistic management of the total environment and development problems in island countries is a vital necessity in the face of global climatic change and sea-level rise.

From the perspective of small island states, therefore, emission control is viewed as a positive necessity. The need for international legal agreements to provide assistance in evaluation, monitoring, management and planning for environmental changes are of paramount importance. In the context of their endogenous capacity to respond to the present problems, small island countries must be considered as particularly disadvantaged and therefore in need of preferential treatment in the framework of any global agreements concerning this issue.

## Vulnerable Coastal Areas and States

Numerous publications have been produced recently on global climate change impacts in the coastal zone including the report of Working Group II of the IPCC and the reports of the UNEP, IOC Regional Task Teams. Individual studies have lacked clarity in the initially defined objectives, or have failed to define the changed conditions or the time frame under which projected scenarios will occur. Most reviews have listed broad areas of impact, but few have considered the implications of several different scenarios with specified time frames for the same geographic location. This has resulted in a lack of direct comparability between individual studies, which has made it difficult to evaluate and compare the results of individual assessments.

Climatic-change impacts in coastal areas will be both diverse and extensive including alterations to physical, biological and human elements. More detailed understanding of the functioning of coastal systems is required to facilitate impact prediction, planning and management. The diversity of local environmental conditions compounds the difficulty of making accurate predictions on local scales. Most studies relating to global-change impacts in coastal areas that have concentrated on the potential impacts of sea-level rise, have either neglected climatic parameters completely or inadequately addressed socio-economic considerations. Attempts at developing policy directions have been based on generalizations of impacts rather than on specific analyses for particular countries or areas.

The Regional Seas Task Team for the Mediterranean produced around fifteen studies and reviews of impacts covering agricultural, social and economic features of the region. They concluded that predicted social and economic changes may outweigh the impacts of climatic changes in this region over the next 50 years. Similar, less immediately obvious conclusions were drawn by the regional task team for the South Pacific which concluded that a major impact on Papua New Guinea might well be the expansion of the region of endemic malaria into the central highlands. Such examples demonstrate the need for a co-ordinated and multi-disciplinary approach to impact assessment rather than a narrow sectoral approach. Potential impacts may be directly related to temperature and other components of climate, including episodic events, or to changes in sea level, or to the combined interaction between several such factors. Establishing whether observed changes result from global climate change due to anthropogenic or natural causes will be a major challenge for the immediate future.

Predicted changes include: increased air and sea surface temperatures, changes to local climates and weather, changed patterns of winds and rainfall in time and space. On a local scale, changes in air temperature cannot be predicted accurately since air temperatures will be affected by local topography and by changes in other local microclimatic parameters including rainfall and wind patterns. Regional, sub-regional and local changes in rainfall and wind patterns cannot be predicted accurately. Secondary impacts include changes in relative humidity, in run-off and river flow rates, in coastal soil fertility, in distribution of coastal biomes, in coastal current and wave regimes, stratification/mixing, in the location and/or persistence of oceanic frontal systems, in salinity and coastal water chemistry, in the distribution, intensity and frequency of storms, in coastal flooding and changes in human comfort at specific locations.

Frequency of coastal flooding would be increased by a rise in sea level. Flooding occurrences would also be changed by alterations to coastal current regimes affecting wave climates, by changed storm patterns and by changes in rainfall which might enhance river based flooding in major river systems. It has been suggested that a general world-wide increase in inundation is likely and the impacts of such changes can only be moderated by correctly planned development of the coast based on an assessment of vulnerability in both the short and long-term. River flooding will be affected by changes in the temporal distribution and absolute volumes of rainfall, and may be exacerbated or mitigated by anthropogenic activities within watersheds.

The inter-connections, feed-back loops and consequences of changes in single physical parameters mean that impacts cannot be assessed on a sectoral basis and a systems approach to untangling potential impacts is imperative. For example, changes in rainfall and temperature will affect relative humidity which will alter evapo-transpiration rates hence affecting the hydrological cycle and local water balance. Such changes will affect coastal vegetation distribution and abundance which will in turn alter animal distribution and abundance and the overall productivity of natural and agricultural systems on land. Such changes will also affect human drinking water supplies and require changes in freshwater management practices. In addition these changes will alter coastal water salinity and mixing which will change coastal marine ecosystems, fish production and mariculture. All of which will have varying social and economic impacts in different areas.

For many coastal cities reliant, at present, on groundwater supplies, increasing sea level will restrict the volume of available freshwater, and saline intrusion will increase. It may result in changes to coastal vegetation, agriculture and soil fertility as well. Changes to riverine and groundwater supplies of freshwater will alter sediment and nutrient inputs to coastal and near-shore areas and will change the salinity regimes of currently productive coastal marine ecosystems. Whilst total global fisheries production is not expected to decline as a consequence of global climatic changes, changes in the geographic location and extent of important commercial fisheries may be expected as a consequence of changes in the global ocean circulation and, at a local scale, as a consequence of changes in coastal water productivity. Such changes could have important implications for established fisheries and on the economies of whole countries which are currently dependent on development income from fisheries.

Coastal ecosystems are likely to suffer considerable impacts as a consequence of predicted changes. Coral reefs may be one such system. They are areas of high biodiversity being the marine equivalent of tropical rainforests as sources of species, genetic and ecosystem diversity. The potential impacts of changes to coastal fisheries are well illustrated by changes along the Pacific Coast of Latin America, when raised coastal water temperatures occur during El Niño years. Abundances of demersal and coastal fish change, with warm water species replacing those normally characteristic of these fisheries. Such changes in species composition and abundance place economic and technological strains on local fishing communities requiring adaptation of catch, processing and marketing technologies and local knowledge of changed fishing grounds.

Understanding the nature of potential impacts at a local level requires data and models which describe the current local situation and yield detailed local-level predictions of future climates. Given that regional climate predictions may not be available for one or more decades, priority will need to be given to improving the state of knowledge concerning coastal zones at local, regional and global levels and to ensuring that compatible data acquisition and exchange systems are in place in time to feed appropriate data into the regional models as they are developed.

The consequences of sea-level rise are more likely to be experienced by less-developed countries and include: increased frequency and extent of flooding; rearrangement of coastal unconsolidated sediments and soils; increased soil salinity in areas previously unaffected; changed wave climates; accelerated dune and beach erosion; upward and landward retreat of the boundary between freshwater and brackish waters; greater upstream intrusion of saltwater wedges; and changes to bank and wetland vegetation; changes in the physical location of the terrestrial aquatic boundary; changes in coastal water clarity and circulation; and changes in sediment sink volumes. The magnitude of such changes is difficult to predict.

As a consequence of the primary impacts, a variety of secondary impacts can be identified which include amongst others: changes in off-shore bottom profiles; changes in sediment and nutrient flux rates; changes in marine primary production; and changes in terrestrial (coastal) primary production. A simplified consideration of sediment sources and sinks illustrates the problems of quantifying future changes. Essentially, sediments in coastal areas originate as a consequence of land-based erosion. They are carried by rivers to coastal areas and, ultimately, some are removed from coastal environments and deposited in oceanic sinks. During this process, sediments may remain temporarily in one or more of several locations, including river beds, flood plains, deltas, dunes and beaches. Any rise in sea-level effectively increases the volumes of all these sinks resulting in potentially increased residence times at each transitory sink along the way. Less sediment may arrive at the coast per unit time and the supply of sediment to beaches down current may be reduced resulting in erosion. In an accreting area with high sediment inputs, rising sea-level may result in a slowing and/or cessation of accretion depending upon the balance between inputs and the increasing volume of the coastal sink. Changes of sediment levels in coastal waters may enhance primary production by increasing nutrient availability or reduce it by increasing turbidity. Any concurrent changes to the sediment inputs resulting from natural causes such as changed rainfall patterns, or anthropogenic influences via changes to land use in the catchment, and/or management of river flows, would further alter this balance.

Such complex interactions and feedback loops make the prediction of physical changes to coastlines due solely to rising sea level, difficult if not impossible at the present time. Certain critical areas of impact resulting from second and higher order changes may be identified. For example changes in beach plan form will alter current and wave regimes and hence local patterns of erosion and deposition and distribution of sub-tidal substrate types. Changes to substrates will alter the distribution patterns of benthic organisms, while changes in coastal currents will alter recruitment patterns of benthic populations. Such changes alter vulnerability of the coastline to wave attack, flooding and inundation and thus affect capital investment in construction and the suitability of coastal areas for settlement.

Changes in nutrient levels in coastal waters will change marine based primary productivity and may change the frequency of harmful algal blooms impacting fish and shellfish resources, thereby affecting subsistence and commercial activities. Changes in marine primary production will affect energy flow to and standing stocks of, higher trophic levels including finfish for human consumption. Such changes will alter the economic viability of living-resource based activities by affecting commercially important species such as penaeid prawns and shrimp. Changes in the salinity of coastal wetlands may also alter the distributions of human disease vectors hence, changing the epidemiology of vector borne diseases.

In many coastal areas current economic and social activities are exacerbating an already critical situation. Potential impacts of climatic change and sea-level rise are over-shadowed in many areas by existing problems of environmental management and current, environmentally unsound development practices will increase susceptibility to predicted global climatic change impacts. Some coastal states are particularly vulnerable, for example between 8 and 10 million people live within one meter above sea level in each of the unprotected river deltas of Bangladesh, Egypt and Vietnam. Major centers of population such as Sydney, Shanghai, Louisiana and Bangkok are particularly vulnerable. The ability of developing countries to respond to local or national threat is severely constrained by economic considerations.

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# Appendix I

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# Appendix II

## GLOSSARY OF ACRONYMS AND SPECIAL TERMS

| | |
|---|---|
| B & R | Baumgartner and Reichel |
| CalCOFI | California Co-operative Fisheries Investigations (USA) |
| CCCO | Joint SCOR-IOC Committee on Climatic Changes and the Ocean |
| CCD | Calcium Carbonate Compensation Depth |
| CTD | Conductivity, Temperature, Depth |
| CPR | Continuous Plankton Recorder |
| E | Evaporation |
| EEZ | Exclusive Economic Zone |
| EAZO | Energetically-Active Zones of the Ocean |
| ENSO | El Niño Southern Oscillation |
| FAO | Food and Agriculture Organization of the United Nations |
| FCCC | Framework Convention on Climate Change |
| GCM | Global Circulation Model |
| GCOS | Global Climate Observing System |
| GEMS | Global Environment Monitoring System (UNEP) |
| GEWEX | Global Energy and Water Cycle Experiment |
| GLOSS | Global Sea-Level Observing System (IOC) |
| GOEZS | Global Ocean Euphotic Zone Study |
| GOOS | Global Ocean Observing System |
| ICSU | International Council of Scientific Unions |
| IGBP | International Geosphere-Biosphere Programme (ICSU) |
| IGOSS | IOC-WMO Integrated Global Ocean Services System |
| INC | Intergovernmental Negotiating Committee (on a Framework Convention on Climate Change) |
| IOC | Intergovernmental Oceanographic Commission of UNESCO |
| IODE | International Oceanographic Data and Information Exchange (IOC) |
| IPCC | Intergovernmental Panel on Climate Change (UNEP-WMO) |
| JGOFS | Joint Global Ocean Flux Study (SCOR-IOC) |
| OALOS | Office for Ocean Affairs and the Law of the Sea (UN) |
| P | Precipitation |
| PAC | Programme Activities Centre (UNEP) |
| PW | Petawatt |
| RMSL | Relative Mean Sea Level |
| SBD | Schmitt, Bodgen and Dorman |
| SCOR | Scientific Committee on Oceanic Research (ICSU) |
| SECTIONS | On-going project of the USSR to investigate the role of the ocean in short-term climate change and variability |
| SLOCUM | An experimental ocean sounder that draws it propulsive power from the thermal stratification of the ocean |
| SWCC | Second World Climate Conference |
| TOGA | Tropical Ocean and Global Atmosphere Programme (WCRP) |
| TRMM | Tropical Rainfall Measuring Mission |
| UN | United Nations |
| UNCED | 1992 United Nations Conference on Environment and Development |
| UNCLOS | United Nations Convention on the Law of the Sea |
| UNEP | United Nations Environment Programme |
| UNESCO | United Nations Educational, Scientific and Cultural Organization |
| WCP | World Climate Programme |
| WCRP | World Climate Research Programme |
| WHP | WOCE Hydrographic Programme |
| WMO | World Meteorological Organization |
| WOCE | World Ocean Circulation Experiment (WCRP) |
| WWW | World Weather Watch |
| XBT | Expendable Bathythermograph |