WORLD CLIMATE PROGRAMME

RESEARCH

WORLD OCEAN CIRCULATION EXPERIMENT IMPLEMENTATION PLAN

Vol. II

Scientific Background

The World Climate Programme launched by the World Meteorological Organization (WMO) includes four components:

> The World Climate Data Programme
> The World Climate Applications Programme
> The World Climate Impact Studies Programme
> The World Climate Research Programme

The World Climate Research Programme is jointly sponsored by the WMO and the International Council of Scientific Unions.

WOCE IMPLEMENTATION PLAN

VOLUME II

'SCIENTIFIC BACKGROUND'

CONTENTS

1   INTRODUCTION

1.1   Background

The World Climate Research Programme (WCRP) was established by the World Meteorological Organization and the International Council of Scientific Unions (ICSU) with the objective of determining the degree to which climate can be predicted and the extent of man's influence on climate. In order to address various climate issues the WCRP has been divided into "Streams". Stream Three is concerned with the prediction of climate changes over periods of decades. Since the major scientific problem limiting such predictions is the inability to describe and model the circulation of the world ocean, the organizers of the WCRP have established the World Ocean Circulation Experiment as the principal activity within Stream Three. WOCE is being organized in conjunction with the Scientific Committee on Oceanic Research (SCOR) of ICSU and the Intergovernmental Oceanographic Commission (IOC) of UNESCO. The Experiment is being planned by the Scientific Steering Group (SSG) for WOCE which was established by the SCOR/IOC Committee on Climatic Changes and the Ocean (CCCO) and the WMO/ICSU Joint Scientific Committee (JSC).

The Goals and Objectives of WOCE have been formulated by the SSG and published in the WOCE Scientific Plan (WCRP Publication Series No 6, 1986). The Scientific Plan articulates the rationale for the experiment and outlines a coherent and feasible approach for reaching the Goals and Objectives. It provided the framework in which detailed planning of WOCE has taken place.

Since the publication of the Scientific Plan, WOCE has been developed both nationally and internationally. Much attention has been paid to the Core Projects to which the Scientific Plan gives priority. Planning meetings have been held for each Core Project and working groups established by the SSG have formulated detailed experimental plans. Developments have also taken place in ocean modelling and eddy-resolving models are being used to examine problems of primary interest to WOCE. Changes have occurred in the scheduling of satellite-borne sensors and there is an increased understanding of their capabilities and the ground-truth data needed to obtain maximum benefit from their measurements. There have also been various technical developments regarding oceanographic instrumentation.

Within nations, formal structures, including national committees for designing and implementing contributions to WOCE, have been formed and national WOCE programmes developed. These have provided valuable input to the formulation of global WOCE experimental plans. Regionally, meetings have been held to involve nations that have not participated to any great measure in the initial planning of WOCE and to find ways they can participate. The need to involve a large number of coastal states in WOCE has been recognized. This WOCE Implementation Plan takes into account developments that have taken place since the publication of the Scientific Plan and provides the basis for moving forward from scientific planning to implementation.

Although the Implementation Plan provides a detailed scientific framework for WOCE, it should be expected that the experiment will continue to evolve throughout its lifetime. Even without limitations on resources needed to carry out the experiment, it may easily be that new information will necessitate changes in various aspect of the field programme. The possibility of changes has been indicated where possible.

1.2   Organisation of the Implementation Plan

This plan has been prepared in two volumes. The first gives an overview of the Goals and Objectives of WOCE and the strategy for meeting them. It provides the details of the structures necessary for the implementation of the WOCE field programme, data management and modelling programme. Detailed tables of resources needed for WOCE are presented and summaries of these resources provided.

This, the second volume, contains the detailed description of the three Core Projects which form the heart of WOCE. It provides the scientific rationale that has led to the WOCE field programme, the details of the experimental elements of which it is composed and how, taken together, they constitute a coherent programme meeting the overall objectives of the Core Projects and of WOCE itself.

The first volume is highly referenced to the second, especially regarding the detailed resources needed to carry out the experiment. Although this second volume, which reiterates some of the material contained in the first volume, may be considered as a relatively self-contained description of WOCE and its Core Projects, a full understanding of the scope of WOCE and the complexity of its implementation can only be obtained from the material contained in the two volumes.

The modelling aspects of WOCE are only discussed in detail in Volume I. However, the scientific development of the experimental programme presented in this volume is inherently linked to the existence of numerical models for the oceanic circulation, the information they provide and the data that is needed for their further development and testing.

Throughout this volume, experimental arrangements (for example, a hydrographic section or float array) are given a code which identifies them in a unique way. The definition of this code is given in Chapter 5, Volume I.

2   GOALS AND SCIENTIFIC STRATEGY FOR WOCE

2.1.   Goals and Objectives of WOCE

In order to address the needs of Stream Three of the WCRP, the WOCE Scientific Steering Group developed formal Goals and Objectives for the experiment. As stated in the Scientific Plan for WOCE (WCRP Publications Series No 6, 1986), they are as follows:

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, mega-metres 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 on-going climate observing system.

This Implementation Plan primarily concerns the experimental programme necessary to meet Goal 1 and its Objectives, although some aspects of the programme will be directly applicable to Goal 2.

2.2   The WOCE Strategy

The design of a field programme to meet the Goals and Objectives of WOCE requires decisions regarding the scope of the programme and the utilisation of resources that will be available from supporting nations. As a basis for focussing on the critical issues that must be addressed within WOCE, the SSG has developed the strategy of concentrating on three Core Projects. These are Core Project 1, 'The Global Description'; Core Project 2, 'The Southern Ocean'; and Core Project 3, 'The Gyre Dynamics Experiment'. All three Core Projects are required to meet the objectives of Goal 1 and their aims are complementary, overlapping geographically, while sharing most of the main observing systems.

Although the WOCE strategy is to give priority to the Core Projects, it is recognized that other oceanographic experiments can make significant contribution to the Goals and Objectives of WOCE. These

could include for example regional studies allowing an examination of particular features in one ocean basin or a comparison of similar feature in different ocean basins. Such experiments are encouraged provided they do not use resources needed for the implementation of three Core Projects which constitute the minimum coherent programme that can meet the objectives of WOCE.

The scope of the three Core Projects and how they meet the Goals and Objectives of WOCE is given in the Scientific Plan and briefly reiterated in Volume I of this Implementation Plan. They are also described below so that this volume can stand alone as a scientific description of the WOCE field programme. However, as noted earlier, a full understanding of WOCE can only be obtained from the two volumes of this Implementation Plan and the background provided by the Scientific Plan.

The objective of Core Project 1 is to obtain the global data set with which one will be able to describe the circulation of heat, fresh-water and chemicals, the formation and modification of water masses, and the statistics of ocean variability. These constitute the zeroth order description of the role of the ocean in the planetary climate system.It will make use of the availability for the first time of satellite measurements of the global surface wind-field and sea-surface topography as well as of the global deep circulation using neutrally-buoyant floats.

As a basis for the design of the Core Project 1 field programme, consideration has been given to a number of components of the oceanic system that are of particular importance to the prediction of decadal climate change. These include: the surface layer which is the part of the ocean most subject to seasonal and interannual variations due to its interaction with the atmosphere; the abyssal circulation that the decadal time scale is an important part of the circulation; the tropical ocean where special questions need to be addressed concerning the transport of water, heat and salt across the equator; eddies and their importance in transporting various oceanic quantities; and the general question of the oceanic transport of heat and fresh-water and their budgets. These are discussed in Chapter 3 where the field programmes for Core Project 1 are presented on the basis of the questions needing to be addressed.

Core Project 2 is concerned with the large-scale aspects of the circulation in the Southern Ocean in much the same way as Core Project 1. It also addresses the special aspects that give the Southern Ocean an especially important role in climate. These include the Antarctic Circumpolar Current which links the circulation of the Pacific, Indian and Atlantic Oceans and provides the connections that transform the oceanic heat flux from a regional to a global phenomenon. In addition, south of the Circumpolar Current large quantities of heat are lost to the atmosphere and deep water masses are formed which flow northward. The details of these features of the Southern Ocean and the programmes to address unanswered questions are presented in Chapter 4.

Lastly, Core Project 3 is discussed in Chapter 5. It is that part of WOCE which is designed to clarify those processes of which oceanic models are sensitive to the parameterisation. The basic strategy is to study one oceanic basin in enough detail that developments can be made in models for that ocean basin which can be extended to the global ocean. The data sets to be collected include enhancements of the global coverage provided for the basin by Core Project 1. Within the basin large-scale experiments are to be located to examine various aspects of the gyre-scale circulation, the abyssal circulation, and cross-equatorial flow. In addition, more traditional process-oriented experiments of particular importance for meeting most objectives are also to be conducted.

The Atlantic Ocean has been chosen as the site of the basin-scale experiments for Core Project 3 and it is only experiments which are to be expected to be carried out in the Atlantic, that are described in Chapter 5. It is recognized, however, that for scientific and logistical reasons it may be necessary to carry out some elements of Core Project 3 elsewhere. Such experiments may be developed in the future as Core Project 3 evolves over the course of WOCE.

3 CORE PROJECT 1

'THE GLOBAL DESCRIPTION'

3.1 Scientific Basis

3.1.1 Scientific Goals

Goal 1 of WOCE is to develop models useful for predicting climate change and to collect the data necessary to test them. The central objective of WOCE Core Project 1 is to obtain a global description of the ocean circulation so as to provide a basic picture of the circulation and its variability, to relate this to atmospheric forcing, and to refine understanding of ocean dynamics based on the observations and related modelling. All components of Core Project 1 are designed to achieve the aim of a global description of the zero-order mean circulation, the air/sea flux fields and their variations seasonally and interannually, and the corresponding response of the oceanic circulation and water properly fields.

The design of Core Project 1 is based on the following ideas:

(a) A zero-order global circulation field can be obtained by inversion of a global description of the three-dimensional density, temperature, salinity and tracer fields, a two-dimensional deep Lagrangian velocity field and sea surface topography determined from satellite altimetry.

(b) In the development of eddy-resolving oceanic circulation models, knowledge of the actual distribution and values of eddy kinetic energy provides a powerful test of the models.

(c) The development and testing of thermodynamically-forced, as well as of dynamically-forced oceanic models, is greatly impeded by the lack of a consistent description of the air-sea flux fields driving the circulation.

(d) The ability to estimate all components of air-sea fluxes directly is limited and it will be necessary to also measure the annual cycle of heat and salt content in the upper layers of the ocean to test directly the consistency between estimates of the forcing of the ocean by the atmosphere and its response.

(e) The oceanic meridional heat flux across a given latitude circle, estimated for a given year or season around the globe, serves as a simple zero-order constraint on the global atmospheric-oceanic meridional heat flux.

Following from these ideas, the major observational components of Core Project 1 are:

(a) a large-scale, full-depth, global hydrographic/tracer survey covering the entire ocean once,

(b) a global deep float release employing a mixture of pop-up and acoustically-tracked floats,

(c) satellite altimetry calibrated with a sparse, global sea-level network,

(d) sparsely-sited moored arrays in all ocean gyres to map the vertical structure of the eddy field,

(e) current-meter arrays across western and eastern boundary currents plus seasonal occupation of zonal hydrographic sections, to at least 1500 m, to obtain estimates of the oceanic heat and salt flux across selected latitudes,

(f) enhancement of surface meteorological measurements to calibrate satellite-derived wind and sea-surface temperature measurements regionally for estimates of air/sea fluxes,

(g) a surface layer programme using standard hydrographic measurements, XBTs, XCTDs, moored and drifting temperature and temperature/salinity chains, surface drifters and acoustic Doppler profiling

systems to obtain a global description of the evolution of the distribution of heat, salt and momentum on a monthly-to-interannual basis in response to the air/sea forcing,

(h)   a sparse array of seasonally-occupied, eddy-resolving XBT/XCTD or upper layer CTD sections to determine the seasonal variation of the strength of the major oceanic gyres,

(i)   current-meter arrays or special float releases to measure deep boundary currents and exchanges between basins to provide some critical estimates of the strength of abyssal circulation,

(j)   current-meter arrays and other direct velocity measurements to estimate the strength and mechanisms of trans-equatorial exchange.

The fields of temperature, salinity, velocity and tracers at a 500 to 1000 km scale are to be sampled once during the WOCE period to obtain a zero-order mean description. Interannual and annual variations will be examined on a much coarser spatial scale. Velocity observations to produce a global mapping of the mean will occur continuously throughout the WOCE period.

The measurement techniques to be used in these projects are discussed in Section (3.2). Each primary method or technique is discussed in terms of how the method contributes to the goals of Core Project 1, with some consideration of the strengths and weaknesses of the method. Additional types of measurements or experimental designs which address Core Project 1 goals are encouraged even if they are not specifically included here; however, the plans listed in the text below represent a community effort to define a realistic programme to arrive at a globally consistent estimate of these fields over the WOCE period.

3.1.2 Large-scale Circulation

Ascertaining the large-scale circulation is the primary goal of Core Project 1. A fundamental scientific assumption is that understanding the significance of apparent changes in the ocean circulation to climate and climate change can only follow a complete description and understanding of the circulation as it existed at one time. The relationship of the large-scale circulation as determined during the WOCE to the mean circulation over much longer periods falls under Goal 2. But the snapshot of the global circulation and water properties which will be obtained during an approximate 5-year period is the essential reference for both past and future ocean observations.

Provision of a unified picture of the circulation during one five-to-ten year period will permit the identification and understanding of any changes observed in the circulation.

3.1.3 Surface Layer

The surface layer, by which is meant the oceanic mixed layer, is the interface between the atmosphere and the ocean interior and is that part of the ocean most subject to seasonal and interannual variability due to fluctuations in the forcing. Primary goals of surface layer observations are the determination of the forcing of the ocean interior and the description of the velocity, temperature and salinity fields within the upper ocean and, specifically, in the long-term mean, the seasonal cycle and interannual variations, as well as the dynamical mechanisms that govern these variations.

Core Project 1 will make global estimates of these fluxes across the air/sea interface and of their variability, and will estimate the rates of storage in the surface layer, as well as the fluxes of momentum and buoyancy to the ocean below the surface layer.

The Core Project 1 surface layer programme includes measurements of velocity, transports of heat and salt, and heat/salt fluxes and content. Surface layer velocity measurements for the purpose of determining circulation, divergence and momentum balances include the use of surface drifters, acoustic Doppler profiler sections, meteorological observations, satellite scatterometry, and altimetry. Estimates of heat and salt transports, inter-gyre transports and the vertical structure of surface transports require temperature and salinity profiling and satellite radiometry. These measurements will also aid in the determination of surface forcing

through the fluxes of heat and fresh water as well as being useful for the determination of steric levels and dynamic height changes. Re-analysis of meteorological fields produced by various agencies, given the additional measurements which will be made during WOCE, will also be an important component of this programme.

3.1.4 Abyssal Circulation

The mix of surface altimetry, surface and deep floats, global hydrography and tracers will provide estimates of the major circulation patterns at all levels. However, the mean currents at abyssal depths are known to be small and it is unlikely that adequate estimates of the convergence or divergence of transports of deep and bottom waters between various deep basins could be obtained without direct measurements using floats. In addition, there are many deep basins where the source and mechanism by which new deep water enters have yet to be discovered.

During WOCE the advective pathways of all deep water sources and inter-basin connections must be identified. Determinations of the advective fluxes of major deep waters into and out of all deep basins are necessary to confirm mixing parameters based on tracer distributions. The measurements include temperature, salinity and velocity from moored instruments in key deep passages as well as careful analysis of the hydrographic and tracer data from those deep basins.

3.15 Tropical Circulation

The equatorial area is characterized by a zero in the Coriolis parameter which causes a breakdown in the geostrophic approximation. Equatorial currents are accordingly much more time-dependent and directly related to the surface wind and thermodynamical forcing than currents at higher latitudes. The upper layers of the tropical ocean are strongly coupled with the lower atmosphere in spectacular air-sea interactions (ENSO) that play an important role in earth's climate on time scales of months to several years. This strong connection is the primary justification for the on-going TOGA experiment. TOGA is focussed on the upper 500 m of the water column and the associated variability; thus, TOGA will add little to the knowledge of pathways and rates of inter-hemispheric exchanges at depth and their temporal variations on any time scales. From a WOCE perspective, the equatorial areas cannot be viewed as isolated when considering the global circulation. The following scientific questions concerning the equatorial zone are part of the WOCE objective of understanding global circulation:

(1)   How are the northern and southern subtropical gyre circulations connected at the equator? Although TOGA will help answer this question, additional studies are necessary, especially at the boundaries of the equatorial basins, because the equatorial circulation is mostly zonal and the meridional residual flow is almost unknown.

(2)   By what paths and in what magnitude does water at all levels cross the equator?

(3)   What are the relative contributions to cross-equatorial exchange of the upper and deep oceans?

(4)   What physical processes drive equatorial exchanges and how is the change of sign in the potential vorticity of water masses crossing the equator to be interpreted?

(5)   Why are meridional heat transports across the equator so different from ocean to ocean? Although a mean poleward transport is required to balance atmospheric heat input at the equator, the heat flux diverges symmetrically in the Pacific, while in the Atlantic it is northward and in the Indian southward.

Observations and models must be combined in the tropics to yield answers to these and other scientific questions. Specific observational plans are included in the basin plans of Section (3.4). Elements of the plan are at least one zonal hydrographic sections between 5° and 10° N and S of the equator in each ocean, western boundary current studies, float deployments at several levels, instrumentation on TOGA moorings in deep water, and the general Core Project 1 global observational network.

Estimates of heat transport in the tropics will be greatly improved by use of three-dimensional, primitive equation eddy-resolving ocean general circulation models which make full use of large-scale surface wind data and avoid the restriction that the motion be quasi-geostrophic.

3.1.6 Oceanic Heat and Salt Flux

Heat and freshwater transports by the ocean are a critical component of the climate system. Determining their values as a function of location and season is essential not only as a zero order description of what the existing state of the world climate is, but also as a crucial test of any model with pretence to climatic reality.

An integrated programme to determine heat and freshwater transports in the ocean interior for climate studies and direct oceanographic use thus specifically requires: (1) a well-measured, subtropical section in each ocean basin to directly estimate meridional transports, including a one-time hydrographic section and moored arrays to monitor boundary current transports, (2) one-time sections across the Antarctic Circumpolar Current south of Africa, Australia, and South America to estimate inter-basin transports, (3) monitoring of the flow through the Indonesian Archipelago, (4) a sparse network of deep (1000m) XBT/XCTD lines on ships-of-opportunity to determine transport variability in all oceans, particularly near the subtropical latitude designated in (1), and (5) the best estimates possible of wind stress and surface layer temperature and salinity to determine the Ekman-layer contribution to transports. In addition, the remaining network of hydrographic lines coupled with direct velocity measurements, satellite altimetry, and surface flux measurements will permit direct estimates of oceanic heat and freshwater transports in other locations, albeit with somewhat greater uncertainties.

3.1.7 Eddy Statistics

Long-term current-meter moorings from both the North Atlantic and North Pacific have shown that eddy kinetic energy levels vary with distance from western boundary currents, with depth, and in some areas with season. In addition, the distribution of eddy kinetic energy is somewhat different in the North Pacific than in the North Atlantic and the vertical structure of eddy kinetic energy as well as its dominant frequencies differ in space and, sometimes, in time.

The spatial description of surface eddy kinetic energy will be obtained from altimetry, surface drifters, acoustic Doppler current profilers and from the upper ocean and surface temperature and salinity fields. A cruder estimate will be obtained on the deep surface at which the large-scale, deep, float release occurs.

Additional information in the vertical will be inferred from hydrographic sections. Already much is known about the vertical structure of the eddy field in some parts of the North Atlantic and North Pacific from long moored current-meter records. A few more such moorings, well-instrumented in the vertical, will be used during WOCE to provide estimates of the vertical structure in regions where such measurements are not yet available.

3.2 Methods

To reach the objectives of Core Project 1, a number of observational programmes will be executed. Details of the plans are discussed in Sections (3.3) and (3.4). The basic tools are described in this Section. Observational techniques which are not discussed here include inverted echo sounders, bottom pressure measurements, moored acoustic Doppler current profiling, and electromagnetic measurements. These may be useful adjuncts to boundary current observations and elsewhere and may be included as more detailed plans are formulated. Additional technologies which may be developed and be appropriate for WOCE Core Project 1 are encouraged.

Each method discussed here is presented in terms of the objectives of WOCE Core Project 1 and guide-lines are provided for its use.

3.2.1   Hydrography

3.2.1 .1 Objectives

Hydrography is one of the primary observational tools in Core Project 1. Traditional measurements of the density field are central to obtaining the geostrophic flow throughout the water column. WOCE will provide, in addition to estimates of the geostrophic flow, direct Lagrangian velocity measurements at one subsurface depth as well as at the sea surface, sea surface topography through altimetry, and direct measurements of abyssal flows in passages and along boundaries. The combination of all these measurements will produce estimates of the absolute velocity field. As direct velocity estimates from any method are neither error-free nor universally available, global oxygen, nutrient and geochemical tracer data will be collected to constrain models of the circulation.

Although hydrography is a traditional method and fairly high quality measurements are available in many ocean regions, there are compelling reasons for a new global survey to be completed during WOCE.

First, there is the necessity of determining the absolute circulation throughout the oceans and at all depths, requiring not only the new tools capable of measuring absolute velocity, but also the simultaneous measurement of geostrophic flow which extends the absolute velocity field to all depths.

The global hydrographic survey will include routine measurements of temperature, salinity, oxygen and nutrients using well-calibrated CTDs and bottle sampling with good vertical resolution at relatively closely spaced stations. This survey is subsequently referred to as the "one-time" survey; the sections are to be used specifically in studies of heat and freshwater transport, abyssal circulation, and cross-equatorial flow in addition to providing information on global circulation throughout the water column. Core Project 1 hydrography also includes repeat occupations of several of the sections in the one-time survey, as discussed in Section (3.2.3); specifications for these observations are not as stringent as for those of the one-time survey. The repeated observations are important for quantifying temporal changes and for determining the extent of aljasing in more sparsely repeated surveys. Further hydrographic measurements will be made in conjunction with the global exploration of the western and eastern boundary currents and abyssal currents; these are discussed in the context of moored current-meter arrays with supporting hydrography. More extensive regional surveys around the mooring lines may also help to meet important WOCE scientific goals.

Sampling in the one-time survey is to be of the highest possible quality, normally including continuous vertical profiling with a CTD and water sampling at 36 levels at each station for salinity, oxygen, and nutrients (silicate, phosphate, nitrate and nitrite). Specifications for the hydrographic programme are discussed in Vol.1 Section (2.1.2). Both the vertical and horizontal sampling planned is more intensive than in most previous large-scale surveys, none of which was global in scope. The survey will be an improvement on previous surveys in the following ways:

(1)   It will provide a global data base with full coverage of oxygen, nutrients and geochemical tracers, as well as of temperature and salinity. The precision, accuracy and internal consistency of the new data set will be higher than in the historical data base.

(2)   With water sampling normally at 36 levels per station, vertical coverage will be significantly improved.

(3)   CTD profiles of temperature, salinity and oxygen are inherently of much higher vertical resolution than most historical data.

(4)   As station spacing along the sections will be nominally 30 nm, spatial aliasing of the eddy fields will be significantly reduced and property mapping improved, permitting quantitative use in models.

(5)   The new data set will include many more land-to-land long sections than are now available. The few that are now available have had a disproportionate influence on the interpretation of the general circulation. The large number of meridional sections will be of particular use in understanding the relationship of the subpolar, subtropical and tropical circulations.

(6) Simultaneous velocity measurements using floats, acoustic Doppler current profiling, surface drifters and altimetry will provide much better estimates of the total flow field.

3.2.1.2 Experimental Design

Hydrographic measurements in the one-time survey will be administered by the WHP whose specifications are included in Vol.I Section (2.1.2). Sections in the global grid are ideally no more than 1500 km apart, although this requirement is relaxed in some areas of the Pacific with known comparatively homogeneous properties. Station spacing along the sections is nominally 30 nm with closer spacing near boundaries and across intense currents. These choices are dictated by the need to map large-scale distributions of flow and water properties with minimal eddy aliasing along the sections. One of the many uses of the sections will be to estimate heat, freshwater and mass transport; one latitude in each sub-tropical gyre and the "choke points" south of the continents in the Southern Ocean have been designated for more intensive transport measurements, including boundary current measurements and repeated hydrography. The latter includes XBT/XCTD lines on commercial ships across the subtropical gyres and possible repeats of the hydrographic sections. To produce the most consistent estimate of global heat transport by the oceans, all five zonal subtropical "heat" transport sections will be made during a short period in WOCE, well into the period of direct float, surface drifter, and altimetry measurements.

Beyond the specifications of a consistent sampling of heat transport sections, the global ocean is most reasonably sampled basin by basin to obtain the most nearly-synoptic view of water properties. This requirement is most crucial for transient tracers, as discussed in Section (3.2.2). Because of the contribution of deep water formation to the properties at depth in the various oceans, such quasi-synoptic occupation is most important in the North and South Atlantic, slightly less so in the Indian and South Pacific, and least important in the North Pacific.

The basic design of the one-time survey in each ocean includes at least one meridional and one zonal section through each gyre and each major topographic basin to capture the absolute minimum data necessary to define the circulation: sections to provide mapping capability are then added to produce the plans shown in Section (3.4). Each hydrographic section presented in Section (3.4) is justified individually on the basis of its designation as a heat transport section, as the primary section through a given gyre and its boundary currents, as important for exposing a major feature of the circulation at the surface, mid-depth or in the abyss, or as a mapping section to create a minimally acceptable section grid. The full programme is designed to stand alone without major need for historical data to fill gaps, although the relatively coarse spacing of sections in some regions will require some use of historical data there. The sections listed in Section (3.4) are not meant to be inflexibly placed; but any change to the plans presented must address the underlying reasons for the existence of the sections. Detailed modification of the sections, to account for topographic features and strong currents, will be fine-tuned at the time of proposal and implementation in consultation with the WHP advisory committees.

The sampling scheme along each section consists of small and large volume stations, depending on the relative amount of tracer work, to be described in Section (3.2.2). "Small" volume stations include the standard hydrographic measurements (CTD, temperature, salinity, oxygen and nutrients augmented by tracers, including chlorofluorocarbons CFCs, tritium ^{3}H, helium ^{3}He and other small-volume geochemical tracers) with total water volume per sample of 10l. "Large" volume stations include tracers which can only be measured with large samples, on the order of 100l and more. All normal sections will include small volume stations at the 30 nm station spacing that is needed to resolve the density field. Specifications for large volume sampling are listed in the next sub-section and details are described in the specific regional plans.

3.2.2 Geochemical Tracers

3.2.2.1 Objectives

The measurement of tracers in Core Project 1 relates both to the determination of the large-scale integrated mean circulation on the one hand and to the determination of local and essentially instantaneous flow fields and mixing on the other. The large-scale integrated mean circulation of the oceans includes the effects of mixing and relates the major regions of the ocean to each other, such as the surface ocean to the

abyss, or the deep Atlantic to the deep Pacific, Tracers provide constraints to this aspect of the circulation that are complementary to those of hydrographic observations. Given the large amount of variability in the oceanic flow field, velocity estimates obtained by dynamic calculations from a single realization of the density field need not produce velocities that are entirely consistent with the long time-scale averages defining the mean circulation. The use of tracers provides information on the long-term averaged circulation.

Chemical tracers also make important contributions in defining the extent, rate and variability of water mass sources and modification processes. Emphasis should be placed on time-series observations at selected stations and along selected sections, especially with regard to the decadally varying transient tracers such as the tritium/helium-3 pair, the chlorofluoromethanes (CFMs) or chlorofluorocarbons (CFCs) and bomb-radiocarbon. Those begun by GEOSECS, TTO, INDIGO, SAVE and other major programmes will be extended by WOCE.

3.2.2.2 Experimental Design Criteria

Many tracers have been used for studies of ocean circulation, mixing, and water mass modification. Recommendations for the WOCE Hydrographic Programme are based on the following criteria:

(1) Demonstration of a significant and reliably measurable variation in oceanic concentration which is correlated with large-scale circulation and mixing processes and which varies independently from the other tracers measured in the programme.

(2) The conservative nature of the tracers with respect to biogeochemical processes, or the existence of techniques for correcting for non-conservative behaviour.

(3) Target sampling and analytical precision that can resolve appropriate circulation and mixing processes, and demonstration that such precision can routinely be achieved.

(4) Mechanisms for continuing control of data quality, including the participation of more than one laboratory in the analysis of each tracer.

The tracers for which measurements during WOCE are recommended can be divided into three groups: (1) Chlorofluorocarbons, tritium/radiogenic Helium-3, and radiocarbon which meet all the above criteria and which should be sampled on all WOCE cruises with resolution appropriate to the tracers, (2) Radium-228, Argon-39, Krypton-85, and primordial Helium-3 which meet the criteria in only some regions, or which for other reasons (for example, difficult measurement procedures) will be sampled on a more limited basis, (3) Strontium-90/Caesium-137 (Greenland and Norwegian Seas, North Atlantic), stable isotopes of water (Oxygen-18 and Deuterium D), and noble gases which in addition to helium which are primarily appropriate in polar regions.

Table 3.1 lists the tracers recommended for the WOCE Programme along with recommendations for their use in Core Projects 1 and 2 with a summary of a few relevant properties. Also listed are estimates of the time scales of applicability of each tracer and a characterization of our knowledge of its source function. The transient tracers to be measured all have source functions that behave differently from each other, either with respect to description or rate of change or exchange with the atmosphere or the bottom of the ocean, an important consideration in tracer modelling.

Chlorofluorocarbons (CFCs) are chemically stable, non-bioactive gases that enter the oceans by surface gas exchange. The ratio of F-11 and F-12 in the atmosphere was changing continuously until about 1975 and can be used as an age diagnostic. F-11 and F-12 should be measured on all upper ocean and deep ocean small volume samples where their presence is demonstrated. WHP station spacing is adequate for mapping most regions. Measurable CFCs are expected to be present in half to two-thirds of all water samples collected, and measurable meso-scale variability is to be expected.

Tritium, ^3H, a radioactive isotope of hydrogen with a 12.45 year half-life, is produced in the atmosphere by cosmic ray spallation and was also produced by nuclear weapons testing in the 1950s and early 1960s. The global inventory of cosmogenic tritium, 3.6 kg, has been completely dwarfed by the 500 kg produced by nuclear weapons testing. Tritium is scavenged from the troposphere by vapour exchange and

Table 3.1 Tracers of Oceanographic Interest

Tracer	Chemical Form	Biological or Chemical Activity	Time Scale of Applicability*	Source Function Description[§]	How Well Known?[†]	WOCE Application?[‡]
SMALL VOLUME TRACERS						
(1) Chlorofluoro-carbons (CFC's)	gas	none(?)	up to ~30 y	~exponential increase	2	yes
(2) Tritium	water (HTO)	none	up to ~30 y	variable	4	yes
(3) Helium-3						
(a) Radiogenic	gas	none	~1 mo - 30 y	tritium decay	1	yes
(b) Primordial	gas	none	--	-- (ridge crests)	5	limited
(4) Bomb Radiocarbon[**]	CO_2	active	up to ~30 y	~exponential decrease	2	yes
(5) Stable Isotopes	water ($HH^{18}O$, HDO)	negligible	--	--	3	polar
(6) Noble Gases	gas	none	--	--	4	polar
LARGE VOLUME TRACERS						
(1) Natural Radiocarbon[**]	CO_2	active	~20-50000 y	--	2	yes
(2) Radium-226	ionic	active	~50-5000 y	-- (sediments)	5	no
(3) Argon-39	gas	none	~20-1000 y	--	2	limited
(4) Silicon-32	SiO_2	active	~30-500 y	--	4	no
(5) Radium-228	ionic	negligible	~5 mo - 30 y	-- (sediments)	5	limited
(6) Krypton-85	gas	none	up to ~30 y	~exponential increase	2	limited
(7) Strontium-90/ Cesium-137	ionic	negligible(?)	up to ~30 y	variable (point source)	4	N. Atlantic
(8) Beryllium-7	ionic	negligible	~1 d - 6 mo	--	4	no
(9) Radon-222	gas	none	~4 h - 10 d	--	2	no

*   The information in the "Time Scale of Applicability" column summarizes time scales to which the tracer is most applicable. A dash is used for those tracers which have no intrinsic time scale (i.e., non-decaying tracers with steady inputs).

§   A dash indicates that the input is steady state. The input is from the atmosphere unless otherwise indicated.

†   Our knowledge of the input is characterized as (1) excellent, (2) very good, (3) good, (4) fair, and (5) poor.

‡   The column of recommendations briefly summarizes recommendations made in the implementation plan. Limited indicates that limited work is recommended, and polar and N. Atlantic tracers are of particular interest in those regions.

**   The radiocarbon has been separated into a small volume bomb component and a large volume natural component fol-lowing our recommendation that the AMS technique should be used primarily for samples where bomb radiocarbon is present.

precipitation on time scales of the order of 1 month. The most powerful use of tritium is in concert with measurements of its daughter, ^{3}He.

Since ^{3}He is released to the atmosphere at the air-sea interface the fraction in the ocean arising from the radioactive decay of tritium can be established in most regions, making possible an age estimate for a water parcel with a precision of about 1 month since it left the surface. This estimate is sensitive to mixing. Primordial 3He can also be used to study the circulation in the deep oceans, especially in the Pacific. However, its source function (hydrothermal activity) is spatially variable and difficult to characterize in detail so that quantitative constraints are only obtainable on large scales. ^{3}H and ^{3}He should be measured on the same water sample in all regions where the bomb transient is present. Though a priori a dense mapping comparable to CFCs is desirable, a coarser sampling strategy is recommended, largely focussed on shallower waters, and to the ^{3}He plume in the deep Pacific. Given the present measurement capacity, only one of 3 to 4 of the samples recommended for CFC measurement can be measured for ^{3}H/^{3}He.

Radiocarbon, ^{14}C, with a 5730 year half-life is, like ^{3}H, produced by cosmic ray spallation in the atmosphere and was also a by-product of nuclear bomb tests. Its atmospheric concentration in the form of $^{14}CO_2$, doubled at the time of the bomb tests in the early 1960s. It can be measured with precisions of up to 0.2% on water samples of the order of 200 l and about 0.5% on samples of 0.2-0.5 litres. Small volume samples should be collected in the upper ocean at about half the spatial resolution of ^{3}H/^{3}He where a strong bomb signal is present. Meso-scale variability will be less measurable than for CFCs, because of the long equilibration time with the atmosphere. Oversampling is recommended to allow flexibility in the analytical work and to allow for more detailed coverage in the event that future increases in the precision of the technique exceed our present estimates. In the deep ocean, the collection of large volume radiocarbon samples is recommended, especially in the deep Pacific where the higher precision is needed to resolve the major features of the circulation and where a more significant fraction of the signal relates to radioactive decay. The WHP sampling at 300 nm station spacing for large volume samples is necessary to resolve the deep ^{14}C distribution adequately to separate mixing processes from radioactive decay. High precision measurements of total dissolved inorganic carbon in the same samples are needed to correct for biogenic carbon and carbonate.

Argon, ^{39}Ar, with a half-life of 269 years, is an ideal geochemical tracer as it is in steady state, its atmospheric concentration is well-known, its entry to the oceans is rapid and is non-bioactive and chemically inert. A limited number of these measurements should be made (about 250 samples), which is about the available capacity for making this measurement. This would help in interpretation of radiocarbon measurements, particularly in correcting for biological cycling.

Radium, ^{228}Ra, the 5.75 year half-life daughter of ^{232}Th, has a sediment source which is difficult to determine. However, its relatively steady distribution and radioactivity allows it to be used for quantitative flow and mixing estimates. The upper ocean source of this tracer is in shelf areas outside the boundary currents and it can only enter the thermocline waters by crossing these currents Measurements should be made on large volume samples collected for radiocarbon ^{14}C in the deep ocean and additional measurements made in the upper ocean in special circumstances. The WHP 300 nm for large volume sampling is adequate.

Krypton, ^{85}Kr, with a half-life of 10.76 years, is an inert gas produced when uranium and plutonium undergo fission by bomb testing and nuclear reactors. Its concentration in the atmosphere is well-documented and its entry to the oceans by gas exchange is rapid. Measurements of this tracer require about 200 l. Its greatest value is that its ratio to that of F-11 and F-12 has continued to change during the last decade adding to the ability to determine water mass age. Limited sampling of this tracer in the upper ocean (possibly in the same sample as ^{228}Ra) and areas of deep water formation is recommended.

Strontium, ^{90}Sr, and *Cesium,* ^{137}Cs were produced by nuclear bomb tests and entered the oceans very much like tritium. Many more measurements were made of these tracers than of tritium during the 1960s but few since the early 1970s. Since tritium can be measured with much greater precision using much smaller samples, these two isotopes should be measured only in the North Atlantic where the large releases from Windscale in the British Isles provides information on the flow of water into the Greenland and Norwegian Seas and the deep western boundary current.

Stable isotopes of water (the $^{18}O/^{16}O$ and deuterium/hydrogen ratios) are affected by evaporation/precipitation and by freezing/melting of sea ice roughly linearly with salinity but with different slopes for the two processes. The combination of stable isotope ratios with salinity measurements makes it possible to differentiate water masses that have had their salt changed by evaporation/precipitation from those that have been changed by freezing/melting. Stable isotope ratios are extremely low in glacial ice in Antarctica and Greenland and are sensitive diagnostics of the presence of glacial melt waters. These tracers should mainly be part of polar activities.

Noble gases are supersaturated in the ocean with respect to the atmosphere in polar regions due to processes involving the release of air bubbles trapped in glacial ice shelves which melt at depth. This can be used to trace the presence of water masses containing this melt water. These tracers should be part of polar activities, especially in Core Project 2, because of the deep ice shelves found primarily in the Antarctic.

3.2.3 Repeat Hydrography

Repeat hydrography includes all measurements of temperature and salinity for provision of temporal information, including single repeats of sections in the one-time survey, regularly-repeated sections (monthly, seasonally, annually, etc.), time series stations, XBT/XCTD surveys from commercial ships, and underway measurements of surface temperature and salinity. All but the latter are discussed in this Section; surface salinity and temperature are considered as part of the meteorological measurements from research and commercial ships.

3.2.3.1 Objectives

Repeated hydrographic stations and/or sections will contribute to all of the scientific objectives of Core Project 1.

In regions where temporal variability is relatively small, repeated sections or stations test the representativeness of the one-time Core Project 1 hydrographic survey as an estimator of the mean circulation field. Where the one-time survey will be used to estimate the mean, there must be sufficient repeated data in the domain to place an error bound on the mean estimates. In regions where time variations are relatively large, and a single realization does not yield an acceptable estimate of the mean, the mean field must be determined through averaging of repeated measurements.

Measurements of the temporal evolution of the large-scale ocean circulation and of the associated fluxes of mass, heat, and salt are to be achieved by repeat hydrographic observations in combination with drifters, moored instruments, and satellite altimetry.

Annual and interannual fluctuations in the storage of heat and salt in the upper ocean are to be measured by repeated sections or individual stations. These will be used with the measurements of heat and fresh water transport and the air-sea flux computations to complete the large-scale heat and salt balances.

Three modes of repeated measurements have been distinguished: time series stations made by research vessels, repeated sections made by research vessels, and repeated sections made by commercial volunteer ships. In some cases a particular objective will be accomplished by combining more than one mode of measurement. There are some uncertainties in existing technical developments, such as the XCTD, making it unclear whether salinity profiles are exclusively in the domain of research vessels or whether they can also be collected from commercial ships. Relative characteristics of research vessel and commercial volunteer ship operations are:

- Research vessels are not limited by shipping routes or schedules, can sample to the ocean bottom, provide highly accurate observations, and sample salinity, oxygen, and other tracers.

- Commercial volunteer ships are limited to sampling temperature to 850 m depth, give repeated regular access to remote regions and, with, additional development work, could include XCTDs, XBTs to 1000 m, and acoustic Doppler measurements.

In accordance with the relative advantages of the two types of platforms and their logistical and cost limitations, the proposed scientific objectives for the three types of operations are:

(a)   Time series stations using research vessels

-       to identify secular changes in deep water masses, deep T/S characteristics, and steric height of the sea surface.

-       to provide information on the temporal evolution of temperature and salinity profiles at individual locations as a complement to less frequently repeated hydrographic sections made by research vessels or volunteer ships. That is, the time series measurements supply information in the time domain which is missing from sections, while the sections provide information on spatial gradients which is missing from the time series.

-       to provide comparison data to check the accuracy of XBT/XCTD, sea surface T/S, and possibly other observations made from commercial ships or satellites.

(b)   Repeated sections using commercial ships

-       to observe the variations of large-scale geostrophic velocity in the upper kilometre and of the zonal and meridional fluxes of heat and salt on time scales of seasons to years. This objective includes the observations of changes in the subtropical and subpolar gyre interior circulations, the boundary currents, the location of the gyre centres, and the tropical current systems.

-       to estimate the statistics of the thermal field in the upper kilometre. To carry out unbiased sampling of the large-scale field and to assess the possible contribution of eddy processes in the general circulation, it is necessary to know the variance of the eddy field and the spatial and temporal covariances.

-       to measure changes in the heat and salt content of the upper ocean on basin scales.

(c)   Repeated sections using research vessels

-       to observe temporal variability in special regions where commercial ship sampling is insufficient or unavailable. In contrast to the commercial ship programme, the emphasis is on repeated observation of features which are much smaller than the ocean in scale but are important in the general circulation. Examples are western boundary currents, flow over deep sills between major ocean basins, and the bifurcation regions at eastern boundaries which separate the subtropical and subpolar gyres.

-       to measure variations in the zonally integrated meridional flux of heat and fresh water at a few key locations.

-       to detect changes in the deep T/S relation or other property/property relationships.

3.2.3.2 Experimental Design Criteria

(a)   Time series stations using research vessels

Time series stations require frequent use of a research vessel making selection of such stations strongly dependent on the availability of a suitable vessel. Locations are limited to sites near mid-ocean islands and coastal sites near research institutions. A few stations per major ocean basin is appropriate. The emphasis of the programme is to obtain high quality, deep data on a regular basis from a few locations rather than a data-set of uneven quality, depth coverage, and sampling rate from a larger number of stations. The institutions must be committed to maintaining the stations for at least a decade.

Because the sites for time series stations are close to islands or coastlines, and there are likely to be large spatial gradients in these locations, the time series stations should be supplemented with additional sampling of spatial gradients. An example is the repeated section in combination with the Ocean Weather Station P time series.

(b)   Repeated sections using commercial ships

There will be two modes of sampling from commercial ships. The first is an extension of the present TOGA and TRANSPAC XBT networks. The low-density sampling of these networks will be extended to the middle and high latitude oceans. XCTDs will be included where T/S variability is large and the sampling depth should extend as nearly as possible to the base of the thermocline. Industrial production of XCTDs still has to be extended to account for accuracy and precision needed for large numbers of probes. This expansion will primarily be aimed at the measurement of heat and salt storage in conjunction with the TOGA heat storage measurement programme in the tropics.

In the second mode, sampling will be by high-density (eddy-resolving) XBT/XCTD measurements along a subset of ship tracks. The high-density sections will be used to determine spatial statistics of the temperature, salinity, and geostrophic velocity fields and to measure temporal changes in large-scale geostrophic velocity without aliasing effects from meso-scale features. The tracks include zonal ones from coastline to coastline near the centre of the subtropical gyres and near the centre of the subpolar gyres, two or three meridional tracks crossing the equator and terminating at high latitudes, and a few additional tracks in the western oceans across the western boundary currents. The value of the high-density sections would be considerably enhanced by the addition of acoustic Doppler current profilers on the participating ships.

The two sampling modes complement one another in several respects. The high-density mode samples coherently from coastline to coastline, but it does not sample large areas between the tracks and the repetition rate might be no greater than seasonal. The low-density mode provides the missing areal coverage and a greater repetition rate while lacking the spatial resolution for unaliased sampling and the ability to sample small-scale features such as boundary currents. Design of the combined network is aimed at reinforcing these complementary aspects.

(c)   Repeated sections using research vessels

Because of the cost-effectiveness of commercial ship operations for temperature and salinity profiling in the upper kilometre, the bulk of the repeated observations on ocean scales will be carried out from commercial ships. Research vessel usage is reserved for observations that require one or more of the following:

-       measurements that must extend into the deep ocean, for example to measure the variability of a deep western boundary current.

-       measurements in areas not regularly visited in all seasons by commercial ships, such as the Southern Ocean.

-       measurements or measurement accuracy not attainable from commercial vessels.

3.2.4   Sub-Surface Floats and Surface Drifters

3.2.4.1 Objectives

WOCE requires combined data sets that substantially improve the quantitative description of the general circulation of the ocean. Although much can be learned from indirect measures of velocity (altimetry and hydrography using geostrophy or tracer measurements inferring advection), direct velocity measurements are needed. The combination of altimetry and direct observation of near-surface flow is needed to determine the near-surface geostrophic and wind-driven flow components. Direct velocity observations at depth (where absolute measurement accuracy is greatest) are needed to tie down the geostrophic shear profiles obtained from hydrography.

By their nature current-following drifters and deep floats provide observations which are (a) typical of a region and are less subject to site bias than moored observations, and (b) are economically advantageous when horizontal spatial coverage is required. On the other hand, floats and drifter arrays are quickly randomized by currents so that it is difficult (a) to separate spatial and temporal variability or to separate horizontal and vertical structure, or (b) to obtain intensive observations at a specified site.

When used in conjunction with the WOCE Hydrographic Programme, a global velocity mapping programme benefits from the advantages of current-followers (particularly logistically) and is little affected by the disadvantages as emphasis is placed on observing large space and time scales. Additional moored velocity measurements are required in regions where higher spatial resolution is needed, particularly in western boundary currents.

3.2.4.2 Experimental Design

(a)   Surface drifters

The near-surface region is the most difficult part of the ocean in which to make accurate velocity measurements. Although it is perhaps the oldest ocean velocity instrument, the surface drifter is the most difficult to make perform well and to calibrate. Recently the quantitative understanding of drifter current-following performance has increased substantially.   The primary error source is wind forcing, either directly or through surface waves. However, it is now feasible to (a) reduce the error to the order of 2 cm/s in 10 m/s winds and (b) to correct for these errors with 30% residual error.   Requirements for accurate current following dictate special purpose drifters not carrying thermistor chains or meteorological sensors other than barometers.

To obtain the measurements needed for Core Project 1, it is important to establish (a) the minimum acceptable current-following accuracy and longevity for drifters, (b) a mechanism to provide rigourous testing of all designs before they are accepted for WOCE use, and (c) a mechanism for ensuring that all surface drifter designs meet these criteria. Ensuring that these needs are met is part of the existing programme development.

Almost all surface drifters employ the satellite-based Service Argos for positioning and data relay.   In this system all buoys use the same radio transmitting frequency and when too many are transmitting in a particular geographic region interference can degrade positioning and data relay. The failure mode is gradual and depends on the amount of data sent by each buoy as well as their number.   Experience suggests about 200 buoys within a 5000 km diameter region can coexist. Thus, the level of drifter activity anticipated during WOCE should not overload the Argos system unless there is an unforeseen demand for data transmission capability by other users.

The cost of surface drifters is closely linked to (a) the cost of Argos transmitters and (b) the charges for Argos tracking and data relay services. A drifter cost of the order of US$2500 is expected in large volume production. By sacrificing temporal resolution and having buoys transmit only every second or third day, the Argos charges, and the load on that system, can be much reduced.   For most designs the lifetime over which drifters have good current-following performance is not known, but could probably reach two to three years with engineering diligence.

(b)   Subsurface floats

Subsurface floats differ primarily in how they are positioned. Acoustic tracking permits the continuous tracking needed to infer velocity over intervals of a day. However, acoustically-tracked floats require moored stations to provide positioning and thus are most appropriate in high spatial densities.   Pop-up floats which rise to the surface for tracking (for example, ALACE) are suitable for observing velocity averaged over several weeks and have logistical advantages. For Core Project 1 purposes, the requisite low-density arrays are best provided by pop-up floats.

The most mature float design uses SOFAR tracking; the float transmits acoustic signals which are received at moored listening stations and recorded. Work is underway to have these stations relay the data through satellite lines, thereby extending the listening station servicing interval and reducing cost. Low frequency acoustics is employed so that ranges of the order of 2500 km can be achieved. The buoys are large so that logical costs are relatively high. SOFAR floats have a demonstrated lifetime of at least five years.

The next most proven approach is the RAFOS float (RAFOS is SOFAR reversed). Moored sound sources are used with floats which receive the acoustic transmission and record the timing information, which after a prescribed period, is relayed via Argos when these buoys pop to the surface. The buoys are small and

easily managed in large numbers. They have a proven lifetime of about one year but five years is feasible. Work is underway to have them rise periodically to the surface for data relay and then return to depth for further acoustic tracking. Operational costs for RAFOS floats may be 50% lower than for SOFAR floats.

The Autonomous Lagrangian Circulation Explorer (ALACE) is a small subsurface current-following float which rises to the surface on approximately monthly intervals to be located by the satellite system Argos. They are less expensive to build than SOFAR floats and are used in low density arrays when deployment is done from ships-of-opportunity. Information on short (< month) time scales and short space scales is lost. Prototype floats have been tested for a few months and the first operational deployment is scheduled for early 1989.

The present design is capable of 50 cycles from a depth of 2000 m over a five-year lifetime but longevity is unproven. Because Argos positioning determines the surface drift, the error from this is small (0.3 mm/s) for submergence-cycle periods of the order of one month. Operational costs should be less than half that of SOFAR floats used in reasonably dense arrays.

3.2.5   Moored Current-meters

3.2.5.1 Objectives

Proposed moored current measurements are directly related to the goals and objectives of the Scientific Plan for WOCE. They will be used both for direct estimates of current structure and transport, using coherent arrays in relatively confined areas, and for exploration of the vertical structure of the eddy field, using single moorings or incoherent, large-scale arrays.

(a)   Boundary/choke point arrays

Direct current and transport measurements at crucial choke points of the ocean circulation and in conjunction with hydrographic sections for heat flux measurements require the deployment of moored current-meters. Most are designated for boundary regions or in confined passages of abyssal circulation. Although it is possible to obtain such currents and transports through other techniques (for example, hydrography combined with floats or ADCP measurements; PEGASUS current profiling) the required resolution of the variability cannot be practically achieved by alternate methods.

The moored array programme for boundary current/choke point measurements has three phases: an exploratory phase for unexplored currents to determine the scales and magnitudes of the current field which are needed to design an array; an intensive phase (18 months - 2 years) using an array spanning the current regime with a resolution sufficient to estimate the transports; a monitoring phase when a reduced set of instrumentation and techniques based on the information gained in the intensive phase will be used to extend the measurements through WOCE. The monitoring phase is of particular relevance for Goal 2 and may be extended to decadal time scales when considered necessary during the course of WOCE.

(b)   Eddy statistics arrays

For exploration of the vertical structure of the eddy field in mid-ocean, it is necessary to deploy a small number of moorings, because the combination of single-level float deployment, surface drifters, and altimetry will not permit full determination of the vertical structure of variability. Such measurements are lacking in most of the world's oceans with the exception of the northern part of the subtropical gyres of the North Pacific and North Atlantic. Arrays in the North Equatorial Current of these two oceans will provide the information necessary to complete the description of the mean and fluctuating flow in a subtropical gyre. Other oceans require exploratory single moorings or small arrays to determine whether the structure is sufficiently different from that of the explored oceans to warrant additional, more intensive work. Any moorings set to explore eddy variability require a minimum of five current-meters with reasonable vertical distribution so that each part of the water column (surface layer, intermediate depth and abyss) is sampled.

3.2.5.2 Experimental Design

(a)   Boundary current/choke point arrays

Design of a generic moored array experiment in a boundary current or across a passage during each of the three phases has the following elements:

During the exploratory phase, ship CTD/XBT/ADCP sections, deep floats, PEGASUS etc. will be used to roughly define the vertical structure, current magnitude, horizontal extent of the current and its meandering and, in some cases, the existence of the current itself. Many of the boundary currents which are to be measured during WOCE do not need an exploratory field effort since historical data and satellite SST can yield the necessary additional information.

During the intensive phase there will be coverage of the boundary current by a moored current-meter array with adequate resolution to provide time series of total transport as well as transport in isopycnal/temperature layers. Minimum duration is 18 months.

Moored ADCPs, possibly combined with conventional current-meters on the same mooring, will be used in strongly sheared currents such as deep overflows, equatorial currents and intense, near-surface currents. Several hydrographic sections taken during mooring deployment and/or direct current profiling (ADCP, PEGASUS) will provide data for dynamic height calculations enabling better estimates of the current field array from the moored instruments. The estimates of the boundary current transport and structure can be improved by the use of sea-level stations, bottom pressure gauges, inverted echo sounders, existing (or specially deployed) submarine cables, altimetry, and where possible, SST measurements.

During the monitoring phase some measurements will be continued using as a design basis the information gained during the intensive phase. For example, a combination of sea-level measurements and inverted echo sounders may be useful transport indicators. If the vertical structure of the current is complicated, some moored current profile measurements may have to be continued. Geostrophic current profiles could possibly be based on moored temperatures alone if a reliable T/S relation is available. Hydrographic sections will be used with the fixed-point measurements to check on the continuity of the relationship between the transport as calculated from the full instrument array and the reduced set in the monitoring phase.   It will be necessary to make a timely evaluation of the measurements to determine how to monitor the current. One could use two repeat array deployments in the intensive phase (say one year each) and evaluate the first year's data during the second year to continue into the monitoring phase without a gap of insufficient coverage.

(b)   Eddy statistics moorings or arrays

Sampling in different oceans will be either for a thorough description of eddy variability (for instance in the North Equatorial Current of the North Pacific and North Atlantic), or exploratory in nature. The duration of the experiment and number of moorings used will depend on the particular location and purpose of the measurement. However, the time series should be of sufficient duration so that comparisons can be made with results from simultaneous Lagrangian experiments (deep float and surface drifter release). As mentioned above, a minimum of five measurements in the vertical is necessary, because the purpose of the moored measurements is to provide the vertical resolution that the Lagrangian experiments will miss. Measurement at the depth of the deep float release is a natural and obvious requirement. Most experiments will use current-meters. However any type of moored instrumentation which provides information on vertical structure throughout the entire water column may be substituted.

3.2.6   Acoustic Doppler Current Profiling

3.2.6.1 Objectives

Acoustic Doppler current profiling will be used to obtain extensive mapping of upper ocean current shear and velocity, providing a reference level for geostrophic calculations and a framework for the interpretation of the surface drifter measurements. The ADCP directly measures the vertical shear of horizontal cur-

rents with very high spatial resolution.   Spatially averaged sections of horizontal currents, combined with precise navigation to produce absolute velocities, will provide an independent reference level for the calculation of geostrophic velocities.   In regions where the mixed layer is deeper than the shallowest ADCP measurement (between 10 and 20 m), the large-scale Ekman transport estimated from wind stress can be compared with the measured mixed layer transport, using a mixed layer model to extrapolate to the surface.   Of greatest value will be repeated ADCP sections for the examination of the temporal variability of upper ocean currents. The repeated sections will permit a computation of mean currents and will provide a measure of the variability around a single, spatially averaged section.

3.2.6.2 Measurement Technique

The shipboard ADCP obtains the relative velocity between the ship and water by measuring the frequency shift of a short pulse of high frequency sound transmitted from the ship and reflected by drifting plankton, assumed to be passive tracers of the water motion.   Range-gating the return yields the along-beam velocity as a function of depth and a 3-dimensional velocity vector can be determined.   Its accuracy depends strongly on the accuracy of the heading information provided by the ship's computer. To compute absolute earth-referenced velocities, precise navigation is required to remove the motion of the ship. Available navigation systems are the TRANSIT and GPS satellite systems and LORAN C. When the ocean floor is within sonar range, the bottom echo provides a measure of the ship speed over the ground.

3.2.6.3 Accuracy

Averaging is necessary to reduce the noise inherent in the instrument and to remove wave-induced ship motion. The tidal signal has also to be considered in designing a sampling scheme. Its impact on the accuracy has to be estimated by region. Relative velocity (shear) can be measured to within 1 cm/s over 10 m vertical scales for 10 min averaging. Errors in absolute velocities can, to some extent, be corrected by varying the ship's heading and consistently-good measurements obtained to 200 m.

Residual errors over one-hour averages are of order 5 cm/s for TRANSIT navigation and 0.5 cm/s for GPS navigation. With the advent of continuous GPS coverage, absolute currents will be calculable with a high degree of accuracy.   Repeated sections are needed to compute the mean, the uncertainty in the mean and the amount of spatial averaging required.

3.2.6.4 Experimental Design Criteria

ADCP sections are envisioned to be taken both by research and volunteer commercial ships. The ADCP is relatively inexpensive and many research ships have used ADCPs to advantage during the past 5 years.   It would now be practical to have the ADCP as standard equipment on all oceanographic research vessels and ADCP measurements on all WOCE hydrographic sections would greatly enhance the value of both data sets. An advantage of the research ship measurements is the quality of the data. By far, the largest errors in estimating absolute currents arise not from instrument error but from errors in removing the ship motion, that is, uncertainties in transducer alignment, gyro and position, and only research ships are likely to be able to manoeuvre so as to meet these standards.

The advantage of using volunteer commercial ships is their ability to make repeated sections. Because commercial ships steam at greater speeds than research vessels, the spatial sampling will be coarser but it will also be more uniform and synoptic since no station measurements are made. However, the data quality of ADCP measurements made from volunteer commercial ships needs to be assessed. For example, it is not known if commercial ships are willing to make routine calibrations or if high quality navigation would be available. Because a network of XBT commercial volunteer ships will be part of WOCE, the outfitting of a few of these ships as prototypes for an ADCP programme will be explored, including priorities of a seagoing ADCP operator and a GPS receiver. The emphasis must be on obtaining useful, high quality data rather than a large quantity of data of uneven quality.

3.2.7 Surface Meteorology

The ocean circulation is driven by the fluxes at the air/sea interface, including wind stress, the fluxes of sensible and latent heat, the fresh water flux (the difference between precipitation and evaporation) and the absorbed and emitted short and long wave radiation. All ocean circulation models require the surface stress as the primary input field. Thermodynamically active models of the type required to model climate require all of the fluxes listed as externally posed boundary condition data. Satellite scatterometers, combined with in situ data, will provide measurements of surface stress on a global basis. The determination of the thermodynamic fluxes is one of the most difficult problems facing WOCE. The strategy to be used is a combination of conventional measurements at or near the ocean surface, meteorological and ocean satellites, and improvement of conventional meteorological surface analyses. The two types of measurement are mutually interdependent. Satellites require in situ data for calibration, while the in situ data alone cannot provide the global coverage available through satellites. The conventional analyses will be improved through the use of the measurements themselves, the data assimilation in numerical models and through modelling changes. WOCE is relying on the WCRP for assistance in this latter effort. Surface data will be gathered from the existing World Weather Watch system, enhanced by additional surface observations obtained through special efforts.

The basic meteorological quantities that need to be measured include SST, air temperature, wind speed and direction, barometric pressure, humidity (which may be obtained from the wet bulb depression), long wave radiation, and precipitation. Stress, sensible heat flux, latent heat flux and evaporation are determined from these basic data using bulk formulae. Accuracies of 10 Wm-2 are sought in estimates of the mean values (averaged over monthly and longer time scales) of each of the four components of heat flux; accuracies of approximately 1 mmd-1 are sought in evaporation and precipitation; and an accuracy of 10% or 0.01 Pa is sought in stress.

The majority of conventional surface meteorological data are provided by observations from the Voluntary Observing Ships (VOS). 'These data contain random errors due to inadequate sampling, poor instrument calibrations, ship air flow disturbance, etc. Effects such as heat contamination from the ship and salt contamination of wet bulbs result in systematic biases. Random errors can be reduced by averaging VOS data in those regions where dense shipping lanes give a relatively large number of VOS reports, in other regions long time and/or large spatial averages are necessary. There is a need to increase the number of VOS reports from all areas. Methods of assessing the systematic biases are by comparison of the VOS data with meteorological buoys, research ships, or with a higher quality subset of the VOS. The latter approach requires the choice of a set of particular vessels and carefully calibrating the exposure of their suite of meteorological instruments.

The quality of VOS observations of cloud cover may not determine the incoming solar radiation to the desired accuracy. Comparisons of incoming solar radiation as a function of elevation and cloud cover using weather ship data show very large scatter of the results.

In view of these uncertainties, some level of ship-based measurements of incoming short wave radiation will be needed during WOCE. It is not clear that such a programme could be conducted from surface drifters. Net short wave radiation is estimated by measuring downwelling short wave radiation with a pyranometer and multiplying by $(1 - \alpha)$, where α is the albedo. Instruments must be carefully calibrated and gimbal mounted to compensate for ship or buoy motion. Even so, residual motion, and the difficulty of obtaining a clear sky view from a ship, will cause errors additional to those due to the radiometer.

Downward long wave radiation is measured by a similar sensor fitted with an opaque dome. Errors due to radiative heating from parts of the ship in the field of view can be large and are additional to errors due to motion and sensor deficiencies. Upwelling long-wave radiation must be inferred as the graybody emission of the sea surface plus the reflection of downwelling long wave radiation by the sea surface (while taking empirical into account) model further dependence on air temperature and humidity. Errors in measuring SST will enter in the graybody formula and are thus potentially large, but there are also uncertainties in the sea surface emissivity, sea surface reflectance, and the empirical model dependence on air temperature and humidity.

Errors in the buoyancy flux will be associated with both total heat flux and precipitation estimates. For the water flux, evaporation is inferred from a bulk formula involving a product of wind speed and humidity.

Precipitation is not yet measured reliably since estimates of precipitation are very difficult to make at sea. Meteorological buoys or drifters will have to be used in remote areas to supplement ship reports and in all areas in a sparse array to provide validation data for the satellite-derived wind estimates. It is possible that hydrophones suspended from these drifters will be able to provide rainfall estimates from an analysis of the acoustic noise. Results form the WCRP 'Global Precipitation Climatology Project' will be important in this context.

The opportunity exists within WOCE for substantial drifting buoy deployments. There are plans to maintain an array of the order of 1000 for the 5-year period 1991-1995. The majority of these buoys will be designed primarily to follow surface currents. However, FGGE type measurements of sea level pressure (SLP) and of sea surface temperature (SST) should be incorporated, giving these buoys a particular importance in numerical weather prediction and surface flux computations.

The value of southern hemisphere SLP measurements from drifting buoys was demonstrated during FGGE. The addition of a SLP capability to a drifting buoy is not difficult technically, but approximately doubles the cost, and requires support from the meteorological community. Operational weather prediction agencies producing global or southern hemisphere analyses should be the most interested. The data will be made available in real time through the Service Argos link to the GTS on a daily or twice daily basis. A data centre will also be needed to continually provide quality control, validation and archiving. The high quality archived data would be available for any future re-analysis activities.

The sea surface temperature measurements will be made primarily for the purpose of estimating horizontal heat advection in the upper ocean. However, they will also provide an in situ SST network for incorporation into satellite SST products, either for blended analyses, validation, or bias removal. With such a global in situ network an SST accuracy of 0.5º C may be achievable.

Satellites determine the sea surface temperature (from radiometers), the surface stress (from scatterometers on ERS-1) and sea state (from altimeters on ERS-1 and TOPEX/POSEIDON, as well as by synthetic aperture radars on ERS-1 and RADARSAT). Of these fields, SST and the surface stress are the most important, but knowledge of the sea state is also useful for determining wave-induced contributions to the surface stress (which can reach values of 50% in high winds) and to other flux fields, and also for correcting for sea state bias in satellite scatterometer and altimeter measurements. Satellites also provide estimates of the surface radiation budget and of precipitation areas and intensity, and atmospheric water content (from radiometers).

The in situ data collection has to be matched to the satellite programmes. One of the principal challenges is to produce reliable reconstructions of all surface flux fields, globally and throughout WOCE, by properly combining all relevant data from different sources in a comprehensive data and model combination. (see Section 3.3.1).

3.2.8   Air-sea Interaction Buoys and Temperature/Salinity Chains

The main use of drifting or moored air-sea interaction buoys in Core Project 1 is for the verification of the surface fluxes of heat and momentum which have been determined from remote sensing or from atmospheric general circulation models and to obtain data from information sparse regions. Observations of the evolution of the upper ocean temperature and salinity field on a monthly or more frequent basis over the global ocean are also (a) to provide data to test and verify coupled atmospheric/oceanic models and (b) to provide a constraint on regional estimates of the evaporation-precipitation difference. While much of the world ocean can be covered by ships-of-opportunity or even research vessels carrying out hydrographic surveying for other reasons, there will remain the remote, seldom-visited regions where often the most profound effects due to extreme weather conditions are most likely to occur. Drifting or moored air-sea interaction measurements and near-surface T/S chains will be valuable in filling these gaps. Both moored and drifting air-sea interaction buoys will be deployed. As drifting or moored temperature/salinity chains (many without salinity measurements) may often be employed in conjunction with air-sea interaction buoys, they are considered together in this Sub-section.

3.2.8.1 Drifting Flux Buoys

Bulk air-sea interaction parameters include sea surface temperature (SST), sea level pressure, air temperature and air humidity. Wind speed and wind direction are normally measured at about 3 m above the water-line, the thermistor chain to measure the temperature profile extend6 to about 150 m below the surface. The thermistor chain data are used to measure the storage of heat in the seasonal thermocline and to ascertain whether the seasonal changes of heat storage in the upper ocean correspond to heat flux changes derived from the meteorological parameters measured by the buoy and other large-scale means.

An effective strategy for verification is to deploy drifting buoys where ship traffic is sparse and where there is a significant seasonal signal or irregular events occur in arrays should be on the scale at which flux analysis is produced by atmospheric numerical models (about 5º x 5º scale at 30ºN). A possible approach is to use an initial grid of 12-16 drifting buoys, encompassing 15º of latitude and 30º of longitude. The expected lifetime of sensors is about one year requiring a total of 72-96 units during the WOCE Intensive Observation Period. At least one deployment in each of the Atlantic, Pacific and Indian Oceans is recommended. Possible regions for deployment include the Trade Winds regions, the Arabian Sea and Western Equatorial Pacific which exhibit very different rations of sensible to latent heat and time variabilities.

The surface fluxes available for WOCE can also be improved, as noted in Section 3.2.7, by providing sea-level pressure and temperature sensors on some of the drifters used for surface velocity measurements. The data would be used by operational numerical weather prediction models that provide surface flux estimates.

Drifting air-sea interaction buoy arrays are effectively deployed from research or military ships-of-opportunity and require about 30 minutes of ship time per deployment. Prototype buoys are currently in use in TOGA (thermistor chains) and 'Ocean Storms' (thermistor chains, wind sensors, SST, air temperature). A humidity sensor has to be adopted for drifting buoy use. The principal advantage of drifting buoys over moored buoys is that the formerare less expensive and are easier to deploy from ships-of-opportunity. The disadvantage is that a predetermined array cannot be maintained.

The precise mechanical configuration of the drifting air-sea interaction buoy to be used in WOCE does not yet exist. Engineering and testing are still needed in the following areas:

- Propeller wind sensors currently used are subject to rapid deterioration. Wind speed can be measured accurately (within 0.5 m/s) with subsurface high-frequency acoustics and wind direction by conditionally sampled buoy direction. This scheme needs to be implemented and tested.

- The humidity sensor needs to be added to the drifting buoy platform and data stream.

- The current buoy hull and sensors and superstructure are based on pre-FGGE engineering. New lightweight hulls with lightweight sensor towers that extend to 3 m above the surface can and should be made.

3.2.8.2 Moored Flux Buoys

Moorings with surface buoys carrying meteorological packages are required for deployment in areas: (1) where the most accurate measurement of the basic observables and most accurate determination of the long-term air-sea fluxes is desired, (2) which have sparse coverage by ships and drifters, (3) in locations where it is desirable to obtain both in situ forcing and upper ocean response, and (4) where a relatively accurate value at a fixed location is needed to anchor or ground-truth data from drifters. Data at the original sampling rate will be stored in the buoy; averaged data will be telemetered via Argos.

With sea surface temperature, the primary difficulty lies in making a good measurement of the near surface temperature of the ocean. With diurnal heating, SST may be up to 3º C warmer than the temperature at depth of 1 m; and, during a shower, relatively fresh water can be found at the surface that is cooler than the water below. Sensors placed on a buoy hull may be affected by the thermal mass of the hull and be heated by the penetrating radiation. Aspirated air temperature sensor shields can be used to attempt to bring the error in air temperature down to approximately 0.2º C; a surface-piercing thermistor string with sensors

shielded from radiative heating can be used together with intelligent sampling to keep error in SST of similar magnitude.

In addition to moored buoys deployed specifically for WOCE use, the atmospheric community currently maintains a number of moored buoys which monitor meteorological parameters. These operational measurements will be used in WOCE, although the data must be reported at a frequency high enough to be of use with satellite measurements. Attachment of temperature/salinity chains to these moorings in selected regions may also be useful.

3.2.8.3 Temperature/Salinity Chains in the Upper Ocean

Temperature chains have been developed that have survived months at sea suspended from a surface drifter, but problems remain in the development of conductivity or salinity sensors that retain their accuracy over long periods in the upper layers of the ocean. Monitoring the upper ocean salinity field is the best possibility of constraining estimates of evaporation/precipitation over the ocean. Development of such salinity chains as well as the development of the XCTD remains a high priority for WOCE technological development.

T/S chains will be used in Core Project 1 not only to monitor the upper layers in remote locations but also to monitor deep mixed layer development in regions such as the Labrador Sea where water mass transformation through deep convection occurs. These instruments will also be used on mooring arrays in some western and eastern boundary currents so that estimates of salt flux can be obtained in addition to the more common mass and heat fluxes.

3.2.9 Altimetry

A central part of the strategy for the global description of the ocean is satellite altimetry. The surface dynamic topography and its time variability are critical elements in deducing the general circulation of the ocean and its physics; the ability to make these measurements from spacecraft has been one of the major drivers leading to the formulation of WOCE.

The altimetric spacecraft available during the early to mid-1990s, that is during the WOCE Intensive Observation Period, should be at least one order of magnitude more precise and accurate than previous systems. Use of the data from these systems in conjunction with the other Core Project 1 observations, including global estimates of the wind field from scatterometry, to make truly quantitative estimates of the ocean circulation is one of the central themes of WOCE.

The following specific missions will be adequate to meet the needs of WOCE:

(1)   Two altimetric missions, to be flown beginning about 1991 for a five-year period. One such mission (TOPEX/POSEIDON) will be a dedicated altimetric mission, offering the highest achievable accuracies and precisions (precisions approaching 1 cm.) over all wavelengths of interest, in an orbit specifically chosen to produce an optimum result. A second mission (ERS-1), with minimum temporal overlap with TOPEX/POSEIDON of one year, will extend orbital coverage to the highest achievable latitudes (circa 73°) to give coverage of the near-polar regions. The overlap in time will permit adequate calibration of the lower accuracy mission by the higher one, and the special orbit of TOPEX/POSEIDON will permit global tide measurements adequate to correct ERS-1 for tidal contributions to sea-surface elevation.

(2)   A gravity mission capable of determining the earth's geoid at an absolute accuracy of 2 cm or better down to scales of the order of 100 km. The purpose of this mission is to produce a geoid consistent with the dominant energetic scales of the ocean circulation and the anticipated accuracies of the altimeter missions. No such mission is currently scheduled, but adequate designs exist (in the NASA GRM, and CNES GRADIO), and there is no need for temporal simultaneity with any other WOCE-related observations. Approximately six months of observations in orbit are required and the mission should be flown within the 1990s soon enough to permit its use with the major WOCE data sets.

3.2.9.1 Calibration

Calibration of altimetric systems is a complex subject, because measurements are made on spatial scales ranging from the order of 10 km to global (order 40 000 km) with utility on time scales from hours and days to many years, and the error sources and calibration procedures differ for the different scales.

As with more conventional observations, there are two distinct types of calibration which will be employed. The first is not really calibration at all but is the conventional oceanographic custom of systematically comparing the observations with a variety of independent measurements or inferred quantities so as to develop confidence in the collective system. The Core Project 1 activities will include comparisons of eddy kinetic energy as a function of space scale, time scale, and various geographical locations with the suite of in situ measurements from surface and subsurface drifters, current-meters, and time series hydrography.

For gravity field calibration, a major activity will consist of direct comparisons of absolute in situ measurements by floats and current-meters with geostrophic estimates computed by contemporaneous altimetric minus geoid estimates. The numbers permit direct calculation of the geoid slope, independent of any a priori geoid estimate and lead to a default strategy in the absence of a geoid spacecraft mission. If such a mission is flown, the comparison of the calculations becomes a consistency check on both.

More direct absolute calibration will lie in the hands of project teams for the missions. This approach involves instrumenting specific open ocean locations with laser tracking systems, tide-gauges, and sampling systems for atmospheric water vapour and electronic measurements, etc. and arranging the orbit for near-overhead passes. The direct Core Project 1 approach to calibration of the global scale variability (not the meso-scale) is through use of the open ocean tide-gauge network. Within the error estimates of a local tide-gauge, any variability inferred from an altimetric mission must be consistent with that inferred from the altimeter. Thus a fundamental calibration effort is focussed on the global tide-gauge network (see Section 2.3, Vol.1 for more detail).

With the arrival of global absolute positioning systems (for example, GPS plus VLBI), absolute calibration of the altimeter systems by positioning of the global tide-gauge network is possible. The SSG is discussing with geodetic experts and mission Science Teams the extent to which such efforts will be rewarded.

3.2.10 Sea Level

Global sea-level variations as inferred from conventional in situ tide-gauges have proved to be very useful indicators of large-scale general circulation changes. These indicators have been particularly useful in the tropical Pacific, where the natural distribution of islands, the large signals connected with tropical variability, and the comparatively benign operating climate have led to an unusually good distribution of observations.

Maintenance and expansion of the existing network is important to Core Project 1 for a number of related reasons. As already described, tide-gauges will be one of the major calibration methods for the important altimetric missions. In the tropics in general and in other locations where the spatial scale of both available islands and the variability gives rise to coherent fluctuations in neighbouring gauges, these data permit direct estimates of variability strength, time and space scale, as is already possible in the near-equatorial Pacific Ocean. Finally, with a view toward WOCE Goal 2, the existing tide-gauge records provide the longest extant oceanographic time series. For the generation of a true ocean climatology such records must be maintained indefinitely, and new ones started.

The strategy for tide-gauges in WOCE is to maintain the existing network as it stands for TOGA and to extend it as far as possible through the offices of GLOSS, in accordance with the following needs:

-       To gain altimetric calibration sites in oceans with sparse island distributions (specifically the North and South Atlantic), where otherwise altimetric arcs are far from any direct calibration sites.

-       To instrument the high-latitude Southern Ocean, both for altimetric calibration and as an independent determinant of variability in this poorly observed region.

- To instrument narrow straits and channels (Drake Passage, Indonesian passages, etc.) where there is evidence of coherent, energetic mass flux monitorable by surface elevation.

This strategy must be tempered by a large measure of logistic and economic practicality. Figure 3.1 displays: (i) existing gauges, (ii) first priority WOCE gauges. Because the use of these gauges as described is to a large extent statistical, no single gauge is of critical importance. What is to be emphasized is the need for instruments as homogeneously distributed globally as possible for calibration, and for instruments in as many regions with strong variability as is practical.

3.2.10.1   Data Flow

Because of the multiplicity of uses for sea-level data, several different routes for data handling are both necessary and possible. To obtain the best possible final data products, all instruments should record values at minimum intervals of one hour (and preferably more often), and every effort should be made to have the data in digital form, discretised with a least-count not exceeding 1 cm. The reasons for the small sampling interval are so that each instrument will provide a state-of-the-art set of tide calibration values for the altimeters, and so that the tides and other high frequency signals can be removed with adequate digital filters to prevent any significant aliasing into lower frequencies.

The details of the reporting of tide gauge data and its management for WOCE purposes are described in Volume I.

3.3   Specific Plans for Global Data Sets

3.3.1   Air-Sea Fluxes

WOCE requires an extended data base encompassing both conventional meteorological and oceanic surface measurements and satellite observations. Enhanced in-situ data collection will be provided by surface drifters, ships of opportunity, IGOSS, research vessels and island stations. A number of planned ocean satellites or sensors (ERS-1, TOPEX-POSEIDON, NSCAT), together with existing operational meteorological satellites, will provide global coverage of data required for air-sea flux computations: in particular, sea surface temperature, cloud cover, radiative fluxes, surface winds and sea state.

In order to compute the complete set of surface fluxes required for quantitative ocean circulation studies, very large quantities of data of rather different origin and quality must be simultaneously analyzed. This can be achieved only through the development and implementation of a sophisticated data assimilation and analysis system.

The joint JSC/CCCO Group on Air/Sea Fluxes has initiated the development and implementation of a "Global Data Assimilation Programme for Air-Sea Fluxes" for both the WOCE and TOGA scientific communities. The principal tasks are: (i) the development of improved satellite sensor algorithms which make optimal use of the availability of first guess fields from models; (ii) the improvement of boundary layer flux parametrisations (in collaboration with other groups such as the Working Group of Numerical Experimentation of the WCRP); (iii) the incorporation of sea state effects in both the sensor algorithms and flux computations, (iv) the design of extended data quality procedures suitable for the new oceanographic satellite data, and (v) the implementation and testing of the complete end-to-end system.

There is a need to install a data assimilation system for air-sea fluxes at least at one operational global weather centre. The centre should have at its disposal a high quality global atmospheric model, a sophisticated meteorological data assimilation system and standard data quality control procedures. The principal extensions required to upgrade an existing meteorological data assimilation system to provide air-sea fluxes are the incorporation of the satellite sensor algorithms within the system and the quasi-real time transmission of the required satellite data to the assimilation centre. In addition, the simultaneous operation of a global wave model would enable the application of improved sensor algorithms and boundary layer flux computations including sea state corrections. ECMWF is producing analyses and archives for the WCRP. Its
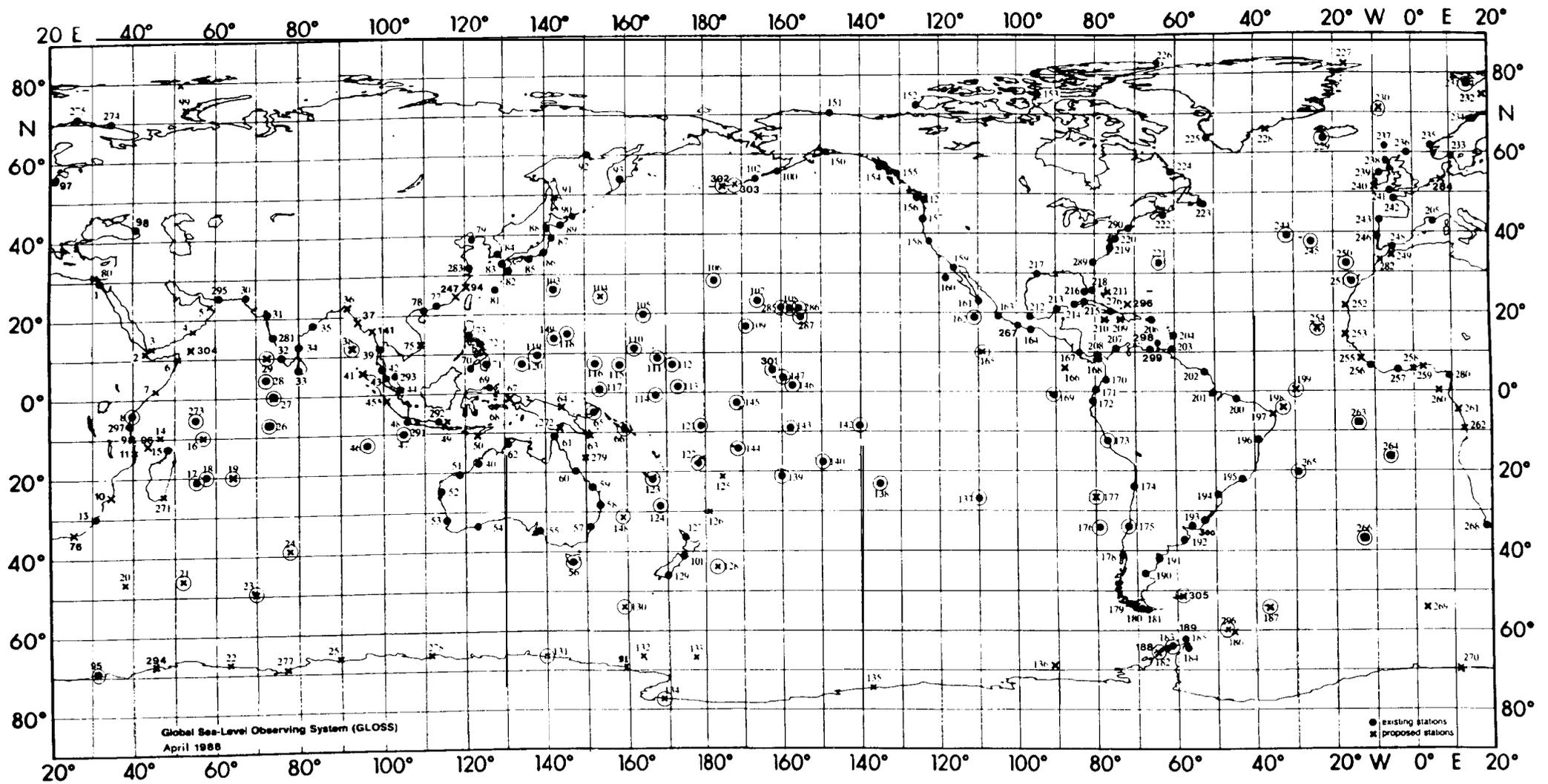
Fig (3.1)   The basic GLOSS global network of in situ sea level gauges. Gauges marked with a circle
are to be used for the 2-months 'A' data set.

data, the 'WCRP Level III-A Atmospheric Data Set', are to be made available to the WOCE community for research purposes.

In addition to the data assimilation system, there is also the need for upgrading and optimisation of the in situ data base required as input for the system. This includes data collected from VOS ships-of-opportunity, IGOSS, research vessels, and surface drifters. Research ships engaged in WOCE will be outfitted with sensors and related hardware for automatic onboard logging and Argos telemetry of the meteorological data. These will be the same sensors and basic data-logging packages as those being developed for use on moored buoys (see Section 3.2.8). Data sampled at the original rate will be stored onboard for later recovery; averaged data will be telemetered. Ship's power will allow greater use of more power-demanding and potentially more accurate sensors than on the buoys; however, flow disturbance and heat contamination by the ship will complicate measurements of wind speed, air temperature, humidity, and SST. Multiple sensors installed at several locations on the ship could alleviate this problem. Gimbals and/or motion compensation should be attempted for long and short wave radiation measurements.

3.3.2   Global Velocity Field

Core Project 1 will directly map the large-scale general circulation on a global basis, a task most efficiently accomplished with current-following drifters and floats.   The global velocity programme involving drifters and floats is, in scale and objective, a close relative of the WHP and the satellite-based programmes to map surface winds and sea-surface height. Altimetric coverage will provide global observations of the long-wavelength components of the absolute sea surface topography and of its variability . The altimetric component of the velocity programme is described in Section (3.2.9).

The global velocity mapping programme has the following objectives:

(a)   Measurement of the velocity at one level using floats in conjunction with hydrography in establishing the full-column absolute geostrophic velocity field and its associated transports of heat and other tracers. The resolution of this map should be comparable to that of the total world hydrographic data base (averaging 500 to 1000 km over the globe).   The accuracy must be sufficient to provide a meaningful constraint on models (dynamical and those inferring transport from the distribution of properties)(AFG, PFG, IFG, SFG).

(b)   Characterisation of the large-scale transport in the upper layer so that the magnitude and effect of both geostrophic and ageostrophic wind-driven flow is determined. Hydrography, satellite altimetry and the float-derived reference velocity field will map the absolute mean near-surface geostrophic flow with low resolution and its variability with higher resolution.   Satellite scatterometry will map oceanic surface winds responsible for the Ekman component of the ageostrophic flow.   Drifter observations will map the total flow, including the ageostrophic component, and will describe low-frequency large-scale variability. The basic spatial resolution should also be of the order 500 km (ADG, PDG, IDG, SDG).

(c)   Characterisation of eddy activity and the effect of eddies on transport by mapping eddy energy, single particle diffusivity and Lagrangian time scales with global coverage at the surface and on the subsurface reference level.

(d)   Provision of observational resolution above the basic global standard in regions where it is needed. For example, vertical resolution should be increased near the equator so that cross equatorial flow at several levels can be determined where geostrophy can not be used for vertical extrapolation of velocity. Similarly, in recirculation regions outside western boundary currents both horizontal and vertical resolution should be increased. Such circulation features can not be described with 500 km horizontal resolution and intense eddy variability prevents hydrography from establishing the mean shear in such regions with sufficient accuracy.

The global velocity programme will involve different instrument types and sampling densities in different regions. It is planned as a global programme providing a minimum level of observation everywhere. Enhanced sampling in particular regions will be as given in the Regional Plans (Section 3.4) and for Core Projects 2 and 3 (Chapters 4 and 5).

Drifter Drogue depths

Surface drifters can be made to follow currents at a given depth or the average over some depth range. Engineering studies are required to determine if there is an accuracy trade-off in this choice. Study must also be made to establish the sampling depth(s) required to meet WOCE scientific objectives. This key decision should be made in conjunction with setting minimum acceptable performance standards for WOCE drifters and establishing procedures to test different types (see Vol.1, Section 2.4).

Subsurface float depths and types

The level for the global float release is to be that which is the best velocity reference for use with hydrography. The level need not be the same for each basin, but as a general rule floats should be placed on some mid-depth level (say between 1500 and 2500 m) where (a) eddy noise is less than near the surface so as to minimize the record length required to reach an accurate mean velocity, (b) topographic influence is less than at greater depth, and (c) acoustic tracking ranges are relatively long.

It is logistically inefficient to mix float types and tracking. Acoustic tracking is dictated in the North and South Atlantic by the Core Project 1 programme, including determining the cross-equatorial flow, as well as the concentrated Core Project 3 programmes there.   Interest in the Kuroshio and its recirculation and in the formation of intermediate water in the northeast Pacific also indicate acoustic tracking in the North Pacific. Size and logistic difficulties make much of the Southern Ocean, southern Indian Ocean and South Pacific inappropriate for moored tracking stations and thus dictate use of autonomous floats. The southern ice-covered side of the Southern Ocean is accessible only with SOFAR floats. The efficient use of the various float types in various regions will provide a substantial scheduling problem.

Sampling density

In both the surface and subsurface programmes there will be a regional variation in the sampling density in response to (a) the accuracy and resolution required to answer specific questions, (b) the varying difficulty of sampling (for example, eddy noise), and (c) logistical problems. Until the desired resolution in each region is better known it is not possible to state the numbers of floats or drifters required for all the components of WOCE. The following is, however, a rough estimate of what will be required to achieve an average resolution comparable with the hydrographic data set and a mean velocity of sufficient accuracy for the global velocity programme.

As a guide, there are about 3000 high-quality deep hydrographic stations in the Pacific which has an area near 165×10^6 km2.   If these were uniformly distributed the station spacing would be near 250 km. Some smoothing is required to describe the general circulation. Thus, a target resolution for global mapping of velocity for use in conjunction with hydrography would be about 500 km.   Roughly 1100 such resolution cells are needed to map the world ocean.

The accuracy of an average velocity estimate is roughly the standard deviation of eddy fluctuations and divided by the number of independent observations averaged, which for record length L and integral time scale is approximately the square root of LT^{-1}. Observations at the surface and at mid-depth indicate an integral time scale between 15 and 25 days (the T here is twice that often reported as the integral scale). Thus, a five year record will provide the equivalent of more than 100 independent observations and reduce uncertainty of the associated mean velocity to less than 10% of the eddy variability. In most regions, this provides a substantial improvement over what can be deduced indirectly from hydrography. For example, 3 cm/s eddy motion at mid-depth would lead to 3 mm/s uncertainty while 30 cm/s variability in a near-surface boundary current extension would give 3 cm/s uncertainty.   Neither of these accuracies can be approached on the 500 km scale with inverse calculations. On the larger scale, inverse analyses of cross-basin sections give basin-wide average velocity estimates with mm/s uncertainties, greater than could be achieved by averaging the 500 km velocity field to a comparably low resolution.

As a rough guide about 5 years of observations in each of 1100 resolution cells will be required to adequately map velocity at either the surface or at one subsurface level.

3.4 Specific Plans for Regional Data Sets

3.4.1 The Atlantic Ocean

3.4.1.1 Introduction

The Atlantic Ocean is the most saline of all the world oceans. It has significant exchanges of water masses, heat and salt with several marginal seas, regions in which important transformations of water take place, and a complex thermohaline-driven circulation with water masses moving both northward and southward along most of its western boundary regions. The Atlantic Ocean as a whole and the North Atlantic in particular has been well surveyed over the twentieth century with large-scale surveys such as the METEOR sections, IGY, GEOSECS, TTO, LONG LINES and, finally, SAVE, providing several snapshots of its hydrographic structures over the last 60 years. Consequently, in planning the WOCE Core Project 1 programme for the Atlantic, determination of the temporal variability over periods of months to decades has been given as much priority as the determination of the mean over the WOCE Intensive Observation Period.

The Atlantic is the source of several important water masses: North Atlantic Deep Water, Labrador Sea Water, Mediterranean Water, Antarctic Intermediate Water and, if the Atlantic sector of the Southern Ocean is included, Antarctic Bottom Water. The circulation of these water masses from their source regions throughout the length of the Atlantic basins is a particular focus of this plan. The equatorial exchange of these water masses will be studied both in the context of the Core Project 1 measurements described below and in a Core Project 3 study of abyssal circulation to be carried out spanning the equator in the Brazil Basin. The Atlantic is the one ocean where there quite clearly must be a significant cross-equatorial heat and salt flux and WOCE Core Project 1 will endeavour to estimate these.

The second important question to be considered by WOCE in the Atlantic is why the Atlantic is so much saltier than the rest of the world ocean. The Atlantic receives low salinity water from the Arctic and high salinity water from the Mediterranean Sea and the Indian Ocean. Monitoring of the upper ocean salinity field is considered to be of very great importance for the Atlantic, if it is to be determined whether high salinity inflows are sufficient to create the salinity excess or whether there is a greater excess of evaporation over precipitation over the Atlantic than over the rest of the global ocean.

3.4.1.2 Hydrographic Measurements (one-time survey)

As with other ocean plans, the hydrographic/tracer sections for the Atlantic Ocean have been chosen so that at least one zonal and one meridional section passes through each ocean gyre and each major oceanic gyre. Sections are not necessarily straight but are offset and curved to pass through significant channels between basins or to remain within a given basin. Many sections are repeats of earlier hydrographic sections in order to provide an estimate of long term changes in the ocean's hydrographic structures. The sections are shown in Figure 3.2.

All sections will be occupied at least once during WOCE following the complete and stringent specifications of the WOCE Hydrographic Programme in terms of the quality of the water sampling and the data collection. Each CTD station will be occupied to the ocean bottom and water samples will be collected at depth intervals of no greater than 200 m and analyzed for salinity, oxygen, nitrate and nitrite, phosphate and silicate.

<u>Zonal Sections</u>

A1   57º N: This section from Ireland to Labrador cuts across the northern parts of the subpolar gyre giving a measure of the waters entering and exiting the Nordic Seas and Arctic Ocean. The section runs from the north tip of Ireland northwest to Cape Farewell then from the southwest coast of Greenland near 60º N southwest to the Labrador coast near Hamilton Harbour (Seal Island). Particular care must be taken along the continental slopes of Greenland and Labrador and the slopes of the mid-Atlantic Ridge to map the deep boundary undercurrents found there. This section will be repeated (see Section AR7).
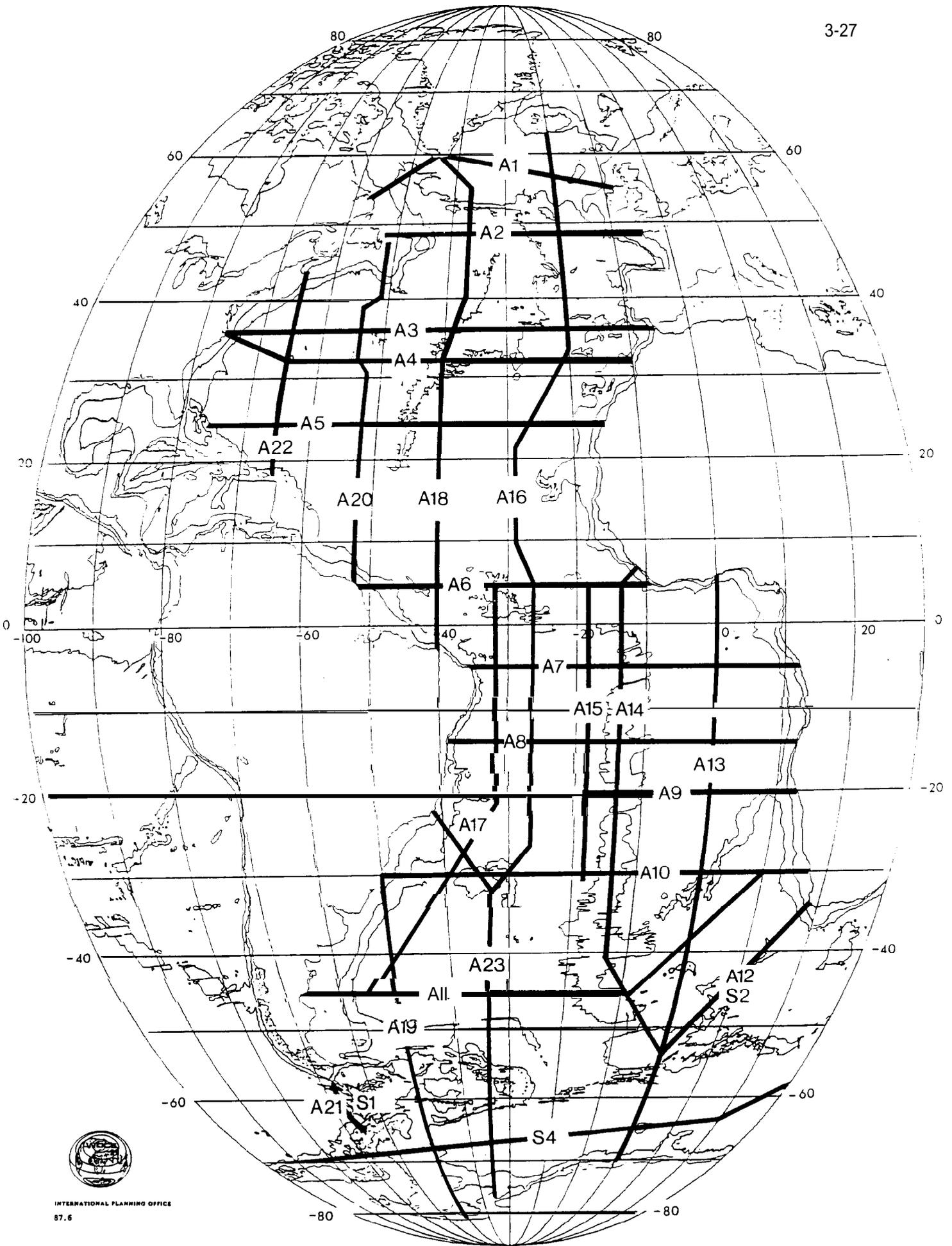
Fig. (3.2)   One-time WHP Survey of the Atlantic Ocean

A2   48º N: This section from the English Channel to Newfoundland is a repeat of a 1981 LONG LINES Section and a near repeat of a 1957 IGY section. It will measure waters going northward in the North Atlantic Current and their recirculation southward in the eastern basin as well as the surface, intermediate and deeper equatorward flows near the western boundary.

A3   36º N: This section is a repeat of IGY and LONG LINES sections. It crosses the northern part of the subtropical gyre. Comparison with earlier sections will show possible decadal change in the water mass structure of the North Atlantic.

A4   32º N: Morocco to Bermuda to Cape Hatteras. This section passes through the centre of the subtropical gyre and, while the part east of Bermuda is to be occupied only once, that between Bermuda and North America should be occupied in each season.

A5   24º N: This section repeats the IGY and LONG LINES sections for decadal variability and also in combination with current meter arrays at the eastern and western boundaries will provide estimates of oceanic meridional heat flux.

A6   5º N: This section from Africa to South America is to provide an estimate of meridional flows in various water masses into and out of the equatorial region. A further review following analysis of data presently being collected by programmes in the tropical Atlantic may result in this section being moved to 6º or 7º N to avoid the Gulf of Guinea and Amazon plumes. This section also plays a prominent role in the Deep Basin and Tropical Experiments of Core Project 3 and will be repeated for the latter (see Vol.II, Section 5.3.4).

A7   4º S: This section, similar to A6, south of the equator will provide estimates of flows into and out of the equatorial region. It plays a similar role as the 5ºN section in the Deep Basin and Tropical Experiments of Core Project 3.

A8   13º S: This section is of lower priority because of the occupation of a SAVE section running obliquely across the South Atlantic from 10º S in the east to 20ºS in the west in January, 1988, during which complete hydrography and extensive tracer work was accomplished.   It is part of the hydrographic programme of the Core Project 3 Deep Basin Experiment.

A9   20º S: This section cuts across the northern part of the subtropical gyre of the South Atlantic and will provide an estimate of mass, heat and salt transport into its western boundary current.

A10   30º S: This section crosses the centre of the subtropical gyre of the South Atlantic and is the principal meridional heat flux section for the South Atlantic. It also plays a major role in Core Projects 2 and 3.

A11   45º S: This section from South America due east to 45º S, 9º W and hence northeastward to 30º S, 10º E will, when coupled to the 30º S section joining to the African coastline, provide estimates of meridional flows in and out of the Atlantic basin. The section is kept to the west of the Agulhas Retroflection region to avoid contaminating the mean mass, heat and salt transports with two large and variable fluxes in opposite directions.

Meridional sections

A12/S2   19º E: This section (section S2 of Core Project 2) starts from the coast of Africa at 33ºS, 18º E and goes southwesterly to 53º S, 0º and thence south along 0º to Antarctica (65º S, 0º). It avoids cutting directly across the Agulhas Retroflection region but, by being just to the west of it should provide an estimate of the net exchange from the Indian to the South Atlantic Ocean.

A13   0º: This section runs along the prime meridian from Africa to Antarctica joining the 19º E section at 53º S. The common portion of the two sections south of 53º S need only be occupied once if the two sections are occupied closely in time. The section cuts down the centre of the eastern basin of the South Atlantic. The stations close to the Walvis Ridge will be carefully sited in order to look for exchange of water masses across the ridge.

A14 14º W: This section begins at the African coast near 8º N, 12º W, crosses the shelf and slope normally to 5º N, 14º W, then goes due south following the crest of the Mid-Atlantic ridge south of the equator. At 40º S, the section will angle to southeastward again along the ridge crest to join the two previous meridional sections at 53º S, 0º. The crossing of the African continental shelf and slope normally will allow a good estimation of any exchanges in and out of the Gulf of Guinea. These stations across the shelf and slope will be the common start of both this section and the 5º N zonal section. Stations will be densely spaced across each of the important rift zones of the mid-Atlantic ridge in order to detect exchanges of water masses across the ridge.

A15 19º W: This section runs along 19º W from 5º N to 30º S in order to map the eastern end of the Brazil Basin. As Sections A16 and A17, it also is part of the hydrographic programme for the Core Project 3 Brazil Basin Experiment.

A16 ca. 20º W: This section is a repeat of a LONG LINES section. It follows the centre of the eastern basin by running south from Iceland along 20º W to 35º N; thence SSW to 22º N, 29º W; south to 11º N, 29º W; SSE to 7º N, 25º W; south along 25º W crossing both the equator and the Mid-Atlantic ridge. It then follows the centre of the western basin by continuing south along 25º W to 24º S; SSW to 32º S, 32º W. This section will have dense station coverage where it crosses the equator and the Mid-Atlantic ridge as this is where major exchanges of deep water between the western and eastern basins are believed to take place. Similar special detailing of station spacing will be done where the section crosses between the Brazil and Argentine basin near 30º S.

A17 32º W: This section starts at 5º N, 32º W near the crest of the mid-Atlantic ridge and heads south along 32º W to 21º S then heading southwestward generally parallel with the South American coast to 45º S, 54º W. The section will be adjusted to pass through the centre of several deep channels or gaps between basins. It is designed to run somewhat off-shore of the western boundary currents of the subtropical and subpolar gyres in order to be able to close the mass budgets of the interior circulations of these gyres. In order to quantify the western boundary currents up to five short sections running perpendicularly from this section into the coast should be occupied.

A18 40º W: Starting at Cap Farewell (59º N, 43º W), the section goes southeasterly to 55º N, 35º W crossing the flows in the Irminger Basin, then south along 35º W to 40º N, crossing the Charlie Gibbs Fracture Zone and the major branches of the North Atlantic Current normally, then veering west of south to 28º N, 40º W crossing the mid-Atlantic ridge very obliquely with decreased station spacing across the Oceanographer and Hayes Fracture Zones, and finally south along 40º W to the Brazil coast looking for flow across the equator within western boundary currents.

A19 50º W: From the coast of South America at 30º S, this section goes south along 50º W through the Argentine Basin and across the Circumpolar Current into the western edge of the Weddell Sea. Closer station spacing will be necessary as this section crosses the region of complex topography and the Circumpolar Current south of 50º S.

A20 52º W: This section follows the LONG LINES section from the edge of the Grand Banks to the north coast of South America. It goes southward along 52º W from the Grand Banks, then jogs westward to 54º W from 40º N to 30º N to avoid the Corner Seamounts before returning to 52º W to continue southward to the South American coast. It crosses the subtropical gyre of the North Atlantic away from the tight recirculation region and also provides an estimate of the flow along the South American coast as it enters and exits the equatorial region.

A21/S1 64º W: This section crosses Drake Passage and is described under Core Project 2 as choke section S1.

A22 65º W: This section goes southward from the southwestern tip of Nova Scotia to Bermuda crossing the Gulf Stream and the western end of the tight recirculation region and then continuing southward along 65º W to Puerto Rico. The section will cross the shelf and slope off Nova Scotia normal to the slope to avoid difficulty with the strong tidal flows entering and exiting the Gulf of

Maine. Closer station spacing will be used as the section crosses the Gulf Stream, the position of the stream being determined at the time of occupation from thermal imagery.

A23   35º W: This section departs South America at Rio de Janeiro and runs southward near 32º S, 32º W, then to Antarctica, crossing the ACC after it resumes a zonal course east of the Falkland Plateau. Poleward of the ACC it crosses the western segment of Weddell Gyre, ending in the Filchner Depression of the Weddell Sea, a major site of shelf water outflow. Outflow of Antarctic Bottom Water would be observed in the eastward flowing limb of the Weddell Gyre over the flank of the South Scotia Ridge as well as along the pathway for bottom water flow into the Argentine Basin north of the Scotia Arc. The Pacific water flowing into the Scotia Sea would also be measured.

3.4.1.3 Small Volume Tracers

Geochemical tracers over and above the classical set of nutrients, oxygen and salinity will be sampled on stations along the sections listed in Section (3.4.1.2). These tracers include the chlorofluorocarbons (CFCs), helium (^{3}He), tritium (^{3}H), and AMS-^{14}C. The first of these tracers is particularly important because of the relatively young 'age' of most of the deep and intermediate waters of the Atlantic and the fact that they were not measured on earlier large-scale geochemical sampling programmes in the Atlantic such as GEOSECS and TTO. For the deep waters of the eastern Atlantic (north of the Walvis ridge and away from the boundaries) a less dense spatial sampling for CFCs, ^{3}He and ^{3}H may be acceptable. Highest priority regions are in the subpolar gyres and particularly the boundary regions between the subpolar and subtropical gyres, the western boundary regions at all latitudes and depths, the tropics, and the subduction regions of the sub-tropical gyres. In addition to sampling along these sections, existing time-series measurements of tracers at stations such as Panulirus Station off Bermuda will be continued.

Samples for oxygen ^{18}O should also be collected in the northwest Atlantic upper layers to attempt to trace the contribution of ice melt waters to the freshening of the surface layers.

It is also expected that sampling for total carbonate/alkalinity or some similar measurements of the carbon dioxide content of the water column will be specified by JGOFS and will be carried out on these hydrographic sections.

3.4.1.4 Large Volume Tracers

At this time, it seems likely due to previous geochemical tracer programmes in the Atlantic (GEOSECS, TTO and SAVE) that there will be a reduced requirement for large volume sampling north of the Circumpolar Current. However, SAVE is just entering its field phase and large volume sampling for radiocarbon and other long-lived tracers in data-poor regions will have to be specified at a later date.

3.4.1.5 Hydrographic Time Series from Research Vessels

Because much of the deep and intermediate water of the world ocean is transformed within the Atlantic and its marginal seas, significant variation of the properties of these water masses have already been observed in the Atlantic at decadal and shorter time scales. These changes have been observed from time-series stations and sections maintained by a variety of institutions and nations for a variety of reasons. Some of these time-series have already been terminated; it is important for WOCE to maintain the survivors and to reactivate others so that interannual change can be detected, quantified and eventually modelled over the WOCE period.

As well as the importance of detecting interannual changes, there is also a need for better estimates of the annual cycle within the principal circulation gyres. This is particularly relevant in the forcing fields where significant annual cycles exist. While valuable information on the annual cycle of the velocity fields should be obtained from global altimetry, surface drifters and deep floats, repeat hydrography over a few key sections is necessary to determine annual cycles in the baroclinic field.

The following repeat stations and sections should be continued or started during WOCE. They are shown in Figure 3.3.
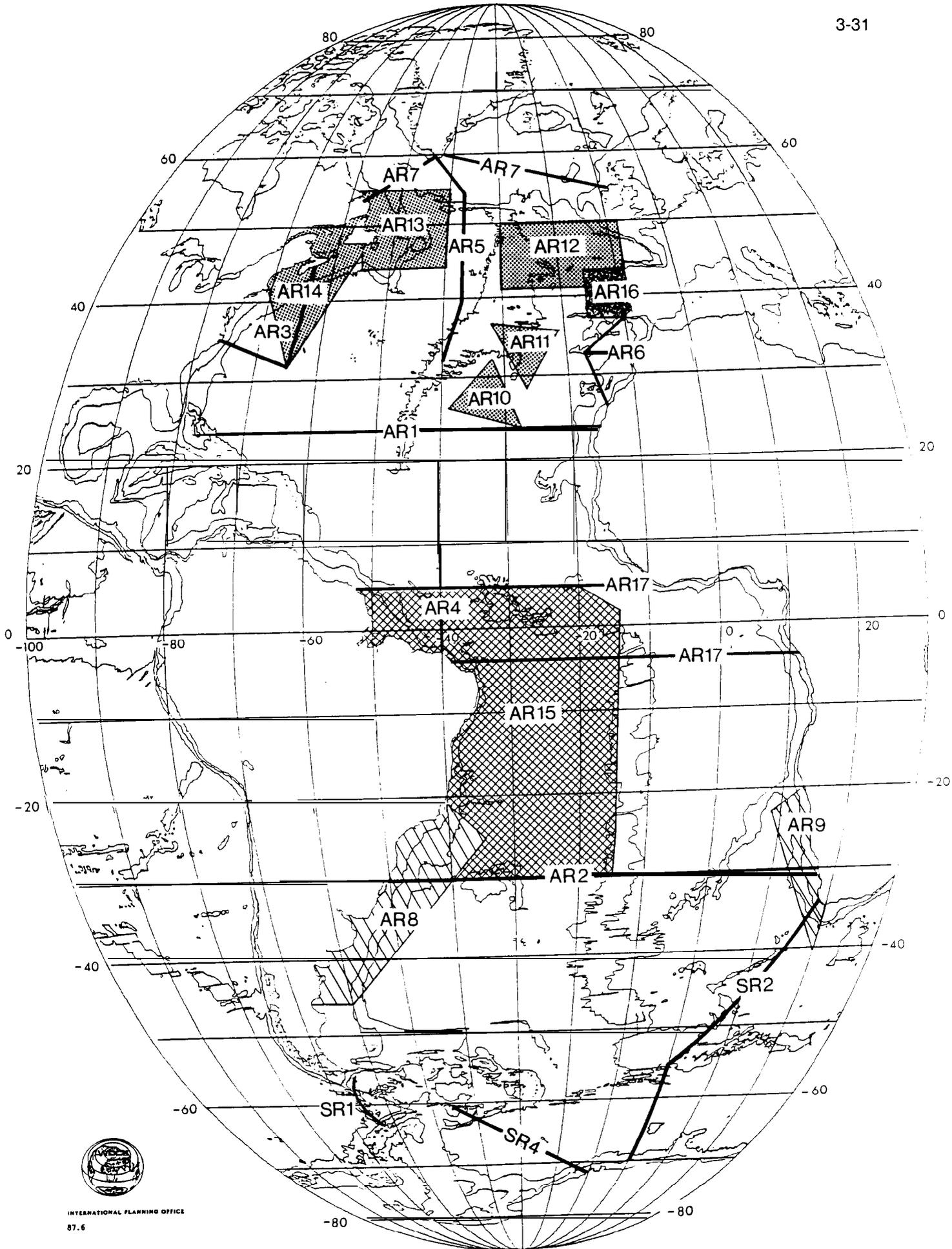
Figure 3.3   Repeat Hydrographic Sections in the Atlantic
Note: AR10-AR15 are described in Section 5.3

Repeat Hydrographic Sections

AR1   The meridional heat flux section at 24º N is to be repeated, at least in its upper 1500 m, once in each season in order to get a zero-order estimate of how the heat flux associated with the heating and cooling of the upper layers varies over an annual cycle.

AR2   The meridional heat flux section at 30º S is to be repeated, at least in its upper 1500 m, once in each season in order to get a zero-order estimate of how the heat flux associated with the heating and cooling of the upper layers varies over an annual cycle.

AR3   While many hydrographic sections have been occupied across the Gulf Stream from Bermuda to various points on the North American east coast, a systematic repeat of such sections will be especially valuable during WOCE to provide information on the response of the subtropical gyre, near its latitude of maximum transport, to variations in the wind stress integrated over the gyre. A hydrographic section from Cape Cod to Bermuda, returning alternately to Nova Scotia or Cape Hatteras, should be occupied quarterly over several years during WOCE. If full depth CTDs are not possible, the section should be occupied to 2000 m and the vessel should also be equipped with an ADCP. During full-depth occupation of the section at intervals of the order of a year, full small volume tracer sampling would be valuable, especially in the regions of the western boundary undercurrents.

AR4   There is a similar need to look at western boundary currents in the tropical regions more frequently in time. A repeat of the 40º W section south of 10º N at least one time in each season should indicate whether there are significant seasonal changes of the flow into and out of the equatorial regions along the north coast of South America.

AR5   The 40º W section from Cap Farewell south to 33º N should also be occupied at least one time in each season and at least in its upper 2000 m. This section will allow the estimation of systematic changes in the various branches of the North Atlantic current as a function of season and changing wind stress.

AR6   There is a need to look at the seasonality of the boundary currents and possible upwelling along the eastern boundaries. The seasonal occupation of a hydrographic section from Morocco to Madeira with alternate sampling of the return sections Madeira to Lisbon and Madeira to the Canaries would provide estimates of the boundary currents and allow their structures and strengths to be compared to phenomena such as upwelling off the African coast. These sections should be run using a vessel equipped with modern navigation equipment (GPS) and an acoustic Doppler current profiler ADCP.

AR7   The 57º N section, should be occupied at least from Greenland to Ireland one time in each season during the WOCE Intensive Observation Period to depths of 2000 m. Salinity measurements are vital for this section. This section along with its continuation across the Labrador Sea should also be occupied late each winter or early each spring to depths of at least 2000 m. These measurements are important for an estimation of the amount and characteristics of the various mode waters transformed during each successive cooling season. Occupation of this section to the bottom with small station spacing over ridges and continental slopes will allow estimates of the various overflows into the Atlantic from the Nordic Seas.

AR8   The western boundary region from about 5º S to Drake Passage should be rather extensively studied using both hydrographic sections and moored instrumentation. A series of hydrographic sections should be occupied from the continental shelf into the ocean interior at about 5º latitude intervals from 20º S to 45º S quarterly for two years.

AR9   A similar intensive series of hydrographic sections accompanied by direct current measurements is required for the Benguela upwelling region along the western coastline of Africa. The processes taking place in this region may be an important route by which Indian Ocean water is exchanged with the waters of the South Atlantic subtropical gyre. Eastern boundary upwelling itself may be an important mechanism governing water mass transformation in the upper layers.
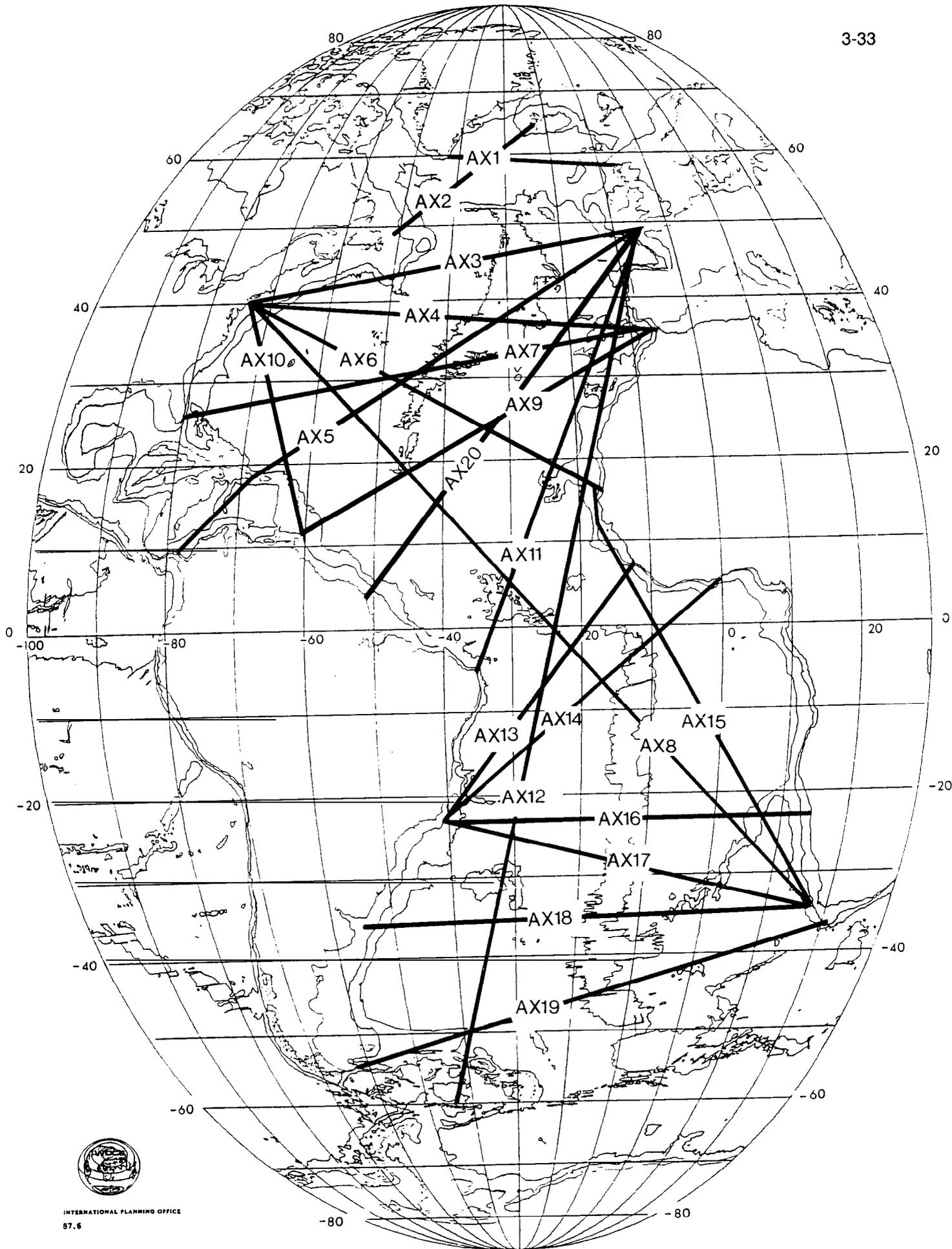
Figure 3.4   VOS Programme for the Atlantic. Note that some of these lines in the equatorial region are occupied as part of the TOGA programme

Time-series Stations

ARS1-3   Time series hydrographic stations off Bermuda (Panulirus), Newfoundland (Station 27), and Ocean Weather Ships presently being occupied at monthly or higher frequencies should be continued. The tracer sampling programme at Panulirus is a particularly valuable addition to the normal hydrographic sampling.

ARS4-11   The establishment of similar stations in the eastern North Atlantic and in the South Atlantic for ten years is required. Stations near the centre of oceanic gyres or in the outflows from marginal seas are of the greatest value. For the North Atlantic, new stations are needed off the Bahamas, Barbados, Madeira, Cape Verde Islands, Canaries, Azores, west of Ireland, and south of Iceland.

ARS12   The occupation of similar near-shore but oceanic stations in the South Atlantic is also strongly encouraged.

3.4.1.6 XBT/XCTD Sections from Ships-of-Opportunity

An XBT/XCTD network is required for the purpose of monitoring the seasonal and interannual variability of the upper ocean. The primary goal of this series of measurements is the determination of the annual and interannual changes in the heat and fresh water contents of the oceanic upper layer. This network should be developed from the TOGA network of XBT lines crossing the equator by extending the data collection to higher latitudes.

The aim is to have an XBT/XCTD section through each 10" square of the Atlantic each month. Sections should be occupied to below the depth of the seasonal thermocline; this means that in western boundaries and higher latitudes, depths of at least 1000 m are necessary and in some regions such as the Labrador Sea, 2000 m. The salinity measurements are particularly important at higher latitudes where salinity is often the dominant effect in determining whether or not convection occurs.

Considerable preliminary work has been done by IGOSS in establishing potential routes in the Atlantic; this effort should continue. Routes from the English Channel to New York, Panama, French Guyana and eastern tip of Brazil; from Gibraltar to Baltimore, Miami and Trinidad; from New York to the English Channel, Dakar, Cape Town and Trinidad and French Guyana; from Iceland to Grand Banks and from north Scotland to Cape Farewell will provide a sparse but probably adequate sampling if the sampling frequency is bi-monthly or better. The higher latitudes are more'sparsely sampled; however, there is hope that fisheries research vessels will continue to collect hydrographic data in the course of fisheries investigations in these regions and that this data will be exchanged in a timely enough fashion for to be useful.

In the South Atlantic, similar routes will have to be developed. Routes from Cape town to Cape Horn, Buenos Aires, Rio de Janeiro, New York and Dakar; from Rio de Janeiro to various African ports in Angola, Nigeria and Liberia; as well as supply routes from the Northern hemisphere to Ascension, St Helena and Antarctic bases will provide a sparse coverage. Again, as in the North Atlantic, contact must be made with fisheries organisations to ensure that data collected by them routinely is exchanged within the WOCE framework. The proposed ship-of-opportunity lines are shown in Figure 3.4 (AX1 -20).

3.4.1.7 T/S Chain Measurements

T/S chains will be important in areas in which there is infrequent shipping traffic to ensure adequate sampling of the T/S structure of the upper layers in time. When these areas are also the areas in which significant water mass transformation is believed to take place, they will be the essential measurement system to ensure that WOCE monitors these transformations over each winter. Upper ocean T/S chains should be maintained, at least over the winter months, in the central Labrador Sea to monitor the changes in the upper 2000 m of the water column leading to renewal of Labrador Sea Water. Because of the cyclonic nature of the circulation in these regions, it is possible that surface drifters rather than surface moorings could be used. Similar T/S chains should be moored in the Brazil/Falklands/Malvinas Current region in order to monitor mode water formation in the high latitude South Atlantic. Such chains should report their data daily or more frequently via satellite links.

Fig. (3.5)   Mooring sites in the Atlantic Ocean

T/S chains may also be used in place of repeated hydrographic stations at time series stations such as the sites of the ocean weather ships when they are abandoned.

3.4.1.8 Surface Flux Drifters (**ASFDG**)

Surface flux drifters will be required in those regions where there are unlikely to be 5 ship weather observations per 10° square per month. This is the case south of 40° S and in the northwest Atlantic. It is likely that the flux sensors can be mounted on the same buoy or drifter that will support the T/S chains referred to in the previous Section.

3.4.1.9 Direct Boundary Current, Passage and Eddy Statistics Measurements

A.   Boundary Currents

To obtain estimates of their mean transport and its variability direct velocity measurements should be made in the boundary currents at the locations shown in Figure 3.5. The mooring arrays for these measurements will have to be carefully designed, taking in account what is known about the particular area and current. This will allow the design of a minimal mooring array capable of monitoring variation in the boundary current transport at a later stage.

ACM1-4   The most important boundary current measurements are those associated with the western and eastern ends of the heat flux sections at 24° N (ACM1 and 2) and 30° S (ACM3 and 4) which cross the subtropical gyres at these latitudes. In the case of 24° N, this involves monitoring the transport through Florida Strait where extensive measurement programmes have indicated that good transport estimates can be made from cross-channel differences in sea-level and voltage as measured by a cable. For the other three locations, both exploratory and intensive mooring arrays will be required. In addition, at the western end of 24° N, the possibility of flows off-shore of the Bahamas, in both the upper and the bottom layers, needs investigation.

The transports of the western boundary currents of the major oceanic gyres need to be measured (**ACM5-7**).

ACM5   across the Gulf Stream near its latitude of maximum transport SE of Cape Cod,

ACM6   across the North Atlantic Current near its latitude of maximum transport east of the Grand Banks, and

ACM7   across the equator and the northern South American slope near 50_o W. This latter array, to measure the cross-equatorial flow along the northern coast of South America can be better designed following the results of pre-WOCE and TOGA experiments which will set current meter arrays in this region.

ACM29   The flow of low salinity waters deriving from Arctic surface outflow, glacial ice melt and land runoff will be monitored on the Labrador Shelf and Slope using an array of current meters, ice drifters equipped with T/S chains and moored T/S chains. Array will be co-incident with Section Al. This measurement must be continued throughout WOCE.

B.   Passages

Direct measurements of the transport of deep and bottom waters between ocean basins are necessary at locations shown in Figure 3.5 in order to serve as a constraint on the strength of the abyssal circulation.

ACM8   The inflow of North Atlantic Deep Water into the Atlantic over the Greenland-Iceland-Faroes-Scotland ridge system should be monitored using moored current-meters equipped with temperature and salinity sensors so that the T/S properties of the waters overflowing the ridges can be monitored in time. A full array is likely to involve about eight moorings with 3 or 4 current-meters each for the Denmark Strait, and six moorings for the rest. A continuation of such measurements

throughout the WOCE period, at least at some minimum level, will be valuable for the interpretation of measurements within these deep waters made further downstream at a later time. Monitoring for T/S variability alone would require considerably fewer instruments.

ACM9 The inflow of Mediterranean Water into the Atlantic should be measured near the Straits of Gibraltar. The results of a multi-institutional study of the flow through the Straits of Gibraltar carried out during 1986/87 will help design an effective array to determine the net salt flux into the North Atlantic from the Mediterranean during WOCE.

ACM10 An abyssal mooring array near the sill at the Ceara Rise near 4° N is required to measure the transport of Antarctic Bottom Water into the North Atlantic. Moorings should be in place for at least a year.

ACM11 A mooring array in the Romanche Fracture Zone is required for estimation of the exchange of deep waters between the western and eastern basins of the Atlantic. Neither the spatial nor temporal scales of this exchange are known. Initial exploratory measurements are needed before an array designed for longer term measurements can be set.

ACM12 A mooring array in the Vema Gap (Channel) is required to estimate the transport of deep waters into the western basin of the Atlantic. Neither the spatial nor temporal scales of this exchange are known. Initial exploratory measurements are needed before an array designed for longer term measurements can be set.

ACM13 A mooring array in the Hunter Gap (Channel) is required to estimate the transport of deep waters into the western basin of the Atlantic. Neither the spatial nor temporal scales of this exchange are known. Initial exploratory measurements are needed before an array designed for longer term measurements can be set.

ACM14 Investigations are also required into the possible exchanges of deep waters over the Walvis Ridge into the eastern basin of the South Atlantic. Tracer measurements being obtained in the South Atlantic (1987/88) coupled with recent LONG LINES sections through the eastern basin and across the Walvis ridge should permit a better estimation of whether there is a significant flow of deep water into the eastern basin across the Walvis Ridge. If there is, a search for the pathway of this water and the design and the setting of a mooring array to measure its transport would be necessary.

C. Eddy Statistics

A few current-meter moorings, heavily instrumented in the vertical, will be required to provide some indication of the vertical and temporal characteristics of the eddy velocity (and temperature) field throughout the Atlantic. The North Atlantic has had a large number of such long term moorings and has little requirement for additional moorings during WOCE, with the exception of the eastern tropics **(ACM15).** On the other hand, there have been few nearly full depth current-meter moorings in the South Atlantic that have been set for a year or more. It is likely that the structure of the eddy field in the South Atlantic will be similar to that of the North Atlantic and Pacific. A few moorings spaced from near the Brazil Current to the interior of the subtropical gyre **(ACM16** and **ACM17**) could be used to test that similarity.

The South Atlantic has two likely unique sources of eddy energy, the Antarctic Circumpolar Current and the Agulhas Retroflection Region. Approximately 6 to 10 moorings are required in the higher latitude South Atlantic on both the western and eastern sides in order to determine the vertical structure of the eddy field and whether that vertical structure changes with season and distance from Drake Passage, the ACC and/or the Agulhas Retroflection Region. Moorings should be in place for 18 to 24 months.

3.4.1 .10 Deep Float Releases

Deep floats will be released throughout the world ocean at some common depth level in order to establish a deep reference level for velocity (see Section (3.3.2) on the global velocity field). In the Atlantic, 2500 m is the best choice since it is shallow enough to avoid major topographical constraints and is within the

North Atlantic Deep Water Core layer. Special float releases are also required in the Atlantic to look at particular water masses and their movement in particular regions. While the general deep float release is likely to be of the pop-up type; the special releases may be mixtures of SOFAR and RAFOS floats.

AF1   Approximately 12 pop-up floats should be released at the end of winter in the Labrador Sea Water in the central Labrador Sea in order to follow the spreading of this water mass over a period of five years. Releases at the end of two different winters of the order of five years apart and hopefully with different intensities of convection are important. Floats should be positioned at periods of 50 to 100 days over five years.

AF2   SOFAR or pop-up floats should be released at a depth of 5000 m along 24° N from 60° W to the Mid-Atlantic Ridge at an initial spacing of 50 km in order to determine how Antarctic Bottom Water spreads northward in the western basin of the North Atlantic. If pop-up floats are used they should be positioned every 50 days, at least initially.

AF3   Special float releases will be a valuable tool to determine the pathway and volume flux of various cross equatorial flows. In addition to the 2500 m floats, which should capture the North Atlantic Deep Water core layer, floats should be released at 1000 m in the Antarctic Intermediate Water and at 4000 m in the Antarctic Bottom Water layer. Floats should be seeded into these latter two layers around 5° S with a greater concentration in the west. A combination of SOFAR and RAFOS floats would be preferable to pop-up floats to resolve narrow intense flows that may exist close to the equator.

3.4.1.11 Sea-Level Measurements

Sea-Level measurements will be principally used to provide calibration information for the sea surface altimetry. The required stations and the frequency of reporting are given in Volume I, Section (2.3).

Sea-level stations may also be useful in the longer term monitoring of the strength of gyre circulation. Wherever there are to be current-meter arrays aimed at estimating the strength of the boundary current of an oceanic gyre, sea-level data in the vicinity should be collected and examined for any significant correlation.

3.4.2 The Pacific Ocean

3.4.2.1 Introduction

The Pacific Ocean is most appropriately discussed in terms of its three principal regions, the North Pacific, the tropics, and the South Pacific. Each has its own set of problems.

The North Pacific is the least well-ventilated of all the world's oceans as there is no present day local source of deep water. The thermohaline environment of the subpolar North Pacific, where deep water might be expected to be formed, is dominated by a surface layer of low salinity which arises from an excess of precipitation and river runoff over evaporation. There is also no apparent intermediate water formation in the North Pacific and any such formation processes probably occurs in adjacent seas under arctic brine-formation conditions. The net result of the lack of water mass formation is that the North Pacific is the most stratified of the major oceans, with the probable result that the influence of surface processes driving the baroclinic circulation do not extend as deeply as they do in other oceans. The deep water of the North Pacific is more uniform in temperature and salinity than the deep waters of other oceans, resulting in the need for especially careful and stringent measurements in order to measure the actual gradients. Nutrient gradients in the deep water are much larger and equally indicative of circulation as long as the sources are well understood. The goals of the suite of measurements for the North Pacific are discussed in some detail in the report of the Core Project 1 Planning Meeting (WCRP-2, 1988) and include understanding heat, freshwater and surface fluxes, gyre circulation and its variability; the abyssal circulation, water mass modification and the interaction of marginal seas with the main body of the North Pacific.

The tropical Pacific is characterised by several features, including the large interannual variability associated with ENS0 phenomena, monsoon forcing in the western region, the relatively narrow deep passages for bottom water transport and flow into the Indian Ocean. The coincidence of the WOCE Intensive Observation Period with TOGA permits efficient use of resources and suggests combined studies, with WOCE emphasizing studies of the deep water circulation. The basic goals of tropical studies as discussed above in Section (3.15) apply for the Pacific Ocean, including estimates of cross-equatorial transports, particularly of intermediate and deep waters.

The South Pacific is the largest and most remote of the world's oceans and is, not surprisingly, sparsely sampled. Nevertheless, the measurements that have been made are generally modern and of good quality, thus affording a better base than was available until recently in the South Atlantic. Specific goals for a South Pacific observational programme are described in an appendix to the Core Project 1 Planning Meeting Report (WCRP-2, 1988). Of particular interest in the South Pacific are the exchanges with the Indian Ocean and South Atlantic via the Southern Ocean and Indonesian Archipelago, the role of the South Pacific in Subantarctic Mode Water and Antarctic Intermediate Water formation, and the description of the variability of the East Australia Current and of the important bifurcation region in the eastern South Pacific where the west wind drift splits into a portion that recirculates in the subtropical gyre and one that enters Drake Passage.

3.4.2.2 Hydrographic Measurements (one-time survey)

In developing the one-time hydrographic/tracer survey, similar guide-lines were used as for the Atlantic. These include that (1) there be zonal sections near 24º N and 30º S as part of the measurement of meridional heat transport, (2) there be at least one meridional and zonal section through each major gyre, (3) there be zonal sections enclosing the equator to the north and south, (4) there be a section across the Antarctic Circumpolar Current south of Tasmania to measure the transport, (5) sections be run from land-to-land where possible, and (6) the section spacing not be so coarse that mapping would become impossible. The last requirement is partially met by maximum section spacing of approximately 20' in the eastern Pacific and 10' in the more energetic western Pacific. Although some sections are included purely in order to satisfy the mapping criterion, these are necessary since a primary goal of the hydrographic survey in conjunction with sea-surface altimetry and direct velocity measurements is to determine the circulation at all depths. It is important that the precise location of the sections which cross major topographic features, boundary currents, and passage throughflows, be examined to ensure best sampling strategy. A number of sections repeating observations made ten to thirty years ago are required to determine if there have been long-term shifts in water properties.

All sections will be occupied at least once during WOCE following the complete and stringent specifications of the WOCE Hydrographic Programme in terms of the quality of the water sampling and the data collection. Each CTD station will be occupied to the ocean bottom and water samples will be collected at depth intervals of no greater than 200 m and analyzed for salinity, oxygen, nitrate and nitrite, phosphate and silicate. Figure 3.6 depicts the locations of the following Pacific Sections.

Each section is described briefly below.

Zonal Sections

P1   47º N to 58º N: This section runs southeastward across the Okhotsk Sea, the Kuril Islands and East Kamchatka Current to 47º N, 160º E, turns eastward following 47º N through the subpolar gyre and angles northeastward at 170º W in order to cross a relatively undersampled and central part of the subpolar gyre. The section is a partial repeat of a 1985 section at 47º N with a crucial extension into the Okhotsk Sea and eastern Pacific.

P2   35º N: This section crosses the central North Pacific, following the Kuroshio Extension in the western North Pacific and samples the northern part of the subtropical gyre in the eastern Pacific. It is a repeat of a 1976 section and is included for mapping purposes to avoid a large gap between the central subtropical and subpolar sections.
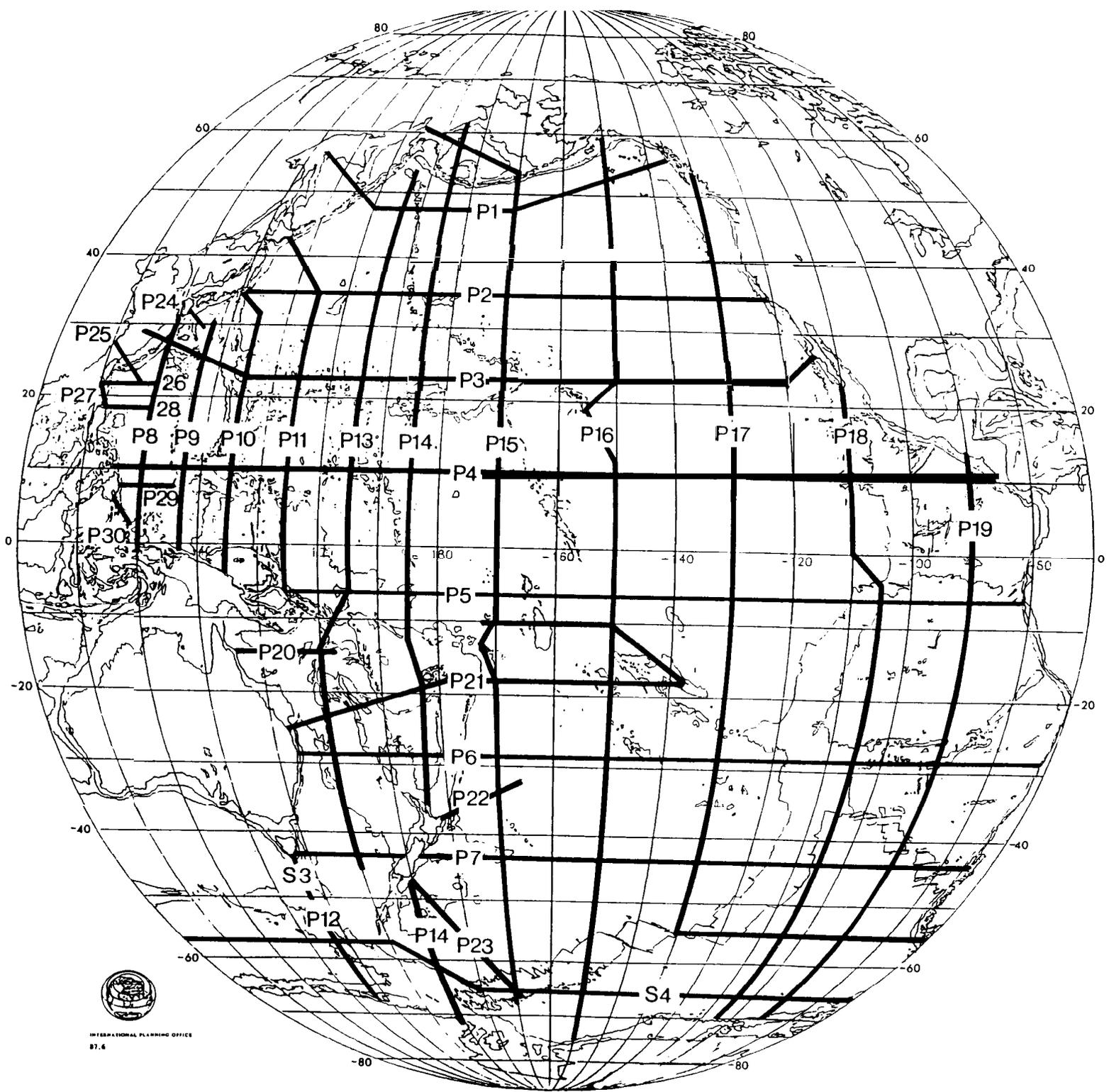
Fig. (3.6)   The WHP one-time survey in he

P3   24º N: This section crosses the East China Sea, the Kuroshio, the lzu Ridge and continues eastward across the central subtropical gyre. It is the section to be used to measure meridional heat transport in the North Pacific in conjunction with boundary current measurements and repeated hydrography from merchant vessels. It also repeats a 1985 section.

P4   10º N: This section lies between the North Equatorial Counter Current and North Equatorial Current and is the northern section bracketing the equator for cross-equatorial transport estimates.

P5   7º S: This is the southern section bracketing the equatorial region, for cross-equatorial transport estimates. In the west, it runs into Buka Is. at about 155º E and then continues obliquely southwest to New Guinea. A deep zonal section was occupied along 15º S in 1987 and should be of use in filling the gap between 7º S and 28º S. At low latitudes, much of the meridional warm water transport is ageostrophic and it is important that direct measurements of shear in the upper ocean be made in addition to the hydrographic measurements.

P6   28º S: This section crosses the central subtropical gyre and is the designated section to be used to measure meridional transport in the South Pacific. It repeats the 1967 SCORPIO section.

P7   43º S: This section crosses the southern side of the shallow portion and the centre of the deeper portion of the subtropical gyre. It is important for measuring the transport into the Pacific Ocean and is the southernmost section north of the Antarctic Circumpolar Current. It repeats the 1967 SCORPIO section.

Meridional Sections

P8   130o E: This section and the following three meridional sections have been occupied repeatedly over the past several decades by various Japanese agencies. The suite of four sections samples the western, energetic region of the subtropical gyre and perturbed region north of the Kuroshio Extension to approximately 1500 m. All sections are to be occupied once during WOCE following the full specifications of the WHP and with all small volume tracers.

P9   137º E: Meridional section occupied repeatedly by Japanese agencies, as for P8.

P10   145º E: Meridional section occupied repeatedly by Japanese agencies, as for P8.

P11   155º E: Meridional section repeatedly occupied by Japanese agencies, as for P8.

P12/S3 146º E: This section south of Tasmania crosses the Antarctic Circumpolar Current. It is to be used to measure the transport and is to be repeated as part of Core Project 2.

P13   165º E: This is the westernmost meridional section that includes both the North and South Pacific. It begins in the north where the Emperor Seamounts and boundary trenches meet, crosses the subpolar gyre, the Kuroshio Extension and subtropical gyre, and crosses the tropics at a position of intensive TOGA studies in the western Pacific (repeat hydrography and moored measurements). The line is shifted westward to 160" E in the South Pacific in order to cross the Coral Sea and the off-shore extension of the East Australia Current in the centre of the Tasman Sea.

P14   175º E: This section crosses the Bering Sea and Aleutian Islands, the boundary currents south of the Aleutians, the subpolar gyre east of the Emperor Seamounts, runs across the Emperor Seamounts/Hawaiian Ridge and the equator and continues to Fiji. The eastward shift in the line north of Fiji could be placed elsewhere; in particular it might be usefully located along the Emperor Seamount chain in order to measure the flow through the chain. South of Fiji, the line crosses the South Fiji Basin to the northern end of New Zealand following the route of commercial vessels which are used for repeated XBT surveys.

P15   170º W: This section divides the North Pacific between its regions of high energy in the west and low energy in the east. It commences in the north as the second, more zonal section crossing the Bering Sea, crosses the Aleutian Islands and boundary currents, the central subpolar gyre,

the Hawaiian Ridge, the central Pacific Basin (where it might be reoriented to cross gaps in the ridge running north from the Line Islands), continues southward east of the Kermadec Trench, intersects the Chatham Rise and crosses the Antarctic Circumpolar Current.

P16 150º W: This meridional section crosses the North Pacific near a 1984 section between Alaska and Hawaii, crosses from Hawaii to the Line Islands across the broad deep water flow into the eastern North Pacific, crosses the equator and the centre of the Southwest Pacific Basin and, finally, the Antarctic Circumpolar Current. The southern end of the line is of high priority for Core Project 2.

P17 130º W: This eastern North Pacific and mid-South Pacific section is located in data-poor regions of both oceans. It crosses the southeast corner of the subpolar gyre in the North Pacific (where it might be reoriented to better cross the deep shelf and boundary currents), crosses the eastern part of the subtropical gyre, the equator, and the central South Pacific as the easternmost section west of the East Pacific Rise. At 57ºS the line turns eastward in order to provide necessary sampling of the deep flow in the Bellingshausen Basin, a particularly data-poor area.

P18 110º W: This section crosses the Costa Rican dome in the North Pacific, coinciding with the heavily sampled TOGA line at the equator. South of the equator, it swings across the East Pacific Rise to 105º W and continues southward east of the East Pacific Rise, crossing the Antarctic Circumpolar Current.

P19 90º W: This tropical and eastern South Pacific line crosses the equator at the Galapagos Islands, boxes in the eastern boundary region of the South Pacific, and is the only meridional section that crosses the deepest parts of the basins east of the East Pacific Rise. The southern end of the line is of high priority for Core Project 2.

Short Sections

Several shorter sections terminating at either land boundaries or at other sections are required in order to provide enhanced sampling of the Kuroshio, the Mindanao Current, the East Australia Current and of the deep western boundary current in the South Pacific, including the flow through the Samoa Passage. In instances where sections terminate at other sections, they extend beyond the intersection point by a few hundred kilometres in order to facilitate estimation of a smoothed field.

P20 A track from Australia to 163º E along 15º S repeats the western boundary segment of the 1987 trans-Pacific section, sampling the Coral Sea Basin.

P21 An oblique line from the Australian coast at about 24º S to New Caledonia and then on to Fiji closes off the northern end of the Tasman Sea domain and samples the West Fiji Basin. Fiji is near the centre of the subtropical gyre at the ocean surface, with primarily westward flow in the thermocline through the islands in the region. This line continues eastward from Fiji to Tahiti, then northwestward to about 10º S, 162º W, then westward to cross the 170º W section. These latter segments form a survey of the deep flow through the Samoa Passage and Penrhyn Basin. The Fiji-Tahiti line runs across the northern end of the Southwest Pacific Basin, cutting across all of the abyssal flow from the South toward the North Pacific. Any part of the flow entering the Penryn Basin is sampled by the segment northwest of Tahiti, while the short segment along 10º S should be oriented to sample near the sill of Samoa Passage.

P22-23 Two additional segments are suggested to add to the sampling of the structure of the deep western boundary current east of New Zealand. P22 extends northeast from East Cape (North Island) New Zealand, crossing the 170º W meridional section. This line crosses the deep western boundary flow north of Chatham Rise. The second, P23, extends southeastward from the South Island across the northern Campbell Plateau, then across the southern arm of the Southwest Pacific Basin, terminating at the crest of the Pacific Antarctic Ridge at about 64º S, 168º W.

P24-30 A set of seven short sections at the western boundary in the North Pacific is included to survey the Kuroshio, the Mindanao Current, and flow into the Indonesian Archipelago. All of these sec-

tions will be occupied once as part of the one-time survey with stations to the ocean bottom and the full set of WHP sampling. They will also be occupied on a repeated basis at various resolutions and to various depths. From north to south, the sections are:

P24   A short section running southeastward from Kyushu across the Kuroshio.

P25   A section across the East China Sea and Ryukyu Islands.

P26   A zonal section at 22° N from Taiwan to 130° E.

P27   A meridional section between Taiwan and the Philippines across Bashi Strait.

P28   A zonal section at 18° N from Luzon to 130° E.

P29   A zonal section at 7° 30' N from Mindanao to 130° E.

P30   A section running southeast from Mindanao across the inflow into the Indonesian Archipelago.

3.4.2.3 Small Volume Tracers

Geochemical tracers other than the standard nutrients, oxygen and salinity measurements to be collected in the hydrographic survey, will be sampled on all of the sections listed in the above group. The tracers include chlorofluorocarbons (CFCs), helium (^{3}He), tritium (^{3}H), and AMS-^{14}C. These will be collected at all stations as outlined in Section (3.2.2).

3.4.2.4 Large Volume Tracers

It is proposed to measure deep ocean ^{14}C (P-counting) and ^{228}Ra at every 300 nm station along all WHP sections in the Pacific Ocean. ^{228}Ra should be measured in the upper ocean in the North Pacific and in the South Pacific only if a five-fold increase in detection efficiency can be achieved. Upper ocean ^{228}Ra sampling in the basin interior, where gradients are weak, need not be done at the full 300 nm resolution. ^{85}Kr is to be measured at all stations where ^{228}Ra is sampled in the upper ocean. Approximately ten ^{39}Ar stations will be occupied throughout the Pacific.

3.4.2.5 Hydrographic Time Series from Research Vessels

Repeated hydrographic sections are essential for understanding variability on seasonal to decadal time scales. Included in this group of sections and stations are sections which have been run by various agencies and institutions for many years, proving themselves to be valuable in terms of understanding temporal variability, and which would be extremely valuable if continued. Also included are ocean stations (or short lines of stations) where it is felt the possibility exists of establishing a time series with water sampling for various tracers and salinity which cannot now be measured from volunteer ships. Such time series require an extensive institutional commitment and therefore have been proposed only where some possibility exists for establishment. Proposed stations and sections are shown in Figure 3.7.

Measurements on repeated sections and stations will generally be made to a depth of 1500 m. A survey to the ocean bottom to full WHP standards is recommended once during the time series. Most of this work is listed in Section 3.4.2.2 of this Volume. Repetition rates for sections vary from quarterly to yearly and rates for each section are listed in Chapter 5 of Volume I. Repeat Stations should be occupied at least once per month. Total numbers of stations are calculated assuming a five-year WOCE observing period.

<u>Repeat Hydrographic Sections</u>

PR1-4 These four meridional sections at 130° E, 137° E, 145° E and 155° E have been run at various intervals by Japanese agencies for many years, some with more regularity than others. Continuation is of high value to WOCE and is strongly supported since the group samples the energetic western subtropical gyre and western tropical Pacific.

Fig. (3.7)   Repeat hydrography sections and stations in the Pacific Ocean

3-44
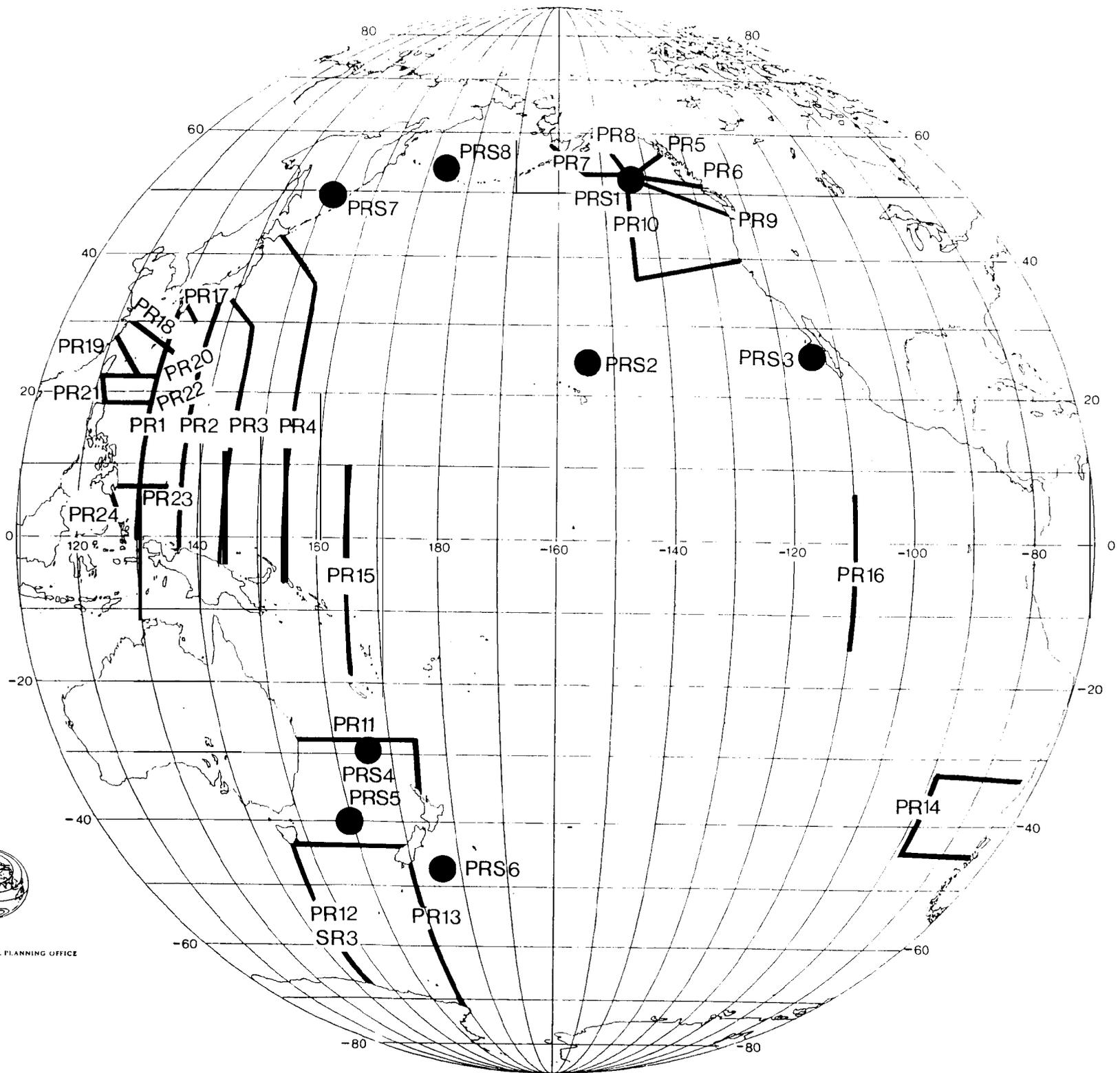
PR5-10 These sections sample the eastern subpolar gyre and of the broad interior eastward flow between the subtropical and sub-polar gyres. The bifurcation "point" at the eastern boundary is variable and wanders between 40° N and 50° N. Repeated sections will provide information on the relationship between: (1) the transport of the west wind drift and the eastern boundary and northern boundary currents, (2) the wind stress curl and the branching point, and (3) the Sverdrup interior transport and the boundary currents. The two central lines (PR5-6) from Canada to the position of OWS Papa have been run for many years, providing important information on variability of the subpolar gyre and westward propagation of events from the coast. The two northern lines (PR7-8) from Alaska to OWS Papa have been started recently and will provide monitoring of the Alaska Current and eastern subpolar gyre. The two southern lines (PR9-10) will provide the subtropical bounds on the region of bifurcation.

PR11 A repeated section along 28° S from Australia to 178° E and then south to the northern tip of New Zealand is needed to describe the time variability of the East Australia Current and the transport into and out of the Tasman Sea. The East Australian Current (EAC) differs from the surface western boundary currents in other oceans in that the eddies are of the same magnitude as the mean current so that it appears discontinuous in time and along the coast. Thus, part of the problem is to acquire sufficient data to properly define the EAC and to assess its contribution to the subtropical gyre circulation.

PR12 Repeated sections from Tasmania to Antarctica are required to monitor the flow south of Australia from the Indian to the Pacific Oceans. This section is one of the primary transport sections in both Core Projects 1 and 2. Flow estimated from this single section, combined with measurements in the Indonesian archipelago, will be compared with the flow through Drake Passage to produce net interocean transport estimates.

PR13 Repeated sections from Tasmania to New Zealand and then south to Antarctica could replace the single section from Tasmania to Antarctica and would provide the same information for interocean transport estimates. They would, in addition, provide information on flow which enters the South Pacific to the east south of New Zealand and that which flows north into the Tasman Sea.

PR14 Repeated sections in the eastern South Pacific to monitor the bifurcation of the west wind drift are recommended. Ideally, this requires seasonal cruises with CTD measurements to the bottom. The capability does not exist locally to carry out such a programme, although a less extensive and frequent programme could conceivably be supported. This could include maintenance of a single mooring off the coast of Chile at 35° S with current meters and thermistor chains (PCM14), supported by ships on the way to and from Antarctica. Large fishing vessels in the area could possibly also be used for hydrographic and XBT work.

PR15 The tropical portion of section P13 from 10° N to 17° S along 165° E. This section is currently being occupied four times a year as part of TOGA. It will be continued as part of SURTROPAC, being repeated twice a year during the WOCE period.

PR16 The tropical portion of section P18 from 5° N to 15° S along 110° W. This section is currently being occupied repeatedly as part of TOGA in conjunction with a cross-equatorial current meter array.

PR17-24 This set of eight short sections provides repeated sampling of the Kuroshio and Mindanao Current. The northernmost three sections: southeast of Kyushu (PR17), the continuation of long term measurements along the North Pacific Heat Flux line across the East China Sea (PR18), and the southern line across the East China Sea, (PR19) are currently being occupied 2 to 4 times a year as part of a Japan-China Kuroshio experiment and should be continued during WOCE.

PR20 This section at 22° N (east of Taiwan to 130° E) provides repeat hydrography at the location of the heat transport section and boundary current moored array.

PR21 This section from Taiwan to Luzon across Bashi Straits closes the western boundary current sections.

PR22 This section from Luzon to 130º E at 18º N samples the Kuroshio near its formation region.

PR23 This section at 7º 30' N east of Mindanao Island samples the Mindanao Current.

PR24 This section southeast of Mindanao Island samples the flow into the Indonesian Archipelago.

Time-series Stations

The following repeated time-series stations are to be occupied continuously to a depth of 1500 m on a monthly basis beginning with WOCE and extending for a ten year period.

PRS1 An ocean station at the position of OWS Papa is recommended for monitoring water properties more often than each individual line to and from the station. If the entire network of lines to OWS P (PR6-11) were occupied regularly, the need for a separate ocean station could be eliminated.

PRS2 An ocean station north of Hawaii is required to monitor changes in properties in the central subtropical gyre. A position close to Hawaii was chosen for logistical reasons, although the station should be located as far from the island chain as is practical. This station is also a recommended USA GOFS time series station.

PRS3 An ocean station in the California Current at 24º N, the latitude of the meridional transport section, is required. The location of this station is not ideal for work from a local institution and may need to be moved northward for logistical reasons. However, intensive work is needed during WOCE at this location in order to monitor the boundary region for the transport estimates.

PRS4-5 Two stations (either hydrographic stations or moored thermistor/salinity chains) should be occupied in the central Tasman Sea to provide an index of the eastward flowing EAC on the basis of the dynamic height at the two stations. Station locations are nominally 28ºS (Norfolk Island) and 40º S in the central Tasman Sea.

PRS6 An ocean station or moored thermistor/salinity chain off the Chatham Rise east of New Zealand would yield observations of Subpolar Mode Water and Antarctic Intermediate Water and, in conjunction with the station off Chile, could provide an index of the circulation. This station should not be too close to the meandering front off the plateau.

PRS7 An ocean station or T/S chain in the Okhotsk Sea would be ideal to study dense water formation in the North Pacific.

PRS8 An ocean station or T/S chain in the Bering Sea would also be useful for study of dense water formation. Although it would be of lower priority than a station in the Okhotsk Sea, it may be more feasible.

3.4.2.6 XBT/XCTD Sections from Ships-of-Opportunity

An XBT/XCTD network is required to monitor the seasonal and interannual variability of the upper ocean. Two modes of operation are foreseen, as outlined in the discussion on methods (Vol.II, 3.2.3 and Vol.I, 2.6.1), one following the TRANSPAC and TOGA modes with wide spatial coverage but somewhat sparse temporal coverage, and the other with widely-spaced lines with heavy sampling along the lines. It is recommended in the latter mode that coverage extend to 1000 m depths and that lines be run at least seasonally.
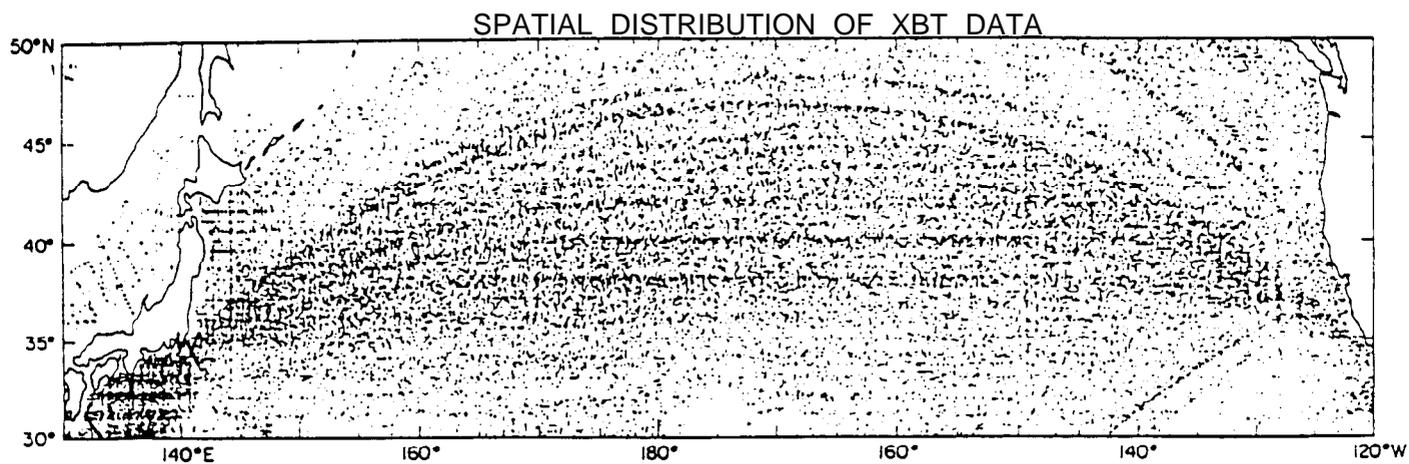
SPATIAL DISTRIBUTION OF XBT DATA

Fig. (3.8a)   The TRANSPAC Network in the Northern Pacific Ocean

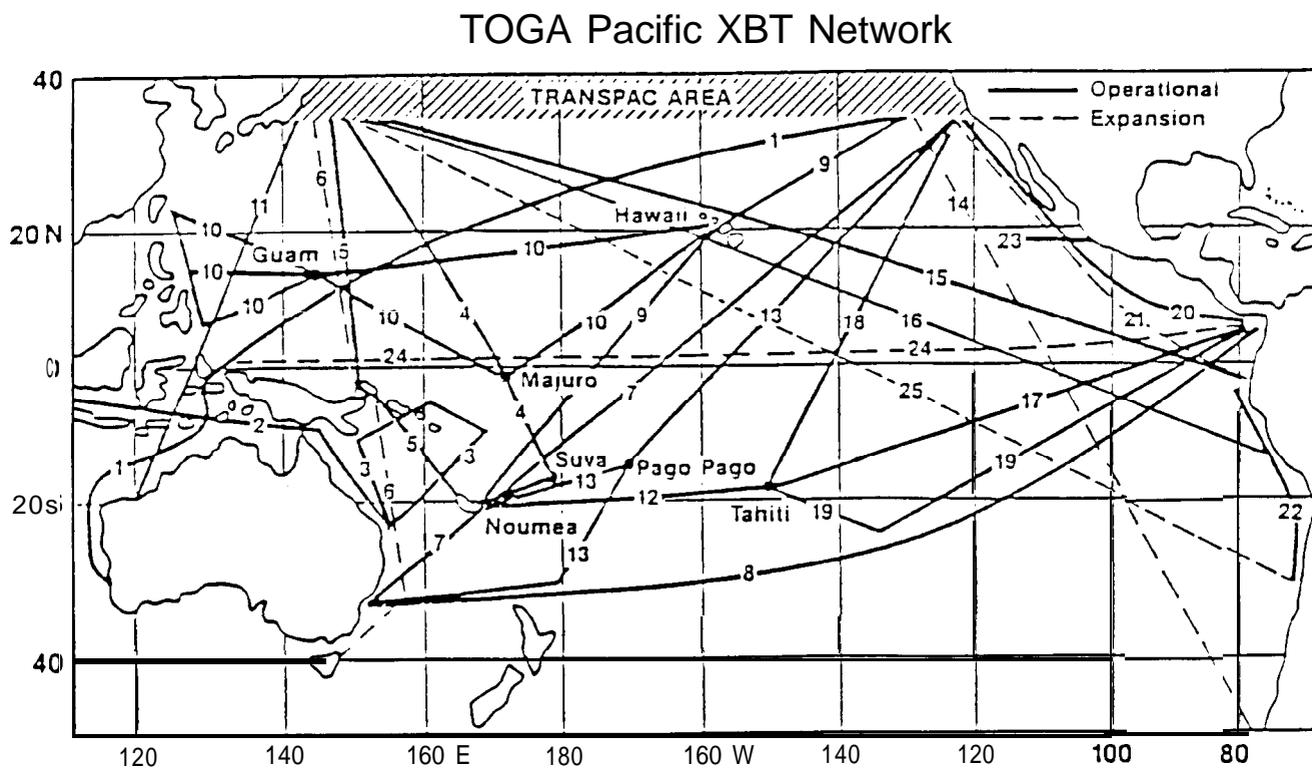## TOGA Pacific XBT Network

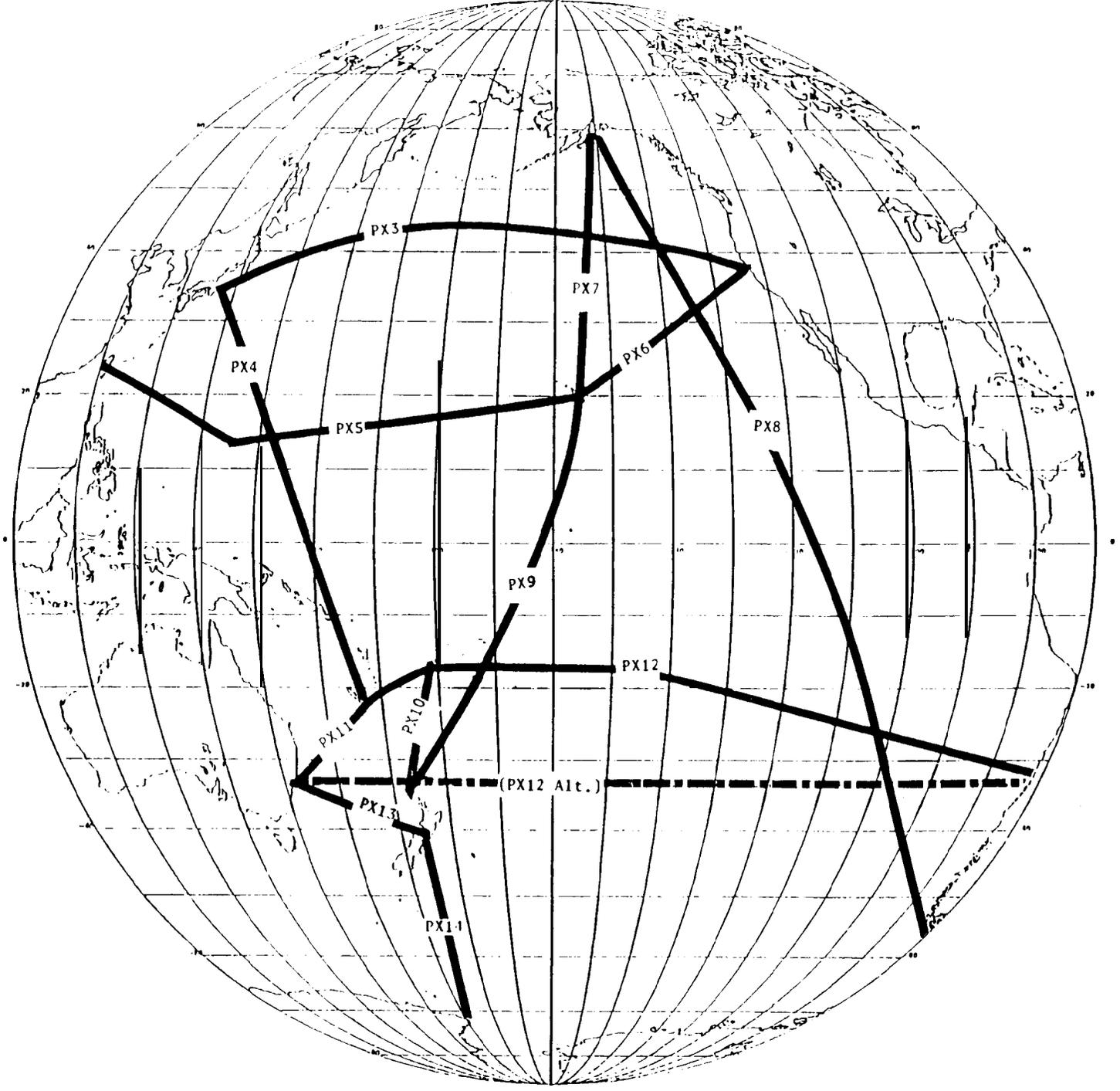Fig. (3.8b)   The TOGA Pacific XBT Network

Fig.·(3.8c) VOS high-density lines in the Pacific Ocean

3-48

A.   Low-density broadcast network for heat and salt storage in the upper ocean

PX1   Continuation of TRANSPAC network and dense sampling of Japanese waters (Fig.3.8a)

PX2   Continuation of TOGA network (Fig.3.8b) between 30° S and 30° N.

B.   High-density (eddy-resolving) sampling to 1000 m along a sparse network for changes in large-scale circulation, to be repeated four times a year for the duration of WOCE

PX3   Tokyo to San Francisco

PX4   Tokyo to Noumea

PX5   Taiwan to Guam to Hawaii

PX6   Hawaii to San Francisco

PX7   Hawaii to Kodiak

PX8   Valdez, Alaska to the Drake Passage

PX9   Hawaii to Auckland

PX10   Suva to Auckland

PX11   Sydney to Suva

PX12   Suva to Tahiti to Valparaiso (alternatively, Sydney to Valparaiso)

PX13   Sydney to Wellington

PX14   Christchurch to McMurdo.

3.4.2.7 T/S Chain Measurements

In the event that usable T/S chains are developed, and that regular hydrographic observations are not feasible at desired locations, T/S chain measurements would be valuable monitors of upper ocean evolution. Possible locations, as replacements of ocean stations, include all individual stations mentioned in Section (3.4.2.5), with the exception of the station off Hawaii, where extensive water sampling is planned as part of the GOFS programme.

3.4.2.8 Surface Flux Drifters

Surface flux drifters with thermistor chains are recommended in all regions which are not adequately covered by merchant ship observations. The average drifter spacing should be 500 to 1000 km. Regions for deployment in the Pacific are the eastern tropical Pacific, central and eastern South Pacific and the Southern Ocean.

3.4.2.9 Direct Boundary Current and Abyssal Circulation Measurements

Intensive direct velocity measurements need to be made at a number of important locations in order to define current velocity, structure, transport, and variability. Proposed locations are shown in Figure 3.9. Of central importance are the arrays at either end of the heat flux sections at 24° N (PCM1 and PCM2) and 28° S (PCM3 and PCM4). Also of importance are direct measurements of variations in boundary current structure and transport along the boundary and of the separation of the western boundary currents into the interior. Thus arrays are proposed at several locations in the Kuroshio and East Australia Current. Unless specified as "deep measurements", measurements should extend from the ocean surface to the bottom.

Fig. (3.9)   Mooring Sites in the Pacific Ocean

3-50

Abyssal circulation studies include moored arrays at locations in deep boundary currents and across fairly narrow passages which constrict deep flow. The deep boundary current field of the North Pacific is the least well-known of all the oceans. At low latitudes the deep western boundary is so poorly defined that it may make little sense to speak of an interior flow tied to a boundary current. At higher latitudes, boundary currents ought to exist, but deep water in the North Pacific is so nearly homogeneous that tracer evidence for strong flows is indistinct. The expected northern boundary current has been identified but evidence for western boundary currents is only suggestive. Deep western boundary currents in the South Pacific have been fairly well identified, and the one in the Southwest Pacific Basin is the greatest in the world ocean. The deep transport along the eastern flank of the East Pacific Rise is expected to be smaller and the observational strategy less clear because of the rough, broadly sloping topography.

PCM1 An array is required to measure the transport and variability of the Kuroshio at the western end of the North Pacific heat flux section at 24º N.

PCM2 An array is required to measure the transport and variability of the California Current at the eastern end of the North Pacific heat flux section at 24º N.

PCM3 An array is required to measure the transport and variability of the East Australia Current at the western end of the South Pacific heat flux section at 28º S.

PCM4 An array is required to measure the transport and variability of the Peru Current at the eastern end of the South Pacific heat flux section in the at 28º S.

PCM5 Measurements of the Kuroshio are required in Tokara Strait and south of Honshu. Together with measurements at 24º N and across the Izu-Ogasawara Ridge, this will provide information on the structure and variability of the Kuroshio. An additional array in the East China Sea across the Ryukyu Islands and off the Boso peninsula is desirable.

PCM6 Deep current measurements east of Hokkaido or farther north are needed to determine the structure and variability of the deep flow. No direct velocity measurements are currently available in the deep water along the western boundary. This array would provide information linking flows along the Izu Ridge and the northern boundary.

PCM7 Deep current measurements east of the Izu-Ogasawara Ridge are required since the ridge is the effective western boundary for deep circulation in the North Pacific.

PCM8 Deep current measurements south of the Aleutians are required to provide better transport structures than were obtained from an earlier experiment at 175º W which showed strong, nearly steady deep currents.

PCM9 Deep current measurements are required northeast of Chatham Rise where the deep flow enters the Southwest Pacific Basin from the south.

PCM10 Deep current measurements are required east of the East Pacific Rise in the deep flow into the eastern South Pacific. The transport is expected to be smaller here than off the Chatham Rise.

PCM11 Deep current measurements are required in Samoan Passage which is the deepest passage between the South Pacific and North Pacific. Observation of the flow through the passage is central to understanding the abyssal connection between the two oceans.

PCM12 Deep current measurements are required in Wake Passage between the Central Pacific Basin and the Northwest Pacific Basin to monitor flow into the western North Pacific. An array at this location is of lower priority than for the Samoan Passage.

PCM13 Measurements of the Mindanao Current at about 7º N. This array measures the southward flow along the western boundary which is fed by the North Equatorial Counter current.

PCM14   Deep circulation measurements are required in the eastern South Pacific at 35⁰ S off South America. An array with current-meters and thermistor chains could be maintained in association with repeat section PR14 or supported by ships on the way to and from Antarctica.

3.4.2.10   Deep Float and Surface Drifter Releases

The surface drifter and subsurface float programme outlined in Section (3.3.2) provides for a basic global mapping of velocity in addition to enhanced sampling in regions of special interest. Deployments for the global float programme and one setting of drifters can be accomplished from the hydrographic lines in Figure 3.6 with minor augmentation in the eastern Pacific between 30⁰ S and 30⁰ N. Additionally, there are several Pacific regions warranting enhanced sampling.

PF1   The recirculation region of the Gulf Stream is now being described using floats. A complementary study of the Kuroshio recirculation needs to be carried out, but a resolution exceeding the global plan is required in both the horizontal and vertical.

PF2   The entire South Pacific western boundary current region including the Tasman Sea, South Fiji Basin and the deep western boundary current region east of New Zealand should be covered with acoustically tracked floats at two levels (thermocline and about 2500 m).

PF3   Float sampling for a velocity reference level must be of the highest quality under the major transport and flux sections at 28⁰ S and 24⁰ N.

PF4   The pathways of cross-equatorial transport, both at the surface and at depth, should be defined by enhanced sampling using two or three levels of floats within $\pm10°$ of the equator across the entire Pacific, with highest sampling in the west.

PF5   Deep water flow from the Samoa Basin through the Samoa Passage or into the Penrhyn Basin should be studied with deep float releases in conjunction with hydrographic lines (see 3.4.2.2) and current meters (see 3.4.2.9).

PF6   The pathways of deep flow between the Southern Ocean and the South Pacific should be examined by direct deep float measurements, near the 43⁰ S and 57⁰ S hydrographic lines on both side of the Pacific Rise.

PD1   The entire South Pacific western boundary current region including the Tasman Sea, South Fiji Basin and the deep western boundary current region east of New Zealand should be covered with surface drifters.

PD2   The pathways of cross-equatorial transport, both at the surface and at depth, should be defined by accelerated sampling using drifters within $\pm10°$ of the equator across the entire Pacific, with highest sampling in the west.

3.4.2.11   Sea Level Measurements

An extensive network is already in operation in the Pacific Ocean, particularly in the tropics and mid-latitudes; additional stations are needed in high latitudes. The global network was presented and discussed in Section (3.2.10) and details are given in Vol.1 Section (2.3).

3.4.3 The Indian Ocean

3.4.3.1 Introduction

The Indian Ocean is unique among the world's oceans in several respects:

- it has the strongest seasonal forcing cycle of all tropical oceans through the reversing monsoon wind system, resulting in a seasonally reversing western boundary current, the Somali Current, the seasonally reversing NE/SW Monsoon Current north of the equator and an Equatorial Counter Current in the southern hemisphere which exists during the NE monsoon;

- it has an equatorial current system quite different from the other oceans; firstly, there exists dominantly equatorial convergence instead of divergence; secondly, it has an eastward near-surface jet of semi-annual period; and thirdly, "stacked" undercurrents exist, the generation of which may differ from that in other oceans:

- it is divided into three basins by meridional ridges resulting in the existence of three deep northward western boundary currents;

- it has strong southward western boundary currents: the Agulhas and the East Madagascar currents, which respond to boundary discontinuities in retroflection regimes;

- it has no moderate, polar or subpolar northern regime and a net southward heat export across the equator;

- it has a unique thermohaline structure due to intrusions from marginal seas (Red Sea, Persian Gulf, Arabian sea and Bay of Bengal) and Pacific-Indian Ocean throughflow.

Numerical models, particularly regional models of the monsoon driven circulation and of the southern hemisphere western boundary currents, have evolved to a stage where they are contributing significantly to our understanding of Indian ocean circulation phenomena. A coordinated numerical modelling effort is needed for the planning and subsequent analysis of the Indian Ocean programme.

A list of problems in the Indian Ocean regimes and brief justification of their importance are given below.

A. Polar to Subtropical Indian ocean

· The Agulhas Current is the strongest western boundary current in the southern hemisphere, and the associated retroflection and return flow off southern Africa encompasses a flow regime marked by high eddy kinetic energy, and vigorous interaction of different water masses and large heat loss areas.

The East Madagascar Current appears to retroflect off the southern tip of Madagascar but its role in coupling the East Madagascar and Agulhas Currents is not known.

· Subtropical Mode Water is formed in the Agulhas gyre and Subantarctic Mode Water north of the Antarctic polar front. Studies of mode water formation in general and regional measurements of its formation and penetration into the thermocline in the southern Indian Ocean are needed.

· The Leeuwin Current flows poleward and against the prevailing wind. Its role in the Indian Ocean heat and fresh water budget and its connection to the Indian Ocean-Pacific throughflow is not understood.

· Deep northward western boundary currents exist along the 90º E Ridge in the Western Australia Basin, the Central Indian Ridge in the Central Basin and the Madagascar Ridge in the Madagascar Basin with a joint transport that has been estimated to be 15 Sv at 19º S. The return flow remains to be identified - seasonal and/or interannual variability in the Somali Basin and the circulation in the deep basins off southern Africa need to be quantified.

· Other objectives relevant to WOCE in the Indian Ocean sector are included as part of Core Project 2.

B.   The Northern and Monsoon-driven Circulation

°   There is a mean near-surface northward cross-equatorial transport in the seasonally-reversing Somali Current with a subsurface maximum at about 200 m and variable southward undercurrents in the depth range 400-1200 m with small mean transport. Below 2000 m there are indications of a variable western boundary current which is in the wrong sense to remove the heat gained by the Indian Ocean from the atmosphere north of the equator. Clarification is needed of the oceanic heat balance, and where transports return across the equator.

·   The zonal equatorial current system of the Indian Ocean has several important features. These include:

    (a)   the reversing current of relatively saline water south of India/Sri Lanka, which flows eastward in the summer monsoon, and westward in winter. Its transport has not been measured, but it seems likely to influence the longitude of cross-equatorial transport and its seasonal variability, away from the western boundary.

    (b)   an eastward surface jet running along the equator in the monsoon transition periods accompanied by semi-annual changes of slope of the thermocline in the E-W direction. Below this, a complicated vertical profile of predominantly zonal currents is found on the equator, part (but not all) of which is also of semi-annual period with downward propagation of energy.

    (c)   the south equatorial counter current, which exists only in the winter monsoon, separated from the south equatorial current by a frontal zone, the role of which in the meridional transfer of heat and salt needs to be considered.

    (d)   The South Equatorial Current, which is reinforced by the Pacific-Indian Ocean throughflow, may leave the Indian Ocean by way of the Mozambique Channel, although its characteristic low-salinity core is not recognizable beyond Madagascar. It appears to have less seasonal variability than would be expected from the strongly varying wind stress curl.

    These zonal monsoon-driven currents provide striking contrasts with other equatorial regimes and are readily amenable to study by means of satellite altimetry. They should be given attention in WOCE.

·   The summer cooling of the surface layer of the Arabian Sea is another phenomenon unique to the Indian ocean. With the onset of the SW monsoon, the combination of very strong wind stress and its curl distribution results in a SST cooling of about 4 ^{o}C between April and August. The processes involved include upwelling (both coastal and open-ocean), advection, and entrainment of water from below the mixed layer, as well as heat exchange through the sea surface. Their relative importance varies from place to place and needs study.

·   Direct measurements of the magnitude of the throughflow between the Pacific and Indian Oceans have yet been made. The throughflow seems likely to be large enough to contribute significantly to heat and salt fluxes in the Indian Ocean.   Its seasonal and interannual fluctuations need to be studied in relation to variations in Pacific-Indian Ocean pressure gradient and as to whether within the Indian Ocean itself it has some dynamical significance.

C.   Oceanic heat flux

·   In the annual average, the Indian Ocean appears to gain heat from the atmosphere at all latitudes north of 10-15° S, and consequently must export an increasing amount of heat southward through the same latitude range. The situation is complicated by the Pacific-Indian Ocean throughflow. This makes it advisable to choose a zonal section north of 10° S, for the purpose of enclosing a large area to the north in which heat exchange with the atmosphere has the same annual mean sign. Variable meandering, mainly zonal, currents are to be expected at all latitudes north of 15°S; the least undesirable choice of latitude for a heat flux measurement seems to be 5° S. A suitable subdivision of the rest of the area for heat flux purposes would be provided by measurements on sections at 20° S, (including the Mozambique Channel), 32°S and between Java and Australia across the Pacific-Indian
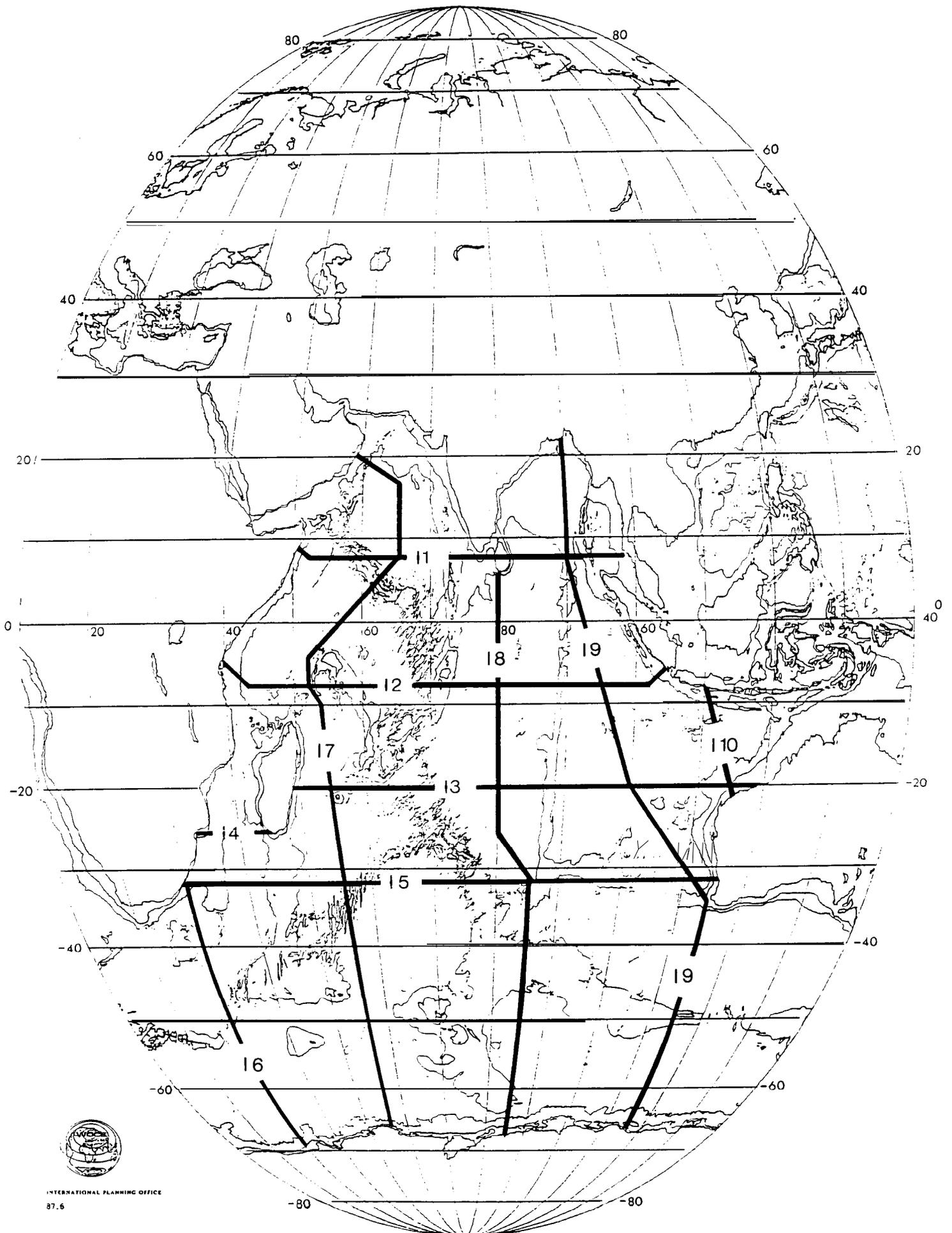
Fig. (3.10)   One-time WHP of the Indian Ocean

Ocean throughflow. For a meridional heat flux section, the most suitable choice would appear to be at 80º E, from Sri Lanka to Antarctica.

3.4.3.2 Hydrographic measurements (one-time survey)

Basin-wide sections

Ten sections are shown in Figure 3.10. For the deep water, this network provides at least one, but no more than two, meridional and zonal sections across each basin. At intermediate depths, there are three or four sections running through the region occupied by each of the major water masses of the Indian Ocean sector. In order to enhance the sampling in critical areas, intensive surveys (Figure 3.11) are proposed for the Agulhas Current and retroflection, Somali Current and Arabian Sea, and Indonesian through-flow. Studies deemed necessary for these regions have more of a Core Project 3-type character and are not discussed in detail here.

Zonal sections

I1   8º N: This section closes off the Arabian Sea and Bay of Bengal, and crosses the Somali Current where it is deep.

I2   8º S: This section has been chosen to cross the observed zonally-extended trough in mean dynamic topography that suggests minimal zonal currents. At both ends, it should run north to about 5º S at the coasts to cut the boundary currents at a latitude where they are more confined, particularly in the west. This section is needed to provide a near-equatorial meridional heat flux measurement. It is far from ideal for this purpose, with variable meandering zonal currents running along it, but seems to be the best choice. The likely accuracy attainable in these circumstances needs to be further explored.

I3   20º S: This section has been chosen to cross the subtropical gyre between Madagascar and northern Australia.

I4   25º S: This section crosses the Mozambique Channel between Africa and Madagascar.

I5   32º S: This section crosses from Africa to Australia and is the principal meridional heat flux section for the Indian Ocean. It repeats a section worked in 1987.

Meridional sections

I6   30º E: This section crosses the Agulhas Current and the Agulhas Return Current eastward of the complex eddy field of the retroflection. Further south, it crosses the ACC before it encounters the Crozet Plateau. Comparison with the ACC structure measured on I7 will reveal any alteration of the structure (filamentation) induced by ACC/topography interaction.

I7   55º E: This section goes from Arabia to Antarctica.   It crosses the central Arabian Sea, veers to the southwest to pass west of the Seychelles-Mauritius plateau and through the Mascarene and Madagascar basins then merges with the Core Project 2 section along 57º E south of 32º S.

I8   80º E: This goes along 80º E from Sri Lanka southward to 25º S, veering to the southeast to 90º E to merge at 32º S with the Core Project 2 section. This section is the mid-ocean section across which heat and fresh water fluxes will be measured.

I9   100º E: This section between the Bay of Bengal and Australia, passes through 20ºS, 100º E and then veers to the southwest tip of Australia where it merges with the 115º E section of Core Project 2.

I10   110º E: This short section from Java to Australia closes off the Indonesian through-flow regime.
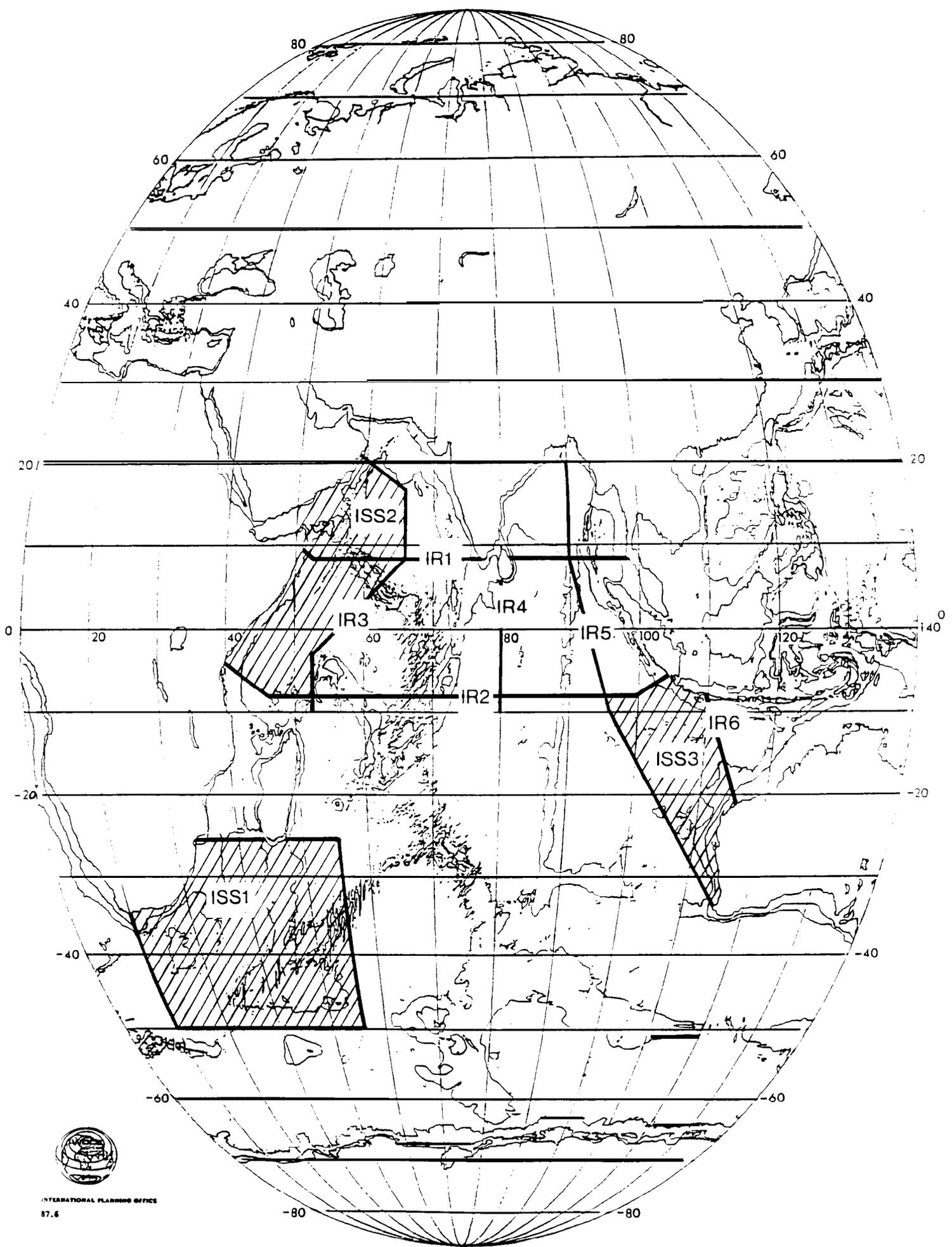
Fig. (3.11)   Repeat Hydrography in the Indian Ocean

The three meridional sections I7, I8 and I9 will provide meridional measurements in each of the three large basins and marginal coverage of the zonal current system. The northern parts of these sections should be carried out twice, during the extremes of the winter and summer monsoons.

Special survey areas

Three regions are marked for special surveys beyond the scope of WHP lines and mooring lines.

Studies deemed necessary in these regions are more process-oriented and only briefly mentioned here. The regions are:

ISS1   The Agulhas Recirculation Regime: The study of thermocline ventilation, eddy/mean flow interaction in the Agulhas recirculation gyre.

ISS2   The Somali Current/Arabian Sea Regime: The study of the Arabian Sea gyre response to the monsoon onset including the joint effects of entrainment, advection of upwelled water from the Somali and Omani coasts and Ekman pumping in determining mixed layer depth and surface cooling.

ISS3   The Pacific/Indian Ocean throughflow Regime: The study of the seasonal/interannual throughflow pathways and variability as well as water mass transformation.

3.4.3.3 Small Volume Tracers

In addition to nutrients, oxygen and salinity, small-volume tracers will be sampled along the sections listed in paragraph 3.4.3.2. They will be particularly required in the Central and Eastern Indian Ocean not covered by the INDIGO programme. Since GEOSECS occurred in 1978 and INDIGO in 1985-1987, repeat measurements of transient tracers should be made during the WOCE period.

3.4.3.4 Large Volume Tracers

High precision radiocarbon large-volume carbon is to be measured in the deep ocean areas not covered by the GEOSECS and INDIGO programme, mostly in the Central and Eastern Indian Ocean. Samples for ^{85}Kr and ^{228}Ra should be obtained in the upper ocean layer.

3.4.3.5 Hydrographic Time Series from Research Vessels

Sections I1,I2 and I10 and the northern parts of I7, I8 and I9 will be carried out at least twice at the extremes of the winter and summer monsoons.   These are shown In Figure 3.11.

3.4.3.6 XBT/XCTD Sections from Ships-of-Opportunity

For the Indian Ocean no XBT/XCTD lines are proposed beyond those planned for TOGA (Figure 3.12).

3.4.3.7 T/S Chain Measurements

Surface drifters with thermistor chains should be released along with a portion of the current-following surface drifters. Approximately one-third of the required 560 drifters should be equipped with thermistor chains (see Vol.I, Section 5.4).

3.4.3.8 Surface Flux Drifters

Surface flux drifters with thermistor chains are recommended in regions which are not adequately covered by merchant ship observations (see Vol.I, Section 5.4).
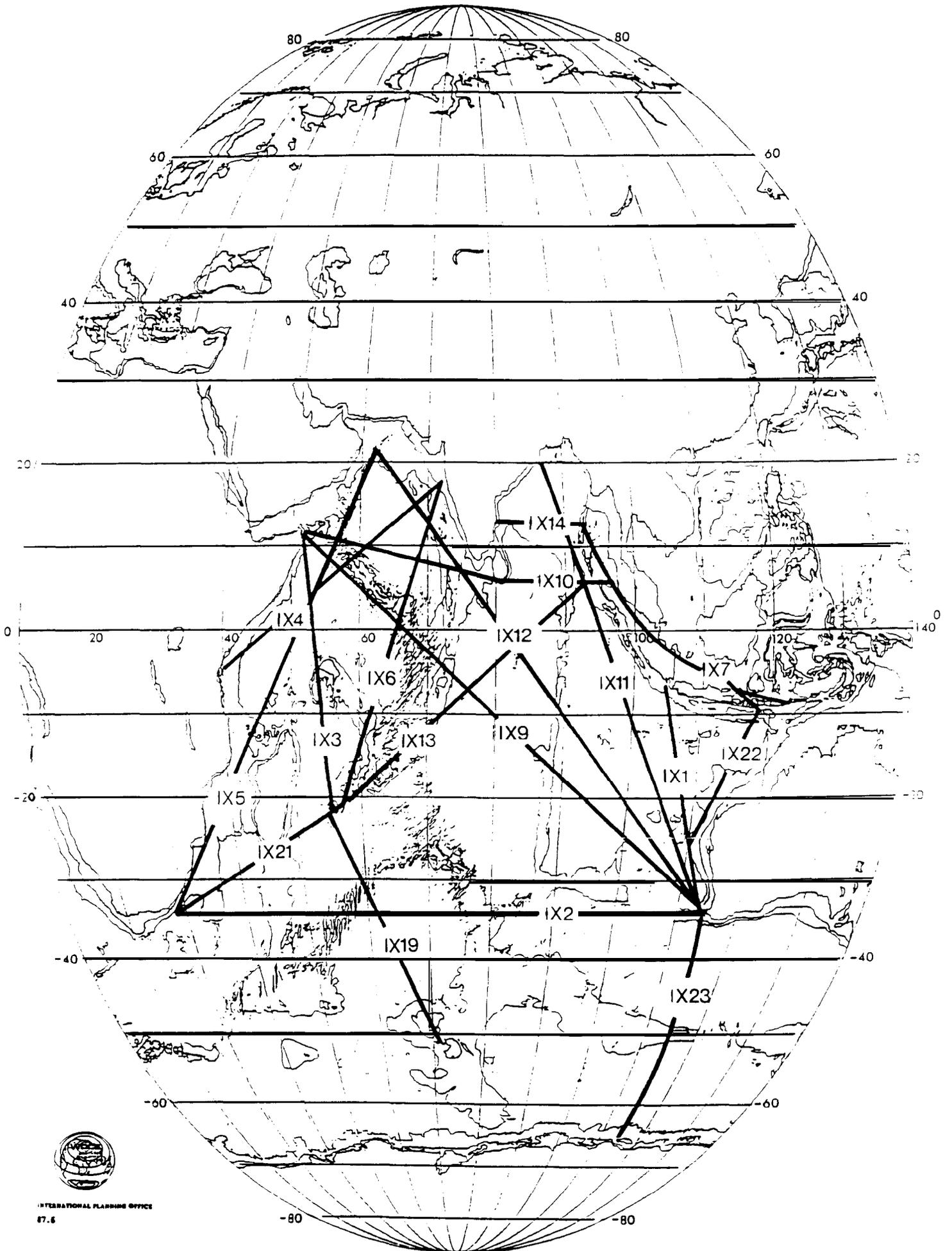
Fig. (3.12)   VOS Network in the Indian Ocean

3.4.3.9 Boundary Current Transport Measurements

Following the general approach given in Section (3.2.5), moored boundary current arrays are proposed for a number of locations shown in Figure (3.13). They are:

ICM1   Measurements are needed of the Agulhas Current, at the western end of the heat flux section at 32° S.

ICM2a&b   Measurements are needed of the Leeuwin Current, at the eastern end of the heat flux section at 32° S. Both (a) and (b) are needed for heat flux determination across the 32° S section but are also in fairly unknown boundary currents, of which the transports, and their seasonal and interannual variations, need to be determined.

ICM3   Measurements are needed of the three northward deep boundary currents, along Madagascar, the eastern slope of the central Indian Ridge, and of the 90° E Ridge.

ICM4   The Indonesian Seas throughflow needs to be monitored during WOCE. It is anticipated that after an initial intensive experiment with moored instrumentation and hydrographic sections in which sea-level measurements are calibrated as indices for transport only a moderate array is needed during the course of WOCE.

ICM5   An array needs to be located at the western end of the 8° S section. Near the surface, the East African Coast current flows northward with apparently fairly steady currents while the deep western boundary current exists below 2500 m. Both need to be sampled.

ICM6   Similar measurements need to be made at the eastern end of the 8° S section. Not much is known about the currents off Sumatra and exploratory shipboard profiling prior to array design will be required.

ICM7   Measurements are needed of the Somali Current at 9° N, at the western end of section II. This array is to measure the seasonal cycle of Somali Current transport in the northern branch, and of the deep boundary current which had been found to flow in opposite directions during two previous studies.

Special measurements are needed of the Monsoon jets:

ICM8   A mooring line is required along 80° E to extend southward from Sri Lanka to across the equator at 2°S to simultaneously measure the transport variability of the SW/NE Monsoon Current north of about 2° N, and the seasonal and interannual variations of the equatorial jet and undercurrents.

ICM9   Two moorings are required along the equator, the western one at about 55° E and the eastern one at 93° E, are required to measure propagating events (as recommended by the CCCO Indian Ocean Panel).

Estimates of the required number of moored stations and number of instruments per section, considering the specifics of each array, such as: assuming only deep boundary current measurements at ICM3, a reduced array at ICM4, and a large array covering two current regimes at ICM7, yield a total requirement for approximately 200 current-meters if all intensive phase measurements were to overlap. In addition, the monsoon and equatorial current arrays ICM8 and ICM9 would need 8 self-contained upward-looking ADCPs for measuring the near-surface current structure. In the monitoring phase it is estimated that the moored instrumentation requirement may drop to between 20 to 40% of the intensive phase requirement depending on how well transport is correlated with simple monitoring indices.

3.4.3.10   Float and surface drifter programmes

The global float release at 2500 m and about 500 km horizontal resolution is appropriate for the Indian Ocean.
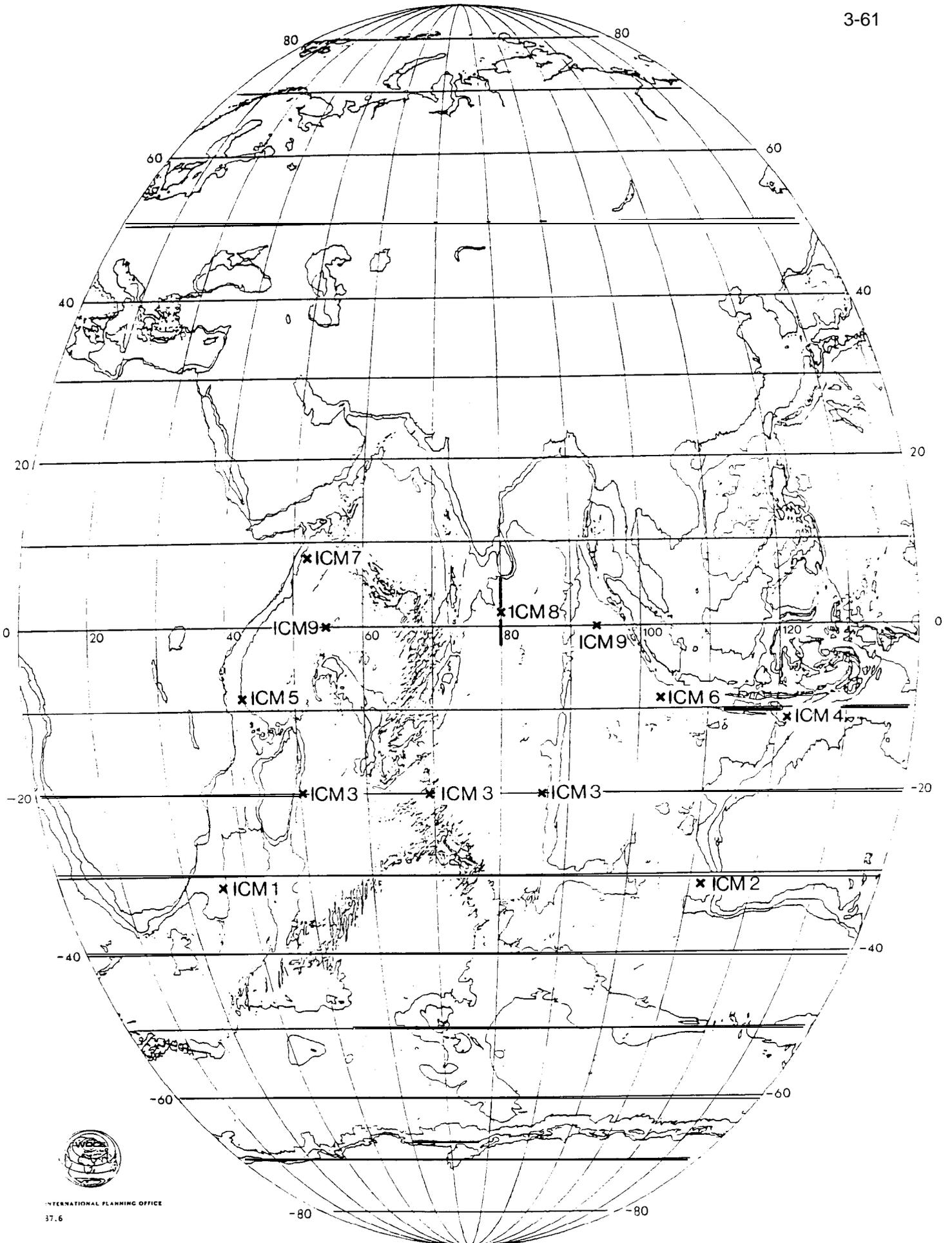
Fig. (3.13)   Mooring Sites in the Indian Ocean

Sequential release of pop-up floats will be made where currents enter the Indian Ocean basin to explore their further paths, particularly in two regions:

IF1   Special releases will be a valuable tool to determine the pathway and volume flux of various cross equatorial flows. In addition to the 2500 m floats, which should capture the Deep Water core layer, floats should be released at 1000 m in the Antarctic Intermediate Water and at 4000 m in the Antarctic Bottom Water layer. Floats should be seeded into these latter two layers around 5º S with a greater concentration in the west. A combination of SOFAR and RAFOS floats would be preferable to pop-up floats as one would like to be able to resolve narrow intense flows that might exist close to the equator.

IF2   In the deep northward western boundary currents along the three meridional boundaries (measured by array ICM3 of Section 3.4.3.9) floats are needed to investigate where the water spreads and the preferred pathways for exchange among the basins. The depths of these floats will be about 3500 m.

IF3   In the Pacific-Indian Ocean throughflow regime (Timor Channel) floats are needed to investigate the path of this water in the Indian Ocean and explore whether in fact a link exists to the South Atlantic. These floats need to be at a shallow level, 700 m or less.

ID1   Surface drifters could be released in conjunction with deep float release or along the frequently travelled line near 55º E (as marked in Figure 3.10). Seasonal release at 1º resolution between 12º N and 15º S would require approximately 100 drifters, one-third of them with thermistor strings. With an assumed 2.5-year lifetime, they would be distributed throughout the entire tropical and subtropical Indian Ocean. These releases should be repeated 2 times, depending on the lifetime of the drifters, to give an approximately 5 year coverage and provide information on interannual variability.

3.4.3.11   Sea level

Sea level measurements will be used for altimeter calibration. Details of the sea level programme are given in Vol.I, Section 2.3. Sea level measurements in the Indonesian Archipelago are required in order to measure Pacific Ocean to Indian Ocean throughflow.

4   CORE PROJECT 2

'THE SOUTHERN OCEAN'

4.1   Introduction

The importance of the Southern Ocean in the global climate system is well documented through the Southern Ocean's influence on the water mass characteristics of the world ocean (about 55 to 60% of the ocean volume owes its characteristics to Southern Ocean processes); as the site of a major heat sink for the world ocean (the poleward heat flux across 60° S is estimated as 5.4×10^{14} W); and as the principle link between the three major oceans (the Antarctic Circumpolar Current has a characteristic transport of 130×10^6 m^{3}s^{-1} or 130 Sv, where Sv = Sverdrup = 10^6 m^{3}s^{-1}). However, the dominant mechanisms responsible for water mass formation and spreading, the meridional and inter-ocean flux rates and the magnitude of the annual cycle of ocean-atmosphere exchange, in the presence of the spatial/temporal variance of the sea-ice cover, are only vaguely known.

Ventilation in the Southern Ocean is induced by a combination of regional Ekman upwelling and intense thermohaline or buoyancy forcing by the atmosphere. The cryosphere complicates water mass modification in two ways: the highly spatial and temporal variable sea-ice cover strongly influences the coupling of the ocean and atmosphere with regard to momentum, heat, water and gas exchange; and the ocean interaction with glacial ice influences the characteristics of water masses, and may be a significant factor in glacial ice budgets.

4.1.1   The Role of Core Project 2

WOCE will enable much improved quantitative estimates of the role of the remote and hostile Southern Ocean in the climate system. The effort will contribute to the construction, improvement and verification of large-scale ocean models. This will include dynamic/thermodynamic modelling of the sea ice cover. Eddy resolving models are of special importance to the Antarctic Circumpolar Current (ACC), where observations indicate a significant contribution of eddies towards meridional fluxes. Coarse-scale models with proper parameterisation and topography are important in evaluating the role of form drag, induced at the major topographic features encountered by the ACC.

Because of the vastness of the Southern Ocean, its remoteness and environmental factors, Core Project 2 will rely heavily on remote sensing from satellites (microwave and IR Radiometers, altimeter, scatterometer and visible light images); arrays of moored instruments and the Lagrangian measurements from drifters and floats. The use of satellite-telemetry data-links are of special importance for the latter as well as for tide gauges placed at remote Islands. A number of different mooring approaches are anticipated: clusters for eddy statistics and transport monitoring arrays across interbasin passages (Choke Points) and other circulation features. Drifters equipped with various meteorological and ocean sensors, including temperature/conductivity (T/C) chains would provide meteorological and upper ocean information needed to improve the determination of ocean-atmospheric flux. Hydrographic and tracer sections as part of the WOCE Hydrographic Programme along various meridians and zonal lines will provide the required property distributions from which the primary frontal zones, water mass spreading pathways and time-scales information can be resolved.

The Core Project 2 Planning Meeting, held in Bremerhaven, F.R. Germany in May 1986, discussed the WOCE-related scientific problems of the Southern Ocean (WCP-138, Anon. 1987a). Three basic themes for Core Project 2 were identified:

•   the Antarctic Circumpolar Current including interbasin exchange and the dynamic balance of the ACC.

- meridional transports including that through and out of the Southern Ocean, eddy fluxes across the ACC, cyclonic gyres, shelf-slope exchange, deep boundary currents and water mass spreading pathways.

- ocean-atmosphere fluxes including water mass modification, mixed layer seasonal evolution, ocean/sea ice interaction and polynya generation and ocean-glacial ice fluxes.

The various expeditions into the Southern Ocean over the last 60 years have defined much of the large-scale thermohaline or water mass structure and associated baroclinic circulation pattern. However, it is surprising how few details of these patterns are known, particularly to modern standards of resolution. In addition, little is known of water mass residence-times or formation rates, and the barotropic circulation pattern which is substantial in the Southern Ocean, is not resolved. The water masses produced by the intense ocean-atmosphere interaction within the Southern Ocean, often involving sea and glacial ice, spread into the global ocean. The nature of the coupling of the Southern Ocean with the rest of the global ocean is poorly known. Where do Southern Ocean water masses enter the larger scale system, at what rates and by what processes? Where is the compensating southward flow?

In view of the global impact of the Southern Ocean, improvement of our knowledge of the basic large-scale characteristics of the thermohaline and tracer fields as well as the circulation pattern of the Southern Ocean and the nature of the interaction with lower latitudes regions of the global ocean is placed on high priority during WOCE. To substantially improve our knowledge of the Southern Ocean and properly place it into global climate models, a series of activities are recommended as part of Core Project 2. These are divided into the Large-Scale and Specific Experiment components described in Section (4.3).

4.2   Primary Scientific Problems

In this section, the basic oceanographic issues and questions are presented. These must be addressed to advance our quantitative understanding of the Southern Ocean and its place in the global ocean and climate system. The Core Project 2 programme is based on these requirements for progress, much of which is rooted in the need to refine and validate numerical models of the general ocean circulation.

4.2.1   Requirements of Models

Modelling ability and computational power have reached the point where it becomes feasible to consider real-time assimilation of Southern Ocean data into a simple layered model (or with similar reduced physics), although costs are still too high to contemplate doing this with a complex OGCM (Oceanic General Circulation Model). Thus Core Project 2 occurs at the right time for a large modelling endeavour and there are indications that this endeavour is just beginning, in both the USA and Europe.

There is substantial work towards developing of eddy resolving model for the Southern Ocean (see Vol. I, Chapter (4) for a discussion of modelling). Improved description of the stratification, water mass time-scales and circulation, both baroclinic and barotropic components, their mean and variable parts, is needed to test the validity of these models. The basic questions that will arise about the validity of the model are the main design criteria for the field activities recommended within Core Project 2.

Models have, at a very simplistic level, to reproduce:

- the approximate water mass and tracer structure of the Southern Ocean,

- the coarse description of the direction of flow of the major currents. The gyres in the subtropical basins, and those in the peripheral seas such as the Weddell and Ross Seas, should circulate in the right direction,

- the seasonal variation of the ice cover.

Assuming that a model can reproduce these gross features of the Southern Ocean, the next test involves a simple set of numerical comparisons, such as whether the model reproduce:

- the observed mean flux of the ACC,

- the net circulation in each of the subtropical gyres,

- the observed fluxes through deep gaps.

If the model can successfully reproduce the mean state of the Southern Ocean one must ask

- whether the model simulates the observed variation of the ACC flux over time both seasonally and interannually.

The most stringent test of models for decadal climate prediction will be whether they

- reproduce the observed mean and eddy fluxes of momentum, freshwater and heat

The need for data to allow these tests to be carried out in models for decadal climate prediction, has guided the design of the Core Project 2 field programmes.

4.2.2   General Description of the Southern Ocean Thermohaline, Tracer Structure and Circulation Pattern

The major justification for having a Southern Ocean Core Project within the WOCE Goal 1 is to improve the description of its role "both as a pipeline for mass transfers between the other oceans and, on the zonal average, as a region where heat supplied at low latitudes is lost to the atmosphere". Therefore one needs to quantify the amount of heat and freshwater exchanged with the atmosphere, the meridional fluxes and formation rates of a variety of water masses and the exchange of these products with the oceans further north. These processes are interrelated and strongly dependent on the large-scale, time-averaged circulation and its variability.

The present knowledge of the Southern Ocean circulation is based primarily on the historical hydrographic data which has provided the basic qualitative description of the baroclinic circulation and water mass distribution. Direct, long-term current measurements have lead to fairly accurate estimates of the Antarctic Circumpolar Current (ACC) mass transport, its variability and the potential role of the variability in the meridional transport of heat. These measurements however are confined to the Drake Passage and the validity of extrapolating these results to other areas needs to be explored. The barotropic component of the circulation is significant, particularly south of the ACC, yet it is an elusive component that can be studied only via direct measurement. Improving the present knowledge of the three-dimensional circulation of the Southern Ocean is mandatory in order to establish quantitatively its role in the global circulation.

A "block diagram" showing the water mass structure and sense of the circulation was developed by Deacon (1937) based on the circumpolar expeditions of the DISCOVERY. This schematic portrays the zonally averaged conditions. Data collected after the DISCOVERY period has not altered the schematic, but these data suggest caution, in that the schematic is a gross over-simplification of the Southern Ocean. The schematic does not show that there are significant variations with longitude as well as time variations, in the water mass characteristics. However, the Southern Ocean has an array of component regions as diverse as any other major ocean. These distinct regimes are responsible for unique contributions to the larger picture of the general circulation.

Antarctic Bottom Water forms at a number of sites and in a variety of forms (Gordon, 1973, 1982; Foster and Carmack, 1976; Carmack and Killworth, 1978; Jacobs et. al. 1985). There are year to year variations in the bottom water flowing out of the Weddell Sea (Foster and Middleton, 1979, 1980). North Atlantic Deep Water introduces salty water of high oxygen content into the circumpolar belt, but deep waters with other characteristics, derived from the Pacific and to a lesser extent from the Indian Ocean, also influence the Circumpolar Deep Water (Georgi, 1981). Antarctic Intermediate Water probably does not form uniformly around Antarctica, nor is it the only or even primary ventilator of the sub-thermocline stratum of the ocean.

The deep mixed layer just north of the Polar Front, in the Subantarctic Zone, is the source for a water mass ventilating the mid to lower thermocline as Subantarctic Mode Water (McCartney, 1977, 1982; Georgi, 1979; Molinelli, 1981).

The subtle spatial variations in water mass characteristics within the relatively homogeneous Southern Ocean, make it a difficult task to detect the spreading pattern and sources of these water masses. The strong interaction of the ocean with the polar environment under a variety of boundary conditions, as well as the nearly homogeneous thermohaline field, and the small scales associated with high latitude processes, make tracers with well-defined source functions particularly well suited for Southern Ocean studies.

Basic Questions: What is the large-scale water mass structure and spreading pattern and what is the general circulation of the Southern Ocean?

These questions will be primarily answered within Core Project 2 by measurements of the WHP and the drifter and float programmes, although many of the more specific elements of the Core Project 2 field work will provide crucial results.

4.2.3   Antarctic Circumpolar Current (ACC)

4.2.3.1 Inter-ocean Exchange

Reliable values for the ACC transport and variability through the Drake Passage exist for the International Southern Ocean Study (ISOS) observing period of the 1970s (see the review by Nowlin and Klinck, 1986). The ISOS current-meter and pressure transducer 1979-1980 time series in the Drake Passage indicate a transport above 2500 m of 130 Sv with a standard deviation of 10 Sv (Whitworth, 1983; Whitworth and Peterson, 1985). The baroclinic mode accounts for 70% of the transport, with the barotropic mode accounting for the remainder mainly at the higher end of the frequency range. The pressure-transducer data set from sensors placed at 500 m depth on both sides of the Drake Passage, which extended to March 1982 (Whitworth and Peterson, 1985), agrees with the current-meter results to within 24 Sv.

Extended pressure records across the Drake Passage indicate that the variability seen during the 1979 monitoring period is characteristic of the longer period and that it is largely barotropic and could be monitored with a simpler experiment. Thus, it seems unnecessary to plan for a major, expensive absolute transport monitoring experiment during WOCE. Rather, we should plan to obtain a suite of estimates of the zonal heat, salt and volume fluxes by the ACC south of South America, Africa and Australia or New Zealand, as discussed within the choke point experiment.

The basic question is, what are the mean zonal transports of mass, heat and salt by the ACC between the three oceans?

4.2.3.2 Thermohaline Structure of the ACC and Associated Fronts

The Southern Ocean has a distinct structure marked by various fronts (Deacon, 1982). While many are circumpolar, such as the Polar Front, or Antarctic Convergence, they, like the ACC, display much variability in characteristics with longitude. Within the upper water column, characteristics change abruptly across the fronts. The fronts separate stratification zones (Gordon et al, 1977a,b) with stronger baroclinic currents associated with the fronts. The water masses associated with the fronts and zones of the Drake Passage are discussed by Gordon, Georgi and Taylor, 1977a; Sievers and Nowlin, 1984; Nowlin and Clifford, 1982. The ACC is composed of two current cores separated by the Polar Front Zone, in which the near-surface characteristics are intermediate between those of the Antarctic Zone south of the current and the Subantarctic Zone to the north. The fronts are the Polar Front and the Subantarctic Front. They are probably circumpolar though significant spatial variations occur (Emery, 1977; Hofmann, 1985). Widths of the fronts are 50 km or less at Drake Passage (Nowlin and Clifford, 1982). Additionally, there is the shelf-slope front at the continental margin and the Weddell-Scotia Confluence at the northern limit of the Weddell Gyre (Gordon, 1967; Deacon and Moorey, 1975; Patterson and Sievers, 1980).

The geostrophic shear at the fronts, with reference to measured subsurface currents or to deep reference levels, indicates maximum geostrophic surface speeds at the ACC cores of 30-45 cm/s at Drake Passage (Whitworth, 1980). With a very deep pressure surface as the reference, closely spaced stations along the Greenwich Meridian yield similar surface speeds (Whitworth and Nowlin, 1987). The geostrophic shear associated with these fronts extends deep into the water column and even down to the bottom in Drake Passage (Nowlin et al., 1977).

The basic question is whether these fronts are found within the full circumpolar belt and if not, where do they occur, what is responsible for their generation and what effect do they have on the meridional transports of mass, heat and fresh-water?

This question is approached with the WHP sections (and possibly by the drifters) and by the choke point experiment (Section 4.3.2.1).

4.2.3.3 The Relationship of ACC Variability to Atmospheric Forcing

To a first approximation, wind forcing is responsible for the Southern Ocean circulation. The westerlies within the circumpolar belt are quite strong, with the maximum westerlies situated in close proximity to the ACC (Nowlin and Klinck, 1986). Wind stress within this maximum of more than 0.2 Nm^{-2} occurs over extensive sectors. This is particularly the case in the Indian Ocean sector, where the northern extent of Antarctica's ice cap compresses the atmospheric thermal gradient over the ocean strengthening the zonal winds. The wind field produces Ekman divergence (upwelling) south of the ACC and convergence (sinking) to the north. Observation of the ACC within the Drake Passage indicates that the ACC transport is closely related to the zonal wind stress (Wearn and Baker, 1980). A simple linear Sverdrup model seems to fit the gross latitudinal form of the ACC (Baker, 1982).

The basic question is what are the time and space scales of response of the ACC to atmospheric forcing?

The answer requires a better estimate of the space and time-scales of the forcing as well as the ocean response. This will be provided by global wind-field assimilations using satellite scatterometer and additional input from air pressure sensors placed on drifters. A programme of across-ACC deep sea pressure measurements and sea level gauges at selected locations around Antarctica will give first-order information on the frequency-amplitude response of the ACC as a function of location, that is information on the zonal wavenumber response. These sites would be mainly related to the choke point experiment, though many more islands should be used for the sea level gauge network, as discussed in the large-scale circulation plans (see Vol II, Chapter 3).

4.2.3.4 The Dynamical Balance of the ACC

Munk and Palmen (1951) recognized that the Sverdrup model of the sub-tropical gyres was not applicable to the special geometry of the Southern Ocean. Without a meridional boundary, there is no eastern boundary to support the zonal pressure gradient of the Sverdrup interior, nor a western boundary on which a boundary layer could exist to close the circulation.

Munk and Palmen and others (Welander, 1976; Bye and Veronis, 1976; Hidaka and Tsuchiya, 1953; Bryan and Cox, 1972) explored other methods to balance the wind-stress but nearly all gave unrealistic results. However, deep reaching currents offered the possibility of significant pressure torques on the ridge systems and topographic features of the Southern Ocean to balance the momentum budget for the ACC. These terms play a major role in the zonal momentum budget for the atmosphere. There are four principal topographic features (Kerguelen Plateau, Macquarie Ridge, the South Pacific Ridge, and the South Antillean Arc). Munk and Palmen estimated that a pressure head on each ridge of about 4 cm was sufficient to balance the total integrated wind stress on a latitude circle. The balance is inviscid in the sense that it is manifested as a difference in the essentially geostrophically balanced pressures on the two sides of a ridge. The mechanism behind this pressure difference may be viscid, inertial, or a rectification of time-dependent effects. If the deep flow follows roughly the same pattern as the shallow, and retains "a few percent" of the surface pressure gradient magnitude, then the mechanism of form drag is viable. While we do not know the absolute

dynamic height, a nearly linear relationship between the dynamic heights as various pressures relative to various reference pressures has been noted (Lutjeharms, 1981).

Basic Question: How is the ACC's energy dissipated?

This issue would be approached in a variety of ways, including the eddy statistics arrays and a possible form drag experiment. However, much might be done with a eddy resolving model, which has been properly validated with observations from the WHP and drifter/float measurements.

4.2.4 Meridional Transports

4.2.4.1 Eddy Flux across the ACC

The heat flux across the ACC and polar front at about 53_o S is 3.1 x 1014 W (Gordon and Owens, 1987). The heat flux across 60" S is larger, amounting to 5.4 x 10^{14} W. This poleward heat flux must be accomplished by the ocean to maintain a steady state condition. The ocean can accomplish this by three methods: mean flow, eddy flux and Ekman layer transport. The Ekman flux carries 1.5 x 10^{14} W heat to the north, so the mean and eddy flux must carry 4.6 x 10^{14} W to the south.   Mean flow has been ruled out as being significant in regard to meridional heat flux by de Szoeke and Levine (1981). However, the ACC forms an effective block to mean meridional flux only to a depth of about 2000 m.   Below that level, submarine features allow boundary currents to bridge the circumpolar belt. The near bottom currents of cold Antarctic Bottom Water (AABW) balancing southward flowing warmer Circumpolar Deep Water (CDW) might account for 25%, but direct measurement of these features are needed to assess this means of heat transfer.

Using time series of current-meter and thermistor measurements the eddy heat flux across the ACC has been estimated for the Drake Passage and at a site southeast of New Zealand (see Nowlin and Klinck, 1986 for a review) with values from 3.7 x 10^3 W/m^2 as an average for Drake Passage to 30 x 10^3 W/m^2 for the upper 2000 m in northern Drake Passage and at the New Zealand site. Extrapolation around Antarctica leads to a poleward total eddy heat flux value of 3 to 6 x 10^{14} W. Thus, eddy heat flux seems to be the prime "mover" of heat. Unknown is how representative the Drake Passage and New Zealand areas are for the full circumpolar belt.

Basic Question: What is the total heat flux by eddy processes and how large is it at sites other than the Drake Passage?

This issue is addressed explicitly by the eddy statistic experiments.

4.2.4.2 Water Mass Spreading Pathways and Rates

Southern Ocean water masses spread into much of the world ocean. This spreading may be accomplished by widespread diffusion and/or by currents confined to passages and western boundaries.   Identification of the process, primary conduits and rates of flow will define the sites and density stratum of the ocean that initially "feels" the effects of the Southern Ocean environment as well as the magnitude of these effects. Global-scale ocean circulation models need to reproduce these features if they are to correctly model the thermohaline circulation.

Basic Question: How, where and at what rates do Southern Ocean water masses invade the world ocean?

Spreading patterns and rates will be best studied using tracer data from the WHP. Specific experiments will monitor the northward flux of Southern Ocean water masses within the major western boundary regimes of the world ocean and are included in the 30" S Choke Point sections.

4.2.4.3 Interaction of the ACC with the Subtropical and Subpolar (Cyclonic) Gyres

The circumpolar belt isolates the region south of 60º S from that north of 50º S. The absence of continuous western boundaries inhibits massive meridional flux by the mean circulation typical of the northern

hemisphere. Such transfer is thought possible at benthic depths where submarine ridges provide the boundaries. As mentioned in Section (4.2.4.1) the eddy field must transfer much of the meridional flux, the inefficiency of this mechanism may explain the glacial state of Antarctica.

The interaction of the ACC with the subtropical gyres to the north and the cyclonic gyres to the south is a poorly explored issue. One envisions filaments of the ACC "peeling-off" into the adjacent gyres, or possibly continuing eddy processes.

Basic Question: How do the meridional fluxes across the ACC interact with the gyres to the north and south of the ACC?

The WHP thermohaline and tracer data will allow identification of the circumpolar contribution to the subtropical and cyclonic gyres, the drifter and float data from the Global Velocity Programme will identify the sites of most active exchange, and the Choke Point experiment including the 30° S heat flux section will provide information on the rates of the interaction between the ACC and subtropical gyres.

4.2.5 Ocean-Atmosphere Interaction

Estimates of ocean-atmosphere heat flux are still subject to large errors. The direct methods are hindered by the lack of meteorological and sea-ice data on concentration and thickness. The indirect method of studying ocean-atmosphere exchange by observing the annual cycle of mixed layer characteristics are hindered by lack of winter data, mainly below the extensive $(20 \times 10^6 \text{ km}^2)$ winter sea ice cover. The strong seasonal variability of the sea ice cover with approximately 10-20% interannual variability of the maximum winter sea ice cover (see fig. 5 of Zwally et al., 1983) further complicates estimates of mean annual ocean-atmosphere energy exchange.

The ocean-atmosphere heat flux has been estimated by a few authors for various sites or latitudes around Antarctica (Gordon and Owens, 1987). South of 60°S at the northern limit of the seasonal sea ice cover, heat loss amounts to an annual average of approximately 30 W/m^2 (Gordon, 1981) but is highly dependent on ice cover. The heat loss north of the polar front leads to the deep mixed layers of the subantarctic zone and formation of subantarctic mode water.

4.2.5.1 Water Mass Modification

The Southern Ocean provides the bulk of the sub-thermocline water masses of the global ocean. The formation processes for these water masses and their production rates have not clearly been defined. This is addressed primarily by the WHP component within Core Project 2, with important contributions from mixed layer studies using temperature sensors and Temperature/Conductivity (T/C) chains on drifting buoys.

(a)   Intermediate Water Masses:

The dominant water mass formed near the polar front is Antarctic Intermediate Water (AAIW; Molinelli, 1981). Its low salinity is clearly seen spreading at the base of the thermocline of the Southern Hemisphere and within the Atlantic into the Northern Hemisphere. During the past decade, traditional theories of AAIW formation were refined and a new interpretation advanced (McCartney, 1977). Subantarctic waters (Subantarctic Mode Water) are characterized by a low vertical stability (pycnostad) and are warmest in the western South Atlantic and coolest in the southeast Pacific. McCartney (1977, 1982) found that southeast Pacific Subantarctic Mode Water undergoes additional cooling in the Drake Passage and western Scotia Sea, and passes into the Atlantic where it can be identified as Antarctic Intermediate Water. However, Piola and Georgi (1982) calculated that the sea-air heat exchanges are insufficient to convert southeast Pacific Subantarctic Mode Water into South Atlantic Antarctic Intermediate Water. Although a subantarctic origin appears unlikely to account for all types of Antarctic Intermediate Water found in the world's oceans (Piola and Georgi, 1982), Subantarctic Mode Water appears to contribute volumetrically significant quantities to the subantarctic and subtropical thermohaline structure (Georgi, 1979).

The <u>basic questions</u> regarding the intermediate water address their formation rates and spreading paths, how their characteristics vary with longitude and how and where they mix into and below the thermocline.

Intermediate water formation studies are best addressed with the WHP observations and by the mixed layer studies utilizing instrumented drifters.

(b)   Water Mass Formation South of the ACC:

(i)   Over the deep ocean south of the ACC and particularly within the Weddell Gyre, the pycnocline is weak; amounting to only 0.2 σ_θ units. In view of the marginal stability of the pycnocline of the Weddell Gyre, slight changes in the magnitude of the entrainment rate of deep water or in the wind induced upwelling rates have a major impact on the thermohaline stratification.

The marginal static stability of the Weddell water column makes the Weddell Gyre susceptible to deep convective processes (Killworth, 1979; Martinson, Killworth, and Gordon, 1981; see Killworth (1983) for a review), as occurred during the Weddell Polynya episode in the austral winters of 1974, 1975 and 1976 (Carsey, 1980). Associated with the Weddell Polynya was massive convective overturning which cooled the deep water by up to 0.5 ˚C down to a depth of 2 500 m relative to the pre-polynya state (Gordon, 1982).

Shorter-lived but recurring polynyas within the subpolar zone have been observed on satellite imagery near 65º S, 5º E (the Maud Rise Polynya), and near 67º S, 45º E (the Cosmonaut Polynya; Comiso and Gordon, 1987). Convective processes at several sites may be intermittent but frequent enough to have a climatic impact.

Significant water mass modification and formation over the deep ocean poleward of the ACC is an important issue in Southern Ocean research, stimulated by:

1.   the observation of the Weddell Polynya in the mid-1970s with associated deep reaching convection and

2.   winter period observations from ships which indicate large entrainment rates of deep water into the surface layer.

More exploratory work is needed to further define the extent and larger scale importance of these processes.

<u>Basic Question</u>: What is the contribution of open ocean deep convection and its relative importance to the total water mass formation rates in the Southern Ocean?

Water mass modification processes over the deep ocean south of the ACC will be studied using the WHP data set. However, the critical winter condition is not well preserved into the summer temperature minimum layer, hence winter observations are needed. Therefore winter expeditions by ship are needed which will make precise observations of the oceanic structure beneath the sea ice and of its relationship to sea ice dynamics and thermodynamics preferably using time-series data from instrumented drifters.

(ii)   At the continental margins the water over the continental shelf is exposed to the harshest form of the Antarctic atmosphere, as very cold dry air flows off the continent. Strong winter winds often remove the insulating cover of sea ice adjacent to the coast (Zwally, Comiso, and Gordon, 1985). These coastal "latent heat" polynyas become potential sea-ice factories, in which massive amounts of sea ice can form and are quickly transported northward. This in turn induces extreme thermohaline alterations of the shelf water, increasing the shelf water salinity by as much as 0.3. The shelf water is also modified in contact with the fronts and bases of the glacial ice shelves, further modifying the characteristics of the water masses (Weiss, Ostlund, and Craig, 1979; Jacobs, Gordon and Ardai, 1979; Jacobs, Fairbanks and Horibe, 1985).

Environmental conditions specifically are responsible for the wide range of shelf water characteristics (Gordon, 1973). How they mix with deep water and the final formation of Antarctic Bottom Water are not known. Killworth (1983) reviewed observations and argues that five requirements appear to be fulfilled for the

production of deep water near oceanic boundaries: a reservoir in which to form dense water, a source of dense water within the reservoir, a 'reason' for the dense water to leave the reservoir, the involvement of more than one water mass in dense water formation, and a combination of densities, topography and dynamics that do actually permit the dense water to sink. Some regions that meet some of these requirements, such as the contact with glacial ice and the atmospheric cooling in coastal polynyas, have been clearly identified.

One of the strongest fronts of the Southern Ocean separates the shelf and deep water (Jacobs, 1986). Across this front must pass the supply of new shelf water, potential bottom water and large volumes of sea ice and glacial ice. Recipes for mixing at the shelf-slope front have been proposed from summer observations as the integrated effects of water mass conversion (Foster and Carmack, 1976), but the actual exchange process is subject to speculation.

The coldest, freshest component and probably most of the Antarctic Bottom Water is formed in the southwest region of the Weddell Gyre (Carmack, 1982). Additionally, salty AABW forms in the Ross Sea, and there is evidence of bottom water formation at many other sites around Antarctica (see Gordon, 1973; Smith, Zhao, Kerry and Wright, 1984; Jacobs, Fairbanks and Horibe, 1985). Estimates of the rate of formation of bottom water in the Weddell Sea range from 1 to 5 Sv (Foster and Carmack, 1976). Ice shelf water is observed leaving the Filchner Depression (Foldvik et al, 1985a,b) forming a slope plume with a transport of 1 Sv resulting in a total of 2 Sv of new Antarctic Bottom Water. Estimates of circumpolar production rates of Antarctic Bottom Water are in excess of 13 Sv (Jacobs et al, 1985). The importance of Antarctic Bottom Water to the world ocean warrants a better understanding of its production processes and rates and the spreading paths.

Basic Questions: What is the rate of Antarctic Bottom Water formation, where are the primary sites of formation, what are the primary mechanisms?

During WOCE, the WHP sections are planned to resolve the AABW spreading pathways and determine its existing rates. The integrated effects of all these processes will be measured. To obtain specific information on flux rates, the Antarctic Bottom Water formation issue will be approached essentially as a "black box" by monitoring the inflow and outflow at the major formation regions, such as the Weddell Sea. This will be done by monitoring the western boundary currents of the cyclonic subpolar gyres and, because of the well-confined process associated with the outflow through the Filchner Depression, monitoring that outflow.

4.2.5.2 Sea ice/Ocean Interaction

Sea ice "interferes" with ocean-atmosphere interaction in a variety of ways:

1.   the thermal effect induced by the reflecting power of sea ice as well as its insulating effect;

2.   the haline effect of brine release during ice formation and melt water introduction during the melting phase. In addition there is the suppression of evaporation by the presence of sea ice;

3.   the momentum balance is affected due to the loss of energy by ice-ice interaction. Proper modelling of the Southern Ocean must include a dynamic and thermodynamic representation of the sea ice cover (Hibler and Ackley, 1983).

The Southern Ocean is exposed to outflow of cold polar air masses resulting in strong surface cooling. This is coupled to a slight excess of precipitation over evaporation (Gordon, 1981). The convergence and divergence of the sea ice *cover* is a *very* significant factor in the redistribution of freshwater. The divergence of sea ice in the southern regions with convergence in the northern regions of its domain, for example in the Weddell Gyre (Hibler and Ackley, 1983), has a larger effect than the evaporation/precipitation difference.

The ocean plays a primary role in wastage of glacial ice, mainly by direct melting of ice along the underside of the shelf ice. The glacial melt water is marked by isotopically light oxygen and helium (Jacobs, Fairbanks and Horibe, 1985; Schlosser, 1986) in the Southern Ocean and their distribution in the Antarctic Bottom Water is a precise indicator of its origin and quantity.

Fig. (4.1)   One-time WHP Survey of the Southern Ocean
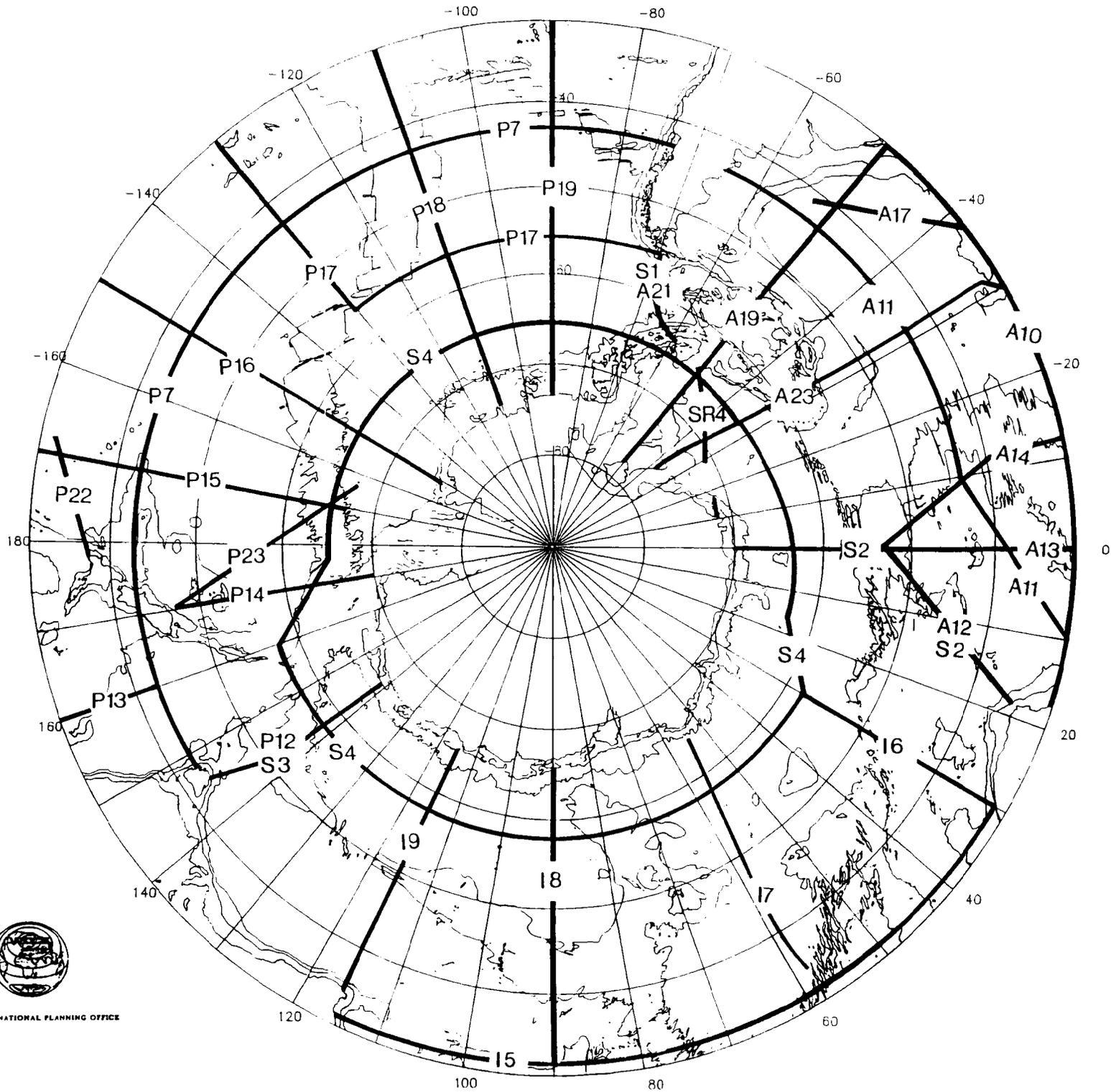
Basic Question: How do sea ice dynamics and thermodynamics influence water mass formation and momentum flux in the Southern Ocean?

To resolve this issue within Core Project 2 an array of sea ice drifters measuring the temperature profile in the surface layer and thermohaline and tracer distributions are needed. Core Project 2 activities are to be co-ordinated with those of the SCAR Group of Specialists on Antarctic Sea Ice.

4.3   Plans by Experiment

4.3.1   Large Scale

4.3.1.1   Thermohaline/Tracer Distributions

WHP in Core Project 2

The general objectives for the design of the WHP sections within WOCE Core Project 2 (Figure 4.1) are the same as within Core Project 1 and are to provide basic observations for the description of the large-scale water mass distribution, their spreading and time-scale characteristics, associated frontal zones and circulation structure as well as to provide tracer inventories. This data base is required for the validation of the ocean circulation models. The WHP data have broad applications, not just in reference to the large-scale characteristics and they will be used for special, more process-oriented projects within Core Project 2.

The limited dynamic range of temperature and salinity in the Southern Ocean demands the highest quality standards set by WHP need to be met. Sampling should follow the general WHP scheme, i.e. 24-36 depths per station and 30 nm nominal station spacing, although some relaxation is suggested for specific areas. Analyses are required for oxygen and nutrients, along with the standard thermohaline measurements at each station along the WHP sections. The survey is to be complemented by measuring the distributions of geochemical tracers, for which the spacing is to follow the basic scheme given in Section 3.2.2.2. The nominal large volume station spacing (300 nm) must be adjusted to water mass boundaries and passage topographies.

The hydrographic survey is to be complemented by measuring the distributions of geochemical tracers that are capable of giving rate information on large-scale water mass spreading and on water mass conversion and ocean ventilation. Sampling for tracers need not be done at each station. With the proposed station spacing of 30 nm, though some relaxation of this spacing is suggested for specific areas, small volume tracers should be analyzed at every other station. To reduce station-time it is suggested that a development of a streamlined rosette/CTD system be encouraged. Large-volume sampling is to be done on an as needed basis, nominally every ten stations. The most stringent requirements apply to the high priority sections, there can be some relaxation of station spacing and large volume sampling requirements for those sections planned for mapping.

The Acoustic Doppler Current Profiler (ADCP) with precise navigation (GPS) is particularly important for Southern Ocean sections. The baroclinic field is very weak, hence reference of the geostrophic shear to the profiler data may be the only practical way to obtain reasonable estimates of the structure of the velocity and transport across the various fronts of the broad circumpolar belt. The determination of the heat and salinity flux across the three Choke Points are best done with a combination of ADCP/WHP sections. It is recommended that these are repeated each year, with additional sections in the winter period.

Tracers

The strong interaction of the ocean with the polar environment under a variety of boundary conditions, the nearly homogeneous thermohaline field, and the small scales associated with high latitude processes, make tracers with differing source and input functions particularly well-suited for Southern Ocean studies. Tracers can resolve the integrated effects of water mass modification *over* a broad range of spatial and temporal scales, aid in resolving the "recipes" for production of the multi-component Southern Ocean water masses, and provide a time-dependent way of tracing the rates of spreading and mixing of waters recently

exposed to the atmosphere and ice boundaries. Since Southern Ocean water masses influence much of the world ocean, identification of their initial characteristics allows improved time estimates for the global-scale spreading rates.

The "rate" information is derived by balancing tracer addition to, and inventory of, an interior water mass. It is then clear that a single distribution of water fluxes between the principal regions of the ocean must account for the inventories of the whole set of transient tracers . Because interior water masses interact, it is imperative to have a complete picture, at the appropriate scale, of the tracer distributions. As many tracer distributions are transient, this requirement is important. In addition, the atmospheric input functions must be known, both in regard to spatial and to temporal characteristics.

Much of the power in the tracer approach rests in the ratio of different tracers at a particular site, i.e., differences in the distributions of the tracers, which arise mostly from the differences in their source functions at the ocean surface. A similar tool uses snapshots of the transient tracer distributions at different times, typically 5 to 10 years apart. The coverage of tracer measurements in the Southern Ocean at present is sparse (see adjoining map, figure (4.2), so that a comparison with the past can be done only in few regions. During WOCE, therefore, at least partial re-occupation of sections on the time-scale mentioned, should be attempted. This requirement is reflected in the Core Project 2 design for the WHP.

As tracers integrate over space and time on scales that depend on the properties of the specific tracer, the tracer approach represents the other extreme relative to point measurements such as those from current-meter moorings. The integrating effect has a specific value when processes are variable or episodic, and tracer-based information poses special constraints on the ocean circulation and spreading, or on its modelling, that are substantially different from those provided by other observing techniques in WOCE.

The relevance of tracer measurements in connection with the Southern Ocean circulation and the Core Project 2 goals are outlined below.

1.   Water mass conversion south of the ACC occurs through upwelling of ACC-derived water into the surface layer, and subsequent formation of deep and bottom water, the latter taking place within the polar gyres and along the continental shelves, both processes being subject to water-ice interaction. Tracer data are used to constrain estimates of rates of conversion.   In the case of upwelling into the surface-layer, gas balances using O_2, ^3He, CFCs, $^{14}CO_2$ are used, and for the deep and bottom waters by the input-inventory technique, using CFCs, ^3H, ^{85}Kr, and bomb-^{14}C are appropriate. Mixing rates in a direction normal to continental shelves can be obtained from upper-ocean ^{228}Ra observations. The actual mixing recipe for the various components of these waters is to be assessed by multi-parameter analysis, including ^3He and nutrients. Even slight addition of glacial ice melt water can be traced by stable isotope (^{18}O, D) and noble gas (He, Ne) observations, and furthermore stable isotope data allow a large-scale distinction between fresh-water input by precipitation and by sea ice melt.

2.   To enable one to apply the input-inventory technique as well as multi-parameter analysis, it is mandatory to obtain tracer data as near to the respective source areas as feasible. This will be supported by studies of the formation processes, particularly in the Weddell Sea, which is presumed to be the main formation region. Such studies are therefore strongly encouraged. In order to assess possible contributions from other, unstudied formation areas, detailed tracer measurements must be carried out on the proposed high-latitude circumpolar section (figure 4.1).

3.   South of approximately 60º S, water mass conversion typically occurs in situations of substantial or even total ice cover, which limits ocean-atmosphere exchange, and this reduces our ability to specify ocean-surface tracer boundary conditions. To overcome this, data for tracers with different ocean-atmosphere exchange rates have to be used. An extreme case of slow exchange is ^{14}C, and it may turn out that only little resetting of the 14C clock occurs in the Polar Zone water mass conversion and ventilation processes. Because ^{39}Ar has a fast exchange, ^{39}Ar observations are relevant to quantify the actual degree of ^{14}C resetting. Of great importance is the precise determination of tracer concentrations of Deep and Bottom Waters in order to provide "end member" tracer concentrations for the Southern Ocean component of the global abyssal circulation.
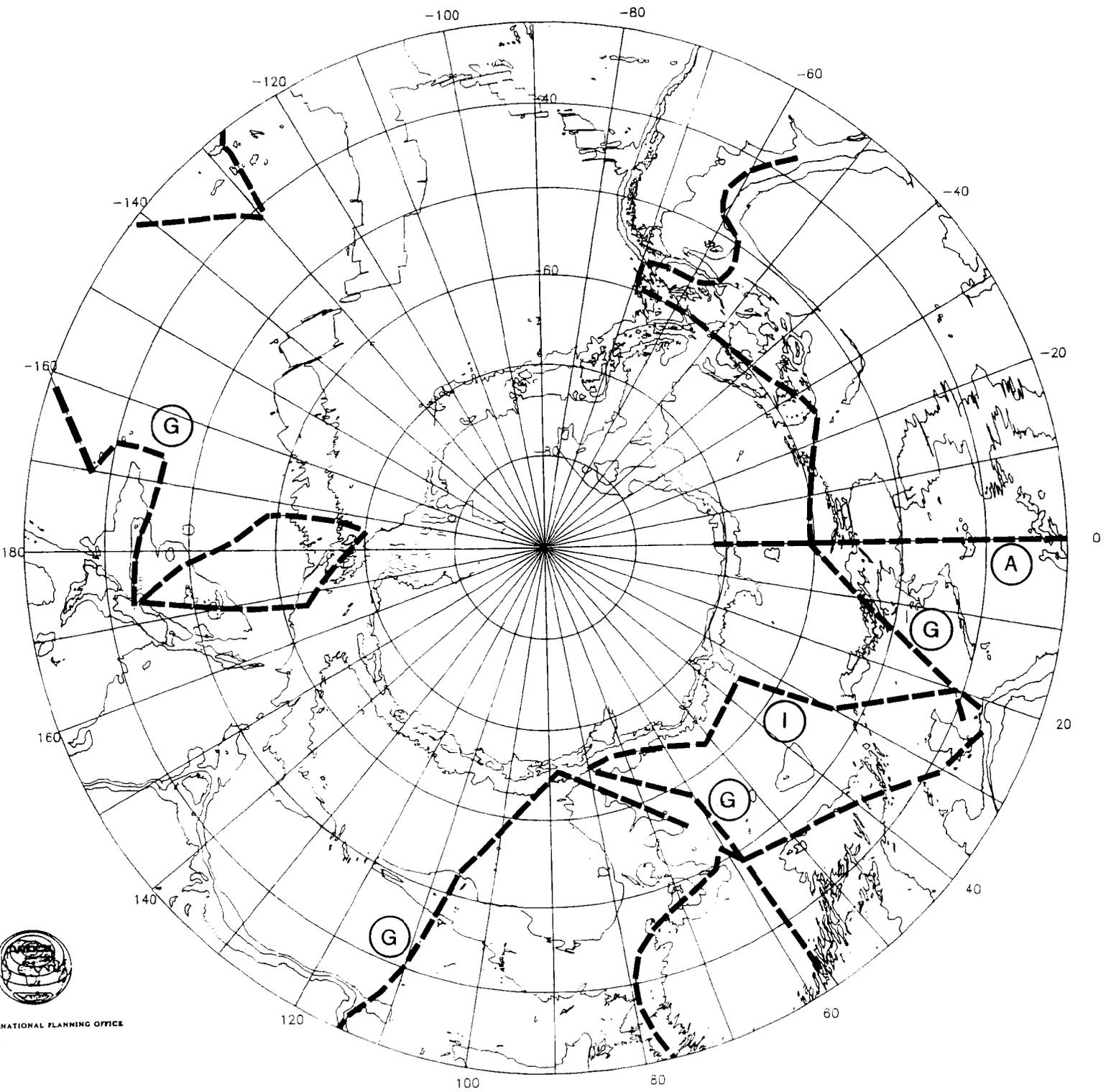
Fig. (4.2)   Historical Tracer Data in the Southern Ocean

(G) GEOSECS (1972-78), (A) AJAX (1984-86), (I) INDIGO (198587)

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4. The Polar Front and Subantarctic Zones feed specific water types into the southern hemisphere sub-tropical gyres and intermediate waters. The rates of this transfer are again to be studied by the input-inventory tracer technique, using, as before, CFCs, tritium ^3H, ^{85}Kr, and bomb-^{14}C. In this region $^3H/^3He$ dating is of limited value only, because low tritium concentrations make tritiugenic ^3He ingrowth small. On the other hand, the strong ^3He contrast that exists across the ACC makes ^3He a sensitive indicator of across-ACC water exchange, unless such water had an opportunity for substantial exchange with the atmosphere, i.e. passed through the ocean surface layer. Observations of ^{14}C (natural component), complemented again by ^{39}Ar in selected places, are necessary for studying the abyssal circulation in this region.

5. Multi-parameter water mass analysis assists the study of inter-ocean exchange effected by the ACC. A special candidate is ^3He, which enters the ACC essentially in the Pacific sector, and shows decreasing concentrations downstream. Nutrients, ^{14}C, ^{39}Ar, and the transient tracers also have great importance. Detailed tracer observations are required at each Choke Point section so that inter-ocean tracer fluxes can be computed.

Sampling Comments

Sampling at 36 depths per station will be desirable at many deep stations, to resolve the often highly structured vertical distributions. CFC measurements should be taken at each depth each station. The possible number of tritium and ^3He measurements (i.e., a factor of three to four less) should be distributed to lesser stations but at comparable vertical resolution. However, care must be taken to sample boundary currents, mixing, end member, and sharp fronts appropriately. Stable isotope and noble gas measurements should be concentrated in the region south of 60° S, and may be more widely spaced outside. Supercooled water is encountered in places, and will require special sampling precautions.

Large Volume Sampling is required for deep-water ^{14}C, ^{39}Ar, ^{85}Kr, and ^{228}Ra, whereas all others can be sampled by using standard rosettes. Large-volume tracers must be done at least once at the Choke Point sections (SI to S3), the Zonal sections (A10, A11, I5, P6 and S4) and at one mid-ocean section per ocean sector (e.g. A23, I7 and P16). For these sections, the small-volume tracers should be sampled twice, on the other sections only once. Large-volume stations should be spaced typically at double the spacing for tritium and 3He. Eighteen depths for deep-ocean stations are regarded as adequate. 39Ar samples, because of the long station-time required, must be restricted to a few characteristic depths and locations, with emphasis on the end member question, and with one station each in the relevant deep ocean basins.

Tracer Repeat Requirements

Pre-WOCE, but post-GEOSECS, tracer programmes exist for the Atlantic sector (AJAX, WWSP86, SAVE) and the Indian Ocean sector (INDIGO) as shown in (fig 4.2). The existence of this work may relax the necessity for large-volume sampling, and for repeated small volume sampling in some areas during WOCE. It is critical not to leave major gaps in the tracer survey, as this would greatly reduce the power of the tracer input-inventory approach.

The most complete set of data comes from the GEOSECS programme in 1972-1978. If this is considered as a picture taken at the time t = 0, a second picture at t + 9 years (1981) exists for the North Atlantic with the TTO results and at t + 13 years (1985-1987) for the western Indian Ocean with the INDIGO data. WOCE thus provides an excellent opportunity to take another picture between 5 and 10 years later.

Only the bomb-^{14}C and tritium have been discussed as they are the only two tracers which have been measured starting with the GEOSECS programme. A first picture now exists also for CFCs.

The study of the inventories of CFCs simultaneously with the bomb ^{14}C and tritium places a strong constraint in resolving the oceanic flow field, as we are considering three tracers which have input functions varying in time with opposite signs.

Carbon Dioxide Measurements in Core Project 2

It is of special interest in the Southern Ocean to measure the difference of CO_2 partial pressure between the atmosphere and the ocean in order to compute the CO_2 flux through the air-water interface. Two main reasons for this are: 1 - the gas exchange coefficient is large as it depends on the wind field which exhibits strong winds in the southern latitudes; 2 -the first limited set of data that we have (Takahashi, 1986) indicates a quite large value of the gradient of partial pressure of CO_2 (pCO_2) between the atmosphere and the ocean which is undersaturated.

For that purpose and in collaboration with JGOFS, it is recommended that measurements of pCO_2 in the atmosphere and the ocean be measured during the WOCE Hydrographic Programme.

WHP Core Project 2 Section Map

Figure (4.1) shows the WHP Core Project 2 sections; these are based on consideration of the summer sea ice limits, though some ice strengthened ship capability is required as discussed below. The placement of the sections are schematic. They must be adjusted to better take into account bottom topographic boundary conditions in order to delineate various water mass formation regimes and cross the expected primary pathways of flow. Final placement depends on further development by groups planning to carry out specific sections and development of other Core Project 2 projects which would utilize the WHP data.

Description of the WHP Core Project 2 Sections

Three categories of WHP sections are needed: Choke Point, mid-ocean meridional and the zonal. There follows a justification for each of these categories with comments specific to individual sections. Further adjustment to Core Project 1 requirements is considered.

Choke Point sections: There are three essential meridional sections across the three choke points (primary passages between Antarctica and South America, Africa and Australia/New Zealand). The final placement would depend on the siting of the choke point flux experiment of Core Project 2. The choke point sections would define the water masses characteristics within the circumpolar belt which separates the major ocean basins and the associated fluxes of mass, heat and salinity accomplished by the ACC and any counter-flows. Because of topography or circulation considerations a choke point need not be the shortest distance between the opposing continents. These sections will allow calculation of the geostrophic shear and with reference to the acoustical current profiler and altimeter data, the absolute velocity field can be determined. This will allow determination of the volume, heat and salinity flux between the major ocean basins. Together with the WHP data one will arrive at the heat and salinity flux at the Choke Points. Accurate acoustical profiler data is an important requirement. Core Project 1 designations are given in brackets after the Core Project 2 specific ones.

S1/A21 South America-Antarctica (Drake Passage): This section spans the Drake Passage to the west of the seamount topographic features within the Passage. The section extends into the Bransfield Strait, where evidence of deep convection has been found. This section will effectively extend the time series measurements made during the ISOS programme (1975-1981).

S2/A12 Africa-Antarctica: This section is placed to the west of the Agulhas Retroflection. The high frequency and high energy variability associated with this feature causes uncertainty in the flux calculations, if S2 were to cross it. This section is well-suited for study of the inter-ocean flux of warm water associated with the Agulhas Current. The section crosses the ACC, the strong front separating the circumpolar system from the Weddell Gyre and central segment of the Weddell Gyre. The Greenwich Meridian segment has the advantage of comparison to the 1984 AJAX section to study time variability (figure 4.2).

An additional section I6 east of the Agulhas Retroflection, along 30° E, is also an important section for the Africa-Antarctica choke point. It will include the Agulhas Current and the Agulhas Return Current, and allows study of the interaction of the Agulhas Current system with the ACC.

S3/P12 Australia/New Zealand-Antarctica: A section south of New Zealand requires a zonal section across the Tasman Sea to fully describe the Indian-Pacific exchange.

Mid-Ocean Meridional Sections: These sections are required to allow description of the interaction of the circumpolar belt with the subtropical anticyclonic gyres to the north and subpolar cyclonic gyres to the south of the ACC, as well as describe the ACC structure away from the confines of the choke points. They also allow intra-basin mapping of the thermohaline and tracer fields. They extend from 30° S (nominal) to Antarctica and match up with Core Project 1 sections coming from the north.

A23 Atlantic sector: The 35° W section crosses the ACC after it resumes a zonal course east of the Falkland Plateau. Poleward of the ACC it crosses the western segment of the Weddell Gyre, ending in Filchner Depression of the Weddell Sea, a major site of shelf water outflow. Outflow of Antarctic Bottom Water would be observed in the eastward flowing limb of the Weddell Gyre over the flank of the South Scotia Ridge as well as along the pathway for bottom water flow into the Argentine Basin, north of the Scotia Arc. The characteristics of the Pacific water in the eastern Scotia Sea would also be determined.

A14 Central Atlantic Sector: The region between A23 and S2 needs to be filled by a north-westerly branch from S2 at 50°S joining with the Core Project 1 section on 14° W after passing through 45° S, 8° W.

I6 Western Indian Sector, 30° E: This WHP section crosses the Agulhas Return Current eastward of the complex eddy field of the Retroflection. Further south, the ACC structure is measured just before it encounters the Crozet Plateau. Comparison with sections S2 and I7 will show the extent to which the Subantarctic Zone and ACC filamentation are altered by the Agulhas system and the Indian-Atlantic Ridge and Crozet Plateau topography.

I7 Indian sector: The 57° E section crosses the ACC east of its interaction with the Crozet Plateau, passing across a major flow path of bottom water to the north. Interaction of the ACC with the Agulhas Return Current can be studied. The eastern end of the Weddell-Enderby Basin, which is very poorly sampled, would be covered by this section. This section has the advantage of comparison with the 1986/87 INDIGO section (figure 4.2). This section should have an east-west connecting section to the African continent, to enhance the choke point objectives (15).

I8 Indian sector: The 90° E section crosses the ACC as it convergences with the mid-ocean ridge. The ACC follows this ridge system into the mid-Pacific. It would provide a view of the ACC structure before it "locks" into the topographic constraint. South of the ACC the section would sample the western extent of an apparent poorly resolved cyclonic gyre south of Australia.

I9 Eastern Indian Sector, 115° E: This longitude marks the western boundary of the longest "channelised" path of the ACC, its transit of the Australian/New Zealand sector. This section would provide information on the initial structure of the ACC. It is firmly associated with the northern flank of the mid-ocean ridge at this point. The bottom water which feeds the eastern Indian Ocean is probably derived for the most part from the outflow of AABW through the Antarctic Discordance Zone (a topographic saddle) of the mid-ocean ridge near 120° E. The 115° E section would define the spreading of these properties into the Indian Ocean. Along the margin of Antarctica near 115° E there appears to be a well developed eastward flow of bottom water derived from a blend of Ross Sea outflow and locally produced Antarctic Bottom Water.

P14 New Zealand "Choke Point" 170° E: The ACC shifts poleward as it leaves the Australian/New Zealand "channel" and appears to initiate a split in the zonal flow, part continuing to follow the mid-ocean ridge and part flowing along the western flank of the Campbell Plateau into the western boundary current of the South Pacific Ocean. P14 will provide information about this structure as well as the characteristics of the water masses entering the Pacific Ocean. The section should swing eastward to allow extension into the western Ross Sea. It is well-suited to measure the initial properties of the bottom water derived from the Ross Sea.

P15   Western Pacific Sector, 170º W: This WHP section would parallel the western boundary regime of the South Pacific. Between the mid-ocean ridge and the Ross Sea the western margin of the Ross Cyclonic Gyre would be encountered. The 170º W section should extend into the central Ross Sea.

P16   Pacific sector, 150º W: This section crosses the ACC where it is pressed against the northern flank of the mid-ocean ridge, representing one of the most pronounced meridional shifts of the current. Closely spaced stations, related to the bottom slope, are required over this ridge. South of the ACC is another poorly sampled cyclonic region, the Ross Gyre. It is noted that even in summer the sea ice can be formidable, requiring a more substantial ice-strengthened ship than for other meridional sections.

(P17,P18)   Central Pacific Sector: The large region in the central and eastern Pacific Ocean is covered by Core Project 1 sections along 105º W and 130º W.

P19   Pacific sector, 90º W: This section crosses the ACC where it is least confined by bottom topography. There is the northward flow of AABW of Ross Sea origin towards the Chile Ridge. The southern end of the section passes through the small cyclonic gyre of the Bellingshausen-Amundsen Seas. Here, as for the P16 section, summer sea ice is substantial.

P22-23   Two additional segments are suggested to add to the sampling of the structure of the deep western boundary current east of New Zealand. P22 extends northeast from East Cape (North Island) New Zealand, crossing the 170º W meridional section. This line crosses the deep western boundary flow north of Chatham Rise. The second, P23, extends southeastward from the South Island across the northern Campbell Plateau, then across the southern arm of the Southwest Pacific Basin, terminating at the crest of the Pacific Antarctic Ridge at about 64º S, 168º W.

     Zonal Sections: These sections focus on the meridional spreading of Antarctic water masses into the subtropical regime (30º S) and away from Antarctica (65º S), as well as the associated southward flux of warmer northern waters. Both cross gyre circulation patterns and so sample major meridional currents, boundary and interior flow. With current-measurements within the boundary regimes, they will allow quantitative estimate of meridional fluxes. The western and eastern segments of the 30º S sections would be used for boundary current monitoring (see Choke Point discussion, below). During servicing of these moorings, a segment of the WHP sections should be done.

A10   Atlantic 30º S section: In the west, this section crosses the Brazil Current before it separates, as well as the northern limits of the Argentine Basin, marking the outflow of Antarctic Bottom Water through the Vema Passage. At the mid-ocean ridge there are possible boundary currents over its flanks. East of the ridge the section first crosses two basins separated by the Walvis Ridge, and then the eastern boundary current of the subtropical gyre, the Benguela Current, with its possible "contamination" by Indian Ocean water (via the Agulhas Retroflection). The A10 section may be moved to 32º S to re-do the IGY section and cross the Argentine Basin south of its northern edge, giving a clearer image of the deep western boundary current.

A11   A zonal section on 45º extending from South America to 8º W and then northeast to intersect A10.

I5   Indian 32º S section: This section crosses very complex bottom topography and must be adjusted to cross as best as possible features at right angles. The section crosses the Agulhas Current, and its apparent strong re-circulation cell, an area of northward spreading of subantarctic water near 60º to 80º E, bottom water spreading routes within numerous basins, and the somewhat anomalous eastern boundary regime of the South Indian Ocean.

P6   Pacific 28º S section: This section must include the Tasman Sea. It follows the SCORPIO section along 28º S, to allow the study of low frequency variability in the water mass characteristics. Of particular importance is the complex western boundary regime which feeds and drains the immense Pacific Ocean.

P7   43º S: This section crosses the southern side of the shallow portion and the centre of the deeper portion of the subtropical gyre. It is important for measuring the transport into the Pacific Ocean and is the southernmost section north of the Antarctic Circumpolar Current. It repeats the 1967 SCORPIO section.

S4   The 65º S section more-or-less parallels the Antarctic Divergence, separating the west from east wind drifts, crossing the mid-section of the cyclonic gyres south of the ACC. These gyres are for the most part poorly resolved, therefore the 65º S "Antarctic Divergence" section should be carried out early in the WOCE period to allow improved experiment design for specific objectives. The summer conditions are ice free with the exception of the Weddell region where summer ice extends from the Antarctic Peninsula to 40º or 45º W. To extend the section into at least the fringes of this area, a ship with icebreaker capability is required. This section may be done by three ships operating in the same summer season.

Timing of the Sections: The Core Project 2 meridional and 65º S zonal sections should be carried out during the austral summer, when most of the circumpolar region is free of sea ice. Yet, even in summer some sea ice will be encountered close to Antarctica. Therefore ships with at least ice-strengthened capability are required to complete the sections over the continental margins. The zonal section along 30º S can be done in any season, though for seasonal synopticity with the meridional sections the summer is recommended.

To further the understanding of ocean/sea ice interaction, there is a need for observations of ocean properties below the sea ice cover, both winter and summer conditions within the multi-year ice. This requirement is primarily for study of the mixed layer characteristics and possible convective events. This can best be accommodated as part of a special study within Core Project 2 or affiliated programmes, rather than as part of WHP. Should a Weddell polynya develop during the WOCE period, sampling at close time intervals within the polynya is suggested in order to resolve the alteration of the water column.

Station Spacing: The horizontal spacing of stations across the ACC should be of the order of the Rossby Deformation Radius in order to resolve the filament nature of the ACC, estimate frontal widths and interpret the eddy fields. The target of 30 nm spacing for WHP sections is sufficient for the ACC belt and is strongly endorsed by Core Project 2. Poleward of the ACC the deformation scale is too small (approximately ten of kilometres) to expect that a meso-scale resolving station spacing can be achieved. However, underway observations of the thermohaline field by thermosalinograph and XBTs would help close this gap. The 30 nm spacing can be relaxed along sections of the WHP north of the ACC, such as along the interior segments of the 30º S sections.

Along continental margins of Antarctica there is a rapid transition from open ocean to continental margin water masses as well as the occurrence of deep reaching convective plumes. As sections approaches Antarctica, the station spacing should be tightened, with a station at 500 m isobath intervals, and still closer spacing for stations over the shelf-slope boundary. The 500 m isobath spacing should also be achieved over flanks of mid-ocean ridges and within submarine passages encountered along the sections, in order the resolve the deep boundary currents.

Repeat Requirements:

For the description of the low frequency variability of water mass and baroclinic structure, it is suggested that the entire Core Project 2 WHP grid be done twice for the basic CTD parameters, at approximately a ten year interval. The Choke Point sections should be done more frequently: every year including at least one winter section in support of the Choke Point Experiment as discussed below. It is recognized that it may not be possible to repeat all of the sections. The top priority for a repeat are the Choke Point sections (annually), and A23; 17; P16 (twice).

The large volume sampling needs to be done only once, along the Choke Point, Zonal, and Mid-ocean sections, A23, I7, P16. The small volume sampling for tracers should be done twice along these sections but elsewhere only once.

The annual, summer Choke Point requirement supports the time series observations planned as part of Core Project 2, for the study of inter-ocean exchange. Sections across the ACC at the Choke Point sections for other seasons are suggested.

It is desirable that the full zonal sections at 30° S and 65° S be done at the ten year interval which is presently not within the IOP. At those parts within the boundary regimes, where time-series observations are planned as part of Core Project 2, WHP sections should be done more frequently, every other year.

While it is impractical to expect the Antarctic base supply vessels to carry out WHP sections they should be used as VOS for collection of various underway data, such as meteorology parameters, XBT and XCDT and acoustical Doppler profilers, to substantially enhance the data set.

4.3.1.2 Large-Scale Circulation Characteristics

During WOCE, direct current measurements will only be possible at western boundary currents and a few locations along the ACC axis. Inference of the ocean circulation in other areas, based on tracer distribution, will require sophisticated models for inversion, including advection, lateral dispersion and diapycnal mixing. Floats and drifters will be the only in situ instruments capable of measuring the large-scale, low-frequency ocean currents directly over large areas and for long times. Drifting buoys will also serve as platforms carrying other sensors providing data that are essential to meet the WOCE objectives. If available in large enough numbers, floats and drifters will provide estimates of horizontal diffusivities, which are important for understanding tracer distributions in the ocean interior.

The flow visualization from floats and drifters will provide a zero-order description of the general circulation during WOCE. This description is essential in order to test the output from numerical models being developed.

The energy distributions will provide a crucial test of the performance of models. Results derived from the analysis of surface drifters and floats indicate that drifters are adequate for mapping the mean and eddy kinetic energy over large areas. Although the altimetric missions will provide the best means for mapping the sea surface, we must depend on floats to map the subsurface eddy kinetic energy distributions over basin or global scales.

(a)   Surface Drifters Programme

Surface drifters have the dual role as sensor carrying platforms and surface velocity markers. In the Southern Oceans the surface drifters deployed during FGGE provided a cost-effective method for both modes (Garrett, 1981; Patterson, 1985; Piola, 1986). During WOCE surface drifters can play a similar role. In addition, to monitor the seasonal evolution of the mixed layer characteristics, some drifters should be equipped with temperature/conductivity chains.

i   Sensors

Surface drifters used in WOCE should be able to measure sea surface temperature (SST) and sea-level pressure (SLP). SST is important for the air-sea flux measurement programme, particularly where remote sensing might be degraded by the frequent cloud coverage. SLP will improve pressure fields for weather analysis and will be used for pressure-corrections to altimetric measurements.

ii   Drogues

Both drogued and undrogued drifters were used during FGGE and although no substantial differences in behaviour were apparent there was no way to determine the drogue survival during the experiment. It is generally expected, though not proven, that drogued drifters will perform better as surface current indicators. Given that surface drifters can provide essential information in the otherwise sparsely sampled Southern Ocean, it is highly desirable that all drifters be drogued. This requirement suggests that different drogue types be tested for survival, cost effectiveness and simplicity of launching.

¨ iii   How many drifters are needed?

Because of the variety of oceanographic regimes found in the Southern Ocean (subpolar gyres, ACC, western boundary currents, subtropical gyres), it is difficult to estimate the total number of drifters needed to achieve an "adequate" sampling both of the SST and SLP and of the velocity field. A crude estimate based on the area, possible drifter lifetime and spatial resolution leads to about 200 drifters per year during the 5-year WOCE period. On average this number of drifters will lead to about 300 reporting drifters at any one time (after year 1). This number will provide a coverage slightly better than that by the FGGE drifters and will therefore be adequate for meteorological purposes. In this scheme, the standard error of mean velocity will be about 2 to 6 cm/s depending on the velocity variance (see the surface drifter discussion Section (3.2.4) of the WOCE Core Project 2 Planning Meeting Report, Anon. 1987a). These values, though, should be viewed with caution. There are further uncertainties of drifter behaviour due to windage and an apparent tendency to concentrate along fronts. Upon averaging over large areas (compared to frontal scales) these effects along the ACC will lead to an overestimate of unknown magnitude of the mean speeds.

iv   Where and When

The FGGE buoy experiment has shown that drifters tend to converge towards the interior of the subtropical gyres where they remain for relatively long periods of time. Typical coverage in the gyre interior was over 200 buoy days/year. While south of 45° S sampling density decreased under 20 buoy days over 4° x 4° areas and two year period. To achieve a more uniform coverage of the Southern oceans during WOCE, deployments should be more intense in the region of the ACC and at the southern edges of the subtropical gyres while the gyre interiors will be covered naturally later on. Initial deployment should thus be distributed approximately 2/3 south of 45° S and 1/3 north of that latitude, in the most uniform way that is practical. Since drifter information increases with time it may be desirable to initiate deployments 6 to 12 months before the WOCE intensive sampling period. Deployments after year one can be designed to cover unsampled areas thus improving spatial coverage of meteorological observations and the surface velocity field.

South of 60° S the winter sea ice poses a serious technical problem for surface drifters. During FGGE, drifter survival time south of 60°S was approximately 160 days whereas north of 50°S it was 320 days. An effort should be made to design a surface drifter capable of withstanding the sea ice formation. Because of the weak baroclinic signal, surface drifters become valuable indicators of mass transport. Meteorological and SST data are also scarce in the subpolar region.

(b)   Southern Ocean Float Programme

For the Southern Ocean, the WOCE objectives call for identifying the main routes for inter-basin exchange. This requirement implies the need for current-measurements at various levels. As floats and drifters will not be available in enough quantities to achieve the required accuracy and spatial resolution, these goals will require the combination of various techniques among which Lagrangian measurements will be essential. A strategy is to seed selected regions which have greatest relevance to the general circulation.

The subsurface float programme is very important as a means to measure the significant barotropic component of the circulation in the Southern Ocean, particularly south of the ACC.

The sound channel in the Southern Ocean undergoes extreme changes in depth. South of the ACC the sound channel occurs within 250 m of the surface during the summer period and at the surface in winter. Within the ACC and in the southern pans of the Subantarctic zone, the sound channel also surfaces in the winter; even during the summer it is generally located within 400 m of the surface. Only in the transition between the subantarctic and subtropical regions does the sound channel descend below 500 m. This creates problems in tracking SOFARRAFOS floats. Listening stations south of the ACC may not clearly observe floats within and north of the ACC (and vice-versa). Also in winter, loss of acoustical energy at the sea surface would limit the range of the signal; the 2500 km range characteristic of the subtropics will not be achieved within and south of the ACC.

In order to provide basic circulation reference data, the WOCE Core Project 1 global mapping strategy (Section 3.3.2) is adopted for Core Project 2. South of 45º S there exist about 200 resolution cells of 500 km scale requiring that number of floats (SFG).   In general, floats could be deployed at roughly 200 km intervals.

i   North of the ACC

North of 40º S, the RAFOS floats can be placed at a deep water-depth. However, south of approximately 40º S, the RAFOS floats should be placed at shallower depth, perhaps near 500 m so that a loss of energy at the sea surface would be minimized.

Deployment at additional levels, within water mass core layers, is required for the transition region between the subantarctic and subtropic regions to better observe the relative motion of Southern Ocean water masses to northern derived water masses. This will require 100 floats which should be released simultaneously with the reference-level floats described above **(SF1).**

ii   Within and South of the ACC

The sound channel limitations suggest that for the region within and south of the ACC (roughly for the area south of 50º S) the best float to use is the ALACE. They should be programmed to pop-up at one to two month intervals, which, with the expected life-time 50 pop-ups, would provide data throughout the WOCE period. South of 60º S there is a sea ice cover for at least part of the year, an ALACE float popping-up under sea ice will not survive the encounter. Therefore, it is recommended that the ALACE floats set out south of 60º S, be programmed to pop-up only during the summer period. The internal clock in these floats should allow for that possibility.

The ALACE floats should measure temperature and pressure during their drift. If it is possible to record the time interval between surfacing and data telemetry, as some correction of surface drift could be applied, using the information from the surface drifter programme. Placing the floats not deeper than 500 m would limit the error introduced by the shear in the water column during pop-up cycles.

Deployment at roughly 200 km intervals along WHP sections is endorsed. Additional deployment on the Choke Point sections to obtain better coverage at these sites is suggested. "Gaps" that develop in the drifter array may be filled in during the WOCE period by deployment from Antarctic supply ships.

Specific experiments with SOFAFVRAFOS technology are recommended within select regions, using the technology developed in the Arctic, for the area south of the ACC. This aspect of float requirements is discussed in the "Cyclonic Gyre" section under Specific Experiments (Section 4.3.2.4).

4.3.1.3 Tide Gauges

A global network of tide-gauges is needed:

-       to calibrate and validate the satellite altimetric sea surface topography, preferably in coordination with seabed pressure recorders,

-       to improve the tidal models in the data sparse regions of the Southern Ocean. These are necessary to eliminate the tidal contribution to the sea surface variability,

-       to monitor variations in the large-scale ocean circulation, through the determination of sea surface slopes,

-       to study long-term changes in mean sea-level, given an exact location and bench-marking of the gauges and the measurement of the relative tectonic movements of the sites.

Sea-level observations in the Southern Ocean are very sparse. Plans exist for installing new gauges, or reactivating or upgrading existing ones, through the GLOSS programme of the IOC. It includes most of the accessible islands of the area and sites along the Antarctic coast and would meet the WOCE needs. Most of these stations have yet to be installed. Although the required technology is generally quite inexpensive, important problems can arise at some of these locations, due to topographic configuration of the islands and adverse climatic conditions.

Precision pressure recorders can be deployed with accepted technology. In these cases, recording stations should have concurrent sea-level atmospheric pressure recorders to allow adequate correction of the observations. VLBI, GPS, DORIS and PRARE systems are needed to relate the sea-level measurements to an absolute geocentric reference system.

4.3.1.4 Upper Ocean Mixed Layer Characteristics

(a)   <u>The Ocean Surface</u>

i   Remote Surface Momentum Flux Observations

Over "long enough" time-scales, good estimates of surface momentum flux will be obtained from NSCAT. The level of accuracy considered good depends strongly on the application. Some simple first-order simulations have been carried out to determine the relative importance of measurement errors and sampling errors to space-time-averaged wind fields constructed from NSCAT data. These simulations (see Chelton and Freilich, 1985) suggest that neither wind speed measurement errors nor the use of bulk aerodynamic methods (including the form of drag coefficient used) are as important as sampling errors in determining the accuracy of wind stress fields. These sampling errors are due to the presence of high frequency variability in the wind field which is not adequately resolved by discrete sampling of winds at a given geographical location. Results for Station P with a mean wind stress magnitude of about 0.07 to 0.10 Nm^{-2} indicate an rms error of about 0.015 Nm^{-2} in weekly averages over 2°-squares. This value is essentially independent of measurement errors in wind speed. For monthly averages, the rms error decreases to about 0.007 Nm^{-2}.

A number of more sophisticated simulations are being done to determine more quantitatively the accuracy of wind stress fields constructed from NSCAT data. These simulations will include the effects of measurement error in wind direction and the effects of spatial variability in the wind stress field.

Scatterometer wind stress measurements will dramatically improve coverage of the Southern Oceans for WOCE, and numerical models of the Southern Oceans.

ii   Remote Surface Heat and Water Flux Observations

The potential for inferring components of the surface heat flux from satellite observations is less satisfactory. Full discussion is found in US WOCE Planning Report No.3 (1985). In brief, surface heat flux accuracies are believed to be of order 10-30 Wm^{-2}. Satellite observations used to have to attain an accuracy better than 10 Wm^{-2}. Surface water fluxes are directly related to latent heat flux, so they are equally poor resolved.

iii   <u>In situ</u> Surface Flux Observations

Since <u>in situ</u> surface meteorology observations are only sparsely available in the Southern Ocean, it is important, given the limitations of remote sensing, to provide good quality surface observations wherever possible. Surface analyses during FGGE benefited markedly from the pressure and temperature observations from around 200 drifting buoys. To a large extent, surface fluxes will have to be estimated from bulk formulae, using surface values output from AGCMs, the quality of which will depend on the surface observations fed into them.

It is recommended that as many ships as possible traversing the Southern Ocean be equipped to take high quality meteorological observations and to report them on the GTS. Research ships and Antarctic supply ships could beneficially launch radiosondes.

(b)   Sea Ice Zone

Primary desired sea ice parameters for WOCE are the ice extent, concentration, thickness and velocity.

i   Remote Sensing

Sea ice coverage should be routinely monitored from satellites for the entire Southern Ocean through satellite microwave measurements from the Special Sensor Microwave Instruments (SSMI). Extents should be obtainable to an accuracy of 30 km from the microwave data, and this should be sufficient for WOCE purposes.

Sea ice concentrations should also be obtainable from the microwave data, to a resolution of approximately 30 x 30 km and an accuracy of approximately 10-15% sea ice concentration. Measurement of ice velocities and thickness will be far more difficult. Ice velocities can be obtained for individual ice floes either by calculations from satellite imagery or by tracking buoys placed on the ice. Satellite Synthetic Aperture Radar (SAR) data allow determination of ice velocities by meticulously identifying the same ice floe on successive images and calculating the average ice velocity. This will not be sufficient for WOCE purposes.

ii   In situ measurements

To provide information on the dynamics and thermodynamics of the sea ice cover, the placement of Argos drifting buoys on the ice throughout the Southern Ocean is planned. Twenty drifters per year, 10 with temperature conductivity chains, are required. Buoys placed on the ice for ice-drift measurements are also able to measure ice thickness. It is probably unrealistic to expect such thickness to be measured routinely during WOCE except in regions where field experiments take place.

Ice-strengthened buoys fitted at least with pressure and temperature sensors and a few with T/C chains should be deployed in clusters during the austral summer and autumn. Buoys would be deployed on existing ice remnants and will freeze in shortly after deployment, positioning and data relay will be supplied by Argos.

Antarctic supply vessels could deploy drifters within the sectors of their respective bases. This gives quite good coverage around the continent, except possibly in the eastern Pacific sector. Clusters of five drifters launched near 12 bases each year would give adequate coverage. Some might escape from the ice each spring and would then serve as current-markers in the open ocean.

A pre-WOCE project is required to test buoy types, locations and methods of deployment. Work is already planned for the Weddell Sea by the U.K. and F.R. Germany. A few drifter deployments are required in the Indian Ocean and Pacific Ocean sectors. These tests are crucial to assess the feasibility of the more comprehensive ice-drifter programme.

(c)   Southern Ocean Mixed Layer

Estimates of ocean-atmosphere exchange of momentum, heat and fresh water are uncertain. The oceanic mixed layer integrates the ocean-atmosphere-ice fluxes, so monitoring of the seasonal evolution of the mixed layer characteristics indirectly yields estimates of some aspects of the ocean-atmosphere interaction, and the coupling between the mixed layer and the deeper stratified layer. In addition, knowledge of the winter mixed layer characteristics would provide end-member information required for ventilation and water-mass modification studies. Monitoring of the Southern Ocean mixed layer, at least in some regions of active water-mass formation, on a seasonal basis is an important WOCE objective.

The characteristics of the surface and mixed layer of the Southern Ocean can best be observed by satellite (scatterometer, IR, Microwave), WHP sections, Argos tracked surface drifters with thermistor/conductivity chains, and moorings.

i   Subantarctic Zone and ACC

The subantarctic zone extends from the Subtropical Front near 30-40º S to the Polar Front near 55º S. This is a region which has been largely neglected as the transition zone between "antarctic" and "subtropical" expeditions. Understanding of the interaction between the ACC and subtropical regions, which includes the poleward outcropping of the southern thermoclines with their ventilation mechanisms, is still inadequate. The subantarctic zone is ice-free year round, so it is accessible to normal satellite observations and ships, and normal open-ocean drifters can be used.

Mixed layers in the subantarctic zone are deepened by winter mixing and cooling. They are the source of winter mode waters, specifically Subantarctic Mode Water (McCartney, 1977), which spread into the mid to deep thermocline layers of the southern hemisphere. Observations over the whole subantarctic zone are needed for assimilation into, and verification of ocean models.

Surface drifters equipped with temperature chains will provide valuable information on the heat content changes of the upper ocean which will otherwise only be available along WHP sections and Antarctic supply vessel routes, mostly during the summer months. In order to determine the density and initial water-type characteristics of the "mode water" mixed layers, it is important that the salinity of the mixed layer be measured along with the temperature. T/C chain drifters in this region should be deployed to determine potential locations of deep reaching winter convection and the associated space and time-scales.

It is recommended that drifters, equipped with meteorological sensors and as many as feasible with T/C chains, be maintained around the subantarctic zone to improve surface pressure and temperature and mixed layer observations. It is recommended that at least 10% of the drifters have T/C chains.

ii   Antarctic Zone and Cyclonic Gyres

The Southern Hemisphere differs from the Northern Hemisphere in having a large area of ocean poleward of the Polar Front, about 30 x 106 km2. Little is known about the mixed layer structure in this region, and special techniques may be needed to observe the mixed layer during periods of winter ice cover. Candidate techniques are WHP activities combined with SeaSoar surveys during ice free periods, special winter expeditions for detailed work below the sea ice and year-round time series with thermistor/conductivity chains under ice strengthened drifters. Moorings with near-surface thermistor chains, current-meters, and upward looking acoustic Doppler profilers may also be useful for specific regions close to the continental margin. Salinity (conductivity) observations under the ice in winter are highly desirable, technological advances to allow for such measurements are encouraged.

Because of its weak stratification and nearly barotropic circulation, the total transport and variability of the circulation south of the ACC is difficult to measure. The full seasonal cycle of the water column needs to be determined. Approximately 20 surface drifters in the central Weddell gyre for two years would provide the mixed layer characteristics as well as the dynamic characteristics of the ice cover as its movement, divergences and response to synoptic weather features.

These drifters should be fitted with 300-m-long temperature/conductivity chains to monitor the seasonal stability of the water column. As the winter season progresses, salt rejection will steadily increase the density of the surface layer. We do not know if the layer ever gets dense enough to overturn the water column. If it does, warm water would be brought up to the surface, detectable by the thermistors. During polynya events this is believed to be the case, but "background" sporadic convection may also occur. Significant entrainment of warm, salty deep water is widespread within the Weddell Gyre during winter, which strongly influences the heat and salinity balance of the mixed layer. In addition, the motions of the drifters should give valuable information on the importance of horizontal advection of water and its role in controlling sea-ice growth and decay.

The surface drifters would be deployed in an incoherent array in the summer and expected to last through at least one winter. Although maximum horizontal coverage is desirable, this will be con-

strained by available ship-time. A dedicated cruise would not be necessary, but deployment could be a major component of a cruise. Coordination with the sea ice studies is recommended.

4.3.2 Specific Experiments

4.3.2.1 Choke Point Fluxes

The passages between Antarctica and the three southern hemisphere continents constitute the largest avenue for interbasin exchange in the world's oceans. The ACC transports approximately $135 \times 10^6 m^3/s$ between the Atlantic, Pacific and Indian Oceans. Anomalous water mass properties injected into this stream in one basin are carried into the other ocean sectors. This interchange is shown by the global distributions of water mass characteristics. Reid and Lynn (1971) traced the southward spread of North Atlantic Deep Water characteristics to the circumpolar current and into the Indian and Pacific basins. Similar pathways may be constructed for intermediate and bottom waters.
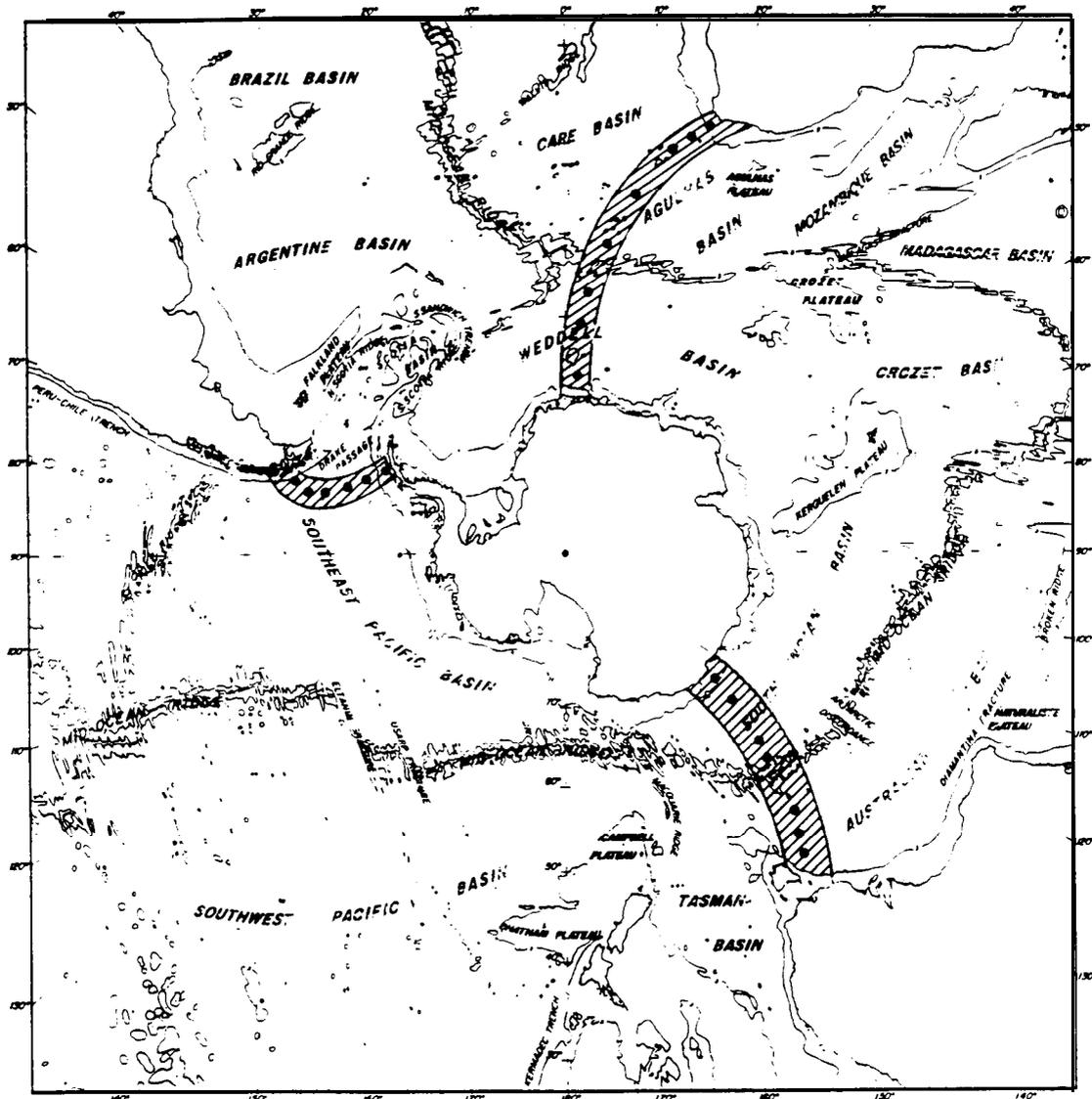

Fig. (4.3) Main topographic features of the Southern Ocean and schematic position of Choke Point arrays

The exchange of water masses by the ACC may in turn be related to the global thermohaline forcing of the ocean. As argued by Georgi and Toole (1982), transport divergences of heat, fresh water and other water mass properties are associated with net air-sea exchanges integrated over entire ocean sectors. Measurement of absolute property transports through the three ACC choke points (Drake Passage, South of Africa and South of Australia) would provide diagnostics for air-sea exchanges over entire oceans. In combination with sampling at the latitude 30° S, the choke point information would yield information about the net water-mass conversions occurring in the Southern Ocean. In addition, time series of the ACC transport and its variability will provide valuable data to study the dynamics of the current and for model tuning/verification.

An extensive current-meter measurement programme was mounted during the ISOS programme to obtain estimates of the time mean ACC transport through Drake Passage and its variability (Nowlin and Klinck, 1986). Subsurface pressure gauges were deployed on either side of the passage to monitor the fluctuations of spatially averaged velocity through the passage. From geostrophy, the difference in pressure between two points at the same depth may be related to the average velocity orthogonal to a line connecting the points, assuming there is no intervening topography between the points which can support a pressure head. As the absolute geocentric height of the ISOS gauges were not known, the pressure difference time series by itself only yielded information about the fluctuations of the mean velocity. However, levelling of the gauges was successfully attempted by using velocity data from moored current-meters. Both the direct velocity measurements and pressure-difference data documented large fluctuations in the ACC transport. Extensive analysis revealed that the fluctuations were predominantly barotropic; the baroclinic transport relative to a deep reference level, as determined from repeated hydrographic sections, varied by only 20%.

Uncertainty in the meridional structure of the barotropic flow-field introduces great uncertainty in the Georgi and Toole (1982) calculations. Although the three choke point sections satisfied the ACC transport constraint when a bottom reference level is used, this flow field is not unique. The field resulting by adding a barotropic recirculation (a flow with no net transport through the passage) to any of the sections also satisfies the mass constraint. The resulting temperature transport through the section can be much different. De Szoeke and Levine (1981) presented a map of depth-averaged heat for the Southern Ocean which shows a 4°C range between Antarctica and the northern end of the Choke Point passages. Georgi and Toole's estimated heat transports can be altered by 20% by adding a barotropic recirculation of order 15 Sv to the velocity field, e.g. by adding an eastward flow of 15 Sv at the northern end of a section and 15 Sv of westward flow at the southern end. While this adjustment represents a rather small change in the structure of the velocity field, it drastically alters the estimates of the heat transport divergence between Choke Points. The heat transport estimated in the three passages only differed from each other by some 20%. This indicates that accurate estimates of the heat transport divergence require the accurate knowledge of the meridional distribution of the barotropic flow field. These observations are needed in WOCE to provide the global heat flux estimates.

An array of instruments is proposed for the three ACC Choke Points to measure the fluxes (mean and their variations) of the ACC and the divergences in the ocean sectors (Fig. 4.3). Monitoring the fluctuations of the volume transport is the most straightforward. Bottom pressure gauges will be deployed on either side of the three choke points and on intervening topographic features within each passage. Watts and Kontoyiannis (1987) demonstrate that modern instruments are capable of providing stable long-time estimates of bottom pressure. Instrumentation to sample the vertical density profile will be deployed at each pressure gauge site to compute the pressure perturbations at depths above the gauges by integrating the hydrostatic relation. Fig. (4.4) gives a schematic of the volume transport array for Drake Passage. Pressure gauges would be deployed at the shelf break and in 4000 m water depth down slope. Pressure gradient information from the two deep sites will be related to the net transport between sites. The shallow gauges allow monitoring of the flow over the two slope regions.

Density profile information is obtained by discrete moored temperature/conductivity sensors. Moorings should be capable of extending to within 200 m of the surface. The technology for moored conductivity sensors needs improvement, although some successful deployments have been made. Over most of the water column, the T/S relation is sufficiently stable so that salinity can be inferred from temperature with minimal error. Uncertainty in salinity of order 0.02 translates to pressure errors equivalent to 3 cm water level when the hydrographic relation is integrated over 4000 m. Using inverted echo sounders at each site would give independent information about the depth average temperature. These data could act as a check of the temperature profile resolution. It is also conceivable that some type of profiling instrumentation could be used

in lieu of the discrete sensors which would yield well-calibrated salinity information in areas of a stable T/S relation.

P   - Pressure sensors

T/S   - Temperature / conduclwty
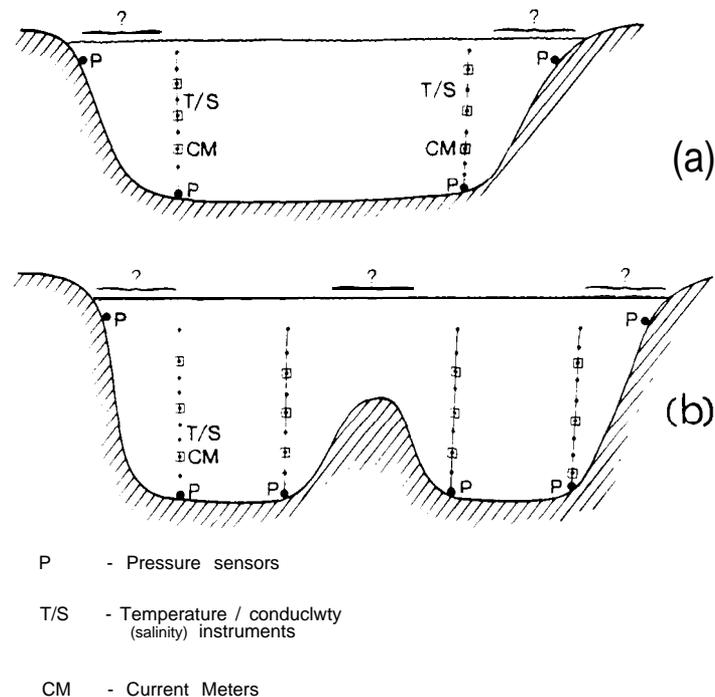   (salinity) instruments

CM   - Current Meters

Fig. (4.4) Schematic design of a transport monitoring array at a Choke Point Section

Rough estimates suggest that relative pressure fluctuation could be estimated within the water column to an uncertainty of 5 cm. For ISOS, fluctuations in pressure difference across the passage of upwards of 50 cm were found; the mean surface height difference across the Passage is thought to be roughly 150 cm.

The remaining two passages have more complex bathymetry which necessitates additional pressure/density profile measurement sites. On the WHP Choke Point sections S2 and S3 a minimum of four deep ocean measurement sites in addition to the coastal sites are required to measure transport fluctuations with reasonable accuracy.

Converting the time series of transport variations to absolute transport time series requires that the pressure gauges be levelled. Direct levelling between land sites using navigation instrumentation may be possible to order 10 cm accuracy. It may also be feasible to use absolute velocity data to level the gauges via the geostrophic relationship. Absolute horizontal velocity information along a path connecting two pressure gauge sites is required. Ships equipped with Acoustic Doppler Current Profilers (ADCP) and accurate navigation units (GPS) will provide this information. Single cruise uncertainty in passage-wide velocity estimates is thought to be of the order of 2.5 cm/s assuming seas are sufficiently calm and the ADCP functions properly. This translates into cross-passage absolute pressure difference uncertainty of 30 cm (roughly 20% of the mean difference). Repeated samples of passage-wide average velocities would improve the estimate. This is reasonably accomplished by the Antarctic supply ships which frequently traverse the three passages. Information from each passage would be valuable. Although we assume the time-mean volume transport to be nearly equal at each passage, it is not certain that the vertical structure of the ACC and hence average surface velocity and sea-level height difference is the same.

Estimates of absolute property transports require knowledge of the meridional structure of the barotropic transports. Information about barotropic transports may be obtained by augmenting the volume transport arrays in the three passages. By instrumenting 2-3 more sites in each passage, time series of temperature/salinity transport fluctuations would be obtained. This number of sites is dictated by both the large-scale structure of the density field and the range of depth-averaged temperature across the passages. Absolute transport time series could be obtained again by levelling the gauge network. The shorter distances between successive gauges makes this levelling process easier and ADCP transits between sites more synoptic. Uncertainty in absolute pressures differences of the order of 5 cm might be expected given a series of absolute velocity sections between gauges. The arrays would then provide sufficient information to give significant estimates of the mean temperature transport divergences within the ACC. In combination with inverse studies of the hydrographicitracer sections, uncertainties in the absolute property fluxes might be further reduced.

Estimation of property transports through the three Choke Points is more difficult. The Drake Passage results suggest that the property transports relative to a deep surface do not vary much with time. The WHP sections, with associated acoustical profiler data along the Choke Point sections will provide - in addition to levelling the pressure gauges - "snap-shot" information on the flux of heat and salinity. This quantity will vary linearly with the changes in the volume flux as measured by the pressure gauge array. In order to test this statement the Choke Point WHP sections will be repeated as often as possible, at least once per year, with an additional winter period crossing. Repeated hydrographic sections are also required to document the variability and estimate mean relative transports and uncertainties. Particular emphasis is needed for the passages south of Africa and Australia as little information from these sites is available at present.

Current-meters are to be placed on all pressure sensor and T/S moorings to provide direct velocity measurements at a uniform level, e.g. 2000 m across the passages. While the primary method used to level the pressure gauges are the WHP sections with good Acoustical Doppler Profiler data, the current-meter data would help to check the WHP section and reduce errors. Drake Passage should have additional moorings of current-meters to provide a better levelling of the pressure gauges. Current-meters are also recommended for the T/S moorings, at least at three levels, as an aid in resolving the vertical structure of the velocity field. For additional discussion and suggestions concerning the Choke Point monitoring array see Annex 3 "Measurement of the ACC Mass and Property Transport" in the WOCE Core Project 2 Planning Meeting Report, (WCP-181, 1987a).

The location of the potential arrays has been considered extensively (Fig. 4.3). The Drake Passage Choke Point **(SCM1)** is best instrumented somewhat to the west of the narrowest point in the passage. Here, the bathymetry is relatively flat and there are no intervening ridges which could support pressure gradients. South of Africa, it is suggested that the array extend southwest from Cape Town before turning south (SCM2). This track lies to the west of the Agulhas Current/Return Current system. The array should extend through Bouvet Island to utilize the sea level information there. South of Australia the array could be run west of Tasmania, crossing the mid-ocean ridge east of the Antarctic Discordance (SCM3).

Mass and Heat Exchanges   across 30 º S

Based on the distribution of continents, the Southern Ocean is generally considered to have a northern boundary at 30º S. The effect of the Southern Ocean on the rest of the world's ocean and also the effect of the world's ocean on the Southern Ocean can then be summarized by the fluxes of mass, heat, fresh water and other properties across the 30º S section. For large-scale numerical models of the Southern Ocean circulation, these fluxes constitute the boundary conditions required for realistic simulations. WOCE Core Project 1 has set highest priority on determination of the meridional heat flux across 30º S in the south Atlantic, south Indian and south Pacific Oceans because this is the latitude where the maximum heat transport is expected in each of these oceans. For Core Project 2, however, the problem is much more than ocean heat transport. It is important to know how much Antarctic Bottom Water and how much Antarctic Intermediate Water flow equatorward across 30ºs into which basins. Where does the poleward return flow occur: only in the deep western boundary current of North Atlantic Deep Water in the South Atlantic or in the broad, mid-depth poleward flows apparently found in the south Pacific, Indian and Atlantic Oceans?

To determine the exchange between the Southern Ocean and the Atlantic, Indian and Pacific Oceans, a combination of zonal sections and moored current-meters are required during WOCE.

In the Atlantic sector, a zonal hydrographic section should be run across 30°S and arrays of moored current-meters should be deployed at the western boundary in the Brazil Current (ACM3) and at the eastern boundary in the Benguela Current (ACM4). The array at the western boundary should include both shallow and deep current-meters to measure the Brazil Current in and above the thermocline, the deep western boundary current of North Atlantic Deep Water and the bottom flow of Antarctic Bottom Water. The array at the eastern boundary should concentrate on measuring the flow of the Benguela Current above 1000 m depth.

In the Pacific sector, a zonal hydrographic section should be worked across 28° S to repeat the SCORPIO section carried out in 1967. Current-meter arrays are required on the eastern (PCM14) and west-ern sides (PCM9) of the section to measure the East Australia Current and the Peru-Chile Current. The northward flow of Antarctic Bottom Water occurs over the deep Kermadec Trench where current-meter moorings would be difficult. Hence, it is more sensible to measure the Antarctic Bottom Water flow both north of this section through the Samoan Passage and south of this section off the Chatham Rise (PCM9) where the measurement problem is simpler.

In the Indian sector, the zonal hydrographic section should be made across approximately 32° S. Current-meter arrays are required on the eastern and western sides of this section in the Agulhas Current along the African coast and in the Leeuwin Current along the Australian coast. To measure the Antarctic Bottom Water, a current array is needed at the eastern edge of the Broken Plateau near 100° E (SCM4). A second current meter array just east of the southeast Indian Ridge near 30° S (SCM5) will measure the cen-tral filament of Antarctic Bottom Water flowing northward into the mid-Indian basin. The other major flow of Antarctic Bottom Water into the Indian Ocean occurs along the southwest Indian Ridge, but the bathymetry appears to be too confusing to allow unambiguous measurements to be made at 30° S. Hence, measure-ments of this flow would be better made both north of this section off Madagascar and south of this section near Crozet (SCM6).

Because the meridional sections across the choke points of the ACC south of Africa, Australia and South America will be made repeatedly during the austral summer, these zonal sections across 30° S should preferably be carried out during the summer also. Such sampling would complement the historical SCORPIO section across the Pacific Ocean taken during June-July, the DISCOVERY section across the Indian Ocean during April-May, and the ATLANTIS section across the Atlantic during April-June.

While it is also of interest to monitor the time variability of the flows across 32°S, these hydrographic sections are too long to be repeated very often. Instead, it is suggested that short hydrographic sections ex-tending out from the coast into deep (order 4000 m) water be taken as often as possible at each end of these sections. Such hydrographic section time-series would measure the time variability of the mid-ocean aver-aged baroclinic meridional flow. In combination with time-series current-meter measurements of the western boundary currents and deep flows, satellite altimetric measurements of sea surface slope and scatterometer measurements of wind stress and hence Ekman layer flow, such time-series measurements should allow an examination of the time variability of the meridional exchange of mass and heat between the Atlantic, Indian and Pacific Oceans and the Southern Ocean across 30° S.

4.3.2.2 Eddy Statistics

A second level of eddy-resolving model validation involves the comparison of model variability with observed eddy statistics. Direct measurement of oceanic fluxes and energy levels, through moored time-se-ries for example, is not providing a sufficiently complete data set for understanding the transfers occurring in the general circulation. The flux problem will ultimately be addressed by the eddy-resolving models. A rea-sonably representative set of observed fluxes are needed in order to validate these models; a three-dimen-sional view of eddy statistics in the Southern Ocean will serve this purpose. However, detailed maps of eddy variability are only obtainable through drifter data at the sea surface and sea level as obtained from satellite altimetry. Both of these methods have been used previously (Patterson 1985, Cheney et al., 1983). For WOCE it will be necessary to extrapolate these surface maps to subsurface levels in order to obtain the three dimensional view of eddy statistics. We know that for much of the Southern Ocean the horizontal motions are highly coherent in the vertical first baroclinic mode. The primary influence on the overall level of eddy activity at the sea surface at any site seems to be the interaction of the large-scale flow with topography or the vicinity of western boundary currents. A major goal of the WOCE Core Project 2 eddy statistics studies is estimating
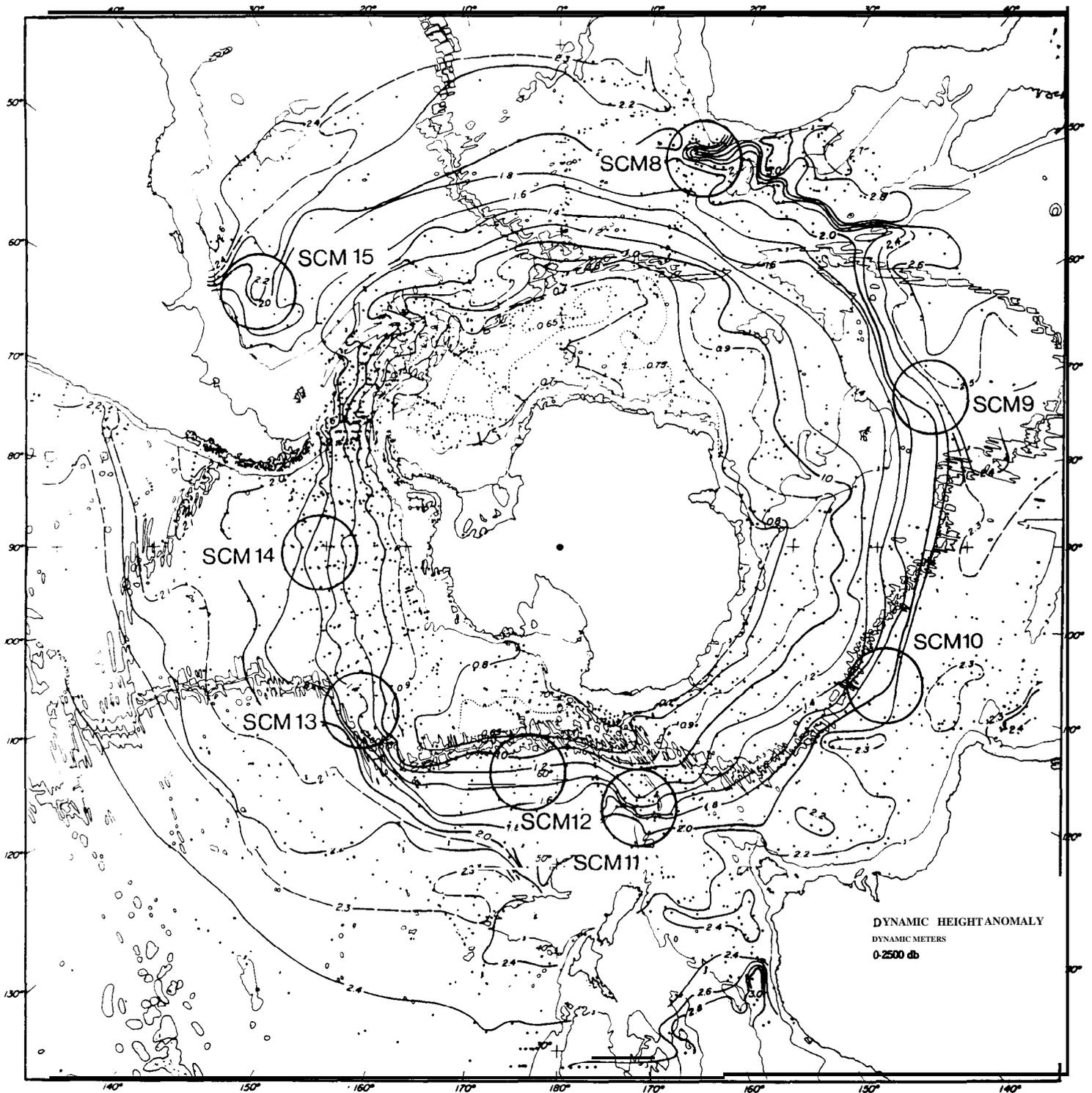
Fig. (4.5)   Proposed sites for Eddy Statistics Mooring Arrays in the Southern Ocean, superimposed on the dynamic height anomaly (dyn m) O-2500 db. (After Gordon and Molinelli, 1982)

the vertical variation of eddy energy and horizontal heat flux in areas of differing eddy energy levels and differing topographic influence.   The aim of this endeavour is to understand the vertical structure of eddy variability in relation to the more readily obtainable altimetric and surface drifter data.

Such a programme should sample a broad range of eddy regimes. Areas, specifically aimed at a variety of topographic features and eddy energy levels at the northern edge of the ACC, where moored current-meters might be considered for deployment are given in Fig. (4.5):

SCM8   South of South Africa, 20º E - high eddy energy in the region of the Agulhas Current Retroflection.

SCM9   Indian Ocean, 70º E - high eddy energy region where ACC crosses the Kerguelen Plateau.

SCM10   South of Australia, 110º E - region of low eddy energy based on Seasat data and historical hydrographic data.

SCM11   South of New Zealand, 165º E - region of high eddy energy based on Seasat data. Also important for study of the bifurcation of the ACC southeast of New Zealand.

SCM12   Pacific Ocean, 165º W - region of low eddy energy based on Seasat data.

SCM13   Pacific Ocean, 140º W - high energy region as the ACC crosses mid- ocean ridge.

SCM14   Southwest of Chile, 90º W - low eddy energy region where the ACC crosses the Southeast Pacific Basin. Determines the statistics of eddies upstream of the Drake Passage in the Bellingshausen Sea.

SCM15   East of Argentina, 45º W - to be used to study the cross/ downstream wavenumber statistics of the ACC in the Atlantic sector.

References to relative magnitudes of eddy energy are based on studies by Lutjeharms and Baker (1980) and Cheney, Marsh and Beckley (1983).

Bryden and Heath (1985) suggested placing mooring arrays at the northern boundary of the ACC as baroclinic signals will be larger and meteorological conditions more favourable. These measurements will directly complement WOCE studies in the southern hemisphere subtropical gyres.

Another type of "array" aimed at looking at the vertical variability of eddy energy and eddy fluxes would be a line of moorings across the ACC, in order to estimate the broad scale of eddy energy decay away from the axis of the ACC.

The subsurface float programme provides a broad view of eddy variability below the sea surface, but this might be confined to a single level. In the case of the pop-up floats a bias introduced into the statistics by their occasional sampling of the surface circulation must be considered.

There are certain regions where the wider programme of eddy statistical description could be augmented in order to determine the detailed structure of the eddy field. In Drake Passage and southeast of New Zealand, coherent arrays of current-meters have yielded information on the eddy momentum fluxes, energy balances and eddy/ocean flow interaction. This type of study is important to the diagnosis of appropriate dynamical balances within models. For example, a coherent array of current-meters and bottom pressure sensors, placed in an appropriate topographic regime, may illuminate the magnitude of form drag as a dissipative mechanism for momentum in the ACC.

Hydrographic work in conjunction with the deployment and recovery of moored current-meter arrays is required to establish the relationship of meso-scale variability to fluctuations on shorter length and time-scales.

A site at which the poleward eddy flux of heat may well be anomalously large is the subantarctic zone southeast of the Agulhas Retroflection, where warm eddies from the Agulhas system penetrate southwards in

the vicinity of the Crozet Plateau. Direct measurements of eddy fluxes are planned for this region, combining underway profiling of the density field with ADCP/GPS velocity data.

The degree to which extra instruments and moorings are deployed at various sites depends on per-ceived material risks and potential scientific losses associated with the particular mooring site. Any individual record recovered will provide some estimate of the mean and variability field. The scattered records of eddy kinetic energy and point estimates of eddy heat flux provide valuable information on the vertical structure of eddy statistics and a constraint on eddy resolving general circulation models. If enough widely scattered sites are chosen for the deployment of single moorings, individual mooring losses may not have a severe impact. In the case of moored arrays, where the processes of eddy variability are investigated, the loss of a single mooring can have a significant outcome on the projected scientific value of the heavily instrumented site. Re-dundant information is highly desirable in the determination of spatial coherence in the eddy field. Clusters of moorings should include at least 4 individual moorings.

Sampling at several levels in the water column is necessary in order to resolve the depth variability of the eddy kinetic energy and heat fluxes. Sampling with a vertical resolution of at least 1000 m is consistent with previous measurement programmes in Drake Passage and south of New Zealand.

Current-meters should be capable of sampling speed, direction and temperature at hourly intervals. Each mooring should be equipped with at least one pressure-sensor so that depth excursions of the mooring may be corrected for in post-processing. Failure to correct for mooring motion can lead to substantial errors in eddy heat flux calculations (Nowlin et al., 1985).

The length of mooring array deployments will be determined by the sampling time required to obtain statistically reliable results. Deployment time requirements are site-dependent because the confidence levels are a function of the magnitude of eddy variability and integral time-scale of the processes. Longer records will provide the best statistical estimates of the mean flow and eddy fluxes. Time-series of at least two years are required.

Because of the close relationship between the eddy statistics programme and the availability of alti-metric measures, scheduled deployments (particularly coherent arrays) during WOCE should occur during the operational period of the satellite altimeters.

4.3.2.3 Form Drag

Essentially by a process of elimination, it appears that the interaction of the ACC with the large-scale topographic features, the form drag, may be the primary mechanism balancing the wind-induced momentum of the ACC. The design of a specific experiment to test this important hypothesis is a fundamental challenge to oceanographers. No experimental approach is identified by the Core Project 2 as yet, but as it is important to the ACC dynamics, it is included mainly as a challenge.

The Southern Ocean may be the ideal place to carry out a form drag experiment: it is an important mechanism and the sites where it may be found are very accessible. The interaction of the ACC with topog-raphy south of New Zealand or in the Scotia Sea makes these areas attractive candidates for such study.

4.3.2.4 Subpolar "Cyclonic" Gyre and Western Boundary Current

The meridional and vertical flux of heat and fresh water, accompanying major water mass formation processes, within the broad ocean region between Antarctica and the ACC (roughly 55º to 70º S), makes this zone a key element in the large-scale climate system. From this region very cold deep and bottom waters form and spread into most of the world ocean. The heat/salinity flux patterns south of the ACC influence the climatic characteristics of the glacial cap and ice shelves of Antarctica as well as the extensive winter sea ice cover. We know very little about this zone, mainly because of the difficulties of carrying out field work in that environment. A WOCE effort within this zone must focus on a few important features to provide dramatic im-provement of this description.

South of the ACC the wind field induces an Ekman divergence and a poleward Sverdrup transport. This transport is balanced by northward western boundary currents at, at least three, at the sites around

Antarctica. These define the subpolar cyclonic flowing gyres. There is only one clearly defined western boundary, the Antarctic Peninsula. It supports the largest and best-formed gyre, the Weddell Gyre, which extends eastward from the Antarctic Peninsula to approximately 20º E, and from Antarctica to about 56º S. Other cyclonic circulation cells are less well defined. They are the Ross Gyre, located north and northeast of the Ross Sea, a poorly defined gyre south of Australia, east of the Kerguelen Plateau and one or two small gyres within the Bellingshausen and Amundsen Seas, between the Ross Gyre and the Antarctic Peninsula. The western boundary currents associated with these gyres are locked onto submarine topographic features.

The subpolar gyres carry poleward the heat and salt delivered by the ACC. The organized gyre circulation suggests that this transfer may occur in the mean field, rather than the eddy field, which in the nearly homogeneous water column south of the ACC would have characteristic scales of only 10 to 20 km. Along the continental margins of Antarctica dense water is formed, feeding the production of Antarctic Bottom Water. The meridional flux within the gyres is modified by vertical processes which introduce relatively warm, salty deep water into the polar surface water and at some locations, by deep reaching convection.

Within the subpolar gyres the baroclinic circulation is weak, the surface baroclinic geostrophic flow relative to a deep reference level is rarely above 2 or 3 cm s^{-1}. Yet the Weddell Gyre western boundary current may carry as much as 70 to 90 Sv. The more-or-less uniform flow from the surface to the sea floor requires only small speeds. The average of 8 cm s^{-1} as measured by drifting ships and buoys, is sufficient to support the large transport. The nearly homogeneous water column and the associated dominance of the barotropic mode is one of the reasons that progress in further description of these gyres has been slow.

Three WOCE activities within the subpolar gyres are recommended. These are: (a) the WHP 65º S "Antarctic Divergence" section; (b) Monitoring of the western boundary current of at least one gyre, preferably the Weddell Gyre; and (c) Lagrangian measurements involving instrumented drifters and subsurface floats.

(a)   WHP 65º S "Antarctic Divergence" Section (**S4**)

This zonal section would resolve the thermohaline, oxygen, nutrient and other chemical tracer distribution across all of the known and suspected subpolar gyres. The Southern Ocean has been measured exclusively by meridional sections. This is acceptable to study the zonally oriented circulation and fronts of the circumpolar belt, but does not resolve the structure of the subpolar gyres, where significant meridional flowing currents occur. A reverse situation exists within the subtropical gyres, where traditionally measurements were made along zonal sections. Recently meridional sections have improved our understanding of these features and their interaction with the ACC.

The Acoustical Doppler Profiler is most important for the Antarctic Divergence section in view of the dominant barotropic circulation. Reference to the Doppler measurements would allow determination of the transports associated with the thermohaline field. The 65º S section provides an opportunity to set out an array of surface drifters for further resolution of the large-scale circulation pattern.

(b)   Western Boundary Current (**SCM7**)

The uncertainty in the transport associated with the subpolar gyres is extraordinarily large. Closing this uncertainty must be placed on high WOCE priority. It is recommended that the transport and thermohaline structure of these features be measured for at least one year duration during WOCE. In view of the difficulty in making such measurements it is likely that no more than one gyre can be measured. The Weddell Gyre, being the largest, best formed and the site of major AABW formation and outflow, is favoured, though effort in the other gyres is encouraged.

Western boundary current monitoring in the western Weddell Sea is difficult because of the year-round sea ice cover, but it is possible to set up an array of current-meters further downstream, where the western boundary current separates from the Antarctic Peninsula to form the Weddell-Scotia Confluence. A disadvantage is that some Weddell water may leak out into the Scotia Sea through gaps in the South Scotia Ridge. However, placement of the array south from the South Orkney Plateau with a mooring in the deep gap just west of the Plateau would capture the western boundary current (Fig. 4.6). This area is ice free during the summer.
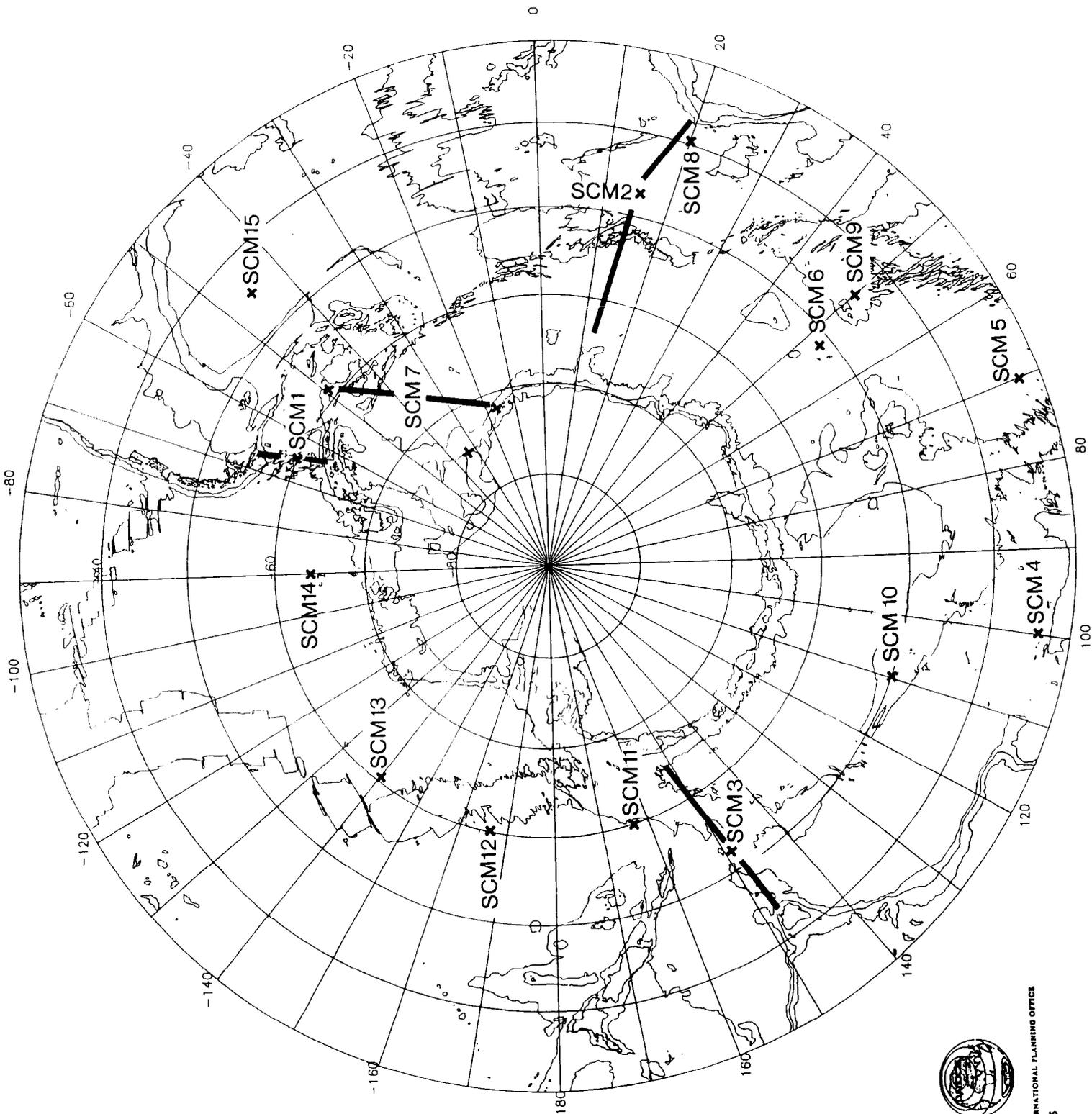
Fig. (4.6)   Mooring sites in the Southern Ocean

Due to the barotropic dominance only three current-meters per mooring are required. These current-meters should also measure temperature and conductivity. It is not feasible to set out a eddy resolving array, but assuming the eddy field is homogeneous and the barotropic pattern has a large-scale structure, a series of five moorings set at 100 km intervals from the flank of the South Orkney Plateau into the gyre will improve the statistical reliability.

During the period in which the western boundary current is measured the inflow of relatively warm-salty deep water into the Weddell Sea by the slope current off Cape Norwegia needs to be measured as well. This will allow inflow-outflow differences to be monitored, essentially treating the Weddell Sea as a "black-box" to determine the integrated alterations accomplished within the Weddell Sea. The relative narrowness of this current based on the thermohaline field, suggests that perhaps three moorings with three current-meters each, would be required.

In addition, two or three moorings with two current-meters each, are to measure the outflow from the Filchner Depression during the western boundary current monitoring period. This will allow explicit inclusion of one of the key bottom water contributors in the "black-box" approach. Temperature/conductivity sensors on these current-meters would be most important.

At the time of deployment and recovery, a CTD section (**SR4**) with acoustical profiler from South Orkneys to Cape Norwegia should be carried out.This helps to resolve the smaller scales of the western boundary current, and the western segment of the Weddell Gyre.

(c)   Lagrangian   Measurements

The significant barotropic circulation component of the cyclonic gyres represent a challenge in re-solving the complete circulation pattern. The 65° S section with high quality acoustical profiler data would provide "snap-shot" views of the meridional component of this pattern. Lagrangian methods, both surface drifters and subsurface floats, would provide the means for a long-term and large-scale description of the general circulation of the cyclonic gyres.

Deployment of surface drifters over the Intensive Observation Period are recommended. About 20 ice-strengthened drifters per year should be distributed annually over this period, with concentration within the Weddell Gyre. They should be designed to survive at least one full year. Thermistor-Conductivity chains attached to perhaps half of these drifters are needed to determine the thickness of the mixed layer and its thermohaline characteristics. These data would provide a seasonal picture of the development of the mixed layer and associated vertical heat flux and distribution of melt water. These measurements determine the combined velocity field of the wind-induced and the density-driven surface layer circulation. It is likely that some of the drifters set out in the open ocean as part of the large-scale circulation study of Core Project 2 would drift into the cyclonic gyres, but unless they are ice strengthened they would not survive the winter period.

To estimate the barotropic component of the gyre circulation, floats at a fixed depth are to be seeded into the gyre. The ALACE floats discussed in the large-scale circulation part of Core Project 2 may give some coverage, but they would be unable to survive a pop-up under the sea ice. Therefore, special RAFOS float deployment experiments are recommended to study the cyclonic gyres. Technology developed in the Arctic environment should be applied to the Southern Ocean study. Deployment of 10 RAFOS floats annually together with 3-4 receiving stations in polar ice-covered regions are recommended. With a life-time of more than one year, the main structures of the southern and western sector of the gyre are to be determined (**SF2**).

Other Subpolar Gyre Activities

It is likely that other activities will be carried out in the region south of the ACC as part of various national programmes. These should be coordinated with the WOCE activities through SCAR.

4.4   Plans by Method

This section deals with the impact of the scientific plans for the Southern Ocean on the resources required. It includes the hardware, the logistics to put the hardware in place and the means of data recovery. Other less widely available techniques will obviously be used and encouraged during WOCE but will be dependent on the expertise of particular groups.

4.4.1   WOCE Hydrographic Programme

The general requirements are presented earlier and are incorporated with Core Project 1 needs in the WHP plans. The summary here is based on activities entirely south of 30º S. As in all ocean basins WHP sections will be worked that extend into the Southern Ocean, here only the specific requirements of the Core Project 2 with respect to station spacing etc. are stressed. Only those sections of the one-time survey that lie in their entire length south of 30" S amount to 14 979 nm with 500 small-volume and 55 large-volume stations and will require 184 days of ship-time.

For the repeat hydrography four sections require 210 days of ship-time; they cover 20 654 nm and 694 stations.

The annual repeat of the Choke Point sections adds 45 days/year (assuming that stations obtained during the return to northern ports are done at less frequent intervals). This would add about 180 ship days over a four year period, approximately the time of the Choke Point Experiment.

4.4.2 Surface Drifters

The scientific design objectives in this technique are :

1.   to measure the near surface water velocity,

2.   to support, and transmit data from, subsurface instruments such as thermistor and conductivity chains,

3.   to provide a platform for robust unattended instruments for flux measurements.

Core Project 2 stresses the first and the second objective. A premium is put on the survival of individual systems, including drogues, for design periods of 2.5 years in the Southern Ocean. The principal role of these instruments for mapping and near-surface eddy statistics calls for on average one drifter/500 km2 south of 45º S, approximately 200 drifters. This is similar to the design goals during the FGGE and is criteria used in Core Project 1.

It is planned to deploy some 400 open ocean drifters over the 5 year period of WOCE, drogued and equipped with thermistors for SST. From a meteorological interest to measure the pressure field in the area, these drifters are suitable platforms. Deployment will best be done during the regular Antarctic supply-ship runs at the beginning and end of the summer season and from WHP ships. This will require early discussions with the principal operators to get their agreement. One will need to get the cooperation of an experienced Antarctic operator in providing coordination of the logistics.

Buoy design for the sea-ice environment shows promising developments (for example, the FRG Winter Weddell Sea experience). A number of buoys complete with thermistor and conductivity chains, typically to 200 m depth, could be launched, with a reasonable chance of survival, freezing in if necessary, and then overwintering before coming free the next summer. Their first objective would be to record the near surface thermal structure rather than doing current-measurements.

The WMO Executive Committee has recommended that WMO Member States deploy a limited number of drifters in the sea-ice zone up to and during the WOCE. The small number of such drifters likely to be available suggests their deployment in a limited area of the Weddell Sea.

There is also a requirement for T/S chains in the subantarctic zone where deep winter mixed layers exist or mode waters form. About 10% of the open-ocean drifters would be needed to measure the seasonal evolution of these mixed layers.

The overall need for drifters within Core Project 2 open ocean, sea-ice regions, Weddell Sea mixed layer amounts to 540 over 5 years, 25% of which are to be equipped with Temperature/Conductivity Chains.

4.4.3 Sub-surface Floats

To provide a basic circulation reference level, the WOCE Core Project 1 strategy is adopted. North of the ACC (roughly for the area north of 50º S) floats will be deployed at one level along the WHP sections in a combination of RAFOS and ALACE floats. There will be 60 RAFOS and 60 ALACE floats, south of 50º S, 80 ALACE floats required.

Deployment at additional levels, within specific water mass layers will require another 100 RAFOS floats.

Specific experiments with SOFARRAFOS technology are required within selected regions, using the technology developed in the Arctic, for the area south of the ACC. This aspect of float requirements for Core Project 2 adds 10 RAFOS floats per year, representing a total of perhaps 50 over the WOCE period.

This brings the total number of floats to 210 RAFOS and 140 ALACE floats over the full WOCE period.

4.4.4 Sea-Level

In situ measurement of sea level is a priority at high latitudes, both because TOPEX/POSEIDON does not reach there but also because of the special importance of the barotropic component in the sub-polar gyres. It is important to attempt to level tide gauges at the Northern and Southern ends of the choke points to determine an absolute datum. This should be carried out for all gauges in the vicinity of the choke points, both at beginning and end of the satellite missions, using VLBI and DORIS techniques.

Present plans identify about 24 potential sites south of 45º S and of value to Core Project 2 provided logistic problems of deployment either in remote locations or in the presence of sea-ice can be solved. Of these, about 10 are on the Antarctic coast at research stations. They too should be levelled to an absolute datum.

For altimetric calibration, about 6 sites, distributed round the Southern Ocean and preferably at island sites, should be capable to relay hourly or more frequent measurements within 2 months of collection.

4.4.5 Moorings-Current Meters

The requirements for moorings in Core Project 2 fall into three Specific Experiment groups: Choke Point, Eddy Statistics and Western Boundary Currents of a Cyclonic Gyre (Weddell Gyre).

(i) Choke Points

There are six "Choke Points": three involving the ACC, within each of the passages separating the major ocean basins; and three along 30º S in each ocean.

ACC Passages: About 22 moorings are required for most of the WOCE period. These would have current-meters, pressure gauges and temperature/Conductivity (salinity) sensors. Profiles along the sector boundaries with an ADCP are required to level the pressure gauges. They should be repeated as often as practical. Otherwise, if the ADCP cannot achieve the precision required, the logistically expensive alternative of a short term current-meter array sufficient to resolve the eddy field is needed.

This would require of order 12 moorings and 24 deep current-meters at the Drake Passage section and greater numbers at the other two passages.

30° S Choke Points: Moorings of current-meters are to be placed at the western and eastern boundaries. It is estimated that 30 moorings are needed, each with 5 current-meters, roughly equally distributed between oceans, along 30° S. Total current-meters for this aspect are 150.

Pressure Gauges: These play a critical role in the measurement of the ACC and are thus of high priority in the programme. At each choke point, gauges are required at the shelf break, (at least in the Drake Passage), at the foot of the slope and on any dividing ridge system on the section. This may require 5 sites per section and if possible there should be redundant gauges at those sites to assist in identifying long term drift.

Therefore a total of 22 pressure gauges are suggested.

Temperature/Conductivity (Salinity) Sensors: These are directly linked with the pressure gauge sites to provide sufficient vertical resolution to resolve the mass field at given levels. The alternative of a profiling T/C recorder may be feasible by the time of the experiment. The number of T/C sensors per section will be of the order of 25, totalling 75 for all sections.

(ii)   Eddy Statistics

A minimum requirement is for about 18 moorings at 8 dispersed sites around ACC belt. Each mooring is full-depth and with typically 5 current-meters, at least one having a pressure sensor to monitor mooring performance and all having temperature sensors with expanded scale in deep water. The use of conductivity sensors should be considered when their accuracy is improved. At a lower priority, the plan recommends some redundancy against failure by adding additional moorings at the same sites. Time series of two year minimum duration are proposed. This requires at least 18 moorings with 90 current-meters for 2 years.

A further recommendation is made that at least one incoherent array be used to study the North-South variation in eddy covariances. This would involve an additional 3-4 moorings and approx 10 current-meters.

At a lower priority it is recommended to measure the coherence of the fields at some of the above sites. This involves approximately 10 more moorings and 40 current-meters. Repeated deployments to achieve the full time-series will multiply the required numbers of current-meters.

The total need is about 31-32 moorings with 140 current-meters. These "eddy" moorings should be deployed during the time of maximum altimeter coverage.

(iii)   Cyclonic Gyre and its Western Boundary Current

The need is for coherent measurements of current, temperature and, if possible, conductivity on normal sections both on the southeastern (continental) boundary and at the northern boundary of Weddell Sea for at least 2 years. Assuming 10 moorings with three current-meters each, a total of 30 current-meters will be required in the water at any one time.

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4.5   Summary of Requirements

	Specific Experiments					**Large-Scale**	
	Choke Point Fluxes	Eddy Statist.	Form Drag	WBC Cyclonic Gyres	Thermo-haline/ Tracer	Circula-tion	Upper layer
WHP	A	A	B	A	A	A	A
Sea Level	A	C	B	B	C	A	C
Drifter (T/C chains)	B	A	B	A	B	A	A
Floats	B	B	A	B	C	A	C
Satellite	A	A	A	A	B	A	A
Moorings	A	A	A	A	B	A	B

A - Critical; B - Supportive; C - does not apply

5   CORE PROJECT 3

'THE GYRE - DYNAMICS EXPERIMENT'

5.1   Introduction

Core Project 3 is that part of WOCE that will study the processes that must be better understood if decadal climate predictions using models are to be made by the end of WOCE. The Scientific Plan states that by studying certain processes in one ocean basin in sufficient detail it will be possible to make major advances in eddy-resolving models of that ocean basin that can be extended to models for the global ocean. A major feature of these advances would be to explain and simulate the dominant modes of variability over a broad spectrum of spatial and temporal scales and to develop parametrisations of important processes that would have general applicability in ocean modelling.

It is difficult to identify the particular processes which must be better incorporated in ocean models in order that these models can better represent the existing state of the ocean, let alone be used for decadal climate prediction. As more is learned about the dynamics of the ocean and models are developed with ever increasing resolution throughout the period of WOCE, new problems will arise and new aspects of ocean physics need clarification. Thus, the experiments put forward for Core Project 3 in this Implementation Plan will need to be augmented and modified during the WOCE Intensive Observation Period.

The experiments outlined in this chapter are for the most part based on the ideas put forward at the Core Project 3 Planning Meetings held in London 2-5 September 1986 (WCP-139, Anon. 1987b) and Miami, 27-29 April 1988. These ideas have been refined by the Core Project 3 Working Group. Two kinds of experiments have been identified: first there is a need for traditional process-oriented experiments that can be carried out in a limited area, secondly basin-scale experiments using many of the same observational techniques as will be used for Core Project 1 but in such a way as to provide more detail in the fields being observed. Measurements made at higher resolution in space and time will allow inferences to be made about the nature and magnitude of key processes within the ocean basin, and will yield more accurate basin-scale averages with which to examine conservation laws and budgets and support studies of the variability of the circulation. They will also allow more accurate and extensive comparisons between observations and numerical model solutions based upon particular parametrisations.

Combining model development with the clarification of important processes is consistent with the concentration of Core Project 3 in one ocean basin. Concentration of both basin-scale and localized Core Project 3 experiments will permit the data obtained for one purpose to be used as background data in support of other experiments and the possibility of discovering unexpected connections between various mechanisms. Modelling studies focused on the Core Project 3 experiment will similarly benefit from a greater density and variety of measurements, as a result of their concentration in a single basin.

The ocean basin selected for the major part of Core Project 3 is the Atlantic Ocean. The principal reasons for this choice are its strong manifestations of diabatic processes (water mass conversion), size, previous measurements, and its proximity to major shipping bases. Its small size requires fewer measurements to obtain adequate resolution. The abundance of previous measurements provides a better historical data base to be built upon and to design experiments. The present plan is to span the subpolar and subtropical gyres of the North Atlantic, the tropical Atlantic, and the subtropical gyre of the South Atlantic, while excluding the peripheral seas except to establish their exchanges with the primary basin.

A variety of measurements in many locations will contribute in the coming decade to the understanding and development of parametrisations of key processes for the general circulation. Not all of these measurements will be made as part of WOCE, and not all of those made in WOCE will be made within the Atlantic Basin. The experiments described in this chapter will be made in the Atlantic Basin and reflect the Core Project 3 planning process with its emphasis on identifying key processes and the benefits of studying them within a single basin in conjunction with extensive modelling studies as discussed above. Those experiments that are relevant to the objectives of Core Project 3 and which for logistic and/or scientific reasons will be carried out outside the geographical limits of the Atlantic basin may be accepted as key contributions to WOCE. However, nations are strongly encouraged to conduct their experiments in the Atlantic basin where possible.

Enhanced basin-scale measurements for Core Project 3 are built upon the global sampling for Core Project 1. This includes the various satellite measurements (sea-level, surface stress, sea-surface temperature, and lower atmospheric quantities) and the network of full-depth hydrographic and tracer sections. Other global measurement programmes will be augmented within the Atlantic to give higher spatial and temporal resolution. In this category are repeated hydrographic sections (generally not to full depth), surface layer heat and salt distributions, near-surface horizontal velocity, mid-depth horizontal velocity, and air-sea fluxes (especially of heat and fresh water).

The horizontal, vertical and temporal resolution of the enhanced coverage is based on the possibility of resolving important scales over the basin. The horizontal resolution scale for statistical analyses (means, variances, mean seasonal cycle) is 250 km, with higher resolution in zones of strong gradients (for example, in boundary currents). In the upper ocean and at the surface, the temporal resolution is seasonal, although some analyses will be made on synoptic scales (for example, Ekman layer response). Detailed vertical resolution will be obtained from profile measurements (heat and salt and perhaps velocity). Velocity will be measured near the surface with drifters and in the vicinity of 2500m with floats.

Lateral exchanges of the Atlantic basin are also to be obtained, including variability where that is important. This includes exchanges with marginal seas (Baffin Bay, the Greenland and Norwegian Seas, the Mediterranean Sea, the Caribbean Sea, and the Gulf of Mexico) and with the Antarctic at 30° S where enhanced temporal sampling is to be obtained in the interior and special studies made in the high variability regions at the boundaries.

The present plan is to sustain the augmented basin coverage for approximately five years.

Within the enhanced Atlantic basin-scale programme there will be additional measurement programmes of lesser spatial extent and/or duration directed at particular processes or circulation regimes.

Because of the impracticality of obtaining high resolution deep sampling of the density field spanning the full basin, several sub-domains have been selected for such sampling. One collection of sub-domains, termed 'control volumes' and having a horizontal scale of about 1000 km, is planned for several sites in the North Atlantic sub-tropical and subpolar gyres. These are described in Section (5.3.2). The control volumes are to be measured simultaneously, with coverage of seasonal extremes and with at least one interannual contrast.

Another sub-domain is the Deep Basin Experiment described in Section (5.3.3). Its objectives are to measure in a well-delimited basin the interior circulation, the deep boundary and passage currents, and the cross-equatorial transport associated with the global thermohaline forcing. Because of the clear indications of deep circulation in the tracer fields, simplicity of topography, and the relative weakness of local mesoscale eddy forcing of the deep circulation, the Brazil Basin has been selected as the site.

A third sub-domain is the tropical experiment described in Section (5.3.4). Its objectives are to determine the interactions of tropical and mid-latitude circulations, particularly regarding meridional transports across the equator.

Within the control volumes and Deep Basin Experiment, additional experiments will be made on specific processes. One of these, described in Section (5.4.3), concerns the use of tracer releases to determine small-scale mixing (diapycnal primarily, but also isopycnal). Since it is desirable to relate the mixing to environmental parameters (that is, the rms shear, stratification and the relative contributions of salinity and temperature gradients to the stability), three tracer releases are planned, one in the thermocline in the eastern sub-tropical gyre control volume and two in the Deep Basin Experiment (at 2000 and 4000 m).

Several surface layer process experiments are also planned (see Section 5.4.2). These include experiments on the subduction of fluid drained from the surface mixed layer and its subsequent migration into and beneath the thermocline along approximately isopycnal trajectories, the response function of currents in the Ekman layer to wind forcing and the vertical distribution of these currents, the deep convection forced diabatically by wintertime surface cooling in weakly stratified regimes with consequent deep penetration of turbulent mixing, and surface fronts that lead to intense, small-scale lateral and vertical fluxes in the vicinity of those associated with intense currents (for example, the Gulf Stream).

The sites for these process experiments are to be within the control volumes or other sub-domains with enhanced resolution. However, as mentioned earlier, some process experiments may best be conducted outside the Atlantic.

5.2   **Basin-Scale   Measurements**

5.2.1   Introduction

The central objective of Core Project 3 is to improve our understanding of processes and to improve models for ocean circulation. A common property of complicated models is that particular features of their solutions can be brought into conformity with nature by altering parameter values and formulae for the component processes, although arbitrary alterations usually make other aspects of the solutions less realistic. Thus, model development and evaluation are best done when both the component processes and the large-scale circulation are described in sufficient detail by observations. This is an important element of the basin-scale measurements of Core Project 3.

Measurements with greater resolution in both space and time will be provided on a global scale by Core Project 1. For the global satellite measurements of sea surface temperature SST, surface wind stress, sea-level height, and various quantities involved in estimating surface heat and water fluxes, the planned Core Project 1 resolution is reasonably good, particularly in time. Greatly enhanced resolution throughout the basin is impractical for the full-depth hydrographic and tracer profiles and additional sea-level measurements around the perimeter of the basin would be of little benefit in characterizing the interior circulation.   However, the global sampling density will be usefully and significantly enhanced in the Atlantic for:

* atmospheric surface pressure, temperature, humidity, and wind and oceanic SST for air-sea flux estimates;

* surface layer circulation;

* upper ocean mass field;

* mid-level circulation in the interior;

* major boundary current transports and

* exchanges with marginal seas and the Antarctic oceans.

In almost all instances, the implementation procedures for making these measurements closely parallel those for Core Project 1.

For the purposes of Core Project 3, the Atlantic basin is taken to lie between approximately 30° S and 60° N latitude, excluding marginal seas. The area of this domain is about 5 x 107 km2 or about 15% of the global ocean. The northern boundary coincides with the southern tip of Greenland, and thus the domain encloses the greater part of the North Atlantic subpolar gyre and the Labrador Current. Lateral exchanges occur with the Greenland, Norwegian, and North Seas and with Baffin Bay. The eastern boundary excludes the Mediterranean Sea, and the western boundary excludes the Gulf of Mexico and some, perhaps all, of the Caribbean Sea. The southern boundary is the most problematic. The area north of 30° S encloses the majority of the South Atlantic subtropical gyre and all of the Brazil Basin (see Section 5.3.3). This is the most northern boundary location of simple shape enclosing all the gyre-scale and process measurements in Sections (5.3) and (5.4). At its eastern and western ends the Benguela and Brazil Currents flow across the line and the regions of greatest eddy variability lie outside the basin to the south. Thus, this line is one of relatively simple circulation compared to other possible basin boundaries farther south (see also Section 5.2.5.3).

Basin-scale data will be analysed to provide statistical and synoptic descriptions for model comparison. The former will comprise means, variances, covariances, and, where significant, mean seasonal cycles, averaged over time within a given horizontal area. Because the ocean is statistically inhomogeneous geographically, suitable analysis areas are non-uniform in size and anisotropic in shape (for example, with longer

zonal scales in the tropics).   In regions of approximate homogeneity the area might be as large as 2.5×10^5 km^2, but in strong gradient zones such as near boundary currents, much smaller areas are preferable. An average analysis area is estimated to be about 0.7×10^5 km^2, which corresponds to a horizontal scale of 265 km. This horizontal resolution is approximately twice that of the global sampling rate in Core Project 1 and, when compromises forced by logistics or finances are required, this relative sampling ratio can be used to guide the partition between the global and basin-scale programmes.

The synoptic data analysis will be on a horizontal scale comparable to the basin dimensions. The time resolution of the relevant measurements must be fine enough to support synoptic analyses which match those from satellite measurements and atmospheric assimilation and forecast models to be used in air-sea flux estimations. Although many of the measurements will be made much more frequently, the most useful analyses will be on scales which are weekly or longer.

The duration of the basin-scale measurements is to be five years. This will yield statistical products which are reasonably representative in time and synoptic products encompassing interannual variability.

5.2.2   Air-Sea Fluxes (**ASFG, ASF1**)

As discussed elsewhere, there is a requirement to determine the air-sea fluxes of momentum, heat and fresh water with comparable resolution and accuracy to that of the enhanced measurements of the ocean circulation in the Atlantic basin. There are many aspects to estimating these fluxes, as discussed in Sections (3.2.7) and (3.3.1). The global data assimilation scheme for air-sea fluxes proposed by the JSC/CCCO Working Group on Air/Sea Fluxes when implemented using satellite data with operational forecast models at centres such as ECMWF, will provide the fluxes at least twice daily on a 2.5^o grid. Increased resolution to 3-4 times daily on a 1$_o$ grid is a possibility. Thus, methodologically uniform products will be available, except when changes are made to the atmospheric model, the assimilation procedure, or to satellite algorithms. A uniform product throughout WOCE, that maximizes both the in situ and satellite data would require reanalysis with at least a six month delay.

Twice daily fluxes on a 2.5^o grid satisfy Core Project 3 needs, provided the flux estimates at each time step and grid point are independent. This proviso means that in situ data from the vicinity of each grid point must get into the assimilation system in time for each analysis cycle. Augmentation of the existing Atlantic jn situ data network to provide these data is part of Core Project 3. In situ measurements are to be obtained from VOS augmented by drifting buoys where necessary. The quantities to be measured include atmospheric pressure, wind, temperature, and humidity, clouds (or radiation) and oceanic SST, although not all platforms will provide measurements of all these quantities.   Improvements to the accuracy of average VOS observations are necessary as is verification of the data, using quality-controlled subsets of VOS. The number of drifting buoys required can be estimated as follows. Assuming the buoys give time-continuous measurements to allow spatial interpolation in synoptic analyses for model assimilation, a horizontal resolution of about 750 km will suffice for the atmospheric quantities.   With favourable spacing, this resolution can be achieved with about 100 platforms in the Atlantic Basin. If the VOS shipping lanes cover half the basin, the augmentation of atmospheric measurements with drifting buoys in the less well travelled regions of the South and Equatorial Atlantic requires a continuously maintained array of no more than 50 buoys. Horizontal resolution of SST needs to be somewhat finer because of persistent smaller-scale features in the ocean but surface layer velocity drifters (Section 5.2.3) will provide a sufficient number of additional platforms for SST measurements so that the blended satellite and in situ measurements will have adequate accuracy and resolution.

The fluxes from atmospheric models will not satisfy the accuracy requirement for all of the Core Project 3 experiments for which additional measurements will have to be made. For example, subduction studies (Section 5.4.3) have stringent requirements for the wind stress curl and surface heat flux and a moored array of surface meteorological buoys will be used to measure accurate surface winds and heat flux parameters, including radiation (**ASFG**).

Process studies measuring the surface fluxes and upper ocean response (for example, heat content changes) can fulfil a valuable role in validating routine atmospheric model products, as will the basin-scale measurements of heat and salt content (see Section 5.2.3). Surface data could still be used in the operational assimilation, provided a parallel research assimilation is performed without this data. Upper ocean heat content changes, which are primarily due to surface heating, can be used to validate the time integral of the

model surface heat fluxes after corrections are made for advection and mixing. This technique improves as the time and space scale increases (Gill and Niiler, 1973). In principle, a similar validation of model freshwater fluxes can be performed using changes in upper ocean salinity.

5.2.3   The Surface Layer (**AD1, AX1-20**)

The surface layer is directly affected by exchanges with the atmosphere and strong vertical mixing. Fluxes of momentum and buoyancy must pass through this layer for the atmospheric forcing to effect a response in the interior circulation. Basin-scale measurements will provide statistical and synoptic analyses, as specified in Section (5.2.1), for surface layer velocity and for heat and salt content, vertical distribution, and lateral transport. The surface circulation features of primary interest are the upper portions of the geostrophic gyres, the ageostrophic wind-driven currents, and the tropical zonal currents. The primary features of interest in the buoyancy field are the surface mixed layer and seasonal thermocline. In the tropical Atlantic, responsibility for these measurements will be shared with TOGA.

As in Section (5.2.2), the primary measurement platforms are ships-of-opportunity and drifting buoys. Along ship tracks measurements will be made by XBT or XCTD profilers; the ships-of-opportunity making these measurements probably will be a subset of those measuring atmospheric quantities (Section 5.2.2). On a few tracks acoustic Doppler profilers will also measure horizontal velocity, hence provide cross-sections of the surface layer transport of heat and salt across the track. Where ship tracks are too sparse, drifting buoys with thermistor chains will provide supplementary information on heat content and vertical distribution; these drifters probably will be the same ones used for measuring atmospheric quantities. The methodology for designing the array for these measurements has been established by Brethetton et al. (1984) and in TOGA: approximately 25 ship tracks, occupied at least seasonally, will be required, together with about 50 additional thermistor buoys throughout the 5 years of measurement. This requirement is as for Core Project 1. Proposed sections are shown in Figure 3.4 (**AX1-20**).

Surface layer velocity, SST, and lateral heat advection will also be measured from drifters drogued in the well-mixed layer just below the surface. Estimates of velocity sampling requirements are based upon the following summary of present experience with Lagrangian measurements in the ocean. An analysis area occupied by a Lagrangian marker will have an independent measurement of velocity about every 20 days, and thus a total of 100 independent measurements in 5 years; this will give about a 10% relative uncertainty in estimates of kinetic energy and Lagrangian diffusivity and (in most locations) mean velocity. This implies the number of markers required is the same as the number of analysis areas desired, which is about 720 in the Atlantic basin (Section 5.2.1/4)(**ADG, AD1**). However, near the surface the correlation time is often somewhat less than 20 days and the velocity mean is often larger relative to its variability than in the ocean interior; thus, it may be possible to obtain the desired resolution and accuracy by relaxing the number required somewhat, to an array of about 600 drifters maintained for five years. The synoptic analyses require that these drifters be not too irregularly distributed within the basin during the five years of measurement; this can be achieved with multiple deployments, partly from some of the VOS.

5.2.4   The Ocean Interior (**AF4**)

Basin-scale measurements of the interior circulation, including its variability as a function of surface forcing, will focus on the two sub-tropical and the northern sub-polar gyres in the Atlantic basin, within and somewhat below the main thermocline, and on the mid-level equatorial circulation. These circulation features comprise the greater part of the response to the large-scale surface wind field, and they are thought to be the energy source for most of the mesoscale eddy variability in the Atlantic basin.

The ocean interior measurements will provide the broader context (and, in a loose sense, boundary conditions) for all of the smaller scale experiments in Sections (5.3) and (5.4) (other elements of the basin-scale measurements make analogous contributions): the gyre circulation between the control volumes (5.3.2), the mean and eddy circulation above the Deep Basin Experiment (5.3.3) and the surface layer scale fields for the tropical experiment (Section 5.3.4), the interior geostrophic response beneath the wind-driven surface layer (5.2.3 and 5.4.2), the far-field distribution and dispersal rates of subduction products (5.4.3), and the vertical structure of the baroclinic fields influenced by smaller scale mixing (5.4.4). The interior measurements will also provide the climatological data base for the mean and variability of the mid-level circulation) which, have been most frequently used as the basis of numerical model assessments.

A primary objective is to measure the baroclinic structure of the main thermocline and the horizontal currents in its vicinity, as well as their variability. Both statistical and the synoptic characteristics, as described in Section (5.2.1), are important.

The principal measurement techniques are hydrographic sections, ships-of-opportunity XBT and XCTD lines, and mid-level acoustically tracked floats. The ship-of-opportunity measurements required for this purpose are the same as described in Section (5.2.3). The floats will be either of the SOFAR or RAFOS type, or perhaps a mixture deployed at a planned depth of 2500 m. At a given level, the sampling requirement is as described in Section (5.2.3), approximately 720 floats for the Atlantic basin, yielding 3600 float years of data over 5 years **(AF4).** There is a much weaker requirement for uniform distribution in space and time, compared to surface velocity drifters, because only the statistical mode of analysis is anticipated for floats. Thus, floats may to some extent be released for particular process studies while keeping in mind the need for overall coverage of the Atlantic basin.

In order to monitor variations on the gyre-scale, quasi-continuous series of the baroclinic structure, corrected for the eddy signal, are needed. Therefore, the above programme must be augmented by autonomous stations measuring the baroclinic structure at strategic sites. Such stations can be moored thermistor strings across the main thermocline, combined with conductivity sensors in locations where the T/S relation is known to vary. In locations of simple baroclinic structure, inverted echo sounders could be used. These have been proposed for the Southern boundary measurements (Section 5.2.5.3) and the tropical experiment (Section 5.3.4) but experimental design questions remain to be addressed. The stations can be combined with bottom pressure gauges and sea surface altimetry to obtain the barotropic mode. The seaward end points of western boundary arrays as described in Section (3.4.1.9) can also contribute.

5.2.5 Lateral Boundaries

5.2.5.1 Boundary Currents

For the major boundary currents within the Atlantic basin, time series of transport, or some reasonable proxy, are required. These currents include the Gulf Stream (both through the Florida Strait and after separation from the coast), the Labrador Current, the Brazil Current, the Benguela Current, and the western boundary undercurrents. It is not clear at present whether additional eastern boundary currents should be monitored in this fashion beyond the eastern boundary process study described in Section (5.4.5). Some of these boundary currents are also included as part of Core Project 1 **(ACM1, ACM2, ACM3, ACM4, ACM5, ACM6, ACM7).** A summary of all mooring sites in the Atlantic is given in Fig. (5.1).

The techniques for measurement are either repeated hydrographic sections, moored current meters, acoustic velocity profilers (either of the Doppler sonar or buoyant float tracking types), acoustic tomography, and electro-magnetic induction measurements. For each current, the appropriate site and technique needs to be identified. The Florida Strait probably is best monitored by continuing the present electro-magnetic measurements at the cable. The western boundary undercurrents in the South Atlantic will be measured with current meter arrays as part of the Brazil Basin experiment (Section 5.3.3).

5.2.5.2 Exchanges with Marginal Seas (**ACM8, ACM9**)

The marginal seas given in Section (5.2.1) have significant exchanges with the Atlantic basin. The mass and tracer fluxes need to be determined, at least in the statistical analysis mode defined above. The measurement techniques are the same as those listed in Section (5.2.5.1), and, for each marginal sea, the appropriate technique and strait or passageway needs to be selected. Measurement of the exchanges across the Greenland-Iceland-Faroes-Scotland Ridge system and with the Mediterranean are included as part of Core Project 1 (Section 3.4.1.9)(**ACM8, ACM9**)**.**

5.2.5.3 Exchanges with the Antarctic (**AR2**)

General arguments in favour of choosing the southern boundary of the Atlantic basin at 30° S are given in Section (5.2.1). This line will be used as a southern boundary for some model calculations and for basin-integral budget calculations. The 30°S line is one of the major heat flux sections specified by Core Project 1 and the boundary transports of the Brazil and Benguela Currents at either end of the line are to be

Fig. (5.1)   Summary map of mooring sites in the Atlantic Ocean

measured in this context (Sections 3.4.1.2 and 3.4.1.5). Also as part of Core Project 1, the 30ºS section is to be repeated, at least in the upper 1500 m once in each season in order to get a zero-order estimate of how the heat flux associated with heating and cooling in the upper layers varies over an annual cycle.

Core Project 2 also focuses on the need for measuring transports across the 30ºS section and in addition to the net heat transport specifies a need to measure the transports of the main water masses which have sources in the Southern Ocean or contribute to the water masses formed there (Sections 4.3.1.1 and 4.3.2.1).

Core Project 3 has the same basic requirements as Core Projects 1 and 2 at 30ºS with more stringent demands regarding resolution in time (**AR2**). Along the section this might be accomplished by more frequent occupation or by the use of moored instruments such as Inverted Echo Sounders or thermistor chains. The exact nature of an array that would meet the requirements of the tropical experiment remains to be determined. At the boundaries the extreme complexity of the Brazil and Benguela Current systems may need enhancement of the Core Project 1 and 2 boundary current arrays to meet Core Project 3 Objectives. However, since a boundary current array to meet the needs of any of the Core Projects remains to be designed in detail, it is premature to specify the nature of any additional requirement for Core Project 3, although it might be by extended areal coverage around 30ºS.

The location of the southern boundary of the Atlantic Basin and other elements of the Core Project 3 Atlantic Experiment are shown in Figure 5.2.

5.3   Gyre-Scale Measurements

5.3.1   Introduction

In this section the three "gyre-scale" experiments introduced in Section (5.1.1) are described.

5.3.2   Control Volume Experiments

One fundamental test of large scale ocean circulation models is that they reproduce the shape, volume transport and response to atmospheric forcing of the major components of the gyre-scale circulation.   In the case of the North Atlantic this would include the Gulf Stream system, the recirculation area of the subtropical gyre, the North Atlantic current and the circulation adjacent to the eastern boundary.

Since it does not seem feasible to resolve changes in the basin-scale density field on seasonal and/or interannual time-scales, the strategy has been adopted of making intensive synoptic measurements in five control volumes. Each would be large enough to allow spatial averaging over the eddy field and yet small enough to be sampled by a single vessel over a period of about three weeks. Such control volumes would be similar to the "beta-triangle" which was centred at 27º N, 32º 30' W and which was visited five times between 1978 and 1981. The results were summarized by Armi and Stommel (1983) and show that, although the property fields were reasonably stable from cruise to cruise, there was large variability of the baroclinic velocity shear. No connection could be made with other similar variability that might exist elsewhere in the gyre or with the large-scale forcing fields.

It is proposed as part of Core Project 3 to sample simultaneously five control volumes located in different regimes of the North Atlantic. These are described below. Measurements would be obtained in late fall, late winter and midsummer with a further occupation at the time of the initial sampling.

The size of each control volume will be chosen to be relatively small with respect to the gyre but large enough with respect to meso-scale eddies so that local slopes and curvatures of the distribution of properties in three dimensions can be obtained by spatial averaging. A triangular region was chosen for the beta-triangle but the actual shape is not critical and may be optimised to make best use of sections connecting the control volume region with the gyre boundaries. A typical control volume might be made with 40 deep hydrographic stations at approximately 100 km spacing over an area of 800 to 1 000 km on a side. The detailed design of each of these control volumes needs to be made. The basic hydrographic geochemical tracer measurements in the control volumes will be supplemented by additional mooring and float measurements,
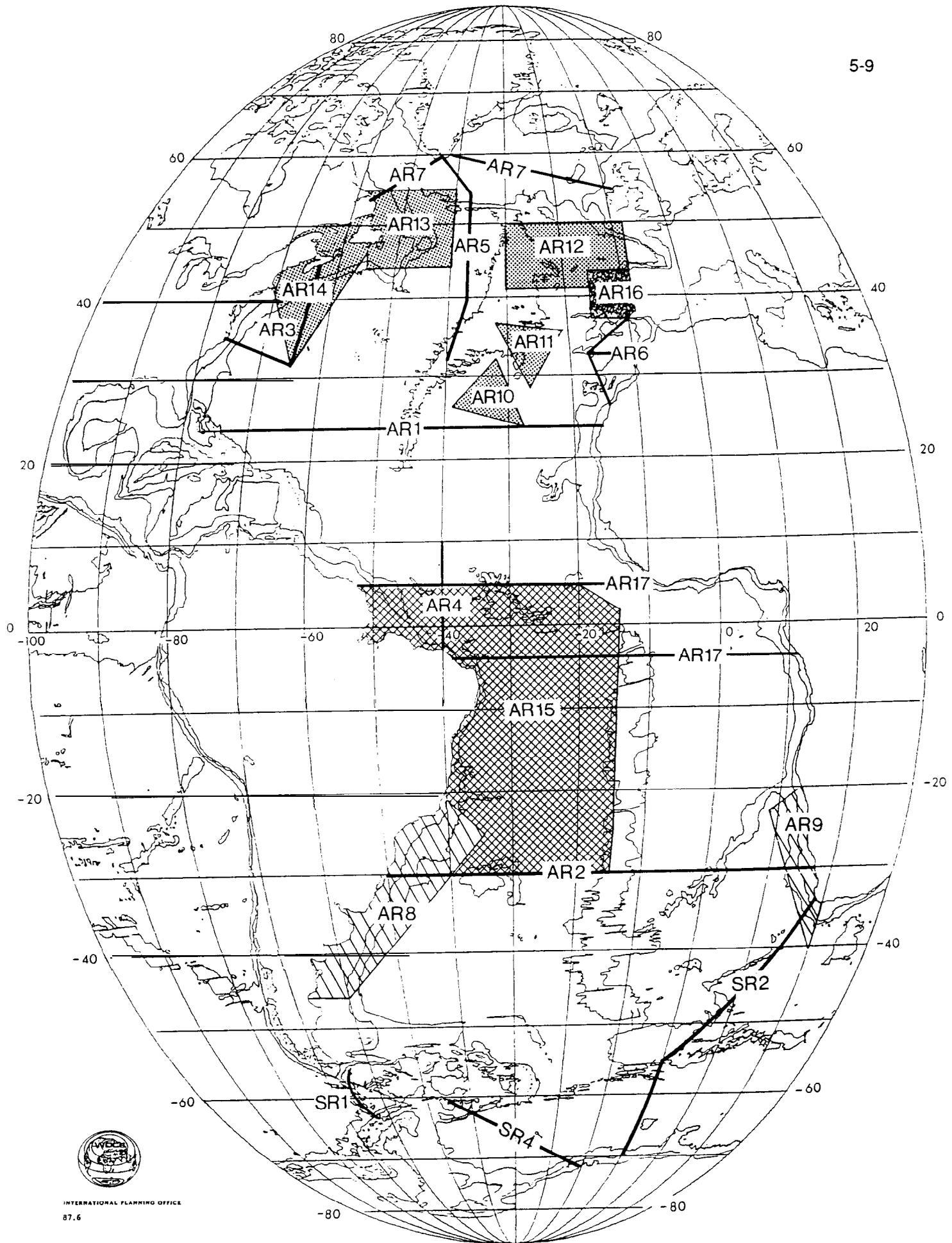
Fig. (5.2) The WHP repeat survey in the Atlantic Ocean and the Elements of Core Project 3: AR10 -
Control Volume I, AR11 - CVII, AR12 - CVIII, AR13 - CVIV, AR14 - CVV, AR16 - Deep Basin
Experiment, AR16 - Eastern Boundary Current, AR17 - Tropical Programme

both to support overall scientific goals of the control volume study and to support process-oriented experiments that are likely to be carried out within the control volume areas.

Because the proposed station spacing is reasonably dense, it will be possible to examine the balances of salt, oxygen and potential vorticity within the control volume region. For the beta-triangle, this was accomplished by fitting second degree polynomials to the salinity, oxygen and pressure distributions on various density surfaces that were computed with reference to the average pressure on each surface. These surfaces closely approximate neutral surfaces, the use of which would be appropriate for connecting a control volume in one region to those in other regions. Sections will also be occupied to connect the control volumes to the nearest gyre boundaries each time the control volume is occupied.

Some aspects of the circulation at larger scales and for a longer period encompassing the occupations of the control volumes will be provided by the measurement of sea-surface elevation by satellite altimeters. These are particularly suited to the investigation of the gyre-scale variability which does not necessarily require the absolute velocity field to be determined. Seasat and preliminary Geosat observations provide examples of the use of such altimeter data.

Measurements of velocity using moored current meters are required to provide the vertical structure of the eddy field as well as estimates of the eddy kinetic energy, the heat flux from the correlation of the fluctuations of velocity and temperature, and the buoyancy divergence from the correlation of the fluctuations of the velocity with the gradient of density as calculated from the vertical shear. It is proposed that at least three moorings be deployed in each control volume in order to obtain smooth large-scale estimates of these eddies statistics. An Eulerian time-scale of O(100 days) and a duration of two years will be sufficient to obtain these estimates with 8 degrees of freedom. Such a duration by providing 6 record-years of data at each depth will also give useful estimates of the vertical structure of the mean current itself. For this purpose the distance between moorings should be large enough to encompass several eddy scales and small compared to the scale of the mean horizontal shear, that is, between 100 and 300 km depending on the region.

The control volumes are also the sites for carrying out the process-oriented studies described in Section (5.4) for which they can provide necessary background information. Some of the direct velocity measurements will also be helpful in carrying out the experiment itself. It is recommended that the first purposeful tracer experiment be located in the main thermocline of the control volume located at the site of the beta-triangle experiment.

The location of the control volumes:

As described above, five control volumes have been selected to be representative of different regimes in the North Atlantic. It is expected that the variability of each will have a different relationship to the surface forcing over the basin and to the changes of the circulation that will at least be observed by the measurement of the basin-scale surface topography by altimeters. Some consideration has been given to logistics and the need to provide a basis for particular process studies. The locations presented are more schematic than exact and the detailed definition of exact sections, mooring locations, float releases, etc. will be made by the principle investigators involved in consultation with the Core Project 3 Working Group. The five control volumes that have been selected are:

(a)   The Beta-triangle (**CVI, AR10, ACM18**)

The beta-triangle experiments were centered at 27º N, 32º 30' W in the southwestern end of the North Atlantic subtropical gyre. This site was visited 5 times between 1978 and 1981 and the oceanography of the area is already well understood. From a climatic point of view it is reasonable to continue measurements at this site.

Its location is such that it includes water in the main thermocline which has been subducted further to the north and which has had enough time to have spread and reached some measure of dynamic adjustment. This control volume should include a section of closely spaced stations south along 32º 30' W to approximately 5º N across the gyre boundary. Additionally, a section should be run east along 27º N to the west coast of Africa. These sections will help refer the changes observed within the control volume to changes in the gyre as a whole and its boundaries in particular.

(b)   Subduction Region (**CVII, AR11, ACM19**)

This is proposed to be centred on 34º N, 27º 30' W in the subduction region of the North Atlantic sub-tropical gyre south of the line of zero wind stress curl. Water which is subducted in this region flows in the direction of the beta-triangle region along isopycnal surfaces that lie below the mixed layer there. This control volume, unlike the beta-triangle, is not in a region of slow return flow of the gyre but instead is at the eastern end of southeastward flow of the gyre. It is a more energetic area of meso-scale activity.

Parts of this control volume have already been extensively studied and include the "Poseidon Box" (Käse et al., 1985). This control volume could be connected to the nearest gyre boundaries by sections along 32º N. It is complicated by the presence of a branch of the North Atlantic Current just south of the Azores and by compact lenses of relatively undiluted Mediterranean water.   It should be connected to the gyre boundaries by occupying the Core Project 1 section along 32º N eastward from the control volume to the shelf. The meridional section used for control volume (a), should be chosen to pass through this control volume on its way to 50º N.

(c)   Northeast Atlantic (**CVIII, AR12, ACM20**)

The proposed site spans the boundary between the subtropical and subpolar gyres in the eastern basin; it extends from the Northwestern European shelf edge at 50ºN 15ºW to the mid Atlantic ridge near 50ºN 30ºW southeast to 42ºN 20ºW and finally back to the shelf edge at 48ºN 9ºW or 42ºN, 9ºW. Its northern side is close to the proposed 48ºN section (49ºN in the eastern part) and that section should be occupied at the same time as the control volume surveys.

Inter-gyre exchange processes may take the form of enhanced mixing in the presence of weak advection, or seasonally varying advection or a combination of the two. The line of the zero annual mean wind stress curl passes across the area and migrates seasonally so that accurate surface flux measurements will be of particular importance. Use will be made of the large volume of merchant shipping and voluntary observing ships that cross this area.

The basic measurements, as in other control volumes, will centre on repeated high quality, full depth hydrographic surveys coupled with moored current, temperature and salinity records, bottom pressures, and neutrally buoyant floats, To strengthen the surface flux measurements, there will be moored meteorological sensors at the corners of the control volume and surface satellite-traced drifters will also be deployed.

The control volume provides a framework of observations within which mixing and stratification process studies can be carried out.

(d)   Southern Labrador Sea (**CVIV, AR13, ACM21**)

This control volume is located in the western subpolar gyre and straddles the boundary between the subpolar and subtropical gyres in the western North Atlantic. The location is chosen in order to concentrate on the annual response of the western boundary current of the subpolar gyre to the annual cycle in the wind forcing and on the spread of the Labrador Sea water from its formation area at the end of the cooling season. In addition, the large-scale processes leading to the formation of Labrador Sea water and the processes by which the low salinity Arctic outflow waters leave the shelf circulation and join the main North Atlantic gyre will be addressed.

This control volume will extend from 46º to 56ºN and 40ºW to 55ºW. The work will consist of a series of short hydrographic sections across the various fronts seen in the region in late autumn, late winter and mid-summer with one season repeated, mooring arrays, deep sea pressure gauges and moored T/S chains. The primary tool to trace the spreading of the Labrador Sea water will be special deep float releases (Section 3.1.10).

(e)   Recirculation Regime (**CVV, AR3, AR14, ACM22**)

This control volume is designed to look at any seasonality of the strength of the tight recirculation gyre of the sub-tropical circulation. It is based on repeated occupation of the Cape Cod to Bermuda to Nova Scotia sections which are included as part of Core Project 1 (Section 3.4.1.5). The control volume is not likely to be triangular, but rather to consist of several parallel sections the order of 100-200 km apart, crossing both the Gulf Stream and the return flow. Stations will need to be quite closely spaced in order to map the details of this active region. This programme will have to be closely coordinated with the on-going programmes monitoring and modelling the Gulf Stream downstream of Hatteras.

5.3.3   The Deep Basin Experiment

5.3.3.1 Introduction

The sub-thermocline general circulation of the oceans has proven remarkably difficult to describe and quantify and no data set exists which could be used to test eddy-resolving general circulation models. Verification of the elegant simple theory proposed by Stommel (1958) and Stommel and Arons (1960) has been restricted to the measurement of deep boundary currents which are the source of the deep water that is assumed to be supplied uniformly to the bottom of the main thermocline. An understanding of this part of the global thermohaline circulation must be obtained before any confidence can be placed in our ability to model the oceans on climatic time scales.

Much of the difficulty in observing the deep circulation has arisen from the presence of the energetic quasi-geostrophic eddy field which in general obscures the weak mean signal. Modern technology provides the opportunity to address this problem. Neutrally buoyant floats are now routinely tracked for years using moored listening stations, in fact one nine year record exists (Owens et al., 1987). Moored current meters can now be deployed for periods of up to at least two years and new CTDs have the capability of describing water masses with the increased accuracy needed for the deep ocean. Many tracer distributions can be sampled with ease and chlorofluorocarbon compounds, Helium-3 and Tritium, have been shown to be especially useful in revealing the flow patterns of the deep overflow waters that supply the deep oceans.   It thus is an opportune time to improve our understanding of the deep circulation as part of WOCE.

The Deep Basin Experiment will make use of the basin-scale measurements of the surface layer and of the determination of the mid-depth velocity field using floats. Knowledge of the mid-level circulation and its horizontal convergence or divergence is essential if the observations of the nature of the balances in the deep water flow are to be put in the context of the global circulation.

5.3.3.2 Objectives

The objectives of the experiment are:

·   to observe and quantify the deep interior flow. Little effort has been expended anywhere in the global ocean to determine the deep interior flow away from the western boundary currents.   Scattered long-term current measurements have been made (for example, Dickson et al., 1985) but it has been recognized that measurements of the mean flow are easiest where the signal is high. Traditionally, neutrally buoyant floats have seldom been used below 2000 m which is above the deep abyssal layer of interest. Property distributions have given some indication of the spreading of water masses but no real quantitative indication of the deep circulation.

·   to distinguish between boundary and interior mixing processes. The classical picture of the maintenance of the vertical profiles of property distributions by the balance between upwelling and vertical diffusion have given values for the vertical diffusivity of the order of 1 cm^2 s^{-1} (Munk, 1966). Although this type of balance may be valid on the average over a basin, little is known about the horizontal distribution of upwelling or vertical diffusivities and whether or not these are dominated by the boundary regions.

- to study the means by which deep water flows across the Equator. Deep western boundary currents away from the Equator are assumed to exist in geostrophic balance with the pressure field but such a balance cannot exist at the Equator. Antarctic bottom water flowing north across the Equator in the Atlantic appears to flow from the deep western boundary south of the Equator to the western flank of the mid Atlantic ridge north of it, although there are no observations at the Equator of this transition. The ability to model this process provides a real test for numerical models of the deep circulation.

- to understand the role of passages in the dynamics and mixing of deep water masses. Deep passages appear to control much of the flow of deep water from one basin to another. Theoretical and laboratory models have been constructed for this process but there is at present little understanding of what happens in a continuously stratified fluid. It is however certain that this control process is ageostrophic and will be poorly represented in numerical models, especially since the width of deep passages is often of the order of the Rossby radius of deformation based on the deep stratification. Passages accelerate the flow, allowing the measurement of the deep transport, but must also be regions of intensified local mixing. The distribution of salinity on isopycnal surfaces shows relatively little change within the Argentine basin but relatively large changes across the Vema Channel which is the main connection to the Brazil Basin.

5.3.3.3 Location

Which part of the Atlantic is most suitable for this experiment has been debated at length. The western North Atlantic is one of the most eddy-intense areas on the globe. Not only do eddies drive their own deep flows (see for example, Holland and Rhines, 1980) but they make more difficult the task of measuring the deep thermohaline mean flow.

The basins of the Eastern North Atlantic are less energetic but are geometrically complex with ill-defined passages connecting them and their western boundaries being the rugged and complicated Mid-Atlantic Ridge. The Angola basin of the South Atlantic has better defined passages but also suffers from a ragged western boundary.

The Brazil Basin has several advantages. Its geometry is fairly simple being roughly rectangular in shape and large enough that it stretches from the equatorial zone to the sub-tropics. It has several connecting passages, two of the major ones having been quite well studied, although the bathymetry and hydrography of the Hunter Channel to the east of the Rio Grande Rise, are not well known. The vertical structure in the South Atlantic is particularly interesting with three principal water masses sandwiched in the sub-thermocline region, one from the Arctic and two from the Antarctic. A basin with equatorial regions is important for WOCE since it allows the examination of cross-equatorial dynamics. For these reasons the Brazil Basin has been chosen as the site of the Deep Basin Experiment.

Existing plans for Core Project 1 provide, including the sections at 5° N and 30° S, sections across the basin at five latitudes and one longitude. In the more immediate future, South Atlantic Ventilation Experiment (SAVE) sections will cross the basin at three latitudes and a further section is planned along 25° W providing valuable background data, especially of tracers. The extent that North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) are tagged with freons within the Brazil Basin is becoming apparent (Weiss, 1988). Helium-3 and Radium-228 data will be available later.

5.3.3.4 Timing and resources

The field programme outlined below relies on proven technology. In order to observe the weak mean flows the programme must be of order five years or more. It is, therefore, essential that work on the Deep Basin Experiment begin at the earliest opportunity with the deployment of long-term site moorings, listening stations or transducers for float work, an initial deployment of floats, and some exploration of the terrain in regions such as the Hunter Channel and the Ceara Abyssal Plain.

(a)   Moored Current Meters (**ACM10, ACM11, ACM12, ACM13, ACM23, ACM24**)

Site Moorings are to be used for the measurement of mean flows and transports where the signal is expected to be large and for obtaining long-term statistics at several sites for the purposes of esti-

mating errors in means determined from float measurements and for judging the importance of long term, interannual variations. Not all measurements will be made simultaneously (**ACM23**).

For these purposes five to seven moorings with 3-4 instruments each need be deployed as soon as possible, for a period of two years.   Information from these will be used to help guide the float pro- gramme as well as further geographic exploration of the eddy field.   It is important to realize that at present there are no long-term direct velocity measurements of any kind in the South Atlantic away from passages. The only information available on the eddy field comes from its expression at the sea surface in the maps of Wyrtki et al. (1976) and Cheney et al. (1983). It is important that the opportu- nity be taken to obtain such statistics in the thermocline as well as in the deep water. Although record lengths of two years are probably sufficient for obtaining estimates of eddy kinetic energies, several of these site moorings, for example those on the abyssal plain, should be maintained for the duration of the programme in order to obtain information on the longer time scales. The location of the site moorings is given in Figure 5.2a (**ACM23**).

Passages are key places for measuring the input to and outputs from basins and therefore, single long term moorings be deployed in the Vema Channel as well as the Ceara Abyssal Plain to observe the long term changes in inputs and outputs.

There are four known exits or entrances to the Brazil Basin for deep water. The Vema Channel (**ACM12**) and Ceara Abyssal Plain (**ACM10**) appear to be the most important to the flow of AABW as the published sill depths of the Romanche/Chain Fracture Zones **(ACM11)** are shallower, (less than 3750m according to Metcalf et al., 1964). However, water found in the deep Guinea Basin has a minimum potential temperature of 1.6 °C which must originate from depths of 4000 m in the western basin. Modern bathymetric studies suggest that the sill depth of the Romanche Fracture Zone is un- certain but perhaps as deep as 4500 m (R. Searle, personal communication). The amount of water flowing through the Hunter Channel (**ACM13**) is also uncertain as is its geometry which needs to be explored as soon as possible. The location of the passage and boundary current arrays is shown in Figure 5.2b.

Experience from other passage experiments and estimates of Rossby Radius of Deformation sug- gests that a two year deployment of 15 current meters on 5 moorings should determine the transport to about 10% with simple geometries such as the Vema Channel or Romanche Fracture Zone but somewhat more resources will be required (20-25 instruments) for the more complicated sills. With four such passages the total basin budget would be obtained to about 20%. Vertical spacing will be such that estimates of the flow of both AABW and NADW are obtained.

The strength and horizontal structure of the Deep Western Boundary Currents need to be studied in some detail since they feed water into the interior that eventually upwells into the thermocline. These are relatively broad deep flows, weaker than their passage counterparts and therefore more de- manding of resources. The situation is complicated by the fact that the AABW and NADW currents are separated in the vertical. Rough estimates suggest the need of order 6-8 moorings with 3-4 me- ters per moorings. Meridional variations are important as these give the amount of water lost to the interior. At least two sections, preferably three, are required (**ACM24**).

(b)   Deep Floats (**AF5**)

Floats will be an important tool for obtaining statistically significant estimates of the spatial variation of the interior mean flow and eddy kinetic energy levels, investigating the spatial continuity of the deep water boundary currents, enabling comparisons to be made with the vertical shear derived from the hydrographic studies and, consequently, providing crucial information for box models and other inver- sions of the combined data.

Without any accurate knowledge of the deep eddy statistics in the Brazil Basin or, indeed, the mag- nitude of the mean flow, it is difficult to be precise about the numbers of floats required. The overall Core Project 3 Atlantic Basin coverage (Section 5.2.4), which is based on about 5 float years for each 2.5° x 2.5° box, should be adequate. However, for the Deep Basin Experiment floats at the levels of the AABW, NADW and Antarctic Intermediate Water (AIW) are indicated. For the dimensions of the
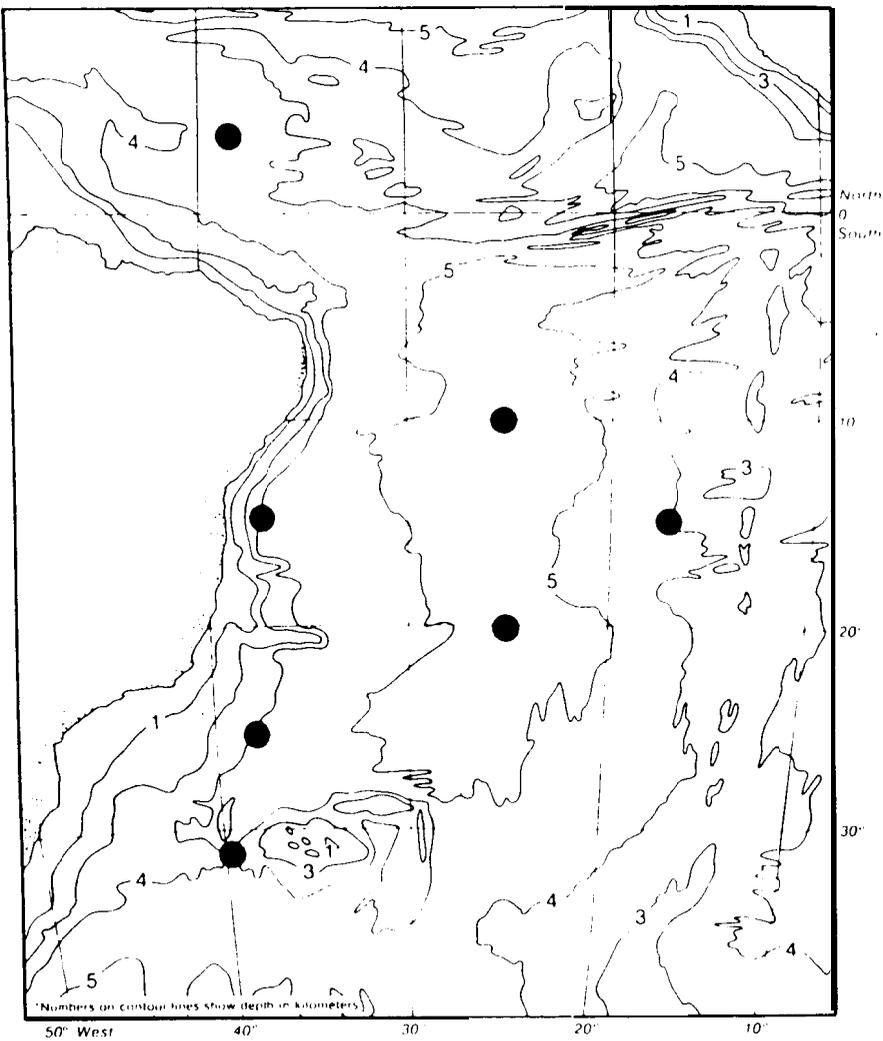
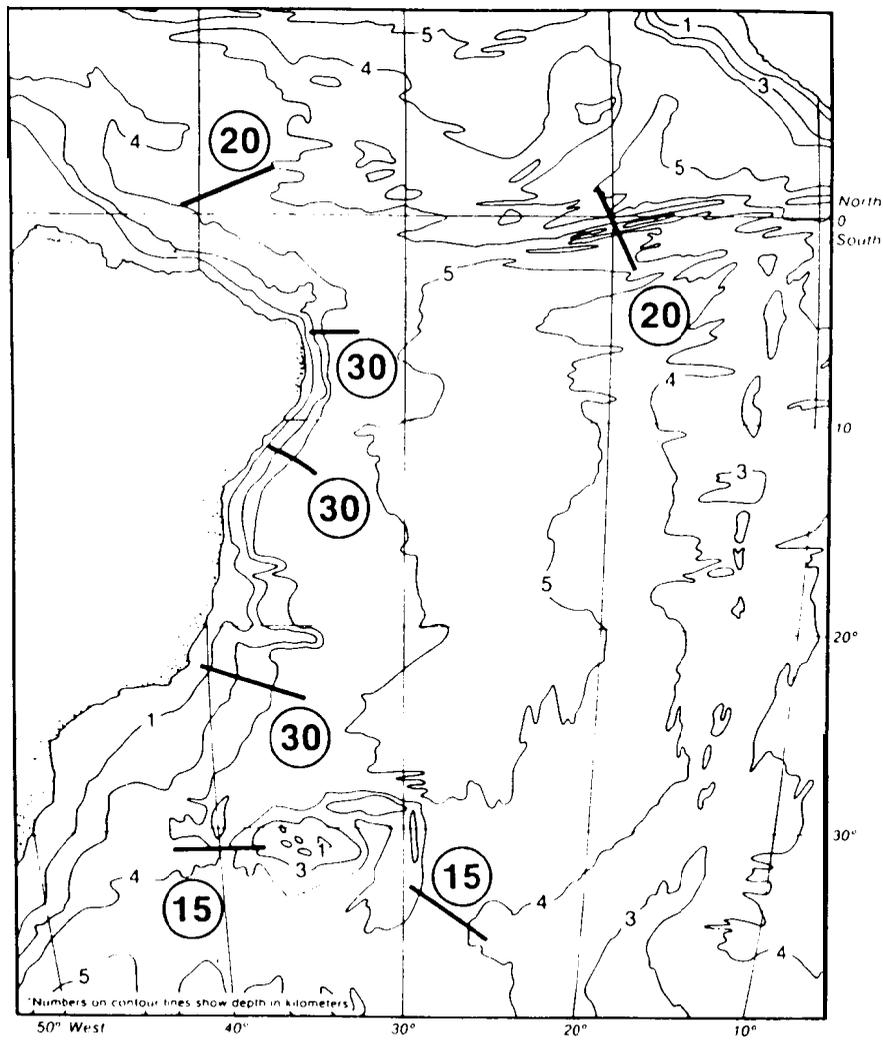Fig. (5.2a)   Deep Basin Experiment Site Moorings

Fig. (5.2b)   Sites of passage and boundary current arrays

Brazil Basin this amounts to approximately 100 floats per level assuming that they will last the duration of the experiment. More floats will be required for the Tracer Release Experiment (order 40) as discussed in Section 5.4.4 and a modest number (order 10) for release within the deep passages and western boundary currents.

The float effort discussed above is a sizable one and should be undertaken in a phased fashion with an appropriate fraction of the resources deployed each year. This approach would also help assure some spatial uniformity of statistics.

(c)   Hydrography (**A6, A7, A8, A9, A10, A15, A16, A17, AR15**)

A detailed hydrographic programme which includes the measurement of tracer properties is a key to being able to achieve the objective of discriminating between boundary and interior mixing processes. Water property measurements are also important for the definition of water masses in, for example, the passages, the western boundary currents, and where there are cross-equatorial exchanges.

Early in the experiment a detailed survey will be carried out in the equatorial regions of the Brazil Basin to help the future design of a more exhaustive study of this special area. This will include sections perpendicular to the topography along the western boundary and the mid-ocean ridge, and perhaps a section along the equator as well as perpendicular to it. Anthropogenic tracers should be measured to determine the path of NADW and AABW across the equator. This could be done in conjunction with the Core Project 1 sections at 8° N and 8° S (**A6, A7**). Early hydrographic tracer surveys are also required within the Hunter Channel and in the Romanche and Chain Fracture Zones.

Later, zonal and meridional sections across the Brazil Basin will be needed so that the basin can be subdivided into enough boxes that some spatial resolution of the cross-isopycnal processes is obtained without so finely dividing it that the spatial variation of the property fields is no longer measurable. Zonal sections at 5°, 13° and 20^oS and meridional sections along the mid-ocean ridge, at 14° W and along the western boundary are suggested as well as sections at the north and south boundaries (**A8, A9, A10, A15, A16, A17**). These are also included as part of Core Project 1. Overall it is estimated that depending on the timing of field programmes, a 50% increase in the hydrographic programme is needed for the Deep Basin Experiment over that required in the region for Core Project 1 (**AR15**). Sections are also required along the current meter arrays as frequently as is possible (deployment and recovery is a minimum).

Useful tracers include the Helium-3 and Radium-228. There should be low but measurable CFCs in NADW but this may not be the case for AABW as the measured concentrations in the Argentine Basin are presently low (0.08 pmol/kg for F-11). If it can be measured, CFCs will be useful tracers for the exchange of water between the deep western boundary current and the basin interior. This would be greatly enhanced if the limit of detection were lowered by a factor of 10. A development programme to achieve this is under way. Tritium may also be measurable in the NADW and would complement the CFC measurements. There may be a small Helium-3 signal emanating from the mid-ocean ridge.

Radium-228, with a half-life of 5.75 years, enters the ocean from the sea floor. Its distribution in the Brazil Basin is suspected to be affected mainly be vertical mixing and advection and horizontal mixing making it most abundant in the bottom 1000-1500 m. It should be possible to use Radium-228 to obtain a basin wide vertical eddy diffusivity independent of other estimates. It requires large volume sampling, but some stations will be made during SAVE and these need not be repeated.

(d)   Tomography

In the direct transmission mode, tomography provides measures of the heat content in a vertical plane and of the slopes of the isopycnals as a function of the vertical, while disposition of instruments in a triangle allows the possibility of estimates of the vertical velocity continuous in time, which would be most important to the aims of this experiment.

In the reciprocal shooting mode, tomography offers the promise of being able to spatially average the eddy field so as to obtain accurate estimates of mean velocity along acoustic rays in a shorter time than would be needed by point measurements from floats or current meters. However, for the deep flow, the tomographic signal will be contaminated by surface effects and it is unclear that meaningful results can be obtained. Several experiments which will be undertaken over the next few years will help clarify the use of this technology.

(e)   Tracer Release Experiments

The Deep Basin Experiment provides an excellent setting for tracer release experiments whose primary purpose is to measure diapycnal mixing in the ocean interior. Tracer releases will contribute directly to the goals of understanding the basin circulation while the other components of the deep basin work will help enormously in the planning, execution and interpretation of release experiments. A description of the proposed tracer release experiments is given in Section (5.4.4).

5.3.4   The Tropical Programme

5.3.4.1 Introduction

The distinctive dynamical feature of the tropical oceans is their rapid adjustment to large-scale changes in the surface winds making possible phenomena such as El Nino. Several programmes have studied how tropical oceans respond to variable winds and have provided (1) data sets that accurately describe the different phenomena that form part of the response, (2) a hierarchy of models that explain the oceanic adjustment to wind fluctuations; and (3) general circulation models of the oceans that simulate the observed variability. The focus of these studies has been the adiabatic redistribution of the warm waters of the upper ocean in response to large-scale changes in the winds.

In the global ocean circulation, the tropics are of special interest because the heat gained across the ocean surface is exported to higher latitudes where it is lost to the atmosphere. Phenomena such as El Nino cause substantial interannual variations in the flux of heat across the ocean surface and affect the meridional transport of heat. In other words, variability in low latitudes influences variability in high latitudes. The converse is also true. Conditions in high latitudes influence the tropics as is evident from the different ways in which the three oceans export heat from low to high latitudes: in the two hemispheres the meridional heat transport is poleward in the Pacific, northward in the Atlantic and southward in the Indian Ocean. These differences are attributable to the thermohaline circulation in the three oceans which are strongly influenced by conditions at high latitudes, especially the cooling of surface waters and the formation of deep waters.

Studies of the full depth meridional oceanic heat transport and of the exchanges between the tropical and subtropical ocean gyres are not being undertaken as part of TOGA, the measurements for which are confined to the upper few hundred metres of the tropical oceans.   Determination of the special role played by the tropics in overall circulation and heat transport must be studied within WOCE. This is best carried out in the Atlantic basin because of the other elements of Core Project 3 there.   The measurements described in this section, together with those of the Deep Basin Experiment (Section 5.3.3), will provide considerable information about the large-scale meridional circulation near the equator.

Extensive measurements are also to be made in the tropical Atlantic as part of Core Project 1. Core Project 3 will augment those measurements as necessary, especially along the latitudes 10°N and 8° W which are roughly the boundaries between the tropical gyre and the adjacent subtropical gyres. Attention will also be given to a critical region in the western equatorial Atlantic, where much of the cross-equatorial flow of warm waters, and of cold deep water, and also the exchange between the tropical and subtropical northern gyre, occurs in this volume.

Direct estimates of the meridional heat transport are in principle possible from measurements but in reality the measurements are far too sparse and need to be combined with models of the ocean. The development of models for the tropical oceans is at a stage where reasonably realistic simulations are possible for the upper ocean and these are being run operationally for the tropical Pacific. It is possible to start running an operational model for the tropical Atlantic implementing available data assimilation schemes. This would lead

to rapid improvements in the model, in data assimilation methods, and the development of near surface data sets, for example, of the fluxes at the ocean surface.

5.3.4.2 Objectives

The objectives of the programme are the following:

· to observe and quantify the ocean circulation throughout the water column in the tropical Atlantic. Of special interest is the meridional circulation, the associated meridional heat transport, and its variability. Relatively little is known about the region below the thermocline and it is unclear whether the pronounced seasonal cycle in the surface layers penetrates into the deep ocean. The circulation at depth and its variability need to be determined including the role of deep equatorial jets and the nature of the cross-equatorial flow of various water masses.

· to describe in detail oceanic conditions in the western equatorial Atlantic where the intense North Brazil Current carries warm surface waters northward across the equator while deep currents transport cold water southward. Variability is very high in this complicated region and the North Brazil Current, which feeds the North Equatorial Counter Current and the deeper eastward currents, flows into the Caribbean Sea during some months but veers off-shore near 5°N at other times. The factors that control this behaviour, which has a large effect on the meridional heat transport, need to be understood.

· to determine the mechanisms of exchange between the tropical gyre and the subtropical gyres to the north and south, the boundaries of which lie approximately along 8° S and 10°N. The strength of the meridional cell that transects the tropical region is estimated to be between 10 and 20 Sverdrups. However, the relative roles played by the Angola Current, the mid-basin circulation and the Brazil Current are unknown at the southern boundary. The western boundary current and mid-basin Ekman transports at the northern boundary need to be quantified. Little is also known about the deep currents across the two latitude circles as well as at the equator.

5.3.4.3 Resources

Seasonal variations in the tropical Atlantic Ocean have such a large amplitude that estimates of the mean values of certain parameters will only be possible with measurements that resolve the seasonal cycle. Although some of Core Project 1 measurements will provide time series with the desired resolution, Core Project 3 measurements need to concentrate on this important variability. It has already been demonstrated that altimeters furnish considerable information about the seasonal thermocline displacements in the western tropical Atlantic. The extremely energetic fluctuations with a period about one month that are observed within a few degrees latitude of the equator emphasize the need for time series measurements in these regions.

The measurements to be made as part of the Deep Basin Experiment (Section 5.3.3) will be primarily below the thermocline in the tropics and will complement the measurements of the Tropical Programme but to the east of the mid-Atlantic Ridge additional measurements are necessary to document deep currents off western Africa.

Cross Gyre Exchange (**AR17,AF3**)

The latitudes 10°N or 8°S, as mentioned above, roughly separate the tropical gyre from the subtropical gyres to the north and south, at least in the surface layers. A study of cross-gyre exchanges requires measurements in the vicinity of these latitudes. As planned, Core Project 1 has a requirement for one-time survey sections at 5°N and 4°S (Section 3.4.1.1) and it is to be assumed that the requirements for the tropical programme and Core Project 1 can be satisfied by the choice of a single section north and south of the equator. Because of the high variability, the tropical programme requires time series measurements along these sections, particularly the one north of the equator (**AR17**). This could be satisfied by repeat occupations of the sections, and/or moored thermistor chains or inverted echo sounders. Since much of the variability needing resolution is in the thermal structure upper ocean an enhanced XBT programme could make a significant contribution. The exact requirements to meet the special objectives of the tropical experiment remain to be specified.

In the equatorial band floats are required to describe the cross-equatorial flow of water at various depths. This equatorial requirement will be met by the enhanced coverage at 2 500 m **(AFG, AF4),** the releases at different depths (**AF3**) and some of the Deep Basin Experiment floats (**AF5**).

Western Equatorial Atlantic

It is in the western equatorial Atlantic, the triangle bounded by the coast of South America, the longitude 35°W and the latitude 10°N, that much of the cross-equatorial fluxes are believed to occur. As mentioned above, this region has a complex and highly variable circulation. In the surface layers and upper ocean the northwestward flowing North Brazil Current is fed by the westward South Equatorial Current and in turn feeds the eastward North Equatorial Counter Current and the deeper eastward currents including the Equatorial Undercurrent. During the northern winter this current flows continuously into the Caribbean Sea but during the summer much of it veers off-shore near 5°N. When doing so the current tends to meander. These oscillations seem to be distinct from waves, with a period of approximately one month, that appear near the equator, and further east, where the latitudinal shear of the surface currents is large. Below the thermocline tracers indicate the presence of a southward coastal current that crosses the equator but which also loses fluid to deep eastward equatorial currents.

Intensive measurements are clearly needed in this western equatorial region in order to describe the relations between the various currents and to determine the fluxes into and out of the region. At present TOGA and STACS are deploying instruments in this region and a number of proposals have been suggested for future work. There needs to be developed a coherent programme to meet the particular needs of the Tropical Experiment within the overall context of Core Project 3 objectives in the Atlantic Basin.

5.4   Process Studies

5.4.1   Introduction

This section describes a number of process-oriented experiments of particular importance to WOCE. It is to be expected that, as WOCE develops, other experiments of this type will both become feasible and be recognized as directly relevant to the Goals and Objectives of WOCE. Some may be best conducted outside the Atlantic (see Section 5.1).

5.4.2   The Structure and Dynamics of the Ekman Layer

5.4.2.1 Scientific Background

Quasi-geostrophic models of the large-scale circulation take the effect of wind forcing as given by the classical Ekman relation with the transport at right angles to the wind, and with the magnitude proportional to the wind stress divided by the Coriolis parameter. The overall structure of the wind-driven gyres in these models depends critically on the Ekman relation. Diagnostic studies of global heat transport show that the heat flux in the Ekman layer at some latitudes is a major contributor to the net poleward heat flux (Bryden and Hall, 1980). Thus, the Ekman transport relation is of central importance in modelling the ocean circulation and its global transport.

For some problems, it is only the transport itself that is important. However, the transport of heat and other properties depends upon the depth over which the Ekman transport occurs in the water column. Interpretation of the anticipated global surface drifter data will depend to a large degree upon our ability to separate the wind-driven current from the geostrophic current. This will require a far better understanding of the depth to which Ekman transport penetrates into the water column.

5.4.2.2 Goals

Measurement programs aimed at verifying the Ekman relation, and learning how deeply the transport occurs in the water column have generally not been conclusive (Davis et al., 1981, Weller and

Halpern, 1983). Recent advances in both in situ measurement technology and the likelihood that satellite altimetry will provide a useful measure of sea surface height, make it plausible that a carefully designed field experiment to measure both the wind stress and the wind-driven transport will be fruitful in achieving the following goals:

·   to determine the wind-driven, ageostrophic transport on space and time scales appropriate to the large-scale ocean circulation.

·   to determine the depth distribution of this transport.

·   to determine the variation of its depth as a function of stratification, the local mesoscale environment, and the surface fluxes of heat and momentum.

5.4.2.3 Necessary Measurements

The central element of the Ekman layer experiment will be an incoherent array of surface moorings each of which will carry the best possible meteorological package to observe winds and other variables needed to estimate surface momentum and heat fluxes. Current measurements will be made by Vector Measuring Current Meters spaced fairly densely along the mooring line. Recent observations suggest (Richman et al., 1987, and Price et al., 1986) that under fair weather conditions the Ekman transport may be strongly surface trapped, and hence special care will need to be taken to obtain measurements as near the surface as possible.

Most previous field studies have had considerable difficulty separating the wind-driven flow from the pressure-driven, geostrophic flow. A key element of the WOCE Ekman layer programme must be to measure the horizontal pressure gradient near the sea surface. Satellite altimeters, offer a new opportunity to measure the surface pressure gradient and surface geostrophic flow, given an estimate of the geoid. The latter can be estimated locally using dynamic height measurements referenced to measured geostrophic currents. The combination of in situ current measurements, dynamic height measurements, and satellite altimetry will make possible redundant, and thus verifiable, estimates of surface geostrophic current.

It is anticipated that the Ekman layer structure will vary considerably with season and wiih location, depending upon surface fluxes and ambient stratification. This study will therefore seek to make these measurements at a variety of locations. If carried out as part of the programme outlined here, the array of surface moorings could extend from the westerly wind regime north of the Azores at around 40º N, and down to the easterly trade wind regime at around 25º N.

5.4.2.4 Resources and Timing

It is assumed that the Ekman layer experiment will be closely linked to the subduction experiment described below. Thus, discussion of the resources and timing of both is deferred to Section (5.4.3.5).

5.4.3   Three-Dimensional Circulation and Subduction

5.4.3.1 Scientific Background

Oceanic subduction is the process which carries water masses from the surface mixed-layer into the main thermocline. It is one element of the coupling between the upper ocean and the general three-dimensional circulation, but it provides an especially sharp focus for the study of surface forcing. Recent theoretical studies (Luyten et al., 1983) have highlighted the important dynamical role of subduction in setting the initial condition for waters which enter the geostrophic flow of the thermocline.

The first systematic evidence of subduction was apparently compiled by Iselin (1939) during his study on the distribution of temperature and salinity in the North Atlantic thermocline. Iselin noted that the temperature and salinity relationship of waters in a vertical profile through the main thermocline bore a striking resemblance to the temperature and salinity relationship found at the sea surface along a horizontal section

made from south to north along the sea surface. The comparison was best when the sea surface data were taken from the late winter. The inference to be drawn is that the waters of the main thermocline are formed, in the sense of acquiring their values of temperature and salinity, at the sea surface in late winter, and conserve these properties as they flow through the thermocline of the subtropical gyre. Because the flow of denser waters from high latitudes must go underneath warmer waters at subtropical latitudes, this process of flow from the sea surface into the thermocline has been termed "subduction".

Jenkins (1987) used $^{3}H/^{3}He$ data to determine the 'age' of upper layer water masses. A striking feature of Jenkins' data is that the horizontal distribution of age on an isopycnal surface is relatively smooth several years after subduction, with little evidence of the mesoscale variability. Whether this is a result peculiar to eddy quiet regions, or is a more general result of sub-eddy scale diffusion is an open question.

It has become clear from recent investigations of upper ocean stratification that mesoscale variability and the presence of frontal structures play key roles in determining mixed layer properties. Studies of seasonal and meso-scale variability in the mixed layer are therefore important as a precursor to subduction studies. The Northeast Atlantic is well suited for studies of upper ocean variability attributable to eddies, fronts, horizontal gradients in thermocline stratification, strong and weak currents, and distance from the shelf edge. Studies of such upper ocean features should, to avoid ambiguities in interpretation, be fitted into a large scale context. This will be provided by the repeated surveys.

Stommel (1979) developed a very simple model of the subduction process which took a prescribed, seasonal cycle of the mixed-layer depth and imposed Ekman pumping. The result is that late winter water was selected for subduction by a process of advection out of the seasonally affected layer. Woods (1985) and Federiuk and Price (1986) have gone on to consider slightly more complex models of the seasonally cycling upper ocean driven by wind mixing and buoyancy fluxes. The late winter mixed-layer depth is set largely by non-penetrative deepening, and hence the late winter properties of the surface layer are determined largely by the annual average buoyancy flux. If more negative buoyancy (heat) is added in a column, then the late winter mixed-layer depth will shoal from the previous year's value, and thereby leave some water at the top of the main thermocline. Large-scale mechanisms that could cause such a negative buoyancy gain in a column include (1) flow into a warmer climate, (2) differential advection by Ekman transport, and (3) downward Ekman pumping which stretches the mixed-layer and thereby increases the overall stability above the main thermocline.

5.4.3.2 Goals

The modelling results described above suggest that to understand how subduction occurs, is equivalent to unravelling the annual average buoyancy budget including the non-local terms due to vertical and horizontal advection. From a Lagrangian point of view, the problem is to track the motion of water from the mixed-layer into the thermocline, and to estimate the buoyancy budget for the column overhead. Again, new in situ measurement techniques combined with satellite-derived estimates of wind stress and surface geostrophic flow make this appear feasible within the WOCE time frame, though still very challenging.

Specific goals of an experiment to study subduction are to:

· determine the age distribution of waters of the main thermocline over substantial parts of the subtropical gyre.

· determine the vertical and horizontal pathways of flow from the mixed-layer to the thermocline.

· determine the principal mechanisms that cause subduction with the ultimate goal of understanding the age distribution of thermocline waters.

· determine the extent to which strict property conservation holds for subducted waters, that is, the role of diapycnal and epipycnal mixing in the thermocline.

· determine the role played by upper ocean conditions, particularly at the end of winter, in controlling the subduction process.

5.4.3.3 Necessary Measurements

The observations necessary to unravel subduction are extensive as they must describe both the geostrophic flow within the thermocline, and the seasonal cycle of the upper ocean which is driven by surface buoyancy fluxes and wind stirring. The measurements have one of two basic functions. One set of measurements will be necessary to describe that subduction has occurred, and a second set of data, mainly near-surface data, will be necessary to understand why it took place.

A central piece of the former data set will be an extensive hydrographic survey of the kind described by Jenkins (1987) to map the "age" distribution within the main thermocline. These data should be obtained as part of the control volume surveys, but should be as synoptic as possible to enable interpretation of the horizontal distribution on isopycnal surfaces. Additionally, truly isopycnal (or isothermal) following floats may be used to observe the vertical and horizontal path of water from the late winter mixed-layer into the thermo-cline.

An extensive surface data set will be required to map the surface flux fields which drive the seasonal cycle, and the Ekman convergence. This can be accomplished with an array of surface buoys carrying mete-orological packages (the same as noted above in connection with the Ekman layer study), and filled in with drifting meteorological buoys of the type to be deployed as part of Core Project 1 flux mapping. Model studies (Federiuk and Price, 1986) suggest that very stringent error bounds should be sought for the fluxes; an an-nual average heat flux of 30 Wm^{-2} can be as important as an Ekman pumping of 20 m per year. Satellite data, calibrated against the high quality in situ data envisioned here, will undoubtedly play a particularly im-portant role in defining the surface stress field. Mapping surface currents, and hopefully their divergence, and sea surface temperature can be accomplished with surface drifters.

These surface layer observations must be supplemented by studies of the uppermost few hundred metres of the water column as a means of identifying the source and properties of the water which will later be subducted. They must take account of both the mesoscale effects imposed by oceanic fronts and the ge-ographical variations of the depth of intermixing. These latter objectives will be accomplished primarily by measurements using towed CTD sensors (SeaSoar or Batfish and ship-mounted ADCP units).

5.4.3.4 Location

The Ekman Layer and Subduction Experiments will conveniently be linked with the Control Volume Experiments (Section 5.3.2).

If the array of surface moorings required for the Ekman Dynamics Experiment extends from the west-erly region north of the Azores at around 40° N down to the easterly trade wind regions at around 25" N, it will span the two southern most control volumes (Sections 5.3.2 a and b) and the eastern recirculation zone of the wind driven gyre. Ekman pumping may dominate the subduction process ventilating the isopycnals 26.0 to 26.5 kgm^{-3}, which penetrate as deep as 500 m under the western half of the gyre.

Another important site for ventilation processes lies further northeast of the Azores between 40° and 50° N. This region lies on the northern edge of the Subtropical Gyre (Pollard and Pu, 1985) where stratifica-tion is much weaker, and winter mixing can penetrate to 300-500 m. McCartney and Talley (1982) have shown that the Subpolar Mode Water so formed subducts beneath the Subtropical Gyre between the isopyc-nals 27.0 and 27.3 kgm^{-3} and can be traced as far south as 36° N. Water is subducted on these isopycnals in winter north of about 45° N, close to the zero of the climatological wind stress curl (Leetmaa and Bunker, 1978) so that Ekman pumping may be a much weaker influence, and geostrophic advection relatively stronger.

It will be valuable to compare these two complimentary subduction regions, which is one of the rea-sons why the third control volume (Section 5.3.2 c) has been chosen to overlap the northern region. If water between 27.0 and 27.3 kgm^{-3} crosses the Azores current to circulate beneath the central part of the wind driven gyre, it can reach depths of 900 m, with the potential to ventilate properties to great depths. Measure-ments in the southern control volumes and ventilation site will show to what extent deeper penetration occurs, and on what time scale.

5.4.3.5   Resources and Timing

It is estimated that measurements will need to be carried out for a period of two full years in order to observe a reasonably well-defined mean flow, and to observe more than one seasonal cycle (a three year deployment would, of course, be desirable, but seems excessive given other, competing demands for resources during the WOCE Intensive Observation Period). The experiment could begin in 1991 or 1992, once TOPEX/POSEIDON and a scatterometer are in orbit. The exact timing will have to be scheduled in collaboration with other WOCE programmes.

Resources required for the field programme to meet the goals laid out above are substantial, and in some cases, slightly beyond the present level of technology. Further development is required on the instruments noted. Conventional hydrographic data will be a very important element of the experiment and needs to be coordinated with that required for Core Project 1 and the control volume experiments discussed earlier.

Elements of the field programme are as follows:

(a)   Moored Array (**ACM25, ACM26**)

A central part of the measurement programme will be an array of eight surface moorings, each carrying a full set of meteorological instruments. Wider Geographical coverage to 50°N could increase this requirement to 14 moorings (**ASF1**). These should include shortwave (solar) radiation, longwave radiation, and humidity. The latter two are not standard measurements from buoys, and will require development before this experiment. The standard for the heat flux estimates is that they give a long-term average with an error of no more than about 30 Wm^{-2}.

The array should be centred across the (mean) Azores high pressure system so that its northern end will be within westerly winds, and the southern end will be within the easterly trade winds, extending roughly from 50° N to 25° N. Resource considerations may lead the observations to be focused on more interesting areas.

Most of the surface moorings should carry a string of about ten VMCM instruments to measure current near the sea surface. This presents no particular technical obstacle other than the appropriate dimension of the surface buoy (**ACM25**). Similar buoys have been deployed successfully in the LOTUS and FASINEX programmes. To reduce ship and manpower requirements, the buoys should be deployable for one year without sustaining catastrophic instrument failures. Present deployments of such buoys are limited to about six months duration so that some extension of buoy lifetimes is required.

To define the field of the mean velocity and to provide a measure of dynamic height around the surface moorings, an additional 12 subsurface moorings having three VACM instruments is required (**ACM26**). These would be set at depths of about 100 m, 300 m, and 700 m, and could be deployed once to cover the full two year period.

(b)   Lagrangian Measurements (**AF8, AD2**)

One aim of this experiment will be to observe this motion directly by tracking SOFAR floats that have been modified to follow water on isotherms. These floats are now under development and testing and should be ready for a fairly large-scale deployment by 1991. Approximately 40 of these floats are required for this programme and could be launched over the two year duration of the moored array. Real time tracking of these floats will greatly facilitate the deliberate tracer release experiment, and support guide the natural tracer survey (**AF8**).

Additional floats will be useful in providing an interpolation of the thermocline velocity between the subsurface moorings. About 120 such floats, deployed mainly during the first year, are estimated to be necessary.

Surface currents and sea surface temperature are to be mapped by surface drifters of the kind envisioned for Core Project 1 global survey. About 120 of these drifters are thought to be required. The

deployment of these drifters within the array of surface moorings will provide an opportunity to calibrate these instruments by comparison with more detailed measurements (**AD2**).

(c)   Hydrographic and Tracer Measurements

Hydrographic surveys of the region will be necessary to define the main thermocline slope, and the structure of the seasonal stratification and isopycnal thickness variations which reveal a major part of the isopycnal potential vorticity distribution. This survey will, of course, have to be coordinated closely with the mid-depth (control volume) surveys, and with Core Project 1 long sections so that detailed discussion of the additional effort required here seems premature. This programme would especially benefit from high horizontal resolution, which might best be provided by instruments such as SeaSoar or Batfish, supplemented by acoustic Doppler current measurements.

The Jenkins (1987) analysis of time-dependent geochemical tracers from the nearby beta-triangle illustrates their great utility in studies of the thermocline. Similar data extended over a larger region should be acquired for this programme. They are regarded as of the highest priority. The optimum time for these surveys is thought to be the late winter, or soon after restratification begins in spring, in order to survey the late winter waters which are subducted.

(d)   Mesoscale Upper Ocean Surveys

A minimum experiment could involve the repeated surveying of a Control Volume over a few weeks following each routine hydrographic survey. This would be accomplished by Seasoar (Batfish) to 400 m and ADCP measurements. A more ambitious plan calls for the use of a vessel for 6 months each year of the WOCE period (from mid-winter to mid-summer) to make monthly surveys of an area large enough to show the seasonal migration of the surface outcrops of isopycnal surfaces.

5.4.4   Purposeful Tracer Release Experiments

5.4.4.1 Introduction

The proper parameterisation of mixing across isopycnal surfaces (diapycnal mixing) and along such surfaces (isopycnal mixing) is essential for the proper development of ocean circulation models. Indeed, in present models the value given to the diapycnal mixing coefficient, or to its vertical profile when it is not taken to be constant, is critical if the proper scale for the main thermocline and/or the ratio of the wind-driven to the thermohaline circulation are to be obtained. These mixing parameters are, however, only known to within an order-of-magnitude at best and their dependence on the large-scale physical environment is almost unknown. Thus, measurements of these parameters need to be included as part of Core Project 3.

Recently, it has become clear that the release of certain tracers yield the promise of direct and accurate measurement of diapycnal eddy diffusivities on scales relevant to the large-scale ocean circulation, that is, length scales of about 500 km and time scales of about 12 months. The essence of the experiments is to inject a chemical tracer, for example sulphur hexafluoride (SF_6), and neutrally buoyant floats into a thin layer about a certain density surface and to measure their subsequent dispersion. The cross-isopycnal spreading of the tracer will yield an accurate measure of the diapycnal diffusivity while the spreading of both the floats and the tracer will yield estimates of the isopycnal stirring and mixing.

What is needed for WOCE is not a representative global value of the diapycnal diffusivity but information as to how diapycnal mixing depends on the characteristics of the larger-scale physical environment. Only in this way will it be possible to obtain parametrisations for use in the next generation of eddy-resolving general circulation models and to have some confidence in their ability to predict climate change in a changing environment. Gargett (1984) has pointed out that even the direction of the deep interior flow may be related to the dependence of the diapycnal diffusivity upon the stratification. In fact, the diapycnal diffusivity is expected to depend on, in addition to the stratification, the kinetic energy supply, the potential for double diffusion, strong shears, or the presence of boundaries or fronts. The experiments being planned as part of Core Project 3 represent the first few of a series that should be performed over the next decade in order to determine how the diapycnal diffusivity varies with these factors. As stated in Section (5.3.2), it is hoped that the

use of a variety of microstructure instruments (free-fall, towed and perhaps moored and float-based types), deployed following the tracer cloud, will enable the single estimates of the diapycnal diffusivity found from the tracer experiments to be extended in the water column with some confidence.

The mean hydrography, the mean current field and the internal wave field will need to be carefully monitored during these experiments in order to place the results in the proper physical context. Thus, advantage should be taken when possible of other programmes that might provide this background information. Tracer releases are presently planned for three different depths between the main thermocline and the abyss and the sites for the experiments have been planned in coordination with the other components of Core Project 3. The first release is to take place at the beta-triangle site during the control volume experiment described in Section (5.3.2) and the deeper releases will take place as part of the Deep Basin Experiment described in Section (5.3.3). The details of the tracer release experiments are outlined below.

5.4.4.2 The Beta-Triangle Site (**AF7**)

A tracer-release experiment is planned for a depth of about 400 m at the site of the control volume experiment (Section 5.3.2.a) located at the beta-spiral experiments (Armi and Stommel, 1983). Enough is known about this site to plan the experiment with some confidence. Armi and Stommel (1983) estimate the mean flow at the site to be of the order of 1 cm s^{-1} to the southwest with an horizontal diffusivity of about 500 m^{2}s^{-1}. This later value is in agreement with the work of Jenkins (1987) based on transient tracer data.

Placing the tracer release experiment within the control volume experiment will enable use to be made of the meso-scale information available from the latter. On the other hand, the float work needed for the tracer release experiment will enhance that carried out for the control volume experiment and provide the opportunity to compare the diffusivities obtained from the two approaches.

The control volume will require moorings to measure the structure of the eddy field and its statistics as well as properties of the main flow and that these moorings will be spaced in an array of about 300 km scale. These moorings would also be used for float tracking.

The tracer will be sampled using a towed array of integrated samplers at least three times. The initial survey must be carried out immediately after the release of tracer and will require two ships. The second survey would take place about 6 months after injection when the patch scale is expected to be small enough (~250 km) so that the entire patch would be crossed several times with virtually uninterrupted sampling tracks. The final survey will occur about 14 months after release. In this case the patch scale is expected to be about 500 km and sampling will be interrupted periodically to allow time for total coverage. In total about 6 months of ship time will be required for the experiment.

The tracer experiment requires the release of at least 20 floats as close as possible to the site of the tracer injection **(AF7)**. Some of these must be trackable in real time for 30 days to allow initial measurement of the tracer spread and six and fourteen months later to guide the ship to the area of sampling surveys.

5.4.4.3 The Deep-Basin Experiment Site (**AF6**)

Two or three tracer releases between 2000 and 4000 m are planned in coordination with the Deep Basin Experiment to be carried out in the Brazil Basin. The aim of the releases is to determine not only the diapycnal diffusivity, but its variation with depth in a 1000 to 2000 m thick layer in the basin interior. If the energy sources for mixing are strongly correlated in the vertical over time scales of 12 months and space scales of 500 km, but vary from year to year, there is a great advantage to performing simultaneous releases at different levels to observe the variation in depth of diapycnal diffusivity.

It is planned to inject the tracers at both 3000 m and 4000 m. The injection at 4000 m is particularly useful because heat diffusing across this level must balance the cold water coming in through the narrow channels feeding the basin below sill depth. If a third injection is possible, it would be performed at 2000 m. The three together would yield an excellent picture of how the diapycnal diffusivity varies with depth and buoyancy frequency in the interior of the basin. The buoyancy frequency in the Brazil Basin passes through a minimum of 0.7 x 10^{-3} s^{-1} at 3000 m depth, and is approximately twice this value both at 2000 m and 4000 m

depth. Thus, measurements at three levels would provide data to check the dependency of diapycnal mixing on stability which has been proposed (e.g. Gargett, 1984).

The deeper experiments pose slightly greater technical problems because tow speeds achievable for the sampling system may be somewhat lower. The deployment time for instruments will also be greater. Thus the patch size to be covered, or alternatively the sampling coverage of the patch, must be decreased by about 50%, for 1 month sampling cruises, in comparison with the pycnocline experiment described above. The time between the sampling cruises will be based on estimates of the time for the lateral scale of the tracer path to reach the desired final patch size obtained from the first one or two years of mooring and float data from the Deep Basin Experiment. In total about 10 months of ship time will be required for a two-level experiment.

The requirements for the floats (**AF6**), and the overall conduct of the float operations described above for the 650m experiment would be very similar for the deep experiments, and, in fact, for any open ocean tracer experiment below 200 m depth or so. This means that a least 20 floats will be needed for each release. The question of whether more than this might be required will be answered by the experience gained from the initial experiments in combination with eddy statistics from the early years of the Deep Basin Experiment.

5.4.5 The Eastern Boundary Experiment (**AR16, ACM27, ACM28**)

One of the most perplexing questions in the simple ideas of subtropical ocean gyre circulation concerns the nature of the eastern boundary. Observations are persistent in suggesting that near the mid-latitude eastern boundary in the North Atlantic there is a net geostrophic flow into the coast, that is, the mean density surfaces do not become level near the boundary suggesting that there is diapycnal mixing along the eastern boundary slope. The observed meridional flow near the eastern boundary is quite large and the boundaries are the sites of upwelling and significant water mass modification in some seasons.

It is proposed to study the eastern boundary in some detail adjacent to the westward facing coast of the Iberian peninsula. In this area the rate and consequences of boundary mixing need to be assessed and the flow into and along the boundary measured along with the fluxes of heat and salt and the modification of water masses by mixing and upwelling.

A significant feature of the area is the saline Mediterranean water that flows northwards along the Portuguese coast in a number of tongues which entrain fresher water as they move northwards. The core of the Mediterranean water and its structure needs to be studied. It is well-marked by its Tritium/Helium-3 content and by CFCs.

The region of study will extend some 300 km off-shore from the continental slope and cover the entire 700 km length of the west-facing Portuguese and Spanish coasts. The spatial variation of tracers on density surfaces, together with velocity information should allow the determination of diapycnal mixing rates and the geostrophic shear and velocity will allow the fate of the geostrophic flow near the wall to be determined. The fluxes of heat and salt could be derived from the velocity and property fields and their divergences related to fluxes into the interior. Important tracers are temperature and salinity (particularly the components perpendicular to isopycnal surfaces), potential vorticity, chlorofluorocarbons, the Helium3flritium ratio (freons), 3He/3H and nutrients.

A detailed experimental programme remains to be developed but could include about 5 hydrographic sections perpendicular to the coast with 10 km station spacing inshore and 25 km off-shore and 2 sections parallel to the coast at 150 and 300 km off-shore with 25 km station spacing, the basic network being occupied at least twice to bracket the summer upwelling season (**AR16**). A detailed study of the salt tongues would need towed instruments but with a depth capability greater than SeaSoar. Two cross slope mooring lines at 38ºN (**ACM28**) and 43ºN (**ACM27**) would be deployed. With six moorings per line this would require about 50 current meters each recording also temperature and salinity. The moorings would be in place for one year.

Further detailed planning will depend on the interpretation of data from recent French, British and Portuguese programmes in the area.

Carrying out this experiment simultaneously with the Control Volume experiments described in Section (5.3.2) will provide data of value to the latter and allow the eastern boundary work to be considered in the overall context of the gyre circulation.

LIST OF ACRONYMS AND SPECIAL TERMS

AABW	Antarctic Bottom Water
AAIW	Antarctic Intermediate Water
ACC	Antarctic Circumpolar Current
ADCP	Acoustic Doppler Current Profiler
ADEOS	Advanced Earth Observing Satellite
AGCM	Atmospheric General Circulation Model
AJAX	1983 Oceanog. cruise along 0" Meridian into Weddell Sea (USA, TAMU SIO)
ALACE	Autonomous Lagrangian Circulation Explorer
AO	Announcement of Opportunity
AMI	Active Microwave Instrument
AMS	Accelerator Mass Spectrometer
Argos	Satellite location and data collection system (CNES and NOAA)
Atlantis	Research Vessel (USA)
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
Bomb-14C	Radioisotope of Carbon - generated by nuclear bomb testing
CCCO	Committee on Climatic Changes and the Ocean (SCOR and IOC)
CDW	Circumpolar Deep Water
CFC	Chlorofluorocarbon
CFM	Chlorofluoromethane
CME	Community Modelling Effort
CNES	Centre Nationa l d'Etudes Spatiales (France)
CTD	Conductivity Temperature Depth (Instrument)
DAC	Data Assembly Centre (WOCE)
Discovery	Research Vessel (UK)
DMSP	Defense Meteorological Satellite Program
DORIS	Doppler Orbit and Radio Positioning Integration by Satellite
DSRT	Deep Sea Reversing Thermometer
ECMWF	European Centre for Medium-Range Weather Forecasts
EGCM	Eddy-resolving General Circulation Model
ENS0	El Nino-Southern Oscillation
EOSC	Earth Observations Science Committee (of ESA)
ERS-1	European Space Agency Remote Sensing Satellite
ESA	European Space Agency
FASINEX	Frontal Air-Sea Interaction Experiment
FGGE	First GARP Global Experiment (WMO)
FRAM	Fine-Resolution Antarctic Model (UK)
GARP	Global Atmospheric Research Programme (WMO/ICSU)
GATE	GARP Atlantic Tropical Experiment
GCM	General Circulation Model
GEOSECS	Geochemical Ocean Sections Study
GF3	General Format No 3
GFDL	Geophysical Fluid Dynamics Laboratory (USA)
GOFS	Global Ocean Flux Study (USA)
GPS	Global Positioning System (USA)

GLOSS	Global Sea-Level Observing System (IOC)
GRADO	CNES Gravity Satellite (France)
GRM	NASA Gravity Satellite (USA)
GTS	Global Telecommunication System (WMO)
HUMICAP	Humidity sensor on drifters (FASINEX)
ICSU	International Council of Scientific Unions
IGOSS	Integrated Global Ocean Services System (IOC/WMO)
IGY	International Geophysical Year (1957)
INDIGO	French programme, Indien Gaz Ocean
IPO	WOCE International Planning Office
IOC	Intergovernmental Oceanographic Commission (UNESCO)
IODE	International Oceanographic Data/Information Exchange (IOC)
IR	Infra-red (Radiometers)
ISOS	International Southern Ocean Studies
ITPO	International TOGA Planning Office
JASIN	Joint Air-Sea Interaction Experiment
JEDA	Joint Environmental Data Center
JGOFS	Joint Global Ocean Flux Study
JSC	Joint Scientific Committee for WCRP (WMO/ICSU)
LONG LINES	Long Hydrographic Sections Programme (USA)
LORAN-C	Long Range Area Navigation System "C"
LOTUS	Long-Term Upper Ocean Study, Woods Hole, 1983
LUCIE	Study of circulation north and west of Australia (Leeuwin Current)
LV	Large Volume water samples (>100 l)
Meteor	Research Vessel (FRG)
MESSR	Multispectral Electronic Self-Scanning Radiometer
MODE	Mid-Ocean Dynamics Experiment
MOS	Marine Observations Satellite
MSR	Microwave Scanning Radiometer
NADW	North Atlantic Deep Water
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (Japan)
NEG	WOCE Numerical Experimentation Group
NOAA	National Oceanic and Atmospheric Administration
NOBREX	North Brazil Current Experiment
NODC	National Oceanographic Data Centre (IODE)
NSCAT	NASA Scatterometer (Satellite) (USA)
NSF	National Science Foundation (US)
OCTS	Ocean Colour and Temperature Sensor
OGCM	Oceanic General Circulation Model
PEGASUS	Current profiling system
POD	Precise Orbit Determination
Polynya	Wind or current driven opening in winter sea-ice
POSEIDON	Satellite Programme (France)
PRARE	Precise Range and Range Rate Equipment (ERS-1)
QCE	Quality Control Experts (WOCE Hycfrographic Programme)

RADARSAT	Radar Satellite (Canada)
RAFOS	SOFAR spelled backwards (float which receives sound signals)
SAC	Special Analysis Centre (WOCE)
SAR	Synthetic Aperture Radar (Satellite)
SAVE	South Atlantic Ventilation Experiment
SCAR	Scientific Committee on Antarctic Research (ICSU)
SCOR	Scientific Committee on Oceanic Research (ICSU)
SCORPIO	Oceanographic Cruise in the South Pacific, 1968, US
SLP	Sea Level Pressure
SIO	Scripps Institution of Oceanography, La Jolla
SSM/I	Special Sensor Microwave/Imager
SOFAR	Sound Fixing and Ranging (float with sound source)
SOP	Ship of Opportunity Programme
SSC	Scientific Steering Committee (US-WOCE)
SSG	Scientific Steering Group (WOCE or TOGA)
SSMI	Special Sensor Microwave Instruments (Satellite)
SST	Sea Surface Temperature
STACS	Subtropical Atlantic Climate Study (US)
Sv	Sverdrup (106m3s-1) Measure of water flow
SV	Small Volume water samples (<1 0 l)
SURTROPAC	Survey of the Tropical Pacific Experiment (France)
T/C	Temperature/Conductivity sensor chains on drifters
T/S	Temperature/Salinity
TOGA	Tropical Ocean and Global Atmosphere (Programme) (WCRP)
TOPEX	Ocean Surface Topography Experiment (Satellite) (USA)
TOPEX/POSEIDON	Ocean Topography Experiment (NASA/CNES Satellite Programme)
TRANSPAC	Trans-Pacific Experiment
TRANSIT	Satellite Navigation (position location) System (USA)
TTO	Transient Tracers in the Ocean (Survey)
UNESCO	United Nations Educational, Scientific and Cultural Organization
US WOCE	United States of America component of WOCE
VACM	Vector Averaging Current-Meter
VLBI	Very Long Baseline Inferometry
VMVM	Vector Measuring Current-Meter
VOS	Voluntary Observing Ship Scheme (WMO)
VTIR	Visible and Thermal Infrared Radiometer
WBC	Western Boundary Current
WCP	World Climate Programme (of WMO/ICSU)
WCRP	World Climate Research Programme (WMO/ICSU)
WDC	World Data Centre
WHP	WOCE Hydrographic Programme
WHOI	Woods Hole Oceanographic Institution, Woods Hole
WMO	World Meteorology Organization (Geneva)
WOCE	World Ocean Circulation Experiment (WCRP)
WWSP86	Winter Weddell Sea Project 1986
XBT	Expendable Bathythermograph
XCTD	Expendable Conductivity Temperature Depth (Probe)

CONTRIBUTIONS TO THE PLANNING OF WOCE

The SSG has been responsible for the planning of WOCE. Past and present members of the SSG are:

D. Anderson*
F. Bretherton*
W. Broecker*
R.A. Clarke
J. Crease
K. Hasselmann
W. Jenkins*
V.M. Kamenkovich
R. Kimura*
M. Lefebvre*
T.J. McDougall
J.-F. Minster
Y. Nagata
A. Sarkisyan*
J. Sarmiento
J.D. Woods
C. Wunsch

*past members.

Many others have contributed to this document through participation on subcommittees and working groups of the SSG, in planning meetings and through formal and informal contacts. In addition WOCE has been supported by the CCCO, SCOR, IOC, WMO and ICSU and various members of their Secretariats. Individuals who have made contributions include:

I.L. Ambar
F. Anderson
M. Annaki
L. Armi
E. Augstein
N. Bagriantsev
D.J. Baker
D. Bradford
P.G. Brewer
M.G. Briscoe
L. Brown
H. Bryden
P. Chapman
H. Charnock
D. Chelton
R.E. Cheney
J. Church
A. Colin de Verdiere
C.A. Collins
N. Daniault
R.E. Davis
R.A. deSzoeke
R.R. Dickson
E. Fahrbach
M. Fiadeiro
M. Fieux
A. Foldvik
M. Fukasawa

J. Garrett
S. Garzoli
S. Garzzoli
J.S. Godfrey
R. Godin
A.L. Gordon
W.J. Gould
M. Grunlingh
T. Guymer
D.B. Haidvogel
D. Halpern
D.V. Hansen
R.A. Heath
R. Heinmiller
P.B. Hines
N. Hogg
W.R. Holland
G. Holloway
D. Hu
H.L. Hua
B. Huber
J.M. Huthnance
V.O. Ivchenko
M.T. Jones
T.M. Joyce
R.H. Käese
I. Kawabe
P.D. Killworth

C. Koblinsky
K.P. Koltermann
G. Krause
W. Krauss
W. Large
H. Leach
J. Ledwell
V. Lee
P. Lemke
C. Le Provost
B. Lettau
B. Li
E. Lindstrom
J.R.E. Lutjeharms
J. Luyten
J. Lyons
J. Marshall
J. Martellet
D. Martinson
G. McBean
M.S. McCartney
A. McEwan
J.C. McWilliams
J. Meincke
L. Memery
Y. Menard
J. Merle
L. Merlivat

R. Molcard
R. Molinari
W. Munk
K.O. Munnich
G.T. Needler
P.P. Niiler
W. Nowlin
Y. Nozaki
D. Olbers
D. Olson
I. Orlanksi
W.B. Owens
C. Parkinson
G. Parrilla
G. Philander
A.R. Piola
R.T. Pollard
J. Price
C. Provost
D. Quadfasel
A. Ratier
J.L. Reid
P. Rhines
K.J. Richards

P. Richardson
J. Richman
H.W. Riepma
P. Rizzoli
A.R. Robinson
D. Roemmich
W. Roether
T. Rossby
W. Rowe
E.I. Sarukhanian
P.M. Saunders
R. Schlitzer
P. Schlosser
F.A. Schott
C.B. Sear
P. Shuzhen
G. Siedler
A. Siripong
W.M. Smethie
D. Smythe-Wright
T. Spence
C.C. Stavropoulos
R.W. Stewart
J.C. Swallow

A. Sy
S. Tabata
K. Taira
K. Takeuchi
L. Talley
P.K. Taylor
B.J. Thompson
K.R. Thompson
E. Tidmarsh
A. Tolkachev
J. Verron
P. Wadhams
R. Wajsowicz
B.A. Warren
A. Watson
R.F. Weiss
G.W. Withee
J. Willebrand
J.R. Wilson
D. Wright
W.R. Young
V. Zalisnyi
W. Zenk
V. Zlotnicki

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LIST OF REPORTS

WCRP-1   VALIDATION OF SATELLITE PRECIPITATION MEASUREMENTS FOR THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT (Report of an International workshop, Washington, D.C., 17-21 November 1986) (WMO/TD-No. 203)

WCRP-2   WOCE CORE PROJECT 1 PLANNING MEETING ON THE GLOBAL DESCRIPTION (Washington, D.C., USA, 10-14 November 1986) (WMO/TD-No. 205)

WCRP-3   INTERNATIONAL SATELLITE CLOUD CLIMATOLOGY PROJECT (ISCCP) WORKING GROUP ON DATA MANAGEMENT - SIXTH SESSION (Ft. Collins, USA, 16-18 June 1987) (WMO/TD-No. 210)

WCRP-4   JSC/CCCO TOGA NUMERICAL EXPERIMENTATION GROUP - FIRST SESSION (Unesco, Paris, France, 25-26 June 1987) (WMO/TD No. 204)

WCRP-5   CONCEPT OF THE GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the JSC Study Group on GEWEX, Montreal, Canada, 8-12 June 1987 and Pasadena, USA, 5-9 January 1988) (WMO/TD-No. 215)

WCRP-6   INTERNATIONAL WORKING GROUP ON DATA MANAGEMENT FOR THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT, (Second Session, Yadison, USA, 9-11 September 1988) (WMO/TD-No. 221)

WCRP-7   CAS GROUP OF RAPPORTEURS ON CLIMATE, (Final Report, Leningrad, USSR, 28 October-1 November 1985) (WMO/TD-No. 226)

WCRP-8   JSC WORKING GROUP ON LAND SURFACE PROCESSES AND CLIMATE, (Final Report, Third Session, Manhattan, USA, 29 June-3 July 1987) (WMO/TD-No. 232)

WCRP-9   AEROSOLS, CLOUDS AND OTHER CLIMATICALLY IMPORTANT PARAMETERS: LIDAR APPLICATIONS AND NETWORKS, (Final Report, Meeting of Experts, Geneva, Switzerland, 10-12 December 1985) (WMO/TD-No. 233)

WCRP-10   RADIATION AND CLIMATE: Report of the First Session, JSC Working Group on Radiative Fluxes (Greenbelt, USA, 14-17 December 1987) (WMO/TD-No. 235)

WCRP-11   WORLD OCEAN CIRCULATION EXPERIMENT - IMPLEMENTATION PLAN - DETAILED REQUIREMENTS (Volume I) (WMO/TD-No. 242)

WCRP-12   WORLD OCEAN CIRCULATION EXPERIMENT - IMPLEMENTATION PLAN - SCIENTIFIC BACKGROUND (Volume II) (WMO/TD-No. 243)