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PREFACE

Time-series ocean data have been an enduring component of monitoring and fundamental ocean research over the second half of this century. Such data have provided invaluable, sometimes unique, information for monitoring and detecting climate change and for understanding variability over a range of time scales in the physics, chemistry and biology of the ocean. In recent times, logistical and cost factors have provided severe constraints on the maintenance and implementation of time series stations, in many cases leading to the cessation of data collection. However, this period has also seen the introduction of innovative, more cost-effective techniques for data collection and greatly expanded utilisation of the sites for research, perhaps making time-series stations once more an efficient observational method.

It was timely then to organise a review of the contribution to ocean science from time series, in particular those recently established under the JGOFS, TOGA and WOCE research programs. Accordingly, this "Climate Time-Series Workshop" was convened to conduct that examination and to:

(i) assess the viability and feasibility of maintaining the existing stations;
(ii) weigh the options for re-occupying sites for which long records exist and for which new technology might offer more cost-effective systems; and
(iii) identify, on the basis of research results from programs like WOCE, TOGA and JGOFS, and scientific plans for new programs, where there are sound cases for establishing new sites.

The motivation for acting now comes from the fact that while both JGOFS and WOCE are winding down their intensive observational phases, planning is accelerating for long-term operational monitoring under GOOS and GCOS, and for research into variability on interannual and longer time scales under CLIVAR.

Time-series data have been considered in several other fora, but rarely with the specific focus outlined above. GCOS sponsored a workshop on long-term climate monitoring in 1995, the papers and recommendations appearing in Climate Change vol 31. Among the various recommendations was the following:

> "Existing long-time-series stations measuring temperature, salinity, etc., should be maintained and, on the basis of further scientific assessment and improving technology, new time-series stations should be established at old sites or at carefully selected new sites. Repeat sections (hydrography) should also be used to construct time series over the full depth for decadal and longer-time-scale applications.".

A major aim of the workshop was to substantiate this statement.

The workshop provided a forum whereby an objective assessment of the unique contribution from time series data could take place and an opportunity to formulate objective criteria and specific suggestions for time-series observations that will be critical in future monitoring. The workshop included an evaluation of the role of various time-series observations

In deducing globally important information, such as transport and storage of heat, water and carbon, and an assessment of emerging technologies that might enable an expansion of the number of time series, or allow establishment in places that are scientifically important rather than logistically convenient.

Scientific criteria were sought by the workshop for the assessment of contributions from time series data in the general area of climate monitoring and climate variability, taking specific guidance on scientific objects from the plans of JGOFS and CLIVAR and the observing system recommended in the OOSDP Report. These criteria and assessments form the basis for conclusions and recommendations on the maintenance and establishment of existing and/or new time series, and for approaching the problem of prioritisation. In the first instance, these tasks were guided solely by scientific objectives, though matters of logistics and cost must be considered as factors.

A rather unique feature of this workshop was that it brought together participants from the biological, geochemical and physical sciences, and mixed research objectives with those of the emerging operational activities as represented by the OOPC. It is important to note that the latter distinction, research versus operational, was not a significant factor for the aims of this workshop. For example, the scientific objectives of GCOS/GOOS related to decadal and longer climate variability are in effect a subset of those of CLIVAR, so the scientific arguments for continuing a station are the same. There may be some distinction with regard to implementation and guardianship, but these are mostly of a secondary nature.

Neville Smith
Chairman
Ocean Observations Panel for Climate

1. INTRODUCTION

The workshop, cosponsored by GOOS,GCOS, WCRP and JGOFS was hosted by SCOR at John Hopkins University, Baltimore Maryland 18-20 March 1997. Chairman Peter Haugan opened the proceedings at 08:30 by requesting those present to introduce themselves and voicing Worth Nowlin's regrets for being unable to attend. In his absence, Neville Smith chaired the first session.

The full list of participants is given in Annex II. The individuals who served on the Organizing Committee are listed in Annex III.

1.1 A TIME-SERIES DEFINITION

Virtually all ocean data sets span some interval of time and so, in the very strictest of senses, constitute a time series. However, there are subsets of the data sets comprising the ocean climate data base which have as a dominant attribute rich temporal sampling. So, for the purposes of this report the following definition of a time-series data set was adopted:

> "A time-series data set, or a time-series station, is one in which temporal sampling is the dominant attribute of the gathered information."

The now almost extinct Ocean Weather Ships provided the archetypal time-series data sets. The modern equivalents tend to be more sophisticated in terms of the suite of measurements taken and often can take advantage of satellite data to provide contextual information for the interpretation of observations.

In many people's minds "time series" have a more general definition deriving more from the primary objectives of the scientific strategy. In very few regions of the ocean can we claim thorough knowledge of temporal variability, so a strategy which aims specifically to redress this deficiency is often thought of as a time series. For example, repeated high-density XBT sections in the Pacific have yielded unique information on the space-time variability of the circulation and on the temporal variability of heat transports. Similarly, repeated hydrographic sections (perhaps only 2 or 3) are providing unique insight into temporal variability of the large-scale circulation.

It was appropriate then to expand the themes of the workshop to include some studies which may not strictly fall within the time-series definition above. For the most part, however, the emphasis was on framing recommendations which refer explicitly to data sets or methods where temporal sampling is the key attribute.

One important time-series data type which was not discussed in any detail in these proceedings is sea level. The GLOSS Group of Experts met at the same time as this workshop to consider a revised implementation plan for sea level which included amongst its objectives, sampling for seasonal, interannual and longer time scales. It was therefore decided not to focus on sea level here with assurance it would be considered elsewhere.

2. REVIEW AND ADOPTION OF THE AGENDA

Participants were invited to comment on the provisional agenda which divided the prepared presentations into four sessions: Perspectives; Science of Single Point Time-Series;

Applications and Repeat Sections; and the Future. A fifth session followed on discussion of overall findings. After brief discussion, the workshop adopted the agenda as given in Annex I.

3. WORKSHOP PERSPECTIVES Chair: N. Smith; Rapporteur: R. Weller

Presentations for this session included the following:

Peter Haugan: Objectives of the workshop
Ed Harrison: Upper ocean, relation to sampling schemes
Sydney Levitus: Deep ocean, relation to gridded products
Gerold Wefer: JGOFS philosophy in making time series observations
Neville Smith: CLIVAR and OOPC views and expectations
Workshop Participants: Reports and accounts of recent events

3.1 OBJECTIVES OF THE WORKSHOP.

Haugan outlined the objectives of the workshop. He noted that an ocean observing system for climate (OOSC) needs to be: permanent, cost-effective, and comprised of a limited number of stations. It will support and provide feedback to research efforts. These research efforts will help define the OOSC, and will include research programs that have decadal duration and some redundancy and research campaigns of limited duration but considerable redundancy in sampling schemes and parameters.

Haugan stated that this workshop intended to address a mix of physical and biogeochemical efforts. It was initiated by OOPC, but will emphasize work at the research program and campaign level as a means of working on the definition of the scientific basis for OOPC. Questions that needed to be answered included: Do long time series have a role beyond support for model and remote sensing systems? How can time series contribute to climate assessment activities? In considering why time series should be used, it should be remembered that time series:

(i) sometimes provide unique data describing significant climate variability for which no adequate model is available or likely to be developed over the next 10 years;
(ii) must be continued to learn about ocean climate variability ;
(iii) can provide long period sampling that may overcome uncertainty due to the lack of temporal and spatial resolution;
(iv) may, though at a point, typify large areas;
(v) may bridge gaps in satellite coverage; and
(vi) have other valuable attributes.

Haugan stated that one objective of the workshop was to update and strengthen such a summary of the attributes of time series and to substantiate claims by referring to presentations of results made at the workshop. The following claims have often been made in the past:

(i) Existing time series are so few that they should be sustained until serious study of impact on predictions reveals them to be of marginal values or until new, more cost effective techniques are available.
(ii) Long time series should be continued in preference to starting new ones or continuing those with shorter or broken time series.

These statements needed to be critically evaluated by the workshop.

Another objective was to review progress from existing time series and come up with recommendations of the siting and type of stations for the future. In the workshop discussions, to prevent overlap with other ongoing reviews and considerations, it was agreed that the following would not be considered in depth:

(i) sea level/altimetry (under review by GLOSS);
(ii) straits (WOCE regional reviews);
(iii) acoustic thermometry (SCOR working group review);
(iv) regional and coastal observing networks (various regional and coastal GOOS organizations);
(v) technology of the future (instead, concentrate on what is now available).

A third objective was to summarize the role of time series observations in achieving progress in present research programs and to consider what role they would play in CLIVAR. Examples of both single point time series and repeat sections would be examined. Then, the role of time series data in the future and the impact of the loss of existing time series in the future would be considered. The choice of parameters to be measured (physical, biogeochemical) was to be considered as well as the locations of stations.

Findings and recommendations would be developed. They would address a mix of scientific and technical issues and should help toward an objective assessment of the unique contribution of time series. An effort would be made to establish scientific criteria for assessing the contribution of time series toward climate monitoring and understanding climate variability.

Following Haugan's remarks, there were remarks about sea level stations (R. Lukas) and about the relative role of in-situ time series and remote sensing (P. Taylor).

3.2 OCEAN CLIMATE OBSERVATIONS AND UPPER OCEAN SAMPLING ISSUES.

Ed Harrison observed that, lately, observation design issues seem to be drifting away from designing to meet a problem to designing for multipurpose use and we need to keep in mind how do we sell our plan when doing this. The basic question is how we build on what we know to explore the less well known. Harrison provided a discussion of sampling schemes for the upper ocean, drawing on experience with designing the TOGA TAO array and lessons from other sampling studies. In designing a sampling system there will be a number of factors. Both the need to support science and the need for an OOSC to be relevant to societal concerns and of economic benefit are important considerations. There will need to be a balance between building on existing knowledge and exploration of what is unknown. A system may be designed to recognize a pattern of variability or it may be designed to understand the mechanisms that cause such variability. The approach of taking many observations to reduce error will help only if errors are random; bias and alias errors must be a concern for a sampling system.

To provide a context for further discussion, Harrison presented some illustrations of the magnitude of various ocean temperature climate signals:

Above the thermocline in temperature waters:

Decadal signals:	
Pacific decadal osc	1.0 to 1.5 deg C
Decadal ENSO	1.0 deg C
Atlantic trop. dipole	0.5 to 1 deg C
Seasonal to interannual:	
ENSO	2.0 to 3.0 deg C
N. Subtropics	1.0 to 2.0 deg C
Global warming:	0.5 deg C/100 years

Such signals need to be resolved amidst the diurnal, synoptic meteorological, mesoscale and other sources of variability. COADS data was used to show that the size of the signals varied geographically. Seasonal and longer period SST anomalies were, for example, largest in the eastern tropical Pacific, the subtropical North Pacific, and the western North Atlantic. The zonal wind anomaly (Pacific decadal oscillation) is very different from the meridional wind anomaly. Time series provide the means to use statistical tools to extract the signals of interest. However, as shown by the COADS data set, there are still large areas of the oceans that are too data sparse to yield significant information about there long term means and variability. Harrison stressed that we need to keep reminding people that because there are such scanty data we have to know a lot about a handful of places where we adequately sample.

In considering how to use time series stations in an OOSC, the following should be considered:

(i) examination of all available time series and the sampling implications of these data sets;
(ii) the use of models as a source of "data" sets for sampling studies;
(iii) data assimilation; and
(iv) connection of the sampling scheme to climate change assessment, to studying particular phenomena or to other needs.

Understanding errors of a sampling system is essential. In order to document variability of the ocean, whether due to natural or anthropogenic effects, we need to eliminate biases and errors in the existing historical databases. We need to construct the most comprehensive oceanographic profile databases possible in order describe the statistical nature of oceanic variability for both time and space scales. In further discussing sampling methods, Harrison used multiple-ship XBT data and pCO_2 time series as examples, stressing the need to sample in a way that provides the means to quantify bias and alias errors. For an expanded discussion of sampling issues see Annex IV.

Lillian Merlivat and Catherine Jeandel commented about the dependence of pCO_2 on SST and on the availability of such data from the KERFIX program.

3.3 DEEP OCEAN: RELATION TO GRIDDED PRODUCTS.

Syd Levitus presented a discussion on the continuation of existing time series to the analysis of large-scale variability in the world ocean. He is actively engaged in adding to the existing data base by rescuing and digitizing old records. This is part of the GODAR (Global Ocean Data Archaeology and Rescue) Project. With the addition of this old data, there is the promise that present climatologies will further improve as data gaps (in time and space) are filled.

Examples of long time series that show evidence for trends were discussed. These included the Panulirus Station "S" data from near Bermuda, where temperatures at 1750 m depth show a decadal signal and a slight warming trend at the bottom of 0.1 deg C over 40 years, and decadal signals of the thermocline. He presented data from Ocean Weather Ship (OWS) "C" (at 52 deg 45 min N, 35 deg 30 min W) that showed quasi- decadal signals of temperature at 100 meter depth with a negative long term trend. He looked at Russian sections data and they did not support the hypothesis of polar front movement to explain the large variance at OWS "C". To look for spatial patterns and to place these long time series in context, spatial EOFs have been computed. The temperature data, based on XBTs and mechanical BTs, show different spatial patterns at 100 and 400 m than at the surface. Levitus pointed out that, based on such results, it is apparent that climate signals penetrate into the ocean in ways that analyses of SST alone would not reveal. Bermuda sea level data were compared against geopotential thickness; change in that data may indicate a decrease in Gulf Stream transport.

Past long time series, principally the OWS, were very valuable, and he recommended there should be an effort to examine new technology as a means to re-occupy these sites. Existing, not yet digitized data is also extremely valuable. Some of the existing data is hard to obtain and has not been well utilized. The need for times series data continues and is expanding. There is recent evidence for large change in the ocean on decadal time scales and of trends. New remote sensing methods add spatial coverage but require in-situ time series for calibration and validation. Some regions, such as the Southern Ocean, are too sparsely sampled for variability and trends to be determined. Point time series with relatively high frequency sampling can unambiguously identify statistically significant change at a location and Levitus stressed they are invaluable for the identification and interpretation of larger scale variability.

Levitus offered the following recommendations:

(i) Existing long-time series stations measuring temperature, salinity, and other variables should be maintained and, on the basis of further scientific assessment and improving technology, new time series should be established at old sites or carefully selected new ones.

(ii) A concerted effort should be mounted to digitize all upper ocean and interior ocean data that presently exist on fragile, non-permanent media and that efforts be continued to trace and make part of the permanent archive temporarily "lost" data.

(iii) Additional existing ocean time series should be constructed based on historical data and made widely available through national and international "data archaeology and rescue" projects under the aegis of the IOC GODAR project.

(iv) A report should be carried out by the OOPC to review the state of the art of ocean sensors and sampling techniques to investigate the capabilities of the new technology to continue and initiate long time series stations in a cost effective way.

A more detailed account with illustrations of the presentation by Levitus is in Annex V.

Discussions following Levitus' talk included comments on the power and value of co-located, multivariate time series (Lukas), the importance of data archaeology (Harrison) and metadata (Koltermann), and on the difficulties in getting data rescue efforts funded (Lukas).

3.4 JGOFS PHILOSOPHY ON TIME-SERIES MEASUREMENTS.

Gerold Wefer presented a summary and overview of the JGOFS philosophy and approach to time series stations. JGOFS primary goals were to:

(i) determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor, and continental boundaries;

(ii) develop a capability to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climate change. The time scales of interest to JGOFS range from seasonal to decadal. JGOFS has used a mix of surveys, process studies, time series of monthly measurements at select sites, and studies of the paleoclimatological records.

Wefer provided an overview of the JGOFS science associated with these goals. The complexity of the systems involved in the carbon cycle has been a challenge. As material settles through the water column, different process are at work on different time scales. Coastal processes add complications. There is evidence of strong variability on short space and time scales. Because of this high frequency variability, time series are an essential component of JGOFS.

Time series stations for JGOFS exist at Bermuda (BATS), Hawaii (HOT), Kerguelen Islands (KERFIX), and the Canary Islands (ESTOC). These stations have been occupied using shipboard sampling and moorings. Results from these stations were discussed in greater detail later in the workshop.

3.5 CLIVAR AND OOPC VIEWS AND EXPECTATIONS.

Neville Smith explained that a primary motivation for the workshop was the need to define the role of time-series stations in designing observing systems for climate that would have multiple applications and serve multiple scientific objectives. He pointed out that depending on how we slice the oceanographic data base we get a different view of what constitutes an effective sampling strategy. Thus the first question to be addressed should be whether time series are an effective strategy for sampling the key space-time signals to be found in the ocean dynamics, be they tropical waves, meridional overturning, or western boundary currents.

Smith, discussed long time series stations from the GOOS/GCOS and CLIVAR points of view. The CLIVAR issues relevant to this workshop are interannual and interdecadal variability. He posed several questions: What is the context for using time series data and interpreting them? What makes a good time series? What if the statistics of the in-situ observations are different from those of time series extracted from models?

The Southern Oscillation Index (SOI) was presented as an example for discussing these issues. The SOI is an indicator of the strength and location of the Walker circulation and thus of interannual variability in the tropical Pacific ocean-atmosphere system. For other time series, similarly powerful rationales should be present. One such rationale might be the "sensing" of high latitude sinking and overturning in the meridional circulation cells in the ocean.

Long time series can be used for assessment, for monitoring, for model validation and science, and in "third party" applications. Examples of time series of value in assessments would be simple, representative indicators of the state of the marine environment, of sustainable development, of sea level rise, of fish stocks, of climate change, and of environmental impact. Time series for monitoring would be limited in the scope of their sampling, perhaps exploiting naturally integrated signals, and provide the basis for decisions (thresholds, critical values) and be essential to developing the statistics and climatologies of variability. Long time series can be used to test models, theories, and hypotheses. They can be assimilated into models or withheld as a means of validation. A baseline system of long time series would provide the foundation for processes studies of particular elements of the climate system, such as for a CLIVAR Australian-Asian Monsoon study. Ocean time series will also be of use to other observing systems, such as those for meteorology and for the coastal zone.

Smith believed that the major issues for the workshop were:

(i) articulating the value of existing time series and the value to be gained by continuing them;
(ii) determining the value to CLIVAR, which runs for 15 years, and to GCOS of any new stations;
(iii) determining how to prioritize long time series sites.

Factors to be considered included how to judge the value of extending existing time series, whether new methods of making observations could provide a cost-effective replacement for a station in the future, the value of single points versus broader sampling in space, and the possible continuation of stations started in CLIVAR into the future.

In closing, Smith challenged the workshop to produce sound scientific arguments, not a wish list, and, if priorities could not be produced, then the workshop should outline a strategy for prioritisation. (See section 6.2 and 6.3 for more on CLIVAR. Also, Annex XXI contains notes prepared by John Toole that address CLIVAR time-series issues. These notes were provided as a background document for the workshop.)

Discussion followed Smith's presentation. Questions were raised about CLIVAR's needs (Lukas), where funding would come from for operational measurements (Taylor), how oceanographers might work to become more involved in IPCC assessments (Harrison).

3.6 REPORTS OF RECENT EVENTS AND MEETINGS

A series of short presentations by D. Karl, P Koltermann, and P. Haugan followed.

Dave Karl reported on a workshop in Chile concerned with process-oriented biogeochemical studies and Long Term Ecological Research (LTER) sites. He suggested that a South Pacific time-series station was needed, with Easter Island a good site, as the region was sparsely sampled.

Peter Koltermann reported on the Dec-Cen CLIVAR workshop in Villefranche that was to provide input to the CLIVAR Implementation Plan. Global sustained measurements will be needed as an element of the effort to identify decadal to centennial variability. Koltermann voiced concern for the lack of observations in the Southern Ocean, especially south of 30 deg S.

Peter Haugan reported on recent discussions by the Association of North Atlantic Time Series Originators. They are considering a joint data center and a web site to make their data available.

The formal session ended and was followed by a recap by Smith and discussion. In the discussion, some raised concern for any approach to time series that would degrade the accuracy of the measurements. There was also discussion of how heavily societal benefits should be weighted in their discussions and deliberations. It was concluded that at this stage the science issues were most critical, with attention to other matters second.

4. SCIENCE OF SINGLE POINT TIME SERIES Chair: G.Wefer; Rapporteur: W.Zenk

The session included the following presentations:

Anthony Michaels: Review of the Bermuda Atlantic Time-series Station (BATS)
David Karl: Biogeochemical Studies at the Hawaii Ocean Time-series (HOT) Station
Roger Lukas: Physical Studies at the Hawaii Ocean Time-series (HOT) Station
Howard Freeland: Station and Line P in the Northeast Pacific
Octavio Llinas: The European Time-series Station ESTOC North of the Canary Islands
Walter Zenk: Time-series of Bottom Water Fluctuations at the Southern End of the Brazil Basin
Catherine Jeandel: The Exploratory Station KERFIX in the Kerguelen Islands

4.1 THE BERMUDA ATLANTIC TIME-SERIES STATION (BATS)

On behalf of Tony Knap, Tony Michaels presented the history and the present objectives of the oldest time-series station in the open ocean. The Bermuda hydro station "S" was initiated by Henry Stommel in 1954 by regular surveys with the vessel PANULIRUS which, for a long time, gave it its name. Since that time, station "S" has been occupied 26 visits per year on the average. Since 1976 the suite of observations has been systematically enlarged. Today they include observations with sediment traps and testbed mooring facilities. In 1989 the Bermuda time series station (BATS) was added as a major part of JGOFS. Since then, 150 cruises or 18 per year have taken place. Besides continuous observations of temperature, salinity, oxygen, fluorescence and light attenuation; discrete samples of salinity, oxygen, total CO_2, nitrate, nitrite, phosphate, silicate and of other bio-geochemical parameters such as POC and pigments are collected. Rates of primary production, bacteria growth and pesticide fluxes are measured as well. Unfortunately, no funding for meteorological observations is available.

The station serves a wider scientific community. Data are available 6-9 months after the observation through modern media and in conventional reports. More than 20 scientists and technicians are involved in the BATS operation.

Michaels presented a wide selection of data examples. Among them were basic physical parameters including mixed-layer depth, nutrients, chlorophyll and dissolved inorganic carbon. In a number of parameters a trend was obviously seen on which further fluctuations on various shorter time scales were superimposed. Of particular interest were El Nino signals in mixed layer depth records, a systematic CO_2 accumulation in the water column and a significant change in the nitrate/phosphate relationship over the period leading to an intermediate maximum of excess nitrate at about 500m below the surface. Further findings concerned the deposition of dust originating from the Sahara desert which plays a role in the fixation of carbon. Dust has increased as the Sahara desert area has increased. Michaels data showed that drifting-by eddies can cause significant perturbations from established previous averages.

More detailed information on the BATS operation can be found on the Internet at http://www bbsr.edu/bats/.

4.2 THE HAWAII OCEAN TIME-SERIES (HOT) STATION

David Karl and Roger Lukas described the HOT sation in two different presentations. This deep-sea station has been in operation for nearly 9 years. It has significantly contributed to the WOCE and JGOFS ocean time series programme. The main objectives of the HOT programme are the description, detection and determination of long-term variations in water properties and fluxes from the near surface to the bottom (4800 m).

Main selection criteria for the HOT site were reasonable proximity to Honolulu Harbor, distance from the Hawaiian Ridge needed to reduce the influence of coastal dynamics and island biogeochemistry, and its well-known (and relatively flat) topography near a previously studied site. Until the end of 1996, 78 HOT cruises were undertaken on a nominally monthly schedule. Core measurements include continuous profiles (CTD, ADCP, etc.), discrete bottle samples (nutrients, CO_2 primary production, etc.), from drifting sediment buoys, towed zooplankton nets, and observations in an Eulerian frame (inverted echo sounder, sediment traps, and met data). Besides the multi-disciplinary character of the HOT station for the detection and determination of low-frequency variations the site also serves in education of students in marine science. Some 3000 ship days for students were estimated for the total time of the existence of HOT.

Karl presented the HOT group's latest scientific interpretation of the obtained bio-geochemical fluxes and on primary production rates. These are intimately related to the seasonal evolution of the mixed layer depth and the ENSO phenomenon. The data have raised serious doubts regarding a constant Redfield ratio. HOT anomalies indicate deviations from the classic ratio N/P = 16 to up to 25 for ENSO periods. Other bio-geochemical enigmas concern primary production vs. nitrate and export flux including summer pulses as well as C-N-P decoupling and the occurrence of dissolved organic matter. A new hypothesis developed on the basis of HOT results proposes that there is a systematic, temporal alternation between N and P control of plankton processes, resulting from complex interactions between the ocean and the atmosphere, that may have important consequences for bio-geochemical cycling rates and processes in the sea. It was further detected that atmospheric nitrogen is a major source of new N for primary production. This N is fixed by trichdermium, a toxic plankton that dominates the plankton population at times in that area of the Pacific.

Lukas presented highlights of the extended physical data of HOT, which are documented in a series of reports (see summary in Annex XX). Volume 7, covering the 1995 (and earlier) results, was distributed among the participants of the workshop. Lukas divided his presentation into near-surface, interior and bottom observations. Some of the upper ocean temperature and salinity variations reflect local wind and precipitation variations associated with climate anomalies. Annually-averaged near-surface temperatures vary from year to year, but the annual extremes vary markedly as well. Unlike the pronounced seasonality of upper layer temperature, the upper layer salinity shows no seasonal cycle; instead an interannual signal is apparent. T-S variability in the interior appears to be largest in the North Pacific and Antarctic Intermediate Waters, reflecting variability in their source regions and/or in advective/diffusive processes along their transport pathways to Hawaii. Interannual temperature variations in the bottom water may be attributed to far reaching baroclinic Rossby waves excited along the Mexican coast during ENSO events, and also to deep cold overflow events from the nearby Maui Deep. Surprisingly large temperature variations (0.02C) observed at the bottom of the HOT station resemble those that were observed in the Vema Channel (see contribution from Zenk in section 4.6).

Lukas concluded that climate signals are emerging from the time series, and that the HOT site is well-suited for time series observations relevant to climate research. It is hoped that CLIVAR will provide the spatial context which is presently lacking and which is needed for robust interpretation.

More detailed information on the HOT operation can be found in Annex VI (by Karl et al) and on the Internet at: http://hahana.soest.hawaii.edu/hot/hot_jgofs.html.

4.3 ESTOC (Estación de SeriesTemporales Oceánicas de Canarias)

The third single-point time series station that was introduced at the workshop was ESTOC, the European time-series station. Octavio Llinas showed the geographic region of this station north of the Canary Islands described and the organizational structure. It is a cooperative effort of groups from two Spanish (Telde, Madrid) and two German institutions (Bremen, Kiel) working under the auspices of JGOFS. The station was started in 1991 after similar set-ups (i.e., HOT and BATS) were studied carefully. Though the station is situated in open ocean waters 60km north of Teneriffe and of Gran Canaria, it suffers from occasional African upwelling, the occasional passing of intermediate Mediterranean salt lenses (Meddies) and the strong influence of Sahara dust. Otherwise it is in an oligotrophic water mass. The observation spectrum includes at least monthly hydrographic observations, a rich ensemble of nutrient and geo-chemical parameters, moored (and drifting) sediment traps and Aanderaa and acoustic Doppler current meters in two subsurface moorings. Twice-a-year cruises collect data around the islands. A detailed description of ESTOC is given in Annex VII.

4.4 KERFIX

Catherine Jeandel described the KERFIX station (KER for Kerguelen and FIX for fixed station) started by France in 1990, 60 miles southwest of Kerguelen Islands. This activity represents the first regular non-costal multi year acquisition of carbon cycle parameters in the Southern Ocean. It aims at a better understanding of the processes controlling primary production in a boreal, nutrient-rich, low-chlorophyll low-silicate area that is not iron limited. Winds at KERFIX are 95% of the time from the west. The initial data showed a decrease in temperature (T), and an increase in salinity (S), in the mixed layer depth, and in the density anomaly from 1991 to 1992. The data analysis is assisted by a physical/biological/chemical coupled model that also is used to devolve the sampling strategy for KERFIX. The model represents well the variability observed for nitrates, silicates, etc. Preliminary results have been submitted for publication. Annex VIII provides a detailed description of the KERFIX programme.

4.5 WEATHER STATION PAPA (P)

Howard Freeland provided a report on Station P. It was first occupied in 1949. A primitive oceanographic program, begun in December 1950, and enhanced with regular bottle casts and plankton hauls in July 1965, was continued until June 1981. After the weather ship program was terminated, sampling along the ship track from the Strait of Juan de Fuca to P was continued to the present. Freeland described the different routes that salmon return to their home streams. During El Nino years they return via the northern route providing Canadian fisherman with a huge advantage. The data show a long-term trend in the upper layer of increasing temperature and decreasing salinity, and therefore, decreasing density. The mixed-layer thickness is shallowing due to this density decrease. The expected nutrient levels are also decreasing more rapidly than expected. Annex IX contains an expanded report on Station P and Line P.

4.6 BRAZIL DEEP BASIN EXPERIMENT

Walter Zenk provided a description of the Deep Basin Experiment, a subproject in WOCE Core 3. He found that Brazil Basin bottom water with potential temperatures below 2°C disappeared from the flanks of the continental slope in the second year of the experiment. Bottom temperatures in the Vema Channel, a major conduct for the equatorward spreading of Antarctic Bottom Water, rose by 0.03°C. Earlier observations over the past 20 years suggest substantially smaller variations (<0.005°C) so the 0.03°C change over a 2-year period appears quite significant (see Fig. 4.6-1). Observational details of this work, jointly conducted by the Institut für Meers-

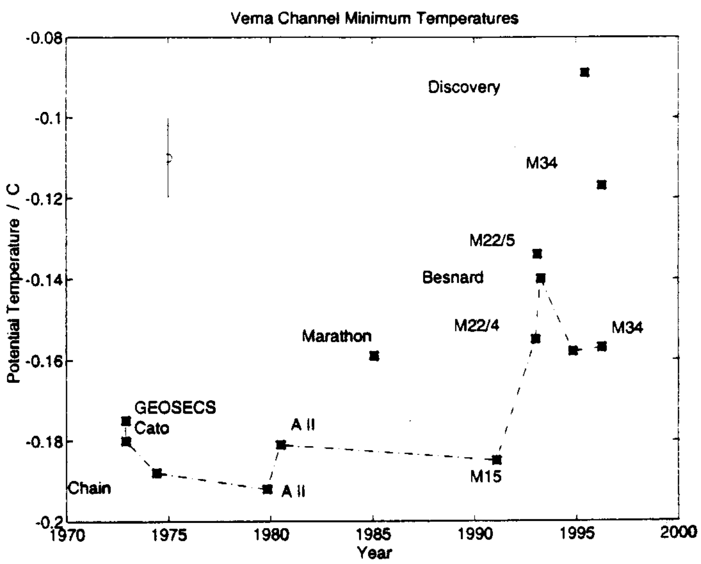

Figure 4.6-1. Time-series of potential temperatures from the bottom of the Vema Channel. This over 4.6 km deep conduit enables equatorward spreading of Antarctic Bottom Water after its passage through the Argentine Basin to enter the Brazil Basin. Only those values that could be located in the cold Weddell Sea Deep Water, the lowest part of Antarctic Bottom Water, were connected by line segments. The given error bar at year 1975 represents a conservative estimate that has decreased with the advent of high-precision CTD instruments during the course of the time-series. For a detailed discussion see Zenk and Hogg (1996) and Hogg and Zenk (1997).

kunde, Kiel and the Woods Hole Oceanographic Institution, can be found in Zenk and Hogg (1996) and Hogg and Zenk (1997). It was hypothesized that the higher temperatures in the Vema Channel may be due to higher temperatures at the source of this bottom water in the Weddell Sea itself. This view coincides with recent observations by Coles et al. (1996), who report an increase of bottom temperatures in the northern Argentine Basin.

References:

Coles, V.J., M.S. McCartney, D.B. Olsen and W.M. Smethie Jr. (1996): Changes in Antarctic Bottom Water properties in the western South Atlantic in the late 1980s. Journ. Geophys. Res., 110, 8957-8970.

Hogg, N. and W. Zenk (1997): Long period changes in the bottom water flowing through Vema Channel. Journ. Geophys. Res. (in press).

Zenk, W. and N. Hogg (1996): Warming trend in Antarctic Bottom Water flowing into the Brazil Basin. Deep-Sea Res. I, 43, 1461-1473.

4.7 SINGLE POINT STATION FINDINGS

The following are common to all of the point time-series stations reviewed.

(i) Logistical constraints can become a major limiting factor, sometimes overruling primary scientific desires.

(ii) The operation on fixed-scheduled time series requires a sound source of trained, dedicated personnel.

(iii) Time series stations show a synergistic effect. They attract additional sub-projects that benefit from the well-sampled environment and its known time evolution in time scales greater than annual cycles.

(iv) Free and timely data availability and exchange are vital for all internal and external users as are scientific analyses beyond pure data acquisition.

(v) Time series have unravelled new dimensions of oceanic variability, especially near the bottom, that were not expected a decade ago.

5. APPLICATION AND REPEAT SECTIONS

Chair: L. Merlivat; Rapporteur: P.Haugan

The session included the following presentations:

Peter Taylor: Meteorological Time-Series Measurements
Ed Harrison (McPhaden et al): Tropical Pacific TAO Array
John Lazier: Causes and Consequences of Interannual Variability in the Labrador Sea
Peter Haugan(Østerhus et al.): Norwegian Sea (Station M)
Peter Koltermann: Decadal Changes in the Meridional Overturning Circulation of the N. Atlantic
Kimio Hanawa: Japanese North Pacific Repeat Sections
Bruce Cornuelle: The Pacific Repeat XBT/XCTD Network and the Tasman Box

5.1 METEOROLOGICAL TIME-SERIES MEASUREMENTS.

Peter Taylor restricted his definition of time series measurements to observations from a fixed oceanic location obtained over a period of years. Thus the weather observations from Voluntary Observing Ships, although the basis of our knowledge of climate over the open ocean, were excluded from his discussion. Time series data are available from buoys, ocean weather ships, and coastal platforms such as rigs, lighthouses, and island stations. Of these, buoys have the advantage of causing minimal disturbance to the quantities that are being measured. Although valuable data sources, weather ships have almost entirely disappeared because of the high running costs. He noted that time series measurements which were started for exploratory research reasons are now recognised as being important for monitoring human-induced changes in the environment; perhaps the most famous example being the ozone profiles obtained over the Antarctic.

Buoy time-series observations cover parameters which are not always available from other systems, (e.g., sea state and surface radiation fluxes) or have significantly higher accuracy than other systems (e.g., wind observations from operational buoy time series compared to ship observations). This makes these time series valuable for calibration of satellite sensors, validation of numerical models and verification of climatologies. Satellite remote sensing has increased the importance of time series rather than decreased it. In particular, the value of the in situ time series to provide observations, and hence also continuity of calibration during unplanned gaps in satellite coverage, cannot be overstated.

A lot of sensors are needed for marine meteorology. Therefore, one will normally prefer moored rather than drifting platforms. Fixed locations are also preferable for satellite calibration. In extremely data sparse areas like the Southern Ocean, other strategies like disposable drifting buoys and full exploitation of the few ships available may be more realistic. For climate purposes in general, it is a problem that so few meteorological time series exist from the open ocean. The existing coastal network needs to be extended with more observation sites in the open ocean. An expanded treatment of Taylor's presentation is found in Annex X.

5.2 TROPICAL PACIFIC TAO ARRAY.

Ed Harrison described the sampling design of the TAO array, which was based on experiments with existing ocean models and the (few) available relevant wind observations in the early '80s. The array was aimed at obtaining accurate surface wind data coverage so that modelling of seasonal and interannual variability of the tropical Pacific, and ultimately, ENSO forecasting, could be performed. The full array was completed with the final deployments in 1994. Assessment of the array design and performance have jus t started, and preliminary results indicate that the "first best guess" sampling design was "pretty good". The observed wind field has less zonal coherence but similar meridional scales to those anticipated. In contrast to the recent past the operational winds produced by models are beginning to more closely resemble the TAO observed winds. The array is well on its way from a research tool to fulfil a role as a component of a permanent observation system in support of operational climate forecasting. At http://www.pmel.noaa.gov/toga-tao/home.html on the Internet, more detailed information on the TAO array is avaialable. A more detailed summary of Harrison's presentation is in Annex XI.

5.3 INTERANNUAL VARIABILITY IN THE LABRADOR SEA

John Lazier addressed the bimodal distribution of the more than 80 year time series of the number of icebergs found south of 48 N, which is coupled to winter air temperature in the area and to the North Atlantic Oscillation (NAO) index. The NAO index was very negative in the 1960s and very positive in the early 1990s bringing very cold winds to the east coast of North America. Hydrographic time series from the Labrador Sea close to the position of the former weather ship BRAVO, give examples of many years of apparent low interannual variation followed by considerable shifts, underscoring the need for long time series to characterise variability. Variations in winter heat loss and summer ice melt and runoff have resulted in average decreases of temperature and salinity of about 0.6 K and 0.06 over the past 35 years and a density increase in recent years in Labrador Sea Water. Such major changes in a water mass formation area carry information content from upstream and from regional atmospheric forcing and are traced downstream in intermediate waters of the North Atlantic. It appears that continued measurements in the Labrador Sea would be well suited to capture integrated effects of variations of local meteorological forcing as well as upstream ice conditions with impact on larger scale circulation. More detail on Lazier's presentation is in Annex XII.

5.4 NORWEGIAN STATION MIKE (M).

Peter Haugan informed about the almost 50 year of continuous hydrographic measurements at weather ship station M in the Norwegian Sea. This weather ship station is still in operation. It goes to port once per month to change crew, and takes hydrographic observations several times per week. A recent cooling and freshening is observed in the Atlantic upper layer, to values lower than those during the so-called Great Salinity Anomaly in the 1970s. This is consistent with reduced Atlantic inflow and increased accumulation of Arctic Surface Water north of the Greenland-Scotland ridge. In the deeper layers a warming trend linked to a warming of source water in the Greenland Sea has recently been broken, indicating reduced supply of bottom water from the Greenland Sea to the Norwegian Sea. Such flow reversal is confirmed by current measurements. In general variability is weaker in the deep layers below the Atlantic layer (i.e., from about 800m) but strong and unexpected events on a several year time scale are found. Recent shorter time series of biogeochemical parameters (notably dissolved organic carbon) show unexpected and hitherto unexplained interannual variability. An expanded report on Station M is in Annex XIII.

5.5 NORTH ATLANTIC REPEAT SECTIONS

Peter Koltermann discussed available data from occupations of coast-to-coast sections in the North Atlantic from the 1950s until the 1990s, and noted that there are severe problems associated with the concept of a mean state of the deep ocean circulation in view of the observed variability. The strong variability of deduced heat transport across 36N compared to 24.5N and 48N was linked to transitions between two-cell and single-cell meridional overturning patterns. This has strong implications on estimates of regional ocean heat storage and geographical distribution of air sea heat flux. Repeat sections of this kind are problematic with respect to aliasing. However, for integral quantities such as heat transport, repeat sections, with interpretation aided by other data, may still be the preferred, if not the only, strategy. It was suggested that repeating the 48N section every 5 years, supplemented by XBT profiles to resolve the seasonal variability in the upper ocean, could be suitable for describing changes in the thermohaline circulation structure, and that the early detection of changes may best be done by observations in the boundary current systems. More detail on Koltermann's report is available in Annex XIV.

5.6 NORTH PACIFIC REPEAT SECTIONS.

Kimio Hanawa described the considerable efforts by Japanese agencies and institutions to maintain repeat sections in the North Pacific. Initiation of several of these go back to the 1970s while others have been taken up more recently. The amount of observations now available from transects along 137E, 155E, and 165E calls for more efforts to extract and analyse valuable climate variability information from these data sets. The coverage with ADCP observations from commercial ships is increasing and expected to continue into the foreseeable future.

Hanawa spoke about the Monsoon Index (the pressure difference between Irkutsk, Russia and Nomuro, Japan) and the linkage to meander and non meander periods of Subtropical Mode Water. He also described the TRITON (Triangle Trans-Ocean Buoy Network) programme which is an extension of TAO further into the western Pacific and into Indian Ocean. More detail on Hanawa's report is in Annex XV.

5.7 THE XBT/XCTD NETWORK AND THE TASMAN BOX.

Bruce Cornuelle described repeat XBT/XCTD lines in the Pacific, most of which were taken 4 times per year, mostly to 800m, but some deeper. The variance estimates emerging from these data display geographical structure, and transport estimates in the Tasman area show an annual cycle in gyre intensity. For that particular area closed by sections on all sides, seasonally varying heat budgets could be set up and compared to surface heat flux from ECMWF and heat storage from TOPEX, demonstrating that heat advection was significant. The synergy between XBT and satellite altimetry was emphasised. The available time series observations, now approaching 10 years duration, also show changes in the structure of the transport across a section ranging from widespread to filamenting. More detail on Cornuelle's report is in Annex XVI.

5.8 SESSION FINDINGS.

In the discussion following the presentations, several general points were made:

(i) There is synergy with and increased importance of time series stations and repeat sections in combination with satellite data.
(ii) Short time series run the risk of underestimating variance.
(iii) Events and regime shifts appear on the longest time scales for which we have observations in both the upper and deep ocean.
(iv) Regime shifts may be detected by time-series stations in water-mass-formation areas and possibly in boundary currents.
(v) Data reveal that deep ocean variability is greater than what was believed a few decades ago.
(vi) Integral quantities such as heat transport may require repeat XBT or CTD sections even if the problem of aliasing makes analysis of such data difficult and requires use of other observations.
(vii) Some of the existing time series data, e.g., station M and North Pacific repeat sections, have been underexploited considering their potential information content; the data show potential for yielding valuable information with additional scientific analyses.

6. **THE FUTURE** Chair: P. Koltermann; Rapporteur: Ed Harrison

The session included the following presentations:

Detlef Stammer: Assimilation of time series observations in models
Roger Lukas: CLIVAR/North Pacific Climate study

Robert Weller: CLIVAR upper ocean
Liliane Merlivat: pCO_2 and other variables for carbon monitoring
John Field: JGOFS successor programs
Neville Smith for Worth Nowlin Jr.: Long Term In Situ Measurements in the Southern Ocean.

6.1 ASSIMILATION OF TIME-SERIES OBSERVATIONS IN NUMERICAL MODELS

Overall, time series data are important for ocean modelling because they provide means for testing forward models (reproducing the evolution of a variable is a stringent test of a model) and, through data assimilation, they provide a way to constrain the solutions produced by models to be relatively realistic.

Detlef Stammer described preliminary results from a global one-degree grid, 20 levels in the vertical model that had been run for twelve years from Levitus temperature/salinity initial conditions. This circulation model produces flows with large time variability of 'climate' indices: Drake Passage mass transport, North Atlantic meridional heat transport at 24N, etc. According to the model variability, snapshots of such climate indices are likely not to be representative of their mean values.

With the same model, Stammer described results using an adjoint data assimilation technique with TOPEX/POSEIDON sea level height data, and a quadratic cost-function and strong constraint on model dynamics. The cost function is minimized iteratively, varying initial and boundary conditions until the solution fits the data within the prior data error estimates. The result presented was obtained after 30 iterations, which saw the cost value reduced from 2.8 to 1.1 (not yet fully converged). The fit produced adjustments of tropical SST by more than 1C in many places, particularly just north of the equator in the Pacific (3C change there). Changes in sea surface salinity were typically $\pm$ 0.3 psu. Only very small adjustments to wind stress were indicated (<0.001N/m2), and net surface heat flux changes were typically $\pm$ 20 W/m2. The net heat flux across 24N in the Atlantic varied from 0.8 to 1.2 PW throughout the year, and very large changes in the meridional overturning circulation resulted, especially in the tropics. Over longer time integrations with data assimilation, the changes introduced by assimilation increase.

Stammer emphasized that these are preliminary results, and lots of experimentation remains to be done. In particular, exploring the consequences of altering the cost function weights and developing model error estimates is important. He suggested that such methods offer the possibility of important advances in understanding what constrains what in the ocean climate system. More detail concerning Stammer's presentation is included as Annex XVII.

6.2 CLIVAR/ NORTH PACIFIC CLIMATE STUDY.

Roger Lukas reminded the workshop that CLIVAR consists of three elements: GOALS, DEC-CEN and Anthropogenic Climate Change (ACC), corresponding roughly to seasonal to interannual variability, decadal and longer variability, and greenhouse gas/aerosol/land surface climate effects. Three Pacific phenomena of particular interest have been identified: North Pacific interdecadal variability, ENSO and its decadal variability, and Asian-Australian Monsoon variability. Mechanisms have been suggested, based on correlations between sea surface temperature indices, surface wind indices and model studies, for each of these three phenomena. A CLIVAR goal is to quantify and understand the shallow overturning circulations and gyre-gyre interactions (Subpolar-Subtropical-Tropical) of the North Pacific in order to advance our understanding of the three phenomena. It is proposed to develop an observing system and data assimilation/analysis system to accomplish this. It is assumed that a basic Climate ocean observing system will exist (thanks to GOOS and GCOS), including in situ and satellite data, and that CLIVAR will sponsor supplemental process studies of whatever duration is required for particular objectives. The hydrological cycle of the Pacific Ocean will receive observational attention, including varying surface freshwater exchanges (rainfall and evaporation) which combined with variable circulation lead to substantial basin wide salinty changes.

A variety of different modes of possible gyre-gyre interaction were presented by Lukas, based on observations and idealized coupled ocean-atmosphere studies. For more detail on a CLIVAR North Pacific climate study see Annex XX II.

6.3 CLIVAR UPPER OCEAN PANEL/ SURFACE FLUXES

Robert Weller opened this presentation with the statement that CLIVAR must be prepared to oversample in its observational programme to nail down the correlation functions in order to define the best guess sampling array. He discussed the on-going need for high accuracy surface fluxes of heat, fresh water and wind stress, in order to meet most of CLIVAR's objectives. Recent observational intercomparisons, and comparisons between observations and operational weather analyses of fluxes produced widely different results. Weller stated that it is now possible to measure weekly net heat flux to about 10 W/m2. Operational fluxes, in the comparisons presented, typically differ by very substantially greater amounts than this. The consequences of using operational fluxes naively were illustrated by several examples, and it was shown that incorrect inferences about the physical processes at work would result. Weller stressed that precipitation and radiation data are poor globally and even in the Sea of Japan where one would expect more.

New profiling instruments as well as new moored instruments have been developed in the past ten years, and improved capabilities continue to be sought. Instrument and platform development are on-going. A ongoing study of North Atlantic Mode Water formation is providing a large-scale test of many of the new technologies.

Lists of the many specific CLIVAR surface observations required to meet CLIVAR objectives were presented. The Anthropogenic Climate Change element has made requests for information rather different than that requested by GOALS and DEC/CEN. In particular, ACC has asked for the establishment of selected ocean sites analogous to the WMO Reference Climate Station Sites.

Weller believes that there is insufficient linkage between modelling being planned and observations being planned. He noted the desire of some CLIVAR elements for increased interaction between the observational Panels and the Numerical Experimentation Groups, with a variety of observing system simulation experiments of interest to many. For a more complete overview of CLIVAR upper ocean observation needs, see Annex XVIII.

6.4 OCEAN pCO_2 AND CARBON MONITORING.

Liliane Merlivat reminded the workshop that the extent to which the ocean takes up CO_2

from the atmosphere is a major uncertainty in the global carbon budget. This uncertainty affects the IPCC Climate Assessment as well as predictions of the future climate of the earth. Developing cost-effective means to determine the net uptake is a priority activity. Takahashi and his colleagues just recently presented a summary of the best air-sea flux of carbon they could make, using data and an ocean model. They estimate the flux to be 0.6-1.3 gigatons/yr of carbon; they also estimate that about 75% of the uncertainty results from using the numerical model to interpolate to fill in the data gaps in the spatial coverage and coverage throughout the seasonal cycle. Merlivat suggests that, at present, we simply do not know the net flux, and that we must have many more observations in order to determine it.

New engineering work on stable sensors for ocean pCO_2 and chlorophyll is making good progress. The CARIOCA buoy, which measures pCO_2 and temperature and carries a fluorometer was described. It has been deployed in the Greenland Sea and the Mediterranean, has a lifetime of about 1 year, making hourly measurements, and may be used as a drifter or may be moored. The pCO_2 sensor uses an optical principle. The CARIOCA buoy will also be used to make measurements at BATS in 1997.

In the Mediterranean, the buoy data suggest that there is very large variability in the air-sea carbon flux. The diurnal cycle often is substantial and there are events which involve delta pCO_2 changes of more than 50 micro atmospheres in just a few days, even when temperature effects are corrected for. Such large variability means that high frequency sampling may be essential if we are to get accurate mean fluxes. Considerable work has been done in the Greenland Sea, and more buoys are to be deployed there this year. Merlivat thought there was a good possibility of using SST data as a proxy for pCO_2 in the Greenland Sea. The goal is to interpret the Greenland Sea and Mediterranean Sea data using the LODYC ocean carbonate system model.

6.5 JGOFS FOLLOW-ON

John Field informed the workshop of a possible JGOFS successor activity, tentatively called SOLAF (Surface Ocean Lower Atmosphere Feedbacks)that is being considered by the IGBP. The present JGOFS timetable calls for the completion of the fieldwork program in 1999, with the Synthesis and Modelling Program (SMP) underway until 2004. SOLAF is being contemplated to phase in while the SMP is going on.

The idea is to bring together elements of the interests of both the JGOFS and IGAC (International Global Atmospheric Chemistry) into a new program that would focus on processes and the rates of each process. The goal would be to obtain long records of relevant processes in each basin.

Field emphasized that SOLAF would be hypothesis-driven, and a variety of hypotheses have been proposed which might be tested as part of SOLAF. These include: the idea of iron control of phytoplankton in high nutrient low chlorophyll (HNLC) environments leading to climatically important control on ocean carbon uptake; the idea that anthropogenic nitrogen may impact marine biota sufficiently to affect ocean carbon uptake; and the idea that anthropogenic effects may have little effect at all on marine biogeochemistry. SOLAF would be strengthened by firm interactions with CLIVAR and ocean physical processes programs.

6.6 LONG TERM MEASUREMENTS IN THE SOUTHERN OCEAN.

Neville Smith summarized the key points of the report that Worth Nowlin had intended to present on the Southern Ocean. The goal is to develop a science-driven long term observational effort in this tremendously undersampled part of the world ocean. The first step is to increase the number of observations in the Southern Ocean, in order to better characterize variability and to identify the phenomena appropriate to CLIVAR. It has to be understood that exploration has to be a part of any Southern Ocean program. On-going monitoring should be examined to assess what is being learned and whether additional parameters should be added.

At present the Antarctic Circumpolar Wave is the only seasonal-interannual large scale phenomenon that has been identified. Of known importance to various aspects of the large scale ocean circulation would be better measurements of: deep and bottom water formation (rates, volumes, variability); sea ice volume and transport; Antarctic Circumpolar Current transport and relationship to wind stress; and 'new' interior water formation. The paper submitted to the workshop by Nowlin and his colleagues is in Annex XIX.

7. RECOMMENDED ATTRIBUTES FOR TIME-SERIES STATIONS

Several themes emerged from the workshop and it is useful to discuss these before considering in detail, specific issues and recommendations. A working group chaired by Neville Smith reviewed the material presented and developed a time series categorization and their common special attributes.

7.1 CATEGORIES OF STATIONS

Many different time series data sets were discussed and it soon became clear that any conclusions which were to be drawn would need to be put in the context of the type or category of station. Four categories of time series stations dominated the discussions.

(i) Exploratory Sites. In some circles these might equally be called "pilot" stations. They were usually located in a region where there was some expectation that interesting variability may be occurring and where there was a dearth of information on temporal change. The idea initially is to "taste" the variability rather than viewing it as an initial implementation of a long-term observing site. The KERFIX station is an example.

(ii) Laboratory Sites. These sites are usually developed in locations where there is more than a reasonable expectation that sampling will reveal a rich variability in several fields. They are usually characterised by multi-sensor sampling and high temporal resolution. The "laboratory" tag derives from the fact that these sites usually offer opportunities for scientists to explore novel data sets or to conduct intensified measurements of their own using the regular time-series data for context. BATS, HOT and ESTOC offer good examples.

(iii) Phenomenological or Process "Sensors". In almost all locations where we have long records (and they are few) we find the records reveal significant variability at interannual and decadal scales. The little we do know about the climate system suggests these time scales result from interactions between the ocean and atmosphere, the ocean providing the memory and delay because of its ability to store heat and because the information carrying pathways in the ocean are relatively slow. It follows then, that if we can find a "sensor" for the variability of these key information pathways, processes or phenomena then this will provide a valuable monitor of important climate variations. Several of the sites, such as BRAVO, possessed this feature as a principle characteristic.

(iv) Climate Reference Stations. Following on from the GCOS Long-Term Climate Change Workshop, the idea of Ocean Climate Reference Stations was put forward. These series would have to be classed as fundamental to climate observing, unique because of their history and quality of data and because of their value in observing variability. It is not clear that any of the time series stations fitted this category though station "S" is perhaps close. The set of sea level gauges being defined by OOPC and GLOSS for long-term, climate change monitoring are probably the best example.

It seems all the time series stations discussed below fall comfortably into one of these categories. This means that, when drafting recommendations, the dominant purpose of the station is clear. Also, in general, one would expect stations in category (ii) to derive from (i), category (iii) from category (ii), and so on. The support of the different categories of station is also likely to be different. The first two remain within research though it is conceivable one or two of the "laboratories" might be considered of long-term value. Category (iii) could be supported by research or operational resources depending upon the judged level of need for expert scientific guardianship. Category (iv) one would assume to be part of the basic (operational) network.

7.2 ATTRIBUTES

One of the avenues we have for approaching prioritisation in a rational way is to find a set of properties or attributes which are common to all time-series and which in some way represent the relative strengths and value of the data. This is an approach that has proven useful for choosing an upper air network of reference stations for GCOS. In the present case, the lack of any deep understanding of temporal variability at most locations in the ocean means that the approach is limited as an objective measure, but the workshop concluded they did provide a valuable yardstick.

The attributes are listed here in no particular order, though they perhaps should be ranked.

(i) Record length. For studies of low-frequency climate variability there really is no substitute for a long observational record. We cannot return to the past and take measurements, though we can sometimes find satisfactory substitutes via models or some other data sets which provide a proxy.

(ii) Temporal sampling and continuity. In order to interpret long records with minimal ambiguity it is essential that the important scales of variability are well resolved. If they are not, variability at higher frequencies can alias into the lower frequencies and distort our interpretation. Equally, significant gaps in the record can introduce sometimes unacceptably high levels of uncertainty as well as make the analysis extremely difficult.

(iii) Data quality and metadata. Perhaps the most important factors hampering analysis of old records is the lack of information describing the data set (metadata) and poor quality of measurements. Time series analysis is fundamentally a signal processing problem. The more the record is contaminated, the greater the level of noise and the harder it is to extract a meaningful signal. Lack of adequate metadata introduces high levels of uncertainty into the processing.

(iv) The "breadth" of the data set. A time-series data set that includes measurements to the bottom, or which includes sections about the site, or which includes several co-located measurements is far more valuable than one that just includes a limited suite of variables through part of the water column. The value of a time-series data set certainly increases non-linearly as further variables are added (though there is also likely some peak).

(v) Data availability. The results presented at this workshop left no doubt that the value of a time-series data set is greatly increased if it is exercised widely. In fact, for future time series, ready access to data is likely to be cited as one of the fundamental attributes.

(vi) Relevance. It is likely this attribute should head the list. As was emphasised in the Introduction, the need for time-series data must be driven foremost by scientific objects. However it is also important that the data have societal relevance and impact, particularly for operational observing systems.

(vii) Logistical constraints. Time-series sites are difficult to maintain so logistical constraints figured high in all discussions of the implementation and maintenance of sites. Most sites were convenient to a land-based laboratory or were in positions which could be accessed with reasonable regularity by ship. This attribute is extremely important when considering new sites: the logistical disadvantages of some locations prohibit any consideration of time-series stations.

(viii) Cost. The cost of maintaining sites is clearly a significant factor. In most cases the scientific (and perhaps societal) benefit must be directly weighed against the cost of collecting the data. The cost is clearly related to logistics, and to the potential for exploiting new technology. The greater the benefit that is seen to be enjoyed from a data set (hence the emphasis on impacts, wide data availability, multi-purpose, etc.), the better the chance of justifying the cost.

(ix) Availability of proxies. We are now appreciating that for many problems there are several methods for getting at the same signal. For example, XBTs, in situ sea-level gauges and altimetry all appear to capture low frequency variability associated with ENSO. For some time series it is conceivable that a proxy might be found in other data sets, thus lessening the importance of continuity.

(x) Exploitation. Time-series data can be exploited for a variety of purposes including science, satellite calibration, education, model validation, model initialisation, process studies, and so on. The degree to which a site is suited to such exploitation clearly impinges on the long-term viability.

(xi) Opportunity. There are some factors which do not follow the logical assessment implied above. For example, there may be strong political or other reasons for maintaining or ending a site which have little bearing on the scientific and demonstrated value of the site.

The Workshop concluded that the categorisation of time series was a useful first step in sorting out the dominant purpose of a data set. The workshop recommended that all existing and proposed sites should be assessed against the attributes listed above.

7.3. OCEAN STATION BRAVO ASSESSMENT.

An assessment of BRAVO was made as an example as of the application of the attributes criteria in 7.2 as recommended above. The BRAVO data set has a useful but broken record, mostly of good quality. Much of the data reaches the bottom which is essential. The data have demonstrated utility for monitoring the formation and flow of intermediate, deep and bottom waters from annual to decadal time scales. It operates principally as a phenomenonological climate sensor though it has been exploited in the past as a "laboratory". The time series are accompanied by good metadata and the data sets have been distributed widely. Its principal relevance at present is to the goals of the DecCen and ACC programs of CLIVAR, and the circulation and inventory goals of the GCOS/GOOS ocean observing system for climate. Its location in the Labrador Sea poses challenging logistical problems, effectively limiting the number of repeat visits per year. The costs fall into the intermediate bracket for time-series stations. It is conceivable that a partial proxy for the information obtained at this site could be found in a combination of the North Atlantic Oscillation Index, sea ice observations and other ocean observations but this is not the case at this time. The site offers some potential for model calibration but its principal purpose is as a monitor of climate variability. Considered in conjunction with hydrographic sections and other time-series (e.g., "Mike") the value of the site is enhanced.

Conclusion: It was concluded that the BRAVO site rates well on most attributes, the only significant inadequacies being the broken record and the limited number of occupations per year. The workshop concluded this site offered one of the best opportunities for monitoring annual to decadal variability in water formation and overturning of the North Atlantic. Thus, it was recommended that BRAVO should be maintained for the long-term under CLIVAR and/or GCOS/GOOS.

7.4 OCEAN STATION KERFIX ASSESSMENT.

As a second example, the attributes of KERFIX were assessed. KERFIX is an "exploratory" site located 60 nm south of Kerguelen Island. The record is young, so it is premature to make judgment on issues of data quality, availability, continuity, etc. An ambitious monthly sampling schedule has been set. Since the station is located around the 2000m isobath, and the amount of other contextual information is limited, the overall impact of the data set is limited. However, it is in a climatic region where little is known about oceanic variability or about the details of physical and biogeochemical interactions. Thus it must rate very highly on novelty and scientific relevance. Its biggest drawback is the harsh environment which imposes severe logistical problems. The extra cost is outweighed to some extent by the political attractiveness of operating a site in Antarctic waters. The uniqueness of the data that have been collected is its dominating asset.

Conclusion: The workshop concluded that the KERFIX time series station was a valuable exploratory contribution, particularly in view of the fact that little is known about temporal variability in this important region where the harsh environment and severe logistical problems, have severely hampered the acquisition of any but occasional observations there. The workshop recommended continuing the KERFIX at least until some "taste of the variability" is determined.

8. ROLE OF TIME SERIES AND REPEAT SECTIONS IN DESCRIBING CHANGES IN THE OCEANIC STORAGE OF HEAT, FRESH WATER AND CARBON

A working group chaired by Peter Koltermann was established at the workshop to examine the role of time series in describing changes in oceanic storage of heat, fresh water and carbon, and to suggest areas where knowledge about these parameters could be derived from time series data. As one of the legacies of WOCE and TOGA, the amplitudes of the variations of T and S in the intermediate and deep oceans have become obvious at magnitudes previously unknown. They indicate a much more intimate response of the full ocean to changes in forcing. With this perspective in mind the working group focussed on application of time series to determine indices and/or variability of meridional overturning, circulation and heat transport in the North Atlantic, North Pacific and Indian Oceans.

8.1 VARIABILITY IN LABRADOR SEA WATER (LSW) AT BRAVO

Approach: To provide estimates of the changes in the Labrador Sea Water (LSW) properties at annual time scales, and possibly the volume of the annual production by maintaining mooring(s) of T, S sensors and conducting repeat sections along WOCE line A1W.

Justification: Labrador Sea Water (LSW), an intermediate water mass found throughout the northern North Atlantic Ocean and along the western boundary to the equator, is formed in the central Labrador Sea via deep convection in winter. The temperature and salinity of the LSW have decreased by 0.6 C and 0.06 over the past 35 years due to variations in both the heat loss in winter and the fresh water supplied from run-off and ice-melt in summer. These changes are linked to the North Atlantic Oscillation (NAO), a seesaw pattern in the atmosphere, which brings multi-year periods of abnormal winter conditions alternately to the Greenland and Labrador Seas. Recent cold winters in the Labrador Sea between 1987 and 1995 created a colder and denser version of LSW which has been spreading throughout the North Atlantic Ocean during the WOCE observing period. Observations of this new LSW in locations remote from the Labrador Sea have resulted in new estimates of the flow rates at intermediate depths which are 4-5 times higher than previously assessed.

8.2 MERIDIONAL TRANSPORTS OF HEAT AND FRESH WATER IN THE NORTH ATLANTIC.

Approach: To provide estimates of the meridional transports of heat and freshwater by continuing the 48 N section with proven methodology for full-depth, closely spaced hydrographic sections along ca.48 N at about 5-year intervals; and by maintaining XBT sections at a sampling frequency sufficient to resolve the annual cycle, Justification: Over the last 40 years the meridional transports of heat and freshwater have shown a considerable divergence north of 24.5 N in the Atlantic. Changes have been greatest at 48 N and can be linked with changes in the atmospheric forcing as described by the NAO Index. The meridional overturning circulation is seen to respond differently in the 1980s from the 1950s and 1990s. Present work suggests that longer-term changes in the supply of heat to Northern Europe might have originated in these changes.

8.3 SHALLOW OVERTURNING CIRCULATION OF THE NORTH PACIFIC

Approach: Describe the shallow overturning of the N Pacific, using the high density XBT, XCTD lines required and feasible as shown in Figure 8.3-1. PX 38, PX 37, and PX 10, and PX 44 are already ongoing and the hydrographic section P2 along 30N should be continued as a repeat section. Support TRITON and associated programmes.

Justification: Three Pacific phenomena of particular interest have been identified: North Pacific Interdecadal variability, ENSO and its decadal variability, and Austral-Asian Monsoon variability. Mechanisms have been suggested, based on correlations between sea surface temperature indices, surface wind indices and model studies, for each of these three phenomena.

A CLIVAR goal is to quantify and understand the shallow overturning circulations and gyre-gyre interactions (Subpolar-Subtropical-Tropical) of the North Pacific in order to advance our understanding of the three phenomena. It is proposed to develop an observing system and data assimilation/analysis system to accomplish this. It is assumed that a basic Climate ocean observing system will exist (thanks to GOOS and GCOS), including in situ and satellite data, and that CLIVAR will sponsor supplemental process studies of whatever duration is required for its particular objectives. Freshwater processes (open ocean rainfall and evaporation particularly) will receive observational attention.

8.4 DEEP AND BOTTOM WATER TRANSPORT CHANGES AS MODULATION INDICATORS IN SOURCE REGIONS

Approach: In order to observe changes of water formation in high latitudes at inter-annual time scales, transports and other hydrographic properties of the deep outflow should be monitored at a few specific sites by near-bottom moorings with current, temperature and salinity recording instruments.

Justification: Bottom waters are formed in high latitudes by deep-reaching convection in winter time. In the Weddell Sea this process is favoured by the irregular presence of polynyas. One such drastic convection phase has been documented, when in the mid 1970s a huge polynya was advected through the eastern Weddell Sea. It caused a deep fresh and cool anomaly in newly formed Weddell Sea Deep Water that was exported towards lower latitudes of the South Atlantic. Source water modulations of varying strength and duration can be observed at a few selected sites around Antarctica where bottom water enters the oceans outside the Southern Ocean. These are: for the Indian Ocean: the deep passage off Crozet Island, and for the SouthAtlantic: the East and West Falkland (Malvinas) Channels. An alternative passage for inflow into the Argentine Basin around the Islas Orcadas Rise has been postulated. Bottom water of the Pacific leaves the Southern Ocean off the Campbell Plateau.

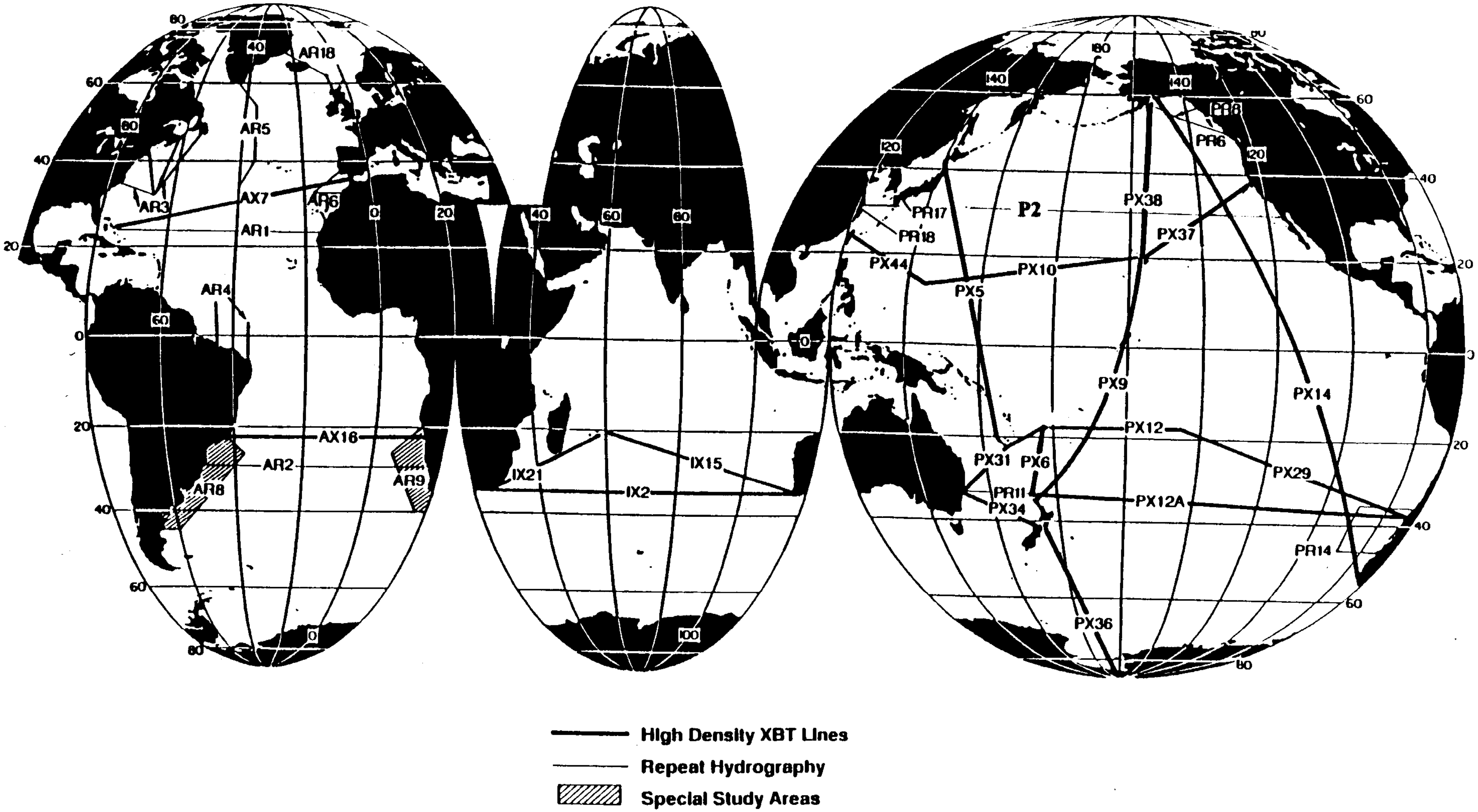

Figure 8.3-1. High-Density XBT (XCTD) Lines.

The chronology of Antarctic Bottom Water also can be observed at less remote sites, while it cascades equatorward through mid-latitude basins. The impact of varying air-sea fluxes in source regions ages while being advected. Anomalies are modified through mixing and diffusion. Recent observations in the Vema and Hunter Channel of the South Atlantic or in the Samoa Passage of the South Pacific showed that substantial variability exists on a wide range of scales. A comparable case is given in the subpolar gyre of the North Atlantic. Charlie Gibbs Fracture Zone represents a conduit for deep westward export of Iceland Faroer Overflow Water from the Iceland Basin. Its variability is thought to reflect integral changes in the formation regime farther north.

Comparing the variabilities of transports and hydrographic properties at fracture zones in subsurface ridges between ocean basins will help to determine the origin and time scales of abyssal circulation changes. In a number of cases it has been stated that these changes are a direct consequence of climate-relevant atmospheric forcing functions.

8.5 INDOPACIFIC THROUGHFLOW

Approach: To determine the strength and characteristics of the water masses that enter the Indian Ocean from the Pacific Ocean and their changes at seasonal and longer time scales.

Justification: The global thermohaline circulation is crucially affected by the input of low-salinity water from the Pacific Ocean that is modified particularly in its salinity when passing from the Pacific to the Indian Ocean through the Indonesian Archipelago. This input of fresh water is to be determined before it enters the global thermohaline circulation as an integral parameter in terms of heat and freshwater flux.

8.6 BERING STRAIT INFLOW

Approach: Determine the transport of freshwater from the Pacific into the arctic Ocean at the relevant time scales.

Justification: The global freshwater transport is set by the transport of freshwater from the Pacific into the Arctic Ocean. Only after it leaves the Arctic ocean is it affected by interaction with the atmosphere through evaporation and precipitation. For a global budget and its potentially time- dependent changes the input into the ocean needs to be know accurately enough.

8.7 INDIAN OCEAN EXPORT OF LOW-SALINE WATERS TO THE SOUTH ATLANTIC

Approach: Annual hydro repeat section at full depth to estimate discharge at annual rates.

Justification: Uncertainties in the global fresh water budget need to be narrowed. The variability of the export to the South Atlantic needs to be determined (along with that to the other oceans) to accomplish this.

8.8 OTHER POTENTIAL APPLICATIONS.

Ocean time series could serve as ocean analogs for climate reference stations as requested by WMO. Specifications for such stations need to be fleshed out.

Historical ocean time series data sets could be improved to be able to establish links with instrumentally derived atmospheric records. Ocean records go back some 50 years, atmospheric some 150 years. After that one can work with proxies and palaeorecords. But present records back to the turn of the century need to be enhanced.

Time series are needed to determine monsoon-related changes of water mass modification in the Indian Ocean and export to other oceans to put constraints on the fresh water budget.

Societal needs for time series data are necessary and could be the subject at a future workshop.

9. THE ROLE OF OCEAN TIME SERIES FOR CLIMATE MODELLING

Another working group chaired by was established to consider the role of time series in climate modelling activities. The working group covered a wide range of modelling and related ocean observations considerations. On the basis of the workshop and subsequent discussions and investigations, Lukas prepared the following summary. In section 9.1, the basic ocean climate modelling activities are discussed. In section 9.2 special issues relating to these activities are raised. In section 9.3, the observational requirements to support these activities are articulated. In section 9.4 and 9.5 specific conclusions and recommendations are made regarding time series observations.

9.1 CLIMATE MODELLING ACTIVITIES AND OCEAN OBSERVATIONAL CONSIDERATIONS

Prime uses of climate-system models are for climate assessments and predictions, and their application to societal problems related to climate variability. Time series observations of the ocean are crucial for improvement of the ocean component of such models, and for achieving a dynamically consistent description of the state of the ocean to support comprehensive assessments and to initialize climate prediction models.

For the purposes of understanding and predicting climate variability and change, the development, testing, and improvement of coupled climate system-models is paramount. The ocean components of such climate system models are, at present, very crude in their representation of important physics and carbon biogeochemistry; the resolution and parameterization of critical processes remain unsatisfactory for these purposes.

Ocean observations are of fundamental importance to the basic goal above, and to the success of the strategy of relying on numerical models to achieve it. The ability to identify model deficiencies and test improvements depends on the availability of a multivariate mixture of spatial and temporal sampling. The requirement is for the quantitative description of coherent spatio-temporal structures, and the mechanisms which link variations in different components of the climate system. While global coverage is desirable, temporal resolution of all energetic processes at fixed points is critical.

Below, the basic ocean climate modelling activities are discussed. In section 9.2, special issues relating to these activities are raised. In section 9.3, the observational requirements to support these activities are articulated. In section 9.4, specific recommendations are made regarding time series observations.

9.1.1 Testing and Improving Climate Models with Ocean Data

Climate models must be tested in order to determine whether they are reliable for particular purposes. Model deficiencies should be identified through such testing, and addressed by model improvement where warranted. Systematic deficiencies should be understood and overcome by specific process studies, and improved parameterizations which derive from those efforts should be incorporated in the models.

An important issue is how the ocean component of climate models can be tested, and how model deficiencies can be identified. Statistical comparison of model simulations with time series of observations (in either hindcast or forecast mode) can provide a measure of model skill. Dynamical assimilation of observations offers a rigorous framework for identifying model deficiencies, in addition to providing a dynamically consistent gridded analysis of the observations (see section 9.1.3). Regions of persistent analysis errors, even where data are present, are indicative of a lack of the model physics.

9.1.2 Forcing Ocean Climate Models

Accurate ocean surface forcing fields are a limiting factor in testing and improving ocean models for climate purposes. This was the major justification for expansion of the TOGA TAO Array in the equatorial Pacific, where model hindcast errors due to deficient physics could not be distinguished from forcing errors (Harrison and Hayes, 1988).

In recent years, the strategy for obtaining global ocean forcing fields for climate modelling has been based on the routine production of atmospheric analyses by numerical weather prediction (NWP) centres assimilating atmospheric observations into weather forecast models. Operational analyses have the temporal resolution which is needed to drive ocean models. Their spatial resolutions are relatively poor from an oceanographic standpoint, seriously underestimating the wind stress curl field. Increases in spatial resolution are ongoing, so this may disappear as an issue. A major issue is that the operational atmospheric analyses suffer from discontinuities due to changes in the analysis schemes and to changes in the forecast models which generate the first guess fields. For climate purposes, these discontinuities likely generate spurious signals in the ocean. The solution to this problem is to use the results of atmospheric reanalyses that have been conducted for climate research purposes by some of the major NWP centres.

Another issue is that the analyses and their error fields must be routinely available to the ocean climate modelling community in order for the basic strategy to be successful. So far, this has not been a significant problem, however the issues surrounding proprietary data have intruded recently.

Recognizing that the derived fields of air-sea fluxes from these analyses contain large systematic and random errors, both the TOGA and WOCE programs invested in the development and deployment of technology to obtain high quality in situ estimates of air-sea fluxes to compare with the NWP analyses and with satellite-based estimates. Such measurements during recent process studies in the North Atlantic, the western equatorial Pacific, and the Arabian Sea have identified problems with various aspects of the analyses from several major NWP centres. Collaboration of experimentalists with modelers at these centres has been encouraging, and it is reasonable to expect improvements over time.

9.1.3 Use of Models to Combine and Interpret Ocean Observations

The ocean circulation is a complex, non-linear and turbulent system. Despite vastly increased sampling due to the recent implementation of new technologies such as satellite altimetry, available ocean data are still and will ever be by far too sparse to obtain a complete picture of the instantaneous ocean state and its evolution in time. The design and evaluation of climate models is therefore based on ocean observations available over a long period of time. Models are constrained to be consistent with those data and the results are used to analyze ocean variability and relevant climate parameters such as meridional heat transport and its release to the atmosphere.

Operational modelling is fundamentally dependent on a continuous data stream of various components of ocean observations. Satellite altimetry has proven to be a very important dataset due to its unprecedented sampling of the ocean globally with high resolution in space and time. Its apparent shortcoming of observing only surface conditions is much reduced recognizing that large-scale geostrophic motions on the rotating earth are predominantly low-vertical-mode and thus ocean surface pressure conditions reflect the deep ocean as well. A real shortcoming with satellite information is that there are no long (in a climate sense) time series, but during the periods when these global scale observations are available, they provide spatial context for the analysis of historical time series.

To combine ocean models with all available data, in situ observations play an important role. They provide information which is largely complementary to satellite data in terms of space-time sampling. The combination of diverse ocean observations with the models allows computation of circulation and its evolution in time which is consistent with the dynamical understanding of the ocean and errors in the data and the models. The results will be the basis for future climate studies by providing useful initial model fields for coupled model runs and for studying ocean variability.

9.1.4 Basic Ocean Observing System Design Considerations

Observation resolution and accuracy requirements are hard to specify. It can be done empirically, assuming that the 'signals' to be observed routinely have been oversampled for a sufficient duration (determined by the period of signals and the degree of nonstationarity). For climate time scales, relatively few locations and variables have been subject to oversampling.

One area of emerging influence of ocean modelling is in ocean observing system design. Observing system design can be pursued within the framework of dynamical ocean (or coupled climate) models through analysis of observing system simulation experiments (OSSEs), such as Harrison and Hayes (1988). A realistic model forced with observed (estimated) surface boundary conditions produces time series of gridded fields of variables which can provide the statistics that are lacking. Within the framework of a statistical or dynamical analysis system, the density and accuracy of observations needed to recover the original signals can be determined through systematic subsampling of the full simulation dataset.

Dynamical ocean model integrations; their relevance to observing system design can be substantially increased by forcing with estimated flux fields (see 9.1.2) and through assimilation of actual observations.

The objectives of the observing system will influence the design process considerably. If no observations have been made in an area, model simulations can provide some idea of the signals which should be resolved in order to provide a zero-order description. If a hypothesis is to be tested by the observing system, that calls for another approach. If prediction runs are to be initialized by the observing system, then skill scores can be developed by comparison of model prediction and subsequent dynamical analysis of existing observations. As the initial conditions are altered by synthetic observations provided by model simulation, the impacts on prediction skill can be assessed.

9.1.5 Climate Analysis/Assessment

Even for the elements of the climate system which are not predictable, it is possible to obtain useful information on the state of the climate system through data analyses repeated in time. With these analyses, not only is the present state obtainable, but the rates of change of different components of the system are accessible. However, the usefulness of the analyses depends on sufficient observations being available. What is sufficient (in terms of variables, distribution, and accuracy) depends on the method of analysis and the particular purpose. In principle, dynamical data assimilation produces an optimal analysis, but only if the underlying physics of the model are reasonably matched to the real world. However, even an optimal analysis may not be very useful if its errors are too large. Thus, attention must be paid to determining the error characteristics of the analyzed fields.

The Intergovernmental Panel on Climate Change (IPCC) periodically assesses the state of the earth's climate system and produces possible climate scenarios based on a range of potential greenhouse gas concentrations. This assessment strongly involves the state of the ocean and its apparent evolution. The overarching issue is to separate the natural variations (e.g. ENSO; interdecadal variability) from those which are forced by anthropogenic factors.

9.1.6 Climate Prediction

Some elements of the climate system are predictable at useful skill levels. Aspects of the El Nino/Southern Oscillation can be forecast by coupled ocean-atmosphere models at lead times up to a year, given a reasonable initial state of the thermal structure of the tropical Pacific. This motivates the continuation of the TAO array beyond the end of TOGA.

Other predictable elements of climate variability are being sought under CLIVAR. Such "mining for predictability" involves both hindcast skill assessment as well as experimental prediction work where warranted. Climate prediction requires a specification of initial conditions over the entire model domain, with the thermal structure of the upper ocean providing the major source of predictability. Skill scores are needed to quantify the performance of the forecast system being used.

9.2 SPECIAL ISSUES

9.2.1 Research Versus Applications Objectives

Climate modelling objectives involve both research and applications. Requirements and recommendations for observations, in particular ocean time series, are different for these objectives even though there is an overlap. A balance between basic research objectives and applications objectives is important.

9.2.2 Optimizing System Design

The results of OSSEs are model (and forcing) dependent; erroneous conclusions regarding signal and error covariances may lead to undersampling, and systematic errors of the mean circulation may lead to misplacement of observing elements. For each specific purpose, model limitations must be assessed to select an appropriate model.

"Optimization" of observing systems is given increased attention as the resources to sustain and develop them become more precious. Optimization is a process which is highly dependent on the assumptions that are made, the criteria that are used, and the ultimate objective for the optimized system. As the objective(s) become(s) more fuzzy, it is more difficult to specify an optimization criterion, and it is more likely that the optimized system is further away from the optimal system needed for a particular subset of objectives. This applies to the design of ocean observational systems.

9.3 OCEAN CLIMATE MODELLING REQUIREMENTS

9.3.1 Testing and Improving Climate Models with Ocean Data

In testing models, their ability to hindcast historical observations is used to provide a measure of their success. This requires long, consistent, single-variable time series at a minimum; multivariate, collocated time series provide a more powerful test of such models because they quantify the relationships between different parts of the climate system. Time series at certain locations are more useful than at others. Some locations are 'pulse points', where a coherent climate signal stands out above the noise of other processes. For example at circulation choke points, topography can amplify climate signals above background noise levels. Time series of certain variables are more useful than others, either due to their intrinsic spatial scales of variability (e.g., pressure versus velocity), or because other variables are dependent on them.

Statistics of Signals and Error Covariances Including Climate Timescales. Identification of model deficiencies through comparison of model output with time series observations requires knowledge of the statistics of the important signals, the environmental 'noise', and the observational errors. These can only be obtained from time series observations. The spatial representativeness of these statistics is often unknown, and must be assessed. For example, the observation of relatively large temperature variations (0.01 C) near the bottom (4800 m) at the site of the Hawaii Ocean Time-series suggests that the circulation of cold bottom waters between bathymetric depressions is episodic. The magnitude of the variability cannot be detected through random, occasional temperature profiles. The comparison of models with deep ocean temperature data must take this into account. However, the lack of knowledge concerning the spatial distribution of such signals is a limiting factor.

Long, Consistent Time Series with Spatial Coverage. The number of long (say, a decade or longer), temporally-resolved and consistent ocean time series is small. These observations do not provide spatial resolution of the major climate signals. Satellite-based observations now are beginning to provide near-global coverage of several ocean climate parameters or forcing factors. However, the temporal sampling of these remotely-sensed observations does not always resolve energetic variability. More importantly, the length of these time series is quite short; high-quality global coverage of SST is only available for the past 20 years. The satellite observations can reveal the spatial characteristics of the signals that have been measured in the scattered long time series, thus improving their value for model verification (see 9.1.3).

Integrating Variables. Variables which inherently integrate the many factors which control their variations act like low-pass climate filters. For example, upper-ocean heat-content variations are due to the sum over time of air-sea heat fluxes, vertical mixing, Ekman pumping, and the convergence of horizontal advective fluxes. The diffusion of ocean tracers along their advective pathways has a cumulative effect, and the impact of individual eddies on the tracer distribution is reduced substantially.

Climate Indices. Climate indices are created by averaging data within a region sensitive to a particular signal (e.g., the NINO3-SST index of central equatorial SST variability related to ENSO), or by projecting observations onto the spatial pattern associated with a particular climate signal (i.e., correlations of observations with an EOF pattern). Such indices filter random environmental noise, increasing the signal-to-noise ratio. Creation of such indices depends on the continued availability of the raw time-series observations needed to create them.

Multivariate Time Series. A critical test of ocean models is that they simulate the relationships among two or more state variables accurately enough for climate purposes. This requires that the dynamics and thermodynamics be sufficiently correct, and that feedbacks among different parts of the ocean climate system are reasonably modelled. A fundamental multivariate objective for climate models is the correct simulation of Temperature/Salinity variability, as the correlations of temperature and salinity are spatially and temporally variable, and these variations provide important information about climate system physics. For understanding of the carbon cycle through biogeochemical models, lack of multivariate time series prior to the establishment of BATS, HOT and ESTOC was a major impediment to progress.

9.3.2 Forcing Ocean Climate Models

In addition to the variable fields needed to calculate the air-sea fluxes to force ocean models, estimates of the forcing field errors are required in order to determine the space-time covariance structure of such errors to assess their possible impacts on the model evolution. Comparison of forcing fields from different NWP centres is valuable for determining systematic biases as well as for cross-checking the analysis error estimates.

In addition to internally generated analysis error estimates, and the errors inferred from differences between analyses, it is essential that some accurate observations are made to provide an independent assessment of the analysis errors. These observations should be withheld from the ingested data stream of the analyses. Moored buoys now can provide the high-quality observations which are needed for accurate air-sea flux estimates. These estimates provide calibration or verification data for comparison with NWP analyses. Moored-buoy sites are also needed to provide a measure of the impacts of NWP model/analysis and satellite orbit/sensor changes on the air-sea flux fields used to drive ocean models. Sites are needed within several different regimes (e.g., trade winds, ITCZ).

Just as with the dynamical analysis of ocean observations, the analysis of atmospheric fields depends on the type, location, frequency, and quality of the atmospheric observations which go into the analysis. While the atmosphere is more heavily observed than the ocean, the decorrelation time scale is much shorter. In addition, the basic in situ observing system of the World Weather Watch has been deteriorating for the past decade. This has been offset to some degree by improvements in atmospheric forecast models, and by the incorporation of satellite observations into the analysis stage.

The operational, near-global coverage obtained from satellite systems relies on a small number of satellite-mounted sensors remaining within calibration over periods of several years. There is also the need to ensure continuity of calibration when one operation satellite is succeeded by the next, possibly because the former has failed. Unlike in situ systems, the sensors can not be brought back to the laboratory for post-deployment calibration; instead comparison with buoy data is normally used. Since the inception of operational satellite systems, ocean buoys have taken on a vital new role. Types of satellite data for which the calibration has been derived or validated using buoy data include sea surface temperature (Reynolds & Marisco; 1993), altimeter wind speeds and wave heights (Cotton and Carter, 1994; Ebuchi and Kawamura, 1994; Gower, 1996) and scatterometer data (Quilfen and Bentamy, 1994; Graber et al., 1996).

The technology now exists both to moor meteorological buoys in the deep ocean and to reliably obtain the measured data via satellite links. Examples of established moored-buoy arrays are the NDBC (Gilhousen et al.; 1990) and AES (Axys, 1996) buoys off North America, the TOGA TAO array in the equatorial Pacific, and the ODBS buoys off Japan. Taking as an example the NDBS buoys, these range in type from the very large 12m and 10m discus designs, through the 6m Nomad buoy to the 3m Discus buoy. Over 20 buoy locations have been maintained in both the Atlantic and Pacific with most time series dating from the mid 1970's to early 1980's. In addition to standard surface meteorological data, spectral wave data and current profiles (using ADCP) sensors are available from some locations.

9.3.3 Use of Models to Combine and Interpret Ocean Observations

Ocean time series enter in this process in various ways. The first one is to constrain the models by ocean observations. This is especially important for the deep model hydrography which needs to be corrected for wrong boundary fluxes due to limited model domains or incorrect representation of the sea floor (resolution often requires an approximation of topographic structures which are important for water mass formation), and for wrong or incompatible surface forcing (momentum, heat, fresh water). Equally important, in situ data from moorings and repeat hydrographic sections are required to estimate the prior statistics of processes and the observational error characteristics, including environmental 'noise'. This knowledge is incorporated into the analysis procedure typically through specification of signal and error covariances, which must be estimated from observations. Those statistics enter the estimation process as weights of the model-data misfits, and determine in a fundamental way the selection of a dynamically plausible solution. Finally, some data are needed as independent information which is withheld from the estimation process for subsequent use during the testing of the resulting solution.

9.3.4 Ocean Observing System Design

For this activity, the requirements for ocean observations are to assess model limitations to select appropriate model for specific observing purpose, and to provide the basis for producing analyzed fields for subsampling studies. The requirements are already given in section 9.3.1 and in 9.3.3.

9.3.5 Climate Analysis/Assessment

In order to determine the climate state (relative to the historical record), along with the rates of change of different components of the climate system, long, consistent time series with spatial coverage are required.

9.3.6 Climate Prediction

Time series observations are valuable for setting initial conditions for predictive models and for determining skill scores.

9.4 CONCLUSIONS REGARDING TIME-SERIES OBSERVATIONS FOR MODELLING

The working group concluded that ocean observations for climate purposes as stated above differ in value and that time series observations contribute in special ways to climate modelling activities. Some specific conclusions reached are:

(i) Integrating variables (such as sea surface height, heat content, and tracers) are particularly valuable for climate purposes.

(ii) Collocated, multivariate time series have proven to be especially valuable for determining climate-relevant feedbacks.

(iii) Dynamical assimilation of observations offers a rigorous framework for identifying model deficiencies.

(iv) As the records become longer, satellite time series data will grow in importance and provide the spatial context that will enhance the value of in situ time series observations for model verification.

9.5 RECOMMENDATIONS REGARDING TIME-SERIES FOR MODELLING

The working group made the following specific recommendations for ocean time series for climate purposes from the perspective of their role in models.

(i) Sustain long, consistent in situ time series of ocean climate variables for:

- (a) direct comparison with ocean model hindcasts,
- (b) determination of statistics of signals and errors,
- (c) assessment of the climate state (relative to historical record) and rates of change of different components of climate system,

(d) specification of initial conditions for climate predictions and for calculation of skill scores.

(ii) Develop additional new in situ time series of ocean climate variables for the purposes above, and to help resolve the spatial structure of important signals.

(iii) Develop and maintain climate indices for key oceanic regimes relevant to the climate system.

(iv) Maintain/sustain existing ocean weather buoys for their contribution to improving ocean surface forcing fields and their error characteristics.

(v) Deploy a limited number of state-of-the-art air-sea flux buoys to improve and calibrate NWP flux fields in distinct regions of the climate system.

(vi) Deploy high-quality meteorological buoys in sufficient numbers and appropriate places to resolve discontinuities in analyses.

10. PERSPECTIVES ON HISTORICAL AND FUTURE TIMES-SERIES

A fourth working group chaired by Sydney Levitus was established to consider lessons learned from the use of individual time-series stations and historical data that can be applied to enhance the usefulness other existing sites and those that might be established in the future. The results of this working group were summarized by Levitus. The principle points developed by the working group were:

Point 1. The international scientific community has the responsibility of advising governments and intergovernmental organizations on issues involving climate variability on local, regional, and global scales. Bodies such as the Intergovernmental Program on Climate Change depend specifically on scientific input from the international scientific community. In order for the community to provide the best advice to these organizations, we must have the most complete oceanographic databases possible. Because international agreements regarding climate variability may have profound effects on society, the best advice possible from the scientific community is required.

Point 2. There is a continuing, and in fact an expanding need, on the part of the scientific community for ocean time series data in order to study the role of the ocean as part of the earth's climate system. Results published during the past 20 years based on existing time series, clearly document relatively large variations in the temperature-salinity structure in some parts of the world ocean. At a minimum, the results imply that parts of the world ocean are undergoing large-scale redistributions of heat and fresh water. These phenomena may or may not be related but clearly represent an opportunity for the community to describe and attempt to understand the large-scale variations in the earth's climate system.

Point 3. The role of ocean 'point' time series, characterized by relatively high frequency sampling, is to unambiguously identify statistically significant change that occurs at any particular location. Point time series are invaluable for use in the identification and interpretation of larger-scale variability that is performed using composites of historical data. For example, a historical time series can be used to identify compositing periods for large-scale analyses.

Point 4. Seasonal-to-Interannual forecasts of the state of the atmosphere and ocean are now being performed using joint ocean-atmosphere general circulation models with results being distributed on a regular basis. Because of the paucity of real-time observations, design of improved observing system and improvements in forecasts using these models will depend heavily on hindcasting experiments using historical observations.

Point 5. Recent advances in technology allow the placement of relatively inexpensive in situ monitoring devices in the world ocean for important state variables such as temperature, salinity, and pressure. However, much of the climate community is not aware of the "state-of-the-art" with respect to new in situ ocean sensor capabilities for these three variables, nor how these systems might be incorporated into a "Global Climate Observing System". The oceanographic community has not presented a comprehensive description of capabilities or plans for future deployment of these new systems.

10.1 RECOMMENDATIONS.

The working group agreed on the following recommendations:

(i) Recommendation 1: As recommended in the report of the GCOS meeting "Long-Term Climate Monitoring by the Global Climate Observing System", and the CLIVAR Science Implementation Plan (1995), concerted efforts should continue to digitize all historical ocean profile data that presently exist on fragile, non-permanent media and that efforts be continued to trace and make part of the permanent archive temporarily "lost" data (e.g., as in the IOC GODAR data archaeology project described by Levitus et al., 1994)".

(ii) Recommendation 2: Additional existing ocean time series should be constructed based on historical data and made widely available through national and international "data archaeology and rescue" projects under the aegis of the IOC GODAR project. In particular, there are many coastal time series that are not easily accessible in digital form. Individual nations should be encouraged to produce CD-ROMs containing their national time series and also make these series available on-line. The NODC/WDC-A "Time Series" CD-ROM should be updated.

(iii) Recommendation 3: An authoritative report should be commissioned to review the state-of-the-art on ocean sensor development and capabilities. The report should be completed, published, and widely distributed within six months of commission. The report should emphasize:

a. accuracy and precision of the instruments;
b. calibration and instrument drift issues;
c. length of time that sensors can be left in place in the ocean;
d. cost of sensors and data processing;
e. difficulty (or ease) and cost of deployment;
f. strategies for providing continuity of existing and replacement time series measurements;

References:

WCRP, 1995: CLIVAR Science Plan, WCRP-89, 157 pp.
Levitus, S., R.D. Gelfeld, T. Boyer, and D. Johnson, 1994b: Results of the NODC and IOC oceanographic data archaeology and rescue projects: Report 1.
KORDI 19, 73 pp.

11. GENERAL FINDINGS AND CONCLUSIONS

The individual sections of this report contain conclusions and recommendations tailored to the subjects addressed in those sections. Taking a broader view, Ed Harrison provided a summary of general findings and conclusions from an overall perspective of the three days of information presented and discussed during the workshop. These are enumerated below.

(i) With few exceptions the ocean stations that have produced the valuable ocean time series observations that we rely heavily on today were not selected on the basis of ocean processes to be studied. Other factors such as logistics, needed weather observations, aircraft beacons, etc., were dominant.

(ii) Nevertheless, from these observations it is clear now that substantial time variability exists in practically every oceanographic time series. This variability typically has a wide range of scales, with both high frequency (diurnal and sub-diurnal, to several weeks) and low frequency (intra-seasonal, interannual and longer period) changes evident in every record that permits examination of these scales.

(iii) This variability is clearest in the upper ocean, where a few long, high resolution time series are available. Low frequency variability appears also to exist in repeat hydrographic sections that show changes throughout the water column in temperature and salinity.

(iv) The repeated occupation of biogeochemical time series sites in the last decade raises exciting questions about the different ways that this system can behave, and the extent to which quantitative relations between the system variables previously thought to be robust (e.g., Redfield ratios) can vary with geographical location and time period. At present these time series efforts are intensive of human effort, but unattended biogeochemical sensor development is occurring rapidly.

(v) Design of a sampling strategy for on-going time series stations or sections is difficult unless the system has been significantly over sampled for at least several years. It is possible to make serious sampling strategy errors in the absence of over-sampled design data sets. Even then, there is the risk that a regime shift may alter the variability sufficiently to make a previously adequate sampling strategy ineffective. There are very few locations and sections which have been sufficiently over sampled.

(vi) Lacking a global ensemble of adequate resolution time series it is not possible to estimate either the benefit to society of having the information or the likely costs of not having it.

To date every such time series has produced new scientific information, which has affected our awareness of the characteristics of the ocean's variability and which has led to new ideas about the mechanisms of oceanic variability or new measurements to further refine our knowledge of such variability.

(vii) The Tropical Pacific observing system, comprised of Ships of Opportunity (VOS), surface drifting buoys, the TAO moored array and a thin net of sea level gauges is the first adequately resolved, "purposeful" large-scale, open-ocean observing system. It is intended to support operational activities of general social and economic concern (e.g., ENSO forecasting). It is only recently fully deployed in its original design configuration, and an assessment of its capabilities is now underway. Recent scientific and forecasting studies indicate that the information obtained from the observing system are central to our present levels of understanding and forecast skills.

(viii) A recently begun and on-going North Atlantic deployment of profiling drifting instruments is taking place without a systematic, internationally co-ordinated, basin-wide design effort. The present drifting, profiling instrument deployments will produce a unique data set within the next few years, and a co-ordinated assessment of the information obtained, and the implications for future sampling of this region, should be a high priority.

(ix) The technology exists (and is steadily improving) to produce point and drifting surface and upper ocean time series of meteorological and oceanic variables at much lower cost and with much greater accuracy than has been available previously. Developing a strategy to make best use of these capabilities should be a high priority for GOOS, GCOS and the various ocean and climate research programmes. Ideally, design of a combination of point measurements, drifting profiles, sections and satellite observations would be considered. Reoccupation, with unattended sensors, of a subset of the old Ocean Weather Station sites merits particular consideration.

ANNEX I

AGENDA

1. **INTRODUCTION**

2. **REVIEW AND ADOPTION OF THE AGENDA**

3. **WORKSHOP PERSPECTIVES**

    3.1 OBJECTIVES OF THE WORKSHOP
    3.2 OCEAN CLIMATE OBSERVATIONS AND UPPER OCEAN SAMPLING ISSUES
    3.3 DEEP OCEAN: RELATION TO GRIDDED PRODUCTS
    3.4 JGOFS PHILOSOPHY ON TIME-SERIES MEASUREMENTS
    3.5 CLIVAR AND OOPC VIEWS AND EXPECTATIONS
    3.6 REPORTS OF RECENT EVENTS AND MEETINGS

4. **SCIENCE OF SINGLE POINT TIME SERIES**

    4.1 THE BERMUDA ATLANTIC TIME-SERIES STATION (BATS)
    4.2 THE HAWAII OCEAN TIME-SERIES (HOT) STATION
    4.3 ESTOC (ESTACIÓN DE SERIES TEMPORALES OCEÁNICAS DE CANARIAS)
    4.4 KERFIX
    4.5 WEATHER STATION PAPA (P)
    4.6 BRAZIL DEEP BASIN EXPERIMENT
    4.7. SINGLE POINT STATION FINDINGS

5. **APPLICATION AND REPEAT SECTIONS**

    5.1 METEOROLOGICAL TIME-SERIES MEASUREMENTS
    5.2 TROPICAL PACIFIC TAO ARRAY
    5.3 INTERANNUAL VARIABILITY IN THE LABRADOR SEA
    5.4 NORWEGIAN STATION MIKE (M)
    5.5 NORTH ATLANTIC REPEAT SECTIONS
    5.6 NORTH PACIFIC REPEAT SECTIONS
    5.7 THE XBT/XCTD NETWORK AND THE TASMAN BOX
    5.8 SESSION FINDINGS

6. **THE FUTURE**

    6.1 ASSIMILATION OF TIME-SERIES OBSERVATIONS IN NUMERICAL MODELS
    6.2 CLIVAR/ NORTH PACIFIC CLIMATE STUDY
    6.3 CLIVAR UPPER OCEAN PANEL/ SURFACE FLUXES
    6.4 OCEAN PCO_2 AND CARBON MONITORING

ANNEX II

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ANNEX IV

SOME SAMPLING ISSUES FOR OOPC

Prepared by D.E.Harrison

How we need to sample depends on our goals. In general, designing a system to recognize a phenomenon whose basic characteristics are known is much less demanding than designing a system to define quantitatively the characteristics of a range of poorly described phenomena. Designing a system to permit study of the mechanisms responsible for a phenomenon is more challenging still. However, if the signal of interest is small compared to the range of variability within which it exists, even designing for recognition can be a challenge.

In oceanography we have depended upon collecting as many data as possible and hoping that we will be able to extract the signal. Our raw materials are means and standard deviations and simple correlation functions. Objective Interpolation provides the basic statistical framework for estimating the errors in the maps we make from our observations, whether of climatologies or of fields over a particular time interval. Unfortunately, OI technics are not so widely used as would be desirable. I hope that OOPC will strongly encourage the practice that any given ocean value be quoted with an estimate of its uncertainty. Sometimes such uncertainties are not simple to evaluate even when the errors are random, particularly when few data are available. Various strategies are possible for constructing error estimates however, and should be encouraged strongly.

Randomness of errors is a powerful assumption. Statistical techniques like principal component analysis, which separate the correlated signals from the uncorrelated, have played an important role. However, bias and alias errors can present serious challenges. Bias error can only be dealt with through comparison with other data; ideally with data of the same variable and of known (high) accuracy. Bias errors are a challenge for every observing instrument, but particularly with remote sensing instruments. Alias errors can be well estimated if high resolution series of quality data are available; they can be surprisingly large for many of the variables of interest to OOPC under conventional sampling densities. In the absence of adequate high resolution records, alias errors cannot be evaluated and may greatly diminish the effectiveness of the observing effort.

OOPC should foster every effort to quantify bias and alias errors in the GOOS and GCOS observing systems. Typically this means that high resolution measurements must be made routinely in at least a few locations. The number and locations of time series required can only be determined once the patterns of bias and the intermittency of the variables of interest are known. Developing a strategy to implement the collection of the needed records will require sustained effort by scientists and the funds required to make the observations will not be trivial.

The effectiveness of error estimates using the OI framework depends heavily on the assumed autocorrelation function (ACF). Kessler et al (1996) illustrate how high resolution time series from the TAO array permit quantitative evaluation of errors in the VOS-XBT fields for the tropical Pacific. The ACF is a more difficult quantity to know well than the mean or standard deviation, and uncertainty in it can cause wide differences in error estimates of a computed quantity. Uncertainty can arise because the background state is not known or simply through statistical uncertainty of the individual correlations at each lag. Harrison et al (1983) illustrate the effect of computing ACFs of subsurface temperature variability using either a linear trend or the climatological mean field, and contrast these results with estimates made more conventionally for a North Pacific sampling study. Harrison and Larkin (1997) provide an example, using 130 years of Darwin, Australia sea level pressure data on a question of climate change. The technique for constructing ACF error bars based on purely statistical uncertainty of the correlations at different lags is described in the latter paper. Because ACFs in large scale oceanography are typically computed from the available observations, rather than from special data sets collected to facilitate estimation of the ACF, it is important to make the best estimates we can of ACF uncertainty, and to carry forward these uncertainties into our mapping errors.

How big are the climate anomaly signals we wish to observe and to understand? Rather than attempt to quantify these, it suffices for our purposes here to note that typically these values are not large compared to the amplitude of diurnal-to-weekly scale variability, or to the range of their climatological monthly means. Depending upon the variable of interest and its location, the primary error sources may be high frequency, seasonal cycle or interannual fluctuations...or some of each. The widely used COADS data set offers a very nice example of the challenges of large scale global surface climate studies. Harrison and Larkin (1996) figure 1 shows the data distribution, in terms of the percentage of months between 1946 and 1993 that have data, and the average number of data per month in the months that have data. Much of the world ocean has fewer than 80% of the months with data and broad sweeps of the tropical and South Pacific and south Indian and south Atlantic oceans have less than 70% of the months with data. Average data per month of fewer than 10 is commonplace except along major shipping routes and across the hearts of the norther subtropical gyres; many areas have fewer than 4. No systematic effort has been presented to estimate the errors in monthly means constructed from COADS, not even for its climatology, to my knowledge. Uncertainty in estimates of anomalies surely is large over much of the ocean. If we wish to estimate long term trends or decadal variations, it is very important to have meaningful error bounds on them.

Not every quantity we wish to observe for OOPC will have a meaningful error estimate associated with it. But we can do much if we explain the importance of making such estimates as often as we can, and if we constantly remind our community of the key role that high quality time (and space) series of observations play - in error estimation of every sort.

Harrison, D.E., W.J. Emery, J.P. Dugan, and B-C. Li (1983): Mid-latitude mesoscale temperature variability in six multi-ship XBT surveys. J. Phys. Oceanogr., 13, 648-662.

Harrison, D.E. and N.S. Larkin (1996). The COADS sea level pressure signal: A near-global El Nino composite and time series results, 1946-1993. J. Climate, 9, 3025-3055.

Harrison, D.E. and N.K. Larkin (1997): The Darwin Sea Level Pressure record, 1876-1996; Evidence for climate change? GRLetters (in press).

Kessler, W.S., M.C.Spillane, M.J.McPhaden, D.E.Harrison (1996) Scales of thermal variability in the equatorial Pacific inferred from the Tropical Atmosphere-Ocean (TAO) array. J. Climate, 9, 2999-3024.

ANNEX V

THE CONTRIBUTION OF EXISTING TIME SERIES TO THE ANALYSIS OF LARGE-SCALE VARIABILITY IN THE WORLD OCEAN

Prepared by Sydney Levitus

1. INTRODUCTION

The purpose of this contribution is first to document examples of multidecadal trends and quasi-decadal ocean variability based on existing time series of measurements from the open ocean. The existence of such phenomena indicate that parts of the world ocean are undergoing significant change in their temperature-salinity properties. This fact, along with the large heat capacity of water, suggests that on decadal time-scales the ocean may play a significant role in determining the earth's atmospheric climate. This is in fact the justification for the WCRP/CLIVAR Decade-to-Century climate variability program which has a special emphasis on "the role of the oceans in the global coupled climate system" (WCRP, 1995). The second purpose is to outline some potential sampling strategies using newly developed technologies.

2. DECADAL VARIABILITY AT STATION "S"

Fig. 1 shows the annual mean temperature at a depth of 1750 m at Station "S" as a function of time (Levitus and Antonov, 1995). Sampling at Station "S" was generally biweekly or monthly (see WHOI and BBSR, 1988). We have computed the standard errors of the monthly averages of all data for each year about the mean for each year and plot (vertical lines) plus and minus one standard error about the annual means. It is clear that from approximately 1959 through the end of the record that a warming at a rate of about 0.7°C per century occurred. Also obvious is a quasi-decadal scale oscillation. The detrended record is presented in Fig. 2. The range of the quasi-decadal scale oscillation is about 0.1°C to 0.2°C.

3. DECADAL VARIABILITY AT OCEAN WEATHER STATION "C"

Fig. 2 shows annual mean temperatures at a depth of 100 m at Ocean Weather Station "C" (located in the subarctic gyre of the North Atlantic) as a function of year for 1947-1985 (Levitus et al., 1994a; Levitus et al. 1995; Levitus and Antonov, 1995). Annual means are presented for three sets of instrument types. One set is comprised only of data from Mechanical Bathythermographs (MBTs), the other set is comprised of data from reversing thermometers or S/CTDs (termed "Hydrostation" data in Fig. 2). Accuracy of reversing thermometers and S/CTDs (0.005-0.02°C) are an order of magnitude better than the accuracy of MBTs (0.1-0.3°C). The data for 1947-1973 were observed by ships of the U.S. Coast Guard while the data for 1976-1985 were made by ships of the Soviet Hydrometeorological Service. For years when both MBT and HydroStation data are available we plot annual means from each set of instruments from both countries. A linear cooling trend and a quasi-decadal oscillation are evident in this series. It is important to note that for years for which overlapping annual means exist from the two instrument sets, excellent agreement exists between the two independently estimated annual means for each year. Results from a comparison of individual monthly means for the two instrument sets shows much better agreement for winter monthly means as compared to summer monthly means (J.Antonov, personal communication). Most probably this seasonal variability in agreement of the two instrument sets is due to different daily sampling times for the two sets of instrument types. The existence of a seasonal thermocline during the summer (which we observe in summer data at this location) and different sampling times for the different instrument types could lead to the observed seasonal variability in agreement of the two sets. Unfortunately, we do not have the appropriate metadata with the MBT profiles (e.g., time of sampling) to check this possibility.

4. UTILITY OF HISTORICAL DATA

It is very clear from the example we presented in section 3 of this report that even older ocean data from instruments less accurate than some more modern instruments are valuable for describing the temporal variability of parts of the world ocean. The issue of the utility of historical data is one of "signal-to-noise" or "signal-to-accuracy", not one of absolute accuracy. Hence, the digitization of historical ocean data (and appropriate metadata) and the placement of such data in internationally available databases. Another excellent example of the utility of historical data is the work described by Dickson *et al.* (1988) who have used data from the early 1900's to the present to document the large decadal-scale changes in salinity that have occurred in the North Atlantic that are associated with the phenomenon known as the "Great Salinity Anomaly".

The work of Levitus *et al.* (1994b) and Levitus and Antonov (1995) clearly show that even in the upper ocean, thermal anomalies at subsurface depths may be of opposite sign to contemporaneous sea surface temperature changes. Hence, to describe the variability of the upper ocean it is just as important to build the most comprehensive archives of bathythermograph data (which sample the upper ocean only) as well as the archives of Nansen and Niskin cast profiles and CTD cast profiles. An example of such upper ocean depth independent variability is shown in Fig. 3 which shows the linear trend of temperature in the North Atlantic at depths of 100 m and 400 m for the 1966-1990 period are of opposite sign.

The utility of historical oceanographic data for describing interannual-to-decadal variability has now been recognized by international programs. Examples include the recommendations and conclusions of the World Climate Research program Science Plan (WCRP, 1995) and the international meeting of experts on the "Long-Term Climate Monitoring by the Global Climate Observing System" (Karl *et al.*, 1995; Trenberth, 1995).

5. SAMPLING STRATEGY

The advent of modern profiling instruments that can be left at a location unattended (e.g., Frye *et al.*, 1996, Doherty *et al.*, 1997) while autonomously profiling for extended periods of time, suggests new ways to monitor the ocean that are relatively inexpensive compared to traditional cruise expeditions. In addition, instrumentsthat can be left unattended at one particular fixed location will be just as important to describe variability of water mass properties at a particular depth. Given the fact that there is now evidence for variability of bottom water properties (Lukas, 1994; Coles et al., 1996) a program to monitor bottom water properties on a regional or basin scale is possible. However, these techniques need to be viewed as complementary to existing programs because these instruments can only measure a limited number of parameters.

New instruments such as the TOPEX/POSEIDON altimeter can now provide global, real-time coverage for sea level. However, in situ sea level measurements are still required for calibration purposes, as evidenced by the discovery of a programming error in the software used to process the TOPEX data. In situ sea level data played an important role in documenting the algorithm error.

Satellite altimeters represent revolutionary ocean observing systems. However, sea level, whether measured in situ or remotely, can only provide estimates of the variability of the ocean density field. Several studies published during the last ten years show that in some parts of the world ocean, observed changes in temperature and salinity are nearly density compensating (Brewer et al. [1983], Levitus [1989]). In this situation, an instrument measuring sea level may detect a small or statistically insignificant change in sea level when, in fact, significant changes are occurring in the temperature-salinity distributions of the water column in a particular location.

We believe the most important regions to monitor with new technologies such as unattended profiling instruments, are water mass formation regions, particularly in polar and subpolar regions. It is these regions that reflect changes in the fluxes of heat and water between the atmosphere and ocean that are commonly believed to play a major role in interannual-to-century-scale variability of the earth's climate system via the ocean's thermohaline circulation. The theoretical ideas behind the importance of these regions can be found in the works by Stommel (1961) and Rooth (1982) which led to a seminal numerical modeling study by Bryan (1986) which has led to numerous further studies including those by Weaver and Sarachik (1991) and Delworth et al. (1993) among others.

It is also in these regions where density-compensating changes of temperature and salinity may mask changes in the advection of heat and fresh water by the ocean's thermohaline circulation (Levitus, 1989). Furthermore, these regions represent hostile environments that are often distant from research ship ports which also make them candidates for monitoring with unattended instruments.

Sampling with new, autonomous instruments should begin at existing time series locations so as to insure thorough intercomparisons of the new instruments with measurements using traditional sampling. Issues of instrument drift need to be carefully examined before monitoring with the new instruments begins on a wide-scale basis. One can refer to the fact that expendable bathythermograph instruments (XBTs)were used for approximately 25 years from their introduction before a correction to the systematic error introduced by an inadequate drop-rate formula was introduced (UNESCO,1994).

6. CANDIDATE WATER MASS FORMATION REGIONS TO SAMPLE

Relatively remote water mass formation regions that are candidates for instrumenting with these new technologies include:

(i) Antarctic Bottom Water Mass formation regions. Multiple instruments could be deployed and set to sample at alternating periods so as to maximize temporal resolution and series length;
(ii) Antarctic Intermediate Water Mass formation region;
(iii) Antarctic Mode Water formation regions.

Other candidate regions include the Mediterranean Sea (Gulf of Lions), Greenland Sea, and Labrador Sea.

References:

Bryan, F., 1986: High-latitude salinity effects and interhemispheric thermohaline circulations. Nature, 323, 301-304.

Coles, V.J. M.s.McCarney, D.B. Olson, and W.M. Smethie, 1996:Changes in Antarctic Bottom Water properties in the western South Atlantic in the late 1980s. J. Geophys. Res.-Oceans, 101, 8957-8970.

Delworth, T., S. Manabe, and R.J. Stouffer, Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model, J Clim., 6, 1993-2011.

Dickson, R., J. Meincke, J. Malmberg, S. Aa, A.J. Lee, 1988: 'The Great Salinity Anomaly' in the Northern North Atlantic. *Prog. Oceanogr.*, 20, 103-151.

Dickson, R., P. Rhines, and J. Lazier, 1997: Prog. Oceanogr., 1997

Doherty, K.W., D.E. Frye, A.A. Hinton, S.P. Liberatore and J.M. Toole. 'A moored profiling instrument', paper in preparation.

Frye, D.E., K.W. Doherty, A.A. Hinton, and J.M. Toole. A moored, profiling instrument for long-term hydrographic observations. EOS, 76 no. 3 suppl. pg OS77, 1996

Karl, T., F. Bretherton, W. Easterling, C. Miller, and K. Trenberth, 1995: Long-term climate monitoring by the global climate observing system (GCOS): An editorial. *Climatic Change: Special Issue on Long-term Climate Monitoring*, 31,135-147.

Levitus, S., 1989: Interpentadal variability of temperature and salinity at intermediate depths of the North Atlantic Ocean, 1970-74 versus 1955-59. J. Geophys. Res.-Oceans, 94, 6091-6131.

Levitus, S., J. Antonov and T. Boyer 1994a: Interannual variability of ocean temperature at depth of 125 meters in the North Atlantic Ocean, Science, 96-99.

Levitus, S., T. Boyer, and J. Antonov, 1994b: World Ocean Atlas 1994, Vol. 5: Interannual variability of upper ocean thermal structure. NOAA Atlas NESDIS 5. U.S. Gov. Printing Office, Washington, D.C., 176 pp.

Levitus, S., and J. Antonov, 1995: Observational evidence of interannual-to-decadal scale variability of the temperature-salinity structure of the world ocean. Climatic Change: Special Issue on Long-term Climate Monitoring, 31, 495-514.

Levitus, S., J. Antonov, Z. Zengxi, H. Dooley, V. Tereshenkov, K. Selemenov, and A.F. Michaels, 1995: Observational evidence of decadal-scale varibility of the North Atlantic Ocean. In: Natural Climate Variability on Decade-to-Century Time Scales, eds. D.G. Martinson, K. Bryan, M. Ghil, M.M. Hall, T.R.Karl, E.S.Sarachik, S. Soorooshian, L.D. Talley, National Acaemy Press, 318-327.

Lukas, R., 1994: HOT results show interannujal variability of the Pacific deep and bottom waters. WOCE Notres, 6.

Ocean Observing System Development Panel, 1995: Scientific design for the common module of the Global Climate Observing System and the Global Ocean Observing System, Report of the Ocean Observing System Development Panel, publ. U.S. WOCE Office, Texas A&M Univ, College Station Texas.

Rooth, C., 1982: Hydrology and ocean circulation. Prog Oceanogr., 11, 131-149.

Swift, J. A recent θ-S shift in the deep water of the northern North Atlantic, In: Climate Processes and Climate Sensitivity, Geophys. Monogr. Ser., 29, ed. J.E. Hansen and T. Takahashi, AGU, Wash., D.C., 39-47

Trenberth, K.E., 1995: Long-term climate monitoring by the global climate observing system (GCOS), Report of Breakout Group B-Climate responses and feedbacks: An editorial. Climatic Change: Special Issue on Long-term Climate Monitoring, 31, 163-180.

WCRP, 1995: CLIVAR Science Plan, WCRP-89, 157 pp.

Weaver, A.J., and E.S. Sarachik, 1991: Evidence for decadal variability in an ocean general circulation model. Atmo-Ocean, 29, 197-231.

WHOI and BBSR, 1988:Station "S" off Bermuda: Physical measurements, 1954-1984. Library of Congress catalogue No. 88-51552, 189 pp.

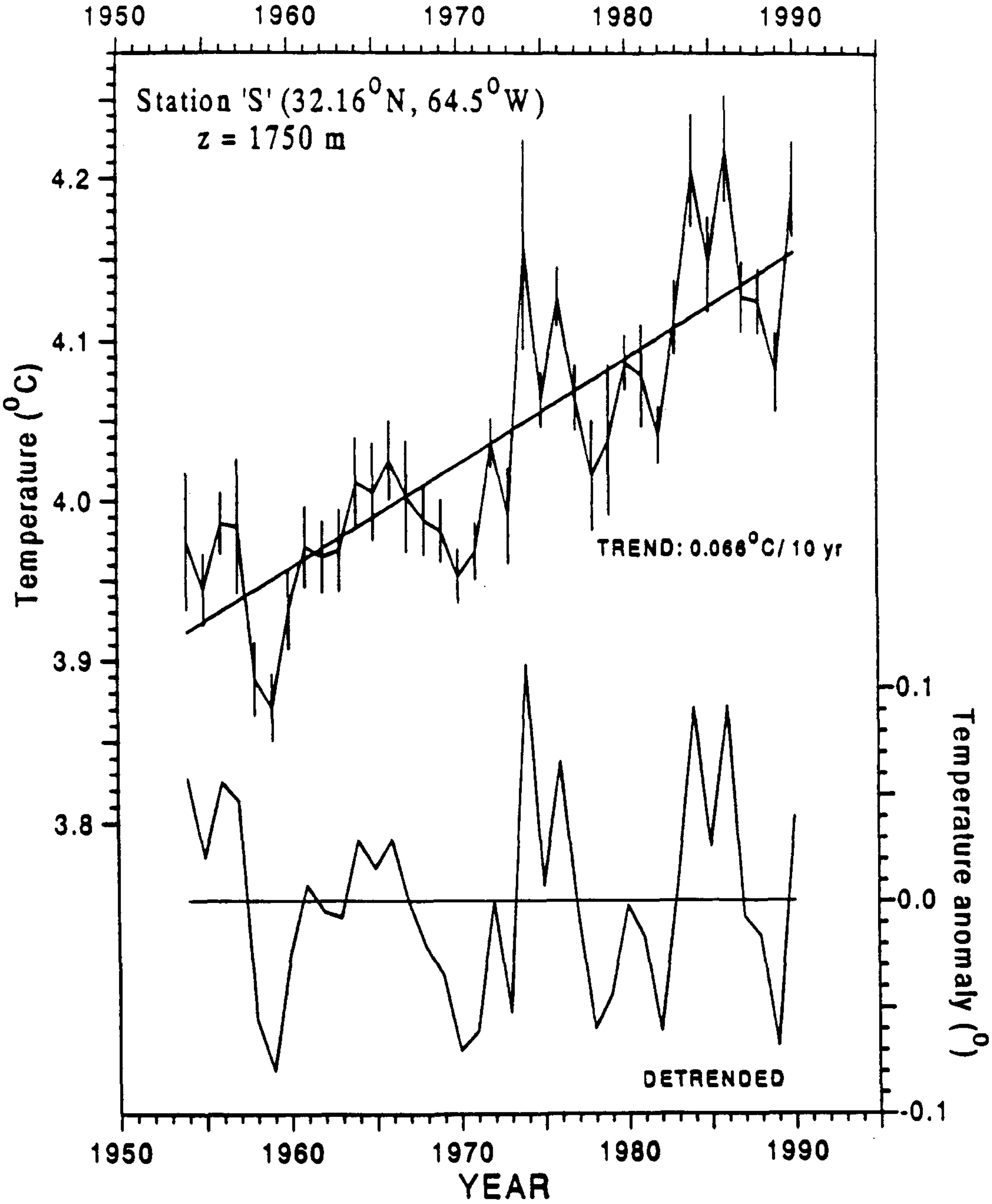

Fig. 1. Time series of yearly mean temperatures at 1750 depth at Station "S" located in the subtropical gyre of the North Atlantic Ocean near Bermuda. The yearly means are computed from the average of the twelve monthly means in each year. The vertical bars extending from each yearly mean represent plus and minus one standard error of the twelve monthly means about each yearly mean. The bottom half of the figure has the linear trend removed.

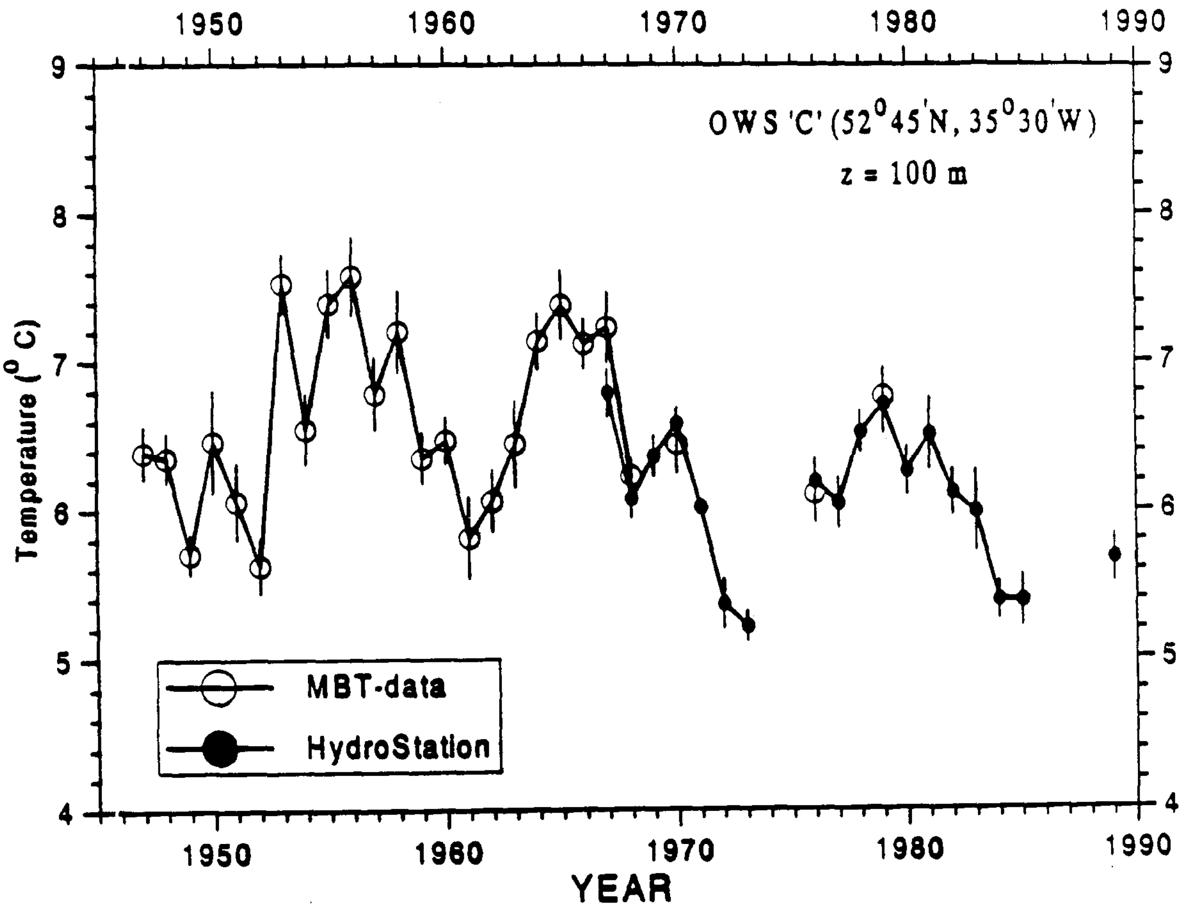

Fig. 2 Time series of yearly mean temperatures at 100 depth at Ocean Weather Station "C" located in the subarctic gyre of the North Atlantic Ocean (52°45'N, 35°30'W). The yearly means are computed from the average of the twelve monthly means in each year. The vertical bars extending from each yearly mean represent plus and minus one standard error of the twelve monthly means about each yearly mean.

LINEAR TRENDS of TEMPERATURE ANOMALIES for 1966 - 90 PERIOD
°C/10 YR

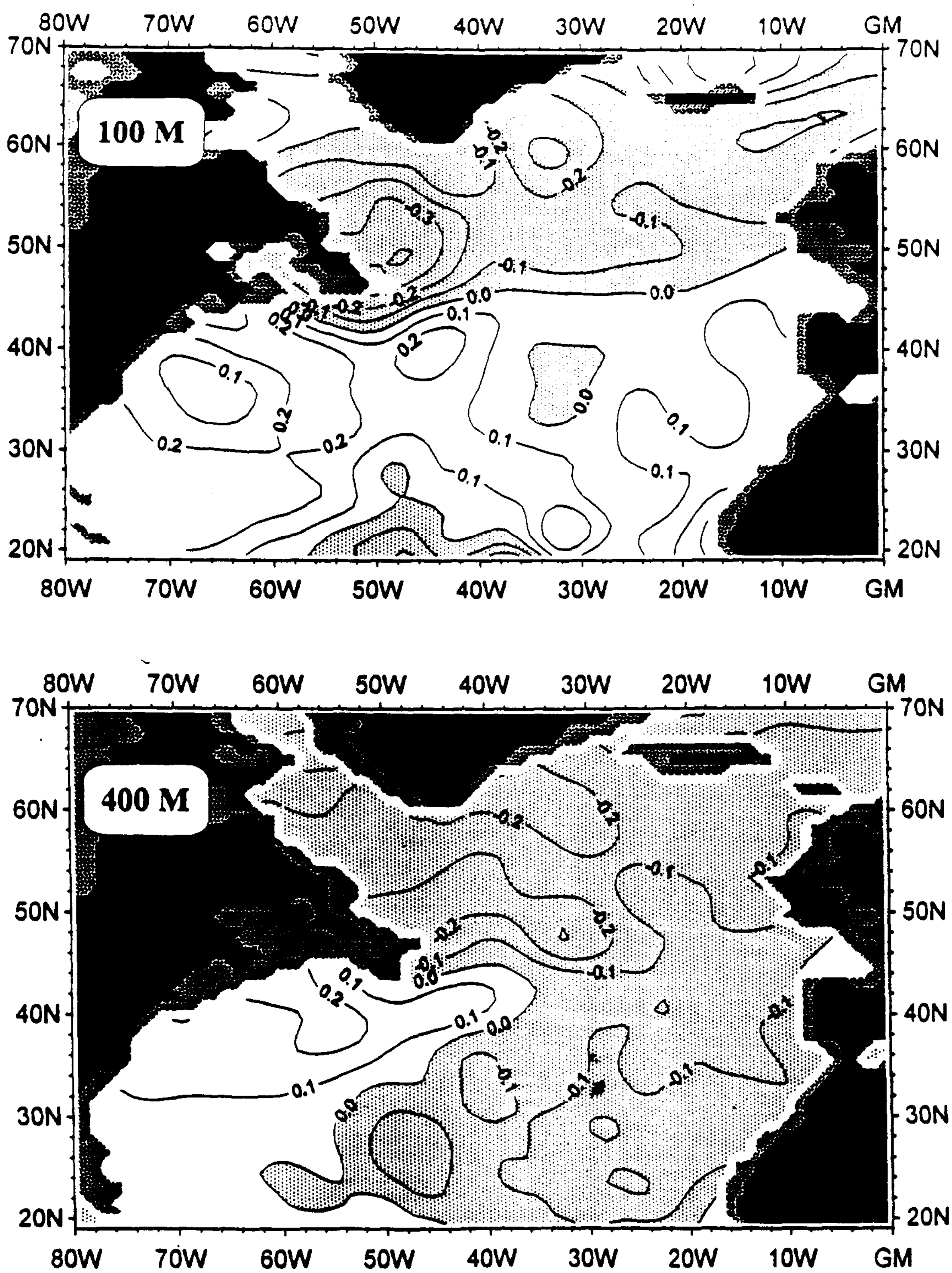

Fig. 3 Linear temperature trend (°C/10 years) at 100 and 400 m depth in the North Atlantic Ocean.

ANNEX VI

BIOGEOCHEMICAL STUDIES AT THE HAWAII OCEAN TIME-SERIES (HOT) STATION ALOHA

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Primary Objective. In 1988, two deep-water, oceanographic time-series stations were established: one in the North Atlantic Ocean near the historical Panulirus Station (Bermuda Atlantic Time-Series, BATS; Michaels and Knap, 1996) and the other in the North Pacific Ocean near Hawaii (Hawaii Ocean Time-Series, HOT; Karl and Lukas, 1996). These programs were established and are presently operated by scientists at the Bermuda Biological Station for Research and the University of Hawaii respectively, on behalf of the U.S.- JGOFS and the U.S.-WOCE ocean science communities. The primary objective of the HOT program is to obtain high-quality time-series measurements of selected oceanographic properties, including: water mass structure, dynamic height, currents, dissolved and particulate chemical constituents, biological rate processes and particulate matter fluxes. These data sets will be used to improve our description and understanding of ocean circulation and ocean climatology, to elucidate further the processes that govern the fluxes of carbon into and from the oceans, and to generate novel hypotheses. These are necessary prerequisites for developing a predictive capability for global environmental change.

HOT Program Structure and Function: The primary objective of HOT is to obtain a long time-series of physical and biochemical observations in the North Pacific subtropical gyre that will address the goals of the U.S. Global Change Research Program. The objectives of HOT specific to the JGOFS program are to:

- measure the time-varying concentrations of carbon dioxide in the upper water column and estimate the annual air-to-sea gas flux
- document and understand seasonal and interannual variability in the rates of primary production, new production and particle export from the surface ocean
- determine the mechanisms and rates of nutrient input and recycling, especially for N and P in the upper 200 m of the water column

Field Sampling Strategy: HOT program cruises are conducted at approximately monthly intervals; the exact timing is dictated by the availability of research vessels. Our primary sampling site, Station ALOHA, is located at 22°45'N, 158°W (Karl and Lukas, 1996). To date, our field observations have not been severely aliased by month, season or year (Karl and Lukas, 1996). From HOT-1 (Oct 1988) to HOT-65 (Aug 1995), with the exception of HOT-42 and HOT-43 (Nov and Dec 1992), each cruise was 5 d in duration. Beginning with HOT-66 (Sept 1995) the standard HOT cruise was shortened by 1 d to provide the shiptime required for additional mooring-based field programs.

Currently, a variety of different methods are used to collect data in the HOT core measurement program. High vertical resolution environmental data are collected with a Sea-Bird CTD. A General

Oceanics 24-place pylon and an aluminum rosette that is capable of supporting 24 12-l PVC bottles are used to obtain water samples from desired depths. We also routinely collect "clean" water samples for biological rate measurements using General Oceanics Go-Flo bottles, Kevlar line, metal-free sheave, Teflon messengers and a stainless steel bottom weight. A free-drifting sediment trap array, identical in design to the VERTEX particle interceptor trap (PIT) mooring (Knauer et al., 1979), is deployed at Station ALOHA for an approximately 2-3 d period to collect sinking particles for chemical and microbiological analyses. Since June 1992, we have supported a bottom-moored sequencing sediment trap array consisting of three MK7-21 (McLane Research, Inc.) traps at depths of 1500, 2800 and 4000 m. The HOT-WOCE component also supports an Inverted Echo Sounder (IES) mooring at Station ALOHA for continuous measurements of dynamic height as well as continuous shipboard ADCP current measurements (R. Lukas and E. Firing, P.I.s). Oblique net tows are used to study the abundances and biomasses of meso- and macrozooplankton (M. Landry, P.I.), and to ground truth particle distributions measured using a towed optical plankton counter (OPC; M. Huntley, P.I.). This latter Office of Naval Research-supported project also provides additional information on the spatial variability of particles (0.3-14 mm equivalent spherical diameter) near Station ALOHA. In January 1997, a full ocean depth physical-biogeochemical mooring was deployed near Station ALOHA to provide continuous measurements of meteorology, upper ocean dynamics, nutrients, dissolved gases and optics.

Sampling at Station ALOHA typically begins with drifting sediment trap deployment followed by a deep (>4700 m) CTD cast and a "burst series" of 12-18 consecutive casts, on 3-hr intervals, to 1000 m to span the local inertial period (~31 hr) and three semidiurnal tidal cycles. The repeated CTD casts enable us to calculate an average density profile from which variability on tidal and near-inertial time scales has been removed. These average density profiles are useful for the comparison of dynamic height and for the comparison of the depth distribution of chemical parameters from different casts and at monthly intervals. Very high frequency variability (<6 hr) and variability on time scales of between 3-60 d have not been adequately sampled during the first phase of HOT. Initial results from the IES network suggest that these frequencies might be important at Station ALOHA (Chiswell, 1996). The recently deployed physical-biogeochemical mooring should greatly improve our understanding of variability in these unresolved frequencies.

Water samples for a variety of chemical and biological measurements are routinely collected from the surface to within 5 m of the seafloor. To the extent possible, we collect samples for complementary biogeochemical measurements from the same or from contiguous casts to minimize aliasing caused by time-dependent changes in the density field. This is especially important for samples collected in the upper 300 m of the water column. Furthermore, we sample from common depths and specific density horizons each month to facilitate comparisons between cruises. Water samples for salinity determinations are collected from every water bottle to identify sampling errors. Approximately 20% of the water samples are replicated to assess and track our analytical precision in sample analysis.

Core Measurements and Protocols: Our list of core measurements has evolved since the inception of the HOT program in 1988, and now includes both continuous and discrete physical, biological and chemical ship-based measurements, *in situ* biological rate experiments, and observations and sample collections from bottom-moored instruments and buoys (Table 1). Continuity in the measurement parameters and their quality, rather than continuity in the methods employed, is of greatest interest. Detailed analytical methods are expected to change over time through technical improvements. The current sampling procedures and analytical protocols are available electronically (see Table 2), or in hard copy (contact: D. Karl at dkarl@soest.hawaii.edu).

Selected HOT-JGOFS Program Highlights: The research conducted at Station ALOHA has provided an invaluable data set on unexpected physical and biogeochemical variability in the subtropical North Pacific Ocean. Some of these results have already been published, but others are part of the continuing time-series measurement program. Selected HOT-JGOFS program results include:

- quantitative assessment of the CO_2 sink which, at Station ALOHA, averages 0.7 mol C m^{-2} yr^{-1} (Winn et al., 1994)

- quantitative assessment of a secular increase in total DIC, in response to rising atmospheric CO_2, at a rate of 1 μmol kg^{-1} yr^{-1} (Winn et al., 1997)

- numerical dominance of photosynthetic (oxygenic) bacteria of the genera *Prochlorococcus* and *Synechococcus* at Station ALOHA (Letelier et al., 1993; Campbell and Vaulot, 1993)

- ENSO-related changes in subtropical North Pacific community structure and biogeochemical cycling rates (Karl et al., 1995)
- quantitative role of *Trichodesmium* and microbiological N_2 fixation in the nitrogen budget (Karl et al., 1992; Karl et al., 1995; Letelier and Karl, 1996; Karl et al., 1997)

- confirmation of general validity of historical estimates of dissolved organic nitrogen and phosphorus concentrations (5-8 M DON and 0.3-0.4 M DOP; Karl et al., 1993; Karl and Yanagi, 1997), and presentation of revised estimates for dissolved organic carbon concentration (80-110 M DOC; Tupas et al., 1994) in surface waters

- quantitative assessment of a secular decrease in the inventory of soluble reactive phosphorus in the upper water column (0-100 m) of ~1.1 mmol P m^{-2} yr^{1}, probably related to the observed shift from N to P limitation with the increase in N_2 fixation (Karl and Tien, 1997; Karl et al., 1997)

- discovery of relatively high, but variable, annual rates of primary production (~14 mol C m^{-2} yr^{-}; Karl et al., 1996), compared to historical estimates (e.g., Berger, 1989)

- convergence of new (export) production estimation by three independent techniques (oxygen mass balance modeling, Emerson et al. [1995]; mixed-layer dissolved inorganic carbon and $^{13}C/^{12}C$ mass balance modeling, Quay and Anderson [1996]; direct measurement of particulate matter export, Karl et al. [1996]) on a value of ~1 mol C m^{-2} yr^{-1} (Emerson et al., 1997)

This latter result is of great interest and suggests that we may have gained first-order closure of the carbon budget at Station ALOHA. While there are still large uncertainties associated with these independent estimates (e.g., O_2 and $^{13}C/^{12}C$ mass balances are 50% of reported values), it is significant that we do not observe large imbalances in the carbon cycle of the magnitude recently reported for the Bermuda time-series site (Michaels et al., 1994). Between site differences in advection may be one explanation for these results.

HOT Program Data Availability, Data Distribution and Publication: A major scientific objective of the HOT program is to provide members of the scientific community with a high quality time-series data set of relevant physical and biogeochemical variables for model validation and other purposes. Each year we publish a HOT Program Data Report that presents data collected from the previous calendar year. HOT Program Data Report #7 was published in Nov 1996. To provide easy access to our data, each Data Report also provides summaries of the temperature, potential temperature, salinity, oxygen and potential density at standard National Oceanographic Data Center (NODC) depths in ASCII files on an IBM-PC compatible 3.5" high-density floppy diskette. Water column chemistry, primary productivity and particle flux data are also presented as Lotus 1-2-3 files. These data are all quality controlled before publication, and a *readme* file provides a complete description of data formats and quality flags. A more complete data set, containing all of the HOT data collected since Oct 1988, including the 2 dbar averaged CTD data, are available from two sources. The first is via the National Oceanographic Data Center (NODC) in Washington, D.C. Another way is self-service; the data reside in a data base on a workstation at the University of Hawaii and may be accessed using the INTERNET or WORLD WIDE WEB systems (Table 1).

Table 1: Universal access to the HOT program data base and other information on program implementation and progress toward stated scientific goals.

Address/File	Data/Information Available
I. *mana.soest.hawaii.edu*	INTERNET access
cd/pub/hot	to access HOT data and information once connected to mana
[Readme.first]	[provides general information about the data base]
/pub/hot/protocols	HOT program Field and Laboratory Protocols Manual
/pub/hot/publications-list	HOT program publication list
II. *http://hahana.soest.hawaii.edu*	WORLD WIDE WEB access to all data, metadata, publications and other program information

Summary and Prospectus: The HOT time-series program has already provided crucial data on the mean states of a representative open ocean ecosystem and on the natural variability therein. Selected biogeochemical data trends were unexpected but are now understandable; others remain enigmatic. As our understanding of the oligotrophic North Pacific ecosystem expands, the core measurement research effort may require modification to accommodate the new paradigms. One of the more interesting and unexpected results to date is the mounting evidence that cyanobacterial dinitrogen (N_2) fixation may be responsible for providing up to 50% of the new N in this ecosystem during the period of our field observations. At the present time we cannot be certain that the processes measured during the past decade are an accurate reflection of the longer-term steady-state, and there is reason to suspect that they are not (Karl et al., 1997).

Long-term time-series programs present special problems for research scientists. Foremost among the major concerns are the procurement of sufficient funding to maintain these costly programs, maintenance of a high-quality data base, retention of dedicated and skilled personnel, and logistical problems inherent in extensive field programs. The HOT program is expected to be in operation for a period of at least 20 years. The emergent physical and biogeochemical data sets that are now available to the ocean sciences community appear to justify the intellectual and financial investments made to date.

References

Berger, W. H. 1989. Global maps of ocean productivity. In: *Productivity of the Ocean: Present and Past*, W. H. Berger, V. S. Smetacek and G. Wefer, eds., John Wiley and Sons, New York, pp. 429-455.

Brewer, P. G., K. W. Bruland, R. W. Eppley and J. J. McCarthy. 1986. The Global Ocean Flux Study (GOFS): Status of the U.S. GOFS program. *EOS, Transactions of the American Geophysical Union*, **67**, 827-832.

Campbell, L. and D. Vaulot. 1993. Photosynthetic picoplankton community structure in the subtropical North Pacific Ocean near Hawaii (Station ALOHA). *Deep-Sea Research*, **40**, 2043-2060.

Chiswell, S. M. 1996. Intra-annual oscillations at Station ALOHA, north of Oahu, Hawaii. *Deep-Sea Research II*, **43**, 305-319.

Emerson, S., P. Quay, D. Karl, C. Winn, L. Tupas and M. Landry. 1997. The carbon pump in the subtropical Pacific Ocean: Implications for the global carbon cycle. Submitted to *Nature*.

Emerson, S., P. D. Quay, C. Stump, D. Wilbur and R. Schudlich. 1995. Chemical tracers of productivity and respiration in the subtropical Pacific Ocean. *Journal of Geophysical Research*, **100**, 15873-15887.

Karl, D., J. R. Christian, J. E. Dore, D. V. Hebel, R. M. Letelier, L. M. Tupas and C. D. Winn. 1996. Seasonal and interannual variability in primary production and particle flux at Station ALOHA. *Deep-Sea Research,* **43:** 539-568.

Karl, D. M., R. Letelier, D. V. Hebel, D. F. Bird and C. D. Winn. 1992. *Trichodesmium* blooms and new nitrogen in the North Pacific gyre. In: *Marine Pelagic Cyanoacteria: Trichodesmium and Other Diazotrophs*, E. J. Carpenter et al., eds., Clair Academic, Dordrecht, pp. 219-237.

Karl, D. M., R. Letelier, D. V. Hebel, L. Tupas, J. Dore, J. Christian and C. Winn. 1995. Ecosystem changes in the North Pacific subtropical gyre attributed to the 1991-92 El Niño. *Nature*, **373**, 230-234.

Karl, D. M., R. Letelier, L. Tupas, J Dore, J. Christian and D. Hebel. 1997. Dinitrogen fixation fuels substantial new and export production in the subtropical North Pacific Ocean. Submitted to *Nature*.

Karl, D. M. and R. Lukas. 1996. The Hawaii Ocean Time-series (HOT) program: Background, rationale and field implementation. *Deep-Sea Research II*, **43**, 129-156.

Karl, D. M. and G. Tien. 1997. Temporal variability in dissolved phosphorus concentrations in the subtropical North Pacific Ocean. *Marine Chemistry*, **56**, 77-96.

Karl, D. M., G. Tien, J. Dore and C. D. Winn. 1993. Total dissolved nitrogen and phosphorus concentrations at U.S.-JGOFS Station ALOHA: Redfield reconciliation. *Marine Chemistry*, **41**, 203-208.

Karl, D. M. and K. Yanagi. 1997. Partial characterization of the dissolved organic phosphorus pool in the oligotrophic North Pacific Ocean. *Limnology and Oceanography*, in press.

Knauer, G. A., J. H. Martin and K. W. Bruland. 1979. Fluxes of particulate carbon, nitrogen and phosphorus in the upper water column of the northeast Pacific. *Deep-Sea Research*, **26**, 97-108.

Letelier. R. M., R. R. Bidigare, D. V. Hebel, M. Ondrusek, C. D. Winn and D. M. Karl. 1993. Temporal variability of phytoplankton community structure based on pigment analysis. *Limnology and Oceanography*, **38**, 1420-1437.

Letelier. R. M. and D. M. Karl. 1996. The role of *Trichodesmium* spp. in the productivity of the subtropical North Pacific Ocean. *Marine Ecology Progress Series*, **133**, 263-273.

Michaels, A. F., N. R. Bates, K. O. Buesseler, C. A. Carlson and A. H. Knap. 1994. Carbon-cycle imbalances in the Sargasso Sea. *Nature*, **372**, 537-540.

Michaels, A. and A. Knap. 1996. Overview of the U.S.-JGOFS Bermuda Atlantic Time-series Study and Hydrostation S program. *Deep-Sea Research II*, **43**, 157-198.

Quay, P. D. and H. Andersen. 1996. Organic carbon export rates in the subtropical N. Pacific. *EOS Transactions of the American Geophysical Union*, **76**, OS85.

Tupas, L., B. Popp and D. Karl. 1994. Dissolved organic carbon in oligotrophic waters: experiments on sample preservation, storage and analysis. *Marine Chemistry*, **45**, 207-216.

Winn, C. D., F. T. Mackenzie, C. J. Carrillo, C. L. Sabine and D. M. Karl. 1994. Air-sea carbon dioxide exchange in the North Pacific subtropical gyre: Implications for the global carbon budget. *Global Biogeochemical Cycles*, **8**, 157-163.

Winn, C. D., Y. H. Li, F. T. Mackenzie and D. M. Karl. 1997. Rising surface ocean dissolved inorganic carbon at the Hawaii Ocean Time-series site. Submitted to *Marine Chemistry*.

ANNEX VII

ESTOC STATION

The time series station ESTOC (Estación de Series Temporales Oceánicas de Canarias) started its operation in 1994. Both the World Ocean Circulation Experiemnt (WOCE) and the Joint Global Ocean Flux Study (JGOFS) science plans included requirements for establishing time series stations using research vessels. Two such stations existed, one at Bermuda and one at Hawaii, both in the interior of the respective oceans.

The Canary Islands region appeared to be an appropriate location for a time series station in an eastern boundary current regime for several reasons. The archipelago is situated in the eastern part of the North Atlantic subtropical gyre, and it is surrounded by deep water. Several Spanish marine science institutions exist on the islands which were prepared to contribute to the operations. In addition, two German institutions were willing to get involved: the Marine Physics Department of the Institut fuer Meereskunde at Kiel University which has a long record of physical oceanographic observations in the subtropical eastern North Atlantic, and the Geosciences Department of Bremen University with its long-standing experience in the research on particle flux in the ocean. The main goals for the ESTOC station work were specified as follows:

(i) to investigate the long-term changes of stratification and circulation on seasonal and interannual time scales in the southwestern approaches to Europe, with the aim of extending the data base which can be used for improving models of the eastern boundary circulation;
(ii) to investigate the biogeochemical cycles in this region, with the aim to better understand the processes controlling the flux of carbon and associated elements in the ocean on seasonal and interannual time scales;
(iii) to provide a focus for ocean studies by European and other research groups in the Canary Islands region;
(iv) to strengthen the oceanographic research capabilities in the Canary Islands region and to improve the scientific interaction between the local institutions and other European ocean research institutions, particularly in Spain and Germany;
(v) to use the time series data as a contribution to WOCE; and
(vi) to use the time series data as a contribution to JGOFS.

The station is positioned at 29°10'N, 15°30'W, about 60 nautical miles to the north of the islands of Gran Canaria and Tenerife. It is the aim to occupy the station with a research vessel once each month for standard observations, including measurements of physical, chemical and biological properties and water sampling. These observations are complemented by measurements with moored instruments.

In order to obtain an improved understanding of the processes governing the region and thereby to gain information on the representativeness of the time series data, repeated process studies are carried out. These interdisciplinary experiments with research vessels combine hydrographic measurements, chemical and biological sampling, productivity experiments and drifting surface-tethered particle trap observations. The cruises are also used to exchange ESTOC moorings and to carry out the standard observations when appropriate. As a further contribution to the process studies, XBT lines were established between Gran Canaria and the station and also between Gran Canaria and the African coast.

The ESTOC work was initiated by a group of four scientists in Spain and Germany who constitute the International ESTOC Committee at present. The members are:

Dr. O.LLinás ICCM. Telde, Gran Canaria	Dr. A. Rodriguez de León IEO. Madrid
Prof. Dr. G.Siedler IFM, U. Kiel	Prof. Dr. G.Wefer GEOB, U. Bremen

Sixteen more scientists from diverse organizations have participated as guests in at least one of the three annual meetings of this committee held up to now.

The local coordinating committee, (Comite Local De Coordinacion Para Estoc) consists of María J. Rueda (ICCM) and Federico López-Laatzen (IEO)

The ESTOC Scientific Committee has the following tasks:

(i) to coordinate the scientific programmes,
(ii) to ensure high data quality and appropriate data dissemination,
(iii) to relate the observations to WOCE and JGOFS and other programmes,
(iv) to coordinate meetings and the publication of documents, and
(v) to encourage the joint evaluation and publication of obtained data.

Monthly measurements started in February 1994, using the research vessel "Taliarte" (a rebuilt fisheries vessel) which is operated by the ICCM in Telde, Gran Canaria. In the monthly station observations the team of the ICCM collaborates with the IEO Tenerife and several groups from the University of Las Palmas. The German groups occasionally participate in the monthly station observations, and provide input to this part of the programme mostly with respect to methods and calibration.

The repeated interdisciplinary process studies are carried out on German and later probably also on Spanish research vessels once or twice per year, combining groups from the ESTOC partner institutions, from the University of Las Palmas and from other institutions in several countries.

The funding for the German contribution to ESTOC is provided by the Ministry of Science and Technology (BMBF), Bonn, as part of the German JGOFS programme. The Spanish institutions obtain their funding from local and national government sources.

ANNEX VIII

KERFIX
A SOUTHERN OCEAN SINGLE-POINT TIME-SERIES STATION

Prepared by Catherine Jeandel

INTRODUCTION

Between January 1990 and March 1995, the research project KERFIX undertook the first regular non-coastal multi year acquisition of parameters related to the carbon cycle in the Southern Ocean at a time series station located at 50° 40' S - 68° 25' E, 60 miles southwest of Kerguelen Islands (see Figure 1). SThe objectives of KERFIX are 1) to monitor the ocean/atmosphere CO_2 and O_2 exchanges and to understand which processes govern these exchanges 2) to observe and interpret the seasonal and interannual variability of the production, flux, decomposition and dissolution of carbon and associated elements at this location. In addition, micropaleontological studies describe the present and past flux dynamic in this oceanic area, to improve the knowledge of the transfer functions of some oceanographic proxies.

This short note presents an overview of the KERFIX programme, the scientific objectives, list of participants and organization of the field operations. Results will be published elsewhere.

2. THE KERFIX PROGRAMME AND JGOFS

One of the most important goals of JGOFS is to improve estimates of CO_2 uptake by the ocean to come to a better understanding of the processes that control this uptake. A recent review of oceanographers' current comprehension and quantification of this flux, underlines our ignorance about the detailed behavior of the solubility and biological "pumps" that move a portion of the carbon that crosses the air-sea interface from the surface waters to depth. In addition, the amplitude of seasonal variations of carbon fluxes relative to that of the anthropogenic signal makes sampling difficult (Sarmiento, 1995).

A useful field-approach to understand the mechanisms governing the carbon fluxes involves the continuous acquisition of parameters from one sampling location in the ocean. Time-series' observations conducted over many years are essential to our understanding of seasonal, interannual and longer-term trends and cycles. Indeed, long-term monitoring allows us to evaluate the seasonal and interannual variations of the key parameters used to estimate: i) the gas flux (CO_2, O_2) at the ocean/atmosphere interface, ii) the primary production and transient particle fluxes in the water column, and iii) their transformation at depth. Time-series for a single biogeochemical process, in addition to process data acquired in specific biogeochemical provinces, will also allow the calibration of coupled physics/chemistry/biology models in one dimension. Such models will improve our understanding of the processes occurring in the water column and will thus contribute to the development of coupled models in 3 dimensions.

The KERFIX programme runs a time-series station located 60 nautical miles southwest of the Kerguelen Islands in the Indian sector of the Southern Ocean. It started in 1990 and was the first "offshore" exercise for regular multi year acquisition of parameters in the Southern Ocean. Between 1969 and 1983 to begin with and then weekly since 1989, UK biologists undertook weekly coastal observations of the temperature, chlorophyll and macro nutrients at Signy Island (Clarke *et al.*; in press). Since 1991, another long-term research project was developed in the Southern Ocean in the framework of the Palmer LTER programme (Smith *et al.*, 1995), but the area investigated is located near the Antarctic continent. The LTER programme is mostly focused on the spatial and temporal variability of the primary production in this area and their link with the annual advance and retreat of sea ice.

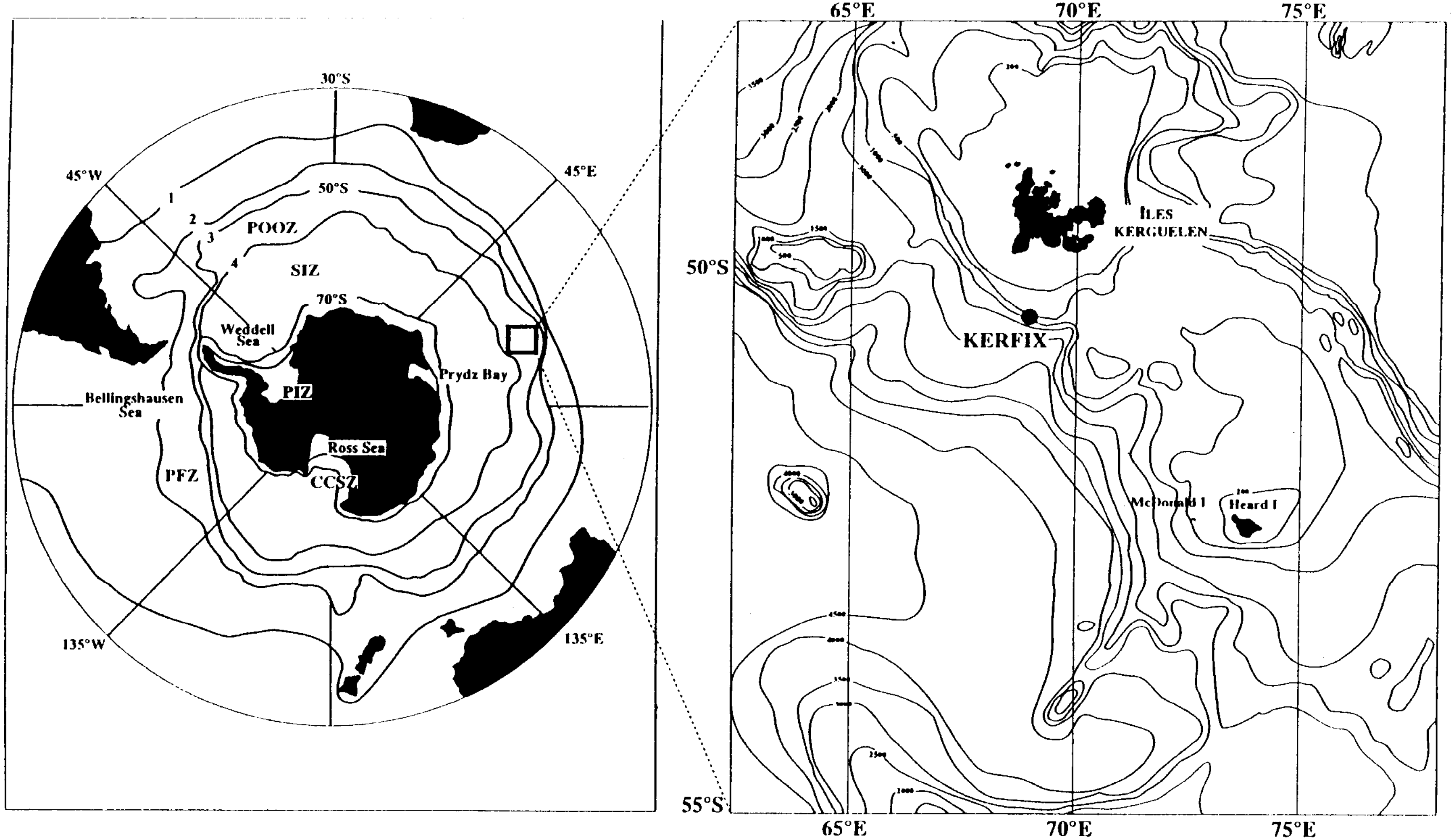

Figure 1. Location of the KERFIX Time-Series Station

One of the main motivations of KERFIX is to contribute to the understanding of the processes that control the primary production, which paradoxically is very weak in this nutrient-rich region. The majority of the parameters acquired as part of KERFIX will be discussed on the basis of simulations using a one-dimensional physical/biological/chemical coupled model (GEOTOP, described in Pondaven *et al.*, in press). This model has been developed since the establishment of KERFIX and has been of great help in designing the sampling strategy.

The physical characteristics of the area have been studied to define the seasonal and interannual variability of the thermal content and the steric height of the water column (Park *et al.*, in press). Current-meter data will allow the determination of the average current and its variability with time (Park, pers. Com.). Time-series of nutrients (Si, NO_3, PO_4 and NH_4) and chlorophyll-*a* concentrations will help to understand the link between phytoplanctonic biomass and nutrient stocks (Fiala *et al.*, 1995; Jeandel *et al.*, 1995). Temporal series of dissolved and particulate lithogenic and biogenic Si and Ba data will help to improve our knowledge of their geochemical cycles and more particularly the mechanisms by which they are (or are not) coupled. (Dehairs and Goeyens, 1989; Stroobants *et al.*, 1991; Dehairs *et al.*, 1995; Jeandel *et al.*, 1996). Finally, a micropaleontological study aims at quantifying the influence of the seasonal cycle on the $^{13}C/^{12}C$ ratio of foraminifera and the productive components of diatoms. This last point should improve the knowledge of the transfer function based on these proxies of paleo-production and their paleo-oceanographic applications.

The KERFIX programme, initiated in January 1990 by A. Poisson (LPCM, Paris), has been driven by C. Jeandel since 1993 and was completed in March 1995. We will give here an idea of the data base structure, currently being worked out.

3. PROGRAMME ORGANIZATION

3..1 SAMPLING SITES

The Southern Ocean, defined as the ocean within the Sub-Tropical Convergence (e.g., South of the Subtropical Front) accounts for more than 20% of the area of the World Ocean. It is characterized by very low surface temperatures and an area of deep-water formation. Thus, the study of its role in the air-sea exchange of CO_2 is of a first order importance. However, because of the rough meteorological conditions affecting this remote area -- mostly in winter! --, undertaking ship-based studies over the entire year is a (difficult) challenge. Laboratory facilities have been developed on the Kerguelen Islands since the beginning of the fifties. More recently (1989), the "Institut Francais pour la Recherche et la Technologie Polaire (IFRTP)" has acquired a coastal oceanographic ship of 25 m length, "La Curieuse", that is based on Kerguelen Island. This motivated the implementation of a scientific programme consisting of a continuous survey of physical, biological and chemical parameters at a selected location, characteristic of the southern part of the Polar Front Zone (PFZ) in the Southern Ocean: KERFIX. The exact location of the sampling station has been selected to satisfy the following constraints: being not disturbed by island effect, presenting enough depth for coming across offshore conditions and a relatively flat bathymetry for a mooring line equipped with sediment traps. On the other hand, the site had to be close enough from the island to reduce the transit time to a maximum of 12 hours, for a boat like "La Curieuse". Thus, the station was established at 50° 40' S - 68° 25' E, 60 miles southwest of the Kerguelen Islands. During 1993, the regular visit of a second site, located only 15 miles off Kerguelen, the Bio-Station (Bio St, Figure 1b), was decided upon to recover active zooplankton to perform grazing and respiration studies.

4. SAMPLING

The number of measurements made at the KERFIX site has progressed in time, as a direct consequence of the improvement in the number and quality of instruments. The parameters acquired as part of KERFIX are compiled in Table 1, together with their acquisition period and the name of the laboratory (and participant) in charge of each parameter. Few "fine process" studies were developed as part of KERFIX, compared to research projects proposed in the framework of other time-series. This is due to the very long distance of Kerguelen Islands from France (which is reached from La Reunion island after a 7-day cruise of R/V "Marion-Dufresne"), and the rough meteorological conditions hampering sampling and measurements.

"La Curieuse" visited the KERFIX site approximate monthly for hydrological (P, T, S, O_2, CO_2, alkalinity and nutrients), biological (phyto-, zoo- and bacterio-plankton), and geochemical sampling (filtered suspended particles). Water samples were collected using 8 l Niskin bottles mounted on a stainless steel cable and equipped with reversing SIS pressure and temperature instruments. Hydrological and bacteriological samples were collected at 24 depths between 0 and 1500 m. For total Suspended Matter (TSM) typical sampling depths were surface; 10; 40; 75; 150; 350 and 500m. Back at the shore-based laboratory, samples were transferred to perspex filtration units and filtered on Nuclepore membranes (0.4 µm porosity) under filtered air pressure. Filters were dried at 50° and stored in petri dishes for later analysis (Dehairs et al., 1995). Chlorophyll-*a* was sampled on the surface cast only. Zooplankton was sampled by vertical hauls (300 - 0 m) using a Bongo net (200 µm mesh). The monthly visits made to the Bio Station (alternately with the KERFIX station) were devoted to the catch of live zooplankton and sampling of natural sea water for biological experiments (Razouls *et al.*, 1995; Razouls *et al.*, submitted).

From April 1993 to March 1995, a mooring was deployed at the same site. This allowed the continuous measurements of the downward flux of particulate material using Technicap sediment trap (PPS5, 1 m^2 section, 24 cups, moored at 200 and 1000 m) and currents from the associated current-meters (Aanderaa RCM7). The time resolution of the particle collection is of one month in winter and 7 to 10 days during the more productive months of spring and summer. Recovery cruises to maintain the moorings occurred annually, with R/V Marion-Dufresne. This ship is large and well equipped with laboratories and a rosette mounted on a Continuous Temperature Depth profiler (CTD) for hydrological sampling. A first mooring line was deployed in April 1993, recovered and re-deployed in February 1994. A second mooring line was recovered in March 1995.

5. ANALYSIS

5.1 KERGUELEN

An important part of the measurements was made by two 'Volontaires Aide Technique' - technical assistants carrying out their military service - at Kerguelen, using the "BIOlogie MARine" (BIOMAR) laboratory facilities. These measurements are identified as "Kerguelen" in Table 1. Temperature and pressure were acquired on-board by SIS sensors. Salinity was determined using an Autosal Guideline salinometer. Dissolved Inorganic Carbon and alkalinity were measured using a Dickson titration (Poisson *et al.*,, 1987). Dissolved oxygen was measured by a Winkler titration (following Carpenter, 1965). Silica, phosphate and ammonium were determined manually, on a Kontron spectrophotometer. As most of the problems affecting the data acquisition were due to the rough sampling conditions, we will explain in the next section how the data were validated.

5.2 KERGUELEN/ METROPOLITAN

Other samples were pretreated in Kerguelen, and then analyzed in France, Monaco or Belgium. Chlorophyll *a* (chl*a*) and phaeopigments were extracted with 90% acetone and their concentrations measured using a spectrofluorometer (Perkin Elmer MPF 66; Neveux and Panouse, 1987).

Concerning the zooplankton, one tow was preserved (5% formaldehyde) for identification and animal counting. Another one was used for dry biomass and further carbon and nitrogen analysis with a Perkin Elmer Analyzer 2400 (Lovegrove, 1961). Live plankton were brought to the laboratory and copepods were picked up within a few hours after capture. Biological process experiments were performed under *in situ* conditions (natural sea water collected simultaneously with zooplankton and maintained at constant temperature). Grazing rates were estimated by the incubation method (Frost, 1972) and the chlorophyll-*a* was analyzed using a Turner Design fluorometer (Strickland and Parsons, 1968). The chlorophyll-*a* results obtained with the Turner (at Kerguelen) and the Perkin Elmer (at Banyuls) apparatus are consistent. Oxygen consumption rates were measured using the Clark type electrode (Strathkelvin oxymeter, Razouls *et al.*, 1995; Razouls *et al.*, submitted) Total bacteria were determined by acridine orange direct count (AODC) following the method of Hobbie *et al.* (1977). Particle related and free living bacteria were counted separately. Biovolumes were estimated using an ocular micrometer. Frequency of dividing cells (FDC) was assessed using the method of Hagstršm *et al.* (1979). The incubations ($^{15}NO_3$, $^{1}5NH_4$, $^{3}0Si$) were made *in situ* and the samples were filtered, stored and analyzed later.

5.3 METROPOLITAN

Other samples were simply stored for further analysis. This is the case for nitrates, for which samples were frozen and analyzed at the Universit de Bretagne Occidentale using a Technicon Auto-Analyzer II. This concerned also the dissolved d^{13}C on Dissolved Inorganic Carbon (DIC) and the trapped and filtered samples (Table 1).

The mass and carbon fluxes of the sediment trap samples were determined on a desalted and freeze-dried aliquot after removal of swimmers and sub-sampling. Total carbon and nitrogen were measured using a CHN analyzer (HERAEUS); inorganic carbon was measured using a UIC coulometer and the total organic carbon computed from the difference between total and inorganic carbon. Zooplankton fecal pellets were enumerated in a liquid sub-sample and categorized according to their geometric shapes (Miquel *et al.*, 1995).

For the total analysis of Ba, Sr, Ca and Al, the trapped sample aliquot (or the Nuclepore membrane for TSM) was digested in Teflon bombs using Suprapur grade HNO_3/HCl. After digestion, volumes were made up to 10 ml (for TSM filters) or 50 ml (for sediment trap samples). Element concentrations were determined using a Jobin-Yvon JY-48 simultaneous (Ca, Sr, Al) and JY-38 sequential (Ba) ICP Optical Emission Spectrometer (Dehairs *et al.*, 1995).

The analysis of d^{13}C on trapped material was performed on about 3 mg of dried material. A few drops of 1 N HCl were added while the sample cup was heated to 80¡C, to eliminate carbonates. This was repeated till no more effervescence was detected visually. Samples were combusted in a Carlo Erba NA 1500 CN analyzer and CO_2 gas was cryogenically trapped in an automatic trapping-box, on-line between CN-analyzer and mass spectrometer. Then, conditioned CO_2 gas was injected into the mass spectrometer (Finnigan-Mat Delta-E). A reference material (USG 24, graphite) was run at the beginning and end of each series of daily analyses. d^{13}C results are expressed relative to the PDB standard. For d^{1}5N analysis, about 15 mg of dried sediment trap material were weighed in a tin cup and combusted in the Carlo Erba NA 1500 CN analyzer. N_2 gas were trapped cryogenically subsequently to cryogenic trapping of water vapor and CO_2. N_2 traps were fitted manually to the mass spectrometer. IAEA N-1 and N-2 reference materials (ammonium sulphate) were run during each series of samples. Results are expressed relative to the composition of atmospheric N_2 (Dehairs *et al.*, 1995).

For electron microscopy, a small piece of Nuclepore filter was cut out and prepared for SEM-EMP analysis. Samples were analyzed half-automatically at 200X magnification. Particle selection was achieved based on their brightness and Ba plus S occurrence. Particles recognized as barites were sized. The obtained projected particle surface was considered similar to the projected surface of a sphere. A particle volume and Ba mass were calculated taking a value of 4.5 for barite density. Final results are expressed in pmol Ba (as barite) per liter (Dehairs *et al.*, 1995).

6. II- RESULTS

6.1 II-1 DATA PRECISION AND VALIDITY

Precision. The logistical constraints of the Kerfix samples collection implied that raw data acquired on Kerguelen Island required a great deal of processing and validation before publication. This work was realized by Diana Ruiz Pino and her team (LPCM). The precision of the parameter acquisitions was controlled regularly by the measurement of triplicates, i.e. the analysis of three aliquots of the same sampling bottle. For each parameter, monthly average values for the mixed layer were also established. The standard deviation of this average (obtained on 8 to 12 data) allowed another estimation of the measurement precision, assuming that concentrations are homogeneous in the mixed layer. In addition, several surface casts have been duplicated, in order to i) check that the water sampled remained stable during the time of sampling (6 hours) and ii) provide an internal comparison of our results. We estimate that the resulting uncertainties on the potential temperature, salinity, oxygen, alkalinity, total inorganic carbon, silica, nitrate and phosphate are ±0.005¡C, ±0.006, ± 3 µmol kg^{-1}, ±0.003 meq kg^{-1}, ± 0.5%, ± 5%, ± 2% and ± 3 to 5 % (of the measured value), respectively. The larger uncertainties on silicate and phosphate data results from the manual technique and the success of this measurement is closely dependent on the analyst's skills; they were different every year.

Validity. In order to assess our data, we compared them to i) historical data acquired in the same area with the "Marion-Dufresne" in the framework of preceding programmes (ANTIPROD (Fr) and INDIGO (Fr)) and ii) simultaneous data acquired with "La Curieuse" and the "Marion-Dufresne" when concomitant sampling was possible (e.g., in January and March 1993 during the CIVA 1 cruise (WOCE) and in February and March 1994 during the ANTARES 2 cruise (F-JGOFS). We also compare our data to the historical GEOSECS 429 station (47°46 'S, 58° 02' E), though this station is located at about 280 nautical miles north-west of KERFIX station. These comparisons show that the processed KERFIX data are similar to those obtained with the "Marion-Dufresne" with calibrated CTD and, for the nutrients, with data acquired on Technicon Auto analyzer II following the WOCE and JGOFS recommendations (Gordon *et al.*, 1994). They are also close to the GEOSECS results, though the two sites do not sample exactly the same water-masses.

7. II-2 FIRST RESULTS

Some of the preliminary results and temporal sections as those of potential temperature, Si, chlorophyll-*a* are presented in Jeandel *et al.* (in press). The works presented during the OOPC workshop are on the verge to be published as part of a special volume of Journal of Marine Systems by Park *et al.* (in press), Pondaven *et al.* (in press) whereas some of them will be written this year Louanchi and Ruiz-Pino (1997). We suggest to the reader to refer to the people in charge of a given experiment to get more information on the first scientific results of KERFIX.

The Kerfix Data Bank will be available as part of the French-JGOFS data base (hydrological and biogeochemical data) on the web by the end of the year 1997. Data can be otherwise obtained upon request to D. Ruiz-Pino, or C. Jeandel (sediment trap and biological parameters).

8. ACKNOWLEDGMENTS

This work would not have been possible without the courageous contribution of eight 20-year old volunteers who accomplished a monastic year in the "far South", performing sample collection and most of the analysis for the KERFIX programme. For this we thank Patrick Heguesippe (1990), Alexandre l'Huiller (1991), Pascal Guyot and C dric Lemarchand (1992), Guillaume Du R au and St phane M nard (1993) and J r™me Maison and David Maguet (1994). We also thank G rard Marellec, Denis Rochard and Pascal Robidou, all three captains of "La Curieuse" as well as their crews for their active participation to the sampling task. Thanks, as well, to captains Jean Huet and Yannick Choimet, Chief Mates Louis Lamy-Jallabert and Laurent Mathieu and all the crew of the "Marion-Dufresne" who maneuvered the mooring and recovery of the instrumental line: recovering means a "dinghy tour in the Yelling Fifties", which is all except a pleasure cruise! The technical assistance of Yvon Balut and Bernard Ollivier (IFRTP) and their teams, was also very precious along the programme duration. We thank Annick Masson (UBO, Brest) for performing the nitrate measurements.

The KERFIX programme was supported by the Scientific Mission of the "Terres Australes and Antarctiques Francaises" (1990-1992) and then by the "Institut Fran ais pour la Recherche et la Technologie Polaire" (1992-1995) and simultaneously by the Centre National de la Recherche Scientifique (INSU/France-JGOFS; 1991-1995). The IAEA Marine Environment Laboratory operates under an agreement between the International Atomic Energy Agency and the Government of the Principality of Monaco.

9. REFERENCES

Carpenter, J.H., 1965. The Cheseapeake Bay Institute technique for the Winkler dissolved oxygen method. Limnol. Oceanogr., 10: 141-143.

Clarke, A. and Leakey, R.J.G., in press. The seasonal cycle of phytoplankton, macronutrients and the microbial community in a nearshore Antarctic marine ecosystem. Limnology and Oceanography.

Dehairs, F. and Goeyens, L., 1989. The biogeochemistry of barium in the Southern Ocean. In: Belgian Scientific Research Program on Antarctica. Scientific Results of phase one (Oct 85-Jan 89). Science Policy Office. Prime Minister Services, Bruxelles, 2: 1-100.

Dehairs, F., Jeandel, C., Miquel, J-C, Shopova, D., M nard, S and Maguet, D., 1995. Seasonal evolution of export production and mesopelagic organic matter mineralization at station KERFIX in the Southern Ocean. *Carbon Fluxes and Dynamic Processes in the Southern Ocean: Present and Past.* Brest (Fr), 28-31 August 1995.

Delille, D., Du R au, G., Guillot, P. and Cahet, G., 1995. Seasonal and depth-related changes in the distribution of bacterioplankton in the Indian sector of the Southern Ocean. *Carbon Fluxes and Dynamic Processes in the Southern Ocean: Present and Past.* Brest (Fr), 28-31 August 1995.

Fiala, M., Oriol, L., Vetion,G., Guillot, P and Maison, J, 1995. Seasonal changes in the size fractionated phytoplankton biomass off Kerguelen Islands. *Carbon Fluxes and Dynamic Processes in the Southern Ocean: Present and Past.* Brest (Fr), 28-31 August 1995.

Frost, B. W., 1972. Effects of size and concentration of food particles on the feeding behavior of the marine planktonic copepod *Calanus pacificus*. Limnol. Oceanogr. 17: 805 - 815.

Hagstrŝm, A., Larsson, V., Horsted, P., Normark, S., 1979. Frequency of dividing cells, a new approach to the determination of bacterial growth rates in aquatic environments. Appl. Environ. Microbiol. 37:805-812

Hobbie, J.E., Daley, R.J., Jasper, S., 1977. Use of nuclepore filters for counting bacteria by fluorescence microscopy. Appl. Environ. Microbiol. 33:1225-1228

Jeandel, C.,Dupr , B., Lebaron,G., Monnin, C. and Minster, J-F, 1995. Longitudinal distribution of dissolved Ba, Si and alkalinity in the western and southern Indian Ocean. Deep-Sea Res., 43: 1-31

Jeandel C., Ruiz Pino D., Gjata E., Poisson A., Brunet C., Charriaud E., Dehairs F., Delille D., Fiala M., Fravalo C., Miquel J-C., Park Y-H., Qu guiner B., Razouls S., Shauer, B. and Tr guer P. KERFIX, a time series station in the Southern Ocean, a presentation. In press at Journal of Marine Systems.

Louanchi F., Ruiz Pino D. and Poisson P. The Southern ocean CO2 sink is increasing. Evidences at Kerfix time-series station International JGOFS Modelling Symposium , 20-26 May 1997, Oban (GB)

Lovegrove, T., 1962. The effect of various factors on dry weight values. Rapp. P.- v. R un. Cons. perm. int. Explo. Mer, 153: 86 - 91.

Miquel, J.-C., Jeandel, C., Thomas S. and Carroll, M.,1995. Particulate carbon fluxes in the open Southern Ocean (Indian Ocean Sector): contribution of zooplankton faeces. *Carbon Fluxes and Dynamic Processes in the Southern Ocean: Present and Past.* Brest (Fr), 28-31 August 1995.

Neveux, J.and Panouse, M., 1987. Spectrofluorometric determination of chlorophylls and pheophytins. Arch. Hydrobiol 109: 567-561

Park, Y., Charriaud E. and Jeandel,C., 1995. Westward counter-currents at the Polar Front on the continental slope southwest of Kerguelen. *Carbon Fluxes and Dynamic Processes in the Southern Ocean: Present and Past.* Brest (Fr), 28-31 August 1995.

Park, Y., Charriaud, E., Ruiz-Pino, D. and Jeandel, C., submitted. Seasonal and interannual variability of the mixed-layer properties and steric height at station KERFIX, southwest off Kerguelen. J. Mar. Syst., in press.

Poisson, A., Schauer, B. and Brunet, C., 1987. Les rapports de Campagnes ˆ la Mer. MD53/INDIGO 3. A bord du "MARION-DUFRESNE". Fascicule 2. 3/01-27/02/87.

Pondaven P., Fravalo C., Ruiz Pino D., Tr guer P., Qu guiner B. and C. Jeandel. Modelling the silica pump of the Permanently Open Ocean Zone of the Southern Ocean. In press at Journal of Marine System.

Razouls, S., Du R au, G., Guillot, P. and Maison, J., 1995. Utilization of phytoplankton by copepods: a seasonal survey off Kerguelen Islands. *Carbon Fluxes and Dynamic Processes in the Southern Ocean: Present and Past.* Brest (Fr), 28-31 August 1995.

Razouls, S., Du R au, G., Guillot, P., Maison, J. andJeandel, C., submitted. Utilization of Phytoplankton by copepods: a seasonal survey off KERGUELEN Island at KERFIX station. J. Mar. Syst., submitted.

Sarmiento, J.L., 1995. Modeling the oceanic uptake of anthropogenic carbon. U.S. JGOFS News, 6: 4-6.

Smith, R.C., Baker, K.S., Byers, M.L. and Stammerjohn, S.E., 1995. Primary productivity of the Southern Ocean and the Palmer Long Term Ecological Research Area. Brest (Fr), 110.

Strickland, J D. H. and Parsons, T. R., 1968. A practical handbook of seawater analysis. Bull. Fish. Res. Bd. Can., 167: 1 - 310.

Stroobants, N., Dehairs F., Goeyens L., Vanderheijden N. and Van Grieken, R., 1991. Barite formation in the Southern Ocean Water column. Mar. Chem., 35: 411-421.

Table 1: Parameters analyzed as part as KERFIX program. For each of them the duration of the acquisition, the places where they are analyzed and the laboratory in charge of the given parameter are recalled (the full addresses corresponding to the logos are in the title page).

Parameter	Collection duration	Analytical Place	Laboratory
T, S, P, O_2, CO_2, Alk	1990-1993	Kerguelen	LPCM (D. Ruiz-Pino: ruiz@oceanar.mil.ar)
T, S, P, O_2	1994/95	Kerguelen	UMR 5566 (C.Jeandel:jeandel@pontos.cst.cnes.fr)
NO_3	1992-95	Metrop.	UBO (P. Tréguer:treguer@univ-brest.fr)
Si, P, NH_4	1992-95	Kerguelen	UBO/UMR5566
Chl-a	1992-95	Ker/Metrop.	Arago (M. Fiala:mfiala@arago.univ-perp.fr)
Bacterial	1992-95	Ker/Metrop.	Arago (D. Delille: delille@arago.univ-perp.fr)
Zoo. (biomass)	1992-95	Ker/Metrop.	Arago (S. Razouls: srazouls@arago.univ-perp.fr)
Zoo(grazing)	1993-95	Ker/Metrop.	Arago (S. Razouls)
Incubation N	1992-95	Ker/Metrop.	ANCH (L. Goeyens: lgoeyens@vnet3.vub.ac.be)
Incubation Si	1992-95	Ker/Metrop.	UBO (A.Leynaert:leynaert@cassis-gw.univ-brest.fr
Bio and litho Si	1992-95	Ker/Metrop.	UBO (A. Leynaert)
Filtered particles	1992-95	Ker/Metrop.	ANCH (F. Dehairs: fdehairs@vnet3.vub.ac.be)
$\delta^{13}C$	1992-1993	Metrop.	CFR (Laurent.Labeyrie@cfr.cnrs-gif.fr)
Currentmeters	1993-1995	Metrop.	LOP (Y. Park: lg@mnhn.fr)
Mass Flux	1993-95	Metrop.	*UMR5566 /IAEA-MEL (JC Miquel: miquel@NAXOS.UNICE.FR*
SEM			*ANCH (Dehairs)*
Pigments			*Arago (Fiala)*
Fecal pellets			*IAEA-MEL (Miquel)*
Micropaleontology			*CRESO /CFR (JJ Pichon: pichon@geocean.u-bordeaux.fr)*
Radioinuclides			*CFR (S. Schmidt: Schmidt@cfr.cnrs-gif.fr)*
CIP, COP, NP			*IAEA-MEL (Miquel)*
Si, Sibiogenic			*UBO (A. Leynaert)*
Al, Ca, Sr, Ba, $\delta^{13}C$ *et* $\delta^{15}N$			*ANCH (F. Dehairs)*
Trace elements, Nd			*UMR 5566 (C. Jeandel)*

ANNEX IX

Report on the Line-P and Station-P Time Series

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The weather Station Papa (50ºN 145ºW) was first occupied in 1949 by the US Weather Bureau, and with vessels manned by the U.S. Coast Guard. In December 1950 occupation by Canadian Weather ships began. In 1952 a primitive oceanographic program was initiated at the site with twice-daily bathythermograph casts, these casts continued until June 1981. In July 1956 a full oceanographic program began with regular bottle casts, plankton hauls. Most casts were to a depth of 1200 metres, but we record one cast to 3000 metres in 1957. Gradually stations were added along the ship track between the mouth of the Strait of Juan de Fuca and Stations P until by August 1964 sampling was occurring at Station P itself and at 12 stations along the ship track. The sampling by Weather Ships was on a rotating tour of duty of 6 weeks duration. Two vessels were used with one outbound while the other was heading home.

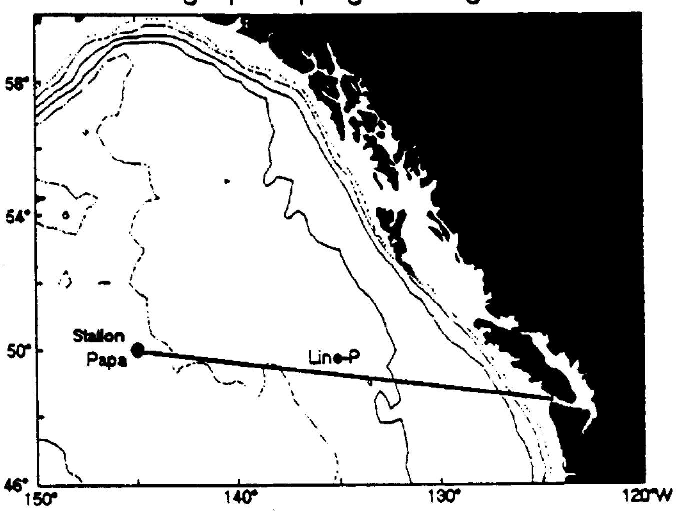

Figure 1: Map of the NE Pacific showing the locations of Station P and Line-P

In June 1981 the weather ship program was terminated, but the sampling along Line-P and at Station-P was maintained by the use of research vessels from the Institute of Ocean Sciences. At the same time the number of stations was doubled from 13 to 26. In many of the old records Station P is referred to as P13 (station 13 along Line-P) and in later records is referred to as P26. Line-P itself also has several designations, it is also the WOCE repeat hydrography line PR6. Under IOS management that sampling along line P varies from one year to the next but is typically sampled 3 or 4 times per year, and this is expected to continue for at least the next 5 years.

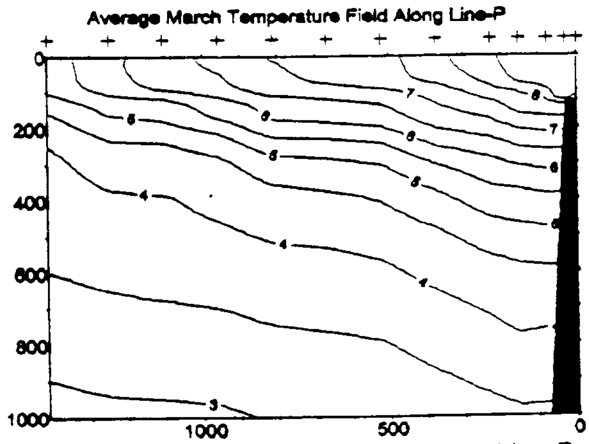

Figure 2: Mean March temperature along Line-P

One of the assets that arises from a "repeat hydrography" time series is the clear and unambiguous definition of a mean state, for example, in Figure 2 we see the mean temperature field over the top 1000 metres of the water column for March, averaged over all data from 1956 to the present. The mean state is in itself not interesting, rather it allows the accurate computation of an anomaly field, as shown in Figure 3. This particular example is exciting in that it shows the thermal response at a high northern latitude to the effects of the 1982/83 El Nino. This picture shows the surprising depth of penetration of the thermal response to the El Nino signal. It is unfortunate that Topex/Poseidon data were not available in 1983. The next time that a large El Nino signal occurs we will be able to monitor the thermal and salinity response, and monitor the changes in the surface pressure field. Thus we will determine the absolute velocity field associated with this anomaly.

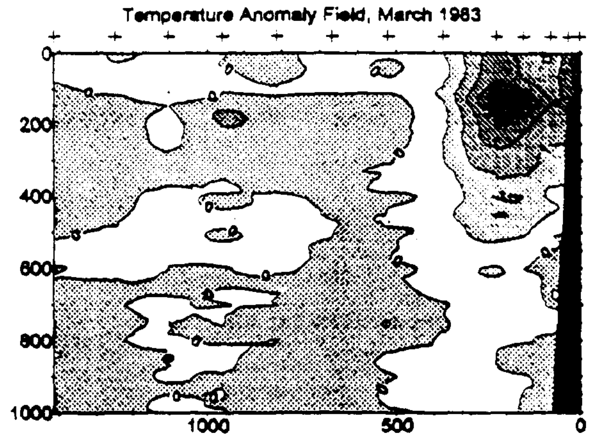

Figure 3: The temperature anomaly field for March 1983.

Along Line-P the experience with long time series is now paying dividends as it allows us to watch as the ocean evolves in quite unexpected ways. It has recently become apparent that the mid-winter mixed layer is substantially shallower than it was 40 years ago. Figure 4 shows a plot of average mid-winter (January-March) mixed layer depths listed by years. The shallowing trend is obvious and amounts to a rate of 60 metres/century from the regression line, shown on Figure 4. At the same time we are witnessing a general freshening, and warming of the surface layers of the NE Pacific. These combine to reduce the density of the upper ocean and so enhance the density contrast across the base of the mixed layer. The lower panel of figure 4 shows a variable proportional to the available potential energy. It is almost level, with no significant trend. Thus there appears to have been no significant change to the energetics of the mixed layer, and the shallowing trend appears to be in direct response to the reduced density.

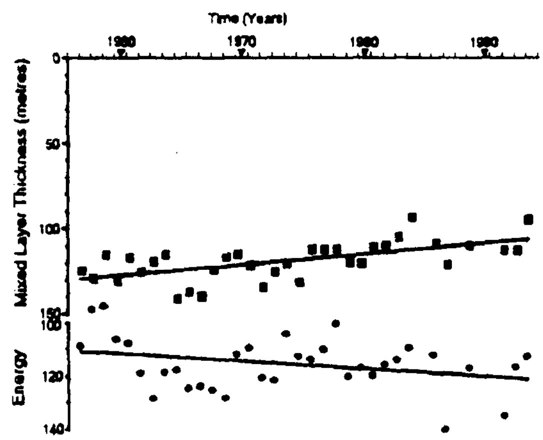

Figure 4: Mixed layer characteristics at Station Papa, 1956 to present.

The importance of this shallowing is in the effect it has on the nutrient balance of the upper ocean. We do see a decline at Station Papa to lower concentrations of dissolved nutrients, but ambient levels of dissolved nitrate are much lower between Station P and the coast. The result is as shown in Figures 5a, and 5b. During the early 1990s winter nutrient concentrations along much of the surface layers of Line-P declined to levels of 5 to 6 Tmol/kg, this is the amount that is typically consumed by spring/summer primary productivity. Thus there is the risk of reducing the dissolved nutrient levels to zero during the summer.

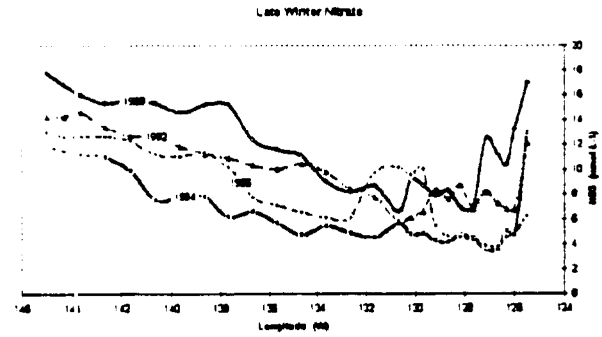

Figure 5a: Dissolved nitrate in the surface layers along Line-P for several winters during the 1990s.

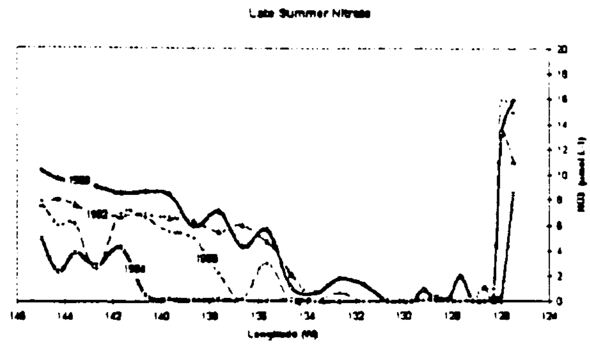

Figure 5b: Dissolved nitrate in the surface layers along Line-P for several springs during the 1990s.

As can be seen in the figure 5b, this did actually occur along large sections of Line-P during the 90s. This had not been previously observed and suggests that physical changes are occurring in the NE Pacific that can and do have repercussions on the chemical and biological environment.

ANNEX X

METEOROLOGICAL TIME SERIES MEASUREMENTS

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1. DEFINITION

For the purposes of this discussion, meteorological time series measurements will be taken to be measurements of meteorological variables obtained from a fixed ocean or coastal location extending over a number of years. Normally they will be obtained as part of an operational observing system but research programme measurements are not excluded if they meet the required criteria. Certain ocean surface variables, in particular sea surface temperature and sea state information, are also often included as part of the meteorological data.

2. PLATFORMS

Typical observation platforms used for time series measurements include:
Coastal platforms: For example lighthouses, lightships, buoys, oil and gas rigs, etc.
Ocean Stations: Ocean Weather Ships, moored buoys, small islands (e.g., atolls).

This note will mainly concentrate on the ocean stations. Ships of opportunity (for example Voluntary Observing Ships of the World Weather Watch system) will be excluded from the discussion since they do not normally provide time series from a fixed location. However it should be noted that such ships form an invaluable component of the meteorological observing system and that time series observations may be available from certain locations where a ship regularly plies a given route.

3. THE FUNCTION OF TIME SERIES MEASUREMENTS

Time series measurements generally fulfil one or more of the following functions:

(i) They provide data from a key location to aid weather forecasting for nearby land areas (e.g. coastal stations). This role includes information for disaster prevention (flood forecasting etc.).

(ii) They provide a long time series for climate research and forecasting. (Perhaps the best example of time series measurements providing unexpected returns was the detection of the ozone "hole" over Antarctica using routine time series measurements by the British Antarctic Survey.)

(iii) They provide data from meteorologically important but otherwise inadequately observed regions, for example the TOGA TAO array.

(iv) They provide data for variables that are not normally available from other observation systems such as merchant ships or satellites. Examples are sea state, surface radiation budget, and upper air measurements from weather ships (although the latter have more recently been implemented on some merchant ships).

(v) They provide calibration or verification data for other observing systems; for example for assessing merchant ship data, calibrating satellite derived data, or for comparison with numerical model predictions.

4. DISCUSSION

4.1 OCEAN WEATHER SHIPS

Perhaps the best known and most ambitious marine meteorological time series measurement system was the array of Ocean Weather Ships. Originally subsidised by the commercial aviation sector, the weather ship system is now considered prohibitively expensive and only one or two sites are still maintained. Apart from surface and upper air meteorological measurements, the weather ships provided, during various periods, time series of surface radiation budget, surface waves, ocean profiles, and other variables. Valuable climate data were obtained, for example the long time series of data from ocean station Papa. However the weather ships were implemented for weather forecasting rather than for climate observations and this has implications with regard to the accuracy of the data. For example, deriving a long time series of consistent weather ship wind observations is not a trivial task given the many changes in ship type and observing practice (Isemer, 1994). It is also clear that a ship is not the ideal instrument platform for many meteorological measurements (Taylor *et al.*, 1995).

4.2 MOORED OCEAN BUOYS

The technology now exists both to moor meteorological buoys in the deep ocean and to reliably obtain the measured data via satellite links. Examples of established moored buoy arrays are the NDBC (Gilhousen et al.; 1990) and AES (Axys, 1996) buoys off North America, the TOGA TAO array in the equatorial Pacific (next talk), and the ODBS buoys off Japan. Taking as an example the NDBS buoys, these range in type from the very large 12m and 10m discus designs, through the 6m Nomad buoy to the 3m Discus buoy. Over 20 buoy locations have been maintained in both the Atlantic and Pacific with most time series dating from the mid 1970's or early 1980's to the present. In addition to standard surface meteorological data, spectral wave data and current profiles (using ADCP) sensors are available from some locations.

Since the inception of operational satellite systems, ocean buoys have taken on a vital new role. The operational near global coverage obtained from satellite systems relies on a small number of satellite mounted sensors remaining within calibration over periods of several years. There is also the need to ensure continuity of calibration when one operation satellite is succeeded by the next; possibly because the former has failed. Unlike in situ systems the sensors can not be brought back to the laboratory for post deployment calibration; instead comparison with buoy data is normally used. Types of satellite data for which the calibration has been derived or validated using buoy data include sea surface temperature (Reynolds & Marisco; 1993), altimeter wind speeds and wave heights (Cotton and Carter, 1994; Ebuchi and Kawamura, 1994; Gower, 1996) and scatterometer data (Quilfen and Bentamy, 1994; Graber et al., 1996). Taking the latter as an example, whereas Voluntary Observing Ship data have significantly greater random errors compared with data from a scatterometer (Kent et al. 1997), the comparisons shown by (Geshelin and Dobson, 1997) suggest that operational buoy data are similar to or of greater accuracy than the scatterometer data.

In addition to the calibration of satellite sensors, buoy data may be used for comparison with data estimated using numerical models or to verify climatologies. For example the new surface flux climatology that is being developed at the Southampton Oceanographic Centre has been compared against buoy data obtained by WHOI during the subduction experiment.

5. SUMMARY

The development of satellite remote sensing systems has increased rather than decreased the value of time-series observations from meteorological buoys. There will be a continuing need for such buoy systems for the foreseeable future. With the exception of the TOGA TAO array the present buoys are predominantly in near coastal areas. Increased numbers of buoys moored in the deep ocean would be of value for satellite calibration, the verification of numerical model derived data, and for verifying climatologies. The Southern Ocean is a major data sparse region which could be sampled by moored buoys. However drifting, disposable buoys may well be a better choice for such a remote area.

6. REFERENCES

Axys, 1996: Meteorological and Oceanographic Measurements from Canadian Weather Buoys. (draft), Axys Environmental Consulting Ltd., Sidney, B.C., Canada, 35 pp. + Apps.

Cotton, P. D. and D. J. T. Carter, 1994: Cross calibration of TOPEX, ERS-1 and Geosat wave heights. J. Geophys. Res., 99(C12), 25025 - 25033.

Ebuchi, N. and H. Kawamura, 1994: Validation of wind speeds and significant wave heights observed by the TOPEX altimeter around Japan. J. of Oceanography, 50(479 - 487).

Geshelin, Y. S. and F. W. Dobson, 1997: Comparative analysis of wind data sets from ERS-1 and NDBC buoys. Fourth International Conf. on Remote Sensing for Marine and Coastal Environments, Orlando, Florida, 17-19 March, 1997.

Gilhousen, D.B., Meindl, E.A., Changery, M.J., Franks, P.L., Burgin, M.G., and Mckittrick, D.A. 1990: Climatic summaries for NDBC buoys and stations. Update 1. NSTL, MS: NOAA National Weather Service, National Data Buoy Center. 454 pp.

Gower, J. F. R., 1996: Intercalibration of wave and wind data from TOPEX/POSEIDON and moored buoys off the west coast of Canada. J. Geophys. Res., 101(C2), 3817 - 3829.

Graber, H. C., N. Ebuchi and R. Vakkayil, 1996: Evaluation of ERS-1 Scatterometer Winds with Wind and Wave Ocean Buoy Observations. Jet Propulsion Laboratory, National Aeronautics and Space Administration, National Space Development Agency of Japan., 78 pp.

Isemer, H.-J., 1994: On the homogeneity of Surface Wind Speed records from Ocean Weather Stations. , Institut fuer Meereskunde, Kiel, Germany, pp. 43 + figs.

Kent, E. C., P. K. Taylor and P. Challenor, 1997: A Comparison of Ship and Scatterometer-Derived Wind Speed Data in Open ocean and coastal areas. Int.J.Remote Sensing, (submitted).

Reynolds, R.W. and Marisco, D.C.; 1993: An improved real-time global sea surface temperature analysis. Journal of Climate, 6(1), 114-119

Quilfen, Y. and A. Bentamy, 1994: Calibration/Validation of ERS-1 Scatterometer Precision Products. Proceedings of Igarss, Pasadena, USA, 945 - 947.

Taylor, P. K., E. C. Kent, M. J. Yelland and B. I. Moat, 1995: The Accuracy of Wind Observations from Ships. COADS Winds Workshop, Kiel, Germany, 31 May - 2 June, 1994, Environmental Research Labs., National Oceanic and Atmospheric Administration, Boulder, Colorado, 132 - 155.

ANNEX XI

THE TAO ARRAY: HISTORY, PRESENT, PROSPECTS

Prepared by D.E.Harrison for

The TAO array is a central element of the ENSO Observing System developed by the EPOCS and TOGA programs for study and prediction of the seasonal cycle and interannual variability associated with the El Nino-Southern Oscillation phenomenon. Information concerning the TAO project and ENSO is available on the Internet:
(http://www.pmel.noaa.gov/toga-tao/el-nino/home.html).

Surface drifting buoys, sections of XBT observations from volunteer ships, sea level gauges and supplemental SST information from satellites comprise the balance of this observing system. The TAO array consists of approximately 70 moorings distributed across the equatorial Pacific, within 9 degrees North and 9 degrees South latitude (see Kessler et al, 1996, figure 1). McPhaden has been PI of the project since 1992, and Milburn has been the lead engineer from the earliest days of the Atlas moorings and equatorial current meter moorings. The latter were developed under the scientific leadership of S.P. Hayes and of D.Halpern, respectively.

The ENSO observing system was developed because existing in situ observations during the mid-1980s were not adequate to define fully the seasonal to interannual variability in the tropical Pacific, much less to provide accurate initial condition fields for forecasting ENSO events. Special efforts had been made by, e.g., Ramage and Wyrtki, to get as many of the surface marine observations as possible, to construct surface wind and SST fields for particular periods of interest. But these were not adequate to define the time rate of change of SST or heat content quantitatively, or to produce surface wind fields accurate enough to justify quantitative analysis of ocean model hindcasts.

The observing system was developed on the basis of several assumptions. Based on the success of ocean hindcasts using a primitive equation model, e.g., Philander and Seigel (1985), it was assumed that this model was good enough to define the area over which accurate winds were needed in order to permit useful hindcasts of behaviour within the equatorial waveguide to be made. It was also assumed that the space and time scales of surface wind variability that had been inferred from tropical island wind observations would permit design of the sampling requirements. The ocean model indicated that wind information was needed between 7N and 7S and all across the basin, if hindcasts of SST accurate to 0.5C in monthly means were to be obtained. The island wind data indicated that a marginally spatially coherent array, relative to the energetic scales of wind variability, needed zonal separation of about 15 degrees and meridional separation of 2 to 3 degrees. Together these led to the TAO array, with about 70 moorings spanning the basin.

Next came the decisions about the instrumentation of each mooring. Because equatorial currents are known to play a major role in SST and thermocline depth changes, the equatorial moorings were instrumented to observe currents as well as temperatures. Because of the cost of current measurements, the off-equatorial moorings would only measure subsurface temperature. All moorings would measure surface meteorology and air-sea interaction parameters, to the extent permitted by the budget and available technology. The instrumentation of the moorings would evolve as technology permitted and as our knowledge of the modes of variability increased.

The deployment and maintenance of such an array requires a considerable effort. A team of engineers and technical support staff build and/or test the instruments and mooring systems, monitor the data quality, and deploy and recover moorings. Ship support requirements are also considerable; the TAO array has received assistance from a number of nations. The TAO home page (http://www.pmel.noaa.gov/toga-tao/) provides a wealth of information about this project, as well as access to near-real-time data from the array. The first time full deployment of the array was accomplished was late in 1994.

The next steps in the progress of the TAO array are several. The basic assumptions underlying the design of the array need to be re-examined, using data from the array itself - are the assumed coherence scales appropriate? The actual statistics of the oceanic and surface atmospheric variables of interest need to be evaluated, both as a basis for validating atmospheric operational analyses, and to help evaluate the effectiveness of the ENSO observing system as a whole. Next the impact of TAO data on the quality of operational meteorology products needs to be determined, and the operational centers may have to alter their analysis procedures or models in order to obtain maximum benefit from the TAO data. Operational and research ENSO forecast efforts need to work with the data in order to learn how to obtain maximum benefit from the observing system, and to compare the impacts of in situ and satellite data on the forecast systems. Research using the observing system observations needs to be carried out to learn as much as possible about the mechanisms at work in the seasonal cycle and during ENSO periods. Coupled model validation needs to be done, using the data, to enhance the development of our coupled ENSO and seasonal-cycle models.

Operationally, the TAO array is also developing. A next-generation instrument package with a wider range of sensors has been developed. The Japanese have agreed to take over deployment and maintenance of the western Pacific part of the array, using their TRITON mooring system that will send data into the existing real-time data stream. Supplemental moorings are being discussed to support the PACS program in the Pacific and the PIRATA program in the tropical Atlantic. Somewhat further along in time, discussions are beginning about an appropriate system to support enhanced studies of the Austral-Asian monsoon system.

Many research literature publications using the ENSO observing system data have appeared (about 200 at last count), and ENSO mechanism research proceeds apace. The surface and subsurface thermal statistics and scales of variability from the array have been evaluated, and used to estimate the errors in mapping both from the array data and from the VOS XBT data, on different time scales. A similar effort for the surface wind statistics and scales is underway. Assessment of the impact on surface wind operational fields indicates that, in the center of the array there has been gratifying convergence between three operational products, but there remains room for improvement over the rest of the array and particularly in the meridional component of the surface wind. Tropical ocean model data assimilation is being done operationally at NCEP and experimentally by many other researchers. ENSO forecasting efforts proceed at a number of institutions and find the TAO data essential for skillful forecasts; different models exhibit differing levels of sensitivity.

Overall, the ENSO observing system and the TAO array represent an outstanding achievement in purposive sustained ocean and air-sea observations. Because the ENSO phenomenon was moderately well defined, because tropical ocean models possessed some useful hindcast skill, and because surface wind scale information was rudimentarily available from other sources, it was possible to design an observing system to meet the descriptive, mechanistic and forecasting needs of the ENSO community. So far, the observing system appears capable of doing the jobs for which it was designed. NOAA has requested funding to make the ENSO observing system operational, rather than continue to operate it in research/quasi-operational mode. Should this funding be approved, the ENSO observing system will represent a "regional-GOOS", motivated by a clear social and scientific need, with clearly defined products as its output.

ANNEX XII

CAUSES AND CONSEQUENCES OF INTERANNUAL VARIABILITY IN THE LABRADOR SEA

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Abstract

Labrador Sea Water (LSW), an intermediate water mass found throughout the northern North Atlantic Ocean and along the western boundary to the equator, is formed in the central Labrador Sea via deep convection in winter. The temperature and salinity of the LSW have decreased by 0.6°C and 0.06 over the past 35 years due to variations in both the heat loss in winter and the fresh water supplied from run-off and ice-melt in summer. These changes are linked to the North Atlantic Oscillation, a see-saw pattern in the atmosphere, which brings multi-year periods of abnormal winter conditions alternately to the Greenland and Labrador Seas. Recent cold winters in the Labrador Sea between 1987 and 1995 created a colder and denser version of LSW which has been spreading throughout the North Atlantic Ocean during the WOCE observing period. Observations of this new LSW in locations remote from the Labrador Sea have resulted in new estimates of the flow rates at intermediate depths which are 4-5 times higher than previously assessed.

The Labrador Sea

The circulation in the Labrador Sea (Fig. 1) is characterized by strong currents on the boundaries and a weak cyclonic flow in the central region. Over the west Greenland continental shelf and slope is the West Greenland Current, an extension of the East Greenland Current which flows south along the east coast of Greenland. The current transports into the Labrador Sea two main upper layer water masses; the cold-fresh waters of Arctic over the shelf and the relatively warm-saline waters over the slope. The latter is a remnant of the Irminger Current, a northern branch of the North Atlantic Current. The Labrador Current flowing over the Labrador shelf and slope is partly derived from and quite similar to the West Greenland Current. Cold-fresh waters of Arctic origin, Baffin Bay in this case, flow over the shelf while offshore is a remnant of the warm-saline Irminger Water. The North Atlantic Current, a north-eastward flowing branch of the Gulf Stream, forms the southern boundary.

Also indicated on the map in Fig. 1 are the WOCE AR7W CTD line occupied by the Bedford Institute of Oceanography (BIO) in the spring of each year between 1990 and 1996 and the Ocean Weather Ship Bravo which obtained approximately twice weekly oceanographic observations between 1964 and 1973.

The deep water sampling periods in the central Labrador Sea since 1960 are indicated in Fig. 2. The Bravo data extending over all the months of 10 years provides the most complete record while in the other years data are available from various programs from BIO, Woods Hole Oceanographic Institution (TTO in 1981) and the U.S. Coast Guard (1962 and 63).

Labrador Sea Water

The composite salinity section across the Labrador Sea in Fig. 3 illustrates the principal watermasses in the region. Of most interest to the present discussion is the Labrador Sea Water (LSW) ying between 300 and 2200 m in the central region seaward of the continental slopes. This figure along with the vertical profiles from the central region in Fig. 4 demonstrate the vertical and horizongal homogeneity of this water mass which is renewed in the central region via deep convection in winter.

Below the LSW, a salinity maximum defines the North-East Atlantic Deep Water (NEADW) and below this, next to the bottom, is the North-West Atlantic Bottom Water (NWABW) or Denmark Strait Overflow Water (DSOW). The NEADW originates in the eastern basin of the North Atlantic partly from water flowing from the Norwegian Sea over the Iceland-Scotland ridge. It enters the western basin through the Charlie-Gibbs racture Zone in the Mid-Atlantic Ridge and flows cyclonically around the Irminger and Labador Seas. The DSOW overflows the Denmark Strait and enters the Labrador Sea as a deep part of the East and West Greenland Currents. It exhibits lower temperatures (T) and salinities (S) than the NEADW.

Over the continental slopes between 300 and 1700 m, shoreward of the LSW, is a region of higher salinity water. This is the Irminger Sea Water (IW) with its higher T and S flowing counter clockwise around the northern end of the Labrador basin as an extension of the West Greenland Current. The fifth important water mass in the section is the low salinity surface layer.

Interannual Variability

The properties of the LSW are mainly determined by the heat loss in winter which drives the deep convection and the amount of fresh water added to the surface layer after a season's ice-melt and run-off. An illustration of the interannual variability in heat loss in the region is given by the number of icebergs found south of 48 N (Fig. 5) which is a direct function of the average winter air temperature in the area (Marko et al., 1994). The variability, especially since the early 1950s gives the impression of bimodal forcing with multi-year periods of very cold winters alternating with relatively mild ones.

The reason for the alternating cold and warm winters appears to be the North Atlantic Oscillation (NAO) in the atmosphere illustrated in Fig. 6. In the average winter winter (Fig. 6b) a low is established in the neighbourhood of Iceland which causes cold north-west winds from the eastern Canadian Arctic to blow over the Labrador Sea and north-easterly winds to blow over the Greenland Sea lying east of Greenland. In years when this low is much deeper than normal (Fig. 6a) the cold winds over the Labador Sea are more persistent while the winds over the Greenland Sea tend to be more southerly and milder than normal. In the opposite phase of the NAO (Fig. 6c) the Iceland Low lies further south than during normal years while the Siberian High normally confined over eastern Russia extends across the Arctic Ocean into northern Canada. Under this regime relatively mild easterly winds blow across the Labrador Sea and cold Arctic air flows from the Arctic Ocean across the Greenland Sea.

A useful index of this changing pattern is the anomaly of the average winter (December, January and February) atmospheric pressure difference between the Azores and Iceland shown in Fig. 7. This shows the extended period of negative NAO through the late 1950s and 1960s plus the recent periods of positive NAO coincident with the recent cold winters over the Labrador Sea.

One of the important results o the extended period of negative NAO in the 50s and 60s, according to Hakkinen (1993), is that the persistent northerly winds across the Arctic Ocean and the Greenland Sea forced large volumes of drift ice out of the Arctic Ocean into the Greenland Sea. When the ice melted a low salinity anomaly was created which entered the Atlantic Ocean in about 1968. This was described by Dickson et al. (1988) as The Great Salinity Anomaly (GSA). It passed through the Labrador Sea between 1968-1971 and subsequently moved around the sub-Arctic gyre of the North Atlantic and re-entered the European Arctic in 1976-77.

The impact of the GSA in the Labrador Sea is shown in Fig. 8 by the time series of salinity from OWS Bravo. The annual decrease in salinity in the summer reflects the run-off from the land and sea ice-melt while the increase during winter is caused by mixing the low salinity surface layer down to greater depths and incorporating the higher salinity water at those depths into the deepening surface layer. Between 1968 and 1972 the salinity of the upper layers decreased more in the summer than it decreased in winter as the GSA entered the region. It was accompanied by several years of relatively mild winter conditions which limited deep convection to just a few hundred metres (Lazier, 1980).

In the 1970s cold conditions returned to the Labrador Sea along with deeper convection causing the abnormally low salinity surface layer to be incorporated into the LSW. This resulted in a significant change in the potential temperature (q) & S of the core LSW as indicated in Fig. 9. In the 1960s the values are clustered around q & S 3.4 C & 34.9 but drop to 3.1 C & 34.85 in the 70s and 80s. During this transition the density of the water mass stayed relatively constant as the temperature decreased to compensate for the lower salinity.

From the late 80s to the mid 90s the LSW has continued to change but in this case the salinity has stayed relatively constant while the temperature and density have increased. This situation is brought about by the continued cold winters in the area which have driven the convectively mixed layer down to the underlying deep water where a higher vertical density gradient exists. Since the convection is essentially non-penetrative the higher stratification tends to limit the depth of the mixed layer. Increased cooling then tends to increase the density of the layer.

The total change in salinity that has occurred in the Labrador Sea over the past 35 years is illustrated by the 1966 and 1994 profiles in Fig. 10. There is an average decrease over the whole water column of 0.06 which is equivalent to a loss of 200 kg of salt per m or the addition of 6 m of fresh water per m . The decrease is not constant through the water column but varies from 0.03 between 2500-3000 db to 0.09 in the LSW at 2000 db. This variation is due (Lazier, 1995) to the changing balance between vertical and horizontal processes through the water column. Deep convection which dominates in the convectively mixed layer to 2000 m carries with it the large salinity varitions in the surface layer. In the layers below the LSW vertical processes are weak and changes are due to horizontal advection.

LSW Spreading in the 90s

The map in Fig. 11 indicates the paths the LSW takes from the Labrador Sea to some of the other regions of the North Atlantic such as the Newfoundland Basin, the Irminger Sea and the Iceland Basin. During the increased number of CTD surveys during WOCE we have been able to observe the changes in the LSW properties as they have arrived in these remote regions.

An example of the changes observed is shown in the q-S curves, Fig. 12 obtained in the central Irminger Sea by German oceanographers in 1991, 92 & 94. The characteristic LSW signature in these profiles is the salinity minimum which clearly increases in density through these years along with the temperature decrease. These changes reflect the inflow of the progressively denser/colder LSW produced in the Labrador Sea between the late 1980s and mid 1990s.

In Fig. 13 are plotted on a q-S diagram points representing the properties at the LSW core in the Labrador Sea, Irminger Sea, Iceland Basin and the Newfoundland Basin. Both q and S increase with distance away from the Labrador Sea as expected from plots of salinity within the LSW core presented by and Talley and McCartney (1982). It is also clear that the properties at each location are changing over the sampling period toward the colder and denser version of LSW.

The same data is plotted again in Fig. 14 to emphasize the changes of potential density anomaly relative to 1500 db (s = sigma1.5) with time. The longest record shown is from the Labrador Sea and shows s increasing strongly between 1987 and 1993 then staying more or less constant. The other records are shorter but all show density increases with time due to the changing LSW. The difference in density between the Labrador Sea and any of these locations is a function of distance and rate of flow. Assuming the latter is constant the time scales for changes to appear in the Irminger Sea or the Newfoundland Basin are estimated to be 1-2 yr and 2-4 yr for the Iceland Basin. The recent work of Sy et al. (1997) suggests from these and other similar observations that the mean speed of LSW to reach the Rockall Trough is 4-5.5 yr compared to a previous estimate of 18-19 years. Thus the rate of flow in the intermediate water appears to be 4-5 times faster than previously suggested.

Conclusions and Expectations

Time series assembled from sporadic observations over the past 35 years in the central Labador Sea have allowed us to discover large interannual variations in the LSW q-S linked to the NAO a multi-year oscillation in the atmosphere.

Spreading of a recent version of LSW throughout the northern North Atlantic has led to a revised value for intermediate water flow 4-5 times more rapid than previous estimates.

Although funding continues to be under pressure the Ocean Circulation Section at the Bedford Institute of Oceanography hopes to continue to occupy the WOCE AR7W CTD line across the Labrador Sea beyond the WOCE observing period.

References:

Dickson, R.R., J. Meincke, S.-A. Malmberg and A.J. Lee, 1988. The "Great Salinity Anomaly" in the Northern North Atlantic, 1968-82. Progress in Oceanography 20:103-151

Fang, A. and J.M. Wallace, 1994: Arctic Sea Ice Variability on a Time Scale of Weeks and its Relation to Atmospheric Forcing. J. Climate 7:1897-1914.

Hakkinen, S., 1993: An Arctic Source for the Great Salinity Anomaly: A Simulation of the Arctic Ice-Ocean System for 1955-1975. J. Geophys. Res., 98:16397-16410.

Lazier, J.R.N. and D.G. Wright, 1993: Annual Velocity Variations in the Labrador Current. J. Phys. Oceanogr., 23:660-678.

Lazier, J.R.N., 1996: The Labrador Sea after Winter Convection: 1990-1996. J. Phys Oceanogr., (submitted)

Lazier. J.R.N., 1995: The Salinity Decrease in the Labrador Sea over the Past Thirty Years. In Natural Climate Variability on Decade-to Century Time Scales, National Research Council, Washington, D.C., 295-302.

Lazier, J.R.N., 1980: Oceanographic Conditions at Ocean Weather Ship Bravo, 1964-1974. Atmosphere - Ocean 18: 227-238.

Marko, J.R., D.B. Fissel, P. Wadhams, P.M. Kelly and R.D. Brown, 1994: Iceberg Severity of Eastern North America: Its Relationship to Sea Ice Variability and Climate Change. J. Climate 7:1335-1351.

Sy, A., M. Rhein, J.R.N. Lazier, K.P. Koltermann, J. Meincke, A. Putzka and M. Bersch, 1997: Surprisingly Rapid Spreading of Newly Formed Intermediate Waters Across the North Atlantic Ocean. Nature, (in press)

Talley, L.D. and M.S. McCartney, 1982: Distribution and circulation of Labrador Sea Water. J. Phys. Oceanogr., 12, 1189-1205.

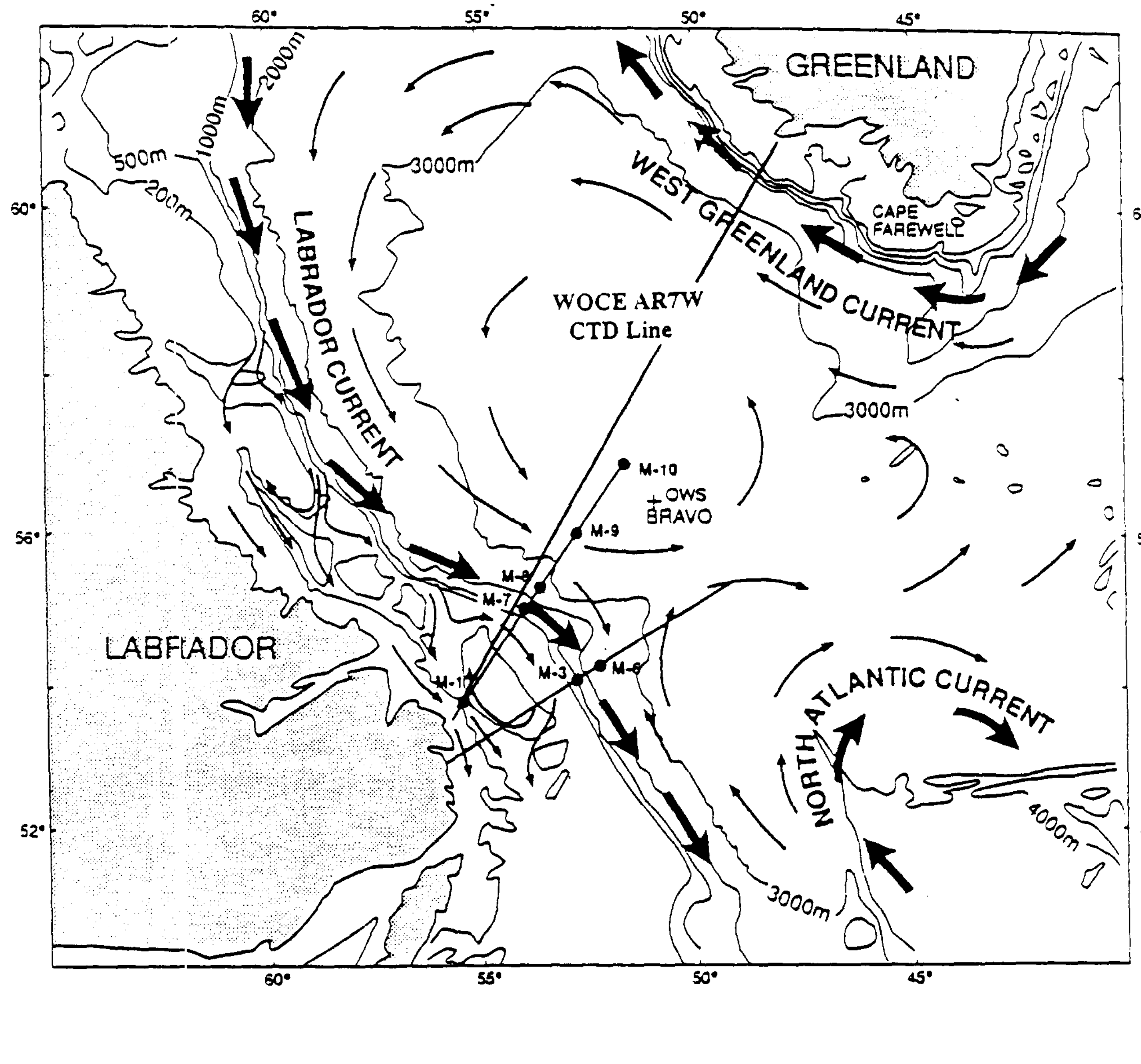


Fig. 1. Map of Labrador Sea showing currents and locations of oceanographic measurements including Ocean Weather Ship (OWS) Bravo, World Ocean Circulation Experiment (WOCE) AR7W CTD line and moorings M-1 to M-10 and two short CTD lines discussed in Lazier and Wright (1993).

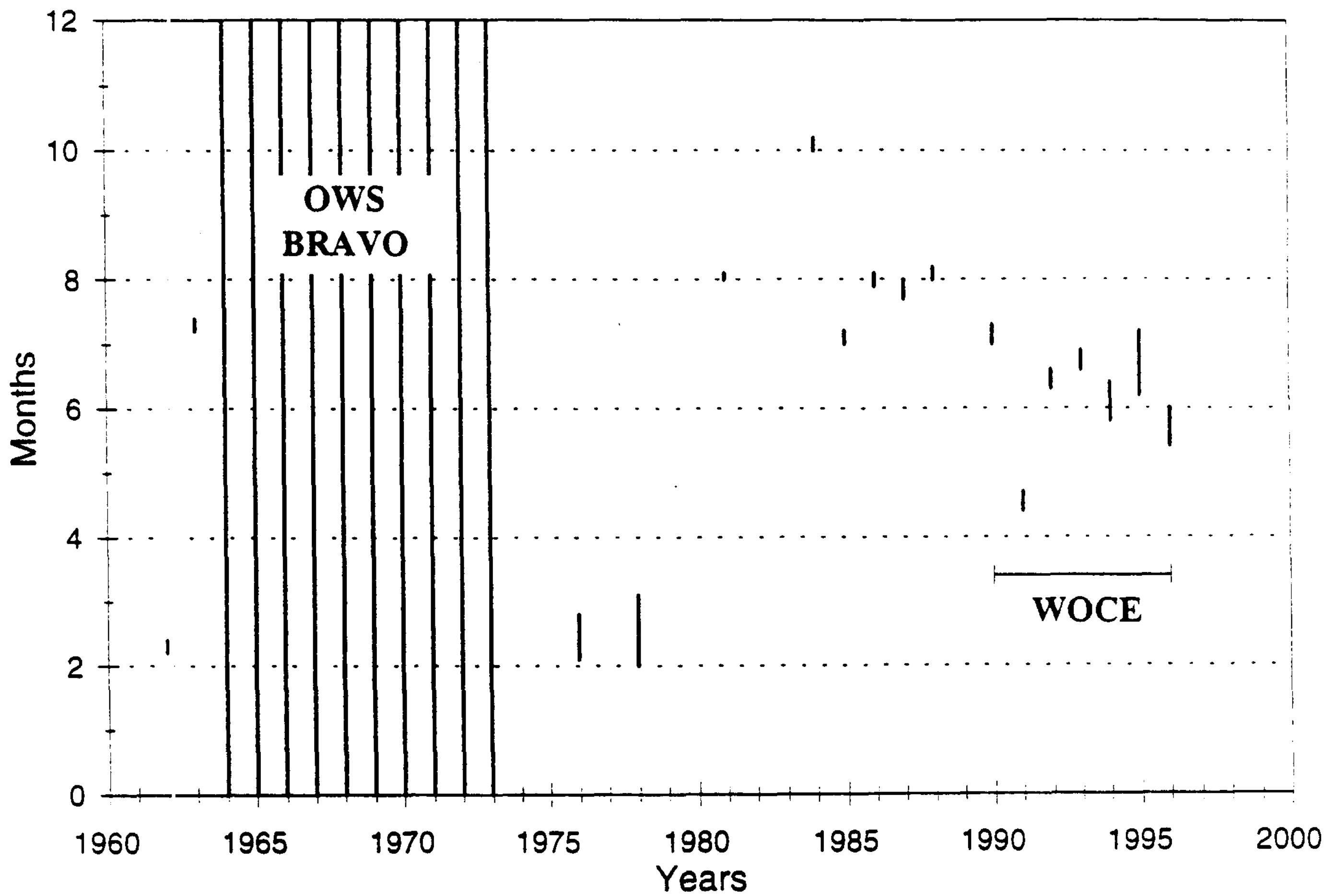


Fig.2 Times of deep oceanographic measurements in the central Labrador Sea between 1962 and 1996 including those from the OWS Bravo and the WOCE AR7W line across the Labrador Sea.

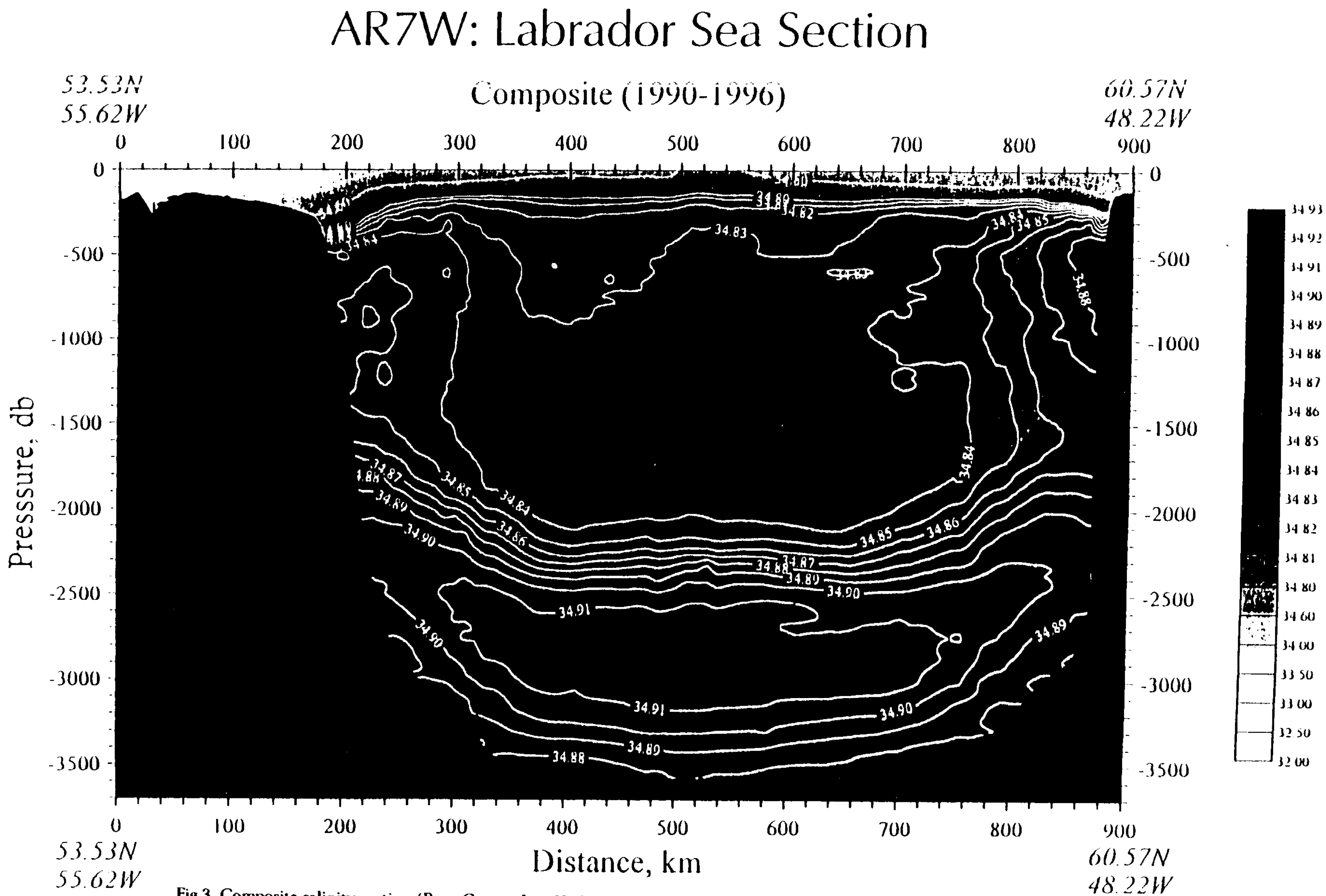
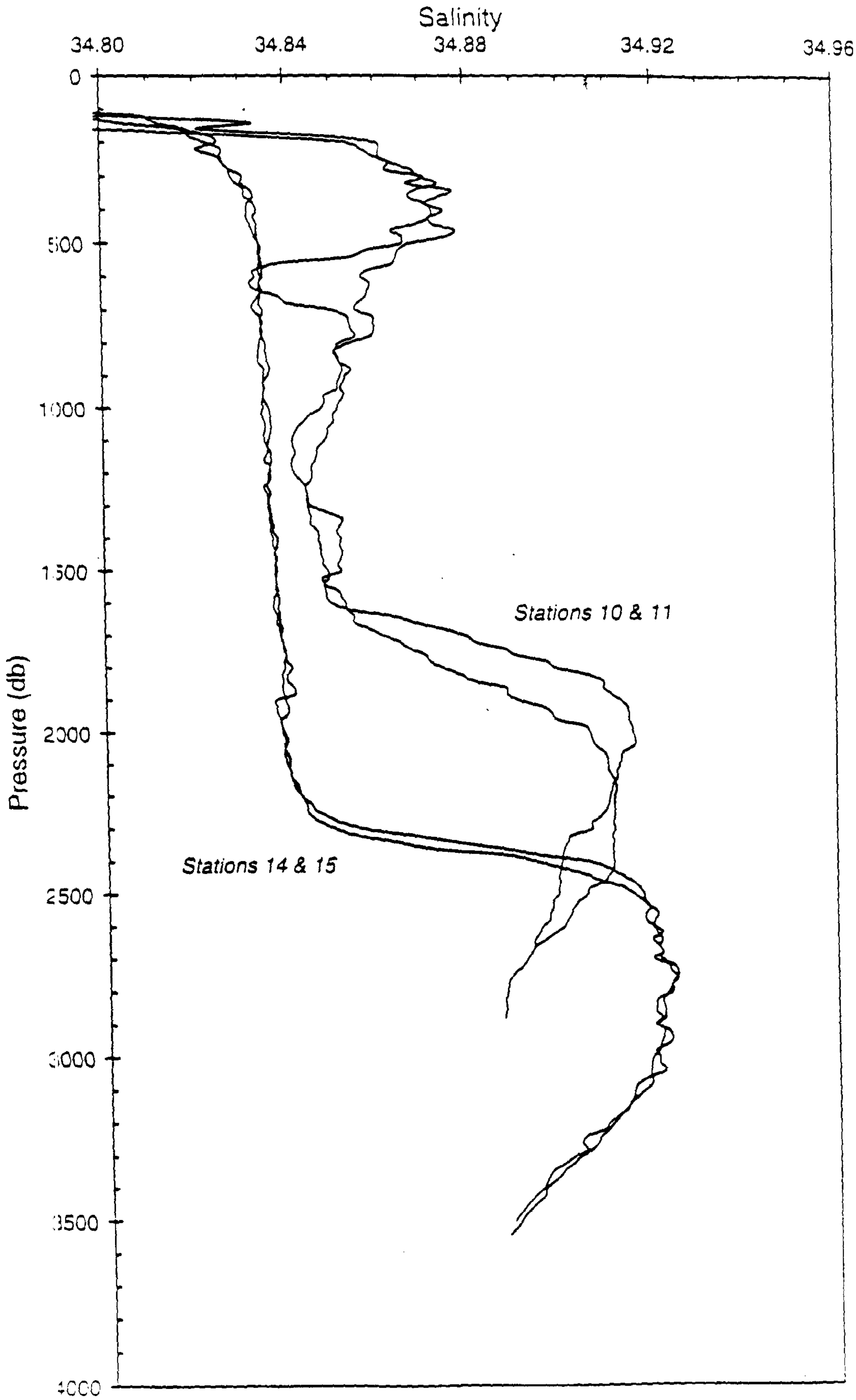


Fig.3. Composite salinity section (Pers. Comm. Igor Yashayaev, BIO) across the Labrador Sea based on observations collected along the AR7W CTD line in 1990 and 1992-1995. Four of the principal water masses are indicated: the Irminger Water (IW), the Labrador Sea Water (LSW), the North-East Atlantic Deep Water (NEADW) and the Denmark Strait Overflow Water (DSOW) a.k.a. North-West Atlantic Bottom Water (NWABW).

Fig.4. Vertical profiles of salinity obtained in June 1993 in the central Labrador Sea and over the continental slope.



Annual Counts of Icebergs Crossing 48° North Latitude (1912-92)

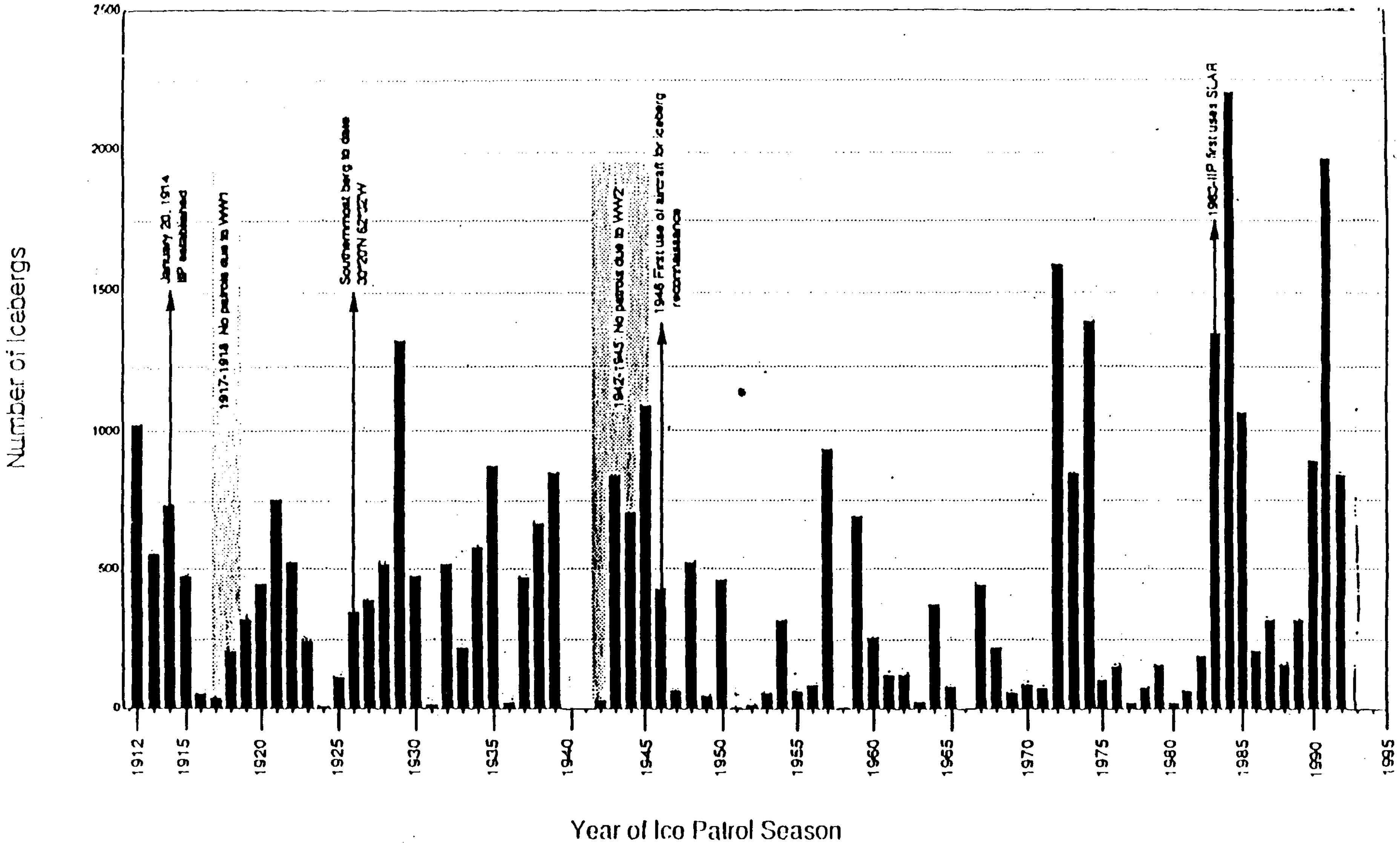


Fig.5. Number of icebergs moving south in the Labrador Current past 48 N between 1912 and 1992, (Pers. Comm. Donald Murphy, USCG)

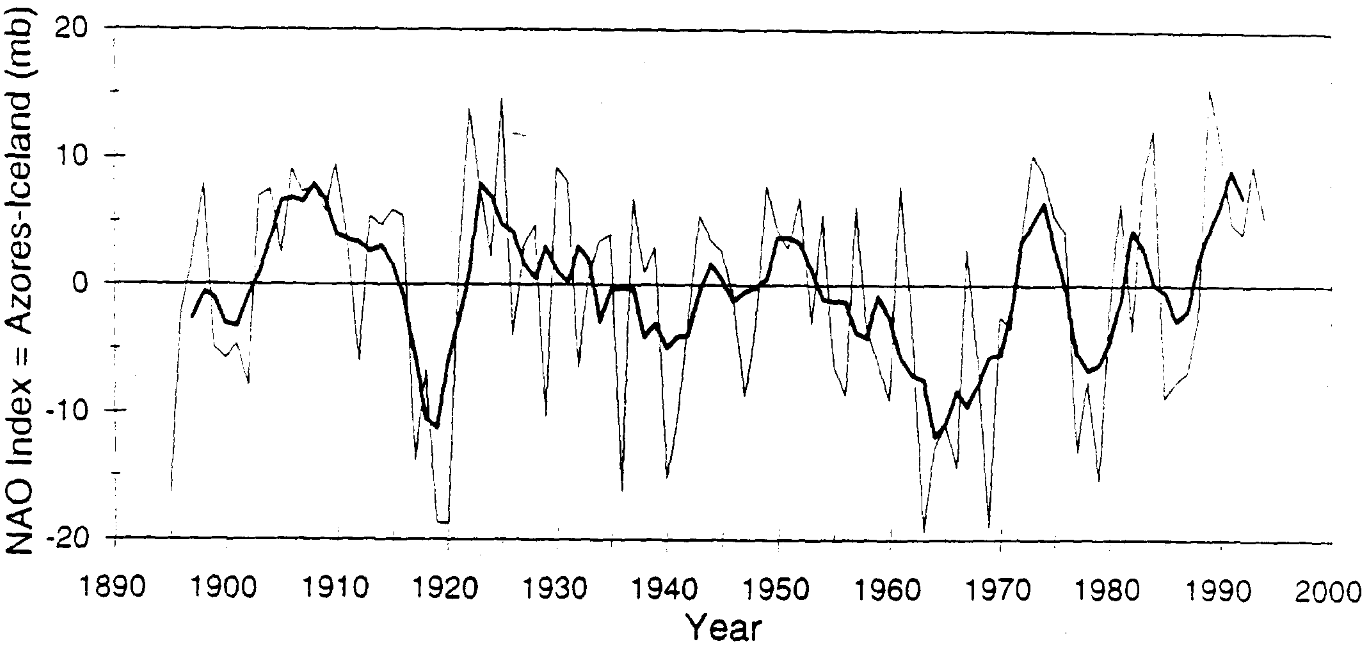
Fig.6. Winter (Dec., Jan., Feb.) surface atmospheric pressure distribution at 3 stages of the North Atlantic Oscillation; a. abnormally deep Icelandic Low - positive NAO index: b. average pressure pattern - zero NAO index and c. Icelandic Low displaced south of Iceland and strong Siberian High across the Arctic Ocean and northern Canada - negative NAO index. Adapted from Fang and Wallace (1994).

a)

b)

c)

Fig.7. The North Atlantic Oscillation index; the anomaly of the average winter (Dec., Jan. and Feb.) atmospheric pressure differences between the Azores and Iceland during the winters of 1895-1994. The heavy line is the 5-year running mean, (Pers. Comm. K. Drinkwater, BIO).



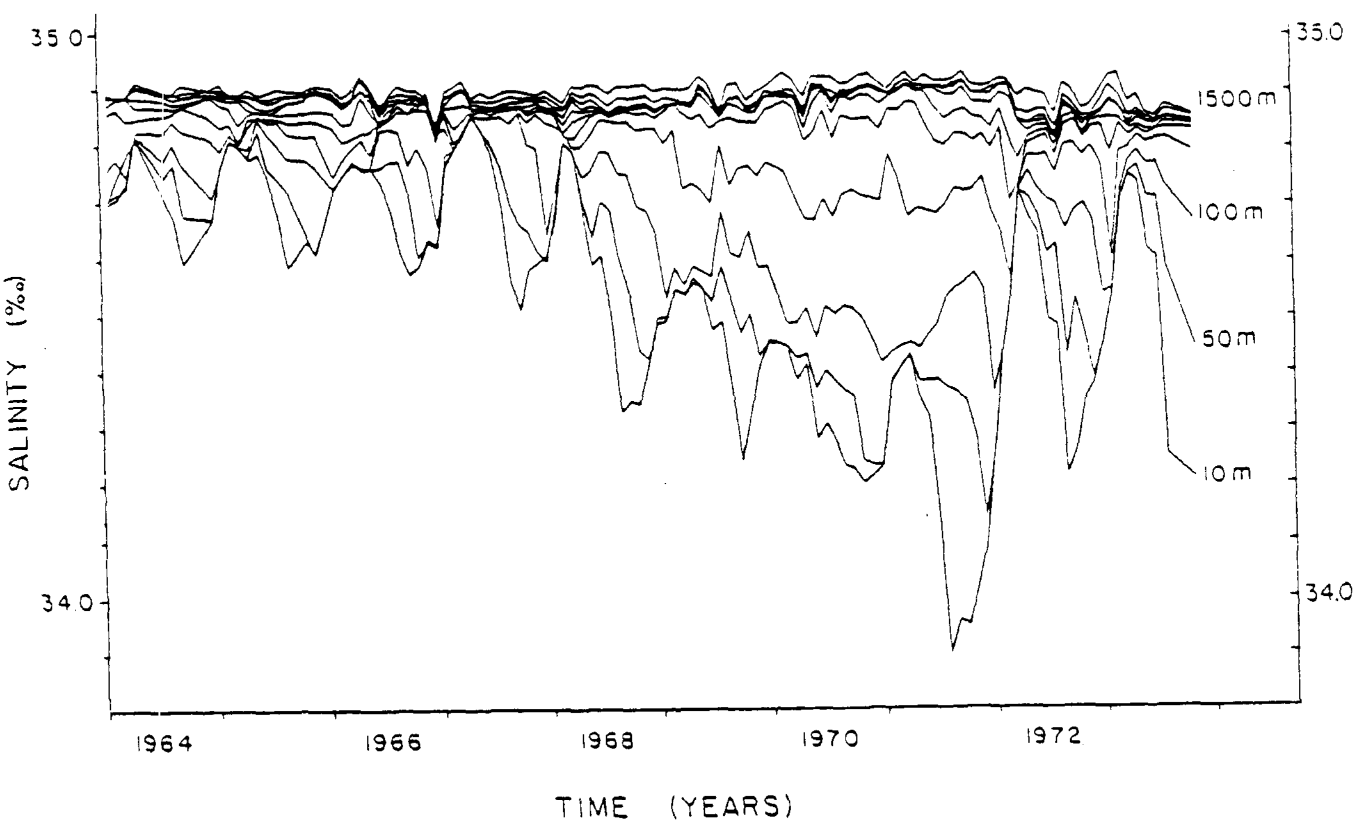


Fig.8. Monthly averages of salinity at eleven depths at station Bravo from 1964 to 1973 from Lazier (1980).

Fig.9. Potential temperature vs. salinity of the core of the Labrador Sea Water during the years for which there are data between 1962 and 1996. Continuous lines are contours of potential density anomaly referenced to 1500 db.

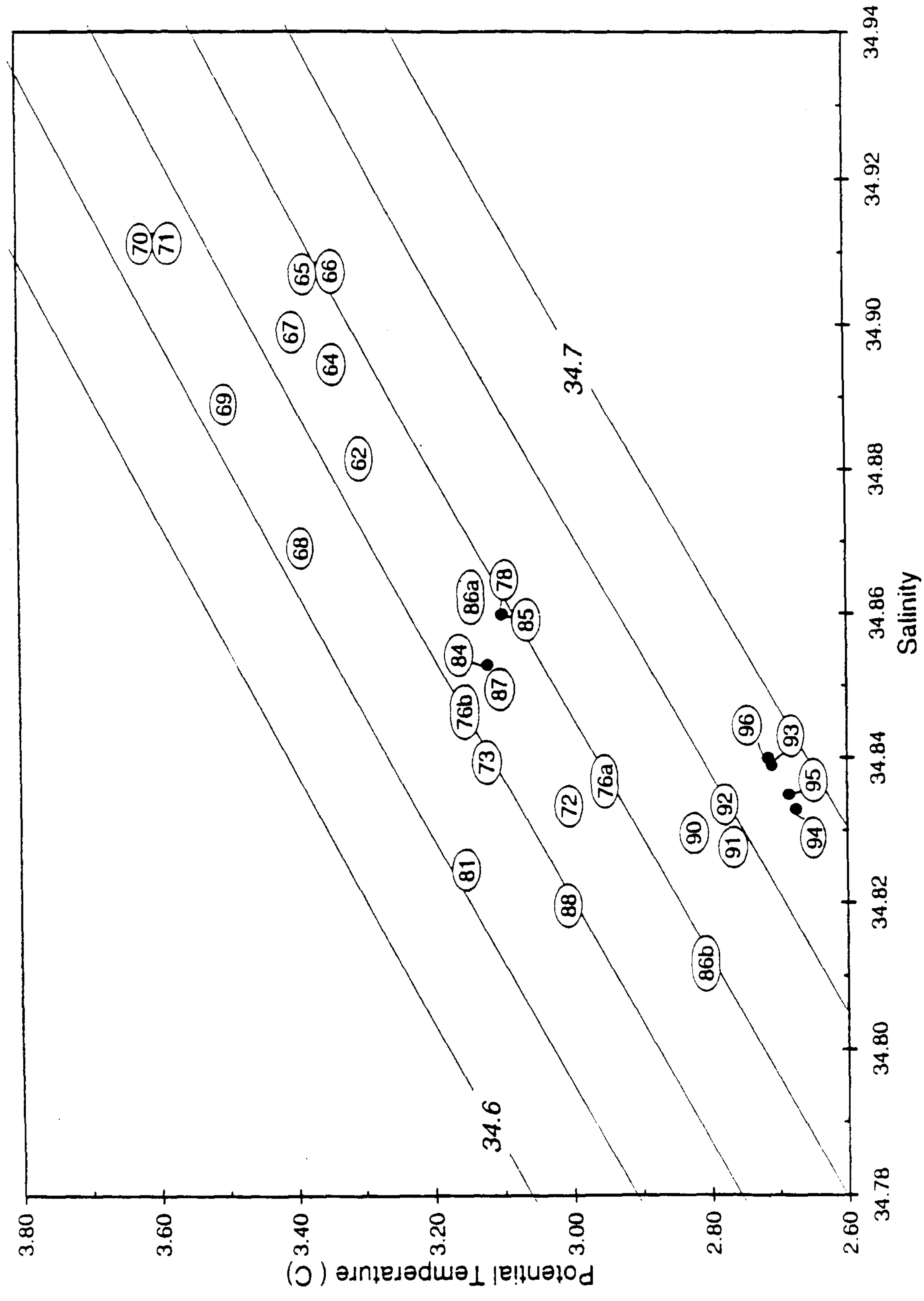


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Fig. 10. A selection of vertical salinity profiles from the central Labrador Sea in 1966 and 1994 from Lazier (1995).

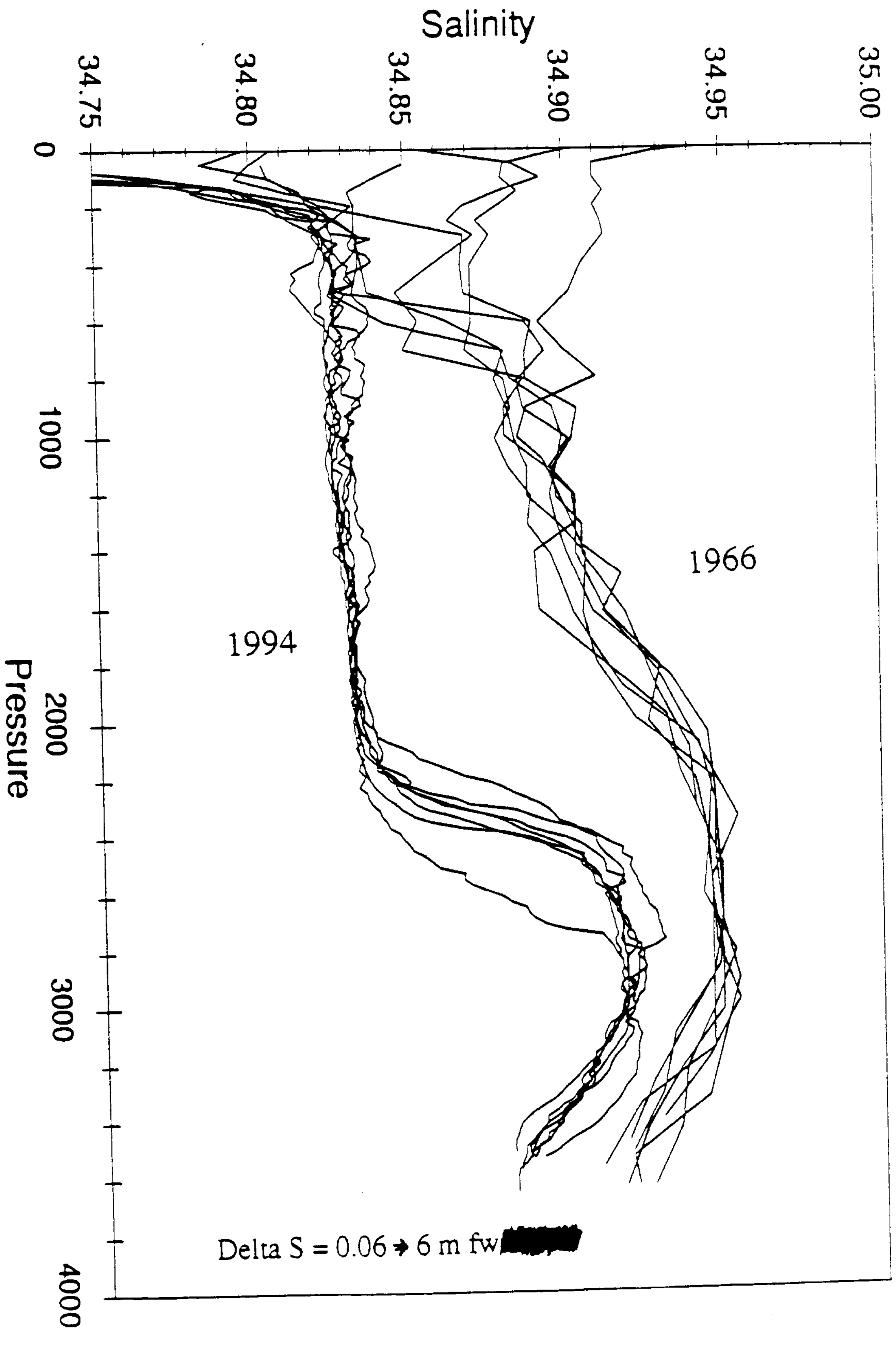


Fig.11. Map with arrows showing flow of Labrador Sea Water away from the Labrador Sea toward the Irminger Sea, the Iceland Basin and the Newfoundland Basin based on work of Talley and McCartney (1982).

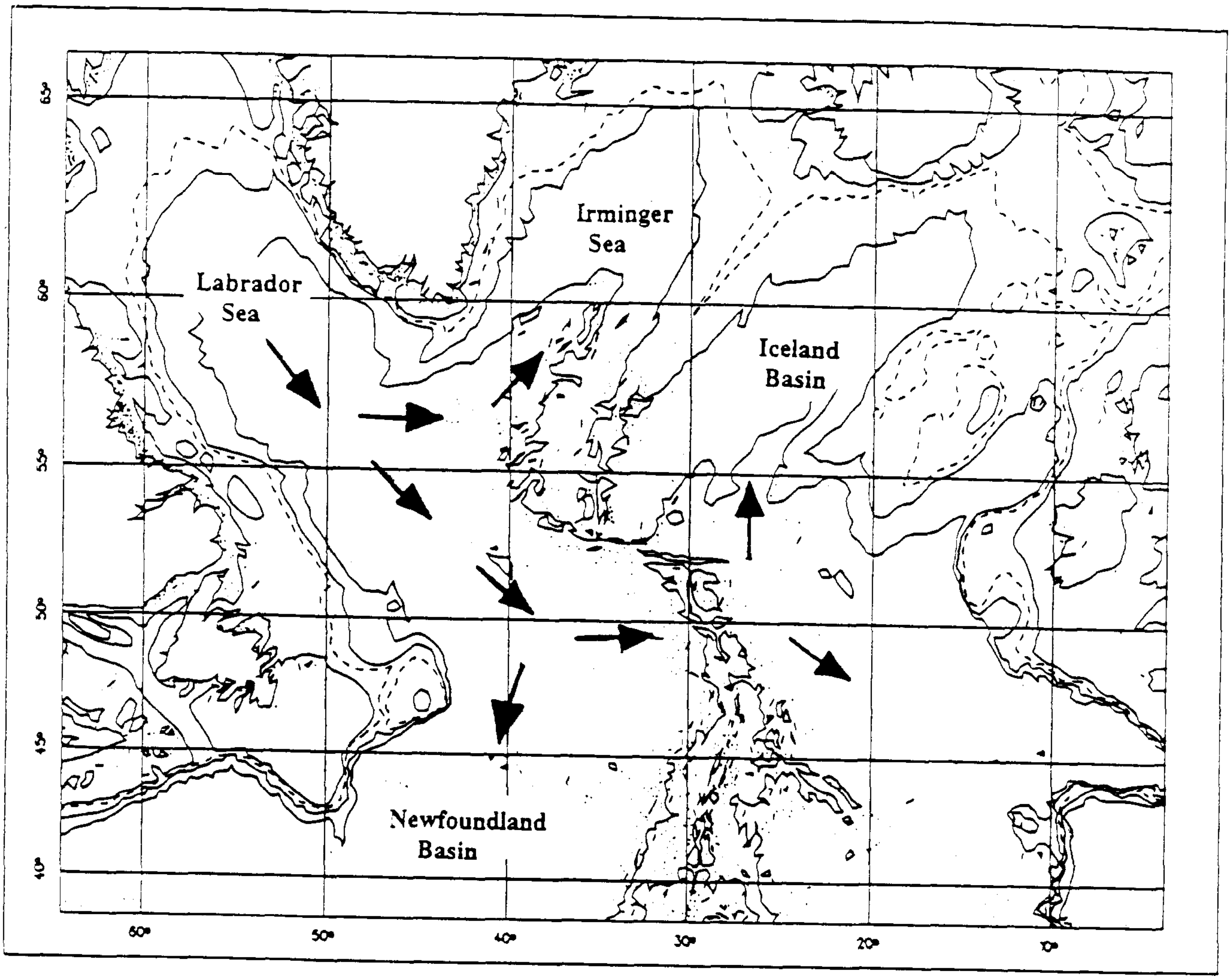


Fig. 12. Potential temperature vs. salinity curves in the Irminger Sea in 1991, 1992 and 1994 from data collected by Alexander Sy, Bundesamt f□r Seeschiffahrt und Hydrographie (BSH) and Jens Meincke, Institut f□r Meereskunde an der Universit„t Hamburg (IFM Hamburg).

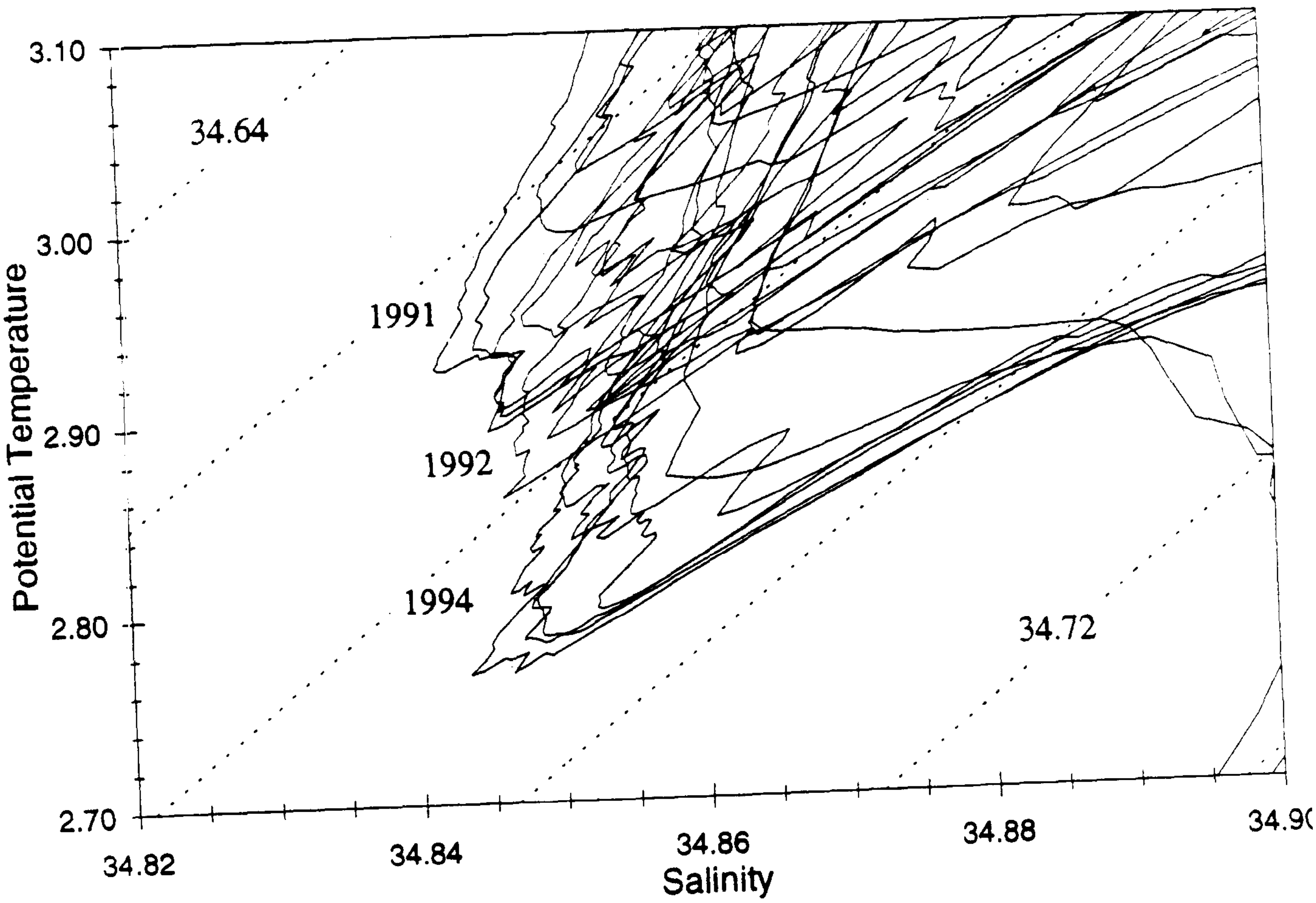
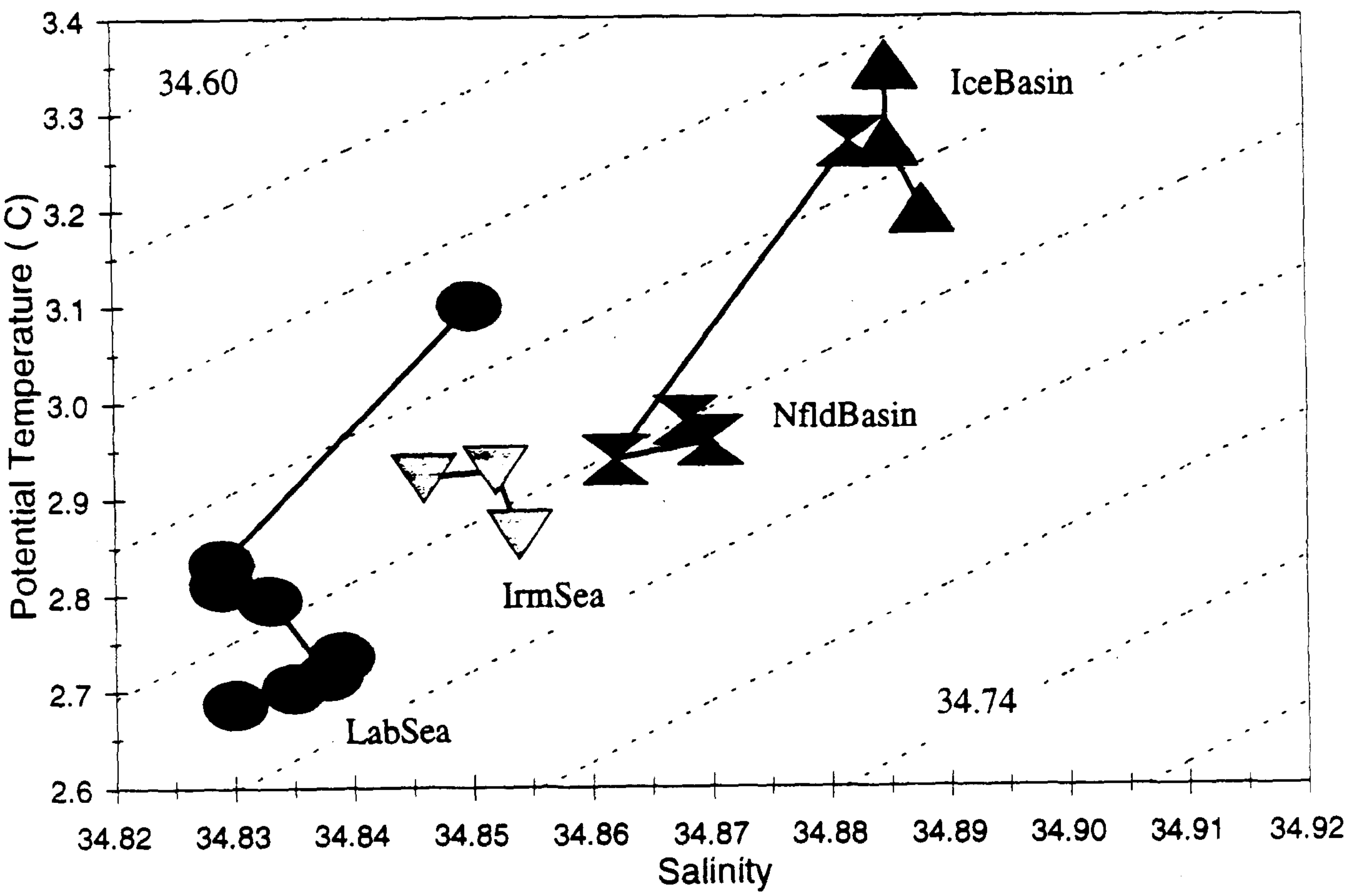


Fig.13. Potential temperature vs. salinity values representing the core of the Labrador Sea Water in the Labrador Sea (1987, 1990-1996), Irminger Sea (1991, 1992 & 1994), Iceland Basin (1991, 1992 and 1994) and Newfoundland Basin (1990, 1993-1995). The Iceland Basin and Irminger Sea data were collected by A. Sy (BSH, Hamburg) and J. Meincke (IFM, Hamburg). The data for the Newfoundland Basin in 1990 were collected by R. Hendry (BIO) and in 1993, 1994 and 1995 by A. Clarke (BIO).



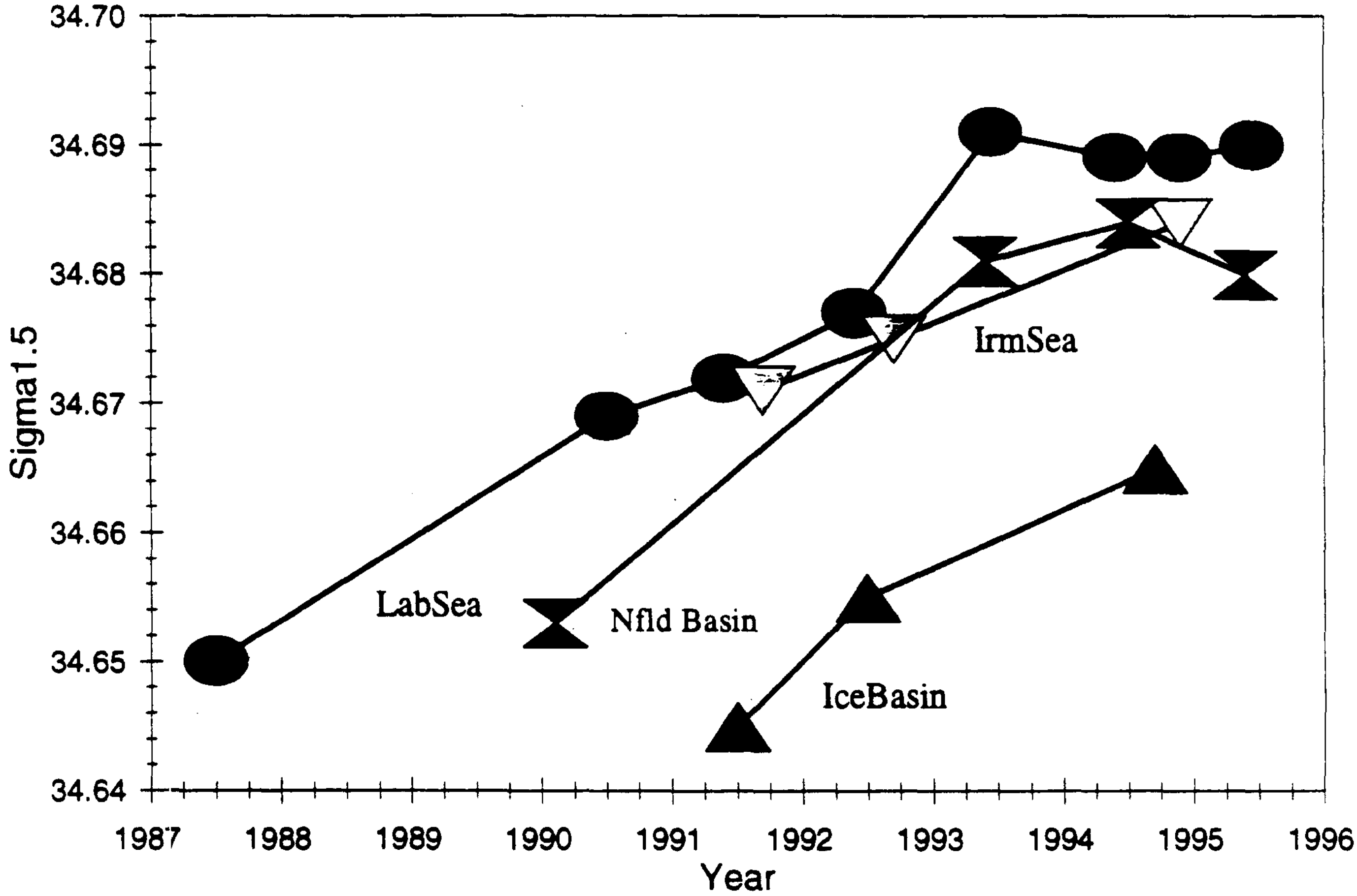


Fig.14. Potential density anomaly referenced to 1500 db (sigma1.5) at the core of the Labrador Sea Water for the years, locations and sources cited in Fig. 13.

ANNEX XIII

Ocean Weather Ship Station M (66°N, 2°E)

The longest existing homogeneous time series from the deep ocean

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Introduction

Having performed daily oceanographic measurements in the deep Norwegian Sea since 1 October 1948, Ocean Weather Ship Station (OWS) Mike, at 66°N,02°E, can present the longest existing homogeneous time series from the deep ocean. Station M is operating above the eastern margin of the Norwegian Sea deep basin where a branch of the Atlantic current is entering the area, Figure 1. The location proved to be strategic both for studying the Atlantic inflow and the Norwegian Sea Deep Water. The OWS M is operated by The Norwegian Meteorological Institute (DNMI) and the hydrographic programme is carried out by Geophysical Institute, the University of Bergen.

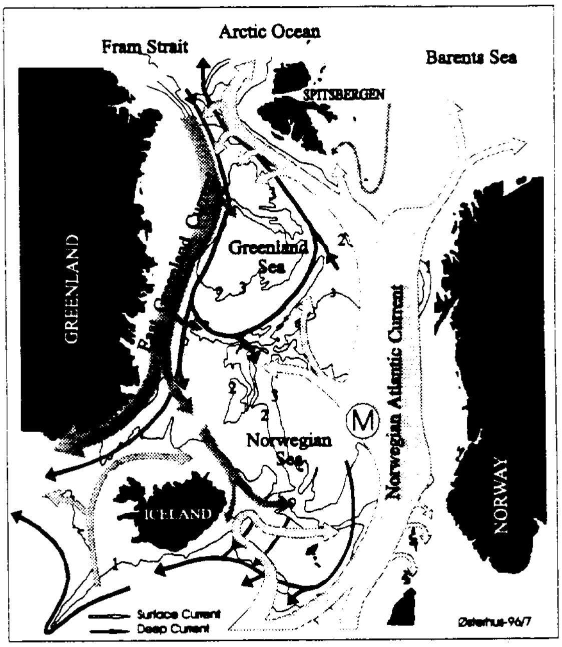

Fig. 1 The main current system (schematic) in the Nordic Seas with the position of the weather ship station MIKE. The open hatched arrows indicate the surface current patterns, and the black arrows indicate the deep/bottom current.

History

With the expansion of civil aviation and growing understanding of the impact of aerological observations on weather forecasts after World War II, ICAO (The International Civil Aviation Organization) demanded a greater network of aerological stations, primarily in the North Atlantic.

In 1946 a plan for a network of 13 ocean weather stations in the North Atlantic was set forth under the auspices of ICAO. The Stations were to supply meteorological services, search and rescue services, and navigational aids to aircraft. The USA, Canada and eighth European countries should be responsible for operating the stations, which were referred to by letters from A to M. Norway was to operate station M (phonetic name Mike) at 66°N,02°E, with financial backing from Sweden and Great Britain.

ICAO attempted to organize an international oceanographical research programme for the weather ships, but failed due to lack of interest, shortage of money and difficulties in procuring the necessary scientific equipment. In Norway, a country which held great traditions in oceanographical research, a small group of three scientists, led by the oceanographer Håkon Mosby , took upon themselves to implement an extensive research programme on station M (Hogstad and Østerhus, 1996).

Håkon Mosby implemented a routine programme within physical oceanography, including serial observations of temperature, salinity, and (since 1953) oxygen weekly at standard depths to 2000 meters, and serial observations of temperature and salinity at standard depths down to 1000 meters 3 or 4 times a week. This programme has been running continuously since 1 October 1948 to this very day only hampered by occasionally extreme weather. The method of obtaining temperature and salinity observations (Nansen bottles with reversing thermometers) has not changed significantly either so the time series are indeed homogeneous.

Some results

Altogether more than 9200 hydrographic stations (Nansen cast) have been performed, including more then 180000 thermometer readings and 90000 salinity samples. In addition to standard observation of hydrography and meteorology several other samples are taken (Gammelsrød et al., 1992). The hydrographic data can be obtain from ICES.

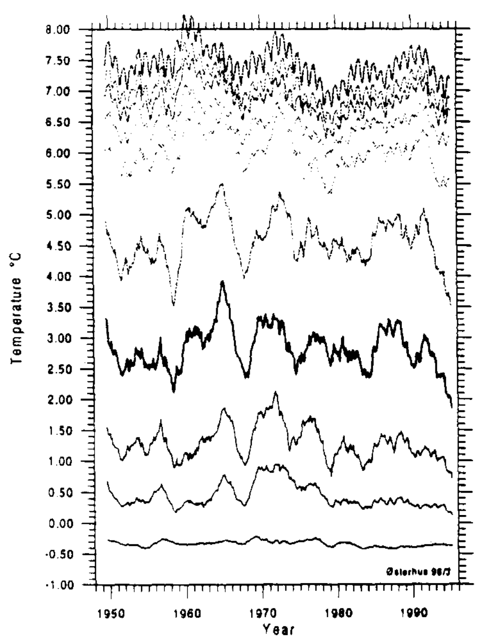

Fig. 2 Time series of temperature in the Atlantic Water (50,75,100,150,200,300,400,500,600,800 m)

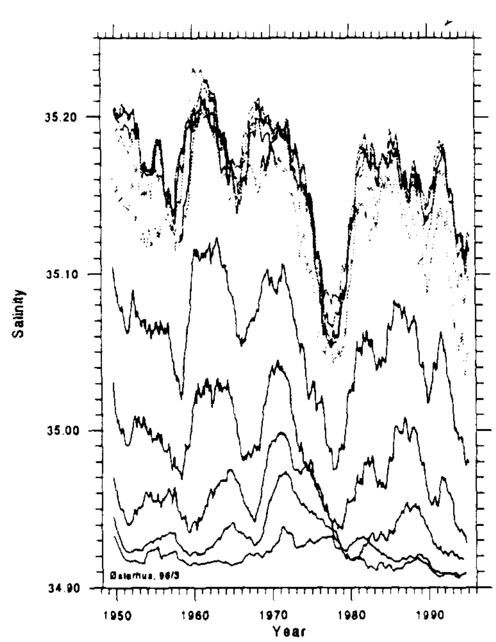

Fig. 3 Time series of salinity in the Atlantic Water (50,75,100,150,200,300,400,500,600,800 m).

Figure 2 and 3 show that the Atlantic water has become cooler and fresher since 1991. For depth below 200 m the temperature and salinity are down to the levels observed during the late 70's, when the so-called "Great Salinity Anomaly" passed through (Dickson et al.,1988). Independent observations (Hansen and Kristiansen, 1994) indicate that the inflow of Atlantic Water to the Nordic Seas has been reduced. The long term trends are a cooling and freshening of the upper layer consistence with a accumulating of Arctic Surface Water in the Nordic Seas (Blindheim et al.,1996).

Smoothed monthly mean temperatures for the 3 deepest standard depths (1200m, 1500m, 2000m) are shown in Figure 4 for the period 1948-1995. Notice that a recent warming has occurred, starting at 2000m in 1985, then gradually penetrating upwards through 1500m in 1987 and reaching the 1200m level in 1990. The temperature increase is about 0.07°C, and nearly constant with depth.

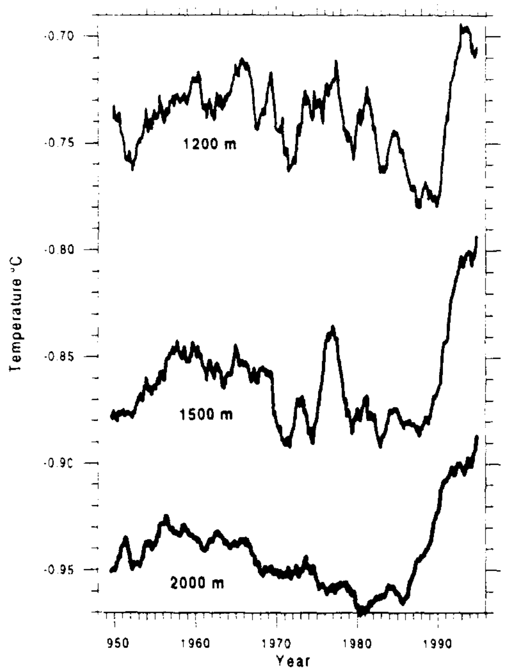

Fig. 4 Time series of smoothed monthly mean temperature at depth of 1200m, 1500m 2000m from the weather ship station Mike.

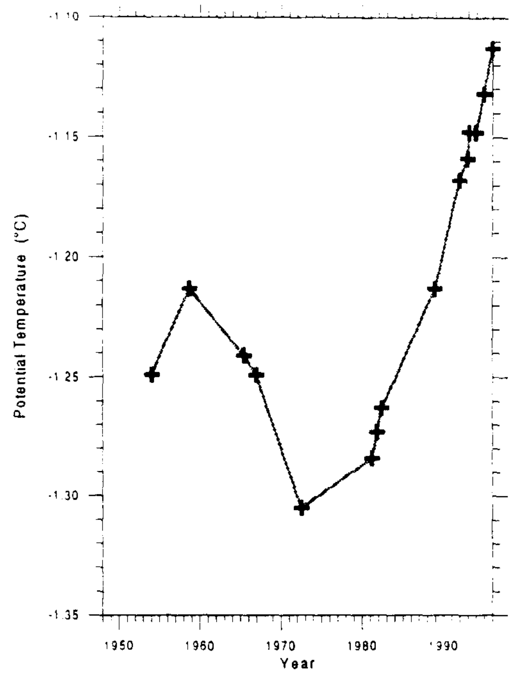

Fig. 5 Time series of the mean temperature below 2000m in the central Greenland Sea.

The low temperature of the Norwegian Sea Deep Water (NSDW) is maintained by the contribution of the Greenland Sea Deep Water (GSDW). The bottom water in the Greenland Sea is renewed locally by surface cooling of relative fresh water, resulting in the coldest bottom water found in the deep ocean. NSDW is formed by mixing GSDW and the deep water from the Arctic Ocean. The recent warming of the NSDW has its forerunner in an even more markedly warming of the GSDW, see figure 5, consonant with the idea that the deep water formation in the Greenland Sea has ceased. The Greenland Sea and the Norwegian Sea basins are separated by the Mohn Ridge (Figure 1), and the exchange of water masses between the two deep basins takes place through a channel which has a threshold depth of 2200 m and is situated just north of Jan Mayen. Since the warming of GSDW appears to have continued unchecked to date, (Figure 5) the cessation of warming observed in the NSDW since 1990 is certainly unexpected, (Figure 4) suggesting that as GSDW production has (virtually) ceased, the transport through the Jan Mayen Channel may have reduced or even reversed, see figure 6, cutting off the deep Norwegian Sea from the influence of the GSDW and its changes, see Østerhus and Gammelsrød, 1996, and Østerhus et al., 1996.

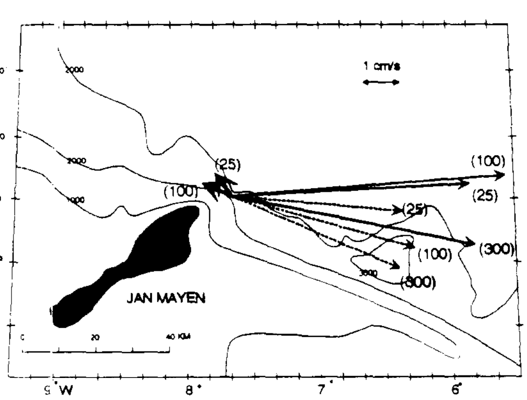

Fig. 6 Results from the current measurements in the Jan Mayen Channel from April to November 1991 (thin doted arrows), September 1983 to July 1984 (thin arrows) and from November 1992 to July 1993 (thick arrows). The numbers in parentheses indicate height of current meter above the bottom. The stability factor (defined as the absolute value of the average current vector divided by the average speed) was 0.91 in 83/84 and 0.18 in 92/93. The mean temperature was -1.01°C in 83/84, increasing to -0.94°C in 92/93.

Planned activity

The OSW M will continue its operation at least to the year 2000. A CD containing quality controlled hydrographic data (as stations data and time series) is planned for the 50 years anniversary in 1998. The history of OWS M is being written. It is proposed that Polarfront should be equipped with an Acoustic Doppler Current Profiler (ADCP). Twenty-four ADCP's and XBT's sections a year across the Norwegian Atlantic Current will be invaluable for monitoring the influx of Atlantic water to the Arctic. Plans for extending the hydrographic, biological and geochemical programmes exist. The future of M depends on us as researchers being able to convince the powers of the purse that these data are really necessary for climate research.

References

- Blindheim J., V. Borovkov, B. Hansen, S-A. Malmberg, B. Turrell and S. Østerhus (1996) Recent upper Layer Cooling and Freshening in the Norwegian Sea. ICES C.M. 1996/C:7.
- Dickson, R.R., J. Meincke, S-A. Malmberg and A.J. Lee. (1988) The "Great Salinity Anomaly" in the Northern North Atlantic 1968-1982. prog. Ocenog. Vol. 20, pp 103-151.
- Gammelsrød T., S. Østerhus and Ø. Godøy. (1992) Decadal variations of ocean climate in the Norwegian Sea observed at Ocean Station "Mike" (65°N 2°E). ICES mar. Symp., 195:68-75,1992.
- Hansen B., R. Kristiansen. (1994) Long-term Changes in the Atlantic Water Flowing Past the Faroe Islands. ICES C.M. 1994/S:4.
- Hogstad R.D. and S. Østerhus, 1996. Verskipstasjon M 1948-1998. A preliminary internal report.
- Østerhus S., T. Gammelsrød.1996. The Abyss of the Nordic Seas is Warming. In prep.
- Østerhus S., B. Turrell, B. Hansen, J. Blindheim, A.J. Bennekom. Changes in the Norwegian Sea deep Water. ICES C.M. 1996/O:11.

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ANNEX XIV

DECADAL CHANGES IN THE MERIDIONAL OVERTURNING CIRCULATION OF THE NORTH ATLANTIC : A FIRST GLIMPSE AT 40 YEARS OF TRANS-OCEANIC SECTIONS SINCE THE IGY

by
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Looking at changes of the ocean's circulation has proven to be difficult. In due course concepts such as a mean circulation have come to depend on the period over which the circulation has been averaged, and if ever it achieved this "mean" state. Looking at such changes beyond years has been even more problematic: adequate data are only available since some 50 years, and do they describe a mean state? Oceanography has been hard-pressed to deliver a description of this futile ocean circulation in view of fascinating descriptions of the ocean's circulation derived from various other data sources, say palaeo-data, on climate time-scales.

Detecting changes in the ocean circulation gives several answers. One is that we know little about the natural variability of the ocean on these decadal time scales. Time series have provided much insight into long-term changes. They are not necessarily at the best location for monitoring changes; their value is in being in existence. Another approach to describe long-term changes in the ocean's circulation is to determine integral properties such as transports. They subsume changes from several different parameters, and if properly understood could help to determine changes in the ocean, be it natural or man-made.

Repeating classical hydrographic sections reveals on smaller spatial scales a plethora of variability. Water masses change their characteristics, boundary currents vary in position, strength and interaction with the ocean interior. The determination of integral properties such as the transports of heat, salt and freshwater from repeated oceanographic sections is one approach to describing changes on time scales of climate variability. Repeated sections will always be problematic with respect to sampling theorems, or aliasing. There, other ancillary data that are well sampled in time, such as forcing fields, upper ocean surveys from XBT lines or from ocean time series, will help to provide information for the periods between individual sections.

In the North Atlantic with its highly variable thermohaline circulation, a section at 48°N has several justifications: it follows the zero wind stress curl, separating the subpolar gyre to the North from the subtropical to the South. If there are changes in the gyres -- strength or position or their interactions -- one would see them there. At this latitude we also find the maximum of the global freshwater transport. If this changes, and the changes would be determined, one would get an indicator of changes in the haline component of the thermohaline circulation. moreover, it is far enough North to measure mostly advective transports, and south enough to avoid the convective further north.

With now five repeats of full-depth coast-to-coast sections since 1957, or over 39 years, we have a better estimate of the changes in the hydrography at 48° N. Neglecting the top 1000 m or so because we have no coverage to resolve the seasonal cycle, and we are heavily biased towards summer data anyhow, the deep layers show a detectable and significant variability both in temperature and salinity. The variability is high in the intermediate waters of either northern or Mediterranean origin, and considerable in the boundary currents. Besides the well-structured western boundary current system, we find considerable changes in the eastern boundary currents and in the boundary currents on both sides of the Mid-Atlantic Ridge (MAR). Although the western, or North American Basin shows the highest overall variability, the eastern basin is far from quiet. In both basins the bottom waters also show varying trends, reflecting changes in composition or strength of the participating water masses. These statistics do not provide yet a picture of why these changes occur, or how.

The observed changes at 48°N (WOCE section A2) have been put into perspective for the large-scale circulation of the entire North Atlantic by using comparable data from sections worked along 24,5°N and 36° N (Dobroliubov et al, 1995) at similar times to describe these observed changes (Koltermann at al, in prep). All sections cover the mid-1950s, the early 1980s and the early 1990s. To determine changes in the water mass characteristics, transports for different water masses, then the total meridional transports of heat through each section at each time frame and finally the meridional overturning circulation (MOC), we cannot use one unique concept. The 1990s are marked by an intense production of Labrador Sea Water since 1987 that then invaded the entire North Atlantic (Koltermann et al, 1994) and has far reaching implications for the subtropical gyre, too (Curry & McCartney, in prep). It contrasts strongly with the 1980s were LSW production was low and its existence in the North Atlantic confined mostly to the northeastern Atlantic (McCartney&Talley, 1982). The northward transport of Mediterranean Water (MW) has increased, as has the southward transport of DSOW. But we get the maximum meridional heat transport at 48°N with 0.62 ± 0.11 PW for the 1980s, and the largest MOC, characterised as the integral of all mass fluxes moving either south or north. In essence we have a northward transport in the upper layers and a southward transport in the lower and bottom layers. This well known picture of a single meridional cell cannot be reconciled with our results for the early 1950s or the 1990s.

For the early 1950s and the 1990s we find an increase in the production of LSW with a detailed history (Sy et al, 1997), a drastic decrease in the transports of DSOW and of MW. The meridional transports of heat for 1957 are0.27 ± 0.15, and for 1993, 0.53 ± 0.12 PW. Heat transports for 36°N and the strength of the meridional overturning circulation follow those at 48°N with reduced variations. Further south, at 24,5° N, we estimate a more or less stable MHT similar to the almost canonical 1.2 PW. The changes from latitude to latitude and over the individual periods indicate a changing heat flux divergence and suggest a varying interaction with the atmosphere. We can only describe these changes by suggesting a two-cell meridional circulation, where the modification of surface and intermediate waters that finally leads to the increased production of Labrador Sea Water LSW results in a southward transport at mid-depth. The progression of Antarctic Bottom Water AABW for both periods in the western and the eastern basins to 48°N is well documented. It leads to modifying the lower NADW, and shows a marked difference in TS-space to the changes in the upper NADW found in the one-cell scenario.

The transition from the single meridional overturning cell in the 1980s to the two cell system of the mid-1950s and 1990s has strong implications for the thermohaline system of both the North Atlantic and the Northern European Polar Seas, (GIN Seas for short) north of the Greenland-Iceland Ridges. In the single cell case, heat and salt are directly supplied to the GIN Seas and salt at least is made available there for convection and production of the intermediate waters such as Greenland Sea Deep Water (GSDW) and Norwegian Sea Deep Water (NSDW). In the two-cell case, the strong production of Labrador Sea Water south of the Greenland-Iceland Ridges recycles the MW contribution and essentially decouples the thermohaline system from that north of the Greenland-Iceland Ridges. Crucial to the transition from the one to the other state is the availability of DSOW. A strong supply of DSOW will lead to the one-cell scenario. A reduced LSW production with an intensive MOC provides favourable conditions for deep convection in the Labrador Sea by bringing salty waters to high latitudes. An enhanced LSW production in turn slows down the MOC thus limiting the supply of salty waters to maintain the convection processes in the Labrador Sea. It is directly passed across the Greenland-Iceland Ridges to the formation areas of the Arctic Intermediate Waters.

What now are the differences in the forcing conditions that seem to have led to this flipover between two states of the meridional circulation of the Northern North Atlantic? In the SST-anomalies (Hansen & Bedzek, 1996) we find no direct clues except strong and pronounced meridional gradients. The NAO index does not directly lead to changes in the forcing, although the accumulated NAO increased since 1902 steadily to level off for the 1950s. It then decreased because of a period of negative NAO indices through to 1972. It remained almost level for some 15 years and only since 1986 started increasing again, suggesting an enhanced zonal atmospheric circulation over the Northern North Atlantic.

Recent work (Dickson et al, 1997) has described the alternating phases of the production of Intermediate Waters either in the Labrador Sea or the GIN Seas in terms of changes in the atmospheric forcing. The changes in the meridional circulation we describe here link those changes to the thermohaline system of the North Atlantic. The mechanisms we see are complementing the buoyancy changes by freshwater supply that lead to the Mid-70s salinity anomaly (Dickson et al, 1988) by a purely thermal forcing component.

The emerging results from our work with repeated sections in the North Atlantic suggest a larger concept of the thermohaline variability and its impact on the meridional transport of heat. They need further substantiation, and a close study of their implications. After a period of intense repeat work in the 1990s for improving also the time resolution at the 48° N section, one would envisage a continuation at say five-year intervals. The section work should definitely be accompanied by a highly resolved upper-layer component such as the present XBT section AX3. As the changes we observe are larger and progressing faster in the boundary current systems one would have to assess if monitoring the TS-properties in these systems would be adequate for an early detection of the transition from one to the other state of the meridional circulation.

References:

Curry, R.G. and M.S.McCartney,(in prep.): Subtropical response to subpolar convection variability.

Dickson, R.R., J.Meincke, S.A.Malmberg and A.J.Lee, 1988: The "Great Salinity Anomaly" in the northern North Atlantic 1968-1982. *Progress in Oceanography*, **20**, 103-151.

Dickson, R.R., J.Lazier, J.Meincke, P.Rhines, and J.Swift, 1996: Long-term coordinated changes in the convective activity of the North Atlantic. Submitted to *Prog. in Oceanogr.*

Dobroliubov, S.A., V.P.Tereschenkov and A.V.Sokov, 1995: Water mass distribution on 36° N in the Atlantic ocean in 1993. *Oceanology*, **35**, 6, 817-823.

Hansen, D.V., and H.F.Bezdek, 1996: On the nature of decadal anomalies in the North Atlantic sea surface. *Journal of Geophysical Research, **101**, 8749-8758.*

Koltermann, K.P., and A.Sy,1994: Western North Atlantic cools at intermediate depths. *WOCE Newslett.*, 15, 5-6.

Koltermann, K.P., A. Sokov, V. Tereschenkov, S. Dobroliubov; A. Sy and K. Lorbacher (in prep): Decadal Changes in the Thermohaline Circulation of the North Atlantic

Koltermann, K.P. and K.Warrach, 1994: Large scale changes in the North Atlantic circulation on decadal time-scales at intermediate depths. *ICES*, C.M.1994/S:7, 16 pp.

McCartney, M.S. and L.Talley, 1982: The subpolar Mode Water of the North Atlantic Ocean. *J. Physical Oceanogr.*, **12**,1169-1188.

Sy, Alexander , M. Rhein, J.R.N. Lazier, K.P. Koltermann, J. Meincke, U. Paul, M. Bersch, A.Putzka (1996): Surprisingly rapid spreading of newly formed intermediate waters across the North Atlantic Ocean, *accpt Nature*

ANNEX XV

JAPANESE NORTH PACIFIC REPEAT SECTIONS

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Tohoku University

1. INTRODUCTION

In this brief report, we will introduce the present status of Japanese CTD repeat sections conducted by Japanese agencies and university: Japan Meteorological Agency (JMA), Hydrographic Department/Japan Maritime Safety Agency (HD/JMSA), Japan Fisheries Agency (JFA) and Faculty of Fisheries, Hokkaido University (HU).

2. REPEAT SECTIONS BY JMA

Long-lines: The following 3 lines are on-going long-line repeat sections conducted by JMA (see Fig. 1):

(i) 137°E line by the **R.V RYOFU MARU** every winter since 1967 and every summer since 1972 interval of 1 degree in latitude from 34oN to 3oN surface to 1250, 2000, 4000m depth or bottom; T, S, O2, CO2, nutrients and others;.

(ii) 155°E line by the **R/. RYOFU MARU** every summer, since 1972 interval of 1 degree in latitude from 34°N to 3°N surface to 1250, 2000, 4000m depth or bottom; T, S, O2, CO2, nutrients and others;

(iii) 165°E line by the **R.V RYOFU MARU** every summer, since 1996 interval of 1 degree in latitude from 50°N to 7°S surface to 2000m or bottom; T, S, O2, CO2, nutrients and others.

Short-lines: In addition to the above long-line sections, the following lines are on-going short-line repeat sections. On these lines, almost the same observations as long-line sections are made basically at intervals of 3 months (see Fig.1).

(i) PH line, along 41.5 N, south of Hokkaido, by the R/V Kofu maru
(ii) 144 E line, along 144 E south of Hokkaido, by the R/V Kofu Maru
(iii) PM line, Northwest of Echizenmisaki, Japan sea, by the /V Seifu Maru
(iv) "G" line, Northwest of Sado, Japan sea, by the R/V Seifu Maru
(v) "A" line, along 31.8 N, East China Sea, by the R/V Chofu Maru
(vi) PN line, Northwest of Okinawa, East China Sea, by the R/V Chofu Maru
(vii) TK line, Tokara Straits, by the R/V Chofu Maru
(viii) PK line, along 135.2 E south of Honshu, by the R/V Shumpu Maru
(ix) "I" line, Southeast of Toimisaki, by the R/V Shumpu Maru

3. REPEAT LINES BY HD/JMSA

Long-lines: The following two lines are on-going long-line repeat sections conducted by HD/JMSA (see Fig. 2).

(i) 144°E line by the **R.V. SHOYO MARU** every winter since 1984 interval of 1 degree in latitude from 34°N to 1°S surface to 4000m depth or bottom; T, S, O2, surface current and others;

(ii) 134.7°E line by the **R.V. SHOYO** every summer and winter since 1994 interval of 1 degree in latitude from 34°N to 5°N surface to 4000m depth or bottom; T, S, O2, surface current and others

Short-lines: Ocean monitoring for near-shore areas is carried out by HD and 11 Regional Maritime Safety Headquarters (RMSH). Repeat intervals are 3-6 months depending on lines. Observations are made from surface to bottom (HD) or 500m (RMSH).

4. REPEAT LINES BY JFA

Long-lines: The following two lines are on-going long-line repeat sections conducted by JFA (see Fig.3).

(i) 179.5oW line by the **T.V WAKATAKE MARU** every summer since 1991
interval of 1 degree in latitude from 38.5oN to 58.5oN
surface to 600 or 800m depth; T, S, plankton and others;

(ii) 165oE line by the **R/V HOKKO MARU** every summer since 1992
interval of 1 degree in latitude from 40oN to 50oN
surface to 1500m depth; T, S, plankton and others.

Short-lines: Ocean monitoring of JFA is carried out by 7 national fisheries research institutions and 39 prefectures. Observational lines are classified into two categories: one is repeat-lines in coastal waters and the other is repeat-lines extending to offshore waters. On these lines, T, S, surface current and other variables are measured at intervals of 1 month (coastal) and 3 months (offshore).

5. REPEAT LINES BY HU

Faculty of Fisheries, Hokkaido University has maintained several long-line repeat sections since late 1970s.

(i) 180°E line by the **T.V OSHORO MARU** every summer since 1979
interval of 1 degree in latitude from 36°N to 48°N
surface to 3000m; T, S, nutrients and others

(ii) 175.5°E line by the **T.V HOKUSEI MARU** every summer since 1979
interval of 1 degree in latitude from 36°N to 48°N
surface to 3000m; T, S, nutrients and others

(iii) 155oE line by the **T.V HOKUSEI-MARU** every summer since 1979
interval of 1 degree in latitude from 36oN to 48oN
surface to 3000m; T, S, nutrients and others.

Insert Figures 1-4

Captions to figures

Fig. 1. Long-line repeat sections by JMA.

Fig. 2. Long-line repeat sections by HD/JMSA.

Fig. 3. Long-line repeat sections by JFA.

Fig. 4. Long-line repeat sections by HU.

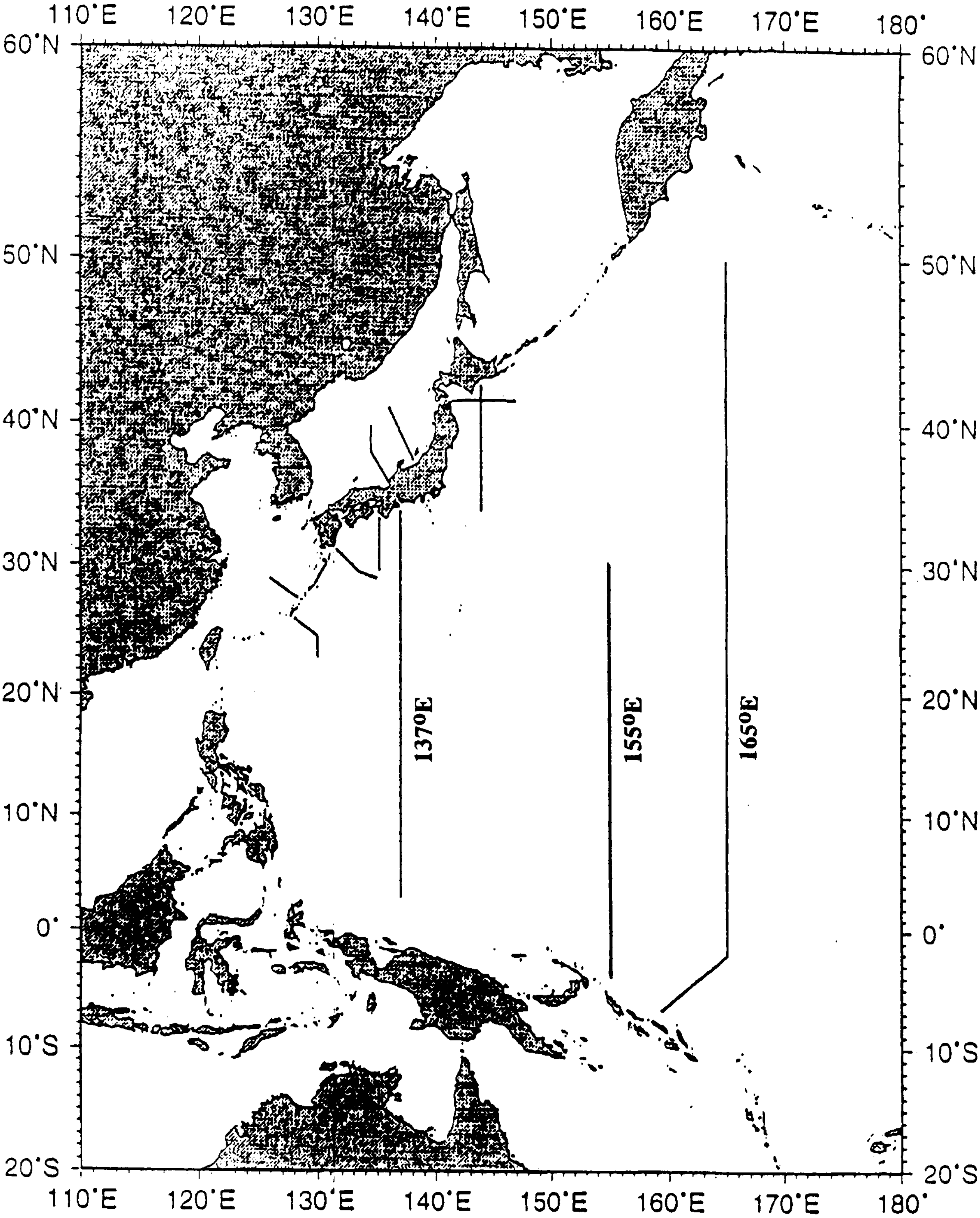


Fig. 1. Long- line repeat sections by JMA.

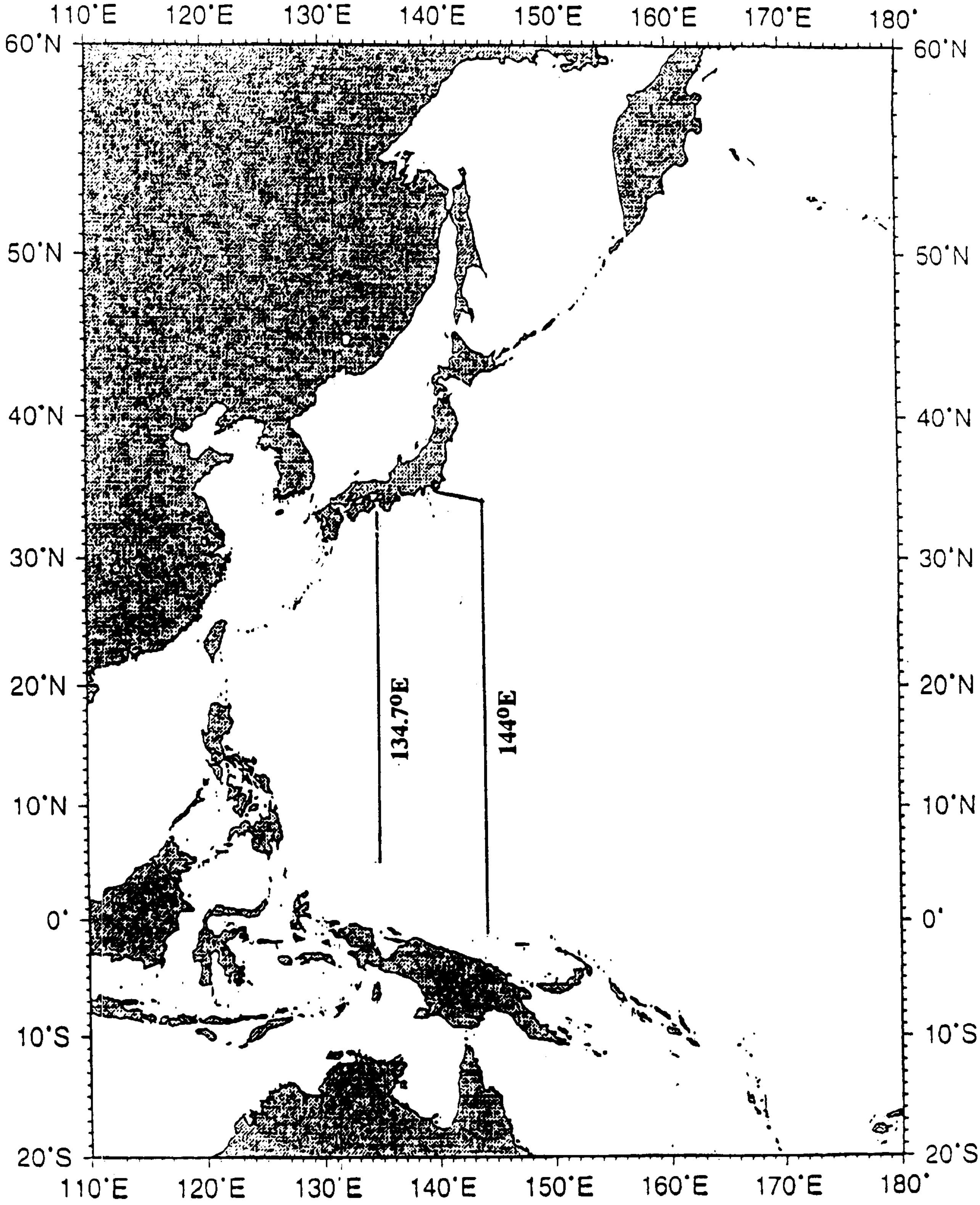
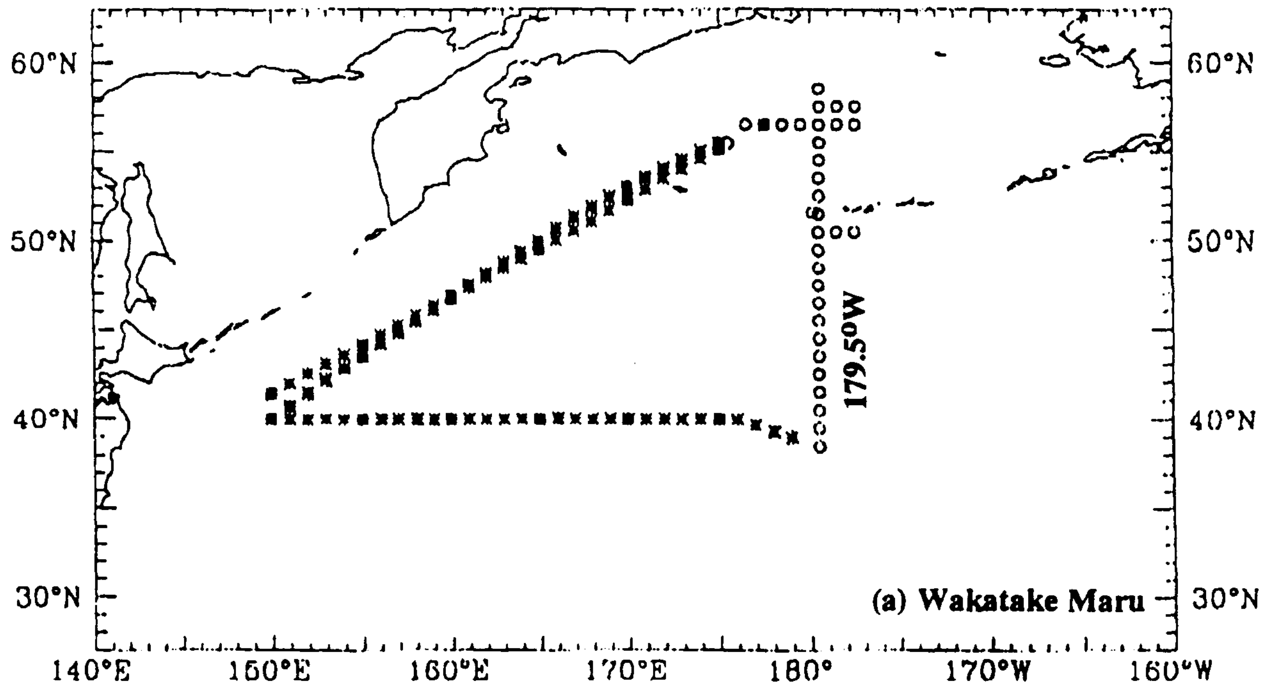


Fig. 2. Long- line repeat sections by HD/JMSA.



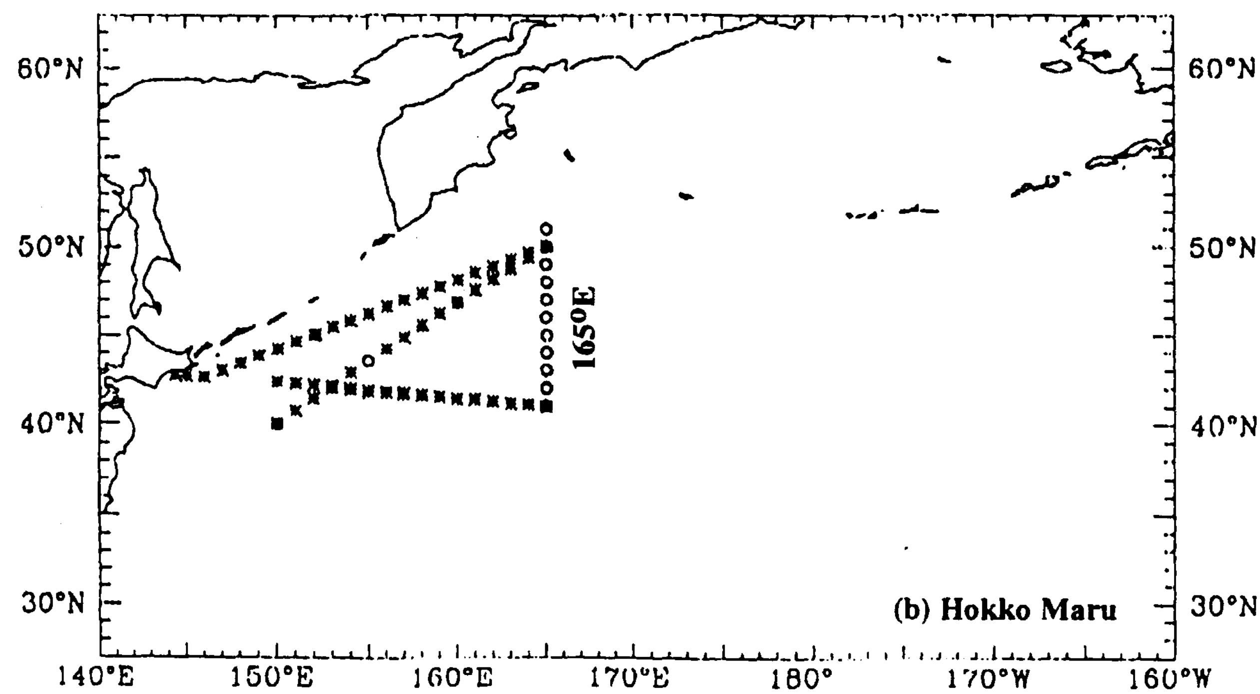


Fig. 3. Long- line repeat sections by JFA.

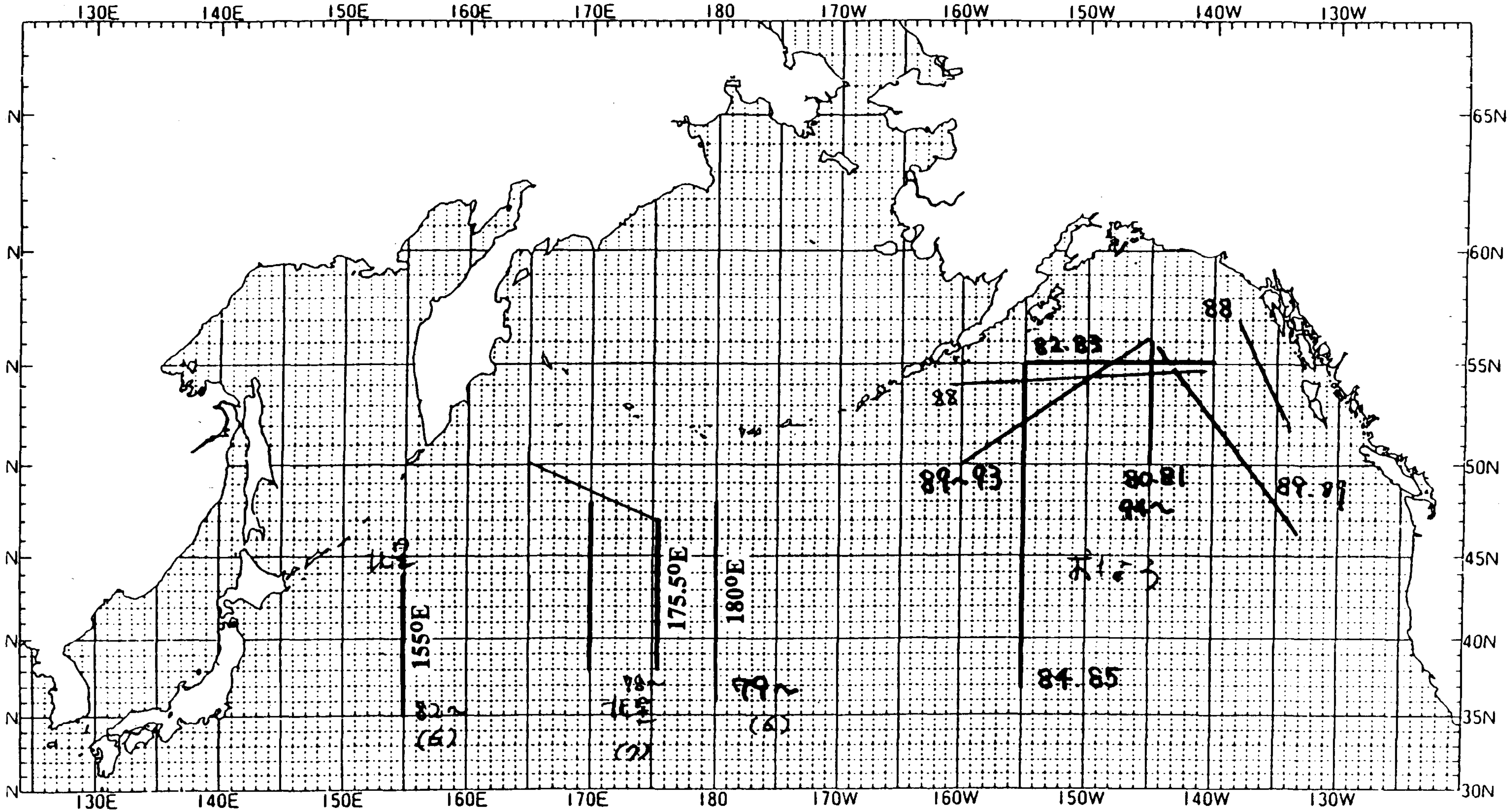


Fig. 4. Long- line repeat sections by HU.

ANNEX XVI

REPEAT XBT/XCTD SECTIONS IN THE PACIFIC

Prepared by
Dean Roemmich, Janet Sprintall, Stephen Yeager, Bruce Cornuelle (all at: Scripps Institution of Oceanography, UCSD, La Jolla CA 92093) and Richard Bailey (CSIRO Marine Laboratory, Hobart Tasmania Australia).

The longest-duration section time series in the Pacific XBT/XCTD network has been occupied approximately quarterly since 1987, sampling between Auckland, New Zealand and Hawaii or the U.S. West coast. The Pacific network now comprises about eight sections, including two across the Antarctic Circumpolar Current (ACC). The probe sampling along track is a minimum of 3 per degree, with higher sampling in regions of shorter scale, going up to 10 per degree at sharp topography, when crossing boundary currents, and near the Equator. XCTDs are dropped sparingly, due to their high cost (>12 times the cost of an XBT). XCTD sampling is determined by the variability in the historical T-S relation. Regions where there is significant T-S variability are sampled by XCTDs to fix the local T-S relation for application to the nearby XBT profiles. The network is designed to resolve currents, in order to observe the long-term variability of fluxes of mass and heat, as well as changes in the details of the Pacific circulation. The sections are meant as a complement to the one-time WOCE section sampling, to see how representative the one-time WOCE sections may be of the long-term mean. The XBTs sample to a depth of about 800 m, although we are experimenting with probes that reach deeper depths.

In one sense, each section is made up of many single-point time series, since the drops are made at specific target locations, although the repeat is obviously not exact. The repeat sections thus allow for similar analyses to the weather station temperature data. Many of the sections have now sufficient duration to give good estimates of the annual cycle, clearly showing the transition between direct surface heating and cooling in the surface mixed layer and deeper variability due to isopycnal motion. The determination of the annual cycle also yields an estimate of the interannual variability, and all of the sections show significant variability at long time scales. The unique aspect of the section time series (compared to the point sites) is their horizontal resolution, and in particular, the resolution of currents and associated fluxes.

Time series sections provide a look at the horizontal structure (in only one plane) of the seasonal cycle and interannual variability. In the longest time series, sampling the subtropical gyre for 10 years, an annual cycle of gyre spin-up/spin-down shows up clearly, and can partly be explained by local wind forcing. The section also shows clear long-term changes in the structure of the zonal transport across the section, with large scales transitioning in 1990-1991 to approximately 2 degree filaments of zonal transport. In spite of the small-scale structures, all of the sections enclosing the Tasman Box show a partial cancellation in transport variability when integrated over the entire section, so that the total transport between coasts has a reduction in variation compared to the transport variability integrated to interior points.

The mean and fluctuating heat balance of the ocean is determined by contributions from air-sea flux, storage of heat by the ocean, and advection by ocean currents. Of these three components, the contribution by ocean advection is the least well known. Estimates from one-time hydrographic surveys point to a strong role for ocean heat transport in the mean climatic balance of the earth. For example,

at 24 degrees N the Atlantic and Pacific combined carry about 2.0 pW poleward (Bryden et al, 1991), compared to 1.7 pW for the global atmosphere at that latitude. Few measurements exist of the temporal
variability of ocean heat transport, but scale analysis suggests that ocean transport fluctuations on interannual time-scales are an important contributor to large-scale heat storage anomalies.

As an example of the repeat section time series, the ocean's heat balance is described for a region of the southwest Pacific enclosed by 3 repeat sections, which is called the Tasman Box (Fig 1). The annual cycle of oceanic heat convergence into the Tasman Box is calculated from the sum of geostrophic and Ekman transports across the faces of the box. Quarterly high-resolution XBT transects have been carried out along WOCE lines PX6, PX31 and PX34 since 1991 (Fig 1). For the period 1991-95, including about 20 transects along each line, geostrophic transport through the faces of the box was calculated for the upper 400 m (relative to 800 m). Ekman transport was added, for the time of each transect, using sea surface temperature and wind stress analyses from ECMWF. Mass and temperature transport time- series were linearly interpolated in time. The mean field of horizontal mass transport was in balance, and mean heat convergence of 36 w/m^2 resulted from the temperature difference between warm waters entering from the north in the East Australia Current (EAC) and cooler waters exiting the region, mostly as eastward flow north of New Zealand. The annual cycle of heat transport into the box contained two components, one resulting from temperature differences between inflowing and outflowing surface waters, and the other from horizontal convergence/ divergence of upper ocean waters, assumed (see ii below) to be balanced by vertical velocity across the 400m surface in the interior of the box. The magnitude of the annual cycle of heat transport is 30 w/m^2 with maximum convergence in December (Fig 2).

Four additional calculations verify the annual cycle of mass and heat transport in the Tasman Box:

(i) A second estimate of ocean heat transport is obtained from the residual of ocean heat storage minus air-sea flux. The annual cycle of heat storage in the upper 400 m, based on historical XBT data in the interior of the Tasman Box (distinct from the high-resolution XBT transects along the faces of the box), indicates maximum heat gain of 180 w/m^2 in December (Fig 2). The annual cycle of air-sea flux, from the ECMWF analysis in 1991-95 averaged over the interior of the Tasman Box, yields a mean heat loss by the ocean of 22 w/m^2 and annual amplitude of about 135 w/m^2, with maximum heat gain by the ocean in December (Fig 2). The residual of heat storage minus air-sea flux (Fig 2) is in reasonable agreement with the direct calculation of ocean heat transport, given the substantial noise levels in all components. Both calculations indicate that ocean heat transport results in a maximum heat gain of about 70 w/m^2 in December.

(ii) A check on the annual horizontal convergence/divergence of upper ocean mass is obtained by calculation of vertical velocity at 400 m. Again the historical XBT dataset, averaged over the interior of the Tasman Box, is used. By assuming that the vertical displacement of isotherms at 400 m is an estimator of vertical velocity, the vertical velocity is found to have an annual amplitude of 5 x 10**-7 m/s with maximum downward velocity in October. The amplitude differs by about 20% and the phase by about 1 month from the values derived from geostrophic and Ekman transport across the faces of the box (The box area is 3.4×10^{12} m^2 and the amplitude of the annual horizontal convergence is 2×10^6 m^3/s, with maximum in November)

(iii) The temporal aliasing of quarterly-sampled XBT transects, as well as concerns regarding the 800 m reference level of the XBTs, is addressed by comparison of the time-varying surface transport derived
from XBT data with surface transport from TOPEX altimetry (kindly provided by L.-L Fu). The XBT dynamic height (0/800 dbar) and the demeaned TOPEX sea surface height are compared for 12 XBT cruises along PX6. High correlation is seen, with an rms difference less than 5 cm. TOPEX heights at 10-day intervals are used to calculate the geostrophic surface velocity and surface transport across each face of the Tasman Box. The substantial annual cycles in surface transport across XBT lines PX6 and PX31 (Fig 3) are verified by TOPEX. The annual amplitude and phase of the net surface transport into the box are similar in the TOPEX and XBT datasets. The TOPEX data indicate maximum surface convergence of about 10^4 m ^{2}/s in November.

(iv) The annual cycle of TOPEX height in the Tasman Box shows a spatial pattern which is characteristic of oceanic advection. During each 10-day interval of the annual cycle, the average departure of TOPEX height during 1993-95 from the 1993-95 annual mean was calculated. An upward bulge in the sea surface (corresponding to a positive anomaly in heat storage) enters the region from the north along the Australian coast at the start of the year. It moves southward alongshore in the EAC, reaching the separation latitude and then moving eastward along the Tasman Front. The feature moves at about 20 cm/s. Height gains along its path are about 2 cm greater than those expected on the basis of air-sea exchange and correspond to anomalous heat gain in excess of 50 w/m^2. The characteristic propagation of height along the axis of the EAC and Tasman Front, at typical advective velocities, argues strongly for an influence by ocean currents.

The annual heat balance in the Tasman Sea, as elsewhwere, is dominated by ocean heat storage and air-sea flux (Fig 2); however, oceanic advection near the western boundary of the subtropical gyre plays a substantial role. We have stressed the annual cycle here because the variety of datasets presently available allow independent checks on the calculation at annual periods and because many realizations of the annual cycle provide statistical confidence. Our intention is to take advantage of the powerful synergy between TOPEX altimetry and XBT data in order to provide closure to the heat budget, including error estimates, at periods of a year and longer. An additional use of TOPEX altimetry will be for estimation of the heat storage term, so that all components of the heat budget can have a common time frame. All tat is required for estimation of the heat budget on interannual time-scales is a sustained period of observations. Preliminary indications are that ocean heat transport has a major influence on the heat balance at interannual time-scales. A recent study by Sprintall et al. (1995) showed that advective heat loss from the Tasman Box in early 1992 preconditioned the region for a strong cold anomaly later in the year which had disastrous economic consequences during New Zealand's winter.

REFERENCES

Bryden, H., D. Roemmich, and J. Church, 1991: Ocean heat transport across 24ON in the Pacific. Deep Sea Res., 38, 297-324.

Sprintall, J., D. Roemmich, B. Stanton, and R. Bailey, 1995: Regional climate variability and ocean heat transport in the southwest Pacific Ocean. J. Geophys. Res., 100, 15865-15871.

Figure captions

Figure 1. The Tasman Box region of the south-west Pacific Ocean, showing the three high resolution XBT transects which define it (red lines). Colour contours show the (1993-95 average) evolution of smoothed sea surface height anomaly (cm) during austral summer, calculated as the deviation from the 3-year annual mean of the Topex data.

Figure 2. Components of the annual cycle of heat in the Tasman Box (W/m^2) of air-sea flux calculated from 1991-95 ECMWF data (red); heat storage from historical XBT data from all years (black); ocean heat transport calculated from 1991-95 geostrophic and Ekman transport across the faces of the box (dark blue); ocean heat transport as the residual of storage minus air-sea flux (light blue, offset by 14
w/m^2 which is the difference between the mean of the residual calculation, 22 w/m^2; and the mean of heat transport from the direct method, 36 w/m^2.

Figure 3. Across track surface geostrophic transport (10^4 m^2/s) estimated from individual XBT cruises between a) Auckland-Fiji (PX6); b) Brisbane-Fiji (PX31); c) Wellington-Sydney (PX34) and d) the net surface geostrophic transport into the Tasman Box.

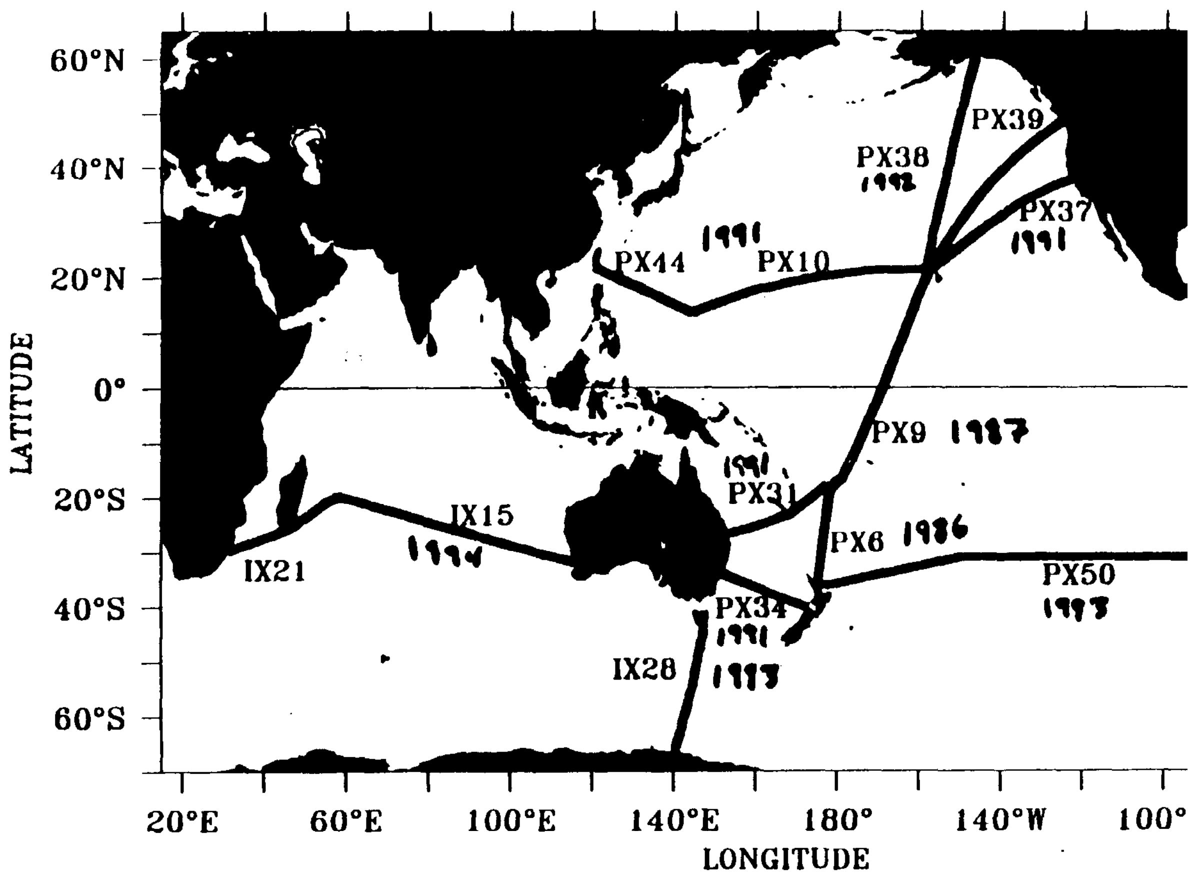
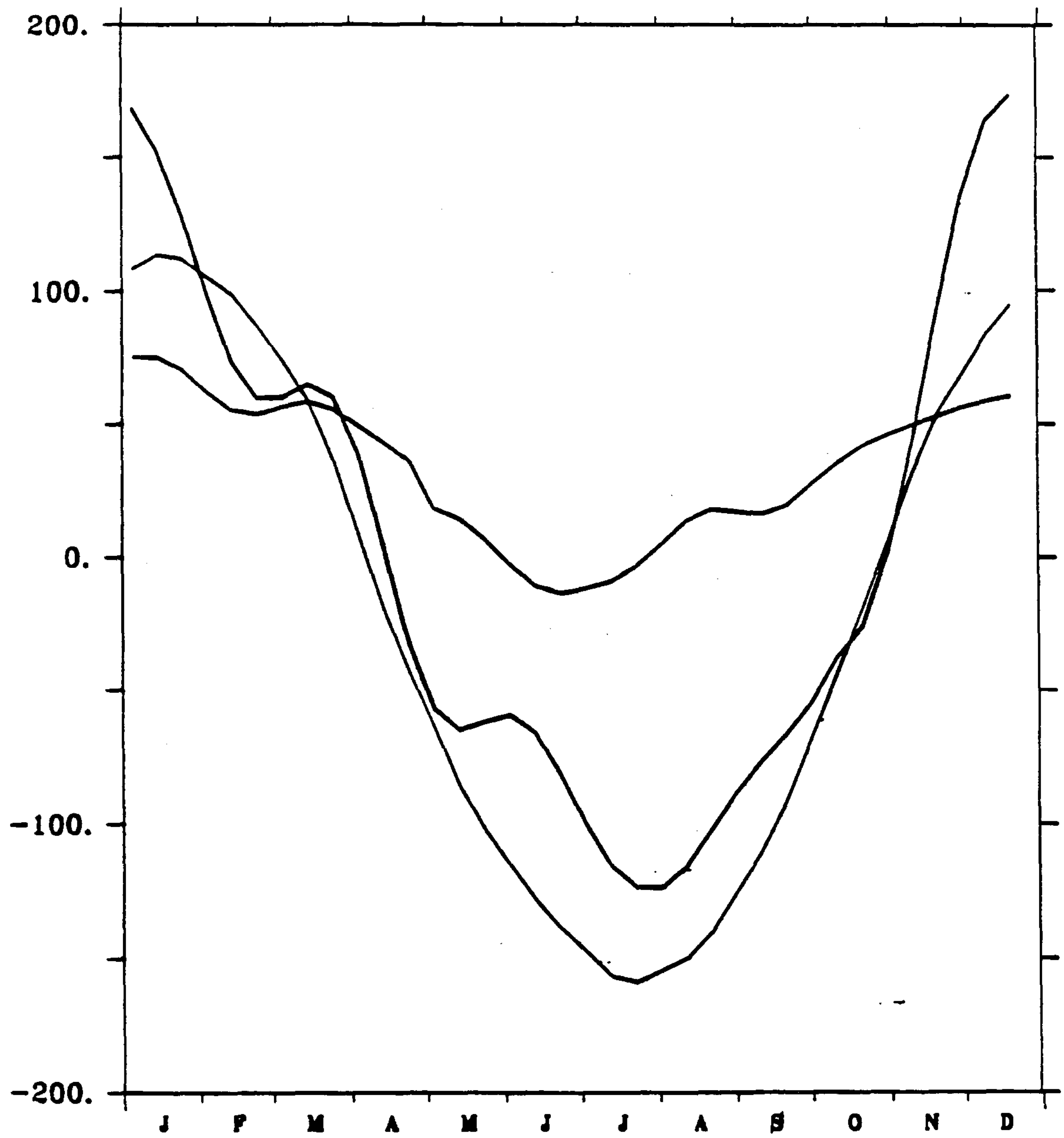


Figure 1. The Tasman Box region of the south-west Pacific Ocean, showing the thre XBT transects which define it (red lines). Colour contours show the (1993-95 aver smoothed sea surface height anomaly (cm) during austral summer, calculated as th the 3-year annual mean of the Topex data.

annual mean, ave   Ocean heat transport 33 W
ECMWF heat loss   25 W
(Could be required to balance)

Annual Cycle of Heat in the Tasman Box (W/m**2)



Air-Sea Flux, ECMWF (1991-95)
Ocean Transport, XBT and TOPEX (1991-95)
Heat Storage, TOPEX (1993-95)

Note that Ocean Heat Xport plays an amplifying rôle

Figure 2. Components of the annual cycle of heat in the Tasman Box (W/m^2) of air-sea flux calculated from 1991-95 ECMWF data (red); heat storage from historical XBT data from all years (black); ocean heat transport calculated from 1991-95 geostrophic and Ekman transport across the faces of the box (dark blue); ocean heat transport as the residual of storage minus air-sea flux (light blue, offset by 14 w/m^2 which is the difference between the mean of the residual calculation, 22 w/m^2, and the mean of heat transport from the direct method, 36 w/m^2.

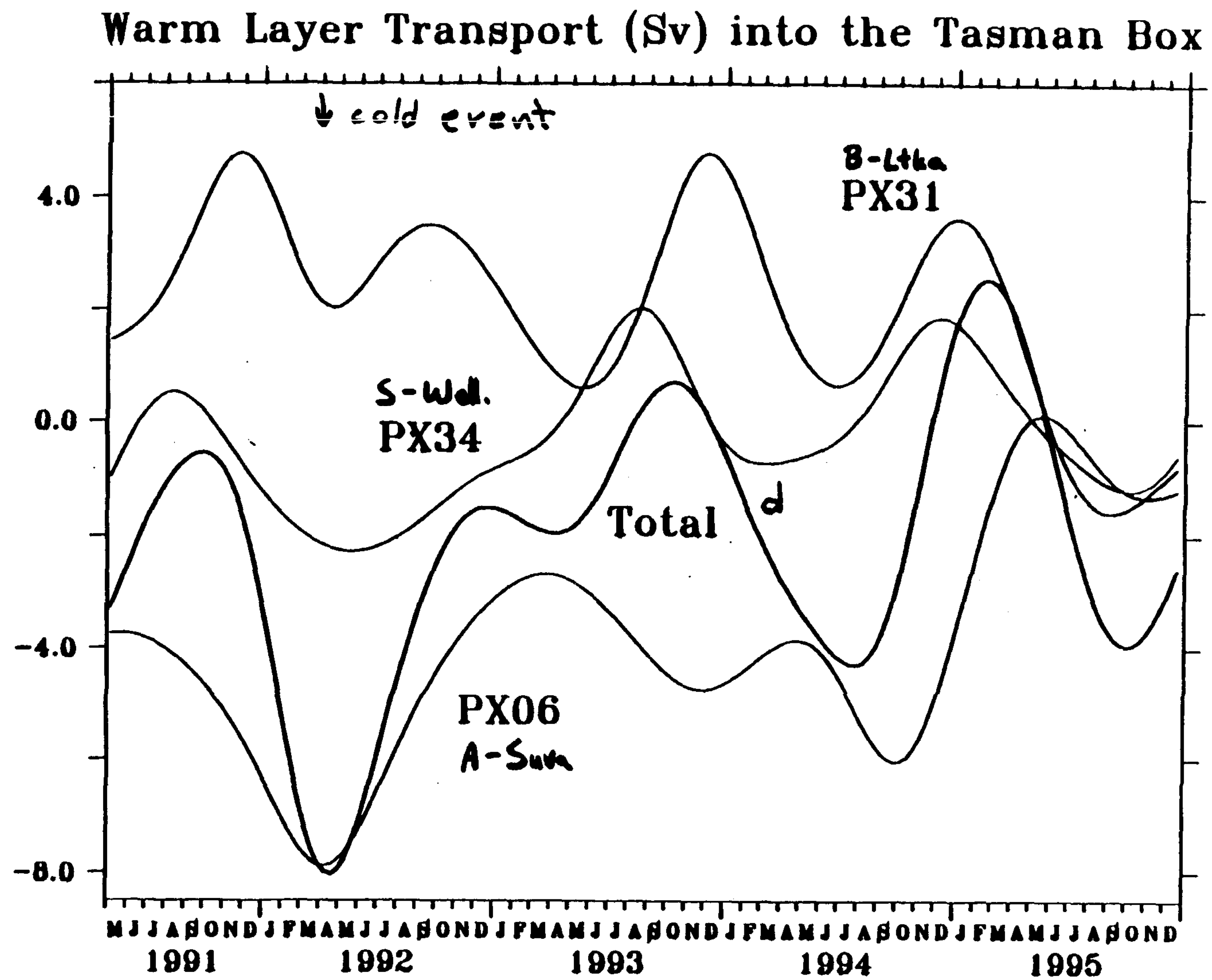


Figure 3. Across track surface geostrophic transport (10^4 m^2/s) estimated from individual XBT cruises between a) Auckland-Fiji (PX6); b) Brisbane-Fiji (PX31); c) Wellington-Sydney (PX34) and d) the net surface geostrophic transport into the Tasman Box.

ANNEX XVII

ASSIMILATION OF TIME SERIES OBSERVATIONS IN MODELS

Prepared by Detlef Stammer

The purpose of this talk is to discuss the role of time series observations in the context of ocean state estimation (often referred to as assimilation). It is also intended to illustrate the complexity of the ocean general circulation and its transport properties which puts stringent demands on a global observing system. Generally the role of ocean time series in models is related to (i) testing and improving ocean general circulation models (OGCMs) and the physics embodied therein, (ii) obtaining statistical descriptions of the ocean which are necessary for model testing and ocean state estimation, and (iii) constraining models by observations to the observed ocean state.

A primary objective of global experiments such as WOCE is to obtain an understanding of the absolute time-varying large-scale circulation of the world ocean, and their impact on climate. To meet this goal, all available data need to be evaluated jointly and in away consistent with data uncertainties and with our best knowledge about ocean dynamics as it is embodied in modern Ocean General Circulation Models (OGCMs). All important aspects of the general circulation and its transport properties can be studied subsequently from the estimated ocean state and its uncertainty.

What is shown here today are first results of a global estimation system for the time-evolving, absolute general circulation of the ocean. Thesystem is based on the general circulation model and its adjoint, which have been developed recently at the Massachusetts Institute of Technology. The forward component is the general circulation model developed by John Marshall and his group and is described in Marshall et al. (1997a,b). The adjoint (backward) component is obtained from the forward component by using the Tangentlinear and Adjoint Model Compiler (TAMC) which was written by Ralf Giering (Giering and Kaminsky, 1997). This system proved extremely flexible since it allows one to easily regenerate the adjoint code whenever a change in the forward code is necessary.

The present focus is on the evolving global circulation as it emerges from altimetric time series measurements. Precise and accurate altimetric sea surface height observations are now available on a routine basis from missions such as TOPEX/POSEIDON (T/P) and represent one of the most complete and important time series observations of the ocean. Moreover, perspectives for sustained altimetric observations are more firm than for any other component of a global ocean observing system. Combined with a general circulation model, high-resolution altimetric observations carry unprecedented information about the large-scale circulation, because they provide a dynamical surface boundary condition for the general circulation (Stammer and Wunsch, 1995). Wunsch (1997) discusses the partitioning of sea surface variability in terms of vertical dynamical modes.

Present results are preliminary. The interest was to gain experience with the full problem of combining a GCM with global and time-varying data sets, so as to gain assurance that there were no major obstacles to a more definitive, but more costly calculation. For this purpose a global model with 2° horizontal resolution and 20 levels in the vertical has be used. To constrain the model to T/P data, the initial potential temperature (θ) and salinity (S) fields are modified, as well as the surface forcing fields over a full year. The first guess forcing fields are taken from the daily analyses of the National Center for Environmental Prediction (NCEP) after averaging over 10 day periods; initial θ, S fields are obtained from the Levitus et al. (1994) January climatology after a dynamical model adjustment over a 1 month period. In the estimation procedure, a combination of changes in the initial state and the forcing fields (often referred to as control terms) is determined which leads to a best fit in a least-squares sense of the model state with respect to observations and their uncertainties over the full data period.

Here the observations are absolute T/P sea surface height data relative to the most recent EGM96 geoid model which are provided as 10 day averages on the model grid over the one year period covering 1993. Because the model in its present spatial resolution is not capable of producing small-scale variability, structures on spatial scales below about 500 km were removed from the T/P observations. Moreover, the model was constrained individually in its mean and time-dependent components of surface pressure, thus separating the geoid error from the distinctly different error in the time evolving components. Surface forcing fields (wind stress, heat and fresh water fluxes) and the mean hydrography from the full one year run were required to stay acceptably close to their initial guesses. For the hydrography the annual mean Levitus et al. (1994) fields are used as observations. Formally all this leads to the following cost function:

$$\begin{aligned} J = & [\frac{1}{2}[W_{geoid}(\overline{\zeta} - \overline{\zeta}_{tp})^2 + W_{\zeta}(\zeta' - \zeta'_{tp})^2 + W_{\tau_u}(\tau_u - \tau_{uncep})^2 \\ & + W_{\tau_v}(\tau_v - \tau_{vncep})^2 + W_{H_Q}(H_Q - H_{Q_{ncep}})^2 + W_{H_F}(H_F - H_{F_{ncep}})^2 \\ & + W_T(\overline{T} - \overline{T}_{lev})^2 + W_S(\overline{S} - \overline{S}_{lev})^2], \end{aligned} \qquad (1)$$

in which the overline on a symbol indicates averages over the one year estimation period, and all other terms represent 10-day averages of model state and observations. In its present setup with 2° spatial resolution and 1 year of data, there are 1.5 x 10^6 elements in the control vector. The weighting matrices in front of each term are important elements in determining a specific solution of the estimation process. Time series observations of the ocean play a crucial role in determining those prior statistics. In principle one needs to specify the full error covariance matrices of each element included in (1). In practice, however, this is not yet possible due to the lack of sufficient information. In the present run, we included the diagonal of the EGM96 geoid model error covariance as W_{geoid} in front of the ζ (overline) term. The time dependent term was weighted by a constant $W_{\zeta} = 3.5$ cm^2 error in the smoothed T/P data. Wind stress and surface flux fields were weighted by 1/3 of their local variance over the one year period, and the differences in the mean hydrography were penalized by uncertainties ranging in the vertical from 2°C near the surface to 0.2° C at depth for potential temperature, and .3 ppm to 0.015 ppm in salinity. Results from this experiment illustrate a time-evolving model state which is consistent with: (1) the absolute T/P sea surface height relative to EGM96 geoid model, (2) the time dependent T/P sea surface height component, (3) the daily NCEP surface fluxes of momentum, heat and fresh water (averaged over 10 days), and (4) the annual mean Levitus θ, S climatology. Final results differ from either the model or the data alone.

During this talk only a few examples can be shown to illustrate the flavor of the model output whic seems now in reach with respect to a global data synthesis. Apart from the missing eddy variability, major elements of the general circulation are present in the results. In contrast to the pure T/P observations, various spurious elements in the data due to errors in the geoid are visually absent in the combined estimate. This is especially clear in the tropical Pacific and the North Atlantic where previously known inconsistencies in the T/P absolute ssh data led to unacceptable features in the inferred ocean circulation (Stammer and Wunsch, 1994).

Variations in the NCEP fluxes of momentum, heat and fresh water emerging from the optimizationare overall consistent with accepted uncertainties in the meteorological analyses. Changes in the estimated model state relative to the unconstrained model show spatially coherent temperature changes on eddy to basin scales scales. Maximum amplitudes are associated with western boundary currents in the northern hemisphere and along the Antarctic Circumpolar Current. As an example, the path of theNorth Atlantic Current is characterized by increased temperatures relative to theunconstrained solution.

The impact of the T/P data on estimates of oceanic transports can be illustrated from meridional heat transports estimated from the Atlantic Ocean, the Pacific Ocean and the Indian Ocean. It is apparent that in all cases the time-varying component in the transports is substantial and increases towards the equator. The presence of those fluctuations in mass and heat transports, if real, puts stringent demands on global climate observing systems. In the North Atlantic, the T/P data inquire an increase in the model-alone estimate of northward heat transport from about .8 PW to almost 1.2 PW at 25°N.

Present results are preliminary for various reasons, including a relatively short estimation period and too coarse a model resolution. Improvements are on their way and include an increased model resolution to 1° or higher and an extended estimation period to 4+ years of T/P data, as well asan improved representation in the topography (e.g., in the present preliminary run the Indonesian throughflow was artificially closed). Moreover, a full geoid error covariance matrix will be considered as well as other improvements in the remaining weights. Another effort presently addressed at MITis the generation of uncertainty estimates of results. Information from in situ data such as XBTs, ATOC temperature integrals,floats and the WOCE hydrography will first be used as independent informationto test the improvement of the estimate above the unconstrained run. They will subsequently be included in the estimation process. Special attention is necessary for the hydrographic data weights which in principle requires the knowledge of the 3-dimensional frequency-wavenumber spectrum of the ocean temperature and salinity field. Ultimately one needs error covariance estimates for all components involved, including the model itself and the atmospheric forcing fields provided by meteorological centers. With an even further increased model resolution, results will aid the complete basic description of the ocean, and its variability. They will lead to an improved understanding of fluxes and inter-basin exchanges and potentially will be the basis of studies of the carbon cycle and biological processes in the ocean.

With respect to a sustained global observing system it is important to note that the present estimation system can be used to optimally design an observing network based on scientific figures of merit such as the poleward heat transports and related through flows through key locations, e.g., the Drake Passage of the Indonesian throughflow. This is an important issue which needs to be addressed in the near future to come up with a firm scientific judgement on required long-term ocean observations -their locations and variables of interest.

Giering, R., and T. Kaminsky, Recipes for adjoint code construction, Journal of Computational Sciences, in press, 1997.

Levitus, S., R. Burgett, and T. Boyer, World Ocean Atlas 1994, vol. 3, Salinity, and vol. 4, Temperature, NOAA Atlas NESDIS 3 & 4, U.S. Dep. of Comm., Washington, D.C., 1994.

Marshall, J., A. Adcroft, C. Hill, L. Perelman, and C. Heisey, A finite-volume, incompressible navier-stokes model for studies of the ocean on parallel computers. J. Geophys.\ Res.}, 5753--5766, 1997a.

Marshall, J., C. Hill, L. Perelman, and A. Adcroft, Hydrostatic, quasi-hydrostatic and non-hydrostatic ocean modeling. J. Geophys.\ Res.}, 5733--5752, 1997b.

Stammer, D. and C. Wunsch, Preliminary assessment of the accuracy and precision of TOPEX/Poseidon altimeter data with respect to the large scale ocean circulation, J. Geophys. Res.}, {\bf 99}, 24000 -- 25500, 1994.

Stammer, D. and C. Wunsch, The determination of the the large-scale circulation of the Pacific Ocean from satellite altimetry using model Green's functions. J. Geophys.Res, 101 (C8): 18,409--18,432, August 15, 1996.

Wunsch, C., The vertical partition of oceanic horizontal kinetic energy and the spectrum of global variability, J. Phys. Oceanogr., in press, 1997.

ANNEX XVIII

OVERVIEW OF CLIVAR UPPER OCEAN LONG-TERM OBSERVATIONS

Prepared by Robert Weller

The following draws from the various meeting reports and planning documents available from the CLIVAR project office. There is a CLIVAR Upper Ocean Panel (UOP) and there are the CLIVAR Numerical Experimentation Groups (NEGs). NEG-1, for seasonal to interannual climate signals, and NEG-2, for decadal to centennial have met, as have the various groups and individuals working to prepare an implementation plan for CLIVAR.

The CLIVAR UOP is working to develop implementation strategies for a sustained upper ocean measurement system in support of CLIVAR objectives in prediction, predictability, monitoring, and basic research. In doing so it is considering in particular: 1) ENSO prediction and predictability, 2) identification and understanding of other predictable elements of the climate system, 3) understanding decadal scale variability of ENSO, and 4) measurements of the global redistribution of heat and mass on decadal and longer time scales. In addition it has the tasks of evaluating the effectiveness of existing observing systems and assessing the appropriate mix of ocean observing platforms, including new technologies.

Based on a review of the work by the Ocean Observations System Development Panel (OOSDP), the UOP took on as initial activities:

SST: Development of a strategy to improve SST products, looking at improved quality control of volunteer observing ship (VOS) SSTs, use of ATSR satellite data to reduce large scale biases and improve coverage, and the number of locations of high quality VOS needed.

Salinity: Review work to date, look for areas in which salinity is critical for monitoring deep and intermediate water formation and toward developing global strategy.

Wind stress: Assess impacts of various products on climate prediction and identify where additional in situ winds are needed.

Fluxes: Consider in context of estimating flux divergence in ocean; assess accuracy of NWP and satellite flux products for estimating flux divergence, and modeling seasonal and interannual variability in ocean.

Sea Ice: Work with ACSYS to monitor ice extent and thickness.

Upper Ocean Mass and Circulation Fields: Consider ENSO prediction and extensions to global tropics, the optimal mix of existing Pacific systems, and strategy for expansion to global tropics, with emphasis on in-situ winds and subsurface temperature. Consider decadal variability by reviewing recommendations to date on sustained upper-ocean observing systems, prioritizing which elements of TOGA and WOCE observing systems should be maintained based on synergy with other observing systems, continuity of time series, and feasibility and cost of continuation. Develop a strategy for maintaining select, high-density XBT lines to enhance satellite altimeter estimates of mass and heat transport.

Sea Level: Assess usefulness of satellite altimetry used with in-situ observations for global coverage of upper ocean mass field.

The CLIVAR UOP is beginning to work toward a quantitative determination of how well the ocean is being observed using analyses based on just data or those produced by assimilation; to identify shortcomings in present observing systems, models, and forecast systems; to determine the observations needed to initialize forecast systems; and to recommend an uppe- ocean observing system for CLIVAR.

The CLIVAR Dec-Cen foci are: the decadal mode in the Pacific with SST anomalies around the equator and strong mid-latitude anomalies of the opposite sign; decadal variability in ENSO; variability of the Atlantic sub-tropical dipole; variability in the North Atlantic Oscillation (NAO); and abrupt climate change in the Atlantic. In support of these, they recommend maintaining existing ocean and atmosphere observing systems and two new elements: 1) a meridional array measuring surface meteorology , SST, and T(z) along 170°W from the equator to 40°N to explore the processes that produce SST and upper-ocean thermal variability there; and 2) meridional arrays along 10°W south from the equator to 15°S and along 30°W north from the equator to 15°N to explore the processes that produce the subtropical dipole. The CLIVAR NEG-2 (dec-cen) has as activities: coupled-model intercomparisons, development of standardized forcing scenarios, refinement of the ocean component of coupled models, conducting idealized sensitivity experiments, and detection of climate change.

The CLIVAR GOALS foci are: improving ENSO predictions by refining the observational system and the models; developing a better understanding of the interannual variations of the Austral-Asian monsoon; developing a better understanding of the Pan American monsoon system; and initiating a study of the interannual variability of the African climate system. The CLIVAR NEG-1 (seasonal to interannual) has as activities: intercomparisons of model simulations, seasonal predictions, intercomparisons of ocean analyses, and intercomparisons of ocean model simulations forced by NCEP, ECMWF, and GSFC reanalysis wind products.

The CLIVAR ACC foci are: prediction, using coupled models of future climate change in response to changes in radiatively active gases and aerosols; detection of anthropogenic climate change within the natural variability on decadal scales; and developing regional predictions of long-term climate change.

What CLIVAR Needs

To an etxent, the work of the OOSDP has fixed the starting point for CLIVAR's consideration of sustained observations. A basic Ocean Observin System (OOS) for CLIVAR would measure: SST, surface wind, surface heat and freshwater flux, surface and subsurface salinity, upper-ocean temperature and velocity, heat and water transports and budgets, sea level, and sea ice.

The CLIVAR Implementation Plan is being written and provides indications of further needs. The Coupled Model Intercomparison Project (CMIP) has indicated some upper ocean and surface fields that would be extracted from various models for intercomparison. As a reality check, the observing system should also provide the following:

* Seasonal and annual mean global maps of surface air temperature, precipiation, sea level pressure, wind stress, net heat flux, net freshwater flux, SST, SSS (sea surface salinity), and ice cover;.
* Global maps of the trend in annual mean surface air temperature;
* Measures of the meridional overturning and horizontal mass transport, globally and in each basin;
* Seasonal mean zonal sections of T(z) and S(z) for each basin.

Besides improved SST and T(z), work with the NCEP coupled model (Leetmaa) suggests that there is value in assimilating surface and upper ocean salinities as well as temperatures. The salinity field in the coupled model was not, until recently, constrained to climatology. Once this is done, approximately 20% of the error in mean sea level is removed.

In support of AMIPs and AGCM validations, CLIVAR needs:

* surface flux fields,
* surface fluxes in tropical Pacific, Atlantic,
* surface fluxes in cold tongue/ITCZ, stratus deck regions..

In support of OMIPs and Ocean Model Validations, CLIVAR needs:

* "state of the art observed fluxes" to force ocean models to see if SST anomalies can be simulated;
* T(z), SST, S(z) - initialization and assimilation;
* high quality observed fluxes to see if data-assimilating ocean models produce similar surface fluxes;
* upper ocean T(z), S(z), u(z) in cold tongue.

The provision, through time series stations at fixed sites (moorings) and through increased sampling by VOS, of improved air-sea fluxes is practical at present. The development of improved moored meteorological sensors during WOCE and TOGA has led to moored systems that can achieve 10 W/m^2 accuracy in month-long means of the net heat flux. With the scheduling of local intercomparisons, even better accuracy was achieved during TOGA COARE (Weller and Anderson, 1996). Deployments in COARE and more recently in the Arabian Sea (for one year, October 1994 to October 1995) have shown that such accurate in-situ fluxes reveal that fluxes from numerical weather prediction AGCMS have large biases, particularly in cloud-influenced fields such as shortwave radiation, differing from each other and from the in-situ fluxes. Biases in Q net are as large as 100 W/m2.

Having good fluxes is not only essentail to motivating improvements to AGCMs and coupled models but their availability is also a key element of work on ocean models and in process studies to be done in CLIVAR. Having accurate fluxes removes uncertainty in surface forcing as an obstacle to these efforts.

For understanding the ocean's role in monsoons, CLIVAR seeks to:

* expand XBT lines to monsoon oceans;
* deploy moorings, drifters, ALACE floats in Indian Ocean;

* establish long-term monitoring of SST anomalies to understand their role in monsoons;
* produce SST maps to look for teleconnections;
* install rain gauges, incoming SW and LW, humidity sensors on moorings;
* upgrade meteorological sensors on VOS in monsoon oceans.;

In the Atlantic, CLIVAR is considering:

* ALACE floats for T(z), S(z),
* 7 moored profiling CTDs - for NAO study, for mode water convection.

In the Pacific, CLIVAR is considering:

* Pacific - XBT lines, broadscale and high resolution;
* S(z) - where (E-P) is large, river runoff important;
* drifters - SST, SSS SLP, near-surface velocity;
* altimetry - SSH;
* expanding TAO to Kuroshio extension;
* repeat hydrography - such as Line P;
* improvement of surface fluxes;
* monitoring boundary currents;
* satellite SST, SLH, winds;
* VOS met and XBT.

In the Southern Ocean, CLIVAR needs observations of:

* sea ice extent;
* ice thickness;
* surface and subsurface T and S;
* surface forcing fields (SST or heat flux, SSS or freshwater flux, wind stress);
* chokepoint CTD sections;
* periodic (every 5 years) CTD sections;
* mid-latitude zonal sections;
* Palace floats for upper ocean T(z), S(Z);
* surface drifters (SST, SLP, SSS).

In support of its anthropogenic climate change effort CLIVAR needs:

* ocean analogs of WMO Reference Climate Stations;
* daily max/min surface temp;
* daily precipitation;
* sea level pressure, at sites, global maps;
* hurricane/typhoon tracks and intensity.

There is overlap between the CLIVAR NEGs and the CLIVAR Upper Ocean Panel, but their planning is not yet integrated with the plans of other elements of CLIVAR that contributed to the draft implementation plan. It is at present difficult to define an OOS for climate that would be synergistic with the observational efforts of CLIVAR with any more detail than already specified by OOSDP and adopted by the CLIVAR Upper Ocean Panel. However, the draft implementation plan reinforces the importance of an obsrvational strategy that can provide good surface fields (SST, SSS, meteorology, air-sea fluxes) and upper ocean temperature and salinity profiles (T(z), S(z)).

ANNEX XIX

SOME REMARKS REGARDING LONG-TERM IN SITU MEASUREMENTS IN THE SOUTHERN OCEAN

Prepared by W. D. Nowlin, Jr.
Collaborators:
Ricardo Locarnini, Alejandro Orsi, Ray Peterson, Thomas Whitworth III

Introduction and Suggested Program

We now have time series from the North Atlantic and the North and tropical Pacific oceans that are long enough to explore for decadal-scale variability. Practically everywhere that records are long enough to meaningfully extract signals, there is energy at seasonal to decadal scales. It seems likely that detecting and describing energetic signals at even longer periods will naturally occur with records of adequate length. With such records, it is then possible to plan further measurements in those oceans to understand the nature of energetic long-term variability and their possible relations to climate variability.

Meanwhile in the Southern Ocean, very few long time series of in situ observations exist. With few exceptions (e.g., the recently identified circumpolar wave), we do not even know what seasonal to decadal variability exists, much less its description. Therefore, it seems scientifically justified to **initiate a program of exploratory monitoring in the Southern Ocean** with a focus on describing climate-scale variability and key climate processes.

Possible objectives of such a program are to detect, describe, and study variability of:

- Deep and bottom water formation (sample in source regions-this may require conventional cruises with follow-on Eulerian measurements from expendable instruments deployed by supply ships.);

- "New" water input into the interior ocean (using supply and research vessels, place expendable current/temperature/conductivity recorders along known pathways);

- Sea ice volume production and exports (begin program at limited number of critical sites);

- Upper ocean thermal and salinity structures (regional focus initially--it would be easiest to begin in the Ross Sea as a pilot project);

- SST, surface wind, and sea level pressure (improvements to meteorological fields via add-ons or changes to the present surface drifter program);

- Transport variations of the Antarctic Circumpolar Current (limited monitoring has been shown to be feasible at check points); and

- The circumpolar wave described by Peterson and White (focus initially on the Drake Passage and a few other accessible regions).

The foregoing are not the only phenomena that might be considered. However, they are known features or phenomena that are expected to have long time variability and be related to variability of climate states of the ocean—and perhaps the atmosphere.

Building Blocks (or, some history and specifics)

There are four blocks on which a Southern Ocean monitoring program should be built: (1) past monitoring as part of research programs, (2) ongoing quasi-operational time series, (3) monitoring as part of ongoing/proposed research programs, and (4) new ideas for monitoring.

(1) **Past research programs** have made time series of limited duration in the Southern Ocean that may provide useful information on which to design longer-term monitoring programs. One such is the International Southern Ocean Studies (ISOS) program, that made measurements of the structure and transports of the Antarctic Circumpolar Current (ACC) from 1974 through 1981. Another is the BIOMASS program from which many repeat measurements of upper ocean thermal structure resulted.

ISOS carried out a five-year series of pressure measurements across the ACC at Drake Passage that, together with a year-long heavily instrumented current meter array across the passage, provided estimates of barotropic versus baroclinic variability of the ACC transport and gave tantalizing glimpses of what appears to be pseudo-periodicity at seasonal-annual periods and interannual variability. Figure 1 shows time series of ACC volume transport constructed from deep pressure measurements across the Drake Passage and a linear model relating the pressure difference to total transport (the model was derived from one year of simultaneous measurements of the transport and the pressure difference).The records were not long enough to establish the nature of such variability with certainty. In Figure 2 are shown autospectra of 500-m pressure and geopotential anomaly at the northern (NP and NT) and southern (SP and ST) sides of Drake Passage and of the pressure difference (delta P_{500}) and net transport; seasonal to annual peaks are evident. Attempts to relate the Southern Hemisphere wind fields with ACC transport time series were not successful; perhaps that was because of the approaches taken, perhaps because of the quality of the wind fields.

(2) **Ongoing quasi-operational time series include**: (i) a surface drifter program, aimed principally at improving numerical weather prediction activities through measurements of SST, surface pressure, and in some cases surface wind, but also collecting data on near surface currents; (ii) sea level observations at selected locations; and (iii) limited sea ice monitoring.

There is the feasibility of a VOS program using Antarctic supply ships. This idea has been discussed for decades, notable with SCAR and IOC. However, only for specific initiatives has such sampling been achieved; e.g., during the latter 1970s, Wm. Emery arranged broad VOS sampling from research and supply vessels with support from ISOS.

Any ongoing monitoring should be examined to assess what is being learned and whether needed additional parameters could be added. For example, questions to ask of the surface drifter program are whether the space-time retrievals of SST and sea level pressure are now adequate when used with other data, e.g., AVHRR from satellites, and prediction programs. Should sampling densities be changed? Are added parameters recommended?

(3) **Ongoing and proposed research programs** are attempting to add some time series of interest. These should be considered carefully and, as reasonable, included in a program of Southern Ocean exploratory monitoring for climate-scale variability.

Tom Whitworth, Dale Pillsbury, and Ray Peterson have been carrying out measurements of pressure, temperature, and conductivity at approximately 1000 m depths across the ACC south of Africa and Australia; Ian Vassie, with support from the British Antarctic Survey, has made similar measurements south of South America. This work follows directly from the ISOS measurement program. Some results are shown in Annex A.

Ray Peterson and Warren White are attempting to obtain additional information with which to better understand the nature of the circumpolar wave reported by them last year. A statement from Peterson regarding their current program and aspirations for long time series is given in Annex B.

Eberhard Fahrbach has a relatively long suite of current meter measurements in the Weddell Sea. Unfortunately, time ran out before he could be contacted for details.

(4) Some **new time series** measurements for interesting exploratory monitoring are suggested here. These suggestions are all aimed at detecting and describing variability in production and outflow of new waters in the Southern Ocean. The first three categories deal with dense water production and outflow from around Antarctica.

(4.1) Monitoring outflow from the continental shelf at selected likely sites of new deep/bottom water production based on best information.

Ricardo Locarnini has demonstrated that both high and low salinity versions of bottom water are produced in the Ross Sea. Figure 3 shows bottom salinity for a region covering the production areas of both types which are clearly delineated by salinities less than 34.70 and greater than 34.72. Figures 4 and 5 show salinity in vertical sections (locations indicated in Figure 3) for synoptic observations across source regions of both types. Potential temperature-salinity plots are shown in Figure 6 to illustrate the difference between low salinity waters at stations 157 and 154 and higher salinity waters at station 83 (locations shown in Figure 3).

Expendable recorders could monitor the outflows from the continental shelf along each of these potential paths in the Ross Sea. A small number of likely deep/bottom water production sites are identified in addition to those in the Ross Sea. As is the case for the Ross Sea, outflows from the Amery Basin and southern and northwestern Weddell Sea are relatively close to the routes followed by resupply ships (of different nations) every year, and so monitoring could be arranged.

(4.2) General monitoring of deep/bottom water formation and input into the interior via the eastward near-circumpolar flow near the Antarctic continental shelf edge (sometimes called the Antarctic coastal current).

Based on the work of S.-J. Kim on the Antarctic coastal current (or fronts over the Antarctic continental slope), it is likely that new water is transported some distance from where it is formed before it is input into the interior. It also is likely that production rates at various formation regions differ from year to year. It could even be true that input sites vary, perhaps depending on the local conditions and properties of new water being formed.

Then the problem of estimating new water production and input is similar to the problem of estimating northward transport of AABW into the northern basins of the global ocean. We can't monitor (or even identify) all the production sites, and we can't measure upwelling rates in the ocean interior, so we monitor deep western boundary currents. If the Antarctic coastal current is the Antarctic equivalent of the deep western boundary currents, it makes sense to monitor its characteristics and volume transport at several locations for as long as practicable.

Expendables are probably the likeliest method, and we should be able to identify likely candidate sites from Kim's work. A long-term program might start with pilot measurements at several places, followed up with more extensive measurements using multi-instrument, multi-level arrays. We'd need to measure temperature and conductivity as well as currents.

(4.3) Monitoring the properties and volumes of young Antarctic waters that have a significant impact on the ocean's climate. It should be feasible with arrays of expendable current meters to monitor the variability in properties of a few crucial, major Southern Ocean water masses.

To detect variability in the **densest types of bottom waters**, expendable current meter arrays could be maintained by supply vessels along the base of the continental slope downstream from considered major source regions. Five areas are shown in Figure 7. Meters would be placed close to the bottom every 500-m isobath from 2000 m to 4500 m. The exact positions could be dictated by the most frequented routes.

To detect variability in the **new shelf water mixtures** injected into the interior at levels well above the bottom, three candidate locations are shown in Figure 8. At these places the subpolar circulation facilitates the export of Antarctic shelf front water directly into the circumpolar waters carried by the ACC. Arrays of disposable current meters could be deployed at multiple depths—perhaps along the 1000-m isobath near the Davis Sea and Wilkes Land and along the sill of the South Scotia Ridge.

To detect variability in **Antarctic Intermediate and Mode water** and lower Circumpolar Deep Water, monitoring locations as indicated by circled Xs in Figure 8 might be selected based on the physics. The positions should be north of the climatological position of the Subantarctic Front and reasonably close to the Falkland Is., Crozet and Kerguelen Is, and the eastern edge of the Chatham Rise. The final selection must depend on the physics and the availability of vessels to deploy new moorings every one or two years. One could use several expendable moorings at each location or moorings more heavily instrumented in the vertical than for the preceding applications; instruments must extend up to intermediate depths.

Annex A: Monitoring across the Antarctic Circumpolar Current
Provided by Thomas Whitworth III

The base map in Figure A-1 shows the locations of instruments at the South American and African choke points. The time series in Figure A-2 is of north-south pressure difference smoothed with a 21-day half-amplitude filter; note that the amplitudes are similar, suggesting that the transport variability at the two choke points is similar. Figure A-3 shows coherence and phase for the time series; they are coherent between 8.4 and 11.4 days (Drake Passage leads Africa by about 1 day) and between 23 and 34 days (Drake Passage leads by 5 days).

Annex B: Measuring the Circumpolar Wave
Provided by Ray Peterson

The basic issues regarding the circumpolar wave that can't be resolved remotely have to do with the depth of penetration of the interannual signals observed at the surface, magnitude of the signals at depth, and how the wave might influence the characteristics of newly-formed water masses that sink: Weddell Sea Bottom Water, Antarctic Intermediate Water (AAIW), and Subantarctic Mode Water (SAMW). The region around Drake Passage is most attractive, both scientifically and logistically, for resolving these issues with long time series. Scientifically, it is because the wave is at its maximal development just west of Drake Passage, and because the region is critical to the three water masses.

As a start, Janet Sprintall, Dean Roemmich, and I recently began in September 1996 making repeat high-density XBT (T-7) sections across the Passage on crossings by the R/V Polar Duke. We have 4 sections and will get 2 more before the Duke goes off line in May; the sampling will resume in September from the L.M. Gould. We plan this as a long-term effort to capture the different phases of the wave as it passes through the Passage. The depth and magnitude of the interannual variations should be resolved.

Eberhard Fahrbach has been deploying current meters in the Weddell Sea over the past few years. From three years of data in the western portion he's seen a warming of the deep and bottom waters that might be related to the wave. Mark Drinkwater at JPL has been working on the hypothesis that anomalies in the surface winds act to either open up more coastal polynyas in the southern Weddell Sea during cold phases when the winds are anomalously northward, or to retard polynya development during warm phases. When there are more polynyas and colder air, there should be more production of the deep and bottom waters, and vice-versa. Drinkwater claims to see this relation on the basis of satellite images, Fahrbach's current meter records, and the phase of the wave. Longer records are obviously needed, but Fahrbach won't have any more instruments in the western Weddell Sea after next year, though he will continue to have them along the Greenwich Meridian. Our idea is to deploy a few of Pillsbury's expendable current meters along a line extending southeast of the South Orkneys, and to keep reinstalling them every couple of years. This seems to be the best place because it becomes ice-free nearly every year and is not far downstream from the regions of dense water formation. Any farther south would be compromised by year-around ice. This area should be serviceable by the Gould at least once every two years.

Regarding the AAIW (the traditional variety formed by dilution of Antarctic Surface Water (AASW) from south of the Polar Front), the wave should alter the temperature of the AASW, its density, and subsequently the characteristics of AAIW. If this can be measured anywhere, it would have to be within Drake Passage and in the Malvinas Current. The XBT line might get some of this, and so would current meters deployed across the Malvinas. The first batch of expendable current meters that Tom Whitworth, Dale Pillsbury, Alberto Piola and I deployed there last year will be coming up on April 15. Long-term collaboration with Piola using Argentine vessels should be feasible.

Mike McCartney has observed interannual changes of a degree C or more in the SAMW of the southeastern South Pacific which are in proper phase with the wave. Although not much of this water gets into the South Atlantic because it turns north with the Peru Current, it is probably a significant component of AAIW in the South Pacific. I think that a small number of Dale's expendable current meters on tall moorings, with near-surface thermistor chains, west of southern Chile would be the best way to monitor these changes. Rodrigo Nunez has expressed interest and willingness to arrange for Chilean ship time, but I haven't pursued it any further yet.

This should all be done rather easily and at reasonable cost. If so, the principal water masses affected would be measured in the right places.

One aspect of the wave's effects that might be resolved remotely is transport of the ACC, but I'm not very comfortable with it. Perhaps bottom pressure gauges should be kept in place across Drake passage, deployed as expendables with upper-level thermistor chains to get at the steric signal.

I have not yet given much thought to what should be done at other choke points—mainly because of all that can and should be done first around Drake Passage.

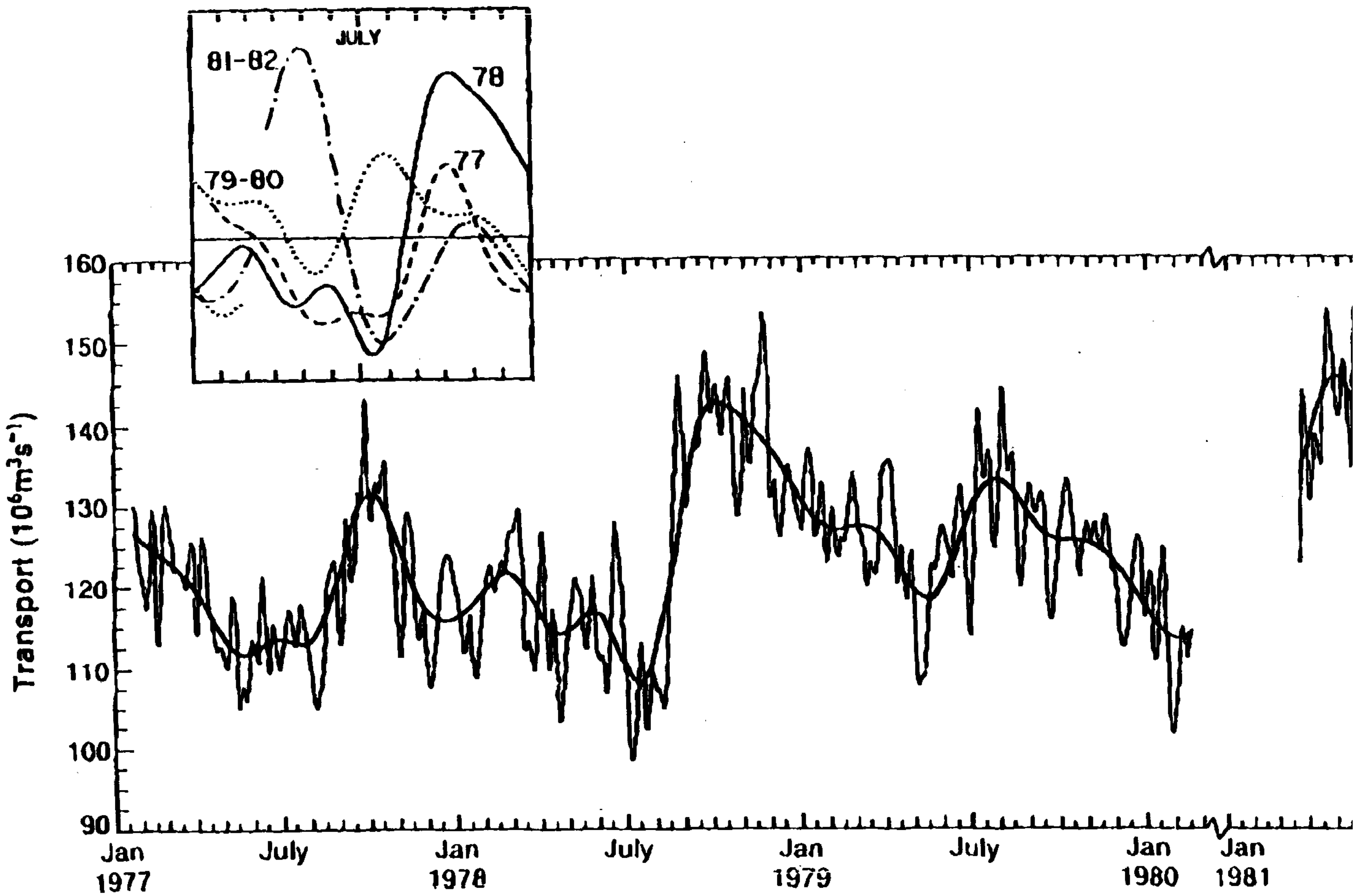


Figure 1. Linear regression model of the net transport through Drake Passage from January 1
1980 and from March 1981 to March 1982. The light line shows 10-day low-pass filtered transp
smoothed with a 90-day low-pass filter to illustrate the low-frequency variability. The inse
segments of the 90-day low-passed series. From Whitworth and Peterson (1985).

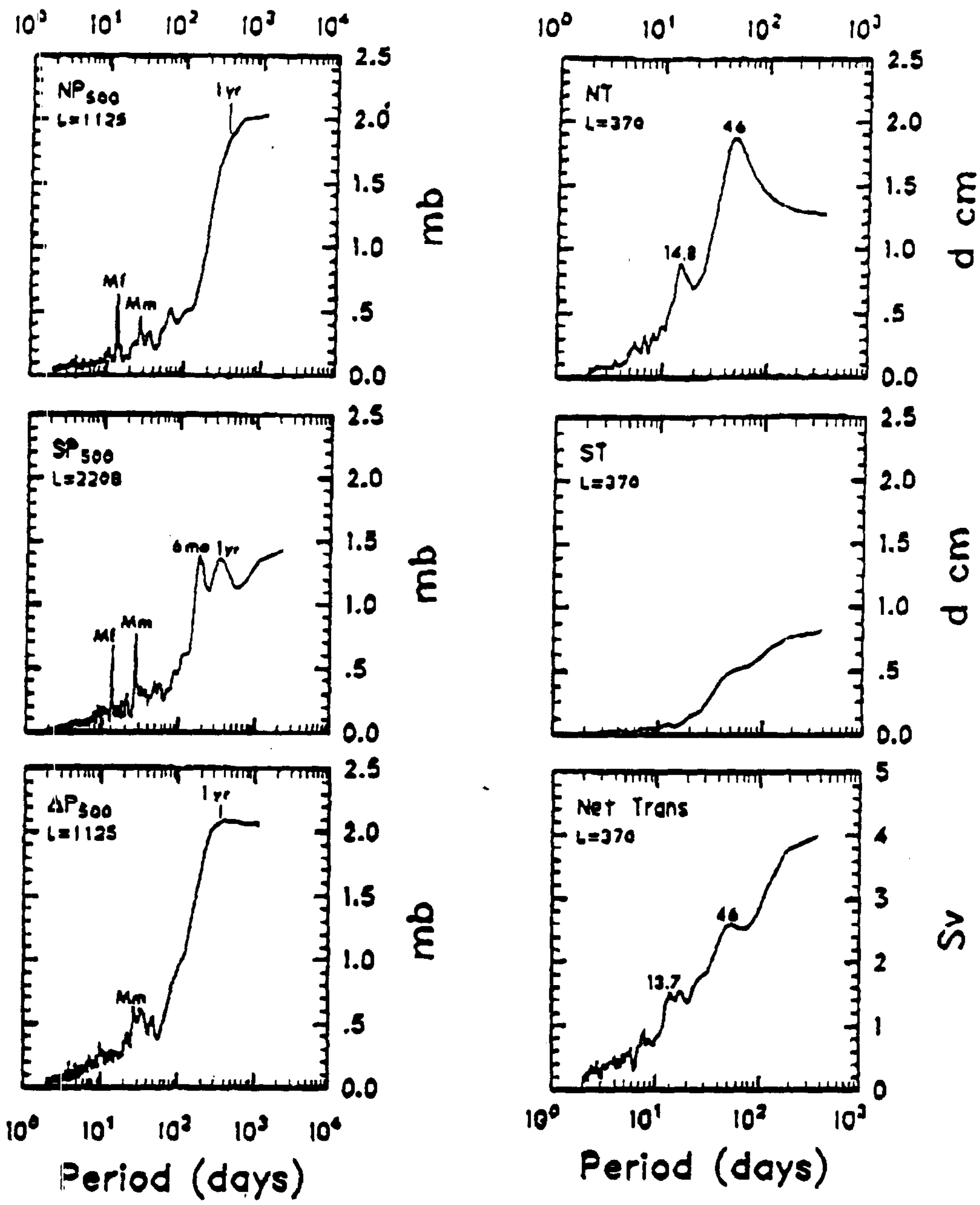


Figure 2. Time series of autospectra of 500-m pressure and geopotential anomaly at the northern (Npand NT) and southern (SP and ST) sides of Drake Passage nad of the difference (deltaP$_{500}$) and net transport; seasonal to annual peaks are evident.

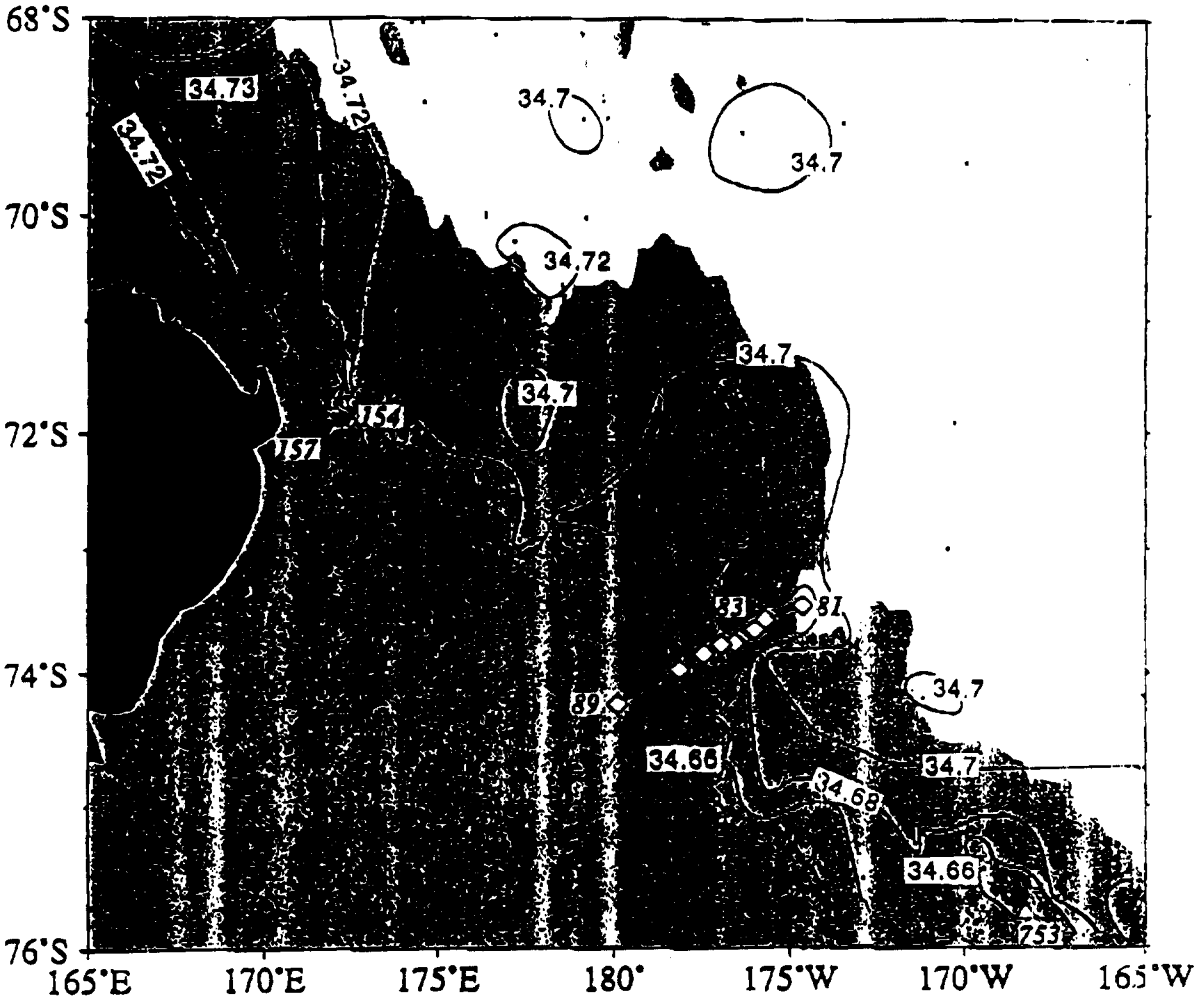


Figure 3. Details of the bottom salinity showing the sources of antarctic bottom waters in the Ross Sea. Depths less than 3 km are shaded. The dash-dot (dot) line indicates the 1-km (500-m) isobath.

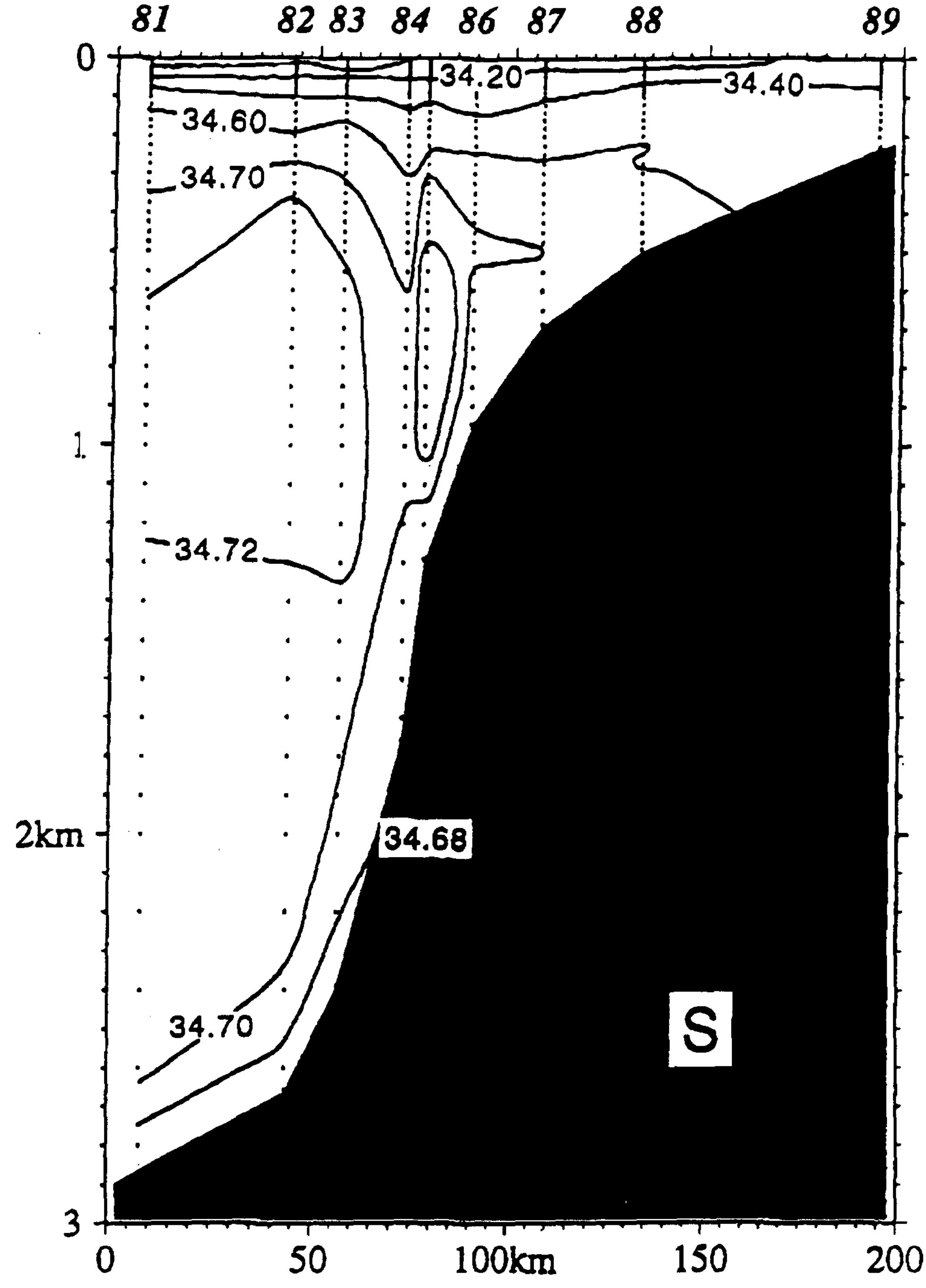


Figure 4. Salinity in a vetical section obtained during USCGC *Northwind* cruise 77, January 1997. Section location is shown in Figure 3.

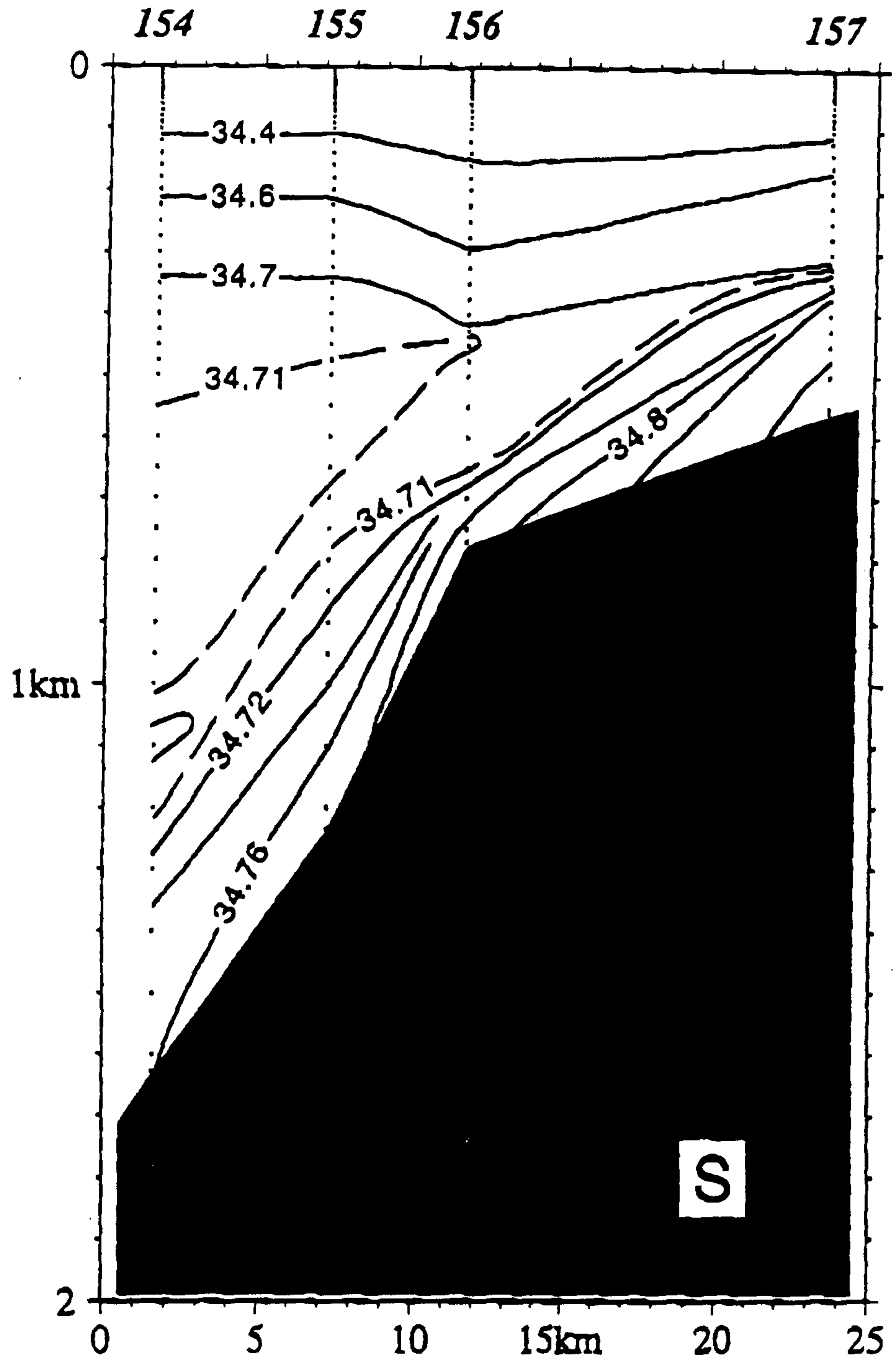


Figure 5. Salinity in a vertical section obtained during USCGC *Burton Island* cruise 78, February 1978. Section location shown in Figure 3.

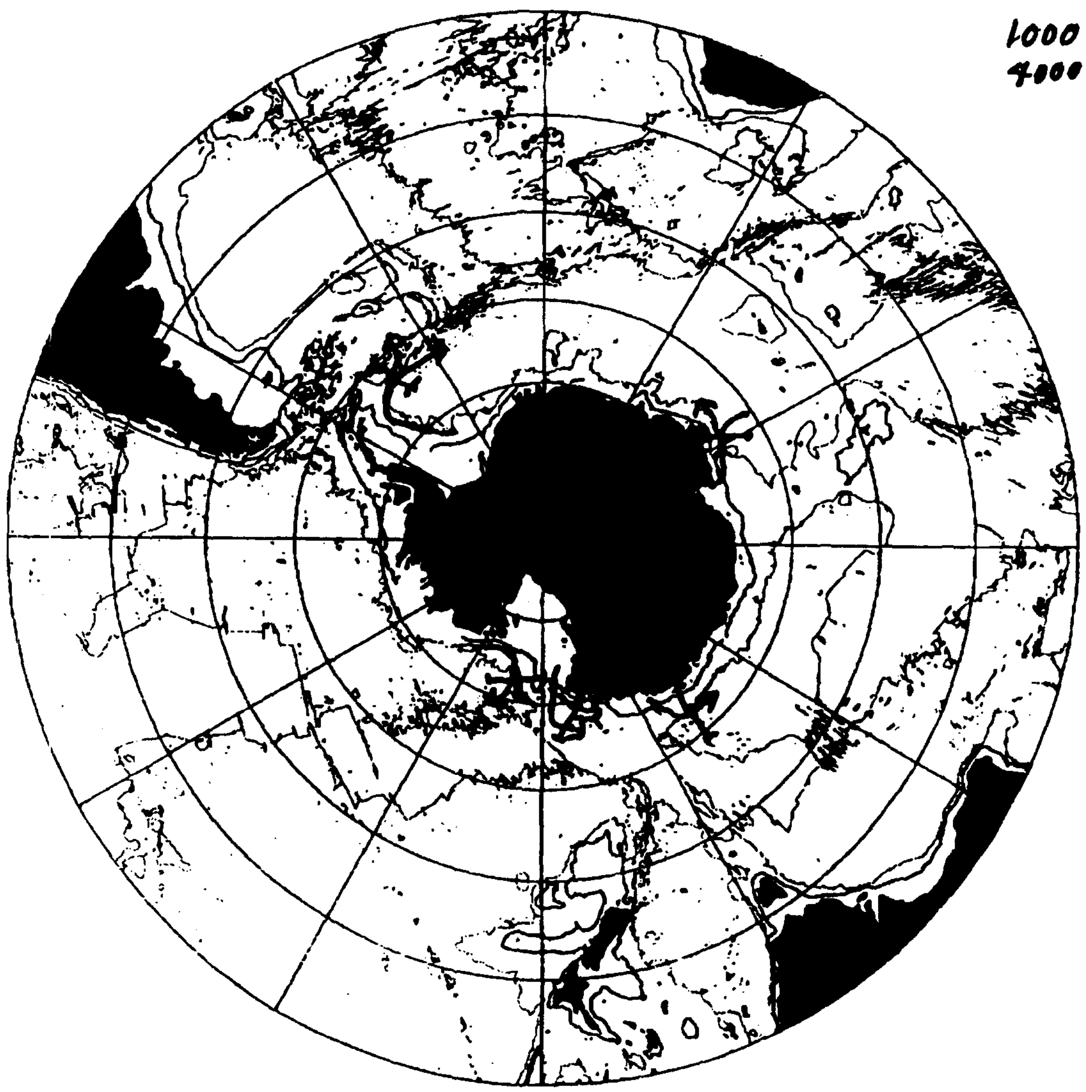


Figure 7. Outflow paths for densest Antarctic Bottom Waters and suggested locations for expendable near-bottom current meter arrays to monitor the properties and variability. The western path from the Ross Shelf edge is for salty bottom water; other paths are for fresh type bottom waters. The 1000-m and 4000-m isobaths are shown.

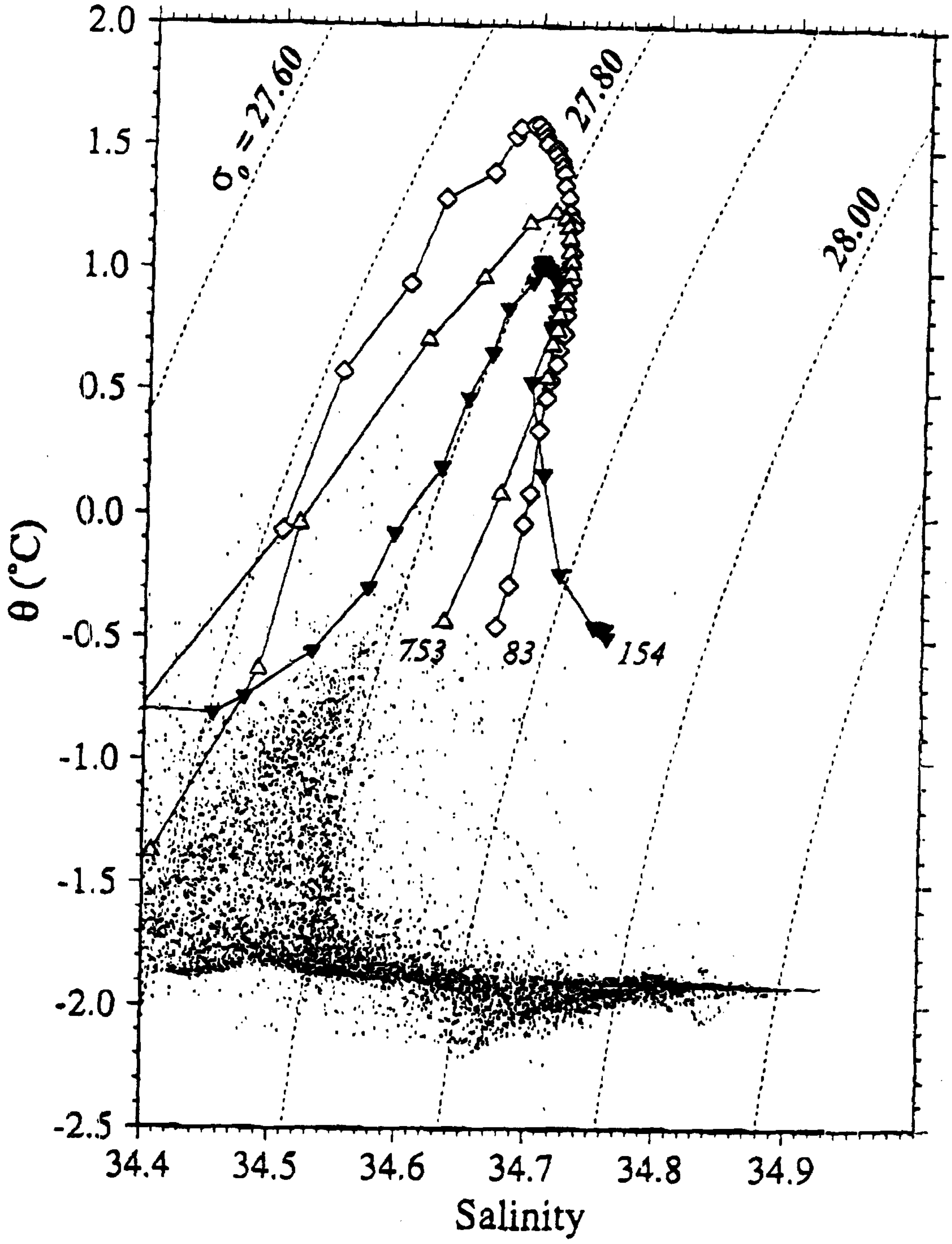


Figure 6. Potential temperature-salinity characteristics of the Antarctic Bottom Waters by the major outflows from the Ross Sea. Station locations are shown in Figure 3. Note the high salinity waters at station 83, compared to the lower values at 153 and 157.

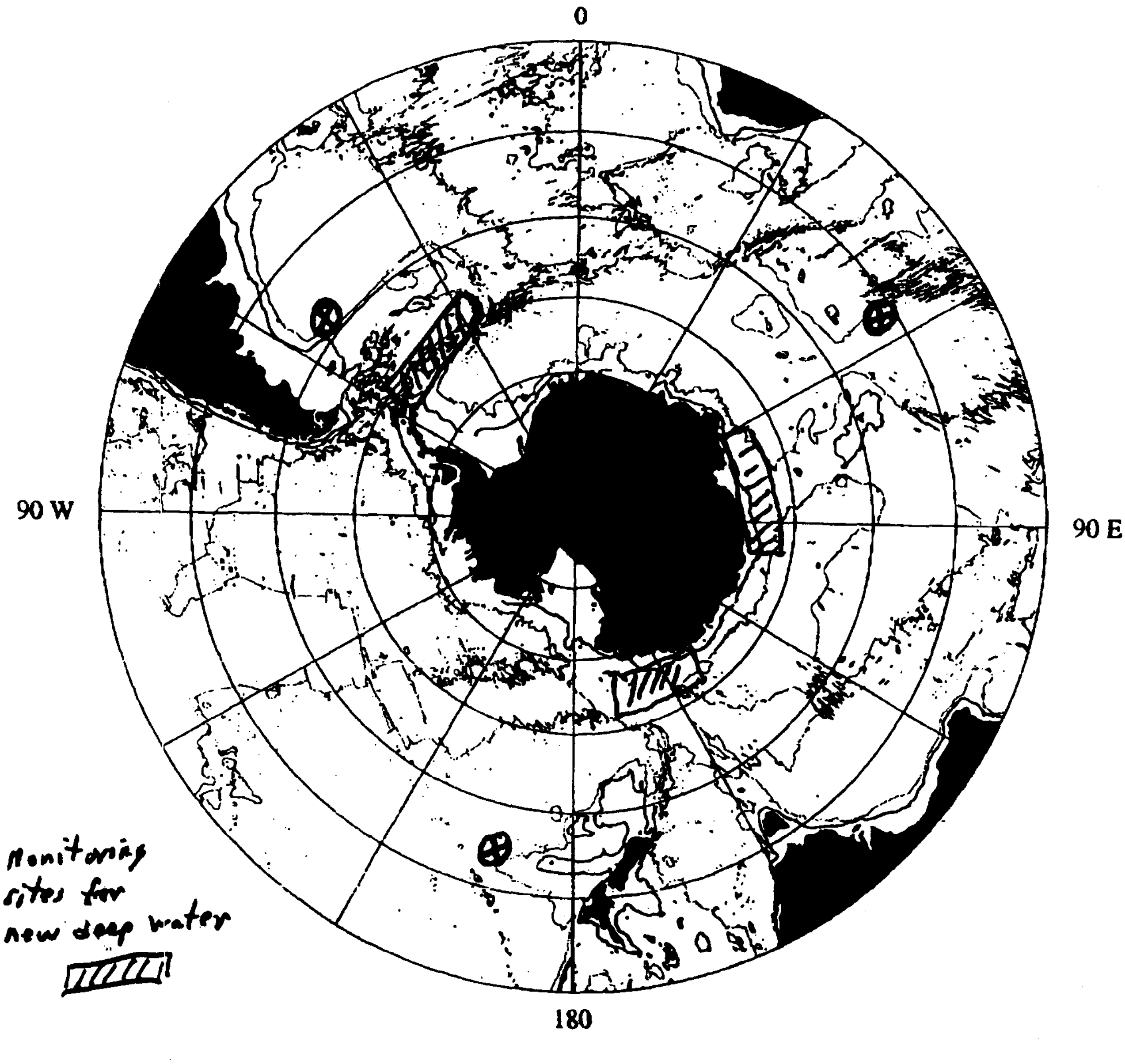


Figure 8. Hatched are suggested areas for moitoring of variability of new shelf water mixtures injected into the interior ocean well above the bottom. Circled Xs are suggested possible sites for detecting variability of Antarctic Intermediate Water, Antarctic Mode Water, and Circumpolar Deep Water. The 1000-m and 4000-m isobaths are shown.

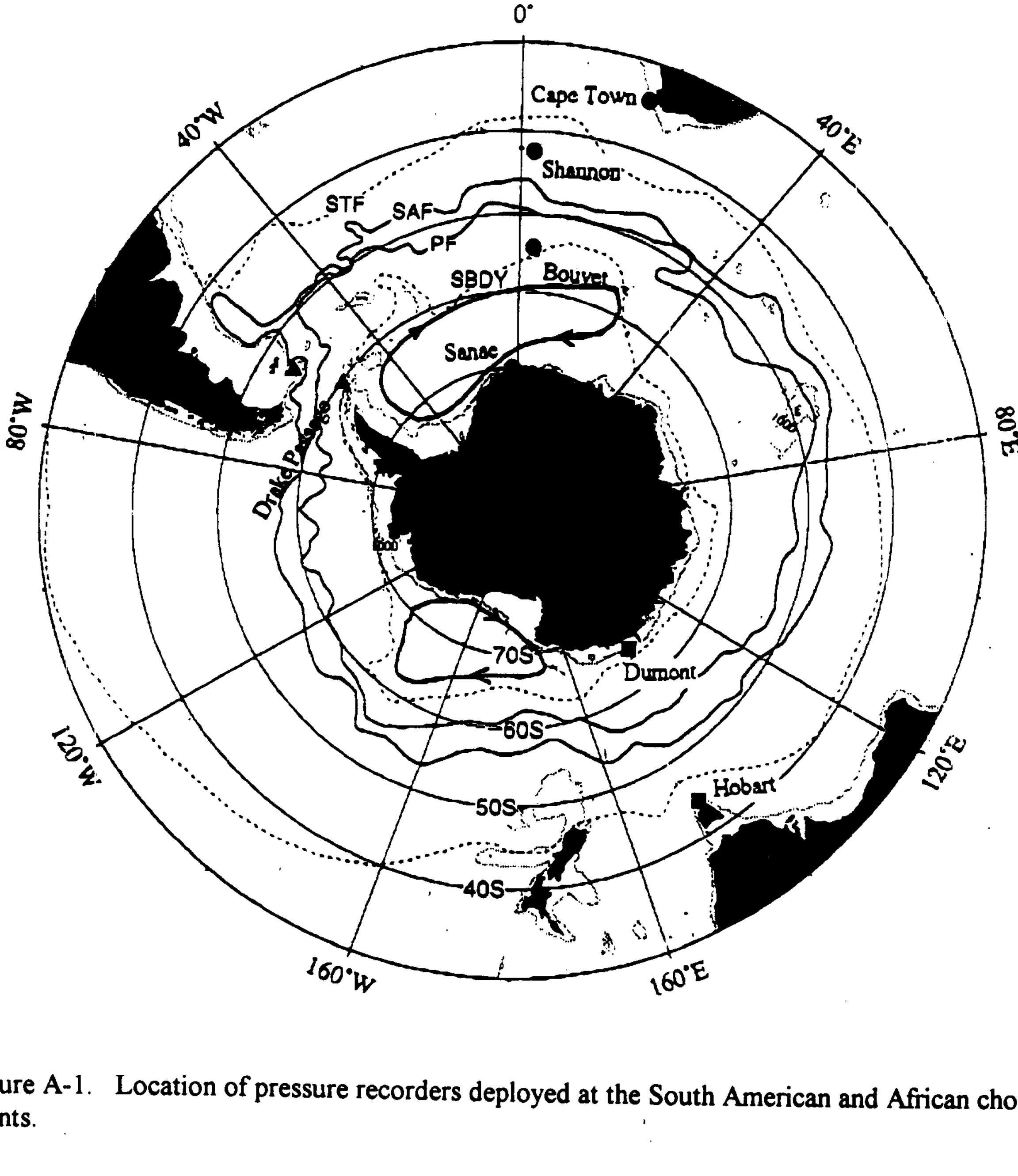


Figure A-1. Location of pressure recorders deployed at the South American and African choke points.

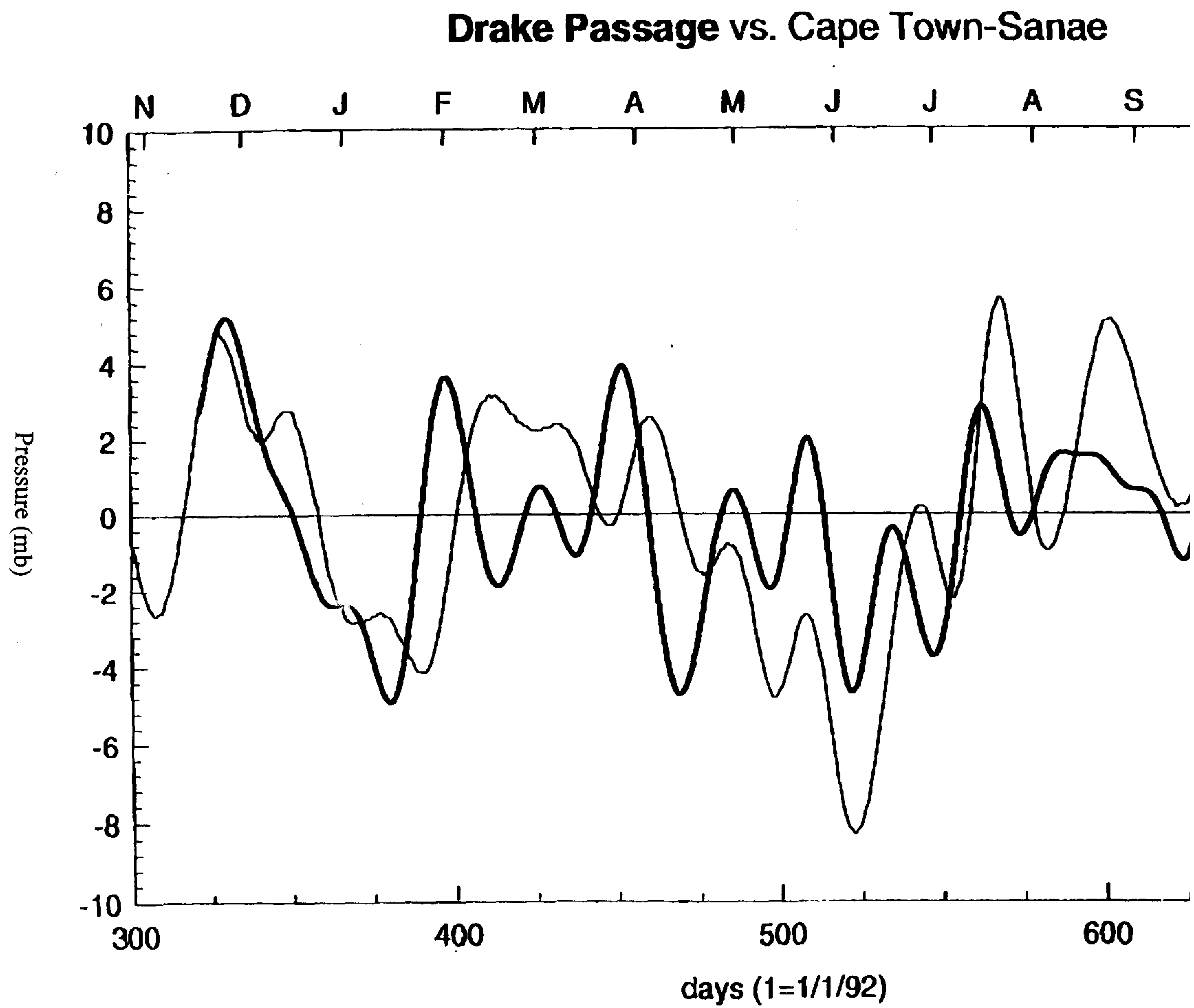


Figure A-2. Pressure difference at Drake Passage (north minus south; heavy line) and between Africa and Antarct SANAE) for the period of concurrent operation. The series have been smoothed with a 21-day filter. The y the scale that would apply if the pressure fluctuations in the upper 2500 m represented barotropic transport c

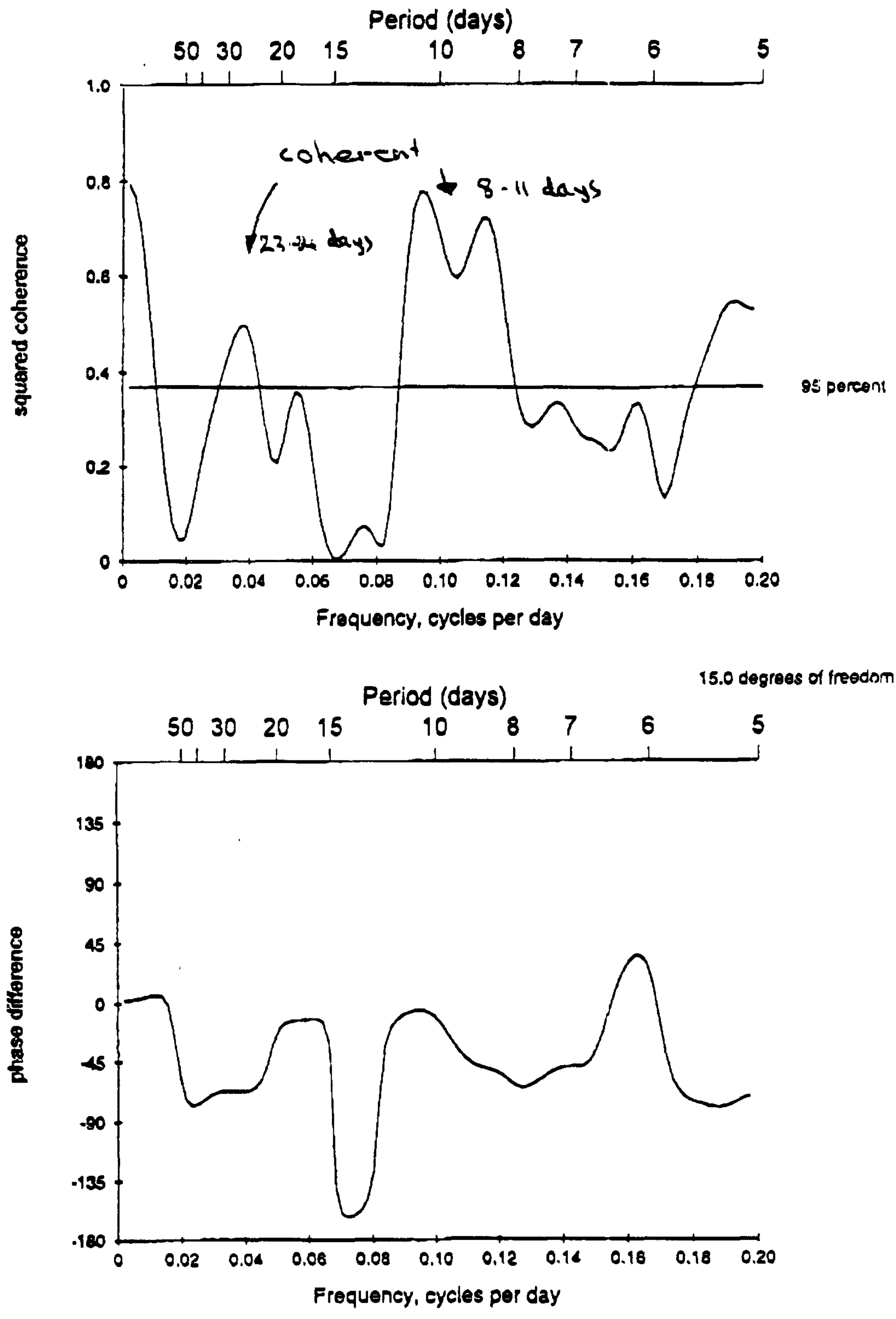


Figure A-3 . Squared coherence and phase for the detided but unfiltered time series shown in Figure A-2.

ANNEX XX

Long-term Hydrographic Variations Observed in the Hawaii Ocean Time-series

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Introduction

The Hawaii Ocean Time-Series is now nearly 8 years long, allowing us to detect interannual variations in water properties from the near-surface layer to the bottom (4800 m). Despite the energetic cruise-to-cruise variations associated with mesoscale eddies, low frequency variability of temperature, salinity and dissolved oxygen emerge without any sophisticated data processing. The dominant interannual signal in the near-surface and near-bottom temperatures is related to the El Niño-Southern Oscillation phenomenon with near-surface variations related to local forcing, and bottom variations related to remote forcing by baroclinic waves. Near-surface salinity reflects more clearly the interannual variations of surface forcing.

Within the water column, there are 3 hydrographic features which dominate the mean profiles: These features are the shallow salinity maximum (S_{max}) in the upper thermocline, the salinity minimum (S_{min}) associated with the North Pacific Intermediate Water mass, and the dissolved oxygen ($dO_{2\,min}$) associated with the Antarctic Intermediate Water mass. When these features are analyzed on potential density surfaces, variations in conservative properties such as T and S can only be attributed to horizontal advection and diapycnal mixing. Variability associated with advection may be due to current anomalies, or may be due to changes in the remote surface forcing of these features in regions of water mass formation. Our observations cannot distinguish between these two modes of variability. So far, the biggest surprises are the detection of ENSO time-scale variability in the near-bottom temperatures, and the trend towards lower values of dO_2 in the Antarctic Intermediate Water. That trend may be associated with trends in other properties and other portions of the water column which are masked by other, more energetic, variability. A longer Hawaii Ocean Time-Series will tell.

Near-Surface Variability

Surface Layer T & S

The upper 100 m represents the more-or-less active part of the upper ocean with respect to interaction with the atmosphere. Thus, it is expected that the average temperature and salinity in this layer would reflect climate anomalies, and this is the case. Some of these variations can be asso-

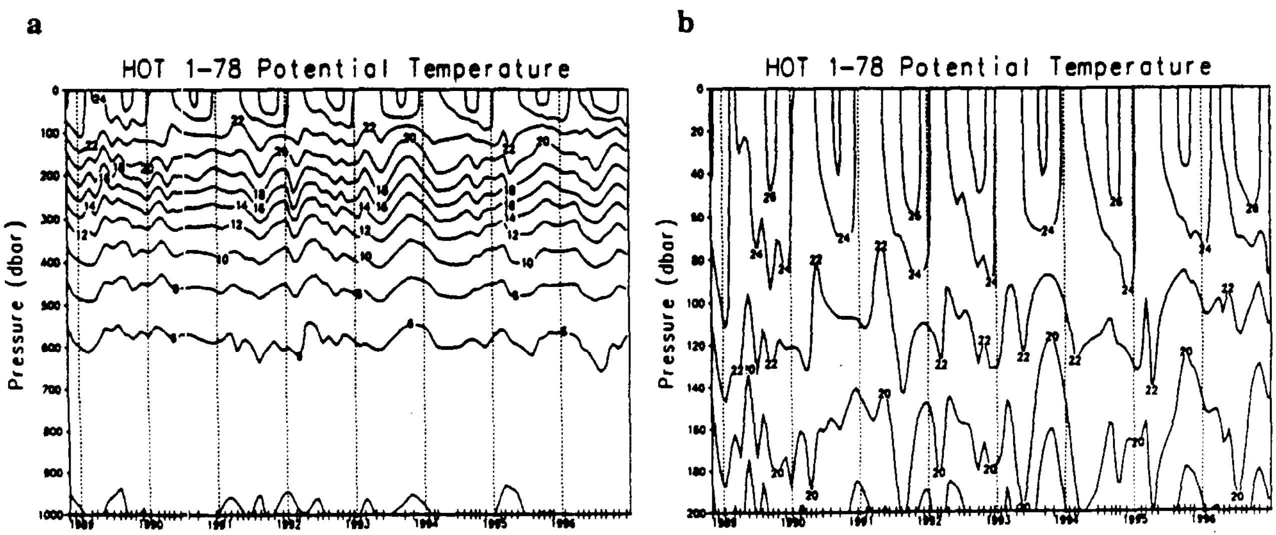


Figure 1. Contours of potential temperature (°C) measured by CTD versus pressure in the upper 1000 (a) and 200 (b) dbar for HOT cruises 1-78. Cruise times are indicated by the tick marks along the bottom axis. Data are the average of all casts for each cruise.

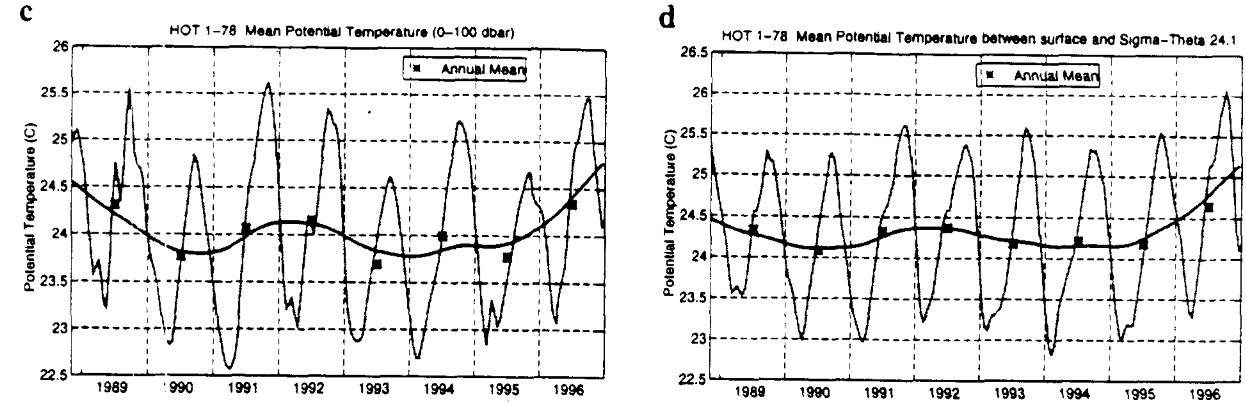


Figure 1. (continued) Time-series of mean potential temperature in the upper 100 dbar (c) and in the layer above the 24.1 σ_θ isopycnal (d). The asterisks show the annual mean. The smooth line is a spline fit to the data.

ciated with local wind anomalies related to El Niño-Southern Oscillation events (cf. Karl et al., 1995; Karl and Lukas, 1996).

Not only does the annual average near-surface temperature vary from year-to-year, but the annual maxima and minima vary markedly (Fig. 1c-d). For example, 1991 has both the warmest and coldest temperatures in the record, making the range of variation maximal for that year. Smallest ranges are seen for 1993 and 1995.

Salinity in this near-surface layer does not show a seasonal

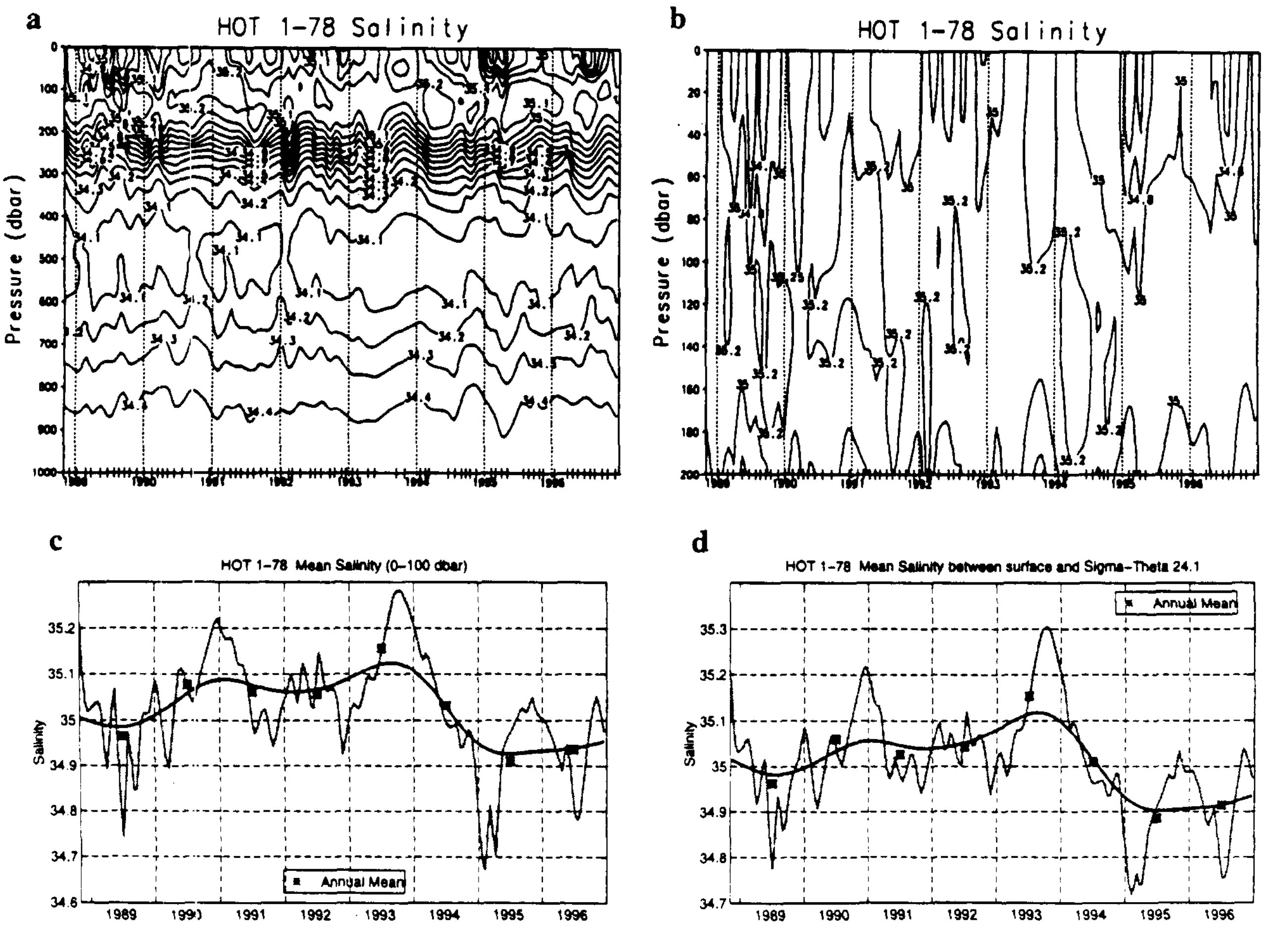


Figure 2. Same as Figure 1, except for Salinity.

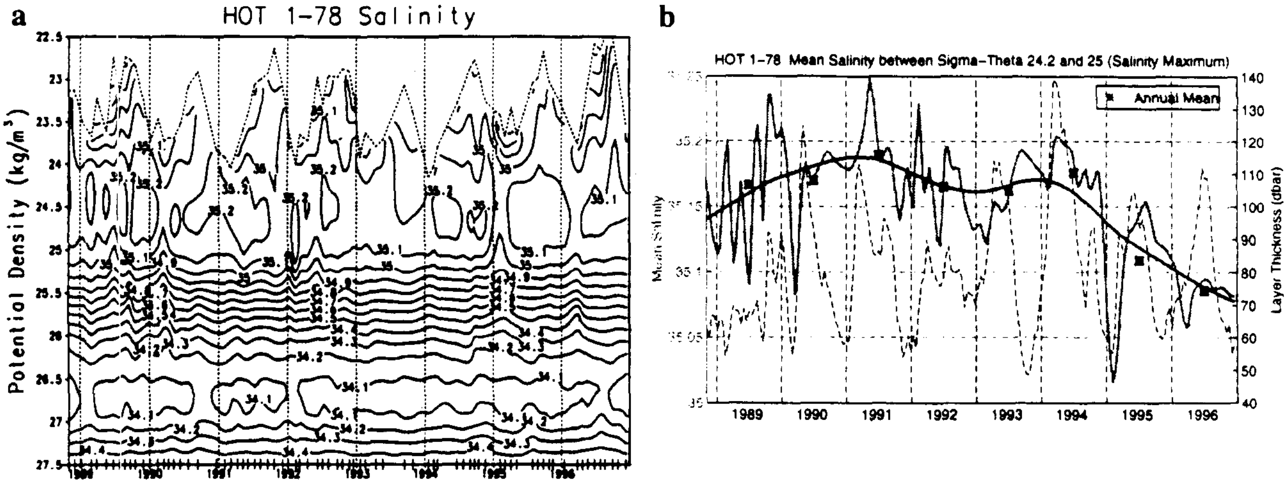


Figure 3. a) Contours of salinity measured by CTD versus σ_θ for HOT cruises 1 to 78. The average density of the sea surface for each cruise is connected by a dashed line. Data are the average of all casts for each cruise. b) Time-series of mean salinity (gray solid line) between the 24.2 σ_θ and 25.0 σ_θ isopycnals. The smooth line is a spline fit to the data. The asterisks show the annual mean. The dashed line is the thickness of the layer between the two isopycnals.

cycle (Fig. 2c), unlike the pronounced seasonality of temperature. Instead, pronounced interannual variation is observed, with relatively salty conditions in 1990-91, 1993, and 1995, with relatively fresh conditions in 1989, late 1991, and early 1995.

The only correlation that can be seen between T and S is that the saltiest conditions are aligned with the coolest annual maxima in 1990, 1993, and 1995. This might be due to windier than normal conditions and increased evaporation and mixing.

Salinity Maximum (S_{max})

The S_{max} is generally centered near 200 m (Fig. 2a), and a potential density of 24.6 σ_θ (Fig. 3a), and is associated with the subduction of salty water in the central gyre and its advection southward to ALOHA. The magnitude of this feature varies considerably on both short and long time scales. The average salinity between the 24.2 and 25.0 σ_θ isopycnals smoothes out some vertically incoherent variations (Fig.3b). It is interesting that the thickness of the layer bounded by these isopycnals varies by a factor of two, with an erratic annual cycle. Interannual variations of about 0.1-0.15 psu are likely due to changes in advection and/or surface forcing of this feature near the Subtropical front north of Hawaii. The maximum salinity seen in 1993-94 was associated with actual ventilation of these isopycnals at ALOHA (Fig. 3a). The annual average salinity in 1995 was significantly lower than in previous years, and this freshening trend continues into 1996.

The North Hawaiian Ridge Current

Currents measured with a shipboard acoustic Doppler current profiler along the cruise tracks to and from the ALOHA station have revealed the existence of a mean flow to the west-northwest along the Hawaiian Ridge at 158°W (Firing, 1996). This North Hawaiian Ridge Current is highly variable from cruise to cruise and from year to year. This variability is apparent in Fig. 4 which shows the magnitude of the current during HOT cruises averaged between 20 and 110 m, and between 21.7°N and 22.6°N. The current component projected on an axis along the ridge is shown, thus large negative values indicate a strong west-northwestward Ridge Current. The slowest variation seen in the time-series is a shift from a strong current of about 20 cm s^{-1}, during the first three years to weaker and more variable currents during the following five years. The mean current was near zero in 1992, 1993 and 1995, strong in 1994 and moderate in 1996. No annual cycle is evident.

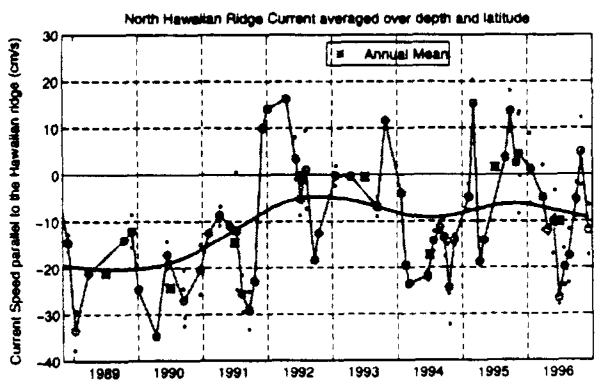


Figure 4. Magnitude of the current (dots) measured with an ADCP during HOT cruises, averaged between 20 and 110 m and between 21.7°N and 22.6°N. The circles are the averages per cruise, and the smooth line is a cubic spline fit to the averages. The asterisks show the annual mean.

Variability in the Interior

Salinity Minimum (S_{min})

The S_{min} occurs near 500 m, and 26.8 σ_θ, about 1 psu fresher than the S_{max} (Fig. 3a). These waters are formed near the surface in the western North Pacific near the Sea of Okhotsk. Interannual variability is comparable in magnitude to subannual variability (Fig. 5). Some of the saltiest conditions (e.g. early 1989, late 1990) are associated with the appearance of salty submesoscale intrusions studied by Kennan and Lukas (1996).

A joint EOF analysis on salinity and dissolved oxygen as a function of potential density (Fig. 6a) shows that the salty periods are associated with lower dissolved oxygen and vice versa. This may indicate an "older" source for the intrusions.

Dissolved Oxygen Minimum (dO_{2min})

The $dO_{2\,min}$ centered near 800 m (27.2 σ_θ; Fig. 7a) is an indication of the age of Antarctic Intermediate Water (AAIW) that arrives at ALOHA. A rich spectrum of variability is seen (Fig.7b), superimposed on a general trend towards lower values of dO_2. This trend in dissolved oxygen appears to occur in other parts of the water column, some places with opposite sign, and these appear to be correlated with salinity variations as seen in the joint S and

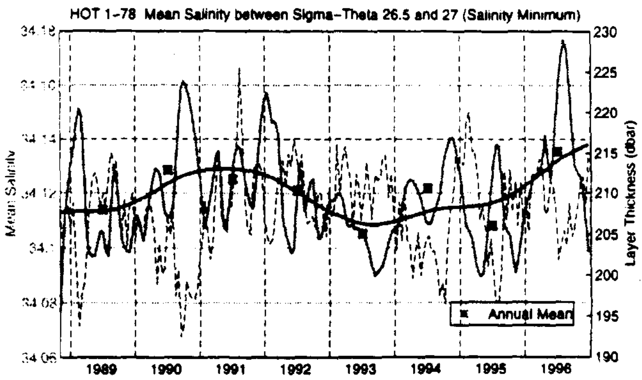


Figure 5. Same as Figure 3b, except for Salinity between 26.5 σ_θ and 27 σ_θ isopycnals.

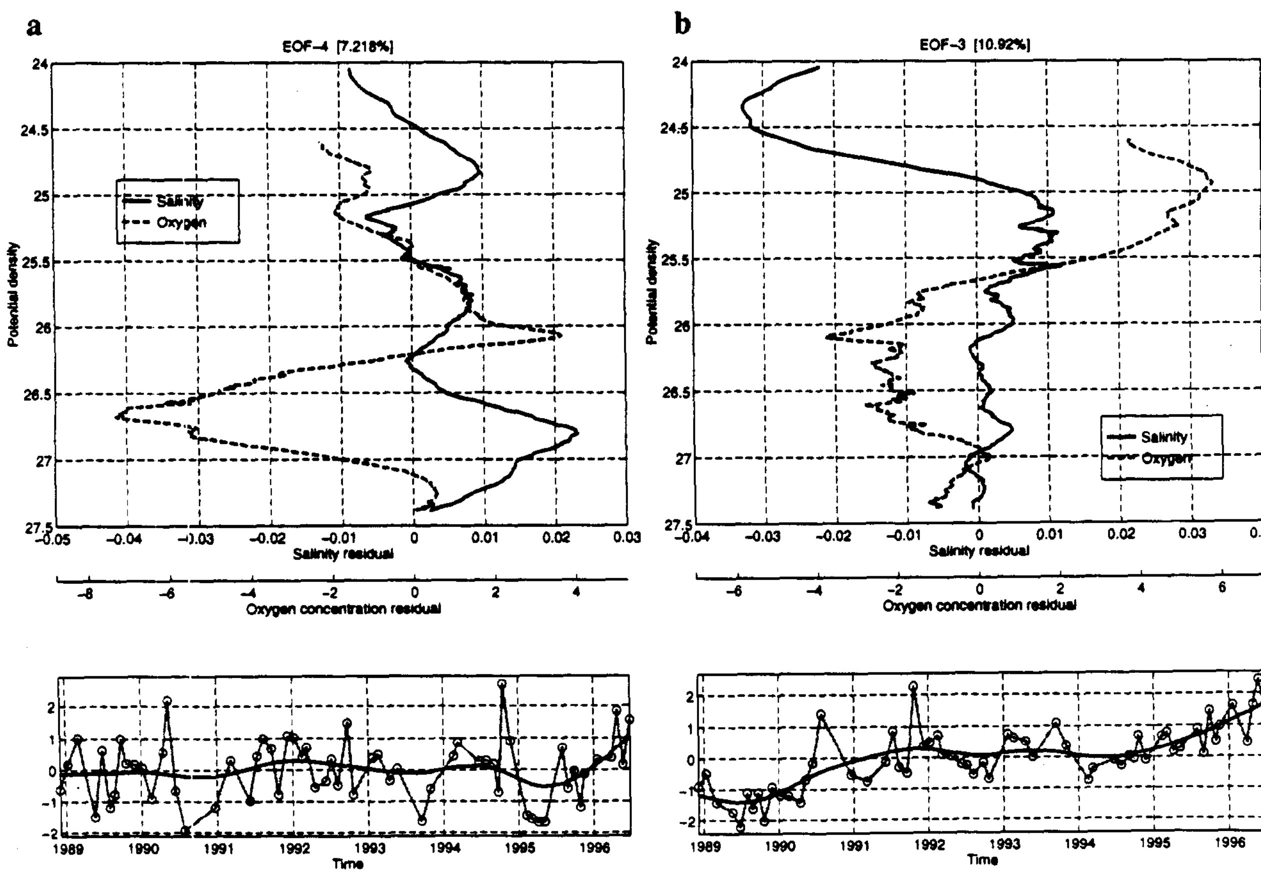


Figure 6. Joint EOF analysis of salinity and dissolved oxygen (µ mol/kg) residuals on potential density surfaces. The mean, annual, and semiannual signals were removed from the data prior to the analysis. The 4th (a), and 3rd (b) EOFs versus σ_θ are shown in the upper panel, and the lower panel shows the time series.

a

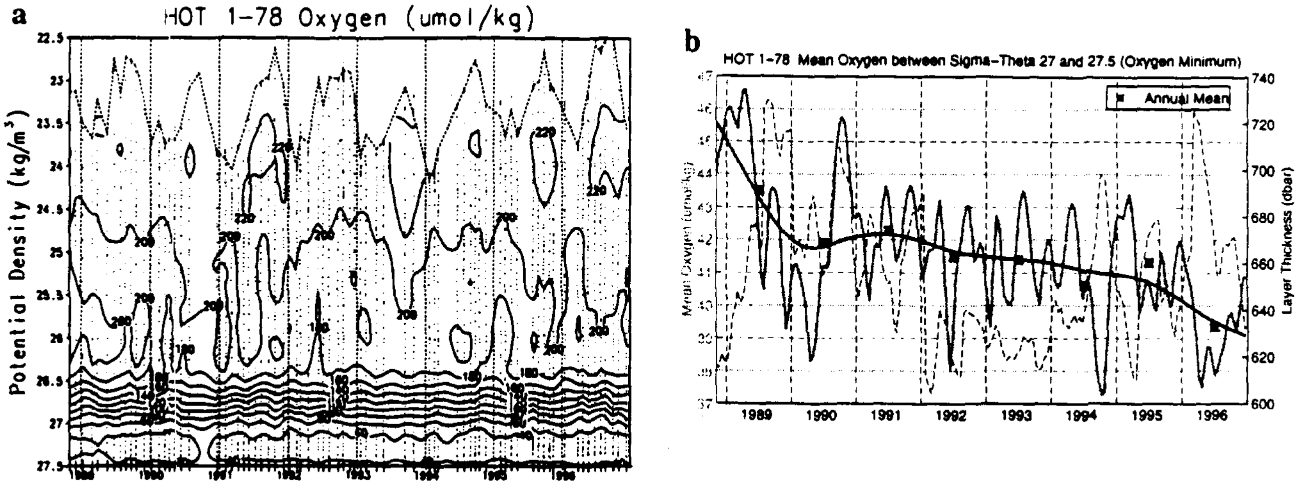


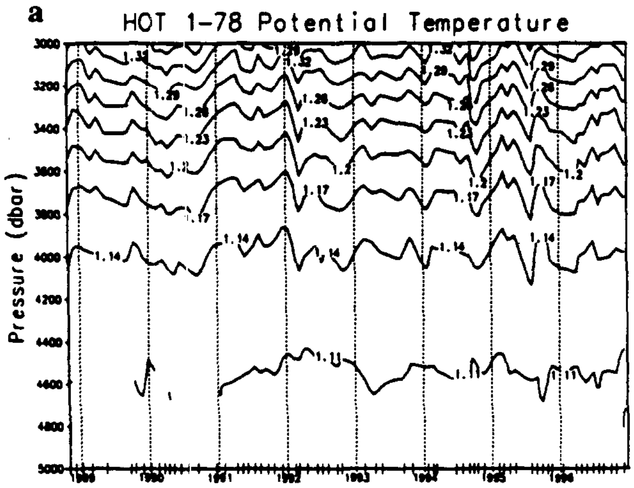
Figure 7. a) Same as Figure 3a, except for dissolved oxygen from discrete water samples. Locations of bottle closures are indicated by dots. b) Same as in Figure 3b, except for dissolved oxygen between the 27.0 σ_θ and 27.5 σ_θ isopycnals.

dO_2 EOF (Fig. 6b). (Note that the trend in the joint EOF is towards lower values of dO_2 in the density range of the AAIW.)

Deep Ocean Variability

Interannual temperature variations in deep and near-bottom waters at ALOHA were described by Lukas and Santiago-Mandujano(1996). Fig.8b shows these variations in 100 dbar averages around 3500 dbar and around 4450 dbar. The character of the interannual variations is biennial near 3500 dbar, and is closer to a period of 3 years near the bottom. These latter variations are likely associated with baroclinic Rossby waves excited along the coast of Mexico during ENSO events.

a



Cold Surges in Bottom Water

During early 1991 and late 1993 and 1995, three Bottom Water events occurred at the site of the ALOHA station, sit-

b

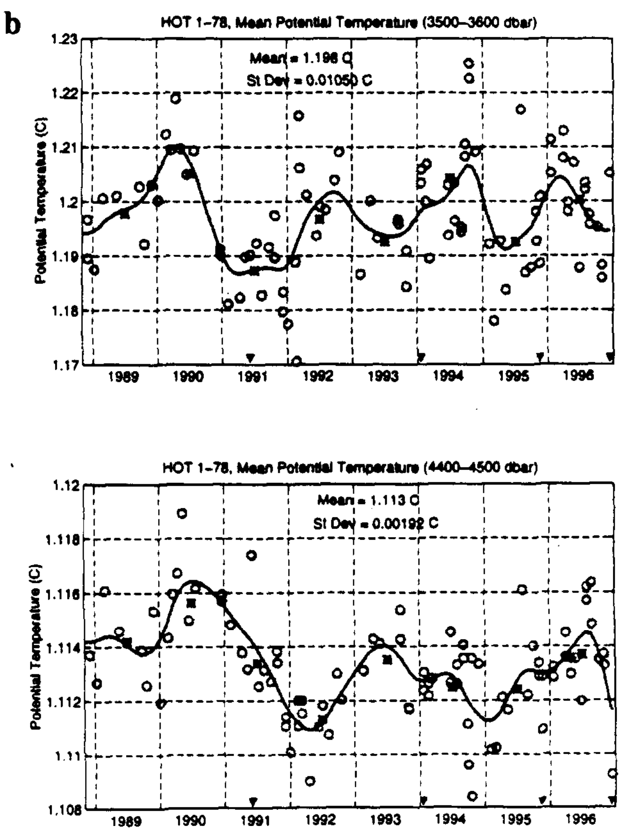


Figure 8. a) Contoured time series of potential temperature (°C) versus pressure below 3000 dbar for HOT cruises 1-78. Tick marks along the bottom axis indicate time of CTD casts which reached to at least 3800 m. b) Time series of Deep Water (top panel) and Bottom Water (bottom panel) potential temperature from CTD profiles (circles). The solid line is a cubic spline fit to the temperatures, and the asterisks are the annual mean for each year. The arrowheads along the horizontal axis indicate Bottom Water "overflow" events.

uated on the northern flank of a bathymetric feature known as the Kauai Deep. Cold anomalies of at least 0.014°C were observed in near–bottom CTD profiles following each event (Figs. 9-10). The anomalies relaxed towards more typical conditions over a period of several months. A fourth event is apparently underway (cruises 78-79 in Fig. 10). The cause of these events is not known.

It is presumed that the cold anomalies in the Kauai Deep originated from overflow of colder water from the adjacent Maui Deep, through the controlling sill that separates them (Fig. 9).

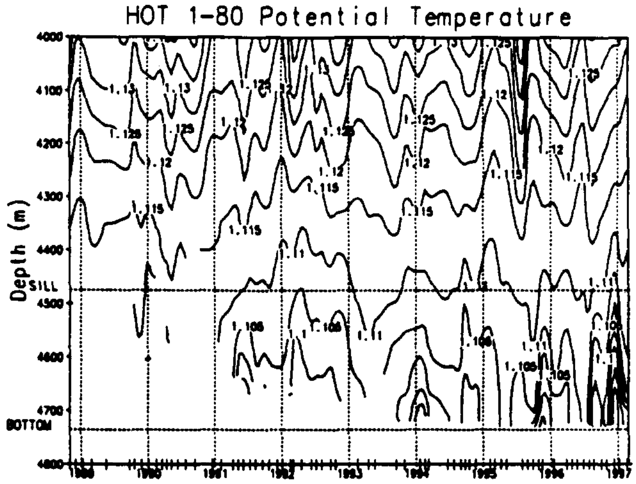


Figure 9. Same as Figure 8a, except versus depth below 4000 m for cruises 1-80. Horizontal lines indicate the depth of the sill (see text) and bottom.

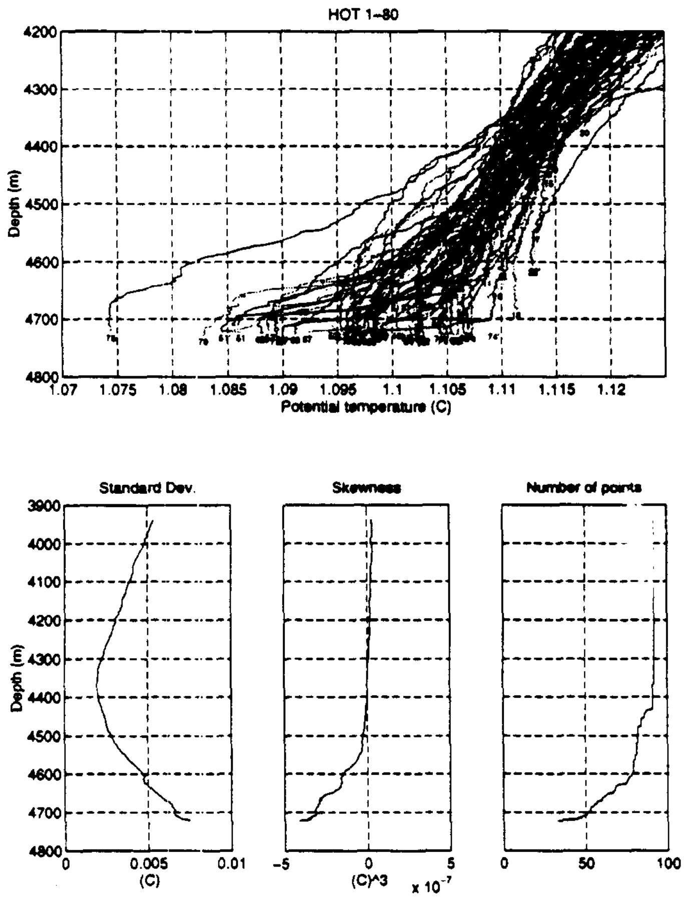


Figure 10. Profiles of potential temperature below 4200 m for HOT cruises 1-80 (upper panel). The thick line is the median from all cruises. The bottom panels show the standard deviation, skewness and number of point used in each 2-m bin average.

Acknowledgments

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References

Firing, E., 1996: Currents observed north of Oahu during the first five years of HOT. Deep-Sea Res. II, 43, 281-303

Karl, D. M., R. Letelier, D. Hebel, L. Tupas, J. Dore, J. Christian and C. Winn, 1995: Ecosystem changes in the North pacific subtropical gyre attributed to the 1991-1992 El Niño. Nature, 373, 230-234.

Karl, D. M. and R. Lukas, 1996: The Hawaii Ocean Time-series (HOT) Program: Background, rationale and field implementation. Deep-Sea Res. II, 43, 129-156.

Kennan S. C. and R. Lukas, 1996: Saline intrusions in the intermediate waters north of Oahu, Hawaii. Deep-Sea Res. II, 43, 215-241.

Lukas, R. and F. Santiago-Mandujano, 1996: Interannual variability of Pacific Deep and Bottom Waters observed in the Hawaii Ocean Time-series. Deep-Sea Res. II, 43, 243-255.

ANNEX XXI

OCEANOGRAPHIC TIME-SERIES STATIONS WITHIN CLIVAR

John Toole
Woods Hole Oceanographic Institution

In this time of concern with global climate variability, only a handful of subsurface ocean records currently exist of sufficient duration (decade or longer) and sampling frequency (resolving the seasonal cycle) to unambiguously document interannual variability. One of the best data sources continues to be the time-series profile data once routinely acquired from a network of ocean weather ships, a system that has now all but disappeared. It is proposed that as part of CLIVAR, this network be functionally emulated as a global-scale array to document water property and ocean circulation changes on seasonal to decadal time scales. Those few time-series station observations now in hand provide a tantalizing glimpse of interannual ocean variability. A sampling of these data sets is given below as motivation for this proposal.

Lazier (1980) observed a suppression of deep winter convection in the Labrador Sea during the late 1960's in data from Ocean Weather Station Bravo. This event was related to an invasion of buoyant, low-salinity surface water (the "Great Salinity Anomaly," subsequently tracked by Dickson et al., 1988 around the subpolar gyre of the N. Atlantic). Hydrographic observations by research ships that periodically visited this area have been used to extend the Bravo record both forward and backwards in time (although obviously not with seasonal resolution). Most recently, a series of intense winters has caused a significant change in Labrador Sea Water, it is currently colder, fresher and more dense than any time in this century (Lazier, 1996; P. Rhines, personal communication).

A recent analysis of historical hydrographic data by Curry and McCartney (1996) documents the spread of Labrador Sea Water influence into the subpolar and subtropical gyre. Using the long record of the Panulirus Station offshore Bermuda, they find a lag of approximately seven years for signals to propagate from the Labrador Sea across the subpolar-subtropical gyre boundary to Bermuda. Comparison of zonal and meridional hydrographic sections through the western N. Atlantic at different phases of this oscillation demonstrates the large spatial scales of these warm and cold events (Roemmich and Wunsch, 1984; Parrilla et al., 1994, Joyce and Robbins 1996). The time-series station data typify large areas of the subpolar and subtropical gyres. In part, the lag between Bravo and Panulirus is manifested as a time-evolving deep shear across the Gulf Stream (seen in the dynamic height difference between Bravo and Panulirus), suggestive of a theoretical climate-oscillation driven by inter-gyre eddy-exchange under study by Spall (1996).

Looking higher in the water column off Bermuda, Talley and Raymer (1982) observed interannual change in 18-degree water, again using Panulirus data. This water mass, formed seaward of the Gulf Stream by intense winter cooling by cold air outbreaks, is presumably advected by the Stream and its recirculation to Bermuda. Transient tracer data collected at Bermuda nicely depict the arrival of such surface-influenced waters to the thermocline. The 18-degree water at the Panulirus station is tagged with tritium prior to 1970. Tritium and helium-3 fronts arrive there in the mid-1970's at ~1000 m depth, and about a decade later at ~2000 m, reflecting the different circulation paths of these waters (Jenkins, 1988). Talley and Raymer (1982) confirmed Jenkins (1982) finding of weak correlation between the intensity of winter cooling and the strength of the 18-degree Water pycnostad at Panulirus. Joyce and Robbins (1996) point to the influence of surface salinity (and buoyancy) on the strength of the pycnostad. Cause of these 12-14-year period salinity oscillations is not known. Analogous to the dynamic height variations noted above at intermediate depths, Worthington (1976) discussed the effect variable 18-degree water strength on the upper-ocean shear across the Gulf Stream.

Superimposed on these decadal-scale oscillations in the Panulirus record, Joyce and Robbins (1996) observed a consistent warming trend at 1500-2500 m depth off Bermuda. Again using available research-cruise hydrographic casts in the area, they extended the record back to 1922. The estimated warming trend over this period is significant with an amplitude of 0.5 degree C / century. The warming calculated from sections occupied in 1954 and 1985 appeared to be caused by vertical motion of the thermocline. (T/S did not change.) The time-series stations in the western North Atlantic thus document changes in gyre baroclinicity as well as convectively-modified water characteristics.

The longest "continuously" occupied station (approaching 50 years) is located in the Norwegian Sea, Weather Ship Station M (or Mike). Akin to what was seen in the Labrador Sea, hydrographic data from Mike reveal large-amplitude decadal-scale variability in water properties that may be related to changes in atmospheric exchange, deep convection and circulation. For example, since 1990, salinity of the northward moving Atlantic Water has decreased markedly, and now approaches values last observed during the Great Salinity Anomaly (Osterhus et al., 1996). At depth during this time, Norwegian Sea Deep Water has warmed and increased in salinity. Properties at these latter depths are believed influenced by Greenland Sea Deep Water (GSDW), a convectively modified water mass. The evolution of deep water properties at Station Mike suggests a change in deep convection within the Greenland Sea. Indeed, a compilation of research cruise data to the Greenland Sea (most recently on an annual schedule) shows that deep convection has been inhibited of late (Bullister, 1996). Analysis of tritium/helium-3 and CFC concentrations has quantified the GSDW renewal rate. For the period prior to 1982, the renewal rate was estimated to be ~0.5 Sv; since then, rate estimates are about a factor of five smaller. Lacking injections by vigorous deep convection, the deep temperature and salinity of GSDW have gradually increased, perhaps due to the influence of Arctic Ocean deep water.

Another weather ship station maintained to the present (but with reduced temporal sampling recently) is in the northeast Pacific, Station P (Papa). Unlike the sites discussed above, deep convection is not observed at P. Nevertheless, one of the more interesting long-term signals in this record concerns the surface mixed layer. The ~100 m thick winter mixed layer appears to have shoaled at a rate of 65 m / century over the last 40 years. Whitney et al. (1994) also report a corresponding decrease in surface nutrient concentrations. Increased surface layer buoyancy as compared to the underlying waters due to a decrease in surface salinity appears responsible for the mixed layer thinning. Interestingly, no change in biological productivity has been seen. One possible explanation is that the increased light available to plankton in the thinner mixed layer has so far compensated for the decrease in nutrient concentrations.

Given these very brief examples, it can be argued that significant interannual variability has been documented everywhere that subsurface oceanographic data have been gathered for long periods. But for most regions of the oceans, we have no long, well-resolved records to document subsurface property oscillations or trends on decadal to century time scales. However, ocean surface property and upper-ocean temperature data (which have better global coverage than subsurface fields) have documented major decadal-time-scale oscillations in the Pacific and Southern Oceans as well as the Atlantic (e.g., Deser et al., 1996; White and Peterson, 1996; Deser and Blackmon, 1993). Furthermore, comparisons of subsurface hydrographic data from the same areas but separated in time by several decades reveal major temperature/salinity changes in the Tasman Sea (Bindoff and Church, 1992) and South Indian Ocean (N. Bindoff, personal communication). These latter analyses cannot speak to the timescales of the changes though, and may be aliased.

To better document and understand interannual variability of subsurface ocean properties and baroclinicity, it is argued that within CLIVAR a global observation network be instituted. Highest priority should be given to maintaining those few stations that presently exist. Beyond that, the array should target areas of known water mass formation and modification, and also the major baroclinic currents. Below I list some possible observation sites.

Partial list of sites to maintain/initiate ocean profile observation programs

Existing stations: Mike, Bravo, Papa, Panulirus/BATS, HOTS, Canaries, ...
North Atlantic: Greenland Sea, Denmark Strait overflow (Charlie Gibbs FZ), 18-degree water formation area, MEDOC area & Strait of Gibraltar overflow, Gulf Stream / subtropical gyre baroclinicity: stations in slope water south of New England, plus Panulirus and Canaries North Pacific: Okhotsk Sea+ overflows, N. Pacific-subtropical Mode Water formation area Indian: Red Sea+ overflow,
Subtropical oceans: Evaporation zones responsible for the shallow salt max layers
Subantarctic: Subantarctic Mode Water belt, AAIW formation west of S. Chile
Southern Ocean: Antarctic Circumpolar Current, Weddell Sea, Ross Sea,
Arctic Ocean

Traditionally, time-series stations have been manned, beginning with the weather ship stations. The costs to maintain a dedicated vessel at sea continuously are highly prohibitive though. Those stations now in operation apart from Mike are maintained by periodic visits of a research vessel. Yet, this technique is itself only viable for sites close to a staging port. The only practical means to expand the observation network globally is to use autonomous instruments and to also build on the existing program involving ships of opportunity. Assuming VOS is discussed elsewhere, I focus here on the former.

There are several techniques now available for unattended acquisition of profile data from the ocean. Most commonly, ocean time-series data in remote regions have been collected using discrete instrumentation on moorings. The ATLAS buoys presently forming an array in the equatorial Pacific Ocean, for example, use a set of individual temperature sensors spanning the upper 500 m of the water column. In similar fashion, surface moorings with discrete physical and biological oceanographic sensors are being maintained or proposed at stations offshore from Bermuda and Hawaii, respectively. Beyond the expense of multiple sensors, a limitation of this technique is the relative calibration of each probe. Discrimination between a truly well mixed layer, and one with residual stratification, can be ambiguous if individual sensors have unknown offsets. This is a particular problem for conductivity sensors that are prone to calibration drift. Profiling instrumentation in which one instrument package moves vertically through the water column significantly reduces calibration uncertainty, and can offer improved vertical resolution compared to conventional mooring. Eckert et al. (1988) describe a kite-like instrument platform that derives vertical lift for profiling from ambient currents. Another approach is presently under development at the Woods Hole Oceanographic Institution (Frye et al., 1996). This full-ocean-depth-capable Moored Profiler uses a traction drive system to propel itself vertically along a standard mooring wire. To date the instrument has been fitted with a CTD; integration of a velocity sensor is underway, and addition of dissolved oxygen, nitrate and other sensors is being explored.

Vertical-cycling free vehicles are also becoming available. The Profiling Autonomous Lagrangian Circulation Explorers (PALACE) deployed during WOCE are presently returning temperature profile data from the upper ~1 km of the ocean. Evaluation of conductivity sensors recently added to the instrument is underway. The PALACE drifts with the ocean currents (thus also providing information on circulation patterns and rates) and so might not remain close to a designated time-series station site. One means to obtain Eularian information with the device is to periodically release instruments at a study site. If deployed in sufficient numbers, horizontal interpolation can be used to develop time-series information at one point. Alternatively, self-propelled free vehicles (gliders and propeller-equipped devices) capable of maintaining station or performing repeated sections are showing promise.

No single technique appears best suited for the many CLIVAR applications sketched above. A mix of technologies is necessary. Relatively low-cost free vehicles and VOS programs are well suited to broad spatial coverage of the upper ocean. As these instrument systems are expendable, costs limit the number of sensors they can carry. Also since they are not recovered, calibration uncertainties may limit their usefulness in the deep ocean. Recoverable moored systems, while more expensive to maintain than the expendable instruments, offer more accuracy control through post-deployment laboratory calibration. If they cycle through depths with stable water properties, in situ calibration information can also be obtained. Because they are re-usable, an initial investment in more extensive and accurate (thus expensive) sensors can be rationalized. Moored instruments appear optimal for local process experiments and monitoring water properties at key sites. Lastly, cruises to deploy and maintain instrument systems offer a platform for collecting water samples. As has been demonstrated, occasional sampling of tracer concentrations and inventories can provide useful integral measures of water mass renewal rates.

References

Bindoff N.L. and J.A. Church (1992) Warming of the water column in the south-west Pacific. Nature, 357, 59-62.
Bullister (1996) Report to the April 1993 ACCP meeting.
Curry, R.G. and M.S. McCartney (1996) Links between Labrador Sea convection and subtropical mid-depth warming/cooling patterns. J. Geophys, Res., 101, 8749-8758.
Deser, C., and M.L. Blackmon (1993) Surface climate variations over the North Atlantic Ocean during winter: 1900-1989. J. Climate. 6. 1743-1953.
Deser, C., M.A. Alexander and M.S. Timlin (1996) Upper ocean thermal variations in the North

Pacific during 1970-1991. J. Climate, in press.
Dickson R.R., R. Meincke, S.-A. Malmberg and A.J. Lee. (1988) The "Great Salinity Anomaly" in the northern North Atlantic 1986-1982. Prog. Oceanogr., 20, 103-151.
Eckert, D.E., E.W. Geller, G.B. White and J.H. Morrison (1988) An autonomous ocean instrument platform driven vertically by the current. Flow Technical Report No. 448, 35 pp.
Frye, D.E.. K.W. Doherty, A.A. Knton and J.M. Toole (1996) A moored, profiling instrument for long-term hydrographic observations. EOS 76, no. 3 supplement, pg OS77. Abstract of poster presented at the 1996 Ocean Sciences Meeting.
Jenkins, W.J. (1982) On the climate of a subtropical ocean gyre: Decade timescale variation sin water mass renewal in the Sargasso Sea. J. Mar. Res. 40, suppl. 265-290.
Jenkins, W.J. (1988) The use of anthropogenic tritium and helium-3 to study subtropical gyre ventilation and circulation. Phil. Trans., Roy. Soc, London A, 325, 43.
Joyce, T.M. and P.E. Robbins (1996) The long-term hydrographic record at Bermuda. J. Climate, in press.
Lazier, J.R.N. (1980) Oceanographic conditions at Ocean Weather Ship Bravo, 1964-1986, Atmos. Ocean, 18, 227-238
Lazier, J.R.N. (1996) The salinity decrease in the Labrador Sea over the past thirty years. Proc. Nat. Acad. Sci. Symp. Decade to Century Time Scales of Natural Climate Variability. Irvine, CA, Sept. 1992. National Academy Press.
Osterhus, S., T. Gammerlsrod, and R. Hogstad (1996) Ocean Weather Ship Station M (66N, 2E) The longest existing homogeneous time series from the deep ocean. Submitted to International WOCE Newsletter.
Parrilla, G., A. Lavin, H. Bryden, M. Garcia and R. Millard (1994) Rising temperatures in the subtropical North Atlantic Ocean over the past 35 years. Nature, 369, 48-51.
Roemmich, D. and C. Wunsch (1984) Apparent changes in the climatic state of the North Atlantic Ocean. Nature, 307, 447-450.
Spall, M.A. (1996) Dynamics of the Gulf Stream / Deep western boundary current crossover. Part II: Low frequency internal oscillations. J. Phys. Oceanogr., in press.
Talley, L.D. and M.E. Raymer (1982) Eighteen Degree Water variability. J. Marine Res. 49, suppl. 757-775.
White, W.B., and R.G. Peterson (1996). An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent. Nature, 380, 699-702.
Whitney, F., H. Freeland and R. Perkin (1994) Repeat hydrography program for Line PR6. International WOCE Newsletter, 16, 37-39.
Worthington, L.V. (1976) On the North Atlantic circulation. The Johns Hopkins Oceanographic Studies, No. 6, 110 pgs.

ANNEX XXII

A PROPOSAL FOR A NORTH PACIFIC BASIN-WIDE EXTENDED CLIMATE STUDY

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Background: The basic physics of ENSO are now understood, and predictions are routinely made of tropical Pacific SST. Other modes of seasonal-to-interannual climate variability are now being explored, involving the subtropical North Pacific, and interactions with the Asian-Australian monsoon system. In addition, robust decadal variations of the North Pacific, and decadal modulations of ENSO, have been documented, and coupled ocean-atmosphere mechanisms have been proposed. The observational basis for improved understanding of these modes of climate variability must be developed.

Objectives: To obtain a quantitative description of the shallow overturning circulation of the North Pacific Ocean and the processes which couple the tropical, subtropical and subarctic gyres.

Strategy: To combine multivariate ocean observations with an assimilation/analysis system, conducting periodic reanalyses with more complete datasets and improved models.

The (re)analysis products must be capable of determining the coherent patterns of upper ocean variability and the processes that cause them. These processes include: lateral (isopycnal) advection; subduction; mixing and entrainment; Ekman divergence; air-sea fluxes; and Rossby wave propagation and reflection. It is not sufficient to simply obtain observations of the patterns and processes; they must be "well-modelled". A critical mass of observations is essential, however.

Present planning assumes a global observing system which includes the following ocean variables:

- thermal structure - XBT (high res + broadcast), TAO + TRITON
- sea level - altimeter + tide gauges
- velocity - surface drifters, floats, CM moorings
- salinity - ? repeat hydrography
- forcing - scatterometer, TRMM, ISCCP + ? NWP

Present planning assumes that CLIVAR will provide enhanced monitoring of:

- boundary flows such as the Kuroshio (TOLEX, PN line, Asakusa line); VOS ADCP; regional tomography
- upper thermocline flow - floats; VOS ADCP
- salinity - PALACE floats? Seacats on surface drifters? Thermosalinograph on VOS? time series stations,

Present planning assumes that CLIVAR (and other major ocean programs) will conduct process studies to further enhance observations regionally with the objectives of improving models used for assimilation and prediction, and to further develop the climate observing system. An example of such a potential process study is on the bifurcation of the North Equatorial Current and the atmospheric and oceanic factors which control the partioning of mass, heat and salt into the Kuroshio and the Mindanao Current. This is relevant to the seasonal-to-decadal variations of the Asian-Australian monsoon system, and to the warm pool of the western equatorial Pacific.

Presently, it is not clear that this component of the tropical-subtropical gyre interaction is simulated properly by any model, because the observational basis for such a determination is poor even for the annual cycle.