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WORLD CLIMATE RESEARCH PROGRAMME

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No. 6

SCIENTIFIC PLAN
FOR THE WORLD OCEAN
CIRCULATION EXPERIMENT

INTERGOVERNMENTAL OCEANOGRAPHIC
COMMISSION

SCIENTIFIC COMMITTEE ON
OCEANIC RESEARCH

THE WORLD CLIMATE RESEARCH PROGRAMME

The major objectives of the WCRP are to determine:
- To what extent climate can be predicted;
- The extent of man's influence on climate.

To achieve these objectives it is necessary:

(a) To improve our knowledge of global and regional climates, their temporal variations, and our understanding of the responsible mechanisms ;

(b) To assess the evidence for significant trends in global and regional climates ;

(c) To develop and improve physical-mathematical models capable of simulating, and assessing the predictability of, the climate system over a range of space and times scales ;

(d) To investigate the sensitivity of climate to possible natural and man-made stimuli and to estimate the changes in climate likely to result from specific disturbing influences.

WORLD CLIMATE RESEARCH PROGRAMME (WCRP)

WOCE Scientific Steering Group

SCIENTIFIC PLAN FOR

THE WORLD OCEAN CIRCULATION EXPERIMENT

List of Acronyms and Special Terms

AGCM	Atmospheric General Circulation Model
ARGOS	Satellite Location and data Collection System (CNES and NOAA)
CCCO	Committee on Climate Changes and the Ocean (of IOC and SCOR)
CNES	Centre National d'Etudes Spatiales (France)
CTD	Conductivity Temperature Depth (probe)
CUEA	Coastal Upwelling Ecosystems Analysis (USA)
DCLS	Data Collection Location Systems
DGFI	Deutsche Geodatisches Forschungsinstitut (FRG)
EGCM	Eddy-resolving-General Circulation Model
ERS-1	Earth Resources Satellite (ESA)
ESA	European Space Agency
FGGE	First Garp Global Experiment
GCM	General Circulation Model
GEOSECS	Geochemical Ocean Sections Study
GLOSS	Global Sea Level Observing System (IOC)
GRAD10	Gradiometer (France)
GRGS	Groupe de Recherche Geodesie Spatiale (CNES)
GRM	Geopotential Research Mission
GTS	Global Telecommunication System (WMO)
ICSU	International Council of Scientific Unions
IGOSS	Integrated Global Ocean Services System (IOC/WMO)
IOC	Intergovernmental Oceanographic Commission (of Unesco)
IODC	International Oceanographic Data Exchange (IOC)
ISOS	International Southern Ocean Studies
JPL	Jet Propulsion Laboratory (USA)
JSC	Joint Scientific Committee (of WMO and ICSU)

MODE	Mid-Ocean Dynamics Experiment (USA)
NASA	National Aeronautics and Space Administration (USA)
NCAR	National Centre for Atmospheric Research (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
NODC	National Oceanographic Data Centre
NROSS	Navy Remote Ocean Sensing System (USA)
PODS	Pilot Ocean Data System (JPL)
POLYMODE	POLYGON Mesoscale Project in the North Atlantic (USA/USSR)
POSEIDON	Satellite Programme (France)
RAFOS	Backwards SOFAR (float)
SAC	Special Analysis Centre
SCOR	Scientific Committee on Oceanic Research (of ICSU)
SEASAT	Oceanographic Satellite (USA)
SOFAR	Sound-fixing and Ranging (float)
SSG	Scientific Steering Group (of WOCE)
SST	Sea Surface Temperature
TOGA	Tropical Oceans and Global Atmosphere (Research Programme on)
TOPEX	Ocean Surface Topography Experiment (NASA)
TTO	Transient Tracers in the Ocean (Research Programme on)
UNESCO	United Nations Educational Scientific and Cultural Organization
WCRP	World Climate Research Programme
WDC	World Data Centre
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
VOS	Voluntary Observing Ship Scheme (WMO)
XBT	Expendable Bathythermograph

Foreword

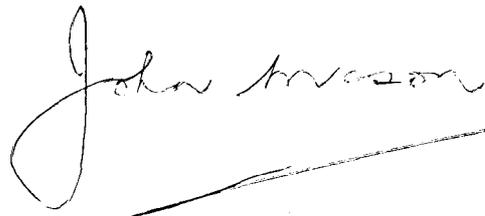The World Ocean Circulation Experiment (WOCE) was born of the juncture of three circumstances:

1. A need, arising from the inception of the World Climate Research Programme (WCRP). It was recognized by both meteorologists and oceanographers that the decadal and longer variations in the climate depend critically on the behaviour of the global oceans.

2. An ability, arising from the advent of new in situ and satellite instrumentation to observe as never before the global oceans. The demonstrated capability of Seasat to make useful measurements of the sea surface elevation and the prospect that there would be other altimeter-carrying satellites was a crucial factor. At the same time, continuation of the rapid advances in computer capability promised to greatly facilitate both the design and the analysis of a global oceanographic experiment and the incorporation of the oceans in global climate models.

3. A willingness, arising from the recognition by a substantial portion of the world's oceanographic community that the time was ripe to turn again to large-scale oceanography from the process studies which have dominated the attention of oceanographers in recent decades.

Thus, A World Circulation Experiment was one of the proposals considered by the very first meeting of the Committee on Climatic Changes and the Ocean (CCCO) in 1979. The Joint Scientific Committee (JSC) and CCCO jointly sponsored a major meeting of oceanographers and meteorologists in mid-1982 in Tokyo to consider a large-scale oceanographic experiment in the WCRP. Its first recommendation was that there should be "a World Ocean Circulation Experiment to understand quantitively the present state of the general circulation, in order to assess the sensitivity of the climate system to changes in external forcing, whether natural or anthropogenic, on time scales of decades to centuries should be implemented vigorously".

In 1983 the CCCO and the JSC jointly established a Scientific Steering Group for WOCE which has produced this scientific plan for The World Ocean Circulation Experiment.

It is our expectation that this plan will contribute importantly to the development of this crucial experiment within the World Climate Research Programme.

Sir John Mason Chairman
Joint Scientific Committee

R W Stewart Chairman
Committee on Climatic Changes and the Ocean

Preface

This Scientific Plan for the World Ocean Circulation Experiment describes the strategy for one of the principal projects of the World Climate Research Programme. It was developed in response to a decision to give high priority in the WCRP to improving our ability to model the ocean circulation. This is a pre-requisite for developing the global coupled ocean-atmosphere models needed for decadal climate prediction, stream 3 of the WCRP.

WOCE will be the first attempt to survey the oceanic circulation globally for a brief period. The aim is to collect a data base that will support the development of the global eddy-resolving ocean circulation models that will become feasible with increased computer power by the end of the century. WOCE will carry oceanography into a new era of global analysis and modelling, similar to the advance in meteorology as a result of the global weather experiment in the 1970's.

The development of satellite observing techniques, in particular, radar altimetry and scatterometry, has made possible systematic global mapping of seasurface height and windstress as well as providing information on the surface fluxes of heat and water. Satellites especially designed for this purpose will be launched at the end of this decade and the beginning of the next. The programme of in-situ measurements planned for WOCE is designed to ensure that the most detailed possible description of the ocean circulation is obtained concurrently with the satellite observations. These measurements are to be focussed in three core projects outlined in the scientific plan. They will require a massive deployment of existing oceanographic research vessels and instruments, and the investment of substantial additional resources. It will also be necessary to upgrade existing procedures for data exchange, processing and archiving, and to establish special data analysis centres to create the data bases required for diagnostic and prognostic modelling. This Scientific Plan describes the goals and objectives of WOCE and a strategy for achieving them in terms of the three core projects and the associated model development programme. The broad strategy outlined here will be elaborated and expanded during the next year or so during the preparation of the WOCE Implementation Plan. These two documents will provide individual scientists, institutions and nations the basis on which to assess their particular opportunities for participating in WOCE and, to develop their own research plans.

The success of a great scientific endeavour, such as WOCE, depends on the degree to which individual scientists can contribute to its objectives and participate in it. This will involve decisions on the allocation of existing resources, and the search for additional means to carry out personal projects that fit within the WOCE framework, especially during the intensive observing period (circa 1990-95). Some of the elements of WOCE will be far more expensive than those normally carried out by individual scientists and institutes. Thus, decisions of national authorities or funding agencies to provide additional resources will be critical to the implementation of WOCE. Although there are still five years before the start of the WOCE Intensive Observing period, the long lead time for acquisition of major facilities and for scheduling existing resources means that it is already becoming urgent for scientists and agencies to decide how they will contribute to the experiment. Some countries have established national scientific committees for WOCE to

focus discussion on these issues. The scientific steering group welcomes this development as a useful mechanism for the planning of WOCE in those nations with scientists interested in participating in the experiment.

The success of WOCE will bring benefits to many marine disciplines, going beyond the particular WCRP objectives which guide the experimental design. In some countries, the motivation for participation may be influenced by potential benefits other than decadal climate prediction and contributions to WOCE may be part of broader national research programmes involving elements that are not specified in the WOCE core projects. National WOCE committees may formulate their own goals and objectives, consistent with their own constraints, but meshing with the WOCE goals, objectives and core projects described in the Scientific Plan. The degree of overlap of a national programme with the international plan will determine the level of the national contribution to WOCE.

The scientific benefits arising from participation in WOCE will come from access to major facilities such as dedicated research vessels, from priority use (on the short term) of data collected individually in component activities, and from priority access (on the longer term) to the higher level data sets derived from the contributions of many participants. Eventually, of course, the WOCE data base will become generally available for the scientific community at large through the world data centres.

F.P. Bretherton
Co-Chairman
WOCE Scientific Steering Group

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Co-Chairman
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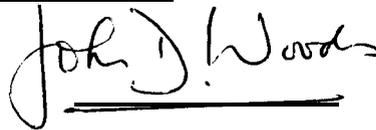
Summary

Goals and Objectives of the Programme

Stream Three of the World Climate Research Programme (WCRP) aims at characterizing variations of climate over periods of several decades and at assessing the potential response of climate to either natural or man-made influences, such as the increase in the atmospheric concentration of carbon dioxide. On decadal time scales, the major scientific problem limiting climate prediction is the inability to describe and model the circulation of the World Ocean. Thus, the World Ocean Circulation Experiment (WOCE) has been designed to be the principal activity within Stream Three of the WCRP. This Scientific Plan articulates the rationale for the Experiment and outlines a coherent and feasible approach to the objectives within which more detailed planning can take place. It also provides a framework within which the relevance of individual proposals and national contributions may be judged.

In order to plan WOCE, the organizers of the WCRP have established the WOCE Scientific Steering Group (SSG), supported by the WOCE International Planning Office in the U.K. The SSG have set the following two basic goals for the experiment;

- Goal 1: To develop models useful for predicting climate change and to collect the data necessary to test them.

- Goal 2: To determine the representativeness of the specific WOCE data sets for the long-term behaviour of the ocean, and to find methods for determining long-term changes in the ocean circulation.

Each of the goals has been further expressed in terms of several specific objectives.

For Goal 1 (which forms the basis of most of the considerations of the current Scientific Plan), the specific objectives concern certain aspects of the global fluxes of heat and fresh water, the dynamical balance of the large-scale circulation, the statistical description of the variability, and water mass formation and modification. Each of these objectives is discussed in some detail in the Scientific Plan.

Goal 1 addresses the development and testing of global eddy-resolving thermodynamically-active models for predicting decadal climate change. Such models are beyond present resources but it is anticipated that the next generation of computers, available within a few years, will make it possible to use such models for ocean basins for extended periods of time. By the end of the century computer capacity should allow the models to be used globally and the data sets to be collected during the observational phase of WOCE will be sorely needed.

Observational Programme

The translation of the objectives of Goal 1 into practical experimental design will involve making decisions about priorities regarding calls on resources available within the international community. In order to facilitate this process, the Scientific Plan identifies three main thrusts or "Core Projects" that will have top priority.

The Core Projects are:

- Core Project 1 - The Global Description aims to obtain data that will
  give quantitative global descriptions of the circulation of heat, fresh
  water and chemicals and of the statistics of eddies. These constitute a
  basic description of the circulation of the World Ocean. Comparison
  with model simulations based on surface fluxes observed at the same time
  will provide a powerful test of the models. The differing roles of the
  various oceanic basins in transferring heat and fresh water and the
  degree of regional agreement between models and the Core Project 1 data
  set will be of particular importance. The description of the global
  ocean required for this purpose must be of similar quality to that
  presently available for the North Atlantic with the addition of the
  measurement of sea surface elevation and fluxes by satellite-borne
  systems.

- Core Project 2 - The Southern Ocean Experiment is concerned with the
  Antarctic Circumpolar Current and its interactions with the oceans to
  the north. This connection of the major ocean basins in the Southern
  Ocean leads to the requirement that the observational strategy for
  studying the oceanic heat flux must be global in nature. Of importance
  are also the large quantities of heat supplied at low latitudes and lost
  to the atmosphere south of the Circumpolar Current as well as the
  formation of water masses to the north.

. Core Project 3 - The Gyre Dynamics Experiment is designed to meet the
  objective of developing accurate eddy-resolving general circulation
  models by a combination of modelling and experiments that will directly
  address key aspects of the dynamical balance of the circulation and its
  response to decadal changes in surface forcing. Priority will be given
  to studying processes that are likely to be the preoccupation of
  modellers at the end of the century when increased computer power has
  helped solve many of today's problems but many important processes will
  still need to be parameterized.

Observing Systems

Although the details of the field programme are not fixed, its broad
outline is clear. The extremely diverse types of observations required and
the multi-year character of WOCE will require the fullest exploitation of the
capabilities and resources of oceanographic institutions around the globe.
Since the experiment is global in nature, the major observational systems
will be deployed in all oceans. Simultaneous measurements will only be
imposed where absolutely necessary. The flexibility inherent in the existing
arrangements for cooperative research in the world-wide oceanographic (and
meteorological) community will be exploited as far as possible.

Major elements of the WOCE field programme include

- Satellite observing systems including at least high accuracy altimeter
  measurement of sea-surface elevation and scatterometer measurement of
  surface stress. The expected availability of these systems has led to
  initially setting the dates for the Intensive Observation Period of WOCE
  as 1990-1995.

- A Ship-based programme to measure the global fields of temperature,
  salinity, nutrients, oxygen, tritium, helium-3, fluorocarbons, etc. as

well as dynamic topography to the extent that major features are contourable at all depths. This programme will require dedicated research vessels staffed by teams of skilled and experienced oceanographers with the highest quality land-based laboratory facilities.

- The measurement of surface ocean fluxes of heat, water and momentum using measurements from satellites, ships and buoys and the analyses of atmospheric general circulation models.

- A system of tide-gauges especially selected to meet WOCE needs within the IOC's Global Sea Level Observing System.

- Floats and drifting buoys to measure the interior and surface ocean velocity and dispersion.

- A variety of standard oceanographic instruments such as current meters and acoustic velocity profilers as well as techniques under development, such as acoustic tomography which may be used for either routine or specialised measurements.

Data Management

Data management for WOCE should mesh closely with that for TOGA but with some shift in emphasis towards delayed-mode quality-controlled data sets. It should include the assessment of the utility of existing data types in achieving WOCE objectives, the assemblage of existing data for WOCE purposes, the assemblage of data sets to be used as boundary conditions on ocean models, and the assemblage of data sets for the critical assessment of theories and models.

The framework of WOCE data mangement has been outlined and will, where possible, use existing oceanographic data handling systems and archives. Of importance to WOCE will be the establishment of Special Analysis Centres for the analysis and preparation of higher level data sets of a particular type and the creation of a Data Information Unit to keep track of data in such a way as to assist participants in obtaining the data sets most able to meet their particular needs.

RESUME

BUTS ET OBJECTIFS DU PROGRAMME

Le troisième volet du Programme mondial de recherches sur le climat (PMRC) tend à déterminer les caractéristiques des variations du climat sur plusieurs décennies et à évaluer les réactions potentielles du climat à des influences naturelles ou anthropiques telles que l'augmentation de la concentration de gaz carbonique dans l'atmosphère. A l'échelle de décennies, la principale difficulté scientifique qui fait obstacle à la prévision du climat tient à l'impossibilité de décrire et de modéliser la circulation de l'océan mondial. Ainsi, l'expérience mondiale concernant la circulation océanique (WOCE) a été conçue pour être la principale activité au titre du troisième volet du PMRC. Ce plan scientifique définit la raison d'être de l'expérience et décrit une approche cohérente et possible des objectifs de nature à permettre une planification plus détaillée. Ce plan définit aussi le cadre propre à permettre d'évaluer la pertinence des différentes propositions et contributions nationales.

Pour planifier l'expérience WOCE, les organisateurs du PMRC ont créé le Groupe directeur scientifique pour WOCE qui bénéficie de l'appui du Bureau international de planification de WOCE au Royaume-Uni. Le Groupe directeur scientifique a défini ainsi les deux buts essentiels de l'expérience :

But 1 : élaborer des modèles utiles pour prévoir les changements climatiques et collecter les données nécessaires pour les expérimenter;

But 2 : déterminer le caractère représentatif des jeux de données spécifiques de WOCE pour étudier le comportement à long terme de l'océan et rechercher les méthodes propres à permettre de déterminer les variations à long terme de la circulation océanique.

Chacun de ces buts comporte en outre plusieurs objectifs spécifiques.

S'agissant du but 1 (qui constitue la base de la plupart des considérations du plan scientifique actuel), les objectifs spécifiques concernent certains aspects des flux mondiaux de chaleur et d'eau douce, l'équilibre dynamique de la circulation à grande échelle, la description statistique de la variabilité et la formation et la modification des masses d'eau. Chacun des ces objectifs est examiné en détail dans le plan scientifique.

Le but 1 traite de l'établissement et de l'expérimentation de modèles mondiaux actifs sur le plan thermodynamique tenant compte des phénomènes de turbulence pour prévoir les variations climatiques à l'échelle d'une décennie. Ces modèles ne peuvent être construits à l'aide des ressources actuelles, mais il est prévu que la prochaine génération d'ordinateurs, qui sera disponible dans quelques années, permettra d'utiliser ces modèles pour les bassins océaniques pendant de longues périodes. D'ici la fin du siècle, la capacité des ordinateurs devrait permettre d'utiliser les modèles à l'échelon mondial et les jeux de données devant être recueillis pendant la phase d'observation de WOCE deviendront absolument indispensables.

SYSTEMES D'OBSERVATION

Les détails du programme sur le terrain ne sont pas encore fixés, mais ses grandes lignes sont clairement établies. Les types extrêmement divers d'observations nécessaires et le caractère pluriannuel de l'Expérience WOCE appelleront l'exploitation la plus large possible des moyens et des ressources des institutions océanographiques de l'ensemble du monde. Comme l'expérience a un caractère mondial, les principaux systèmes d'observation seront déployés dans tous les océans. Des mesures simultanées ne devront être faites qu'en cas d'extrême nécessité. On tirera parti dans toute la mesure du possible de la souplesse inhérente aux arrangements existants en matière de recherche en commun au sein de la communauté océanographique (et météorologique) mondiale.

Les principaux éléments du programme WOCE sur le terrain comprennent notamment :

- des systèmes d'observation par satellite, y compris au moins une mesure à l'aide d'un altimètre de grande précision de l'altitude de la surface de la mer et la mesure à l'aide d'un diffusiomètre des contraintes exercées sur la surface. La possibilité de disposer prochainement de ces systèmes a conduit à fixer initiale-ment les dates de la période d'observation intensive de WOCE à 1990-1995s;

- un programme exécuté à l'aide d'un navire pour mesurer les champs mondiaux de la température, la salinité, les éléments nutritifs, l'oxygène, le tritium, l'hélium 3, les fluorocarbures, etc., ainsi que la topographie dynamique dans la mesure où les courbes des principales caractéristiques peuvent être établies à toutes les profondeurs. Ce programme nécessitera l'utilisation de navires de recherche spéciaux sur lesquels travailleront des océanographes qualifiés et expérimentés en liaison avec des installations de laboratoire à terre de très grande qualité;

- la mesure des flux océaniques superficiels de la chaleur, de l'eau et de la quantité de mouvement à l'aide de satellites, de navires et de bouées et les analyses des modèles de la circulation générale atmosphérique;

- un réseau de marégraphes spécialement sélectionnés pour répondre aux besoins de WOCE dans le cadre du système mondial d'observation du niveau de la mer de la COI;

- des flotteurs et des bouées dérivantes pour mesurer la vitesse et la dispersion à l'intérieur et à la surface de l'océan;

- différents instruments océanographiques normalisés tels que les courantomètres et des dispositifs acoustiques de mesure des vitesses ainsi que des techniques en cours d'élaboration, telles que la tomographie acoustique qui pourrait être utilisée pour des mesures courantes ou spécialisées.

PROGRAMME D'OBSERVATION

La traduction des objectifs du but 1 dans des activités expérimentales pratiques appellera des décisions au sujet des priorités concernant l'utilisation des ressources disponibles au sein de la communauté internationale. Pour faciliter ce processus, le plan scientifique définit trois grandes composantes ou projets de base qui revêtiront la plus haute priorité.

Les projets de base sont les suivants :

- Projet de base 1 - La description mondiale tend à recueillir des données qui permettront d'établir des descriptions quantitatives mondiales de la circulation de la chaleur, de l'eau douce et des produits chimiques, et des statistiques sur les tourbillons. Il s'agit là de la description de base de la circulation de l'océan mondial. Une comparaison avec des simulations de modèles sur la base de courants de surface observés simultanément permettra d'expérimenter très concrètement les modèles. Les rôles distincts que jouent les différents bassins océaniques dans le transfert de la chaleur et de l'eau douce et le degré de concordance régionale entre les modèles et le jeu de données du projet de base 1 revêtiront à cet égard une importance particulière. La description de l'océan mondial nécessaire à cette fin doit être d'une qualité similaire à celle dont on dispose actuellement pour l'Atlantique Nord et comporter également la mesure de l'altitude de la surface de la mer et des courants par des systèmes installés à bord de satellites.

- Projet de base 2 - L'Expérience concernant l'océan Austral porte sur le courant circumpolaire antarctique et ses interactions avec les océans en direction du nord. Cette relation entre les grands bassins océaniques de l'océan Austral montre qu'il est nécessaire que la stratégie d'observation appliquée pour étudier les flux de chaleur océanique ait un caractère mondial. Les grandes quantités de chaleur fournies à basse altitude et perdues dans l'atmosphère au sud du courant circumpolaire ainsi que la formation des masses d'eau en direction du nord revêtiront également une grande importance.

- Projet de base 3 - L'expérience concernant la dynamique des tourbillons tend à répondre à l'objectif visant à établir des modèles précis de la circulation générale tenant compte des phénomènes de turbulence en entreprenant des travaux de modélisation et des expériences qui traiteront directement des aspects essentiels du bilan dynamique de la circulation et de sa réaction aux variations du forçage à la surface à l'échelle d'une décennie. La priorité sera accordée à l'étude des processus qui seront susceptibles de préoccuper les concepteurs des modèles à la fin du siècle lorsque l'accroissement de la capacité des ordinateurs aura sans doute permis de résoudre certains des problèmes actuels mais qu'il faudra encore paramétriser de nombreux processus importants.

GESTION DES DONNEES

La gestion des données pour WOCE doit être assurée en étroite coordi-
nation avec celle de TOGA mais en accordant une plus grande importance aux
jeux des données en différé ayant fait l'objet d'un contrôle de qualité.
Cette activité devrait comporter l'évaluation de l'utilisation des types de
données existants pour atteindre les objectifs de WOCE, le rassemblement des
données existantes aux fins de WOCE, l'assemblage des jeux de données devant
être utilisés comme conditions aux limites sur les modèles océaniques et
l'assemblage des jeux de données pour procéder à l'évaluation critique des
théories et des modèles.

Le cadre de la gestion des données de WOCE a été défini et, dans toute
la mesure du possible, les systèmes et les archives de traitement des données
océanographiques existants seront utilisés. La création de centres spéciaux
d'analyse pour procéder à l'analyse et à l'établissement de jeux de données de
plus grande qualité d'un type particulier et la création d'un bureau de
l'information sur les données pour pouvoir localiser les données de façon à
aider les participants à recueillir les jeux de données répondant le mieux à
leurs besoins particuliers revêtiront une grande importance pour l'expérience
WOCE.

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RESUMEN

Objetivos y fines del programa

La tercera corriente del Programa Mundial de Investigaciones Climáticas (PMIC) tiene por finalidad caracterizar las variaciones del clima durante períodos de varios decenios y evaluar la posible reacción del clima ante influencias naturales o artificiales, como, por ejemplo, el aumento de la concentración de anhídrido carbónico atmosférico. En las escalas cronológicas decenales, el principal prohlema científico que limita la predicción climática es la incapacidad para describir y establecer un modelo de la circulación oceánica mundial. Así, el Experimento Mundial sobre la Circulación Oceánica (WOCE) constituye la principal actividad dentro de la tercera corriente del PMIC. Este plan científico describe con claridad la razón de ser del experimento y esboza un enfoque coherente y viable de los objetivos en el contexto de los cuales podrá realizarse una planificación más detallada. Proporciona también un marco dentro del cual cabe estimar la importancia de las propuestas individuales y de las contribuciones nacionales.

A fin de planificar el WOCE, los organizadores del PMIC han establecido el Grupo de dirección científica del WOCE, apoyado por la Oficina Internacional de Planificación del WOCE en el Reino Unido. El mencionado Grupo ha establecido los dos objetivos básicos siguientes del experimento:

. Objetivo 1: Elaborar modelos útiles para la predicción de los cambios climáticos y concentrar los datos necesarios para probar aquéllos.

. Objetivo 2: Determinar la representatividad de las series de datos específicos del WOCE sobre cl comportamiento a largo plazo del océano, y buscar métodos para determinar los cambios a largo plazo de la circulación oceánica.

Cada uno de los objetivos se traduce después en una serie de fines específicos.

En el caso del Objetivo 1 (que constituye la base de la mayoría de las consideraciones del plan científico actual), los fines específicos se refieren a determinados aspectos de los flujos mundiales de calor y agua dulce, el equilibrio dinámico de la circulación en gran escala, la descripción estadística de la variabilidad, y la formación y modificación de la masa de agua. Cada uno de estos fines se examina con cierto detalle en el plan científico.

El Objetivo 1 trata del desarrollo y verificación de los modelos mundiales de resolución vorticial activos desde el punto de vista termodinámico para la predicción de cambios climáticos decenales. Tales modelos están fuera de alcance teniendo en cuenta los recursos actuales, pero se prevé que la próxima generación de ordenadores, disponible dentro de unos años, permitirá utilizar tales modelos en las cuencas oceánicas para períodos de tiempo dilatados. Antes de terminar el siglo, el aumento de la capacidad

de los ordenadores permitirá la utilización de modelos a escala mundial y las series de datos que se concentren durante la fase de observación del WOCE serán muy necesarias.

Programa de observaciones

La traducción de los componentes del Objetivo 1 en un diseño experimental de carácter práctico implicará la toma de decisiones acerca de las prioridades en el momento de recurrir a los recursos disponibles en la comunidad internacional. A fin de facilitar este proceso, el plan científico identifica tres iniciativas principales o proyectos centrales que merecen la máxima prioridad.

Los proyectos centrales son:

. Proyecto central 1 - El objeto de la descripción mundial es obtener datos que proporcionen descripciones mundiales cuantitativas de la circulación del calor, agua dulce, productos químicos y de las estadísticas de los remolinos. Se trata de una descripción básica de la circulación oceánica mundial. La comparación con las simulaciones de modelos basadas en los flujos de superficie observados al mismo tiempo proporcionará una prueba importante de los modelos. Los distintos cometidos de las diversas cuencas oceánicas en la transferencia de calor y agua dulce y el grado de acuerdo regional entre los modelos y las series de datos del Proyecto central 1 revestirá especial importancia. La descripción de la circulación oceánica mundial necesaria, a este respecto, debe ser de una calidad similar a la actualmente disponible respecto del Atlántico Norte, complementada con las mediciones de la elevación y de los flujos de la superficie del mar por medio de los sistemas de satélites.

. Proyecto central 2 - El experimento del sur del océano se ocupa de la corriente circumpolar antártica y sus interacciones con los océanos al norte. Esta conexión de las principales cuencas oceánicas al sur del océano impone la exigencia de una estrategia en materia de observaciones para el estudio de los flujos de calor oceánico de carácter mundial. También tienen importancia las grandes cantidades de calor suministradas en bajas latitudes y que se pierden en la atmósfera al sur de la corriente circumpolar, así como la formación de masas de agua al norte.

. Proyecto central 3 - El objeto del experimento dinámico de la corriente circular es satisfacer el objetivo relacionado con el desarrollo de modelos precisos de circulación general de resolución vorticial por medio de una combinación de experimentos y trabajos relativos al establecimiento de modelos que tratarán directamente de los aspectos fundamentales del equilibrio dinámico de la circulación y su reacción ante los cambios decenales en los forzamientos de superficie. Deberá otorgarse prioridad al estudio de los procedimientos que pueden

constituir un motivo de preocupación para los diseñadores de modelos al final del siglo cuando una mayor capacidad de los ordenadores ayude a resolver muchos de los problemas actuales, si bien muchos procedimientos importantes deberán ser todavía expresados en parámetros.

Sistemas de observación

Si bien no se han fijado los detalles del programa extrasede, el esquema general aparece con claridad. Los muy distintos tipos de observaciones necesarias y el carácter plurianual del WOCE requerirán la máxima explotación de las posibilidades y recursos de los organismos oceanográficos del mundo. Como el experimento es de carácter mundial, los principales sistemas de observación deberán hallarse desplegados en todos los océanos. Las mediciones simultáneas sólo se realizarán cuando sea absolutamente necesario. La flexibilidad inherente a las actuales disposiciones relativas a la investigación en forma de cooperación en la comunidad oceanográfica (y meteorológica) mundial será aprovechada en la mayor medida posible.

Los principales componentes del programa. extrasede del WOCE son los siguientes:

.   Sistemas de observación de satélite, incluyendo, por lo menos, la medición de la elevación de la superficie del mar con un altímetro de alta precisión y medición de la tensión de la superficie por medio de un dispersómetro. La disponibilidad prevista de esos sistemas ha permitido fijar inicialmente las fechas del Período de Observación Intensiva del WOCE en 1990-1995.

.   Un programa con base en un buque para medir a escala mundial los campos de temperatura, salinidad, elementos nutritivos, oxígeno, tritio, helio-3, fluorocarburos, etc., así como la topografía dinámica hasta el punto de que puedan perfilarse las principales características en toda su profundidad. Este programa requiere la participación de buques de investigación dotados de personal constituido por equipos de oceanógrafos especializados y experimentados, con instalaciones de laboratorio con base en tierra, de máxima calidad.

.   La medición de los flujos en la superficie del océano de calor, agua e impulso, utilizando mediciones de satélites, buques y boyas y los análisis de los modelos de circulación atmosférica general.

.   Un medidor de mareas especialmente seleccionado para satisfacer las necesidades del WOCE en el marco del Sistema Mundial de Observación del Nivel del Mar de la COI.

.   Flotadores y boyas a la deriva para medir la velocidad y dispersión en el interior y en la superficie del océano.

. Una variedad de instrumentos oceanográficos normalizados, tales como medidores de corrientes y trazadores acústicos de perfiles de la velocidad, así como técnicas en fase de desarrollo, tales como topografía acústica, que puedan ser utilizadas para mediciones de rutina o especializadas.

Gestión de datos

La gestión de datos para el WOCE debe estar en estrecha relación con la del TOGA, poniendo en cambio el énfasis en las series de datos de calidad controlada en la modalidad diferida. Asimismo debe contener una evaluación de la utilidad de los actuales tipos de datos para el logro de los objetivos del WOCE, el montaje de los datos actuales para los fines del WOCE, el montaje de las series de datos para su utilización como condiciones límites en los modelos oceánicos, y el montaje de las series de datos para una evaluación crítica de las teorías y modelos.

Se ha esbozado ya el modelo de gestión de datos del WOCE, en el que se utilizaran, cuando proceda, los actuales archivos y sistemas de manipulación de datos oceanográficos. Revestirá importancia para el WOCE el establecimiento de centros especiales de análisis para el análisis y preparación de series de datos de nivel superior de un tipo determinado y la creación de una dependencia de información de datos para seguir de cerca estos últimos, de tal modo que puedan ayudar a los participantes a obtener las series de datos que mas convengan para satisfacer sus necesidades particulares.

РЕЗЮМЕ

Цели и задачи Программы

Задачей третьего направления Всемирной программы исследования климата (ВПИК) является изучение колебаний климата на период до нескольких десятилетий и оценка потенциальной реакции климата на антропогенные воздействия такие, как увеличение атмосферной концентрации двуокиси углерода. В масштабе времени в несколько десятилетий основной научной проблемой, которая ограничивает предсказание климата, является невозможность описать и смоделировать циркуляцию Мирового океана. Таким образом, Всемирный эксперимент по циркуляции океана (ВОСЕ) запланирован в качестве основного вида деятельности третьего направления ВПИК. Данный научный план представляет собой логическое обоснование этого эксперимента и намечает согласованный и обоснованный подход к решению задач, в рамках которых может осуществляться более детальное планирование. План обеспечивает структуру, в рамках которой могут разрабатываться соответствующие конкретные предложения и национальные вклады.

С целью планирования ВОСЕ органы, отвечающие за ВПИК, учредили Научную руководящую группу ВОСЕ (НРГ), которой оказывает поддержку Международное бюро планирования ВОСЕ, располагающееся в Соединенном Королевстве. НРГ установила следующие основные цели эксперимента:

- Цель 1: Разработать модели по предсказанию климатических изменений и собрать необходимые данные для проверки этих моделей.

- Цель 2: Определить репрезентативность конкретных комплектов данных ВОСЕ, описывающих долговременное поведение океана, и разработать методы по определению долговременных изменений океанической циркуляции.

Каждая из этих целей формулируется в виде некоторых конкретных задач.

Для цели 1 (которая формирует основу большинства предложений настоящего научного плана) конкретные задачи выхватывают определенные

аспекты изучения глобальных потоков тепла и пресной воды, динамический баланс крупномасштабной циркуляции, статистическое описание изменчивости, формирования и модификации водных масс. Каждая из этих задач обсуждается более детально в научном плане.

Цель 1 направлена на разработку и проверку глобальных термодинамических моделей по изучению круговоротов с целью предсказания климатических изменений в масштабе десятилетий. Такие модели выходят за рамки существующих ресурсов, однако предполагается, что следующее поколение компьютеров, которое появится в течение нескольких лет, позволит использовать такие модели для океанических бассейнов на достаточно протяженный период времени. К концу текущего столетия компьютеры позволят использовать эти модели в глобальном масштабе, и по этой причине будут крайне необходимы комплекты данных, которые предполагается собрать во время наблюдательной фазы ВОСЕ.

Программа наблюдений

Воплощение задач цели 1 в практически экспериментальные наблюдения потребует принятия решения относительно установления приоритетов при выделении ресурсов в рамках международного сообщества. Этому способствуют в научном плане три главных направления или "основных проекта", которые должны иметь наивысший приоритет.

Основными проектами являются:

.   Основной проект 1 - Система описания в глобальном масштабе направлена на получение данных, которые дадут количественное глобальное описание циркуляции тепла, пресной воды и химических веществ и статистические данные о вихрях. Эти данные составят основное описание циркуляции Мирового океана. Мощным средством проверки моделей будет являться их сравнение с моделями, основанными на потоках на поверхности наблюдаемых в одно и то же время. Особое значение будет уделено определению роли разных океанических бассейнов в передаче тепла и потоков пресной воды, а также определение степени согласованности в региональном масштабе между моделями и комплектами данных, которые предполагается собрать в течение основного проекта 1. Описание поведения Мирового океана, требующееся для этой цели, должно быть такого же качества, как то, ко-

торое имеется в настоящее время для региона Северной Атлантики, при наличии дополнительных измерений колебания уровня поверхности моря и потоков, выполняемых с помощью спутниковых систем.

• Основной проект 2 - Эксперимент в Южном океане связан с изучением антарктического циркулеполярного течения и его взаимодействия с океанами, расположенными к северу от этой области. Связь основных океанических бассейнов в Южном океане определяет глобальный характер стратегии наблюдений по изучению океанических потоков тепла. Важным также является то большое количество тепла, поступающего в низких широтах и уходящего в атмосферу к югу от циркулеполярного течения, а также образование водных масс к северу от этого района.

• Основной проект 3 - Эксперимент по динамике вихрей предназначен для цели создания моделей общей циркуляции, точно описывающих поведение вихрей в комбинации с моделированием и экспериментами, которые будут направлены на изучение ключевых аспектов динамического равновесия циркуляции и ее реакции и изменения внешних факторов, наблюдающихся на поверхности в десятилетнем временном масштабе. Приоритетными будут являться исследования процессов на основе моделирования с помощью ЭВМ, когда в конце текущего столетия мощные компьютерные системы помогут решить многие из сегодняшних задач, однако при этом многие важные процессы все еще будут нуждаться в параметризации.

Система наблюдения

Хотя детальные аспекты программы полевых наблюдений еще не определены, общая картина уже имеется. Весьма разнообразные типы наблюдений и многолетний характер ВОСЕ потребуют весьма полного использования возможностей и ресурсов океанографических учреждений во всем мире. Так как эксперимент является глобальным по своему характеру, основные наблюдательные системы будут размещаться во всех океанах. Одновременные наблюдения могут проводиться только там, где это будет абсолютно необходимо. В максимально возможной степени будет использоваться та гибкость, которая присуща существующей организации совместных исследований мирового океанографического и метеорологического сообществ.

Основными элементами полевой программы ВОСЕ являются:

. Спутниковая система наблюдения, включая по крайней мере, альтиметрические наблюдения высокой точности колебания уровня поверхности моря и измерения поверхностного напряжения с помощью скаттерометров. Предполагаемое наличие этих систем позволяет первоначально оценить время периода интенсивных наблюдений ВОСЕ в течение 1990-1995 гг.

. Программа судовых наблюдений по определению глобальных полей температуры, солености, содержания питательных веществ, кислорода, трития, гелия-3, фторхлоруглеводоров, а также динамическая топография, объем которой будет зависеть от возможностей измерения этих основных характеристик на всех глубинах. Эта программа потребует специально выделенных исследовательских судов, укомплектованных персоналом высококвалифицированных океанографов, располагающих наземными лабораториями, оснащенными высокосовершенной техникой.

. Измерение потоков тепла, воды и количества движения на поверхности океана с использованием спутников, судов и буев, а также анализ моделей общей циркуляции в атмосфере.

. Система самописцев уровня, специально отобранных для удовлетворения потребностей ВОСЕ, в рамках Глобальной системы наблюдений уровня моря МОК.

. Заякоренные и дрейфующие буи для измерения скорости и дисперсии на глубине и поверхности океана.

. Потребуется значительное количество стандартных океанографических приборов таких, как вертушки, приборы акустического определения профиля скорости, а также технические средства, которые находятся в стадии разработки, такие, как акустические томографы, которые могут быть использованы для оперативных или специализированных наблюдений.

Управление данными

Управление данными для ВОСЕ должно во многом совпадать с той системой, которая используется для ТОГА, однако с некоторым акцентом на комплекты данных, собираемых в режиме задержки при обеспечении контроля качества. Эта система должна включать в себя оценку возможности использования существующих типов данных для достижения целей ВОСЕ, сбор комплектов данных, которые могут быть использованы для формулирования пограничных условий в океанических моделях, и сбор комплектов данных для критической оценки теоретических построений и моделей.

Намеченные рамки системы обработки данных ВОСЕ предполагают там, где это возможно, использование существующих систем обработки океанографических данных и архивов. Важной целью ВОСЕ будет создание специализированных центров анализа для проведения анализа и подготовки комплектов данных высокого уровня определенного типа и создание информационного центра данных, который позволил бы оказывать помощь участвующим сторонам в получении комплектов данных наиболее удобным для них способом.

CHAPTER 1

Introduction

The World Ocean Circulation Experiment (WOCE) is a major component of the World Climate Research Programme (WCRP) sponsored jointly by intergovernmental and non-intergovernmental organizations. The WCRP is concerned with discovering if it is possible to predict climate on time scales of several weeks to several decades, and to determine the effect of man's influence on climate (WCRP, 1984). The programme is divided into three Streams concerned respectively with climate prediction over periods of (1) months, (2) years and (3) decades. A major scientific problem limiting climate prediction over decades is the inability to describe and model the circulation of the World Ocean (Houghton and Morel, 1984). The organizers of the WCRP have therefore proposed the World Ocean Circulation Experiment (WOCE) as the principal activity within Stream Three of the WCRP and they have established the WOCE Scientific Steering Group (SSG) to plan and organize the experiment. The tasks of the SSG are to identify the primary goals and objectives of WOCE, to design a core research programme including modelling and fieldwork, to identify the resources needed to undertake the programme, and to work with international and national bodies, research institutes, universities, and individual scientists to achieve the core research programme and to encourage the development of associated projects that support the goals of WOCE. The purposes of this Scientific Plan are to articulate clearly the rationale for the Experiment, to outline a coherent and feasible approach to the objectives within which more detailed planning can take place, and to provide a framework within which the relevance of individual proposals and national contributions may be judged.

The specific needs of Stream Three of the WCRP come at an opportune time for physical oceanographers. During the past decade or so several developments have made it possible for the first time to discuss global oceanic observations as a practical possibility. Firstly, the "mesoscale" programmes; for example, MODE, ISOS, POLYMODE, and CUEA, have delineated the frequency/wave number spectrum of oceanic variations sufficiently well to enable the specification of the sampling rates necessary to avoid aliasing time and/or space fluctuations into lower frequencies, including the mean. Such information is basic for the design of any large-scale measurement system. Theoretical developments and the results of numerical models have been stimulated by these mesoscale programmes and new questions are being posed about the ocean circulation. Secondly, new observation techniques have appeared as a consequence of the programmes that have been conducted by the oceanographic community and of the continuing electronics revolution. One can cite, for example, the ability to measure chemical tracers such as nutrients and fluorocarbons on very small samples quickly while at sea; neutrally buoyant floats trackable over thousands of kilometres by acoustic means or globally using satellites; shipborne rapid profiling methods; acoustic tomography for long-distance average measurements; current meters capable of multi-year in situ observations; and, most conspicuous of all, satellite measurements of the global surface wind-field and surface topography. Thirdly, computer power has been increasing at a rate such that one can now handle global data sets. The conservative expectation is that over the next decade further increases in computer power will allow sophisticated physics to be incorporated into ocean models that can only be

tested by global field programmes using the new observing capabilities. WOCE provides a focus for bringing together the new understanding of ocean physics and sampling requirements with the new techniques for ocean observations and the emerging sophisticated modelling capability in a coherent programme with great general benefits to oceanography. The expected timing of major WOCE activities is indicated in Figure 1.

The success of WOCE will clear the way for the development of computer models that couple together the global circulations of the ocean and the atmosphere for the purpose of predicting decadal climate changes (Woods 1985a). Experience with present ocean models (Robinson, 1983b; Nihoul, 1985) reveals the need to achieve far greater resolution of ocean topography, of transient eddies (the weather systems) and of narrow intense streams which together play a vital role in the oceanic circulation of heat, water and chemicals in the planetary climate system. At present, because of limitations in computer power, these phenomena can only be simulated with barely adequate resolution in a single ocean basin. Basin simulations are promising but they need to be thoroughly tested against as complete and accurate a data set as possible, and then extended to the global ocean as computing capability increases. As the limitations of today's poor resolution are relaxed, model performance will improve until new barriers become apparent. These new barriers will relate to inadequacies in parameterization of processes that are still too small to be resolved such as convection and turbulent mixing in the oceanic boundary layers (Woods, 1984).

The successful development of powerful new computer models suitable for decadal climate prediction depends critically on the availability of data that unambiguously describe key aspects of the large scale circulation resolved in the models and the effects of smaller scale processes which are parameterized. Analysis of existing oceanographic data provides important clues to the selection of those key aspects. For example, the models must accurately describe global circulation, including the fluxes in the Southern Ocean which link the circulations in the Pacific, Atlantic and Indian Oceans. Surface boundary layer processes that control the ventilation of the gyres also play a central role in developing the coupled models. However, **it is** apparent that the existing oceanographic archive, which contains data collected under the influence of restricted dynamical concepts (for example, geostrophy rather than eddy fluxes of potential vorticity) and with local rather than global circulation in mind, is quite inadequate to even answer questions posed by models running today. Its deficiencies will become a major problem in the future. A new global data set is required to meet the specific needs of coupling ocean circulation models with atmospheric circulation models for the purpose of decadal climate prediction. The World Ocean Circulation Experiment is designed to satisfy that need.

The World Ocean Circulation Experiment, targeted at a central scientific problem with many potential beneficiaries, is one of the most exciting endeavours in planetary science. Understanding how the climate system works on decadal time scales will be a major achievement in geophysics; for the first time it will become possible to discuss the global budgets of heat, fresh water and chemicals circulating through the atmosphere and the ocean on a planetary scale (Wunsch, 1984). The impact of decadal climate on Society, especially on the poorer nations economically vulnerable to changes in the global hydrological cycle on land or fisheries at sea, provides a sense of urgency that is lacking in basic research. The potential benefit for mankind motivated the establishment of the World Climate Research Programme and Stream Three of the WCRP will be concerned not only with natural climate variability , but also

84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 2000

PROGRAMME PLANNING

ELABORATION OF SCIENTIFIC ISSUES -

Publication of Scientific Plan

International WOCE Conference

Publication of Implementation Plan

DESIGN OF OBSERVATIONAL PROGRAMME -

OBSERVATIONAL PROGRAMME

PRE-WOCE TRACER AND PROCESS STUDIES - - - - - - - - - - - - - - - INTENSIVE OBSERVATION PERIOD

ERS-1 - - - - - - - - -

TOPEX / POSEIDON

NROSS

R.V. WOCE

Development of Technical and Management Aspects   at sea

DESIGN AND TESTING OF OPERATIONAL INSTRUMENTS - - - - - - - - - - - - - - - - - -

MODELS AND NUMERICAL TECHNIQUES

BASIN-SCALE EDDY-RESOLVING MODELS - - - - - - - - - - - - - - - - -

Real topography general purpose model   Use on WOCE
testing Gyre-Dynamics Concepts   data sets

INVERSE METHODS / DATA ASSIMILATION →

Development of techniques   Use on WOCE data sets

OBSERVING SYSTEM SIMULATION - - - - - - - - - - - - -

GLOBAL-SCALE EDDY-RESOLVING MODELS - - - - - - - →

Low-Resolution   Elimination of   Use with full WOCE
Models   Basin-Scale Problems   data sets

DATA MANAGEMENT

IDENTIFICATION OF SPECIAL ANALYSIS CENTRES
SPINUP OF DATA CENTRES AND SYSTEMS - - - - - - - -

PERIOD OF INTENSIVE DATA COLLECTION

DATA ANALYSIS, DEVELOPMENT OF HIGHER LEVEL DATA SETS →

DEVELOPMENT OF LONG-TERM OBSERVATIONAL SYSTEMS

DESIGN AND TESTING OF NEW OBSERVING SYSTEMS

ANALYSIS OF INTENSIVE OBSERVATION PERIOD DATA →

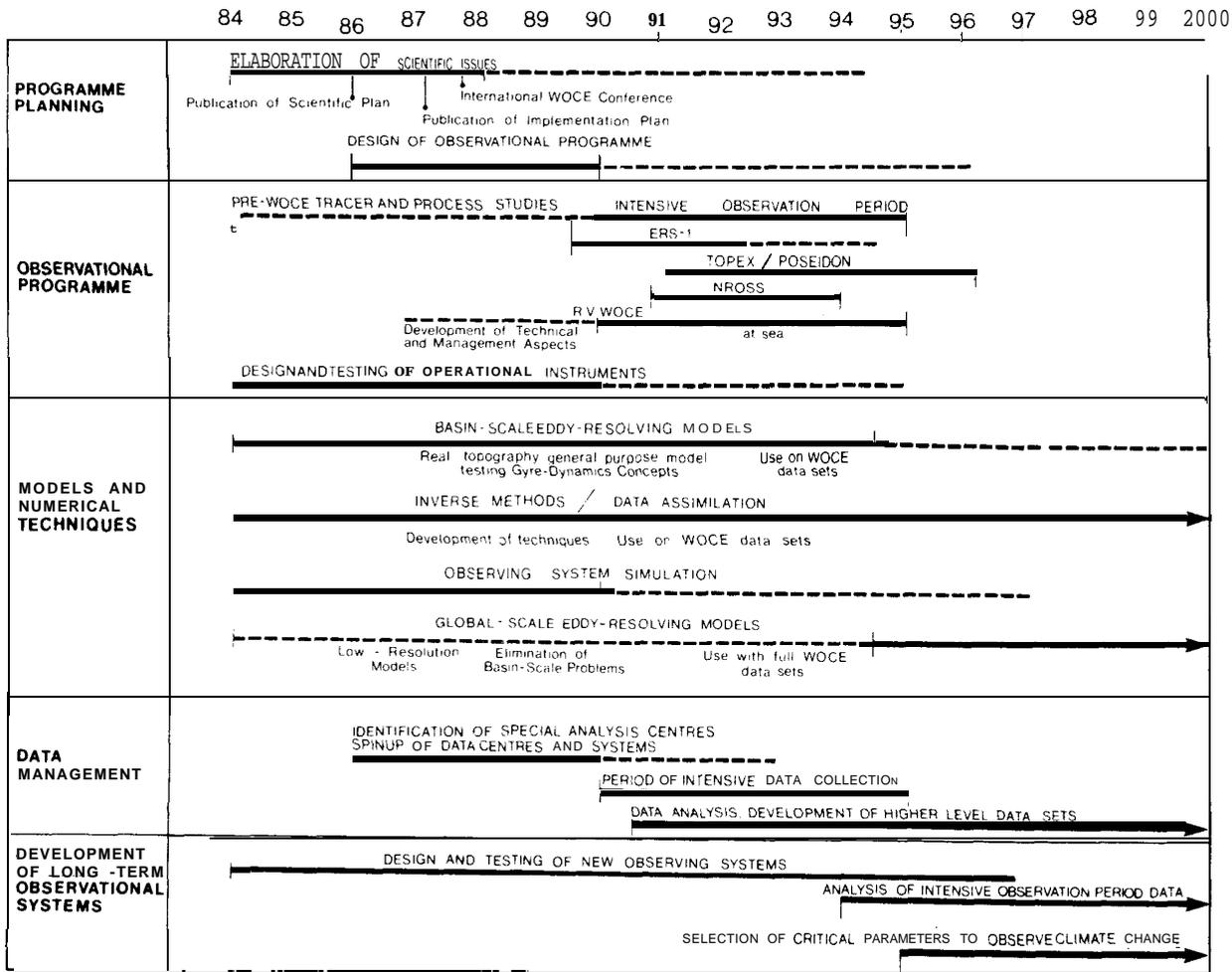SELECTION OF CRITICAL PARAMETERS TO OBSERVE CLIMATE CHANGE →

Figure 1:   Timetable of major WOCE activities

with predicting the consequences around the globe of man's pollution of the
climate system. There are many examples of man's activities that may, within
the next century, have serious effects on our climate around the world. The
most quoted example is the pollution of the atmosphere by carbon dioxide and
other radiatively active gases. Preliminary calculations indicate that major
changes in air temperature, in the pattern of rainfall over the continents, and
possibly in the volume of Antarctic ice (and therefore of sea level) will occur
in the next century. Such changes would require massive remedial investment
over several decades, starting before the major effects are felt. It is
therefore important to have confidence in the model predictions. The accuracy
of existing models is limited by the inadequacy of their simulation of the
oceanic circulation. The World Ocean Circulation Experiment is therefore
aiming at a scientific problem the resolution of which will have great benefits
for mankind, for the rich and the poor, and for those living not only on the
water's edge but also in the interior of continents far from the ocean.

CHAPTER 2

The Goals of the World Ocean Circulation Experiment

The WOCE Science Steering Group has set two goals for the experiment,

Goal 1: To develop models useful for predicting climate change and to collect the data necessary to test them.

Within Goal 1 the specific objectives are:

To determine and understand on a global basis the following aspects of the World Ocean circulation and their relation to climate:

(1) The large-scale fluxes of heat and fresh water, their divergences over 5 years, and their annual and interannual variability.

(2) The dynamical balance of the World Ocean circulation and its response to changing surface fluxes.

(3) Components of ocean variability on months to years, megameters to global scale, and the statistics on smaller scales.

(4) The rates and nature of formation, ventilation and circulation of water masses that influence the climate system on time scales from ten to one hundred years.

Goal 2: To determine the representativeness of the specific WOCE data sets for the long-term behaviour of the ocean, and to find methods for determining long-term changes in the ocean circulation.

Within Goal 2 the specific objectives are:

(1) To determine the representativeness of the specific WOCE data sets.

(2) To identify those oceanographic parameters, indices and fields that are essential for continuing measurements in a climate observing system on decadal time scales.

(3) To develop cost effective techniques suitable for deployment in an ongoing climate observing system.

This Plan explains the intent and relevance of these Goals and Objectives in the context of the decadal climate prediction problem, and introduces the strategy for achieving them. The principal elements of the WOCE modelling and field programmes are then identified and briefly described.

CHAPTER 3

Goal 1

3.1 Introduction: Modelling and Observations

Goal 1 addresses the development and testing of models for predicting decadal climate change. In general, model development involves an iterative cycle of testing various specific model aspects against appropriate data sets, adjusting the model's parameters or description of processes on the basis of this examination, testing the model against a broader set of circumstances, checking whether the model's predictions are qualitatively correct, and identifying further critical quantitative tests for diagnosis of specific model aspects. There must be a strong feedback between the specifications for model testing and the collection of data.

WOCE Goal 1 is concerned with one major iteration of this cycle: the rigorous testing of eddy resolving, thermodynamically active models on the scale of an ocean basin, including at least a cyclonic and an anti-cyclonic gyre, the extension of the modelling techniques so developed to the global ocean, checking the qualitative behaviour against global observations, and testing quantitatively against a limited set of diagnostic measures such as the oceanic heat flux.

The field programme will be intensive, and will take advantage of the opportunity to collect long term global observations from the next generation of ocean-observing satellites. The expected launch date of these satellites is about 1990 and their lifetimes are expected to be 3 to 5 years. The intensive oceanographic programme of WOCE is therefore planned to be concentrated on the period 1990-95, although this may be adjusted because of changes in satellite launch dates, Those measurements in the ocean that need to be made simultaneously with the satellite measurements must be made in that period. Other measurements (for example, some aspects of the deep tracer surveys) will start earlier and continue after the 1990-95 period.

The fact that the intensive field programme extends over several years does not mean that the resulting data set will constitute an average or a synoptic description of the World Ocean during that period. The satellite data will come closest to establishing a time series of synoptic observations. Many of the in situ observations will be made only once as part of a rolling programme extending over five or more years. Some measurements will be repeated to check for significant changes, and there will be a small number of time series. There is no single name that describes such a non-synoptic sample, which aliases most of the changes occurring within the intensive field phase. The word "snapshot" captures something of the spirit in which the WOCE data set should be studied, bearing in mind the sampling problems that distort the image. Despite interpretation problems the WOCE snapshot will be far more coherent and closer to being synoptic than the existing data archive which has been accumulated over several decades. It will also be much more global. The experiment will be designed to minimize the problems of aliasing.

Any experiment designed to meet Goal 1 of WOCE must address the fact that the World Ocean is a continuous whole, demanding a unified global approach. However, the interposition of the continents poses rather different dynamical problems in each region. The strategy of WOCE has been chosen to achieve a satisfactory balance between these potentially conflicting needs for a uniform global coverage, on one hand, and concentration on more regional problems, on the other. The field component of WOCE is based on three Core Projects, each of which serves to meet the specific objectives of Goal 1 in a different way. Each Core Project provides a particular set of specifications to be met by the various observing elements described in Section 6 of the plan. Before discussing the Core Projects in detail, the four Objectives of Goal 1 are elaborated in terms of their contribution to Goal 1 and our existing knowledge of the ocean.

3.2 Objectives of Goal 1

3.2.1 Objective **1:** The **large-scale fluxes of heat and fresh-water and their divergences over 5 years, and their annual and inter-annual variability.**

There is a need for data sets that will reduce the very great uncertainties about the role of the ocean in the global heat, water, and chemical balances (Wunsch, 1984b). The ocean influences the atmosphere by the fluxes of momentum, heat and fresh water through the surface (Woods, 1984). The ocean both stores and transports heat and fresh water and their fluxes in the ocean determine the zeroth-order climatic role of the ocean and the integral properties of the entire ocean-atmosphere system. At the present time, there are very few quantitative estimates of the oceanic storage and transport of these quantities and the extent to which they vary annually and interannually is almost totally unknown. (see for example, Figure 2). Knowledge of how the heat transport within the Earth's fluid envelope is partitioned between the ocean and atmosphere is essential for understanding climate. The existing data base is only adequate for the estimation of heat transport by ocean currents through a few sections (Bryan, 1982).

Heat and fresh water content are fundamental properties of the full three-dimensional ocean circulation and their transport, storage and boundary fluxes in any ocean model must be consistent with their conservation. Thus, this objective involves all the observational and theoretical elements of WOCE since essentially all elements of the ocean circulation, ranging from small-scale mixing, large-scale advection, and forcing on ocean basin scales, influence the transports of heat and fresh water.

Estimates of heat and water vapour storage and transport are made through the use of a great variety of oceanographic and meteorological observations. Direct computations of heat and water flux and divergence can be made by multiplying estimated horizontal water velocities by estimated temperatures and salinities and constraining the results by the requirement that the budgets for heat and water must be balanced over large regions. The accuracy of this calculation is limited by uncertainties in the wind stress (and hence in the Ekman fluxes), by the inability to stratify data by season and year and by uncertainties about oceanic reference level velocities (Dobson et al., 1982). Adequate data for the calculation of multi-year averages or the determination of interannual changes is totally lacking. The WOCE approach to this issue is to rely upon the basic concepts employed today on the assumption that they
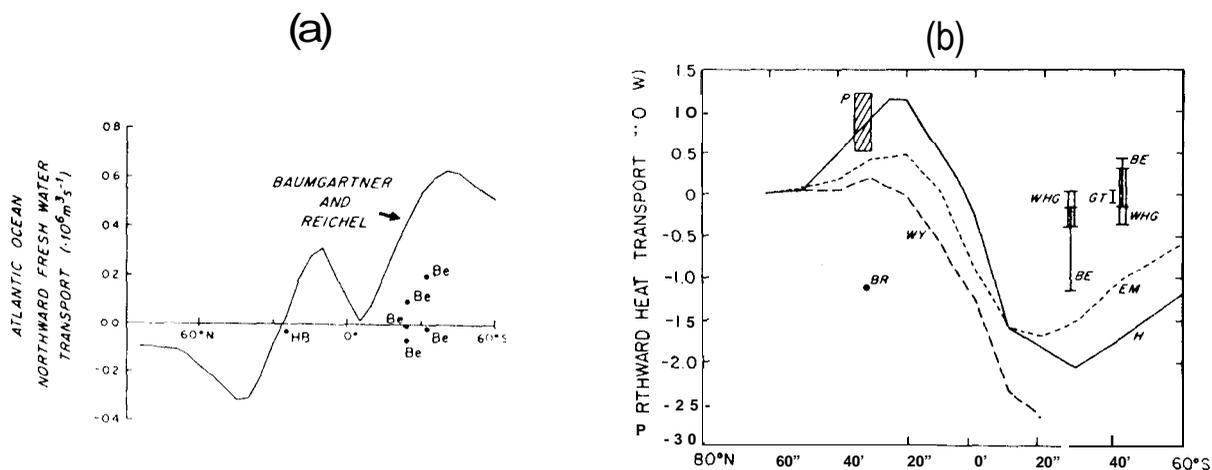
(a)

(b)

Figure 2: Examples of the uncertainty in estimates of the transport of heat and fresh water. In 2(a), from Hall and Bryden (1982), the northward transport of fresh water in the Atlantic Ocean (x 106 m3 s-1) obtained from Baumgartner and Reichel's (1975) values of the net gain of fresh water in the ocean due to evaporation, precipitation and river runoff is compared with values obtained at one latitude by Bennett (Be) (1978) and Hall and Bryden (HB). In 2(b), from Tally (1984), a similar comparison is made for the northward heat transport in the Pacific Ocean as estimated using surface heat fluxes from Emig (EM) (1967), Hastenrath (H) (19.80) and Wyrtki (W) (1965) and values at one latitude by Georgi and Toole (GT) (1982), Bryan (B) (1962), Bennett (BE) (1978) and Wunsch et al (WHG) (1983).

contain the essence of the problem and to greatly upgrade the quantity and quality of the basic data sets. This means that much improved wind measurements, hydrographic coverage, and reference level velocity measurements are needed over periods of time adequate for computing multiyear means and variability about those means.

One method of running an ocean model is to force it with observed surface fluxes of momentum, heat and fresh water. In this case sea surface temperature and salinity are calculated variables, and the fields of sea surface temperature and salinity are required for verification. An alternative strategy is to impose observed surface salinity and temperature (for example, Bryan and Lewis, 1979) in which case the surface fluxes of both fresh water and heat are required for model verification. In either case the fields of sea surface temperature, salinity, and heat and water fluxes are required. Estimates of the surface fluxes of heat and fresh water are limited by the accuracy of measurements of the wind stress, cloud cover etc, and the validity of the semi-empirical formulae used (Dobson et al., 1982). Improvements in the underlying observations are anticipated through the WOCE surface layer data set, the Ocean Observing System Development Programme (IOC, 1984) and other components of the World Climate Research Programme (WCRP, 1984). An alternative potentially powerful method of obtaining the surface fluxes is from atmospheric forecast models in use at National Weather Centres (Mitchell et al., 1985; Gordon and Bottomley, 1985). Assessment of the best method of determining surface fluxes of momentum, heat and fresh water from such models is a priority issue for WOCE. The surface fluxes provide an independent measurement of the transport of heat and fresh water by the ocean (Stommel, 1980).

3.2.2 Objective 2: The dynamical balance of the circulation and its response to changing surface fluxes.

Models designed to predict decadal climate changes are limited by computer power. Substantial changes in computer capacity will, however, occur during and after the WOCE period. It will then be possible to modify climate models to include more oceanic processes explicitly and more sophisticated parameterization of the processes that cannot be resolved. The circulation is sensitive to many processes that are poorly represented in existing models. The problem is to decide which of them demands priority in the allocation of increasing computer power and how best to parameterize unresolved processes given the particular goal of predicting decadal climate changes. The broad motivation of Goal 1 of WOCE is to provide the data sets against which possible changes in model design may be checked and the better model developed. While the other objectives of Goal 1 are directed at providing data on key properties of the system (such as, heat storage and flux, statistics of fluctuations, water mass formation) that models should be able to reproduce, Objective 2 is directed at ensuring the models include the correct dynamical balances and responses to forcing. Only in this way will it be possible to establish the credibility of ocean circulation models so that they can be used with confidence in a forecasting mode.

Models of oceanic climate change must accurately describe the ocean circulation that results from the changing surface fluxes of heat, fresh water and momentum. The flux of momentum via wind stress forces the interior ocean through the surface boundary layer leading to the large-scale wind-driven circulation with its characteristic gyres and intensive boundary currents. The fluxes of heat and fresh water determine both the characteristics of the water masses of the upper ocean and the magnitude of the buoyancy fluxes that drive what is classically referred to as the thermohaline circulation. The steady response of the upper ocean, including the main pycnocline to this dual forcing by momentum and buoyancy fluxes has long been the subject of theoretical study (Veronis, 1969 and Welander, 1971) but with limited results because of the non-linear nature of the problem (see Figure 3). Recently, new theoretical efforts (Luyten, Pedlosky & Stommel, 1982) have renewed interest in this problem which is basic to describing the upper ocean dynamical response on climatic time scales. It forms one of the key elements of Objective 2. Many aspects of the problem can be addressed by considering the fluxes of isopycnic potential vorticity between the seasonal boundary layer and the permanent thermocline (Woods, 1985b). The experimental programme will need to include measurements throughout the annual cycle both in the surface boundary layer and in the underlying upper ocean. Water mass formation by the same processes forms part of Objective 4 of Goal 1.

Another aspect of ocean dynamics important to climate prediction models that needs attention concerns the gyre scale response to large-scale forcing (for example, Anderson and Corry, 1985). This includes not only the adjustment of the sea surface and gyre-scale density field but the changes in the strengths of the western boundary currents and their role in generating eddies in their extension regions away from the western boundary (Holland et al., 1983). The boundary currents and eddies both play major roles in transporting heat and fresh water (Bryan, 1982). Determining the statistical nature of these fluctuating currents is part of Objective 3.

The location, nature and rate of ocean mixing, especially across isopycnals, is also of importance for climate modelling. On long time scales such mixing significantly influences the oceanic distributions of density and isopycnic potential vorticity. The relative important of diapycnic mixing in
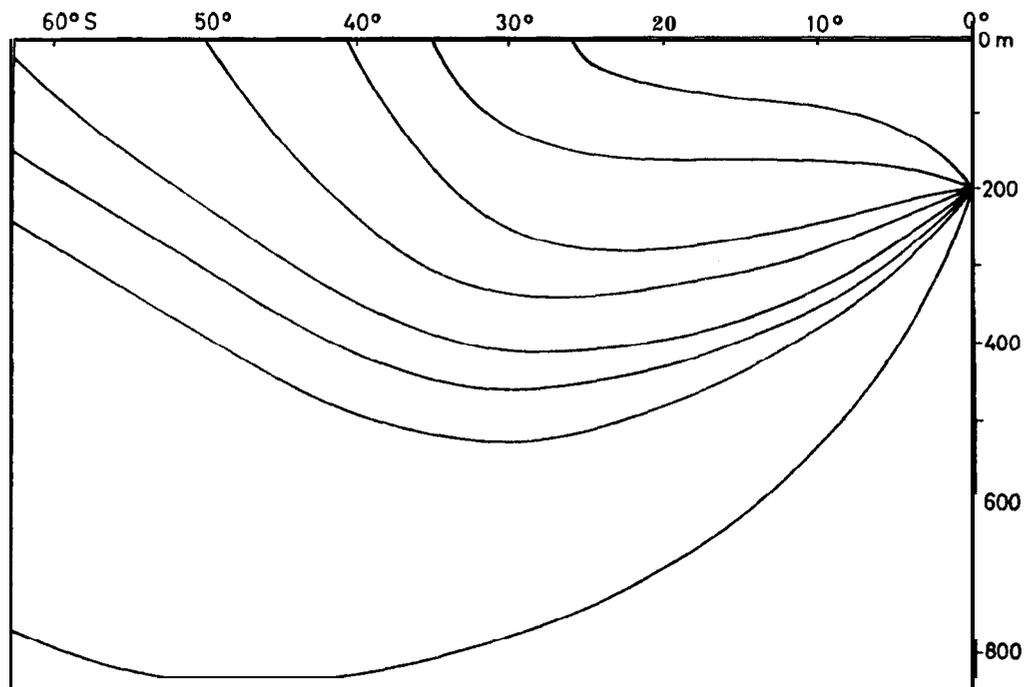
Figure 3: A meridional section of density obtained from solving the ideal fluid equations using observed surface and deep density observations. Note the general similarity to the structure of the ocean but also the singularity at the equator which is typical of such solutions (from Welander, 1971).

the ocean interior and in the turbulent boundary layers is not known (Garrett, 1980). Insofar as the distributions of certain geochemical tracers are influenced by such processes, tracers may prove useful as diagnostics of diapycnal mixing. The correct parameterization of mixing remains a critical climate modelling issue to be addressed in WOCE.

Other dynamical problems will become apparent in the design of the Core Projects discussed later in this document. Some will need to be addressed by the WOCE intensive period, others may be clarified by regional and/or process-oriented research extending over a longer period. All require the use of theoretical and model analyses strongly supported by measurement programme.

Experimental programmes designed to achieve Objective 2 will usually require the most accurate data available from the large-scale observing systems needed for Objective 1. Increased resolution and specialized observing systems will also be needed to provide the data necessary to address some of the questions being posed.
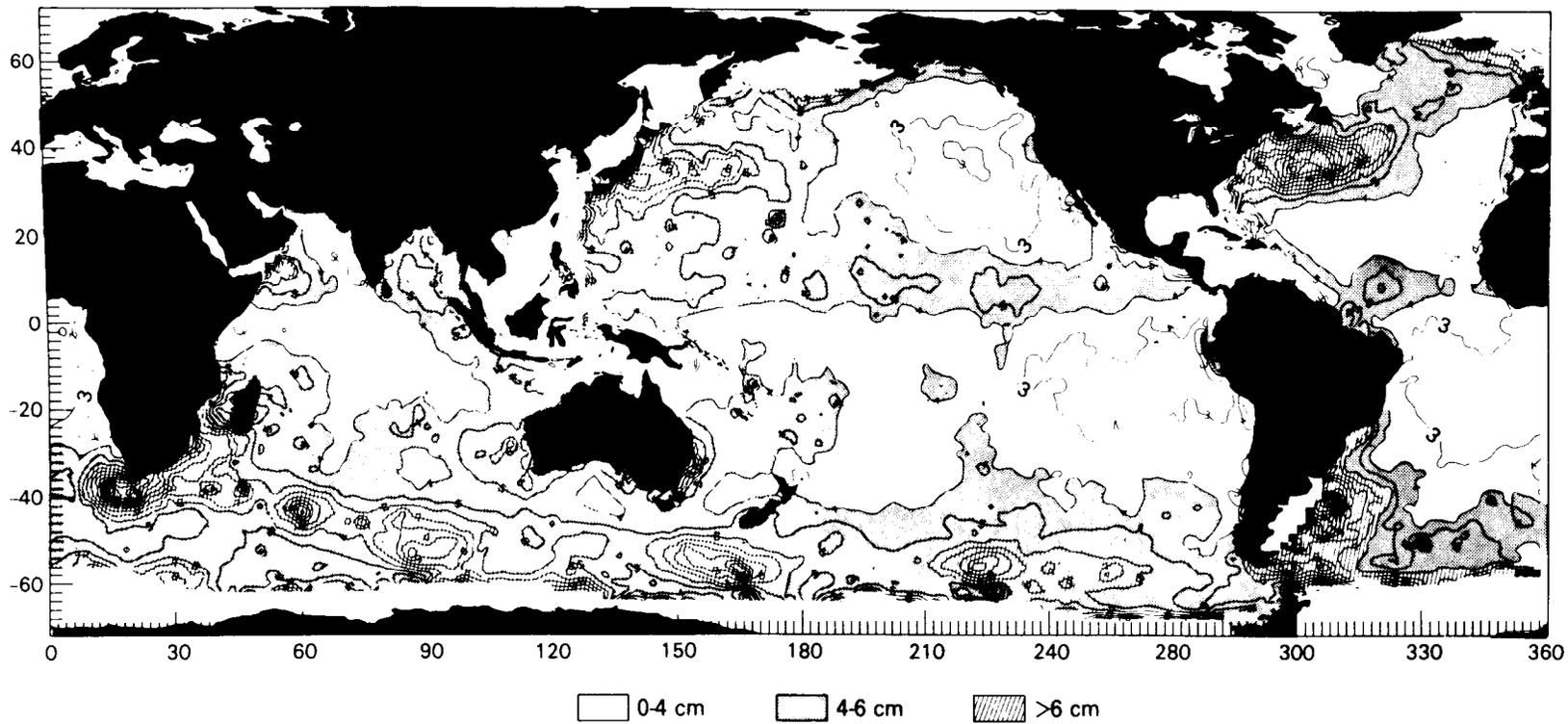
Figure 4: Global mesoscale sea height variability measured by the SEASAT altimeter showing the high variability, especially in the western boundary currents and the Antarctic Circumpolar Current (Cheney et al, 1983).

3.2.3 Objective 3: Components of ocean variability on months to years, megametres to global scale, and the statistics on smaller scales.

One of the great unknowns of the ocean circulation is the extent to which it changes with time. Much classical oceanography is based upon the assumption that data acquired on the large-scale at different times may be treated as synoptic. This has been necessary because of the sparsity of such data and lack of information to the contrary. However, whenever and wheresoever variability in the ocean circulation has been sought it has been found. It would be most surprising if a thermo-mechanical system as complex as the ocean did not vary on all space and time scales through both external influences and internal interactions. Motions on many space-time scales have of course been observed. The tides are a well-studied phenomenon (Hendershott, 1981; Marchuk and Kagan, 1984) and quasi-geostrophic eddies have been observed in many parts of the World Ocean (Robinson, 1983a). Equatorial waves of various kinds are important in describing the atmosphere-ocean exchanges which are the subject of TOGA. On the gyre-scale it is known that in the ocean interior the geostrophic flow as calculated by the $-spiral analysis is variable (Armi and Stommel, 1983), western boundary currents change in magnitude and direction, and low-frequency basin-wide oscillations exist in tide gauge records. Much of this variability may be seen in Figure 4, which shows the global analysis of SEASAT data by Cheney et al, (1983).

For the purposes of WOCE it is convenient to divide variability into fluctuations that occur on time scales shorter than the WOCE intensive observation period, and those occurring on longer time scales. The latter might be referred to as "secular" changes relative to the WOCE snapshot and are the subject of Goal 2. The former is the subject of Goal 1 Objective 3. It is important to determine the variability within the five year WOCE snapshot because:

.   Fluctuations are intrinsic to the mechanisms of the large scale circulation, including exchanges within and between gyres.

.   Unless properly understood and handled, fluctuations in time and space can seriously distort estimates of the mean and of the lower frequency variability. This phenomenon of aliasing is an important sampling issue,

.   Knowledge of the fluctuations (statistical or detailed) can be used to test our understanding of the ocean circulation and specific aspects of numerical models, especially those with eddy-resolving capability,

.   New instrument systems (for example, the scatterometer and altimeter) can be expected to expose new phenomena as regions of frequency/wavenumber space presently unexplored become accessible. For example, Seasat data suggests the existence of previously undocumented fluctuations of large amplitude in the Antarctic Circumpolar Current on time scales of a few weeks (Fu and Chelton, 1985 and Figure 5).

.   The observation of secular changes may indicate fundamental imbalances in a system supposed to be nearly in steady-state, with potential implications for the quasi-steady physics assumed in many ocean models, as well as consequences discussed under Goal 2.

WOCE will provide the data to map some aspects of the variability on scales of
ocean basins and larger, so as to indicate the strength and positions of the
large scale gyres, of the western boundary currents, and of the large tropical
current systems. This will lead to understanding of how the circulation
responds to the varying wind stress and the heat and fresh water transfers to
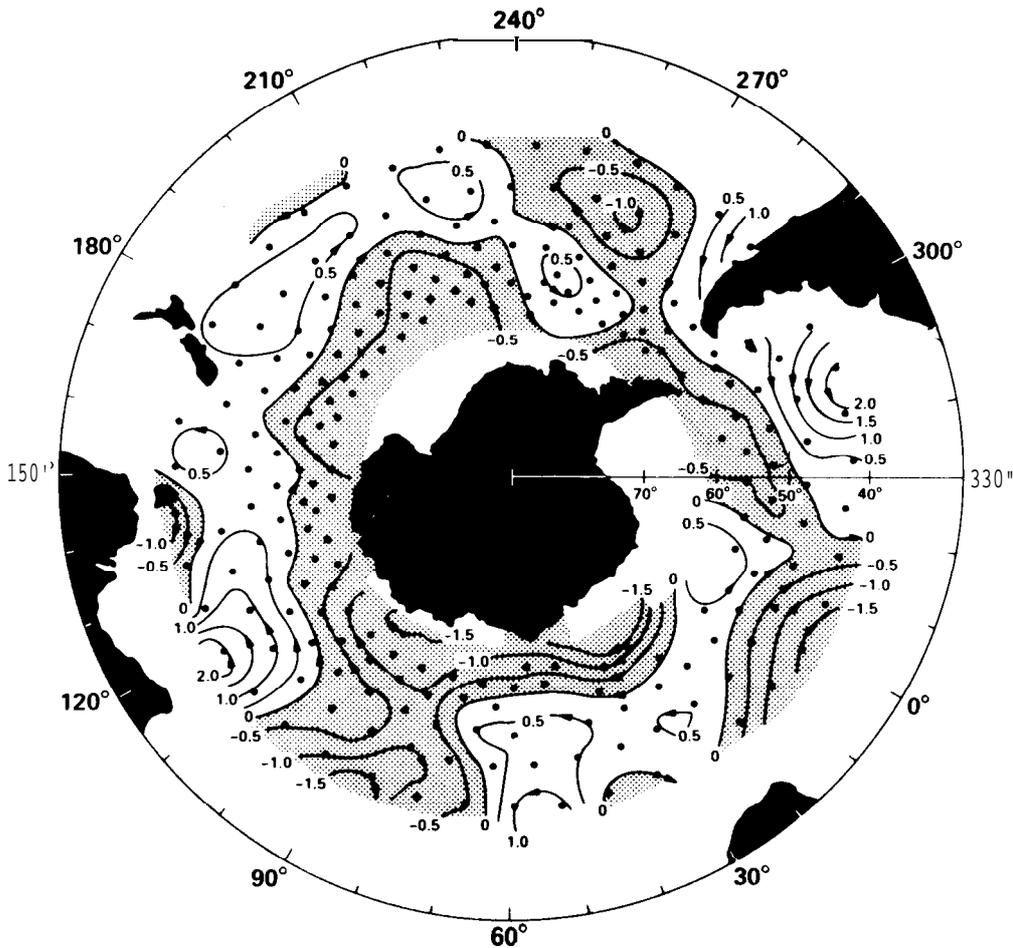and from the atmosphere.

Figure 5: The first empirical orthogonal function of sea level variability
around Antarctica showing previously undetectable modes of
motion. Areas of negative values are stippled (Fu and Chelton,
1985).

There is no WOCE requirement for detailed, day to day, or week to week,
maps of the global synoptic and mesoscale eddy field. What is need are
determinations of the statistics of these fields - their energy density and
time and length scales as a function of geographical position, season, and

atmospheric forcing. Eddies play an important role in the large scale dynamics of the ocean, by mixing potential vorticity and dynamically passive tracers. A full understanding of their origin and role is vital. Detailed studies of isolated features have been taken in recent years (Robinson, 1983a). The WOCE strategy is to map the regional and temporal variation of statistical properties, which will provide a powerful test of eddy-resolving general circulation models (Bretherton, 1984).

Many of the WOCE observing systems will contribute data relevant to Objective 3. Altimeter systems will provide data on variability scales from the mesoscale to the global and on periods from about six days to several years, insofar as they can be seen in changing surface topography. The mesoscale observations will be reduced to frequency-wavenumber spectra (or equivalent) as functions of geography and season, the larger scales will be mapped. In situ measurements of large scale variability (gyre scale and larger) will be determined by deployment of neutrally buoyant floats and repeated hydrographic and chemical observations. The variability of certain key qualities, such as changes in inter-ocean mass and heat fluxes and of important strait, sill, and boundary flows, will be determined through regional arrays employing a variety of observational techniques, including moored current meters, electromagnetic cables, tide gauges.

3.2.4 Objective 4: To determine the rates and nature of formation, ventilation, and circulation of water masses that influence the climate system on timescales varying from 10 to 100 years.

Water masses have traditionally been identified on the basis of their temperature and salinity, often supplemented by information regarding nutrients and oxygen. Identification of water masses from different sources has yielded valuable information about the general circulation of the ocean, especially in the deep layers. For example, Wust, (1935) traced Antractic bottom water into the Atlantic. Reid and Lynn, (1971) followed the flow of North Atlantic Deep Water into the Pacific. In many regions, water mass analysis continues to provide essential information about oceanic transport and mixing. The sensitivity of climate prediction models to particular water masses depends on the location and rate of their sources, and on their circulation and renewal time. For Stream Three climate prediction, water masses can be divided into three categories, with renewal times that are (1) longer than 100 years, (2) 10 to 100 years, and (3) shorter than 10 years. The model predictions of decadal climate changes will depend most critically on accurate simulation of the circulation and mixing of water masses in the second category. They will also depend on accurately simulating the source rates of water masses in all three categories. Objective 4 is concerned with the development of this aspect of the ocean circulation models.

Water masses in the interior of the ocean are ventilated with new water that acquires its initial temperature, salinity and chemical concentrations in the surface mixed layer at certain geographical locations. It is therefore necessary to be able to accurately simulate the properties of water in the mixed layer as a function of the surface fluxes and the circulation. This water is subducted into the seasonal thermocline whenever the turbocline marking the base of the mixed layer rises through the water in response to a combination of processes including Ekman pumping, reduction of the net buoyancy flux through the sea surface, and reduction in the wind stress. Each year, some of the water in the seasonal thermocline flows geostrophically into the permanent thermocline to begin its circulation around the interior of the

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ocean. The annual flux of water with temperature and salinity in prescribed
ranges determines the source function for the recipient water mass. Bryan and
Manabe (1985) have shown that small changes in the surface buoyancy flux
(produced by quadrupling atmospheric carbon dioxide) produce large changes in
this ventilation process. It will therefore have to be simulated accurately in
climate prediction models, which means paying special attention to the seasonal
boundary layer (Woods, 1985b).

Direct measurement of the water mass formation process is difficult, and
may never be performed on a scale adequate to confidently estimate the total or
annual mean rate of formation.   However some progress can be made with
volumetric techniques, using criteria of the spatial extent of the process
(for example, from T,S characteristics).   When used with velocities obtained
geostrophically, or from current meters or Lagrangian measurements, one can
obtain volume fluxes.

A second approach involves the use of those passive tracers which have
inherent time information and known boundary conditions.   One of the most
widely used has been tritium introduced to the ocean from the atmosphere after
bomb tests (see Figure 6).   In the case of steady state, radioactive tracers
(for example, Argon-39), the time information lies in the known rate of decay.
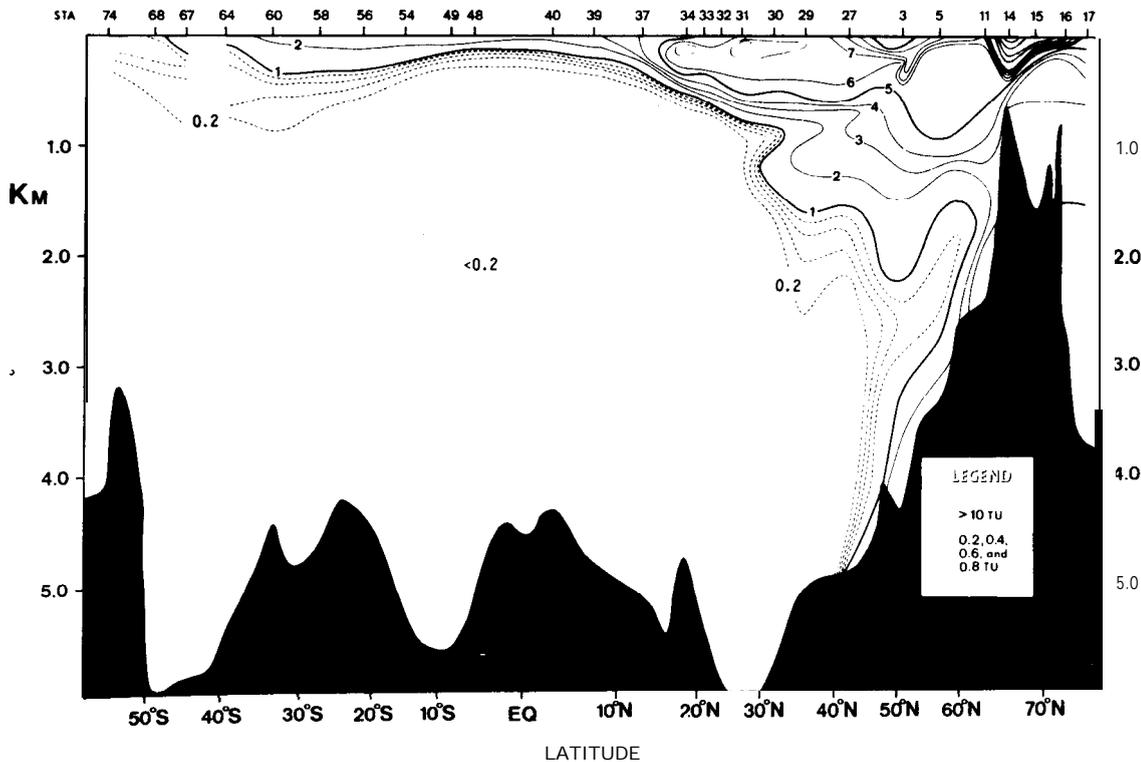

Figure 6:   Tritium in the western basin of the Atlantic Ocean from measurements
taken in 1972-73. The Tritium spike introduced mostly to the North
Atlantic in the early 1960's (see Figure 19) has penetrated the main
thermocline in the North Atlantic anticyclonic gyre and reached
greater depths to the north as a result of deep convection and the
overflow of deep water (from Ostlund and Brescher, 1982).

In the case of the transient tracers, the source of information lies in the known, time varying history of the atmospheric boundary condition coupled with documentation of the temporal evolution of their spatial distribution. The utility of such tracers depends both on the appropriateness of the time variation (either decay or source) to the time-scales being studied, and on the degree to which the boundary conditions and/or in situ behaviour are well known. It should also be noted that the diagnosis of physically interesting processes (for example, formation rates and velocity) is not model-independent, and the measurement of more than one linearly independent tracer, particularly those with differing time constants and/or surface exchange impedances, will generally improve the confidence of the analysis.

3.3   The achievement of Goal 1: The WOCE Core Projects

3.3.1 Introduction.

The translation of the four objectives of Goal 1 into practical experimental design will involve making decisions about priorities regarding calls on resources available within the international oceanographic community and in appeals for the provision of additional resources. It is necessary to agree on criteria for making such decisions. The mechanism adopted in this scientific plan is to identify three Core Projects that shall have top priority for Goal 1. The Core Projects are:

Core Project 1   The Global Description

Core Project 2:   The Southern Ocean

Core Project 3:   The Gyre Dynamics Experiment

All three Core Projects are needed to meet the objectives of Goal 1. Their aims are complementary, overlapping geographically and sharing the main observing systems. They differ in experimental philosophy.

CORE PROJECT 1: Core Project 1 is concerned with obtaining data that can be used to provide quantitative global descriptions of the circulation of heat, fresh water and chemicals and of the statistics of eddies. These constitute the zeroth order description of the role of the ocean in the planetary climate system. Comparison with model simulations based on surface fluxes observed at the same time will provide a powerful test of the models and will no doubt reveal significant errors in them. Clues as to the cause of these errors should be found through examination of the differing roles of the various oceanic basins in transferring heat and fresh water and the degree of regional agreement between models and the Core Project 1 data set. For this purpose the description of the global ocean should be of similar quality to that presently available for the North Atlantic.

The second and third core projects are designed to provide information on particular aspects of the role of the oceans in decadal climate changes that require different experimental considerations than the global average of Core Project 1.

CORE PROJECT 2:   Core project 2 is concerned with the Antarctic Circumpolar Current, the Southern Ocean and its interactions with the oceans to the north.   The Antarctic Circumpolar Current, by linking the circulations of the Pacific, Atlantic and Indian Oceans, provides the connection that transforms the oceanic heat flux from a regional into a global phenomena. South of the Circumpolar Current large quantities of heat supplied at low latitudes are lost to the atmosphere with the resulting formation of deep waters;   to the north there are regions of mode water formation.   Large fluctuations are known to exist in the flow of the Circumpolar Current and model predictions are expected to be particularly sensitive to the way these are represented.   However, little is known of the fluctuations and their role in inter-basin exchanges and this is an area in which WOCE is likely to produce fundamental discoveries that will change our theories of ocean circulation in a qualitative way.

CORE PROJECT 3: Much more is known about the circulations within ocean basins, especially in the North Atlantic, which is the best observed. Nevertheless, recent developments in theoretical understanding of boundary layer processes and mixing by quasi-geostrophic eddies have posed fundamental questions about the design of circulation models, which are sensitive to the method of representing them.   Other processes pose equally important questions.   Improved resolution permitted by more powerful computers will help, but it would be unwise to assume that model predictions will become insensitive to the method of parameterizing motions that remain unresolved.   The ultimate aim of developing models suitable for decadal climate prediction poses challenging specifications for the accuracy to which ocean circulation is simulated.   Core Project 3 will study certain processes of one ocean basin in sufficient detail so that major advances can be made in the models for the basin which can be later extended with some confidence to other ocean basins and the global circulation.   Concentrating on these processes in one ocean basin has many practical advantages.   The fieldwork and associated modelling studies of Core Project 3 will be grouped under the general title 'WOCE Gyre Dynamics Experiment'.

It is expected that the results of Core Project 3 will have general applicability in modelling the global circulation.   Nevertheless,' there are fundamental differences between the ocean basins.   The channelling of the Florida current, the effect of the great width of the Pacific, the Monsoon forcing of the Indian Ocean, and the circulation around Southern Africa are examples of the regional features demanding special attention.   The dynamical problem of flow across the equator may be resolved differently in each ocean because of its geography.   Comparison of similar features in the different ocean basins will be possible using the data sets of Core Projects 1 and 2 and should lead to clarification of certain aspects of the oceanic circulation. Other features may only be addressed by regional studies carried out in addition to the three Core Projects.   The WOCE strategy is to encourage such regional studies, providing they can make a contribution to the goals of WOCE and that their timing does not draw away resources needed for the three Core Projects which must be given priority.

3.3.2   Core Project 1: The Global Description.

Introduction: Most of our existing knowledge of the large-scale ocean circulation has come from hydrographic surveys of various "tracer" distributions, coupled with use of the dynamic method.   For example, vertical

and horizontal sections, of salinity, nutrients, oxygen, have been interpreted as showing the "sources" of different oceanic water masses and inferences have been drawn about how they must be moving about the ocean.   In this way oceanographers such as Wust, Worthington, and Reid, have provided considerable descriptive knowledge of the structure of the large-scale circulation.

The dynamic method, as developed over the past 80 years or so, makes use of temperature and salinity measurements and the equation of state to compute the density field and from it the vertical shear of the horizontal geostrophic flow field.   Combining these with the constraints from transient or radioactive tracer distributions enables certain estimates to be made about the rates of water mass movement.   The dynamic method yields a form of incomplete "clock" establishing relative rates of movement of the ocean circulation on large scales.   The combined use of tracers with geostrophic currents has reached its highest degree of development in the North Atlantic.   Few would argue with the statement that more is known about the North Atlantic Ocean than any other ocean basin.

It is instructive to ask why the North Atlantic is best-known.   Several related reasons exist, not least of which is that the major oceanographic institutions of the western Europe and eastern North America ring the basin. The width of the ocean is less than one third that of the North Pacific, making, trans-oceanic traverses a practical possibility for conventional oceanographic vessels.   Finally, the North Atlantic, for reasons incompletely understood, carries strong watermass formation signals from different regions (for example, the Mediterranean, Norwegian Sea, Antarctic,).   As a result, surveys of the physical and chemical properties of the Atlantic have accumulated over the years and, with some exceptions (nutrients), better property charts can be made for the North Atlantic than for any other ocean basin.   It is no coincidence that during the International Geophysical Year, only the Atlantic was covered with a systematic, high quality, top to bottom, continent-to-continent grid of hydrographic stations.   This survey has until very recently remained the major source of modern information on the circulation of the North Atlantic.   It was the North Atlantic that was recently re-surveyed by an informal consortium at the highest standards permitted by existing instrumentation (Figure 7).

In the other oceans, the data base is largely the result of uncoordinated surveys (see, for example, the Preface to Wyrtki et al, 1971) leaving large gaps in coverage in one or more of the essential fields.   Paradoxically, the best-surveyed ocean, at least in terms of coverage, next to the North Atlantic appears to be the Southern Ocean, as a result of the intensive efforts made to systematically cover that ocean during the 1960's to early 1970's using the R/V Eltanin, a special capability ship available at that time (Gordon et al., 1982 and Figure 8).

Although much remains to be done in the North Atlantic (see Core Project 3), any substantial further progress in understanding the global circulation requires a description of the distributions of heat, fresh water and chemical tracers, the dynamic topography, and the surface forcing of all the oceans that, at a minimum, will permit their discussion with the same confidence that exists now for the North Atlantic.   Such information is necessary, for example, as a data base for any numerical or analytical model able to compute the transports of heat, salt, etc. in the global ocean.   It will also serve as a foundation on which to base improvements to such models and those designed explicitly for the prediction of decadal climate change.   At present in some oceans it is not even clear that the density signatures of all the major current systems (in particular, the deep boundary currents) have been observed, much less their transports been determined.   For the most part the procedures
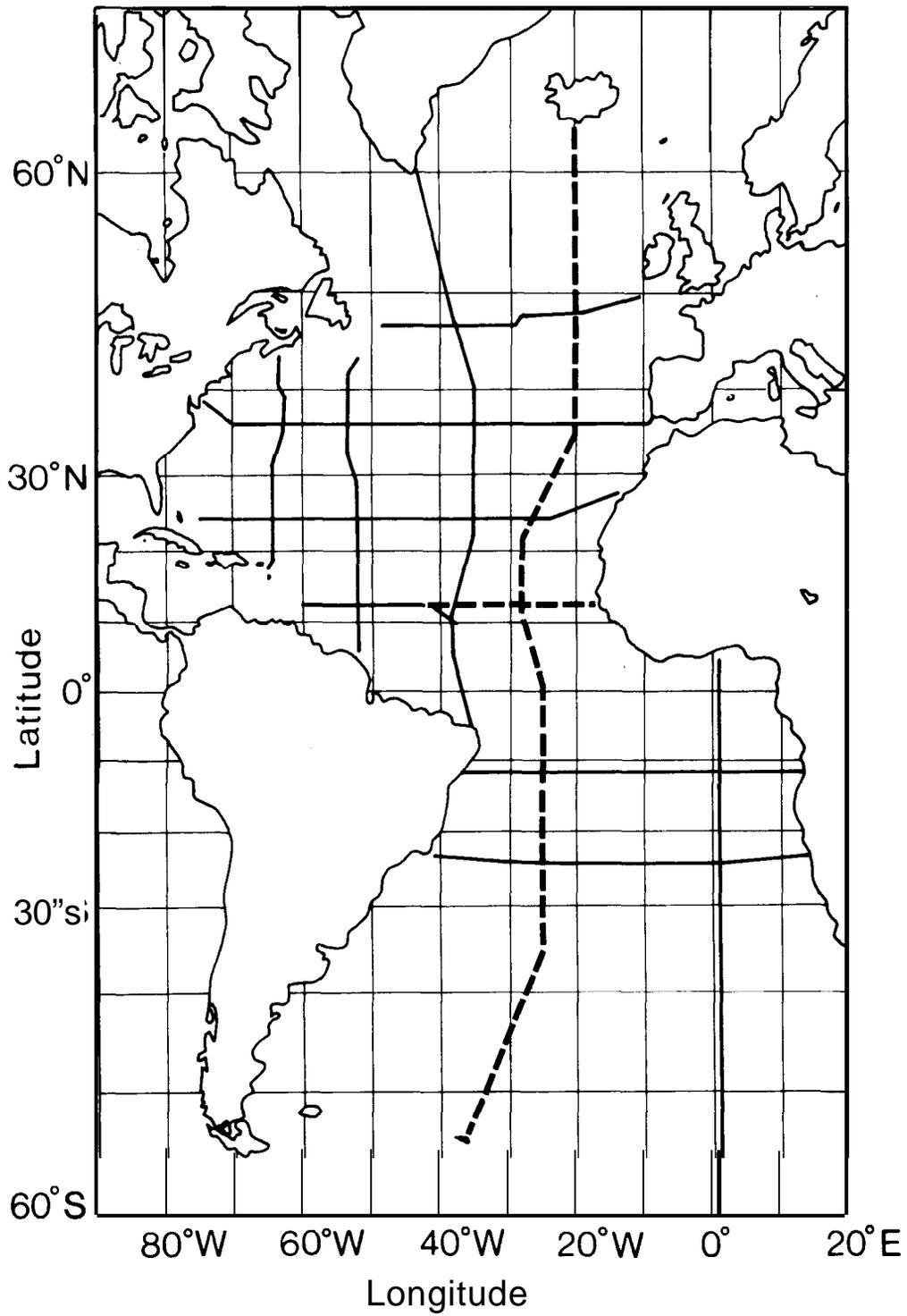
Figure 7:   Sections planned (dotted lines) and recently occupied (solid lines)
            in the Atlantic through the efforts of several laboratories.   The
            North Atlantic coverage is indicative of that required globally.
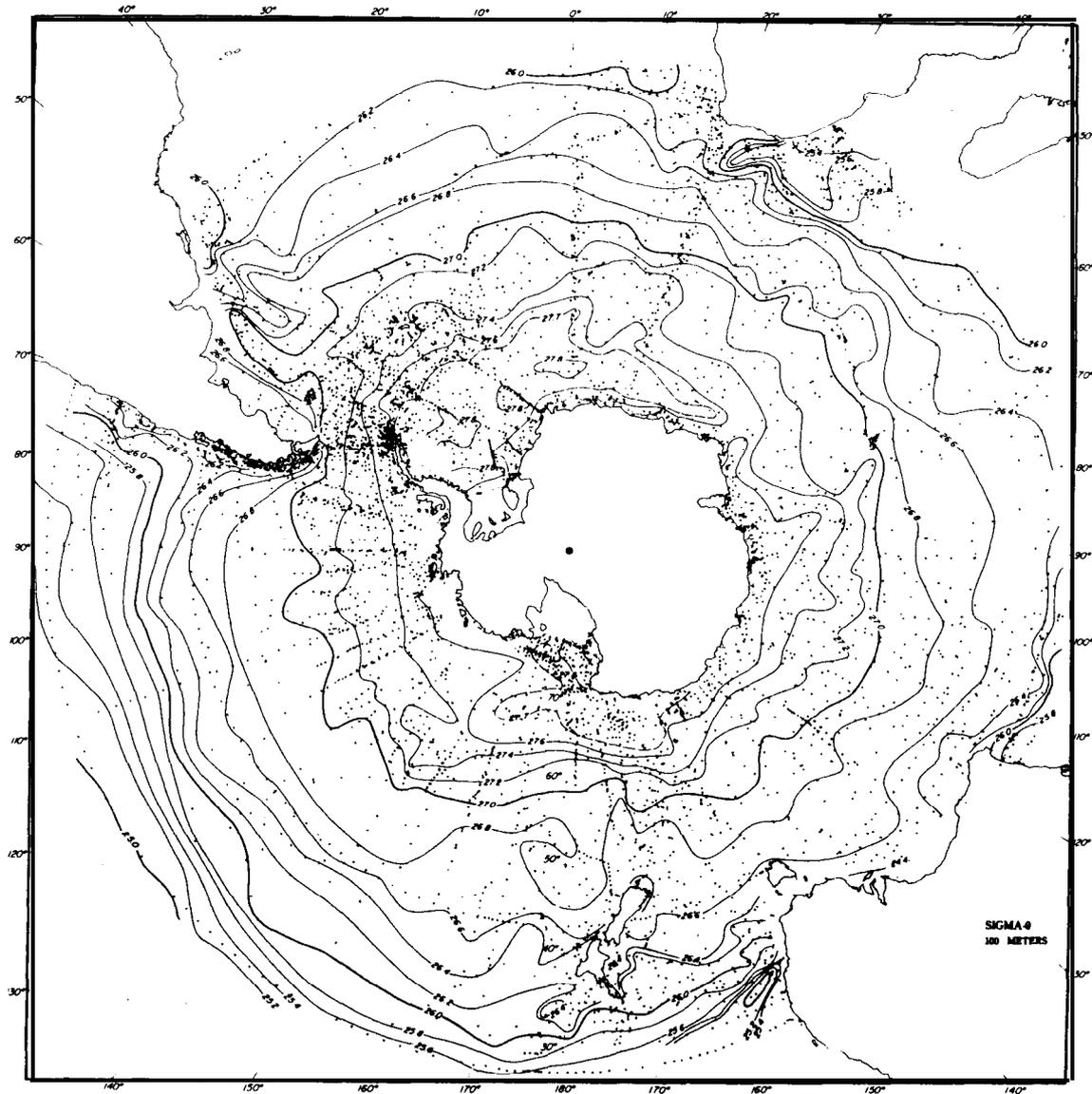
Figure 8:   Chart showing positions of stations occupied by the R/V Eltanin and
            other vessels in the Southern Ocean as well as contours of potential
            density σ_θ, at 100 meters (from Gordon et al, 1982).

for carrying out this major experimental component will be qualitatively
similar to those that have always been used.   Use will be made, however, of
more efficient methods and of chemical tracer observations that have become
possible in the past few years.   Satellite observations of sea-surface
altimetry and forcing will play a more important role in WOCE.   The recent
re-survey of the North Atlantic and the existence of the Southern Ocean survey
demonstrate the practicality of the plan.

The relationship to Goal 1 Objectives: The global programme outlined above
constitutes Core Project 1 of WOCE.   It addresses, at least In part, all of the
objectives of Goal 1 and Objective 1 of Goal 2.   The hydrographic and chemical
tracer data, measurements of the surface altimetry and wind stress and any
direct measurements of velocity will be combined in models in order to
determine the fluxes and divergence of heat and water vapour and their annual
and interannual variability.   The procedures to be used range from conventional
direct estimates, to inverse models to eddy-resolving general circulation
models (EGCM's).   All will address Objective 1 of Goal 1.   Core Project 1 will
contribute to Objective 2 (ocean dynamics) through the measurement of surface
forcing, surface altimetry, and the interior mass field which can be used with
dynamical models to study the large-scale ocean dynamical balances over the
full range of oceanic conditions, though not in such detail as will be done for
an ocean basin in Core Project 3.

The principal contribution of Core Project 1 to Objective 3, on oceanic
variability, is through two disparate means. The first, and probably the more
important, is by the satellite measurement of sea-surface altimetry over the
range of oceanic variability from spatial scales of about 20 km to 10000 km and
time scales of 20 days to 5 years.   Secondly, the in situ variability will be
determined through repeated hydrographic surveys (principally directed at the
annual and interannual components of variation), and through extended time
series of observations from specific fixed stations (for which the Panulirus
Station may be considered the prototype).   Finally, the formation rates and
fluxes of water masses (Objective 4) will be determined through the combination
of all the Core Project 1 elements into models of the circulation, analogous to
those used for heat flux and divergence calculations.

Elements of the Field Programme: The SSG is developing a plan for each ocean,
through a series of workshops intended to elucidate optimal sampling strategies
for each one, dependent upon what is already known.   The elements of the plan
for each ocean will address the following desirable results:

  . Adequate spatial coverage (see, for example, Figure 9) so that all the
     major features of temperature, salinity, nutrients, oxygen, Tritium,
     Helium-3, fluorocarbons, Carbon-14 (to the extent that useful results may
     be obtained using small water samples) and dynamic topography are
     contourable at all depths where signatures of spatial change are
     detectable and, on a coarser scale, some sampling of "large volume"
     tracers such as Krypton-85, Argon-39 and Radium-226 so that their
     large-scale or mean concentrations may be determined. The results of this
     basic descriptive programme will be both the initial background data
     needed for any dynamical/chemical model of the ocean, also a reference
     state against which to determine future climatological changes in the
     ocean, be they in heat or salt content, or stable tracer concentration.

  . In those regions, especially high latitudes, where a strong baroclinic
     annual cycle is expected, surveys will be repeated sufficiently frequently
     to determine the magnitude and phase of the cycles.   Special attention
     will be paid to the depth of winter time mixing at high latitudes, a
     parameter of considerable importance in understanding both the heat loss
     from the ocean and the injection of potential vorticity into the
     geostrophic ocean interior.   Much of this work will probably be conducted
     using expendable probes on ships-of-opportunity.

  . Sufficient surveys will be done in each ocean during the intensive 5 year
     period of the altimeter and scatterometer missions that comparisons can be
     made between the absolute and variable components of flow as determined
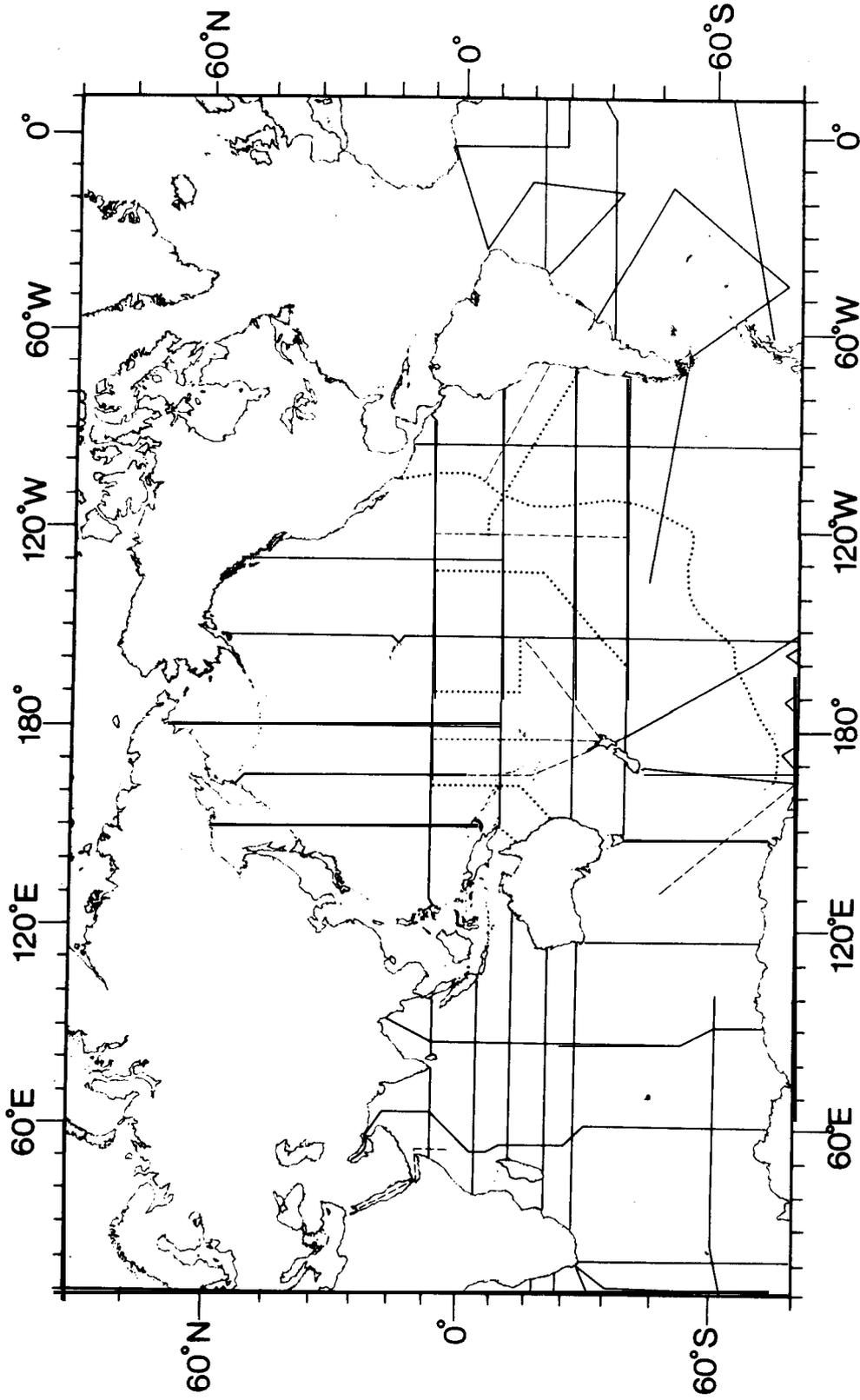   hydrographically and from measurements from the spacecraft.

Figure 9:   One proposal for the global (except for the North Atlantic) hydrographic and tracer coverage needed in WOCE. The highest priority would be given to those sections indicated by a solid line, second priority to those by a dashed line, and lowest priority to those by a dotted line. Although this indicates the type of coverage needed, the final observational programme is yet to be decided and may differ not only in detail but also in approach.

. Tide gauges, neutrally buoyant floats, current meter arrays, etc. will be deployed in each ocean so as to allow the determination of the absolute geostrophic flow fields before, during, and after the altimeter missions.

. As a result of the combination of these measurements into a variety of models, the meridional flux of heat and fresh water will be a known for each ocean as a function of latitude and the flux divergence will be known with an uncertainty of no more than 10%. The magnitude and phase of the annual cycle in each ocean will be determined with an uncertainty of no more than 20%. The major elements of the fluxes in each ocean (Ekman drift, advection, eddy fluxes) will be determined.

. Time series of hydrographic data from stations placed in carefully chosen representative regions will be obtained. The Panulirus hydrographic station off Bermuda upgraded to determine basic chemical tracers (nutrients, fluorocarbons, Helium-3, Tritium etc.) is an example of what is required (Figure 10). The placement of such stations depends on the availability of platforms and manpower and the need for representative stations in key locations.

The major experimental components necessary to accomplish Core Project 1 are satellite altimeters and scatterometers, vessels capable of highest quality hydrographic and chemical measurements (with the capability of meeting the special manpower and endurance requirements in the Southern Oceans (see section 6.3.1)), drifters for deep direct velocity observations in regions of strong flows, XBT's (principally for high latitude work and the determination of mid-latitude temporal aliasing), a tide-gauge network (for both altimetric calibrations and monitoring flows through certain straits), plus volunteer observing ships for the calibration of the satellite scatterometers.

3.3.3   Core Project 2: The Southern Ocean.

Understanding the global circulation implies a thorough description of the role of the Southern Ocean both as a pipe-line for mass transfers between the other oceans and, on a zonal average, as a region where heat supplied at low-latitudes is lost to the atmosphere. Neither of these aspects is presently well described. Nevertheless a 60-year long history of descriptive physical oceanography in the region, has provided a clear picture of the water masses present and of the basic zonal circulation (Gordon et al. 1982). What is largely lacking, in spite of recent efforts, is a quantification of the rates at which meridional transfers take place as well as of the rates of the intense interactions with the atmosphere and the resulting production of the bottom waters that find their way through the deep global ocean. These requirements form the basis for the design of the Southern Ocean Experiment of WOCE. some aspects of these issues have been addressed by a recent SCOR working group (SCOR, 1985). Problems associated with the difficult working conditions, the vastness of the region, and the complexity of the processes involved will make these objectives difficult to attain. Special attention will need to be given to the allocation of resources to the Southern Oceans.

In recent years progress has been made in establishing the total strength and variability of the circumpolar transport across the Drake Passage (Whitworth, 1983). Direct observations of current combined with hydrographic station data suggest that a large part of the variability through the passage is due to variations in the barotropic flow and that the transport relative to
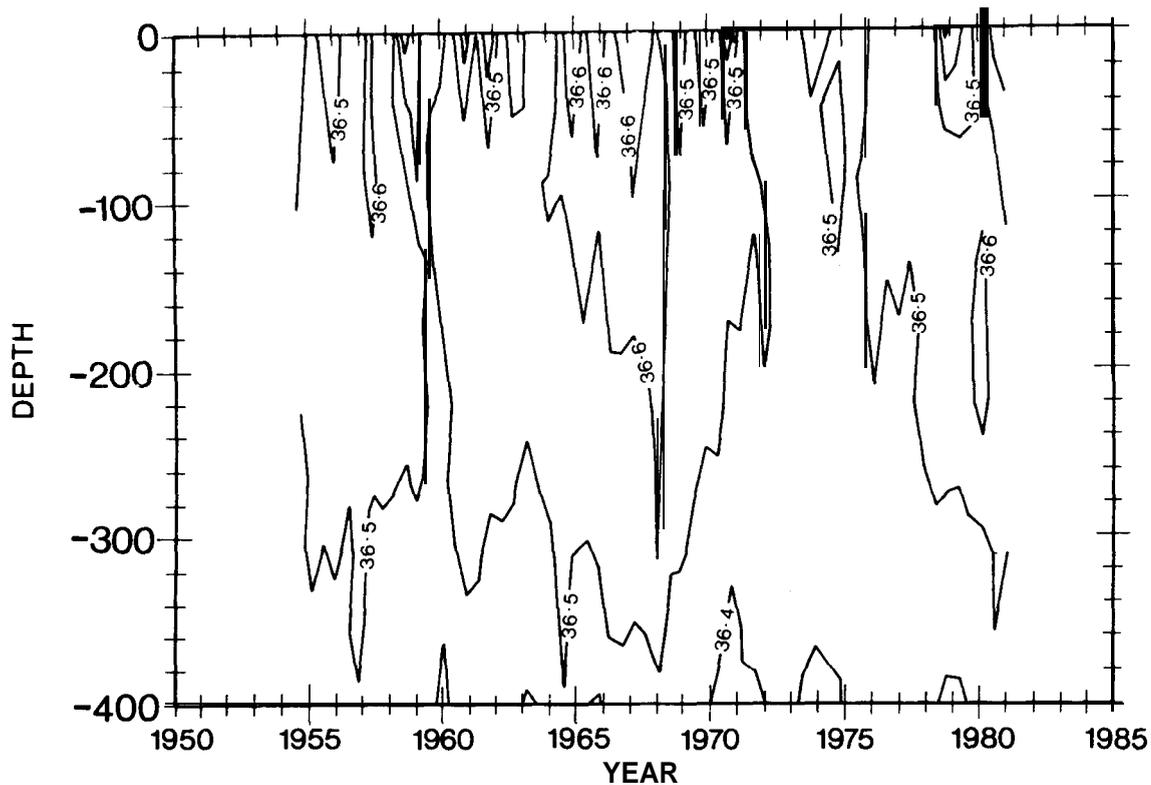
Figure 10:   Salinity as a function of time and depth at the Panuliris Station.
            Variability is evident at all time scales sampled.

a deep reference level is relatively stable at ~108 m3s-1   (Nowlin et al,
1977and Whitworth and Peterson, 1985).   The meridional profile of the total
current has a filamented structure.   The possibility that the Antarctic
Circumpolar Current has a Sverdrup balance exists but evidence of strong
deflections of the flow over the major meridional ridges would necessarily
modify this picture (Stommel, 1957 and Baker, 1982).   The Drake Passage appears
to be the only, and very valuable, in situ experimental site at which the total
circumpolar flow can be measured during WOCE.   Previous work in the area during
the International Southern Ocean Study (Whitworth,   1983 and Whitworth and
Peterson, 1985) should permit a tested and economical sampling strategy to be
developed.   It would use current meters, pressure gauges, and repeated
hydrographic sections supported by what should be an excellent altimetric
coverage by both the TOPEX and ERS-1 satellites.

The zonal heat and fresh water fluxes at other meridional sections south
of Africa and Australia have been estimated using the baroclinic velocity field
relative to a deep reference level.   It seems unlikely that determination of a
reference level velocity by direct current measurement would be feasible on
these long sections and, therefore, in WOCE reliance will have to be placed on
repeated hydrographic sections combined with pressure gauges and sea-surface
altimetry in order to cope with both ice-free and iced cover conditions.   The
latter should be supplemented, where possible by island tide gauges. By
providing the estimates of the surface geostrophic field sea-surface elevation

measurements can, during WOCE, significantly narrow the error bars on the overall velocity field. South of the Antarctic Convergence these should also give excellent estimates of the total geostrophic current since there the baroclinicity is small.

The value of additional instrumented sections across the Southern Ocean should not be assessed with regard to whether they might provide measurements equivalent to those in the Drake Passage but rather whether they might provide key measurements to test future numerical models of the circumpolar ocean. There is still little information as to the extent to which bottom topography, in particular the major ridge system, influences the dynamics of the Antarctic Circumpolar Current. Theoretical evidence is however beginning to clarify the nature of the dynamical interactions between the gyre and circumpolar flows that must be monitored over the period of WOCE.

The meridional transfers into and out of the Southern Ocean are of particular importance to Objective 1 of Goal 1. These have only been partially explored. Past work on meridional exchanges has emphasised the spread of Antarctic Intermediate and Bottom Water and the return of deep water. The experimental method that seems most likely to yield circumpolar estimates of the rates at which watermass exchanges proceed at all depths is that exploiting the time-dependent evolution of the distribution of anthropogenic and radio-active tracers. This technique is beginning to show some success in estimating the rate of production of bottom water in the Atlantic and an enhanced measurement programme in the Southern Ocean would be very effective. It is essential for WOCE to pursue and expand those aspects of transient tracers that can provide measurement of transfer processes on decadal time scales.

It is evident from work in recent years on the boundary currents of the three southern continents that potentially large heat and mass transfers can take place between one ocean and another in comparatively narrow regions. Adequate sampling of these boundary currents is difficult but may be possible by a combination of the systematic measurement of sea-surface elevation for the estimation of the surface currents and regional drifter measurements supported by exploratory XBT and Ship-of-Opportunity sections across the current. Satellite imagery will also be of value.

The regions to the north of the Antarctic convergence are one of the major areas of mode water formation and the geographical extent of this process needs to be mapped as well as the rates of production. A combination of the use of transient tracers, in particular the freons, with XBT measurements supplemented when possible by more advanced CTD profiling systems such as the Batfish appears to provide the best chance of gaining the needed data.

Relationship to the Goal 1 Objectives:

To the extent that it will provide general information of the Southern Ocean, Core Project 2 addresses all the Objectives of Goal 1. It is however, designed to focus on Objectives 1 and 4. In particular, interbasin exchanges are a key element of any overall description of the large scale fluxes of heat and fresh water. Similarly, the large atmospheric exchanges in the Southern Ocean and their attendant water mass formation and modification are basic elements of the global water mass formation and distribution.

Elements of the Field Programme:

The experimental elements to be applied in the Southern Ocean will, by necessity, need all the techniques and tools listed previously for the global description, Core Project 1. Additional methods will be used to address the special operational and dynamical problems of the Southern Ocean:

. The flow through Drake Passage will be measured using a combination of current meter, pressure gauge, and alimetric measurements. Estimates of transports through other sections will also be made, but for the most part have to be done without the aid of direct current measurements because of the long distances involved.

. The large vertical migration of the principal water masses along isopycnal surfaces will pose additional requirements on traditional hydrographic sampling.

. Surface measurements of stress and the fluxes of heat and fresh water will be particularly important for estimates of water mass formation and modification.

. Special emphasis will be placed on obtaining measurements of geochemical tracers for the purpose of estimating rates of formation, transport and modification of water masses.

. The vast measurement programme, requiring hydrographic and geochemical stations with research ships, cannot be achieved with the limited resources of the small fleet of suitably equipped ships operating in the Southern Ocean. Special arrangements will have to be made (see Section 6.3.1).

3.3.4   Core Project 3: The Gyre Dynamics Experiment

Our understanding of permanent gyre circulations rests on classical papers by Sverdrup (1947), Stommel (1948), Munk (1950) and others (see Stommel,1965) who exploited the idea of barotropic potential vorticity conservation. Their theories explained the existence of western boundary currents and the large-scale linear (Sverdrup) return flow to the east of them. An early application of computer modelling to the ocean circulation investigated the non-linear intense flow in the western boundary current. The extension to baroclinic flow led to theories of the permanent thermocline (Welander, 1971), in which isopycnic potential vorticity is conserved along particle trajectories. Layered solutions of the thermocline equations (Luyten et al, 1982 and Figure 11) have recently revived interest in this problem. Rhines and Young, (1982a,b) have investigated the implications of the mixing of potential vorticity on density surfaces. Systematic experimental and theoretical studies of transient eddies in the last twenty years have led to the recognition of their influence on the permanent circulation and computer models have revealed the great sensitivity of the distributions of passive scalars and potential vorticity to eddy mixing (Holland et al, 1983). These developments have stimulated re-examination of all aspects of gyre circulation theory, including the linear regime, the strongly non-linear boundary currents, surface forcing by the wind stress and buoyancy flux, and the general vorticity budget of gyres. Contemporary pre-occupations also include the impact of water masses from marginal seas and the mixing of passive scalars and isopycnic potential
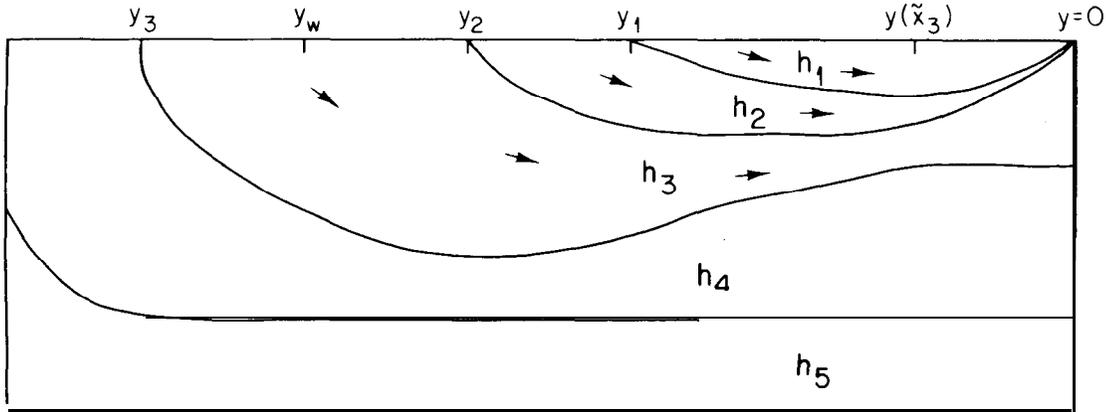
Figure 11: Schematic meridional cross section of the Luyten et al (1982) model
showing the layers of depth, hi, outcropping at latitudes,
yi(x). The Ekman pumping changes sign at yw(x).

vorticity across the permanent streamlines where they are bunched together in
unstable boundary currents.

In principle, it is possible to resolve these issues by means of computer
eddy-resolving general circulation models (EGCMs) in which the non-linear
features are treated explicitly.   Theoretical studies of gyre dynamics
indicate, however, that to increase the horizontal and vertical resolution
sufficiently to construct such global EGCM's will require an increase of
computer power of about three orders-of-magnitude.   This is likely to be
achieved early in the next century.   For the present, high resolution models
for limited regions of the World Ocean can be used to clarify issues that will
arise in the design of future global EGCMs.

Core Project 3 is designed to meet the objective of developing accurate
eddy-resolving general circulation models by a combination of modelling and
experiments that will directly address key aspects of the dynamical balance of
the circulation and its response to decadal changes in surface forcing.   The
aim will not be to study the details of physical processes, but rather to
survey their large scale signatures in sufficient detail to relate the detailed
knowledge gained in other investigations to the gyre-scale circulation. One of
the points to resolve in the experimental design is just how much detail of
each phenomena must be observed to support model development.

The difficulty experienced in deriving an accurate description of the
circulation from existing data, even *in the*best observed basin (the North
Atlantic), emphasises the need to concentrate the measurements into a single
basin.   The choice of basin will depend on a balance between logistic
convenience, background information, and the availability of the essential
features needed to be studied, including both cyclonic and anticyclonic gyres,
a western boundary current, and large regional variation in Ekman
suction/pumping, depth of winter mixing and eddy kinetic energy.

Priority will be given to studying those processes that are likely to
cause modellers problems at the end of the century when increased computer
power is available but many important processes will still have to be
parameterized.   They include the seasonally-varying upper boundary layer, the

high Rossby number mesoscale jets associated with eddy mixing, diapycnic mixing in the thermocline, and the turbulent boundary layers on the bottom and sides of the basin. It will also be necessary to measure transient motions that will be resolved by the models, but which may not be accurately simulated because of the limited spectral window of integration: examples include baroclinic planetary waves, quasi-geostrophic eddies and topographically influenced motion. Finally, the experiment will be concerned with dynamical aspects of the fluxes between the chosen basin and its neighbours, including the overflow at sills and cross-equatorial motion. These will be studied for their impact on the dynamical balance in the particular basin chosen for Core Project 3, rather than for their impact on the global circulation.

The planned activities of Core Project 3 could be grouped under various headings (not mutually exclusive), such as, ventilation of the thermocline, internal-ocean dynamics, eddy dynamics, diapycnic mixing, exchange between gyres, equatorial dynamics, and the deep circulation. The observing systems to be deployed for WOCE will provide special opportunities for studies in these areas after 1990, but some aspects of the fieldwork will start earlier and may continue beyond the planned mission lives of the WOCE generation of oceanographic satellites. The exact composition of Core Project 3 will only be determined after future planning, keeping in mind the priorities set by the requirement for improved models for decadal climate prediction. Some possibilities are discussed below.

There is a solid foundation of knowledge about the physical processes that control the flow of potential vorticity and passive scalars into the thermocline from the turbulent boundary layer, in which the temperature, salinity and chemical concentrations of'seawater are influenced by the surface fluxes. The first steps have been taken to incorporate these processes into circulation models so that the gyre response to changes in surface fluxes can be computed. However,' theoretical studies indicate that ventilation is a highly non-linear process, dependent not only on the wind stress curl (Ekman pumping), but also on advection of water through the seasonal boundary layer, the depth of which varies with the surface fluxes, the mean circulation and the transient eddies. It must be included in CCM's, which will be sensitive to the method of parameterizing the ventilation process. Experimental investigation of the ventilation process demands accurate measurement of the circulation and seasonal cycle in the mixed layer and seasonal thermocline (Woods 1985b and Figure 12).

The interior ocean is driven by wind and buoyancy forcing at the surface, the nature of which is the subject of the ventilation experiment just outlined. Water is subducted from the boundary layer into the permanent thermocline with a given potential vorticity. Recent theories (Luyten et al, 1983, Rhines and Young 1982a,b) make important predictions concerning the lack of ventilation in certain "shadow zones" and the effect of mixing of potential vorticity. Rhines (1985) has predicted that new water subducted from the boundary layer into the thermocline provides only a fraction of the water circulation around the gyre and that the remainder, which increases towards the line of zero wind stress curl, is old recirculating water. Other water masses are introduced by deep convection in the north or the overflows from marginal seas. These also force the ocean circulation, especially the deep flows, and form part of the boundary conditions on the theories just discussed. Models and theories of the gyre circulation must reconcile the roles of all the driving mechanisms and their interacting influence on the interior circulation.

These and other ideas and theoretical predictions raise questions regarding the nature of the large-scale gyre circulation, which provide sensitive tests of ocean models and their ability to describe decadal changes.

Other aspects of the internal ocean dynamics may be equally important. Some could be clarified by accurate mapping of the isopycnic potential vorticity and the velocity field of the permanent circulation, with spatial resolution appropriate to the crowding of streamlines in western boundary currents. The measurement of these quantities in the presence of energetic transient eddy motions poses a sampling problem which will dominate the experimental design.
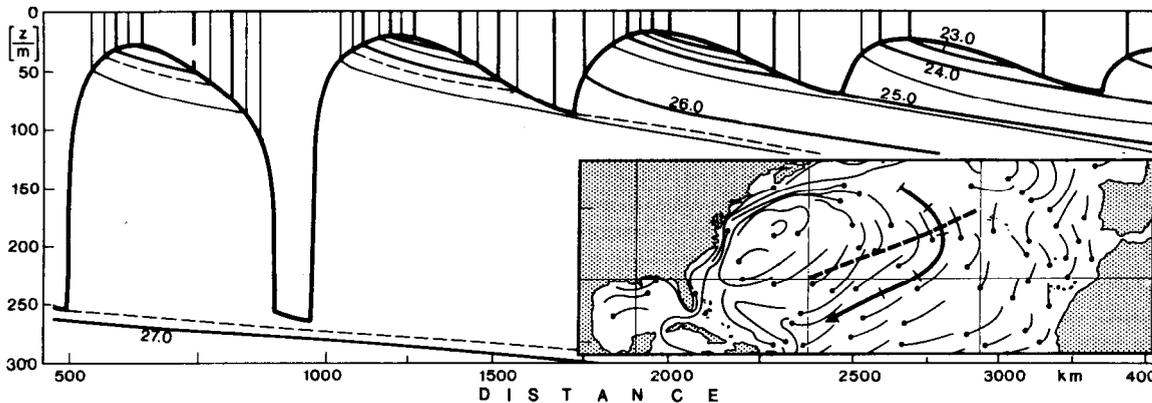

Figure 12: Variation of the depth of the mixed layer and various isopycnals during a 4 year integration of a mixed layer model following the trajectory of water circulating in the Sargasso Sea (according to the general circulation model of Sarmiento (1983)) showing the subduction of water-masses from the seasonal mixed layer. The inset shows the path of the Lagrangian mixed layer integration and annual trajectories of surface waters (from Woods and Barkmann, 1986).

WOCE will be the first investigation of large scale circulation since the discovery and exploration of the quasi-geostrophic eddies that are known to play an important role in the permanent circulation (Robinson, 1983a). The regional variation of eddy kinetic energy is a key variable for WOCE. Eddies receive their energy from the large-scale circulation and in turn diffuse large-scale potential vorticity, heat and other properties, as well as transfer momentum, to deep circulations. They play a major role in the interaction between the gyres. It has been proposed that the regional distribution of eddy kinetic energy may provide a sensitive test of GCM dynamics (Bretherton, 1984). In order to test GCMs by comparing their predicted eddy energy distributions with those observed during WOCE it will be necessary to ensure that all other relevant factors have been observed and simulated. This cannot be achieved on the global scale of Core Project 1, but the prospects are better for doing so in the Gyre Dynamics Experiment. The experimental strategy will be to map the eddy kinetic energy throughout the basin including both the vertical variation and the seasonal cycle (Dickson et al. 1982). Comparisons with the large scale circulation, especially in the deep water, and with the distributions of isopycnic potential vorticity and various tracers should provide opportunities to quantify the role of eddies.

The equatorial zones are regions of special interest. Since the flows there are ageostrophic, the measurement of the inter-hemisphere flow is difficult and may pose problems in the design of Core Project 1. Gyre-scale numerical models often exhibit problems in the equatorial zone that may be

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resolved by greater resolution, although this is far from clear. Greater understanding of equatorial dynamics is required for model development. Although the ocean above 1000 m is being investigated during TOGA, process studies to clarify questions of particular importance to WOCE are required, especially in the deep flows. One such question may be the behaviour of deep western boundary currents near the equator.

In the context of WOCE Goal 1, the principal role of diapycnic mixing concerns the dissipation of the variance of passive scalars and potential vorticity created either during subduction from the mixed layer or during eddy mixing in the thermocline. It is of practical importance to know the rates of diapycnic mixing and its regional variation in the context of the permanent circulation and the eddy energy distribution, as well as that of various tracers. Diapycnic mixing is however known to be so low that it does not appear to present a critical problem for ocean circulation modelling (Garrett 1979) and thus may be of lower priority than other components of Core Project 3.

The site of the Gyre Dynamics Experiment
The North Atlantic Ocean offers the required combination of features within a logistically convenient and accessible area and has already been chosen by the WOCE NEG for a series of GCM experiments. The one process obviously missing is the interaction between the circulation in a basin and the circumpolar current, but is not logistically feasible to mount the Gyre Dynamics Experiment in the Southern Hemisphere.

The relationship to Goal 1 Objectives
Core Project 3 is directed primarily at Objective 2 of Goal 1, the dynamical balance of the ocean circulation and its response to changing surface fluxes. The aspect of ocean ventilation is however directly related to Objective 4, water mass formation, and the investigation of eddy dynamics relates to Objective 3.

Elements of the Field Programme:
Core Project 3 will use all of the experimental elements of Core Project 1 at their ultimate accuracy; for example, determination of the surface geostrophic flow with the accuracy necessary to support all aspects of the programme will require the best possible absolute sea-surface altimetry. In addition, the project will:

.   Use hydrographic station data to map potential vorticity on various density surfaces, to calculate geostrophic shear and to map the distribution of geochemical tracers as indicators of ventilation rates and mixing

.   Require surveys with towed undulating vehicles, acoustic doppler current profilers, XBTs, and surface drifters to map the depth of winter convection and the source of potential vorticity in subduction regions. This will be coupled with the best available surface flux measurements from all sources.

.   Determine the circulation in the upper ocean directly by moored current meters, drogued drifters and tracked floats. In the deeper ocean the use of current meters and deep floats will map the mean circulation and provide information on eddy fluctuations.

.   Various specialized tools such as acoustic tomography may be used to elucidate aspects of particular dynamical problems.

CHAPTER 4

Goal 2

4.1   Introduction: The WOCE Approach to Monitoring

The second goal of WOCE . . . to determine the representativeness of specific WOCE data sets for the long-term behaviour of the ocean, and to find methods for determining long-term changes in the ocean circulation . . . . addresses the need to develop systems to monitor changes in the ocean circulation after the WOCE intensive period.   The WOCE data set will strongly influence oceanographers' ideas about the ocean circulation in the next century even though it will be primarily assembled during a single five year period. Since it cannot represent the circulation as it changes over future decades, the strategy is to use the data set (including the surface forcing functions) to develop models capable of accurately predicting the changes that occur in the ocean circulation as one part of the planetary climate system.   For this strategy to work it will be necessary that the WOCE data set, or specific parts of it, are representative enough of the large-scale long-term behaviour of the ocean so that its use to develop and verify models for climate prediction will have produced models that are valid for that purpose,   From analysis of these climate models and of the WOCE data sets themselves, it should be possible to identify certain sensitive indicators of changes in the ocean circulation located at a few key positions.   Measurements of these indicators should form the basis for a skeletal ocean monitoring system.   The collection of data using this system after the WOCE intensive period is not part of WOCE.   Providing the design basis for the system is.

While it is possible, in principle, to contemplate climate prediction models running solely on atmospheric data, this would require both that the oceanic part of the model responds correctly to the imposed surface fluxes, and that the surface fluxes predicted by the atmospheric part of the model are sufficiently accurate.   This ideal is unlikely to be achieved and one must assume that there will have to be on-going observations of critical elements of the ocean circulation system to constrain the predictions of climate models. Ocean monitoring for this purpose does not require homogenoeous, systematic global observations of the internal structure of the ocean in a manner equivalent to the World Weather Watch.   The aim will be to identify a small number of measurements that can be made economically and which provide the information needed to constrain the impact of limited spatial and temporal resolution, erroneous parameterizations and/or erroneous surface fluxes on the oceanic climate predicted by coupled ocean-atmosphere GCM's.   It is premature to specify, even in the broadest terms, what those measurements should be, although the Ocean Observing System Development Programme (IOC, 1984) has identified a range of possibilities.   The final selection will have to rely on the results of sensitivity studies with models based on the WOCE data set and using computer power available at the end of the century.

The design of an ocean monitoring system for climate purposes will also be influenced by the experience gained during WOCE with new or novel ocean

observing systems.   For example, WOCE should eliminate the need to observe
tides so that they can be removed as a source of error in future altimeter data
and greatly reduce the need for surface calibration of scatterometer winds.
Given the importance of this aspect of WOCE it may be desirable to incorporate
into the field programme a number of new observing systems that are candidates
for long term monitoring, but which have not yet reached a sufficiently
advanced stage of development to justify formal incorporation into the plan for
achieving Goal 1.

4.2 Objectives of Goal 2

4.2.1   Objective 1: The representativeness of the WOCE data sheet

The question as to whether the multi-year WOCE data set will be
reresentative of the behaviour of the ocean over longer time periods is a
difficult problem.   In the long-term it can only be addressed by examining the
predictions of the models that have been developed to describe the data set
(including the surface forcing functions) and which are completely consistent
with it, taking into account sampling errors.   If the predictions are valid,
one will indeed be able to say that the WOCE data set is representative.   The
proof however would require many years of data after WOCE.

A more useful approach, especially if an ocean monitoring system is to be
based on the WOCE experience, is to ask whether the WOCE data set and the
models developed from it are consistent with everything known about the ocean
system that is seen to be important to its evolution or as a measure of that
evolution.   If there is enough redundant information, considerable confidence
that the WOCE data set is representative may be gained.   In this context it
must be remembered that much is known about the ocean system from historical
data which is often of a process-oriented and/or regional nature. More will be
known before the end of WOCE from such sources.   In addition, an important
complement to WOCE in support of model development and testing could come from
the rapidly developing field of paeleo-oceanography. Although usually lacking
in detail, paeleo-oceanographic scenarios provide tests of models of the
complete climate system in distinctly different parameter ranges and may thus
be important for establishing confidence in model performance under conditions
of significant climate change.

Of particular importance as a test of the WOCE data set is the question of
whether or not the ocean models based on it are capable of reproducing within
the limits of error (arising both from the statistical uncertainty of the data
set and from the inadequate representation of physical processes in the models)
these properties of the ocean that are signatures of time-scales much longer
than the WOCE intensive period.   The most obvious of these properties are the
large-scale tracer distributions, including those of temperature and salinity.
Taking this approach, tests of the representativeness of the WOCE data set will
include such questions as whether:

.   There is reason to believe the WOCE data set provides adequate information
     to test the parameterization in models of those processes believed to be
     important for climate prediction; for example, the integrated effects of
     upper ocean ventilation and deep-water formation.

.   Global scale eddy-resolving models can describe both the observed eddy
    statistics and the large-scale distribution of heat and fresh water or
    their fluxes.

.   Such models can also describe the time-dependent evolutions of various
    anthropogenic ocean tracers with appropriate time-scales.

As WOCE is planned and carried out other tests of the representativeness
of the data set will undoubtably become apparent. This aspect of WOCE will be
pursued during the analysis phase of the experiment.

4.2.2   Objective 2: To identify the oceanographic parameters, indices and fields that are essential for continuing measurements in an observing system for climate on decadal timescales.

In order to provide the scientific basis for designing an observing system
that could be deployed on an ongoing basis in a cost effective manner to
monitor climate change on decadal and longer timescales, it will be necessary
at the end of WOCE to identify combinations of variables which are both
sufficient to determine the key features of such change and capable of being
measured to the required accuracy. Efficient selections can then be made from
among such combinations in relation to the available technology and other
constraints.

The numerical models developed and tested in WOCE will be used to test the
sensitivity of inferences about decadal changes in data inputs of various
kinds.   Such an analysis should not be independent of the tests of the
representativeness of the WOCE data set described above.   Information gained
under Goal 1 objective 3 about the ocean variability on shorter timescales will
enable improved estimates of the minimum sampling require. When analysed with
the use of ocean models it may also provide an initial indication of the
magnitude of decadal changes themselves.

The design of a realistic observing system requires actual experience as a
basis for iterative improvements.   There are measurements that can be
identified now that are likely to be included in a future observing system and
for which proven observational techniques are available.   Time series of some
of these measurements exist.   Careful evaluation of their best use as
indicators of climate change can be started now.

4.2.3   Objective 3: To develop cost effective techniques suitable for deployment in a climate observing system.

To be in a position to deploy a cost effective system after WOCE,
development is needed of new observing techniques that show promise of major
advances in measuring key fields or indices.   Some may use new working
principles or employ more appropriate sampling techniques. A criterion for
selecting new observing techniques at this time should also be the expectation
that such techniques, although still under development, could contribute
significantly to the objectives under Goal 1 during the WOCE snapshot.

To achieve this objective, it will be important to foster throughout the countries of the world, -the skills likely to be necessary for the deployment of post WOCE ocean observing systems and the modelling techniques (for example, four-dimensional data assimilation) needed to exploit them for climate prediction.

4.3 Achievement of Goal 2

Much of the achievement of Goal 2, especially as it concerns the representativeness of the WOCE data set will need to be carried out after the intensive field phase of WOCE. Details of this work will be greatly influenced by the final experimental design of the Core Projects that constitute the achievement of Goal 1. Of importance will also be the state of model development, which will also be influenced by the WOCE data sets and availability of the faster computers needed for global models of adequate resolution.

The representativeness of the WOCE data set will actually be attacked initially within the Core Projects of Goal 1. The data set will obviously be compared with historical records where the latter include measurements of sufficient density and quality. Many comparisons of the type listed in 4.2.1 will be part of the cycle of model development and verification that forms the very heart of Goal 1. For example, within Core Project 1 the data obtained on the evolution of various tracer fields before and during the intensive phase of WOCE will be compared with fields computed from global models using the WOCE data set. Consistency of the two fields would at least test whether the hypothesis of representativeness should be rejected. Various technological developments can be studied at this time and indeed must be started in the near future if they are to be available and of proven reliability after the intensive period of WOCE. Satellite ocean observing systems provide an example of the long lead time that is necessary for development of an effective observation sytem. Post-WOCE systems should be of improved reliability and availability. Ocean tomography is another potentially important measurement system requiring a long time for development.

CHAPTER 5

WOCE Modelling

5.1 Introduction

Goal 1 of WOCE addresses the development and testing of ocean models capable of predicting climate change. No single model is likely to be general enough to meet all aspects of this requirement. The achievement of Goal 1 and its more detailed objectives involves the strong interaction between modelling and field activities. As scientific planning continues, modelling results will play a major role in the design of the field programme. The present and future capabilities of ocean numerical models and their role in WOCE are discussed in this chapter.

5.2 Model Characteristics and Use

The ultimate model for climate prediction purposes would be a three-dimensional time-dependent global model capable of resolving the full wave number range of geostrophic motions and of predicting the fields of temperature, salinity and tracers given the surface fluxes of momentum, heat, fresh water, and gases. At present, no model with these characteristics exists, although eddy-resolving general circulation models (EGCMs) have been run for limited-size ocean basins (Figure 13). Using a domain 60" wide from the equator to 65"N, and a resolution of one-third degree in the horizontal and 15 levels in the vertical, such a model requires about ten hours of time on the fastest vector computers to simulate one year of real time (Cox, 1985). It is not practical to bring this model to equilibrium using its full eddy-resolving resolution; coarse grids with special time-stepping procedures must be used for this purpose. Only then can the model be integrated using its full capability for a very limited period of time (-15 years). A global EGCM of similar resolution would require in the order of 100 hrs computer time per simulated year. This is beyond present resources. However, **it is** anticipated that within a few years the next generation of computers will make possible the use of such a model for more extended periods of time, the number of numerical experiments will have to be limited. Thus, oceanographers will be forced to use the results of less comprehensive models, often of basin scale, throughout the planning phase of the WOCE field programme.

Several institutions have used or are using non-eddy-resolving general circulation models of basin or global scale. Most use levels to represent the vertical variation, but at least two are being formulated and tested using isopycnal co-ordinates (Bleck and Boudra, 1981 and Marchuk and Sarkisyan, 1985). The model formulated by Semtner (1974) has been widely used. More recently a computationally faster model has been developed by assuming geostrophic balance in the interior (Maier-Reimer, 1985). Even when used at high resolution this model cannot generate eddies and so they must be parameterized. Most other models in use could, in principle, generate eddies
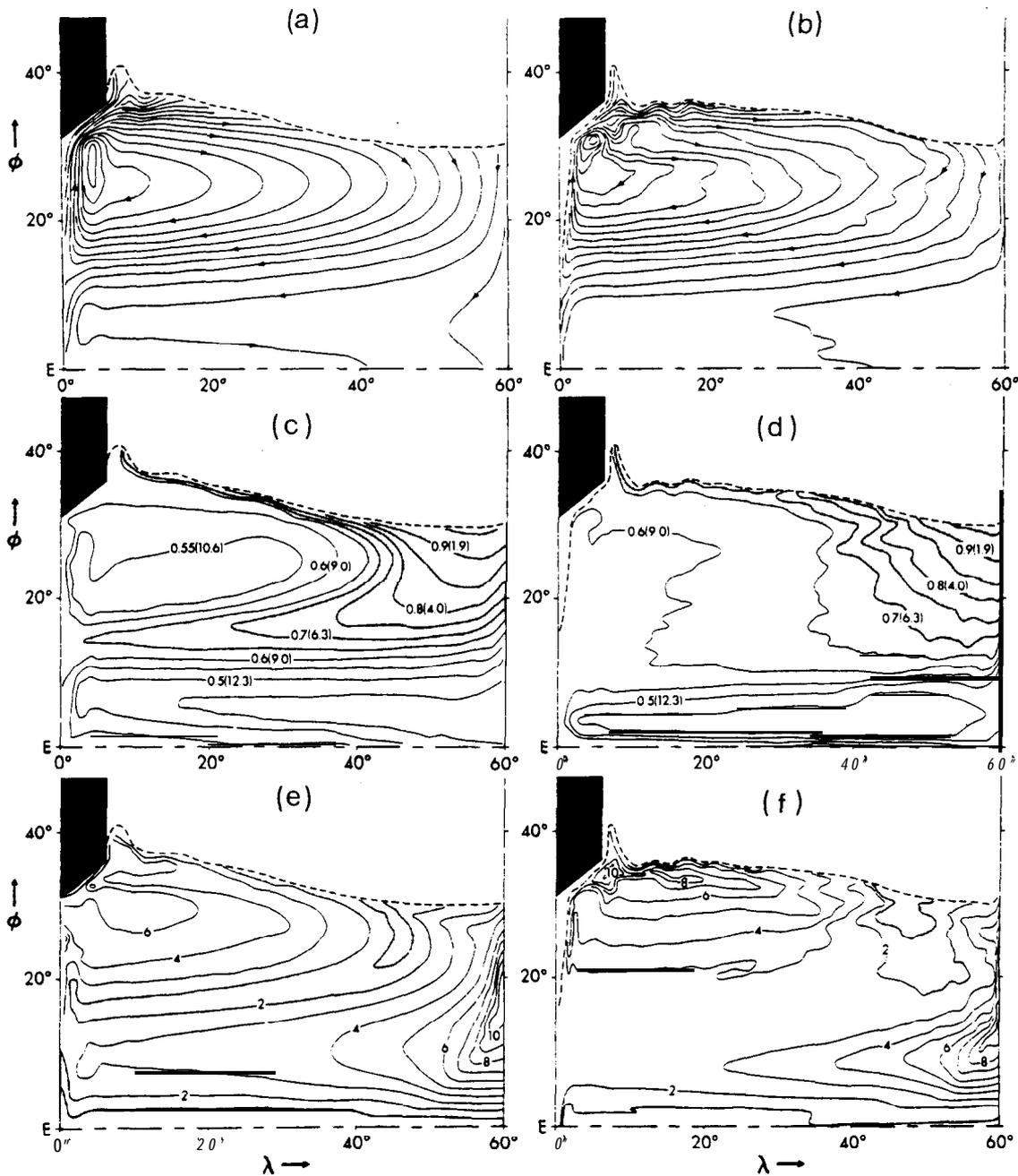
Figure 13:   Results of the integration of a general circulation model with a
grid spacing of one degree (panels a, c and e) and of one-third
degree (panels b, d and f).   The Bernoulli functions (contour
intervals of 5 dyne cm in panels a and b), a passive tracer
(arbitrary units and time since ventilation in panels c and d) and
potential vorticity (units of 10-9 cm-1 s-1 in panels e and f) are
shown on   the σ =   26.0 surface,   lying in   the   subsurface
thermocline.   The position at which the surface   outcrops is
indicated by the dotted line to the north of each panel. The
effect of eddies, which are present at the finer grid spacing, is
evident in both the pattern of flow and the distributions of the
tracer and potential vorticity (from Cox, 1985).

if used at high enough resolution but do not at the normally used resolution of
1-5 degrees that is necessary to conduct many experiments at basin or global
scale.   These models have provided our only results of global ocean-atmosphere
coupling (Schlesinger et al., 1985 and Marchuk et al, 1985).

     Simple models with incomplete physics have frequently been designed for
studying specific processes.   Such models will continue to play a key role in
the development of global circulation models because they can lead to greater
understanding of the more complete models and the processes they describe. Of
special mention are quasi-geostrophic eddy resolving models which have been
used for many studies of eddy dynamics and of the best parameterisations of
eddies in non-eddy-resolving GCM's (Holland et al., 1983 and Figure 14).   Their
use will surely continue, especially if they are generalised to include some
thermodynamical processes (Marshall, 1981).   They can be used to explore the
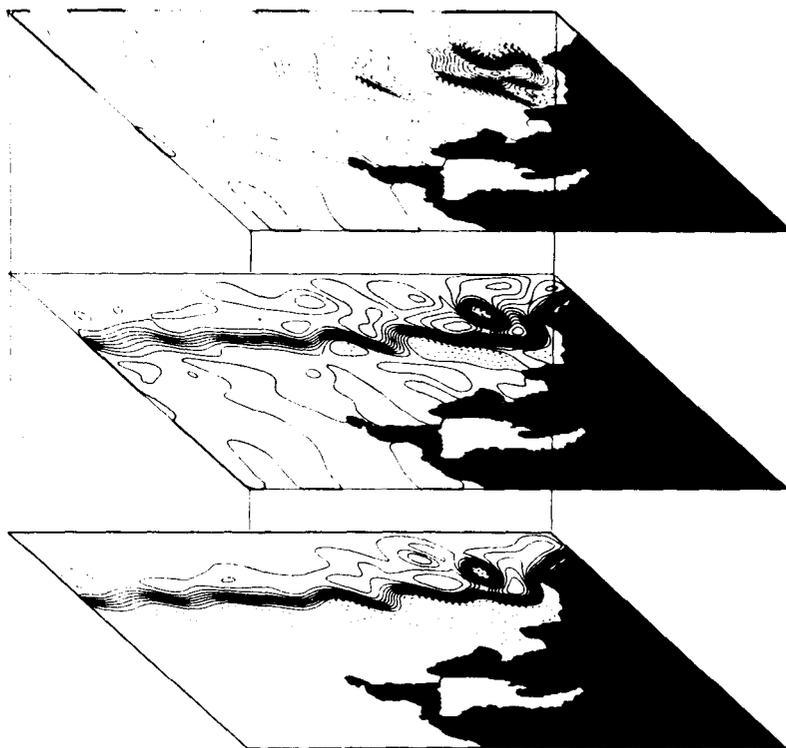

Figure 14:   A perspective drawing of the Gulf Stream region in a three-layer
             ocean basin model.   The layers represent the quasigeostrophic flow
             at 150 m, 650 m, and 3000 m respectively and the flow is forced by
             inflow and outflow alone (no wind is present in this integration).
             The strong meandering of the unstable Stream, the presence of a
             cold-core ring that has broken off from the Stream at an earlier
             time, and the very strong eddy field in the deepest layer are
             evident (provided by Holland).

parameter dependence of many important processes and they require much less computer time than EGCMs.   Initially these models all used depth as the vertical coordinate but recently isopycnic coordinates (Bleck and Boudra, 1981) and vertical modes have also been used. The relative merits of the three types of formulations has not yet been fully assessed.

5.3 Inverse Modelling/Data Assimilation

In WOCE there is the need for techniques to combine dynamical principles with information obtained from various data sets.   For example, the determination of the dynamically consistent, 3-dimensional absolute velocity from the fields of heat, fresh water or tracers; the examination of the role of mixing in the heat, salt and potential vorticity budgets; and the optimum design of an experiment. A reasonably direct method for obtaining the velocity field is to exploit the principle of potential vorticity conservation using the B-spiral technique (Schott and Stommel, 1979, Olbers et al., 1985 and Figure 15).

Models for use with data can incorporate various dynamical principles, such as the thermal wind balance, maintenance of the barotropic vorticity budget, or conservation of heat, fresh water, or mass.   Different types of data can be used with these dynamical principles, including measurements of heat, fresh water or tracer concentration, current, surface fluxes of heat and fresh water, and sea surface elevation. The model can be fitted to the chosen data set using a numerical least squares or maximum likelihood fitting procedure.   Results obtained from the procedure include the best fit model parameters, statistical errors of the parameters resulting from data errors and gaps, and the residual error of the best fit model.   This technique, often referred to as inverse modelling, has not yet been applied to all available data combined with all useful dynamical constraints.   Inverse modelling has however succeeded in combining widely-based data with many of the more important dynamical constraints (Wunsch; 1978, and Figure 16).

Data assimilation provides an alternate approach for combining dynamical constraints with data to yield a description of the ocean state (Bengthorsson et al., 1981 and Marshall 1985).   In this technique data is compared with the first results obtained from integrating a model.   The model is then again integrated forward in time, making use of the new data and the process repeated.   While various techniques are available in principle for combining observations with model predictions, the practical success of the process depends on having a reasonable model and sufficient data to constrain the model.   As for the inverse technique, the analysis produced by data assimilation will be dependent on the model scheme used.   The experience from meteorology is, however, that the analysed fields are very useful.   This is also expected to be the case for WOCE and other large-scale oceanographic experiments.
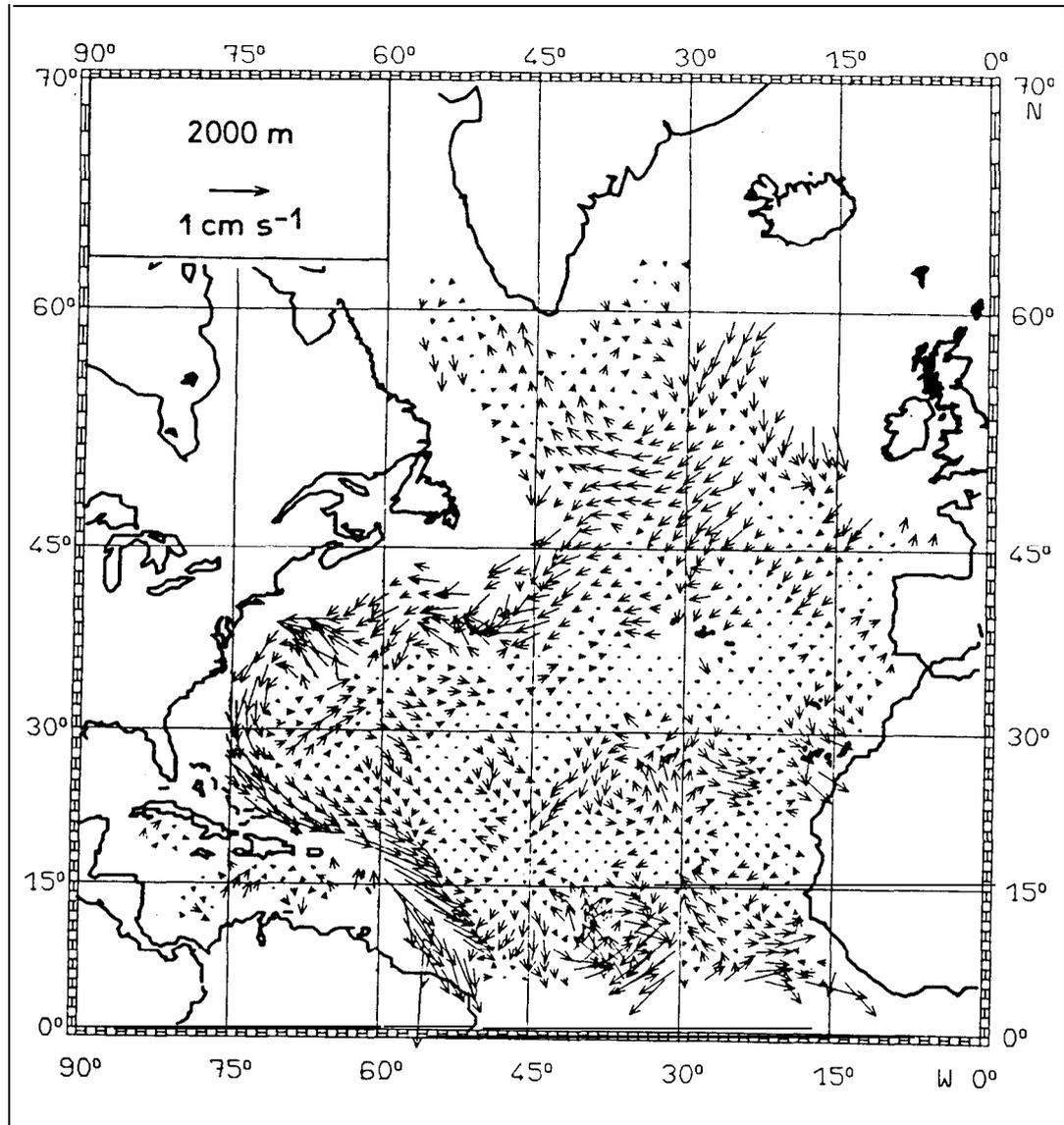
Figure **15:**   The absolute velocity at 2000 m (often taken as the level-of-no-motion), obtained by Olbers et al. using a S-spiral technique with the North Atlantic climatological data base.   One can note the outflow from the Norwegian Sea and subsequent southward flow along the western boundary in agreement with traditional interpretations of the circulation (for example, Reid, 1981).
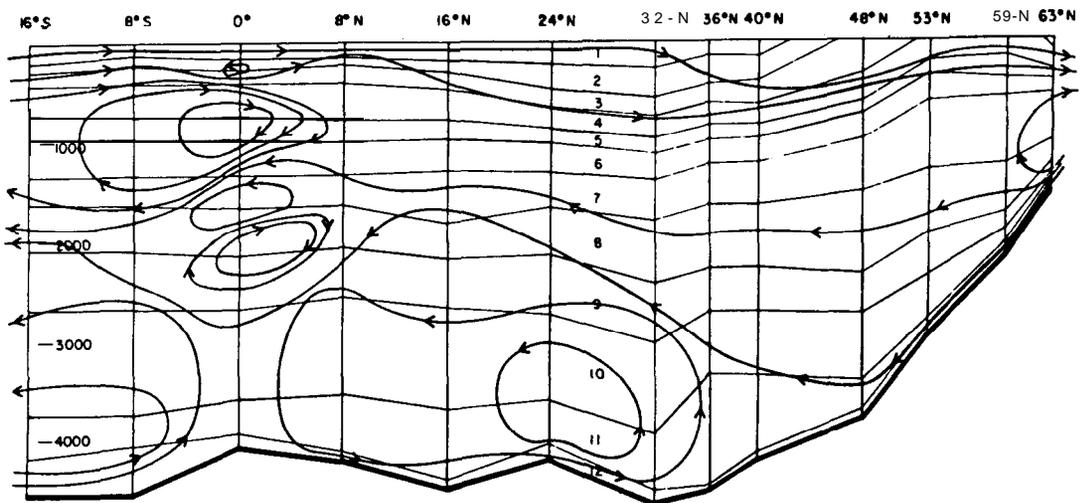
(a)
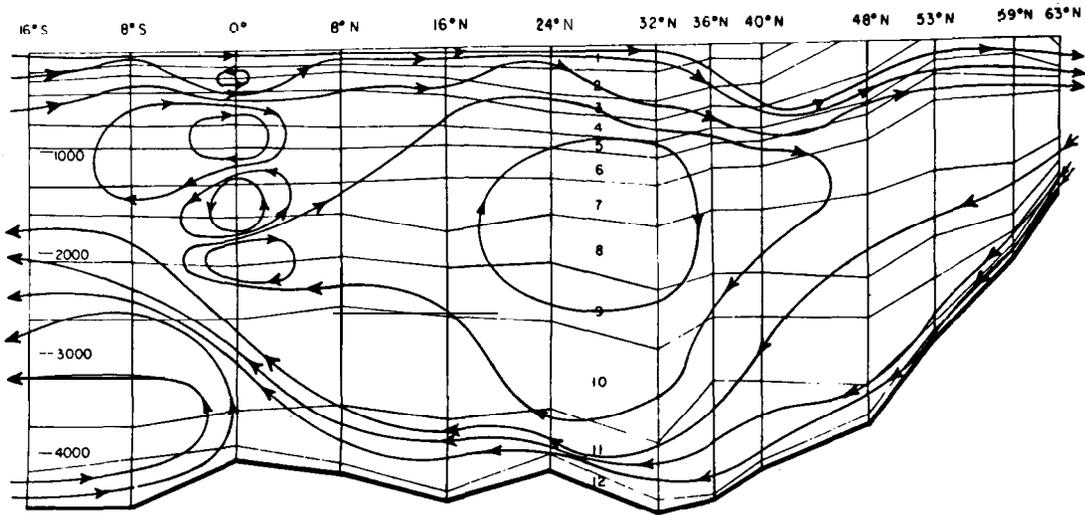
(b)

Figure 16: Zonal integrals of the mass transport from Wunsch (1984a). These are the results of an inversion using many different types of observations. In (a) the inversion has been carried out to maximize the heat flux at 24'N in the North Atlantic, in (b) to minimize the heat flux. Contour intervals are at 5 x 106 m3s-1.

5.4   The Role of Models in WOCE

54.1   Use in experimental design.

During the planning of each project, models can be used to some extent for 'observing system simulation' to help in the choice of experimental strategy. For example, high resolution models can help to determine the important space and time scales in each oceanic region of interest and to give information on the accuracy with which different variables should be measured. One may distinguish, in principle, between two modelling approaches: direct modelling and inverse modelling.

In the direct modelling approach experiments are carried out using various physical assumptions and the model outputs are then investigated to determine whether the consequences of the different physical hypotheses can be tested and distinguished between on the basis of the available data. If discrepancies between the predictions and data are found, the models can be iteratively tuned to improve the fit. The value of alternative data sets for model testing can also be investigated. In this manner, an optimal experimental design and data analysis strategy can be gradually approached through a process of successive trial and error.

Inverse modelling attempts to automate and quantify these iterative procedures. By carrying out inverse modelling computations for different classes of models, the ability of a given data set with specified error bounds to distinguish between different physical models can be expressed quantitatively. By repeating the exercise with different data sets, the advantages and disadvantages of different experimental designs can be assessed, thereby providing a quantitative basis for the development of an optimal experimental strategy.

Although inverse modelling represents the natural approach to designing WOCE, the technique has not yet been applied in its most general form to ocean circulation studies. The difficulty lies in the complexity of realistic ocean circulation models and the need to carry out a large number of ocean circulation calculations in the iterative optimal fit algorithms that characterize the inverse modelling technique. Accordingly, inverse modelling methods have only been applied using various incomplete sets of dynamical constraints. The application of the method has furthermore been mainly restricted to the mean, time-averaged ocean circulation. *An* extension of inverse modelling studies to the variability of the ocean circulation would be valuable for WOCE.

While the distinction has been made here between inverse modelling and a direct modelling approach, it should be recognized that the distinction may become blurred as models are used in different combinations for experimental design problems.

The design of all the core projects of WOCE could greatly benefit from model studies of this type. However, it is likely that initially, models will not play a major role because of the lack of availability of the necessary analyses. Core Project design will however include the numerical modelling community in order to improve this situation where possible.

5.4.2 Data analysis.

Inverse models and data assimilation techniques can play an important role in data analysis as well as in experimental design. The amount of data which will become available is, however, vastly greater than any data amount so far used in inverse models. Development of inverse models with a view to analysing observations is a priority in WOCE. It is unclear at present whether a data assimilation procedure similar to that used routinely in meteorology, and proposed for TOGA, is practical for combining data into a dynamically consistent framework in WOCE. The difference is that in large areas of the extra tropical ocean eddies represent a large part of the variability. Models which explicitly resolve the eddies will be grossly underconstrained since only one instrument (the altimeter) can sample fast enough to resolve them. On the other hand, if non-eddy-resolving models are used, eddy variability must be interpreted as 'noise on the data (eddy-resolving models may be used to demonstrate the effectiveness of this approach). Nonetheless, the data assimilation approach should be explored to determine if it can be a viable method of analysing the data, distinct from inverse modelling.

5.4.3   Relationship of models to core projects.

All the models described above are relevant to the core projects of WOCE. Global GCM's relate most obviously to Core Projects 1 and 2. Basin and global scale EGCMs, as they become available, and inverse modelling have many uses for all core projects. In addition, conceptual models will play a significant role, especially in Core Project 3, the gyre dynamics experiment.

A modelling effort has already commenced, using a variety of basin scale GCMs and other simpler models, to study the Atlantic circulation. The objective is to investigate the consequences of specific design strategies and to highlight areas of special sensitivity or interest; for example, where the signal is large or where model physics is contentious (as indicated by disagreement between differently formulated models). A variety of GCM's will be run to seasonal equilibrium (hundreds of years) to examine the basin ocean state and seasonal cycle. Subsequently a variety of shorter extension runs (-25 years) will be performed to determine the range of interannual variability. Output from the models will include surface topography, mass transport stream functions, heat transport, potential vorticity on isentropic surfaces and a variety of other quantities. These will be compared with observations where possible. They can also be used as indicators of the range of low frequency variability likely to be observed during WOCE. A number of experiments to assess the value of specific proposed measurement programmes is anticipated as well as tracer studies involving Tritium, Strontium-90 and bomb Carbon-14.

5.5 Computing Requirements

The modelling effort required for the design and analysis phases of WOCE is immense. The major goal of WOCE, the development of ocean models for climate prediction, requires modelling effort that is diverse in nature and which cannot be allowed to place undue reliance on any single model. A variety of differently formulated models addressing the whole range of WOCE problems is necessary.

Although many countries are developing modelling capacity, a major expansion in modelling is required to parallel the large field programme. A major increase in computing resources will be needed, to support both the modelling studies and to handle the vast amount of data to be analysed. It is therefore essential that adequate computing resources be made available before, during, and after the WOCE intensive period. In some countries this matter is in hand or being addressed, in others it is not. It should be noted that adequate computing facilities to make use of the data are of relatively modest cost in comparison to the cost of obtaining it. They must be supported.

CHAPTER 6

field Programme

6.1 Introduction

Although details are not yet fixed, the broad outline of the WOCE field programme is clear with the experimental design being based upon the following guiding principles.

. The experiment will be global in nature and the major observational components will be deployed in all oceans.

. The requirement of simultaneity of measurements will be imposed only where absolutely essential.

. The flexibility inherent in the existing arrangements for cooperative research in the world-wide oceanographic (and meteorological) community will be exploited as far as possible.

The extremely diverse types of observations required, and the multi-year character of WOCE require the fullest exploitation of the capabilities and resources of the oceanographic organizations scattered around the globe. Many mechanisms for collaborative research have been constructed in the past years and the scientific community has been able to create arrangements for field operations appropriate to specific needs. Reliance will be placed as far as possible upon existing organisations, groupings and mechanisms for the design and operation of WOCE. The WOCE programme management will, as far as possible, be operated from several different centres; for example, satellite programs will be carried out primarily by government agencies, while the hydrographic, chemical, float and other programmes will be organized and run by various government and private oceanographic laboratories. A role of the WOCE International Planning Office will be to provide overall guidance, communication, and consultation where needed. Independence of work at sea will be encouraged provided it is consistent with the goals of WOCE. Overall data quality is however vital and will require close cooperation between all WOCE groups.

Major elements of the WOCE field programme are discussed below.

6.2 Satellite Altimetry

Satellite altimetry is intended to provide the major global scale measurements of the ocean itself. It provides a framework for the in situ observations. As described in detail by (Wunsch and Gaposchkin, 1980) the altimetric measurement provides an estimate of the surface pressure distribution and its variations. Surface pressure is a dynamical variable

appearing in the boundary conditions of the ocean circulation. Because of the nature of the measurement, one must examine separately the issues of time dependent and time average motions. It is important that measurements of surface altimetry be combined with those of surface windstress in order to determine the ability of models to describe the oceanic response to surface wind forcing. Thus, satellites with altimeters'and scatterometers should be flown at the same time.

The planning for WOCE is built around the availability of two major altimetric systems: the French-American TOPEX/POSEIDON mission, and the altimeter on the ERS-1 spacecraft. TOPEX/POSEIDON will fly in about 1991 with a nominal lifetime of 3 years, and with a potential extension to five years. It is highly desirable that ERS-1 and TOPEX/ POSEIDON should be in orbit simultaneously, because the altimeter system to be flown on ERS-1 is of SEASAT quality and of considerably lower overall accuracy than that of TOPEX/POSEIDON. There are several important considerations. First, there are many thousands of points in each 10 day period when the tracks of the two systems cross each other. As described in Cheney and Marsh (1981) these crossings permit the two systems to intercalibrate in such a way that the combination should ensure that the ERS-1 system accuracy will ultimately approach that of TOPEX/POSEIDON.

Tradeoffs regarding possible spacecraft orbits are made between the density of spatial coverage on the ground, the interval between re-visit times, and the latitude of coverage. Further complications arise from the necessity to avoid undesirable aliases of the many line frequencies of the solar and lunar tides. TOPEX/POSEIDON is planned for a 10 day repeating orbit, with coverage only to latitudes equatorward of about 63". To deal with the polar regions the intention is that ERS-1 will fly to latitudes of about 73". The repeat time of this ground track will be three days shifting at intervals to eight day repeats. In addition to providing the high latitude coverage, this more frequent repeat time will provide the higher frequency sampling necessary for adequate measurements of mesoscale variability in some regions (near western boundary currents). The repeat time will be subject to change during the course of WOCE in the light of experience as the data comes in. The coverage of TOPEX/POSEIDON and ERS-1 are shown in Figure 17.

Some objectives of WOCE need the time average ocean circulation determined over as long a period of time as possible. The approach to be taken for observing the time average is to combine altimetry with known hydrography in dynamical models. The use of altimetry for this purpose requires the subtraction of accurate estimates of the Earth's gravitational equipotential (the geoid) from the altimetric sea surface. Existing geoids provide useful accuracy only to spherical harmonic degree and order of about 6 (wavelengths of about 6-7000 km). Provision of a geoid adequate for oceanographic use is being approached in three ways. First, there is considerable data available in the archives of NASA (USA), CRGS/CNES (France), and DGFI (Germany) that have not been used in calculations of the existing best geoids. The groups involved, sponsored by their agencies, are in the process of computing better gravity fields and geoids. By the start of the intensive WOCE period, it is expected that these efforts will have resulted in a geoid with significantly increased accuracy, which will provide an interim surface for use with TOPEX/POSEIDON/ERS-1 data in the early stages of those missions.

The full benefits of the altimetric missions will not be realized, and hence the goals of WOCE will not be met, unless a further major improvement can be made to the geoid. Estimates suggest that one needs, and could use, geoids with accuracy better than a few centimetres and wavelengths of a few hundred

kilometers and longer. The GRM mission of NASA (USA) will therefore make a valuable contribution to WOCE. This is the Gravity-Magnetic mission. There is no specific simultaneity requirement for GRM - merely that the data sets become available for timely use with the other WOCE data. Additionally, there is the French GRAD10 mission for which studies have been carried sufficiently far to **suggest it** could also directly address the WOCE needs.
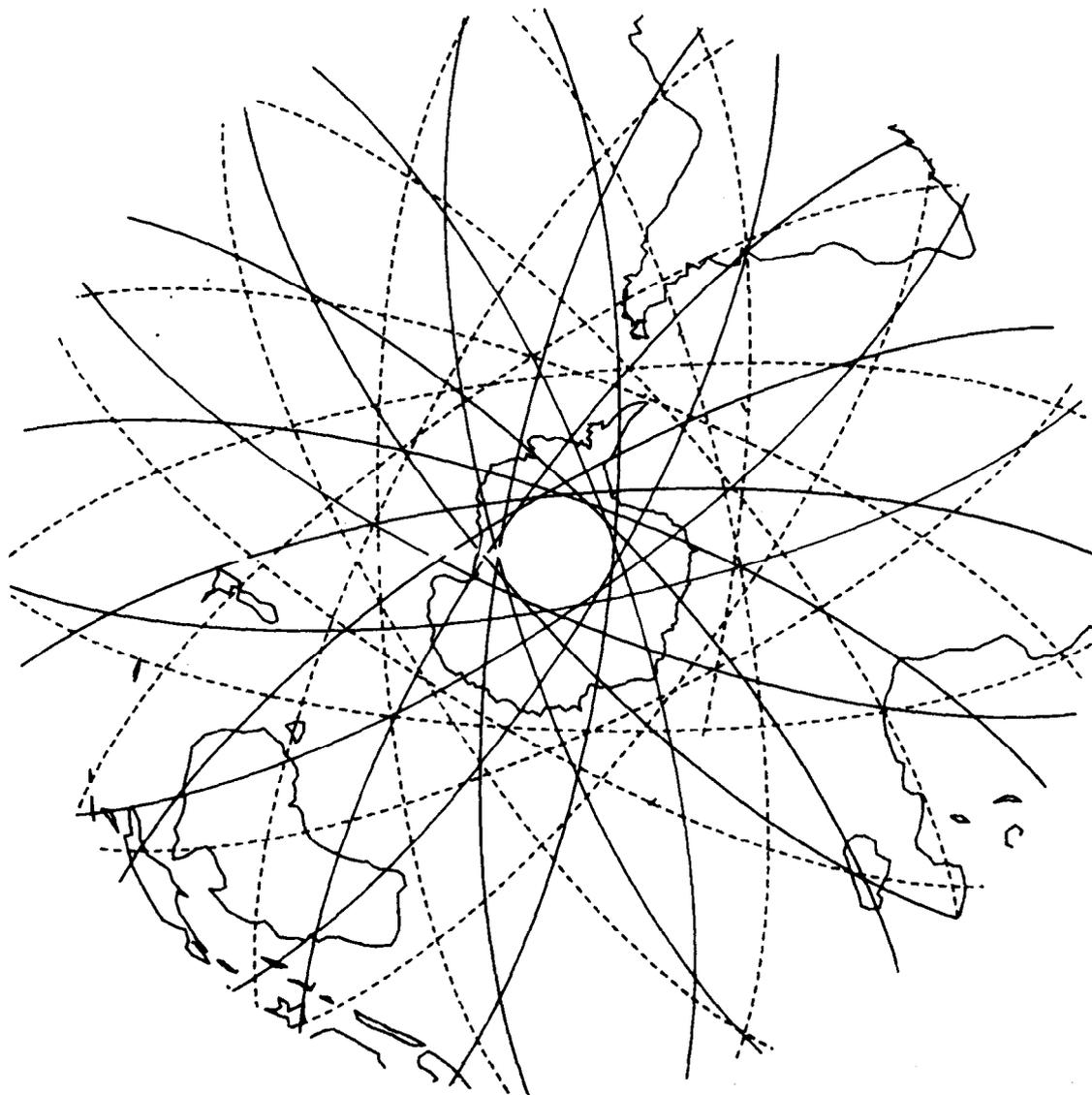

Figure 17: Ground tracks of TOPEX/Poseidon (dotted lines) and ERS-1 (solid lines) on a Lambert equal area polar projection for 1-day of coverage in the Southern Hemisphere. The higher latitude coverage of ERS-1 and the frequency of cross-overs can be seen.

Lastly, one may note that any estimate of the near-surface geostrophic flow made in the presence of an altimetric measurement yields an estimate of the slope of the geoid. Thus, ocean models that synthesize all observations will provide estimates of the geoid. Even in the absence of GRM, one of the end products of WOCE would be improved global geoids.

6.3 Hydrography

6.3.1 Introduction.

The hydrographic field programme is a component of each of the core projects and contributes to the different goals and objectives.

The standard observations of temperature and salinity will provide the dynamical link, on the longer time scales, between the surface pressure field and the interior. In this they will be supported by the kinematic observations of deep drifters and in some cases current meters.

The existing base, particularly that dating from the advent of salinometers but including earlier data, is still a useful source for the statistical definition of the density field. However, particular problems lie in the extremely uneven global distribution of the data set; the Atlantic was comparatively well surveyed during the IGY, the Southern Ocean has been less well covered and the Pacific and Indian Oceans only poorly. A major resurvey was recently started of the Atlantic and is now being extended to the North Pacific. A particular feature of these new surveys is the inclusion of both meridional and zonal sections with close enough station spacing to permit spatial gradients of the density field to be well determined at intermediate and large scales.

WOCE offers a great opportunity to either repeat or augment past surveys in a way that will permit the merging of satellite derived sea-level, wind and hydrographic data sets to estimate the absolute velocity field in intermediate and central waters and, to a lesser extent, in the deep flows. Separate knowledge of temperature and salinity are required to compute the oceanic transports of heat and salt at a number of sections. Essentially the same measurements are needed as for dynamical calculations, except that data must be obtained to the bottom if the Bryden and Hall (1980) technique is to be used to estimate fluxes. Several outlines for global repeated surveys have been developed but much further research is necessary before settling on a final WOCE plan. An example of a recent high quality section is shown in Figure 18.

A strong case can be made for forming a dedicated team of experienced and committed oceanographers to undertake the bulk of the WOCE survey using a consistent set of instrumentation and analytical methods (for the measurement of the geochemical tracers discussed in Section 6.4 the case is at least equally strong). The need for a dedicated research ship or ships for such hydrography and geochemical tracer measurements is thus evident. The completion of the survey will require vessels with long endurance and high-latitude capability, particularly for work in the Southern Ocean (see section 3.3.3). Scientific planning, management, and operation of such dedicated vessels could be by a mechanism similar to that used by the International Ocean Drilling Programme. This concept of dedicated research
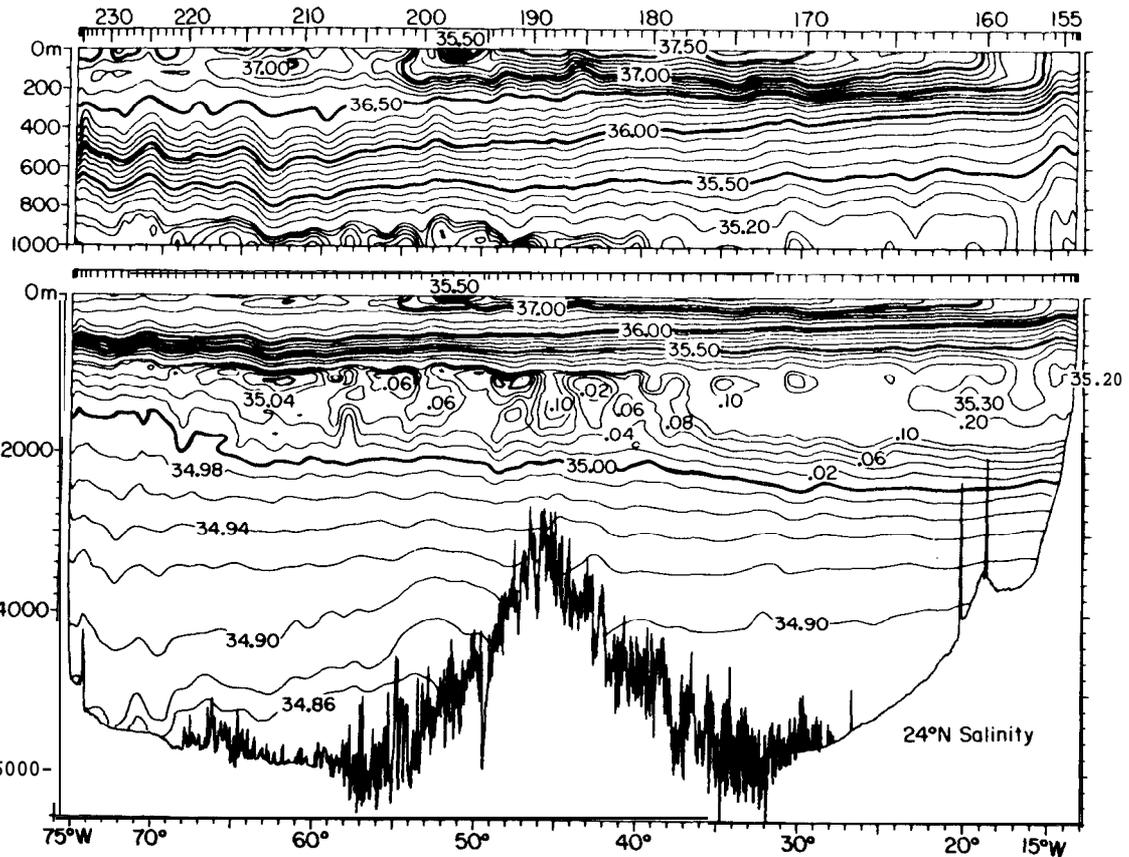
Figure 18: Data from a recent detailed section taken across the North Atlantic at 24°N. Shown is the salinity field. Even with the indicated station spacing several features are only marginally defined in both the near-surface and deep water masses (from Roemmich and Wunsch, 1985).

vessels staffed by teams of skilled and experienced oceanographers and with land based support and laboratory facilities has, for planning purposes, been christened RV WOCE.

6.3.2 Variability.

Little evidence exists on the extent to which variability exists in hydrographic data. This is an important design question for the WOCE hydrographic programme. It is clear however that repeated surveys in certain areas are required to examine the interannual signal in the temperature and salinity fields arising from a number of specific causes, including fluctuations in inter-basic exchanges, variations in evaporation-precipitation, deep convection, and changes in the strength of the gyre and circumpolar flows.

The interannual signal is known **to be** significant in some high
latitude areas; for example, as measured by changes in total content of heat
or fresh water (Lazier, 1980). Deep convective processes are regional in
character and the exchanges across sills are important. An observational
programme to detect these signals does not demand extreme precision but does
demand consideration of concentrated sampling in space and time. A coherent
programme, using the minimum resources likely to be available, is being
considered for the North Atlantic where there is already a good data base and a
number of oceanographic laboratories with interest in the area. The North
Atlantic, as does the Southern Ocean, has regions of deep convection that
supply the world ocean with deep water as well as winter convection that feeds
the central waters. The strength of the gyre can be monitored by sections
across the western boundary current. The hydrographic sampling programme will
require at least seasonal sampling in the high latitudes and annual sampling in
the sub-tropical gyre. These will be supported by a frequent ship of
opportunity programme of XBT's.

The repeated surveys will also be needed to reveal the extent to which the
non-synoptic nature of the large-scale data base degenerates its value. The
representativeness of the hydrographic data is important, not only in the
context of Goal 2, but also as a check on the validity of the interpretations
that will be made. To some extent this can only be achieved by oversampling
the temperature and salinity field in time. It is proposed that WOCE take
advantage both of existing time series of stations such as are typified by the
'Panulirus' station (see Figure 10) and Station 'Papa' (in the past) and by
establishing a few new stations per gyre; for example, in the North Atlantic
near Iceland, Ireland and Madeira. These could provide valuable additional
constraints, in association with other data, for inverse methods, and would
have the advantage of being the hydrographic data with a sampling rate closest
to that of the satellite data. The programme should be extended to the global
ocean by gaining the interest of the laboratories of the regions.

6.3.3 Additional surveys.

The mapping of temperature, salinity, and potential vorticity on isopycnal
surfaces is an informative tracer of water mass formation and spreading.
Although further studies are needed, it appears that mapping on the scale of
the global survey discussed above is unlikely to provide adequate
representation of the fields. Pre-WOCE surveys will go a long way to filling
in the gaps but additional sections, especially in the meridional direction,
will be highly desirable.

6.4 Geochemical Tracers

Potentially the most powerful technique for obtaining both the formation
rates and transport of water masses on climatological timescales lies not just
in the use of temperature and salinity as discussed in the previous section but
in the use of a whole suite of passive tracers. To the extent that a
particular tracer's boundary conditions and in situ behaviour are both
understood and well behaved, it is possible to extract information from its
distribution and evolution which represents an integral over some
characteristic space and time scale. Quantitative rate information arises from

a known radioactive decay constant (for example, with Argon-39) or from observation of the evolution of a transient tracer whose atmospheric history is known (for example, tritium and chlorofluorocarbons). Opportunities arise for comparison of two or more tracers within a given water mass that, by virtue of their differing boundary conditions and "rate constants", provide independent information.   Such comparisons serve as a test on model consistency.   In particular, the use of long-lived tracers provide the best prospect of estimating changes in the circulation of deep water masses.   The difference in the spatial and temporal input of several tracers is illustrated in Figure 19.
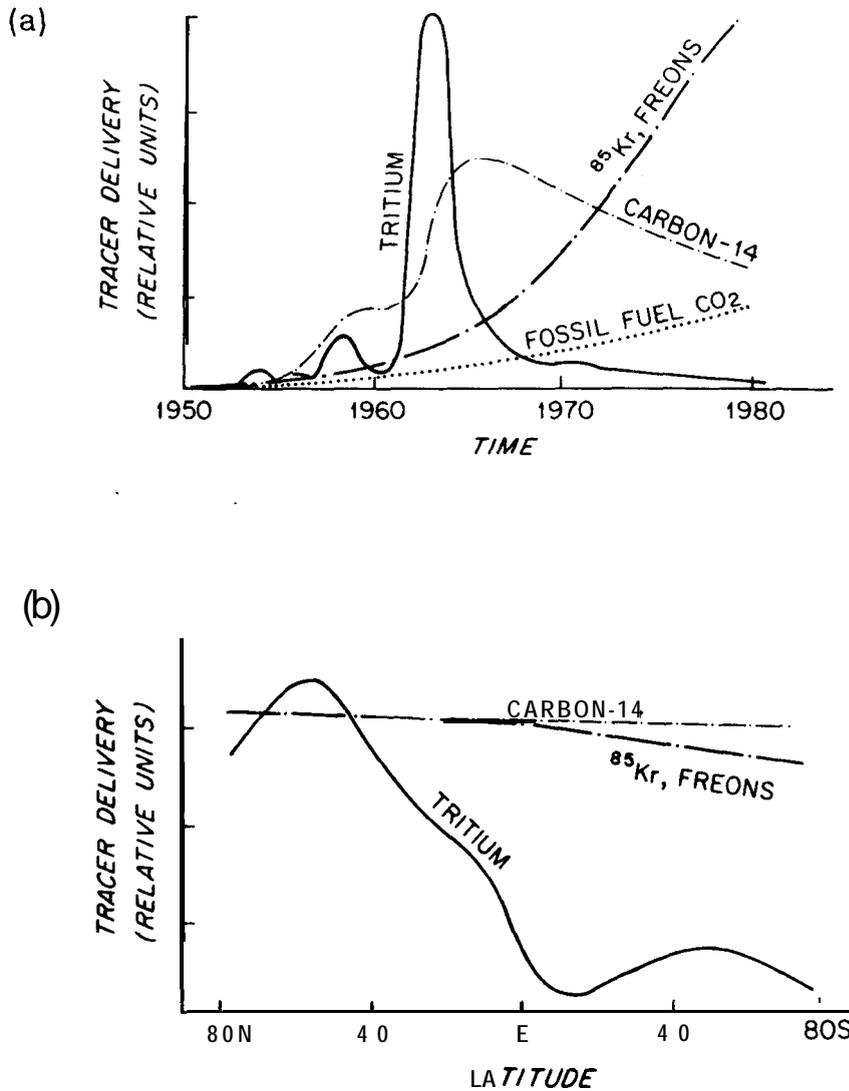

Figure 19:   The surface delivery as a function of time, (a), and latitude, (b) for Tritium, Carbon-14, Krypton-85, carbon dioxide, and the chlorofluorocarbons (freons).   Note how the strong input pulse of Tritium, mostly to the northern hemisphere, contrasts to the steady global increase in Krypton-85 and the chlorofluorocarbons.

Our knowledge of tracer distributions and water mass timescales is best in the North Atlantic as a result of two major field programs: the global GEOSECS (1972) and TTO (1981-1983) in the North and Tropical Atlantic (see Figure 20) and of the continued efforts of many individual research groups.   There is a firm idea of the inventories of such tracers such as Tritium and Carbon-14, and their evolution, permitting the testing of simple transport models.   The level of sophistication of the questions that can be asked and answered with tracers is beginning to rise.   Unfortunately, the situation in the other major ocean basins is less enviable.   GEOSECS provided a coarse-scale coverage of tracers in the South Atlantic (1973), Pacific (1974) and Indian (1978) Oceans, but it is clear that the large scale distributions of these tracers needs to be better defined.
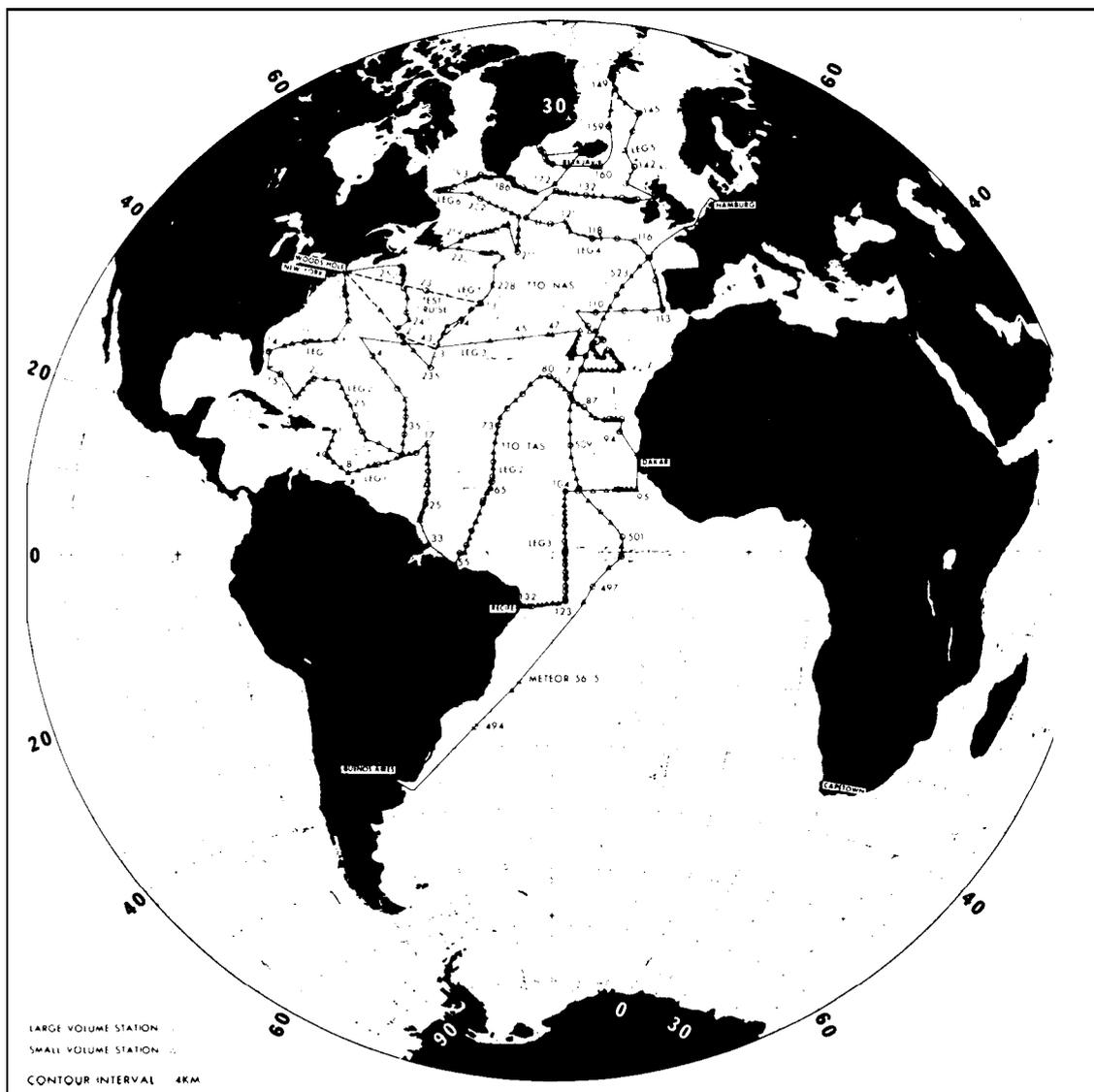

Figure 20:   Cruise tracks and station locations for the Transient Tracers in the Ocean programme (from Brewer et al, 1985).

A preliminary strategy, based on the crudest consideration of the large scale distributions of temperature, salinity and oxygen, can be put forth to indicate the scale of the problem. It is not yet a detailed specification.

. The Global Scale Resolution: This is the coarsest scale of sampling aimed at examining the 100 year advection timescales of the main the thermohaline overturning. The resolution in the horizontal would be of order 3000 km spacing, or a few stations per major ocean basin and in the vertical perhaps 5 or 6 samples. The primary tracers would be Argon-39 and Carbon-14 (the latter to high precision). Special attention will be given to those abyssal basins where these tracers provide tests of steady-state models.

. The Basin Scale Resolution: This refers to a resolution of order 500 km characterizing the tracer inventories in and input to the main thermocline, as well as mode-water formation and circulation. The tracers of interest are bomb Carbon-14 (probably measured on small volume samples), Krypton-85, Tritium, Helium-3 and the chlorofluorocarbons, along with the suite of "classical" tracers such as nutrients and oxygen.

. Small-scales: These are of particular importance in the vicinity of boundary currents, sites of inter-basin exchange, and in special regional process studies. Higher resolution measurements of some of the tracers mentioned above may be required in these regions. Tritium, Helium-3, and the chlorofluorocarbons, as well as oxygen, may prove especially useful. Other tracers, such as Radon-222 and Radium-228, used in parallel geochemical programmes, could supply supporting information.

6.5 Ocean Surface Fluxes

The ocean surface fluxes of heat, water and momentum are needed to run the forcing for the thermohaline and wind-driven ocean circulation. The accuracy to which these fluxes can be determined was investigated as part of the Cage Feasibility Study (Dobson et al., 1982). Some or all of these fluxes can be derived using the data from satellites, from in situ measurements (the Voluntary Observing Ships (VOS) and/or buoys), or by using atmospheric general circulation models (AGCMs). Each of these methods provides 'spot estimates' of the fluxes at given points in time and space. In general the small-scale, high frequency flux variability is of similar magnitude or greater than the climate scale variations. Thus, a large number of spot estimates are needed if the spatially and temporally averaged values required for WOCE are to be provided to acceptable accuracy. Furthermore the net heat and water fluxes are calculated as the difference between component fluxes of larger magnitude but with opposite sign. For example, the total heat flux represents the balance between the latent and/or sensible heat fluxes and the net radiation, itself the sum of the upward and downward longwave and shortwave terms. It is unlikely that adequate sampling can be achieved for each of the components on a global basis. Errors in estimation of individual components can result in uncertainty of the net flux similar to or greater than its magnitude. The usefulness of spot estimate techniques for WOCE flux determination has therefore been questioned (for example, Sarachik, 1983).

An alternative method of flux determination is the budget residual technique. The total heat flux can be obtained from radiation measurements at the top of the atmosphere and the atmospheric heat budget. Alternatively, it

may be calculated from an ocean heat budget applied between basin wide hydrographic sections. Budget techniques may be more successful than spot estimates because they provide the required quantity, the net flux, averaged or integrated over the budget period or region. However, there are several limitations to the budget technique. The net flux typically represents a small difference between large advective terms and the accuracy of the result may be doubtful. Ocean models may require, as input, values of the net flux at higher space and time resolution than is provided by budget. Increased physical understanding necessary to improve climate models requires knowledge of the individual heat flux components in addition to the net flux. Some of these restrictions are overcome by using a variation of the budget technique, that is, the estimation of the fluxes by an ocean model given a prescribed sea surface temperature. However, the WOCE goal of obtaining the data to test such ocean models requires that flux data be obtained by independent means. Thus, **it** will be important in WOCE to estimate the surface fluxes both by budget and spot estimation techniques. The strategy for the latter must therefore be considered in more detail.

VOS meteorological observations can be used to estimate each of the fluxes. The bulk aerodynamic formulae are used to derive the stress, and sensible and latent heat fluxes from observations of air and sea temperature, air humidity and wind velocity. In addition, the radiative flux formulae require cloud amount and, less critically, cloud type. Precipitation is derived from the 'present weather' observations. Unfortunately sampling by VOS is only likely to be adequate in restricted ocean regions such as the North Atlantic and North Pacific. The large expanses of the tropical and southern oceans are poorly sampled. Even in well sampled areas the VOS estimates may contain significant biases of unknown magnitude (Taylor, 1985).

Satellite data can be used *to* estimate some, but not all of the fluxes. Stress can be derived from scatterometer data (see Section 6.6) or microwave radiometer wind speeds in combination with wind directions obtained from cloud motions or other techniques. Net surface shortwave and upward longwave radiation can be estimated from satellite infrared radiances. Precipitation estimates can be made using combinations of infrared and microwave data but adequate accuracy has yet to be demonstrated. Monthly mean latent heat flux can be estimated from microwave radiometer estimates of total water vapour and wind speed combined with satellite derived SST values. However, the algorithm is strictly empirical and adequate accuracy has only been demonstrated on a restricted regional basis (Taylor, 1985). Methods for estimating sensible heat flux or downward longwave flux using satellite based techniques have yet to be demonstrated. In general, all satellite based flux estimates must be validated against in situ data to avoid errors due to sensor drift, changes in atmospheric transmission or oceanic conditions, or the use of inappropriate algorithms.

Drifting buoys (Section 6.10) can be used to provide the data for satellite calibration and validation or to improve the sampling in areas where VOS observations are inadequate. Although drifting buoys can (or soon will be able to) measure all the required fluxes, such 'flux buoys' are too expensive to be deployed in adequate numbers to be the sole source of flux data over the world ocean. Simpler buoys measuring air pressure and sea surface temperature provided valuable data during FGGE for AGCM initialization. Such buoys, with the possible addition of air temperature and, with more difficulty, wind velocity and humidity sensors, will be deployed for WOCE.

AGCM's can be used to provide values of the ocean surface fluxes as a product of the data assimilation and analysis stage. The basic data needed for AGCM initialization over ocean regions are the surface air pressure and

temperature values, and profiles of atmospheric temperature, humidity and wind. Most models also use surface wind velocity measurements. Sources of these data are: for air pressure, VOS augmented by drifting buoys; for SST, a combination of satellite, VOS and buoy data; and for atmospheric profiles, radiosondes and satellite sounders. The AGCM uses these data to model the free atmosphere flow. The surface flux values estimated depend on the use of a boundary layer parametrization that must represent the complex physical processes occurring in a cloud topped boundary layer. Model tuning only ensures that the surface fluxes, in combination with other model schemes such as the convective adjustment and cloud-radiation interaction, maintain the required climatology. Prompted by attempts to couple atmospheric and oceanic GCMs, validation of the model flux values against in situ measurements has commenced, . Present AGCM derived fluxes do not meet the WOCE accuracy requirements, but significant improvements are expected before 1990.

In summary, at present neither satellite nor in situ measurements can alone define the surface fluxes throughout the global oceans. There are potential advantages in using AGCM derived fluxes but considerable development of this technique is needed. The strategy suggested for obtaining WOCE surface fluxes is, therefore, as follows:

.   Satellites offer the greatest promise for global ocean surface flux determination. Attempts to estimate all components of the fluxes using satellite data must continue. However, even the global estimation of only some components of the fluxes can provide useful constraints for the development and evaluation of climate models. All satellite flux estimates must be validated against high quality in situ measurements in areas where these are available.

.   Despite the above, it is probable that over much of the world ocean satellite and in situ data will not be adequate to determine the net heat and water fluxes directly from the observations. The use of AGCMs to produce flux analyses offers the possibility of optimum combination of in situ and satellite data using the constraints implied by the physical processes modelled. It also enables the use of additional information, such as satellite temperature and moisture soundings, which is available on a global basis. The aim therefore is to ensure that **over** all regions the data required for flux retrievals and the development and validation of AGCM flux estimation schemes.

.   In situ measurements from VOS or flux buoys can provide estimates of all the fluxes, at best for some ocean basins only. These will be valuable for regional ocean circulation studies. However, the main and vital use will be for calibration and validation of satellite flux retrievals and the development and validation of AGCM flux estimation schemes. Careful evaluation, and comparison with high quality measurements, will be necessary to identify and remove any systematic biases in the observations.

The satellite measurement (Section 6.6) and atmospheric modelling requirements of the above strategy are assumed to be as for the WCRP in general and are not further discussed in this scientific plan. More details of the role of the VOS fleet are given in Section 6.8.

6.6 Satellite Winds

6.6.1   Introduction.

Measurements of the ocean surface fluxes of momentum, vorticity, heat and water are required for WOCE; all are dependent on the surface wind field, the measurement of which is therefore identified as an important requirement for WOCE.   Surface buoys and Voluntary Observing Ships are the major sources of such data, but they provide coverage and accuracy of limited quality. Satellite microwave scatterometer systems, to be flown on the ERS-1 and NROSS satellites, offer the potential to determine global surface wind to the high accuracy required for WOCE.   However, realisation of this potential will require a coordinated surface wind and wind stress programme within the WOCE. Projects are necessary to provide increased understanding of the physics involved in scatterometry, to obtain high quality data for calibration and validation, and to intercompare satellite scatterometer data.

6.6.2 Accuracy required.

The accuracy required of wind measurements depends both on the scale of the oceanic phenomenon being considered and on the property of the wind field which is of importance.   In most cases the relationshps are non-linear and a wide range of scales are important.   For example, the Sverdrup transport depends on the curl of the wind stress averaged over spatial scales of several hundreds to thousands of kilometres and time scales of weeks to months. However, this average may be dominated by smaller scale, shorter duration, events.   Similarly, models of the global ocean need to simulate the cumulative effects of those motions in the ocean mixed layer which are driven by peak winds lasting only a few hours or days.   In future the critical time and space scales and the corresponding wind field accuracies will be determined more precisely by sensitivity studies using ocean general circulation models. At present only approximate target accuracies can be stated for the surface wind field.

In many large-scale studies monthly mean wind and wind stress data will be combined to follow the development of the seasonal cycle in successive years. The natural spatial scale of such a time average is, over the main ocean expanse, of order 5 degrees of longitude by 2 degrees of latitude.   For some areas and certain studies (for example, the effect of high wind events on ocean mixed layer depth), space and time averages on shorter scales will be required (Harrison, 1984; Saunders, 1976). Typically, 20% of the monthly mean stress is considered an adequate accuracy.   For WOCE this should define the mean stress to an accuracy considerably better than the equivalent observational uncertainty in other critical variables such as the distribution of temperature, or the transport in the western boundary current.   Thus it will allow uncertainties in the imposed wind stress to be eliminated as a contributory factor when comparing model results and observations.   Since the curl of the wind stress is the required quantity for ocean circulation studies, the relative accuracy of the stress between adjacent 5 deg. by 2 deg. averaging areas must be 10% or better.   Although this may seem more stringent, a significant proportion of the scatterometer error sources are likely to be spatially coherent over such distances allowing increased relative accuracy to be attained.

Accuracy specification in terms of percentages is based on the assumption that the error spectrum is similar to the spectral variability of the stress. Providing the sampling is adequate, this is probably true. An accuracy of 20% of the wind stress is equivalent to about 10% of the wind speed or 0.5 to to 0.8 m s⁻¹ for wind speeds up to 10 m s⁻¹ and relative accuracy of 0.2 to 0.3 ms-1 for wind stress curl. In 20 m s-1 mean winds, 1.5 m s-1 absolute accuracy and 1.0 m s⁻¹ relative accuracy would be needed. A 10% wind speed accuracy is also a minimum requirement for definition of the surface turbulent fluxes of sensible and latent heat. These are required to an accuracy of the order of 10-15 W m-2 rms or better (Dobson et al, 1982), which is equivalent to about 10% of the monthly mean flux.

6.6.3 Scatterometer accuracy.

The technical specifications for the scatterometer missions planned during the WOCE are shown in Table 1.

Table 1

Scatterometer specifications

Data sources: Freilich 1985 (NROSS); Haskell, 1983 (ERS-1); WCP-91, 1984 (MOS-2). Launch dates are subject to change.

Satellite	NROSS	ERS-1	Mos-2
Launch date	1989	1989	Proposal
Lifetime (yrs)	3	3	
Scatterometer	NSCAT	AM1	SCAT
Frequency GHz	14	5.3	14
Swath km	2x600	500	500
Range m/s	3 - 30	4 - 24	?

All three instruments have similar accuracy/resolution specifications, that is the greater of 2 m s-1 or 10% in wind speed, 20 degrees in wind direction (after ambiguity removal), and processing to 50 km spatial resolution. *However* for AM1 these values only apply over a 400 km swath. Such accuracies are for individual wind retrievals, the accuracy for monthly mean values depends on whether the errors are random and the number of samples available.

Consider first the sampling density. This must be sufficient to reduce both the random errors in the scatterometer wind retrievals and the noise due to natural small scale variability to an acceptable level. Estimates suggest 60 to 100 independent observations in each averaging domain are necessary (WCP-81, O'Brien et al., 1982), a requirement that would be satisfied by NROSS and ERS-1 combined. If only NROSS data were available, adequate sampling may be obtainable for many areas, since this is a two-sided scatterometer with 1200 km total swath width (see Figure 21). However, loss of data where atmospheric
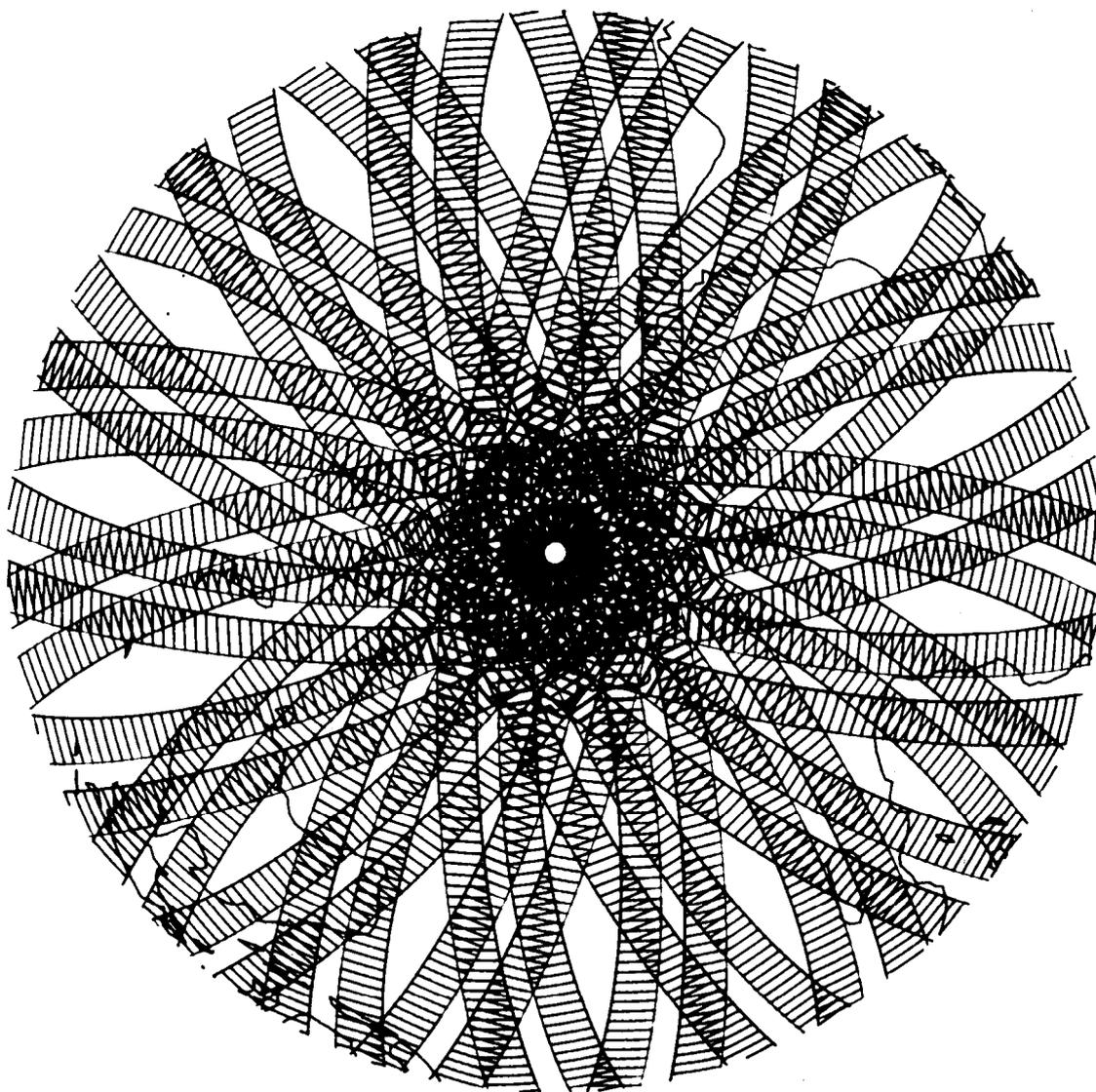

Figure 21: Ground coverage of NROSS in the Southern Hemisphere for 1-day using the same projection as Figure 17.

water concentration is high would degrade this situation. The narrower swath
of the ERS-1 scatterometer, and the possibility of a less than 100% duty cycle,
suggests that sampling by this instrument alone will only be adequate in high
latitudes. Combination with other data would be necessary in other regions.
However the ERS-1 scatterometer should be less affected by rain. In all cases,
it will be important to ensure that the scatterometers are operated
continuously over the ocean.

wind speed is the critical variable when considering the systematic
errors in the scatterometer data. The resolution of the wind direction
ambiguity was a serious problem for analysis of the Seasat scatterometer
measurements. However, the use of 6 antennae on the new satellites reduces the
problem to a 180 degree ambiguity. Only 2% incorrect direction choices would
introduce a significant error; however, use of ancillary data (e.g., cloud
motion vectors) should result in a correct choice. Hence, provided the
capillary wave direction is uniquely related to the wind direction, the wind
direction will be obtained to an adequate accuracy.

Determination of the wind speed requires knowledge of the relationship
between the isotropic surface roughness and the wind stress. This relationship
might vary with surface tension and viscosity (both temperature and hence
latitude dependent), surface contamination, non-equilibrium sea state, etc..
Resulting biases which may exist are of the order of 10-20% (for example, Liu,
1984). Present algorithms are empirical and there is an urgent need for
research toward greater physical understanding. A potentially serious error is
that due to clouds or rain. For NROSS, operating at Ku-band frequency, even
light rain may be significant for 0.5 m s-1 mean accuracy. The effect is
much smaller using the C-band frequency adopted for ERS-1, however, the penalty
is a reduced sensitivity of the backscatter amplitude to wind speed. Wind
retrievals contaminated by liquid water are likely to be biased low, although a
bias high has also been reported (Guymer et al., 1981), again greater
theoretical understanding is required. Elimination of rain contaminated data
may also result in a bias because of the correlation in many regions between
wind speed and rain rate. Combined use of scatterometer and passive microwave
radiometer data, and comparison of the results from different scatterometers,
will be necessary to minimize this error source.

6.7 Surface Meteorological Observations from Voluntary Observing Ships

6. 7. 1 Introduction.

The need for surface meteorological measurements from the VOS fleet has
been detailed in Section 6.5. Unfortunately, there are at present large ocean
areas where very few VOS observations are obtained. There is also the
possibility of systematic errors in the VOS data. Thus, there are two basic
WOCE requirements with respect to VOS observations. Firstly, it is important
that the present system be maintained and indeed that the number of
observations be increased whereever possible. For purposes such as the
initialization of numerical models, globally distributed observations are
required. Secondly, sources of systematic errors in the VOS data must be
identified, the resulting biases quantified and appropriate corrections
applied. Then, using selected ocean areas for which the VOS sampling is
adequate, It will be possible to validate the surface fluxes predicted by

coupled ocean atmosphere general circulation models or estimated from satellite observations.

6.7.2 Sampling improvements.

Sampling studies (Niiler et al., 1985, Taylor, 1985) suggest that at least 20 independent flux estimates per month within a 5 degree by 5 degree or similar latitude/longitude area are required to meet TOGA and WOCE accuracy requirements. In areas where there is significant variability on smaller scales, or large horizontal gradients, more samples will be necessary (Weare and Strub 1981). The fluxes should be well defined in areas with more than 100 observations. On this basis, most of the Atlantic and Pacific areas north of latitude 30'N are well sampled by the VOS. Sampling in the tropical Atlantic and Indian Oceans would become adequate with a moderate improvement in observation density. Sampling in other areas is poor but, at least for tropical areas, significant improvements may be possible (WCP, 1985). The existing density of VOS reports is indicated in Figure 22.

First priority must be given to increasing the number of observations transmitted in near real-time on the GTS. Such data is necessary for numerical model initialization and validation, and for the validation of satellite observations. National meteorological agencies will need to make every effort to recruit more VOS ships, particularly those operating in tropical or southern ocean areas, and to make improvements in the radio communications links. Observer motivation will have to be increased by wide publicity, throughout the VOS system, of the aims of the WCRP and the importance of improved VOS observations for WOCE experiments. This must be continued for the -duration of WOCE by means of regular information bulletins.

Despite these improvements, maximum data coverage will only be obtained by using delayed-mode observations from the GTS and data from ships' meteorological logbooks. The value of observations from these sources must be stressed, and national meteorological agencies are asked to ensure that all delayed mode observations are forwarded to the GTS, 'and that international exchange of ships' logbook data continues to be conducted in an expeditious manner. Fishing vessels which operate away from standard shipping lanes, have been suggested as a potentially important source of increased observations (Cutchin, 1983). Whereas GTS transmission of data may be impracticable, the recruitment of such ships to provide logbook reports for WCBP purposes must be considered.

6.7.3 Accuracy improvements.

In order that WOCE requirements be met systematic biases in VOS data that cannot be removed by averaging must be evaluated and corrections made. Typically, residual errors in the mean air and sea temperatures must be less than 0.3^oC, air humidity errors less than 0.5 g kg-l, and wind component errors less than 0.4 m s-1. There is evidence of biases in VOS data that are of the same order or greater than these limits, although the exact value of these biases is unknown. For example, budget studies (Bunker et al., 1982) have suggested that the latent heat flux from ocean to atmosphere may be underestimated, perhaps by 60%. However, the VOS underestimate the flux by less than 10% when compared to weather ship data (Bunker, 1976; Dobson et al., 1982). If weather ships are assumed to achieve accuracy similar to, or better
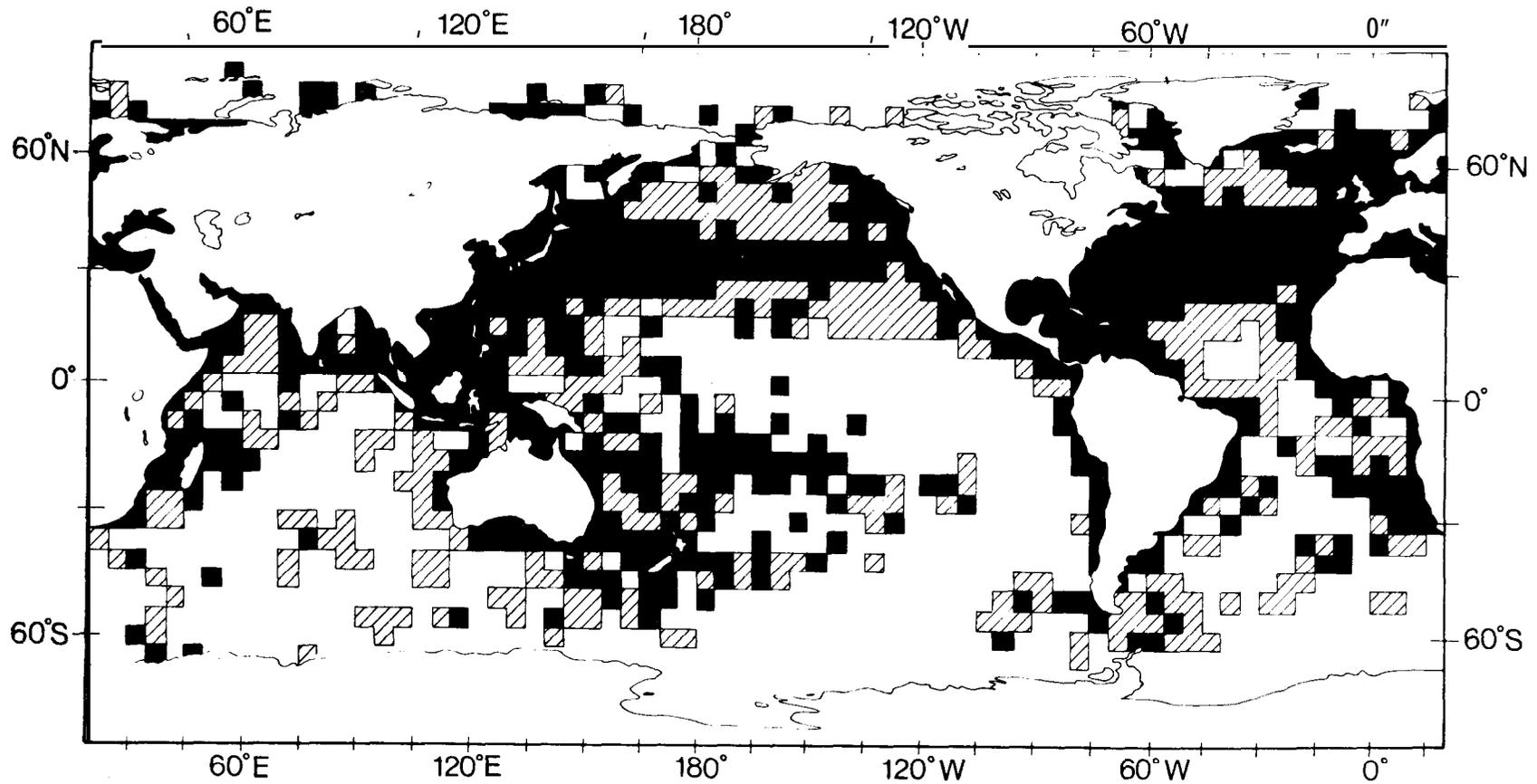
Figure 22:   Average density of meteorological observations during the period   27 November   1978 to 5 January 1979. Shaded = >4, hatched = >2 observations/day for 5" squares.   As well as ship and buoy reports, coastal and island stations are included;   the latter give an exaggerated data coverage in areas such as the SE Pacific.   (Data Source: FGGE Operations report, Vol. 3., Summary of Data Collected 27 Nov. 1978 - 6 March 1979, WMO, Geneva).

than, the research ships that participated in GATE, then the overall underestimate of the latent heat flux by the VOS would be no more than 10 to 20% (Taylor, 1985).   For the WCRP it will be necessary to determine the true value of such biases for all oceanic conditions.   To achieve this there is a requirement that a limited subset of the VOS fleet will provide higher quality measurements of known accuracy.   Data from these ships would serve as reference values for the rest of the VOS observations and for the validation of satellite data, particularly scatterometer and cloud motion wind values, sea surface temperature and near surface humidity. The exact nature of this subset, the number of ships required, the methods of measurement and calibration, the means of reporting, and the necessary data management procedures will require a detailed implementation study.

6.8   Upper Ocean Observations from Merchant Ships-of-Opportunity

In WOCE there is a need for measurements of the change in heat content in the upper ocean, primarily as a way to improve the reliability of estimates of the heat flux.   A significant contribution in this regard can be made by merchant ships-of-opportunity.:   The precision being sought in WOCE for the surface heat flux is about 10 watt m .   This is some 10% of the meridional flux in the sub-tropical Atlantic.   Preliminary' work during the Cage Feasibility Study (Dobson et al., 1982) suggests that some 4 annual repeats of 5 east-west lines of XBTs from ships-of-opportunity would allow this accuracy to be achieved over the 5 year intensive period of WOCE in the North Atlantic.

Estimates of the near surface velocity field are -required to assist the interpretation of the global hydrographic and heat content data.   It is, however, difficult to make these measurements systematically over a wide areas, although inferences can be drawn from data from sources such as drifting buoys and satellite measurements of altimetry and wind-stress.   At present doppler acoustic logs are fitted to several hundred ships and a practical possibility exists of determining near surface currents on horizontal scales of 10s of metres to an accuracy of a few centimetres a second.   The addition of inboard processing enables some existing Doppler configurations to be used as current profilers of the upper ocean boundary layer to depths of the order of 200 m.

National support will be sought for the establishment, following design studies, of XBT sampling lines using regular services of the merchant fleet, especially of those already participating in the VOS system.   For the velocity measurements a GPS navigation set should be installed, together with either electromagnetic or acoustic doppler logs or profilers, in order to permit the absolute determination of the near surface velocity profiles to approximately 0.1 m s-1.

6.9   In-Situ Sea-level Measurements

Plans exist for a Global Sea Level Observing System as part of IOC's Ocean Observing System Development Programme (IOC, 1984 and Figure 23).   It is to serve many research purposes including the needs of TOGA and WOCE.   Within WOCE there is the need:

.   to use the tide gauge network in coordination with sea-bed pressure recorders and inverted echo-sounders to provide both calibration
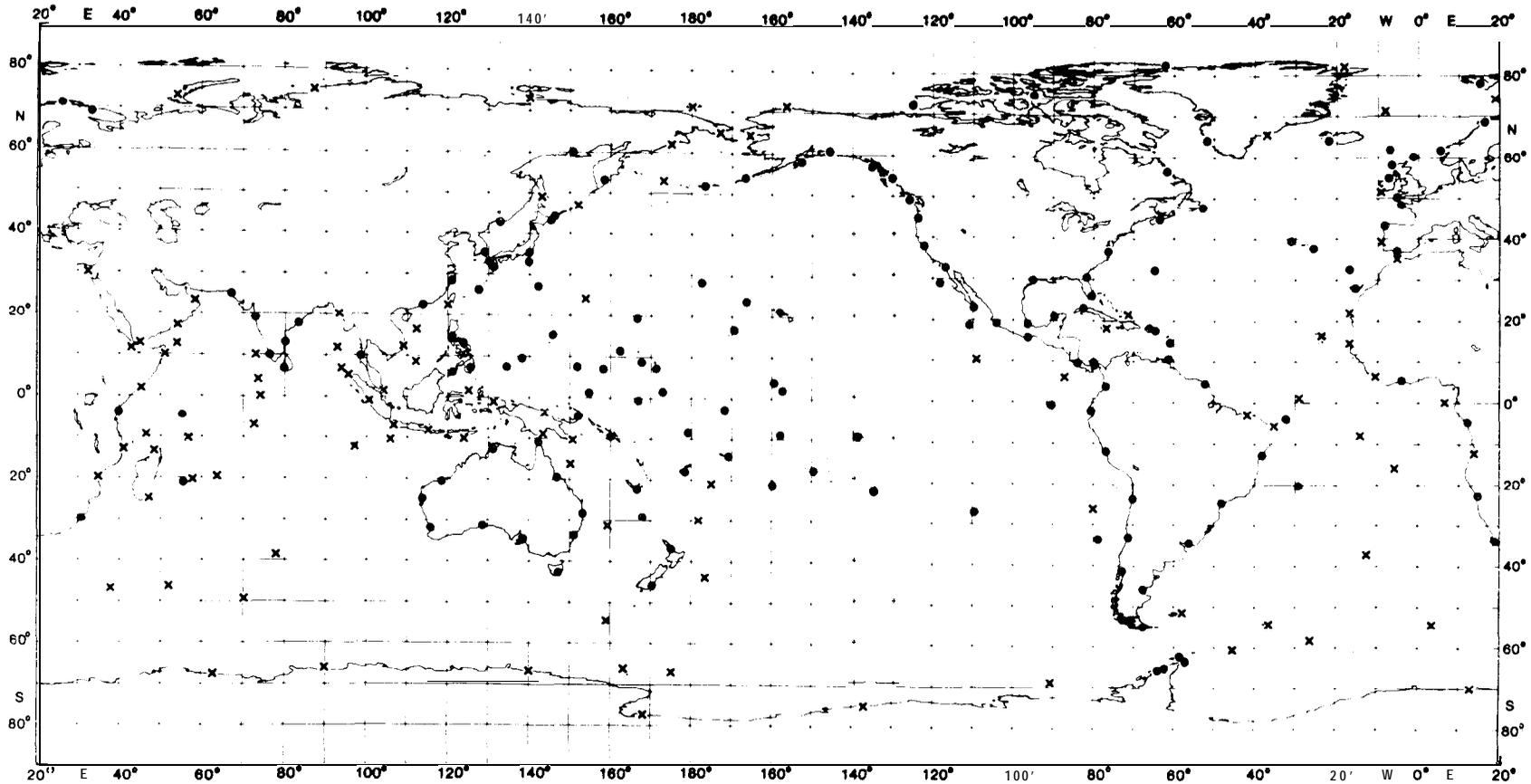
Figure 23: Positions of proposed sea-level stations for the Global Sea-Level Observing System. The dots indicate existing stations and the X's those planned.

points for altimetry and precision basin scale measurements of
sea-surface slope

.   to use an exended network to assist in resolving outstanding tidal
ambiguities and so to greatly facilitate the interpretation of the
altimetric signal for WOCE

.   to obtain precision gyre scale observations at the centimetre level
using a carefully selected subset of tide gauge stations of the
proposed network.   This will enable the estimation of the strength
of the gyre circulation and provide regional measurements of the sea
surface slope across major current systems, including the western
boundary currents and Drake Passage.

A study is urgently required to identify key stations to meet the needs
of WOCE and to allow time to put them in place.   Tentatively 60 sites have been
chosen (in addition to those identified for TOGA and/or those existing for
other purposes) for this purpose and attention is being given to poorly
observed regions such as the Indian Ocean, the Southern Ocean and major
inter-ocean passages.

Implementation of the internationally co-ordinated system will require
major efforts by Member States in maintaining, reactivating, up-grading and
installing new sea-level gauges, and assisting other countries in developing
their national sea-level stations.

6.10 Drifting Buoys and Floats

6.10.1 Introduction.

There are many types of drifters, each developed, or being developed, with
a specific measurement capability. It is useful to distinguish between buoys,
which drift on the surface serving primarily as instrument platforms, and
floats, both surface and subsurface, whose drift is the measurement of
interest.   However, drifters are a class of remote instruments with common
characteristics.   They are expendable, possibly with on board data processing
but with no permanent data storage.   They need to communicate via satellites or
specialized receiving stations. Power limitations and positioning dictate that
these satellites be polar orbiters with Data Collection Locations Systems
(DCLS) such as presently provided by Service Argos. Thus, the maintenance of
DCLS satellites throughout WOCE is essential. All drifters inherently follow a
parcel of ocean, more or less well depending on the type, and therefore the
sampling and measurement characteristics differ fundamentally from other
techniques.

6.10.2 Subsurface floats.

Deep floats have been used successfully during the last decade to explore
the circulation around gyres and the statistics of transient eddies (see, for
example, Figure 24).   Their tracks provide a good approximation to water
particle trajectories.   Modern floats whose tracks lie on isopycnic surfaces
minimize the error, making it reasonable to assume that floats are Lagrangian
tracers.   The floats can be tracked acoustically at frequent intervals, or by
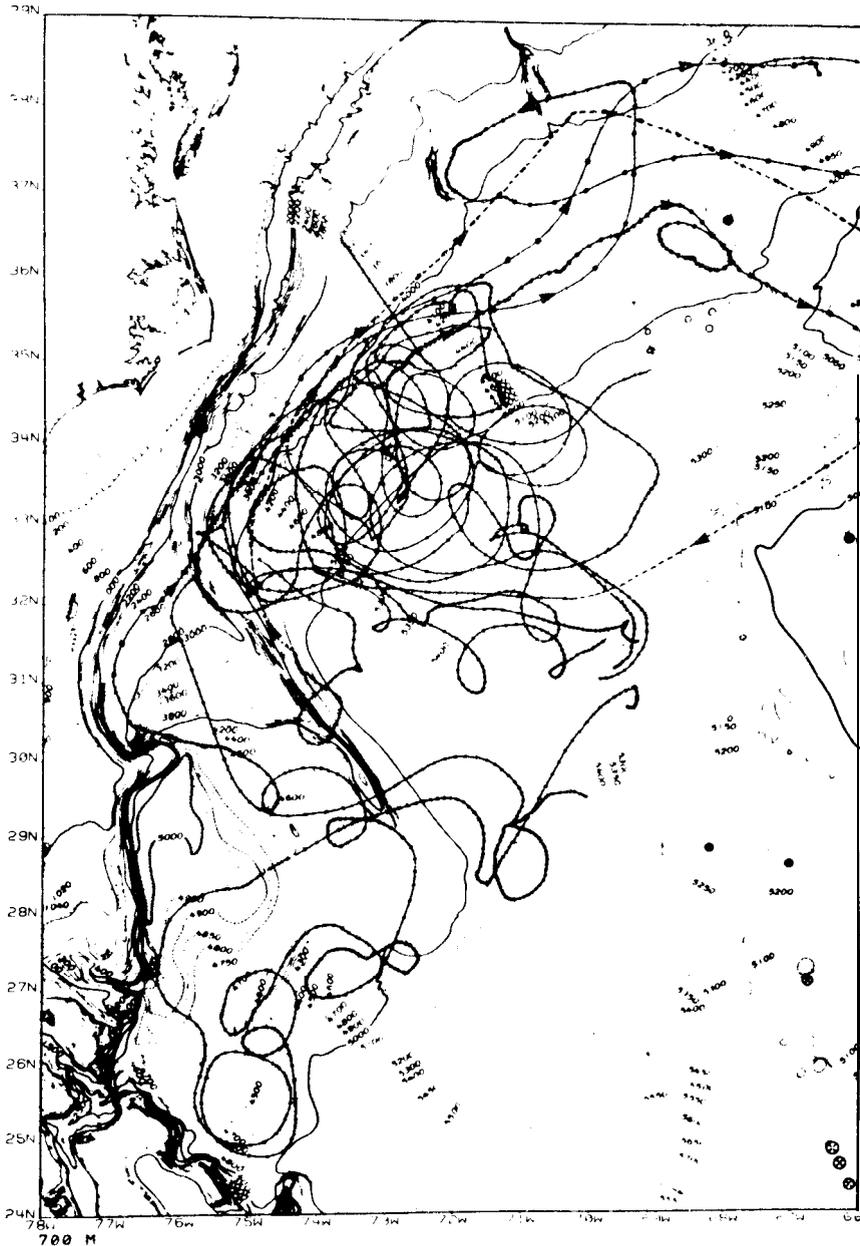
700 M

Figure 24:   Trajectories of floats that have been in the Gulf Stream and which
            lie at a depth of about 700 m (from Rossby et al, 1983).

the Argos satellite system at much longer intervals when the floats briefly
surface between periods of deep drifting.   The latter method is attractive for
exploring the slow circulation in the deep ocean.

     Floats will be used in a variety of ways in WOCE.   The scientific plan for
Core Project 1 requires the deep ocean to be seeded with floats to determine
the velocity field.   Such a direct approach to determining the circulation is
attractive, because it does not suffer from uncertainties that arise in
diagnosing-the circulation from observed patterns of scalars using the inverse
technique.   However, design studies have shown that a large number of velocity
measurements will be needed in each measurement cell (say 1 degree x 1 degree)

to determine the permanent flow to an accuracy of plus or minus 20% in the
presence of much more energetic transient eddies.   The method is therefore
resource limited.   It would, in principle, be possible to seed the ocean with
enough deep floats to determine the deep circulation to the specified accuracy
over a five year period, but the cost would almost certainly be too high.
Given a more modest number of floats, the WOCE strategy will be to deploy them
in selected regions where they can have greatest impact in defining the
circulation.

      Floats will also play an important role in helping to answer fundamental
questions about the circulation at a more qualitative level.   They can
contribute to the central problem of Core Project 2;   namely, the mechanism by
which water carried between basins in the circumpolar current becomes
incorporated into the circulations within the Pacific, Atlantic and Indian
Oceans, and vice versa.   Float tracks will be interpreted, in a manner
analogous to flow visualization in laboratory fluid dynamics, to discover where
and how such exchange occurs and will support the diagnosis of large-scale
circulation using other data.   The results will also draw attention to regional
or phenomenological aspects requiring special attention in prognostic models.

      In Core Project 3, floats will be used in a variety of ways, including to
determine the annual displacement in the seasonal boundary layer, to extend the
altimetric maps of eddy energy at the sea surface down into the thermocline, *to*
explore exchange between the cyclonic and anticylconic gyres, and so on. In
this study of gyre dynamics within a single basin, it will probably be
necessary to use acoustic tracking to achieve eddy-resolving temporal
resolution.   This will require deployment and routine servicing of a number of
moored tracking systems, with data recording and/or data transmission via
satellite.

      WOCE will use a number of different types of subsurface float.   They
include the SOFAR float (used extensively during MODE and POLYMODE), the
closely related RAFOS float and the intermittently surfacing (POP-UP) float
tracked by the Satellite Argos system after drifting in the deep ocean for up
to one year.   Launching a float can take several hours if the ship remains on
station to check the system is operating correctly.   Recovery can involve
significant ship time in searching and will normally not be attempted.   The aim
will be to minimize ship time involved in drifter operations by integrating it
into other oceanographic work.

      The acoustically tracked floats will require deployment of tracking
systems.   The experimental design is not yet complete, but a reasonable working
hypothesis would be of order tens of units per ocean basin.   Servicing the
moorings would be done annually but can hopefully be integrated into other
oceanographic operations as the time involved is largely one of passage.

      The mean useful lifetime of a float should exceed one year.   The
deployment strategy has not yet been worked out and will depend critically on
the number of floats available.

6.10.3 Surface drifting buoys.

      Buoys drifting on the ocean's surface provide a convenient instrument
platform for measurements such as sea level pressure, sea-surface temperature,
and perhaps humidity, precipitation, surface salinity, and near surface
currents relative *to* the buoy motion.   The use of such buoys in indicating the
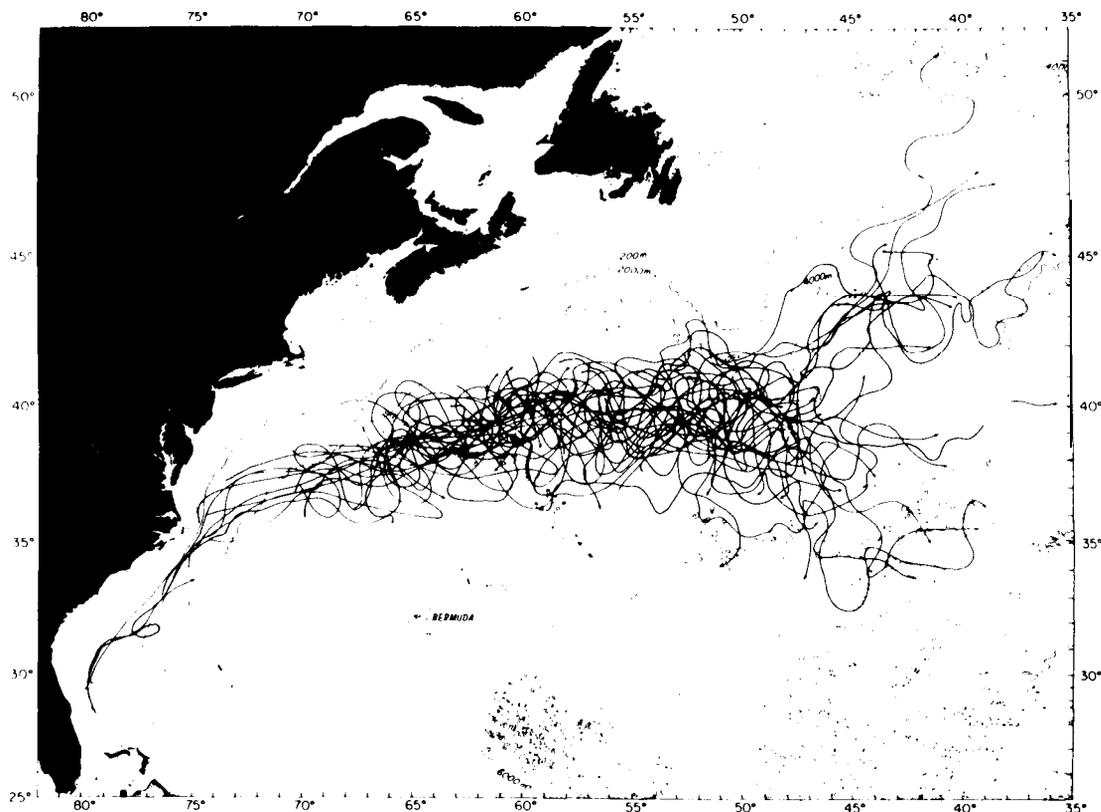near-surface current is shown in Figure 25.

Figure 25:   A selection of trajectories of surface buoys that have been in the
Gulf Stream showing, for example, the onset of convoluted meanders
east of 70"W (from Richardson, 1983).

The satellites primarily collect the data and determine the buoy position,
with the buoy drift being of secondary importance.   The surface buoy needs to
be relatively large to support the sensors and house an adequate power supply
for powering the sensors and for regular satellite transmissions.   Near real
time data return is often advantageous.   The sensor suite is being designed to
be modular to allow any subset to be employed for a particular purpose. Some
useful configurations for Surface Drifters are: sea level pressure and
sea-surface temperatures (as deployed in FGGE); a vertical thermistor chain for
monitoring changes in heat content;   wind velocity, air temperature, air
humidity, sea-surface temperature and precipitation, from which the surface
fluxes of momentum, turbulent heat and moisture can be calculated using bulk
formulae; and an acoustic doppler velocity profiler for near surface relative
currents.   A severe limitation on the number of sensors is the limited bit rate
of the DCLS satellites.   Of order 1000 of the simpler FGGE configuration could
be deployed, but probably fewer than 100 of the more expensive heat flux or
velocity drifters will be affordable and will therefore be used in special
regions.

6.11 Moored Instrumentation

Moored instruments, especially current meters, are capable of providing detailed temporal information at a limited number of depths and sites. Although much of what is presently known about the distribution of abyssal eddy kinetic energy comes from moorings, their inability to cover large geographical areas limits their usefulness as a primary survey tool in WOCE. However, arrays of moored current meters are well-suited for studying most boundary currents, the flow through narrow passages, for monitoring the eddy kinetic energy at a few sites, and for some process studies related to Core Project 3.

There are various laboratories with the capability to deploy instrumented moorings for lengths of time up to two years. The cost of moored instrumentation is not closely related to the length of the deployment, so the capability is being developed to increase the length of deployments. The usual technology involves subsurface moorings, which makes telemetry of the data not feasible at present.

The number of instruments available worldwide are in the thousands, although not all of these are capable of the longer deployment times. The number of moorings possible depends upon the number of acoustic releases available, which is at least several hundred. The principal constraint on moored current meters for WOCE is the ship time and specialized manpower to prepare, to deploy and to recover the instruments and to process the data. Even so, it seems likely that resources should be available for a program of one hundred moorings per year, with most of these being placed in boundary currents and passages between basins, with a few being used to monitor the eddy kinetic energy levels in remote places such as north of the Antarctic Circumpolar current *in Core* Project 2.

6.12 Specialized Research Techniques

There are a number of observing systems that have not been mentioned in detail in this Scientific Plan. Some such as free-fall profiling CTDs are in the early state of development. Others such as those using acoustic tomography, while better developed, are still not considered as suitable for use in a routine way during the WOCE intensive period. In addition, many specialized systems such as towed CTDs or acoustic velocity profilers, which exist within certain laboratories, are only likely to be available on a limited basis in WOCE and are not seen to be of such importance as to warrant special efforts regarding further development or the diversion of major resources at this time. Notwithstanding this present assessment of such systems, many may indeed play an important part in WOCE and form a more substantial part of implementation plan. In addition, some systems used in a limited way in WOCE may well be found suitable as part of ocean monitoring systems in the future.

CHAPTER 7

Data Management

7.1 Introduction

Data management for WOCE should mesh closely with that for TOGA. However, aspects of WOCE require some difference of emphasis.

.   The strongest emphasis on data management in WOCE (as in TOGA) will be on quality and timeliness. Timeliness probably will not include 'near real-time' as in TOGA, except in regard to delivery of <u>in situ</u> calibration data for satellite systems.

.   WOCE will be crucially dependent on non-operational systems,both satellite and <u>in situ</u>, whereas TOGA is heavily dependent on operational systems. The strongest requirement of WOCE will be for delayed-mode quality-controlled data sets.

.   The goals of WOCE emphasize the building and testing of models rather than just their initialisation. Thus, gridded data sets and analysed fields will not be the only end-products required from the experimental programme.

WOCE Data Management can be separated into three components:

.   The assessment of the utility of existing data types in achieving WOCE objectives. This would enable a useful sub-set of existing data to be assembled for WOCE purposes.

.   The assemblage of data sets to be used as boundary conditions on ocean models.

.   The assemblage of data sets for the critical assessment of theories and models.

7.2 Conceptual Framework

A framework within which WOCE data management could be developed, in parallel with other WCRP components, was laid down at a CCCO/IGOSS/IODE ad hoc meeting in Paris in October 1984. It is summarised here.

The flow of data from source to scientist is shown in its simplest form in Figure 26, which shows the links between sensor, scientist, and archives. An important function within the data management flow is that of international data gathering and quality control. This may be organized either on a global or regional scale, but preferably on an ocean basin scale and upwards.   The
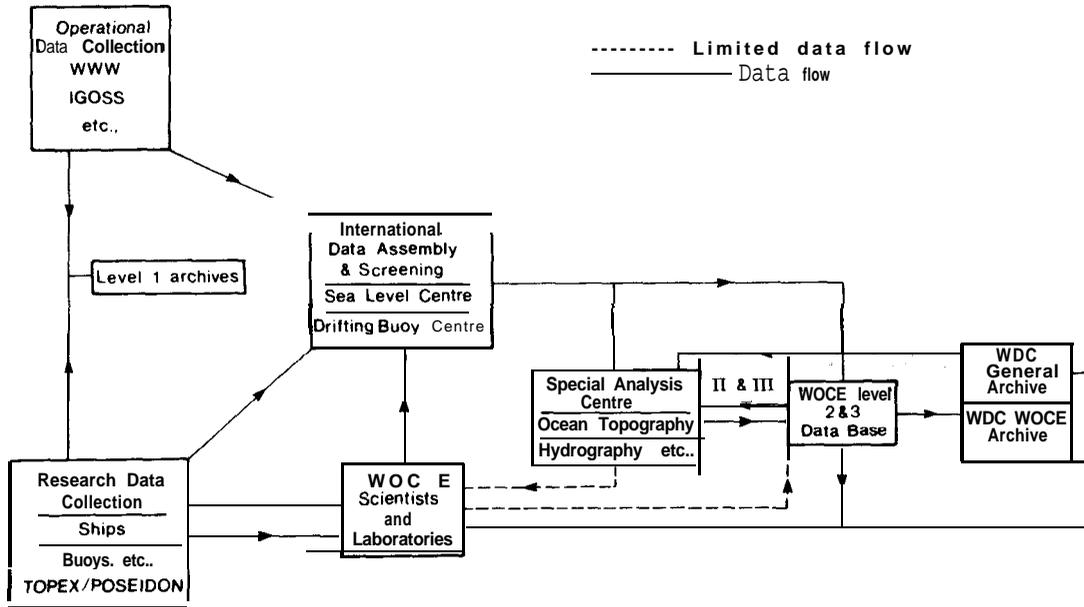
Figure 26: A schematic presentation of the proposed WOCE data management structure

data is then passed either directly to a permanent data archive or to a special analysis centre, which may also provide an intermediate data archival function. Since centres performing this latter function are generally project orientated and of limited life span, it is important to ensure that all data eventually reach a permanent archive.

Because of the multiplicity of data centres, data flow paths and archives, there is a critical need for coordination. Some primary tasks will be to:

. plan data preparation and flow paths, including the coordination of data exchange media and formats.

. inform scientific users as to programme status and data availability, including the preparation of lists of projects and centres, inventories of data holdings of the centres, progress of intercomparison exercises, and summaries of results.

In general data will not flow directly through any coordinating group, although project information assembled in the course of coordination will become part of the permanent data archive.

The concept of data levels used to describe the stages of analysis during FGGE will be used during WOCE (Table 2). The definitions of the various data levels encompass and extend those adopted for TOGA (Plan for the TOGA Scientific Programme, 1984). In addition, for certain data types, particularly satellite data, level 0 data is defined as raw data; for example, as telemetered from a spacecraft that requires data processing for conversion to Level I.

Scientists act as originators of data and as analysts of their own data and of data obtained from other programme components. The main source for the

TABLE 2

Definition of Levels of Data

Level I data are instrument readings, normally in engineering units (e.g. volts), that require conversion into meteorological and oceanographic variables specified in the data requirements. The raw data records are to be retained by the participants but not, in general, exchanged as part of the standard data flow.

Level II data are values of the universal meteorological and oceanographic variables either obtained directly from instruments or derived from Level I data, e.g. wind velocity, sea level, SST. These data are subdivided into two classes with different timeliness characteristics.

Level II-a data are WWW, IGOSS, and other information required for research and monitoring activities in which rapid data availability is important.

Level II-b data are distinguished from Level II-a data by a delayed cut-off allowing the acquisition of a more complete data set and/or the application of quality control.

Level III data are processed products derived from level 11 data by analysis techniques.

latter will be from the permanent data archives through the supply of level II-b and level III data to the scientist. However, there will be many cases in which this route will be too slow for the scientists" research requirements. The level II and III WOCE distributed data bases are designed to provide these data in a timely fashion. The scientist will also be able to obtain data directly from the Special Analysis Centres (SAC's). However, since the SAC's will not necessarily have a User Servicing Interface, which exists at the Permanent Data Archives, data flow to the user may be coordinated or regulated by a data coordination group. An important part of the data cycle is the feedback from the reseacher to the data bases of additional level III data and quality control information concerning level II data.

The importance of establishing a data tracking mechanism is emphasized by Figure 27. which shows a possible flow of data information within the programme. In this model, a scientist needs only to interface initially with the "Data Information Unit" to obtain information as to the status and availability of data that he does not already hold. However, the actual flow of data to the scientist will be along paths defined in Figure 26 or through less formal routes. Further elaboration of a data tracking mechanism is given in Section 7.6.
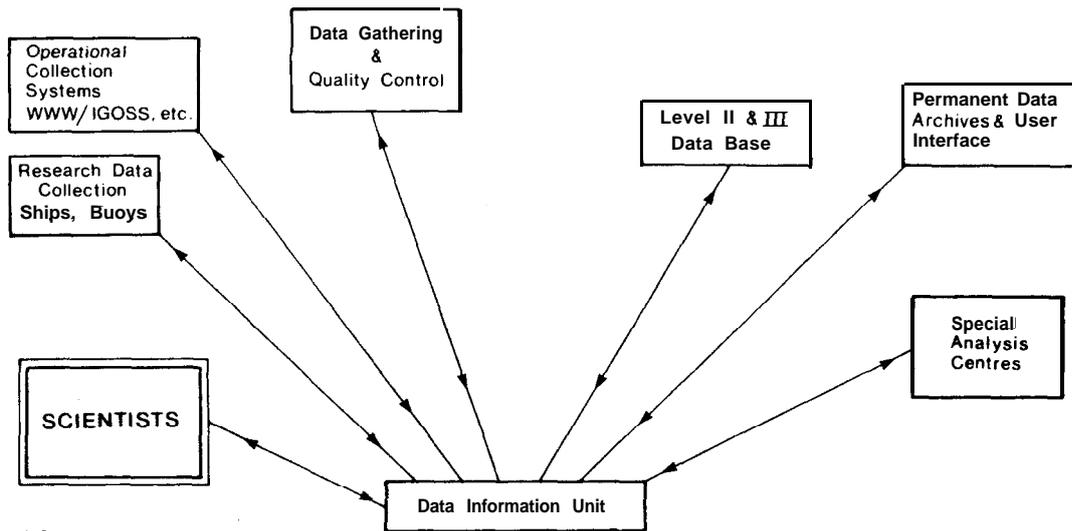
Figure 27:   Illustration of the need to track the flow of information
             between programme elements and the scientific community.

     The operational systems of WMO and IOC and the permanent archive in the
World Data Centres (WDC's) are the only elements on Figure 26 that are in
place. The latter may not, as discussed above, be able to satisfy the criteria
of timeliness in all cases. This does not preclude the possibility that some
of the functions for WOCE will be co-located with the WDC's or supporting
NODC's.

     The following paragraphs discuss some elements of Figure 26 and how they
might be implemented in support of WOCE.

7.3 Operational Data Collection

     Operational   data   collection   encompasses   data   from   meteorological
satellites,   ships of   the WMO's Voluntary Observing fleet, and additional
observations,   mainly of upper ocean   temperatures by merchant   ships-of-
opportunity' operating within the IGOSS system.

     Transmission, processing and distribution criteria for these data are well
defined and are being actively exploited in the initial phases of TOGA.   WOCE
will need to establish interfaces between the operational data distribution and
the WOCE Special Analysis Centres and data bases.

7.4 Research Data Collection

     Research data will be collected from a number of distinct platforms:
satellites (earth observations and data relay), ships-of-opportunity, and
research ships. The procedures for handling research data have not been well
defined and WOCE will need to develop guidelines for their treatment.

7.4.1 Satellites.

Data from satellite sensors such as the TOPEX/POSEIDON and ERS-1 altimeters and the NROSS scatterometer are central to WCRP objectives. It is in this area that the most obvious initial problems will arise. Raw data flows are orders of magnitude greater than for traditional oceanographic observations. Moreover the systems are the responsibility of agencies not under the control of the oceanographic community. These agencies in general do a substantial part of the early processing of the data or commission to have it done. ESA is arranging that there be provision for ERS-1 products up to level II and there seems no doubt that there will be systems in place to handle the altimeter and scatterometer data. These systems may be distributed. In the USA, PODS/JPL can be expected to play a similar role for altimetry and the NROSS scatterometer. Plans for other satellite sensors are at present unknown.

During WOCE, the ARGOS system will continue to act as data collection platforms. From the sensors on drifting buoys and pop-up floats data will be transmitted to the USA and France and subsequently distributed to users. Within the wider framework of the data banks of the IOC/IODE system, the Canadian NODC has made an offer, for example, to take (with the agreement of users) the Argos tapes from Toulouse, France, on a regular basis, to reformat them into the international GF-3 format within 30 days of receipt, to maintain an archive and within 30 days of a request to make available the data, together with information on quality control.

7.4.2 Ships-of-opportunity.

The WOCE programme using ships-of-opportunity is as yet undeveloped. The primary collecting agencies for systems such as Doppler profiling logs will be research groups. If the data route is through the project scientist then the data will be similar in nature to other research data and can be handled in a similar way. If the route is through IGOSS, for example, for real-time XBTs, it falls within the realm of Operational Data Acquisition for which there is a well defined but under-utilised operational GTS format.

7.4.3   Research ships, platforms and moorings.

The collection of data from research ships, platforms, and moorings will rest almost entirely with the laboratories concerned. As part of participating in WOCE, laboratories will agree to calibrate, document and pass on data to the appropriate national or international centres within a short period after collection of the data. The individual investigators and laboratories will have their traditional priority in the initial analysis of the data during that short period, after which other WOCE participants will have appropriate access to it through the national or international centres. National organizations should ensure the timely submission of the data to those centres.

7.5 Special Analysis Centres

The Special Analysis Centres, or their functions, are most important for the success of WOCE as a global experiment. At present, unlike some of the

other elements of the proposed data management plan, there is neither any clear specification of requirements nor, in consequence, any identification of such centres. It is expected that theae will systematically produce the level III data that many research projects will require. The FGGE analogy would be to the ECMWF's role in generating gridded data sets. In WOCE, however, level III 'products' *may* be more diverse.   For example, a centre concerned with sea-surface topography will concern itself with, at least, the following data sets:

     .   Altimetric range data corrected for tropospheric, ionospheric and bias effects

     .   Ephemeris data for each satellite derived from tracking data, force models, station positions

     .   Geoid data derived from gravimetric (satellite and <u>in situ</u>) observations, satellite tracking and mean altimeter data.

         Data from the <u>in situ</u> tide gauge networks.

The Centre would produce sea-surface topography filtered and averaged over a variety of space and time scales. This would be adjusted as successive improvements are made to the input data through better geoid models, ephemerides, etc..

7.6 Data Information Unit

The overall functions of a Data Information Unit have been explained in the Section 7.2.   In the early stages of the WOCE programme, development of data management needs to be closely tied to the development of the research programme.   In particular, the eventual creation of a data information unit needs to be first tested through a pilot or demonstration activity. This pilot period should result in the establishment of a such a unit.

The Data Information Unit would assist participants in WOCE by pointing them towards the location of the data bases most able to match their particular needs.   For example, some potential centres have expressed a willingness to carry out part of the necessary processing and *to* pass data on to specialised groups but not a willingness to interact directly with the scientific community at large. Others, while ready to make their own data immediately available to others for specific purposes, will wish to impart some delay to its general release.   The Unit would also assure that the 'products' flowing back to the WOCE data base as part of the feedback from researchers are of known quality.

The SSG, with some urgency, needs to identify groups willing and competent to assume responsibilities as Special Analysis Centres and for providing parts of the distributed data bases.

7.7 Data Base and Archives

<u>Level I data bases</u>

It is recommended that level I data be maintained by the originating

agencies/ laboratories whenever possible for the duration of the experiment and for the subsequent 5 years.

Level II data bases

The level II data bases are a vital concern of WOCE data management as they must provide WOCE scientists with timely access to quality controlled level II-a and 11-b data.   They may with some advantage be co-located with Special Analysis Centres as long as they may be accessed separately.

It would be appropriate for in situ data to be assembled as regional (ocean wide) data-bases maintained at active and well equipped regional centres.   Steps will be taken to identify potential volunteers for this task.   It is also necessary to confirm that centres such as JPL/PODS, NCAR and equivalent organisations in Europe and Japan will maintain their level 11 satellite data bases for 5 years beyond the duration of the experiment.

Permanent Archive

There is no reason for WOCE to depart from the practice of using WDC's A and B as the Permanent Archive assuming they are willing and able to undertake the task.   It will be essential for the WDC's to maintain the WOCE data set as a readily accessible entity irrespective of any merging that the WDC's might wish to do with other data sets.

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