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Ocean observing system development programme

A World Climate Research Programme Action Plan

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Foreword

Like most advances in oceanography, the oceanographic experiments* being planned for the World Climate Research Programme will depend on the use of a combination of new and old technologies: satellites for measurements of sea-surface temperature, wind stress and direction, and ocean-surface topography; expendable bathythermograph (XBTs) and conductivity/depth/temperature (CTD) recorders; drifting and moored buoys: and acoustic tomography, a new technique utilizing the remarkable properties of sound in seawater. The principal use of ocean research ships will be to take deep hydrographic casts and to follow the sinking of water masses by geochemical tracers. For several purposes, the most useful instruments will be tide gauges installed on open coasts and on islands and used to measure not tides but monthly varations of mean sea level.

The ocean-observing satellites will not be available until the later years of the 1980s. But prior to that time much can and must be done. For example, in the early stages of TOGA, essential observations of currents, water properties, and meteorological parameters can be carried out using drifting and moored buoys, XBTs, XCTDs, surface ships, tide gauges and meteorological observing stations.

The weekly or monthly mean sea-level values from tide gauges can be interpreted directly as variations in the strength of geostrophic currents as well as in the depth of the warm-water layer beneath the surface. Operation of one or more tide gauges and the making of the related temperature and salinity measurements should be feasible for most Member States of the Intergovermental Oceanographic Commission (IOC) and World Meteorological Organization (WMO). These observations should be especially useful to developing countries in helping them to understand the ocean variations off their coasts which affect fisheries and marine resources. For example, if the sequence of events of an El Niño can be carefully followed by a proper set of mean sea-level and surface and subsurface temperature observations, fisheries planning for Ecuador, Peru and Chile should be facilitated.

Determining the variability of the ocean in time and space is an essential element of the oceanographic activities in support of the WCRP. Here the concern is with exploratory time series of ocean measurements lasting over five to ten years to determine the first order statistics of ocean variability; and with continuing time series covering many years to monitor ocean conditions in climatically critical areas.

Both exploratory and monitoring time series are usually carried out as parts of national oceanographic programmes, undertaken for a variety of purposes, including *inter alia,* weather and climate forecasting, and gaining greater understanding of time and space fluctuations in fisheries. The SECTIONS programme of the USSR, the Japanese hydrographic sections along the meridian of 137° E, which have been repeated for many years, the detailed Japanese studies of the Kuroshio region, and the American Transpac XBT surveys are examples. Several time-series programmes are undertaken co-operatively between two or more countries, as illustrated by the collaboration in the SECTIONS programme of the German Democratic Republic, Pacific XBT surveys by the French oceanographers in Noumea, and by the time series of hydrographic observations over many years carried out by the International Council for the Exploration of the Seas.

There are obviously very large gaps in the coverage of the world ocean by present observational programmes, particularly in the Indian, South Atlantic and South Pacific oceans, and many more Member States need to undertake observational programmes to gain understanding of the fluctuations in ocean conditions affecting the living resources under their jurisdiction as well as to contribute to the WCRP.

The Ocean Observing System Development Programme prepared by the SCOR/IOC Committee on Climatic Changes and the Ocean (CCCO) in co-operation with the Joint Scientific Committee for the WCRP describes the principles which should govern the improvement and expansion of ocean observational programmes within the framework of IOC and WMO in support of the WCRP. The Development Programme emphasizes the need for establishing criteria for calibration, reliability and accuracy, the problem of data processing, assimilation and timely distribution for use in model studies and problems of cost effectiveness and sustainability in the development of a world ocean monitoring system for climate purposes.

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* TOGA - Study of the Interannual Variability of the Tropical Oceans and Global Atmosphere.
WOCE - World Ocean Circulation Experiment.

Summary

This report describes the principles which should govern the Ocean Observing System Development Programme (OOSDP) for the purposes of the three streams of the World Climate Research Programme, and discusses issues requiring action in the near future. Because of present limited understanding and experience, both the objectives and the implementation must evolve, building systematically the basis for more effective future designs. At the same time, this approach should support the major research experiments within the WCRP, and, in a few instances, establish a baseline for determining long-term changes. The reports is confined to those observational activities which might be described as monitoring or quasioperational, and excludes all measurements which would normally require a research vessel. Chemistry and biology are also not discussed.

Existing observational subsystems are mostly in place for other reasons. These will need improvements for climate purposes, at the same time as new technology capable of sustained global coverage is introduced, always striving for overall performance of the observational, data management, and analysis system in terms of explicitly stated goals. These, however, will change as understanding of the climate system improves.

For some variables, interim quantitative requirements are known approximately or can be determined in the near future; for others, a substantial period of exploratory time series will be necessary to establish the magnitude of the signal and of the natural fluctuations describing it.

Proposals for action are of four kinds:

- initiation of a limited number of specific, major programmes,
- modifications of details in existing data collection and analysis procedures,
- initiation of development and pilot programmes, and
- studies of major issues requiring clarification or more careful planning.

The actions are summarized in section 3, which also includes suggestions as to which international group should assume lead responsibility for each item.

Because of the iterative and diversified nature of decision making in this field, statements of priority and schedule are necessarily tentative and all actions are dependent on the availability of appropriate resources. It is recognized that these proposals present a substantial challenge to the nations of the world, requiring substantial innovation, dedication and resources, as well as effective international collaboration. Nevertheless, documenting and understanding climatic variability and long-term change will not come about without a concerted global effort which includes addressing directly the needs outlined here.

Contents

1. Introduction

1.1 Structure of the World Climate Research Programme

The World Climate Research Programme has been divided conceptually into three streams of activity:

Stream 1 The physical basis for long-range prediction of weather anomalies

Stream 2 Interannual variability of global atmospheric climate and the tropical oceans

Stream 3 Long-term variations and the sensitivity of the climate system to external influences

The ocean observing system is closely connected to each of these streams, and to be cost effective must serve the requirements of all three. Since the precise programme elements in each stream are still evolving, any statement in this document of such requirements must be regarded as tentative, proposed so that a realistic iterative dialogue can ensue. Nevertheless, many aspects are already clear, and these provide the initial focus of this plan.

1.2 Objectives of the Ocean Observing System Development Programme

In view of the long timescales involved in characterizing the climate system, the present state of our knowledge of the system, and the prospects for important new technology, the ocean observing system must be evolutionary in concept and implementation. Initially it will provide selected multivariable data sets and time series:

(1) To characterize large-scale phenomena on seasonal and longer timescales of variability, leading to analyses with well established quality and probable error characteristics.

(2) To provide input on ocean conditions for atmospheric long-range prediction models.

(3) To provide a data base for intercomparison with new observation technologies and analysis methods, both to enable thorough evaluation and to preserve continuity with past records.

(4) To begin to provide quantitative information on key derived fields, such as wind stress and surface heat flux needed on a broad scale for validation of numerical ocean models.

(5) To provide the basis of experience from which, as deeper understanding becomes available of the mechanisms for climate variability and change, a more cost-effective system can be designed, to be used on a pilot basis for climate prediction.

1.3 Nature of the activity

These objectives have been derived from discussions at the meeting on 'Time Series of Ocean Measurements,' Tokyo 1981 (WCP-11), at the meeting on 'A Pilot Ocean Monitoring System,' Miami 1979, the study conference on 'Large-Scale Oceanographic Experiments in the World Climate Research Programme,' Tokyo 1982 (WCRP-1), at the 4th Session of the Committee on Climatic Changes and the Ocean (CCCO), Paris, 1983, and from the deliberations of the World Meteorological Organization (WMO) and the Integovernmental Oceanographic Commission (IOC). The activity to be undertaken by the Ocean Observational System Development Programme has been variously described as 'Time Series Measurements,' as 'Pilot Ocean Monitoring,' as 'Exploratory Time Series and Monitoring,' as 'Comprehensive Monitoring' and as 'Ocean Observing.' This diversity apparently arises in part from the diverse meanings attached to the word 'monitoring' in different countries, even within the English language, and in part from real differences in concept of the proper function of this programme component.

The activity intended here is characterised by a number of features which set it apart from most forms of oceanographic research. It has a major observational component shared between many individuals. It is undertaken with the intention of continuing on a uniform basis for a number of years, longer than normally considered appropriate to a single research project. It draws on more widely available platforms and personnel than research vessels and research scientists. Satellite systems will play an increasing role during the coming years. It is intended to characterize trends and phenomena rather than providing complete information about individual processes within the system being observed.

Though this type of activity is necessarily deeply embedded in the major experiments of WCRP, it requires a special approach and organisation, with emphasis on orderly development of a coherent system for observations, data management and analysis procedures. The immediate problem is how to adjust present capabilities to provide a system designed to meet the objectives listed above. This requires detailed assessment of the present state of knowledge of the space and timescales of relevant oceanic and atmospheric variables as well as the capabilities of existing instrumentation, and potential data gathering capability.

The initial phase of adjustment must include determination of these factors, and a quantitative evaluation of anticipated end-to-end system performance according to the above objectives. It must be recognised that not all actions required to make the programme successful will fit neatly into such an idealised framework. Considerable experience exists which has already been brought to bear on aspects of the problem. Glaring deficiencies in present operations will often need to be remedied immediately on an incremental basis. Decisions to develop new instrumentation frequently have to be made without complete knowledge of the specific situations in which they will be deployed. To a considerable extent, reliance must be placed on volunteer efforts and collaboration with programmes for which the primary justification is quite different. Thus, care should be taken to encourage and constructively entrain potentially useful inputs of all kinds. Nevertheless, careful assessment of system performance, including analysis procedures and probable errors in their outputs, should be a central part of its ongoing evolution.

Finally, the underlying rationale is significantly different from that of the research experiments. There is perceived to be a need throughout the foreseeable future for observations of the ocean as part of the climate system, both to document year-to-year variations and to assess long-term changes or trends. This activity comprises those things that must be done now to meet this need, either with the expectation of continuing them indefinitely or with a view to designing a system that could be continued indefinitely.

1.4 Underlying assumptions

It is also worth noting explicitly certain assumptions which underlie the World Climate Research Programme and have an impact both on programme structure and on expectations about our eventual ability to predict climate variations and long-term change. For example, it is generally supposed:

(1) That the climate system is inherently deterministic, at least in some respects, and that these deterministic aspects of climate can at least in principle be identified.

(2) That these deterministic aspects can be addressed by numerical models.

(3) That model requirements can be used to specify the observing system necessary for prediction.

(4) That the specified observing system will indeed be practicable.

The plan outlined here adopts these postulates, but also qualifies them:

(2a) Important cause effect relationships in the ocean-atmosphere interaction have not yet been identified. In addition to numerical models, an important tool for identifying them will be the semiempirical study of coherent phenomena from partially complete data.

(3a) At present, knowledge of ocean processes is such that only some requirements for prediction models can usefully be specified.

(4a) Practicable within the coming decade means an ongoing observation system capable of global phenomenological description of several variables, and of meeting quantitative modelling requirements for a few. This is a long way from a complete observing system.

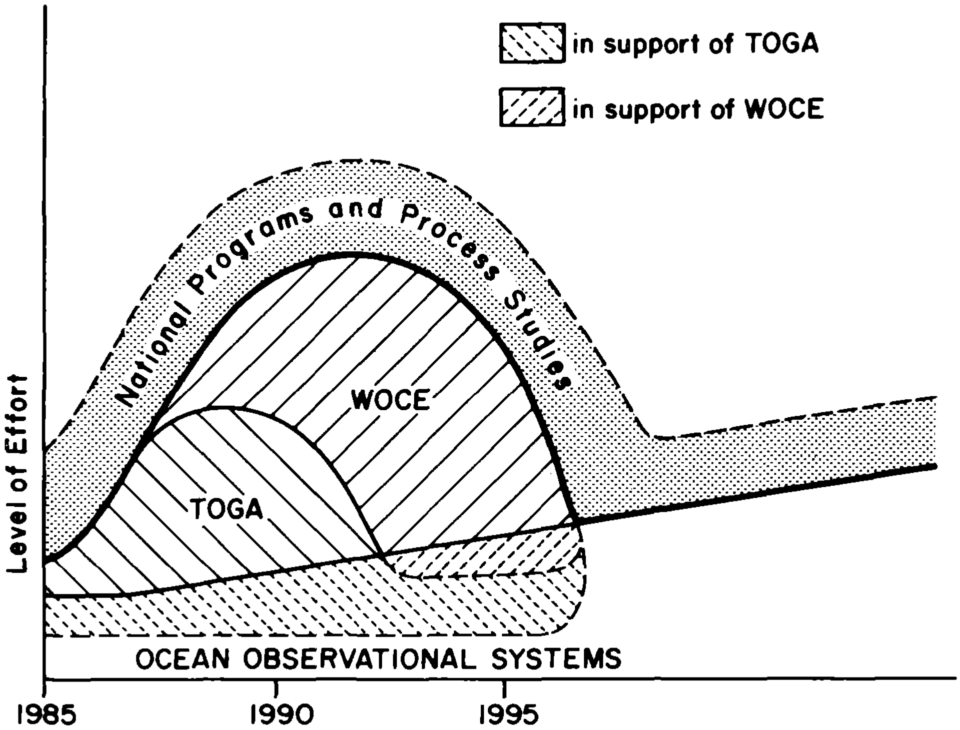
It is also assumed that, during the next decade, the ocean observing system will be supplemented in the research mode by measurements adequate both to increase substantially our understanding of key aspects of the climate system, and to assist in a better definition of observational requirements. A conceptual picture of the whole programme is shown in the Figure. It should be noted that the pieces are interrelated in many ways. For example, measurements of large-scale variability in the upper ocean need to be undertaken now to gain experience for future system design. Yet the priorities are influenced by the requirements of the World Ocean Circulation Experiment (WOCE) and the Study of the Interannual Variability of the Tropical Oceans and Global Atmosphere (TOGA). Likewise, the understanding to be gained from WOCE and TOGA is also essential for the evolution of a cost effective observational system design.

1.5 Requirements for WCRP Stream 1

For Stream 1 the general requirement is for information about the ocean surface layers from which models can predict the evolution of sea surface temperature (SST) worldwide for periods of several weeks, on spatial scales of meteorological importance. In midlatitudes these are 500 km or larger, except near coasts or intense boundary currents. In the tropics higher resolution in latitude will be needed if the locations of atmospheric deep convection are to be modelled correctly. The needed accuracy is being determined by the Joint Scientific Committee (JSC) of the WCRP, but is probably 1-2°C in midlatitudes and 0.5°C in key areas in the tropics. Sea ice cover is also needed. These accuracies imply that in midlatitudes only the more intense, widespread anomalies are significant to atmospheric circulation. However, the longitude of deep convective activity above (for example) the equatorial Pacific does seem to be very sensitive to SST.

There are two types of ocean models capable, in principle, of predicting the evolution of SST -- statistical and dynamic/thermodynamic. The former assumes good knowledge of the seasonal march of temperature and other variables, such as the depth of the mixed layer, and allow observed initial conditions to regress towards climatology according to a formula derived from statistical regression. Simple persistence of anomalies of a certain scale or pattern for the duration of the forecast is a special case of this type. The thermodynamic models use a turbulence model to infer the evolution of temperature and salinity profiles throughout the upper mixed layer and the thermocline below, requiring both detailed initial

SST over the globe and the appropriate time constants for regression is itself a major task, essential for the development of an adequate Stream 1 predictive capability.



Schematic diagram of the relationship of the ocean observing system to other ocean elements of the WCRP, and to national programmes.

conditions and subsequent boundary conditions for local wind stress and surface heat and freshwater fluxes supplied from the atmospheric prediction model.

However, established predictive capabilities are such that, at this time, the additional observational and analysis effort required for the thermodynamic models does not seem justified on a routine global basis for the objectives of Stream 1. Instead, the strategy should be to measure SST anomalies, and suppose that these tend to regress with the passage of time towards the mean value for that location and time of year. In a few regions it may prove necessary to add the regression subsurface information such as the depth of the mixed layer to the data input. The criterion for doing this on a permanent basis should be that the inadequacies of the forecasts of SST distribution are demonstrably degrading the atmospheric forecasts, and that the addition of obtainable subsurface data materially improves this situation. This strategy presupposes that, on timescales of up to a month or so, the ocean influences the atmosphere, but the systematic feedback of the atmosphere on the ocean is overwhelmed by unpredictable noise associated with day-to-day weather fluctuations. A potentially important modification is to include as input into the SST regression atmospheric variables, such as wind direction, which are being predicted by the atmospheric model. It should be noted that the adequate determination of the mean annual cycle of

Here it is important to distinguish skin temperature in the upper 1 mm, which is measured by a satellite or airborne radiometer, from the temperature typical of the upper 1 m or so, which is reported by buoys and ship injection temperature, and is usually representative of the upper mixed layer at 5-10 m, though with a ship-dependent bias. Depending on conditions, these may differ by 1°C or more, which is often as large as the change being predicted. Though a good mixed-layer model will in principle estimate each of these, the distinction is frequently ignored and is not normally made in current routine analysis procedures of SST.

The technology for observations of SST and upper-ocean heat storage observations from volunteer observing ships and specially equipped ships of opportunity is well developed, though it is difficult to obtain the necessary frequent coverage and sampling to average over the variability on the oceanic mesoscale. Also, the realised measurement accuracy of all the surface variables leaves much to be desired. Present practices of reporting and international data exchange are, however, incapable of supplying the information at periods of less than several months, and are therefore quite inadequate for long-range weather prediction. Improved retrievals of SST from satellite infrared radiometry would make a substantial difference to present capabilities.

For sea ice extent, the only practicable method applicable on a global scale is observing from passive microwave radiometers on polar orbiting satellites. The attainable accuracy appears to be adequate.

Thus, the basic capability for meeting the requirements for Stream 1 probably exists, or could be put in place. However, the design of an ocean observing system which is cost effective for this purpose cannot be undertaken immediately, because the sensitivity of atmospheric long-range prediction models to typical uncertainties in oceanic input data has not yet been adequately investigated. It seems likely that special observational efforts will be needed in the tropics, where horizontal differences of 1°C over 1000 km can be very important, whereas in midlatitudes only small improvements over a good climatology will be necessary.

Recent studies note a possible new opportunity for forecasts on a timescale intermediate between Streams 1 and 2. Statistical analysis of historical records show that the January SST and surface winds in the tropical Atlantic are useful predictors for the rains in northeast Brazil in March-April. This conclusion is in accord with earlier modelling simulation studies. The needed SST and wind observations are currently being taken, but the collection of most of the data is very much delayed. This opportunity for medium-range forecasting with important economic consequences could be exploited now on an exploratory basis, if only rapid communications could be arranged, e.g., collection of the ship SST and wind observations by radio or satellite relay.

1.6 Requirements for WCRP Stream 2

If year-to-year variations in seasonal climate are to be documented on a global basis, and at some time in the future possibly predicted, development of the tools for observing the upper layers of the ocean must proceed now. Though some measurements at the ocean surface have been routinely made by volunteer observers for a century, instruments such as the expendable bathythermograph (XBT) have only been available for a little more than two decades, and others such as the Doppler current meter are only now emerging from the development stage. The integration of these into an effective measurement system has barely begun. Sampling noise associated with the small-scale variability in the ocean, large gaps in coverage, and inadequate data management systems have resulted in analyses of uncertain quality and limited usefulness. Indeed a fundamental problem is our inadequate knowledge of the scales and magnitude of the variability present, and the first requirement is for a programme of exploration aimed at defining the basis for a proper system design. Another fundamental problem, not unrelated to the first, is lack of accepted criteria about overall system requirements, and what constitutes an adequate observing system.

Under these circumstances it is sensible to examine the observational needs of the major research experiments in WCRP and to isolate those which are best met by an activity of the type under discussion here. This is both an effective use of resources, and a useful catalyst for a systematic approach to the underlying problems. These needs are not the only ones that must be considered, and a similar effort would probably be justified even if the research programmes did not exist, but the logical next steps for the OOSDP overlap substantially with the research needs.

For Stream 2, the principal element of the World Climate Research Programme is TOGA (Tropical Ocean, and Global Atmosphere, WCP-49; also TOGA-1, Hamburg, 1983). This is aimed at understanding the causes of interannual variations in the Asian and African monsoons, and other widespread intermittent atmospheric phenomena such as the Southern Oscillation, in order eventually to be able to predict them. There is a large and growing body of evidence suggesting that the tropical oceans influence the global circulation of the atmosphere on these timescales. In the Pacific, the Southern Oscillation is closely associated with major changes in the ocean surface layers along the equator and South American coastline, known as El Nino. The working hypothesis of TOGA is that growth of these climatological anomalies is a coupled ocean atmosphere instability, which develops over a year, triggered by as yet unknown antecedents. Elucidation of this coupling will require intensive observational components aimed at quantitative measurements of key processes such as heat budgets over prescribed regions in the equatorial ocean for a limited duration, together with other components aimed at 'thin monitoring' of surrounding regions for at least a decade, to ensure that the context of the intensive efforts is properly described. The intensive observations are properly undertaken as research activities of limited duration, using mainly specialised personnel. They will not be considered further here.

However, though the appropriate balance between the process oriented components and the thin monitoring is still the subject of debate, there is consensus that the present capability to describe phenomenologically the evolution both of the normal annual cycle and the anomalous events must be maintained and, where feasible at reasonable cost, improved and extended. This capability is presently based primarily upon mean sea level (MSL) observations from coastal and island tide gauges, cooperating merchant ship data on SST and wind, and on XBT programmes from selected ships of opportunity, together with a few hydrographic sections from research vessels.

Satellite derived SST and cloud winds are a valuable adjunct in some areas. Direct observations of currents from moored and drifting buoys are just beginning to contribute to this description, though they are relatively few in number. In the future, near-surface current profiles from ships of opportunity, satellite measurements of changes in sea level, and scatterometer winds are all expected to contribute. However, it must be recognized that the assimilation of these new technologies will require a long period of intercomparison and evaluation, including the development of new data management and analysis procedures. It is of the utmost importance that effective continuity with present methods be firmly established, so that existing historical records can continue to be utilized effectively.

In the Indian Ocean, and also in the Atlantic Ocean, attention is concentrated more on the evolution of the normal annual cycle, and the interannual variations have been less well documented. However, substantial widespread year-to-year differences in atmospheric circulation and rainfall patterns have been noted, with considerable social consequences. The extent to which these are responsible for or triggered by changes in the ocean is virtually unknown.

A prudent programme will include the exploratory description of the temporal evolution of a variety of fields and key variables which may plausibly be connected with the dominant monsoon circulations and the upper ocean processes. The initial objective of this programme component must be to establish the space scales of variability on semiannual and longer periods, and the approximate magnitudes of variability on shorter periods which could affect the required sampling density. Some such studies are already complete or underway, in both the Atlantic and Indian Oceans. This information will then be used to evaluate the ability of alternative observational strategies to describe the large-scale phenomena.

It is already clear that certain additional observations such as MSL will be cost effective, and that a major effort will be needed to improve present abilities to document SST and wind fields. It is anticipated that, as in the Pacific Ocean, ongoing measurements of profiles of temperature from ships of opportunity, and possibly also salinity and velocity, will also be important elements of the strategy. Only after considerably more understanding has been gained of the interconnections in the climate system will it be possible to focus this programme more sharply on a restricted set of variables in selected regions.

This analysis of the research needs of TOGA implies that it would be sensible to adopt those related to 'thin monitoring' of the ocean as an interim requirement of the OOSDP. The need to continue for 10 years, and the type of observations involved, require a similar organization. If a predictive capability for interannual variability of climate is ever to be achieved, observations of this type are going to be needed, and the TOGA observing system would be a prototype, or at least would supply the basic data necessary to design a prototype.

1.7 Requirements for WCRP Stream 3

For Stream 3, the long-range requirement is to watch and check for trends and changes in climate on a regional and global scale, distinguishing between alternative probable causes, such as volcanic eruptions or increasing atmospheric carbon dioxide. So far as the ocean is concerned, at this time we do no know how to do this in an effective manner. An integrated quantity such as global MSL can show changes in accumulated heat storage, and hence be a sensitive indicator of large-scale imbalances in the heat budget of the earth, but even this is confounded with melting of the ice caps. Systematic changes in sea ice coverage also have direct impact on the radiative balance of the globe. Most other time series must be interpreted in the first instance in terms of local changes of the ocean circulation, of uncertain significance to global climate.

For this reason, the major international effort in Stream 3 is focussed on the World Ocean Circulation Experiment (WOCE). The objective of WOCE (Tokyo, 1982, WCRP-1) is to understand quantitatively the general circulation of the ocean, in order to assess within the World Climate Research Programme the sensitivity of the climate system to changes in external forcing, whether natural or anthropogenic, on timescales of decades to centuries. The intensive observations in WOCE will be aimed at establishing the rates of circulation and mixing in the various ocean basins of the world, which will be compared with simulations by ocean general circulation models. These observations will be in the research mode, and will not be considered further here. However, they will need to be supplemented by a systematic determination of the average and annual cycle of the surface wind stress and seasonal thermocline over the globe, and by measurements of the magnitude of year-to-year variations in the circulation and near surface thermal structure which may affect the sampling strategy for estimating the mean. At the same time, efforts are needed to improve knowledge of the net heat and fresh water fluxes at the surface of the ocean. WOCE will also have to evolve procedures for establishing how representative is the particular snapshot provided by the intensive observations over the longer-term average.

The objectives and methodology of these supplementary measurements are well suited for consideration under the OOSDP, since they require similar techniques to those discussed above for the tropics. However, the accuracies and coverage needed are distinctly different. For example, the principal forcing on ocean general circulation models is the wind stress, averaged over one month or longer. Such a time average has a natural spatial scale, which determines the spatial resolution required. It is roughly 500 km in midlatitudes, but has smaller latitudinal scale in the equatorial regions. Coverage must be global. A typical signal is 0.1 N/m^2 in midlatitudes and about half that value in the tropics. Determination of the stress field so defined with an uncertainty reliably known to be no more than 20% would be a major advance for present knowledge, and would effectively eliminate a major degree of freedom in fitting model outputs to perceptions of reality. Presently, available ship reports of surface wind are inadequate for this purpose, both in frequency of coverage and because of systematic errors related to anemometer height and exposure. A satellite-borne scatterometer could meet the requirement, but only if it is determined how much of present uncertainties of ± 2 m/s is truly random, and the systematic errors are understood. Though the scatterometer must be regarded as experimental, its evaluation for this purpose must be a key objective in the evolution of a satisfactory observational system.

In addition to supporting the World Ocean Circulation Experiment, exploratory time series of limited extent of a number of variables are needed now to establish the natural variability on shorter timescales, and hence the basis for sampling longer-term trends in the future. This is particularly true in the upper layers of the ocean and regions of deep overturning, where interactions with the atmosphere are likely to be manifest first, and in regions such as the Southern Ocean where our present ignorance is greatest. In the tropical regions, support of TOGA will also accomplish this, but in middle and high latitudes separate efforts will be required. The criteria here should be to ensure, on a region by region basis, that all possible information has been extracted from existing data and then to extend the data base, starting with those variables that can most readily be measured, for just long enough to establish the magnitude and typical patterns of variability on scales up to an ocean basin. Where feasible, similar time series of major current systems are also needed. Priorities should be based on the potential suitability, according to present understanding of the ocean circulation, for long term maintenance of that type of observation.

1.8 The organization of this report

In the following section, the various observing elements are discussed by variable: first, with respect to some scientific, technological, and data management issues, and then in terms of items requiring action in the near future. Finally, these action items are summarized in section 3, together with identification of the international groups who should assume lead responsibility for each item. The overall responsibility for the balance and integrity of the programme remains with CCCO. The selection of items has taken into account the requirements, as best as can be ascertained at the moment, of the three streams of the WCRP, the technological feasibility, and the roles of the WMO and the IOC in supporting the deployment and data management aspects of the various elements. Insofar as possible, it is assumed that the observing components will be upwardly compatible, that is, an observing element implemented to meet Stream 1 requirements will automatically be available for Streams 2 and 3, augmented, of course, to meet the requirements of these streams.

2. Observational elements

Previous attempts to devise a strategy for pilot ocean observing systems in the form of action plans for the IOC and WMO have only defined incompletely the various observing elements with respect to the three streams of the WCRP, and they did not make sufficiently clear the need to implement limited-duration exploratory observing systems before moving to the design of 'pilot' observing systems. Also, the integration of the various elements into a feasible and useful system to provide an information base for climate studies and experimental forecasting remained inexplicit. The plan presented here attempts to redress these previous shortcomings. In this section brief discussions are given of each variable which must be observed directly or inferred from relevant measurements. Observations must always be considered in conjunction with analysis procedures and accuracy requirements for the complete system. This report, then, addresses the questions of what are the key scientific, technological and data management issues to be solved, and what start can be made with proven techniques that will supply needed information.

In reviewing the issues concerned with the variables to be observed or derived, some appeared to be general in nature. These are discussed immediately below in general terms; applicable details will be treated under each variable.

- Overlap of historical and new (mainly satellite) technology. It is becoming clear that satellites offer promise of far better global coverage than feasible using surface-based observing platforms, raising the hope that sampling will at last become adequate to allow acceptable statistical averaging. In addition, the observational data sets will be generally internally consistent (though they may contain systematic errors) and centralized data collection, processing and analysis can offer solution to timely availability of the information. However, attractive though the new technology may appear, it will be crucial to recognise some important issues that will have to be faced in phasing in the new procedures. For example, it would be a great mistake to terminate or even deemphasize conventional surface-based observations too soon. Experience has shown that many years, at least a decade, of careful overlap between satellites or other new technology and historical methods is needed to assure:
    - (i) that proper long-term intercomparisons are made to establish confidence in the new data sets and that systematic errors in both sets are understood and their causes identified insofar as possible,
    - (ii) that operational information-extraction algorithms can be developed, tested and put into practice that will match as closely as required the state-of-the-art algorithms that have been used for research (i.e., nonreal time), and
    - (iii) that reliable experience will be in hand on which to base operational decisions as to whether satellite systems can stand essentially alone to meet observational requirements (with on-going and routine minimal surface-based networks for quality control purposes) or to ascertain what mix of satellite-based and ground-based systems will be needed.
- Error analyses. For all observing systems, be they satellite-based or conventional surface-based, directed efforts will be needed to define the type, characteristics and magnitudes of error fields. That is we need to identify and define the magnitude and nature of systematic errors (e.g., calibration off-sets, time and place dependence), and the character and source of random errors (e.g., instrumental versus sampling nonrepresentativeness). In all error determinations, it will be necessary, ultimately, to judge how much of the apparent residual error is attributable to real instrumental error or natural small-scale variability, and how much is actually due to the impossibility of identifying effects of different time and space sampling characteristics of remote-sensing observations versus observations made in situ. In other words, there is no real 'surface truth'; each observation, whether direct or indirect, has its own instrumental, sampling and natural noise.
- Timeliness of data collection. Most data collection systems used now for surface-based conventional observations fall far short of suppling an adequate sample of the totality of observations to users for near real time experimental forecasting or diagnostic studies. Special efforts must be planned to decrease communication and/or data management delays and to expand the automatic collection of key observations, for example, by satellite relay. It is necessary also to assure that all observations not collected in real or near real time actually do get reported, and do not become irretrievable. These actions are necessary to assure that adequate

observational data sets are available from which an adequately sampled high-quality subset can be derived through appropriate data-management systems. Satellite observations, in principle, are communicated in near real time but delays can occur in the information-extraction process and in subsequent data management systems (relay to users, archiving).

- Data-management systems. Details of how observations and related information are handled impacts how effectively data can be used for near real time operations such as experimental forecasts or for later research studies. Observational reporting must begin to include all relevant ancillary information, such as platform identification, method identification (e.g., intake or bucket temperatures), ship heading, day or night observations. This kind of information must be preserved by the data-management system for analysis of the observations in order to make special platform- or method-dependent corrections and to acquire high-quality data subsets, and must also be preserved in the archiving process to facilitate post-processing research studies.
- Relationship between research and operational observing programmes. Some of the observational programs described in this document, for example, SST and MSL, are well established and are, in effect, already operational; many of the needed improvements can be accommodated in the operational mode. Some others, for example, certain XBT programmes, have been maintained for a number of years, and might soon be declared as 'ongoing,' and possibly as 'operational.' The evolution of an ongoing observing system to meet other needs discussed in this document will require exploratory programmes to acquire an information and experience base (for example, to determine the necessary sampling). The character of such exploratory activities may lie part way between traditional research programmes and ongoing operational ones, in that they have to be maintained for a decade or so, and yet are not intended to be on-going without complete redesign.

2.1 Sea surface temperature

2.1.1 WCRP requirements

- Stream 1 will require SST in near real time for use in diagnostic studies and in forecasts. This will require improved operational analysis methods and establishment of better and routine quality control procedures. The timely acquisition of the necessary global data sets will probably dictate a reliance on satellite observations interpolating between a purpose-designed network of reliable in-situ measurements.
- Stream 2 will require good sampling and quality control over the tropical oceans to define better the apparent association of changes in atmospheric circulation with SST anomalies in the range of 0.5°C up to several degrees. As much as possible of the contamination of observations from ships and satellites by extraneous factors must be removed. For example, use of nighttime-only bucket temperatures and intake temperatures corrected for ship-dependent bias would improve the analyses provided that, as a consequence of selection of only a subset of the data, the sampling were not to deteriorate appreciably.
- Stream 3 will require long-term coherent and stable data sets so that reliable seasonal means can be obtained in which changes such as those anticipated from increased atmospheric carbon dioxide can be identified. Note that this is a baseline measurement not directly related to WOCE objectives. Sampling adequacy must be maintained in the face of even more stringent selection of data to be included in the averages. Even with the most improved satellite system that can currently be visualized, (multi-channel, cloud and aerosol identification, dual-angle analysis, etc.), operational surface observations will be required into the indefinite future, integrated into a well planned data management and quality control system.

2.1.2 Background

Some of the problems inherent in SST taken from ships are well known. Others have only been documented in recent studies. Briefly, the salient points are:

- For a variety of reasons, surface-based SST analyses have observational uncertainties of the order of the climate-related signals being sought (approximately ± 0.5°C).
- Intake temperatures are biased high. The necessary corrections are ship-dependent but may be relatively stable.
- Bucket temperatures may be biased a little low as a result of cooling that takes place after sampling but before measuring; they also tend to be higher than mixed-layer temperatures during periods of light wind. Mixed-layer temperatures, consequently, may be more representative of actual averaged SSTs than are the SSTs themselves.
- Data sets ostensibly comprised entirely of bucket temperatures may nevertheless be contaminated with injection temperatures;

i.e., apparently the mode of measurement was not always reported accurately, or the distinction was lost later in the data handling.

- The real skin temperature is generally somewhat lower than the bucket temperature, and may differ substantially during periods of high heat transfer from ocean to atmosphere. Corrections can be applied if reliable wind, air-sea temperature differences, and wet-bulb observations are available (these may not be practical except from research ships, weather ships, or a very few selected ships of opportunity).
- Given the combination of poor sampling and unsatisfactory quality control, for many purposes it may not be worthwhile to further refine the analysis of the historical marine deck but concentrate instead on building towards a new time series that will have the required quality along with the required sampling density.
- The timeliness of most data collection is woefully inadequate for Streams 1 and 2. In particular it precludes the forecasting of precipitation in N.E. Brazil as described in Section 1.5.
- Carefully done satellite infrared (IR) analyses can now reach accuracies of ± 0.6°C, using High Resolution InfraRed Sounders (HIRS) or Advanced Very-High Resolution Radiometer (AVHRR), but the full potential has not yet been realised operationally. Adequate and routine quality control for instrument effects (degradation of filters) and atmospheric corrections (water vapour, aerosol, and volcanic eruptions) remains a problem. Contamination from scattered or thin clouds is not always detected.

2.1.3 Issues

- Statistical formulae for predicting SST anomalies will require the assembly in usable form of estimates on a global basis of climatological means, by location and season, and of the decorrelation times for a variety of SST anomaly patterns. This will require extensive analysis of existing data and probably special data acquisition programmes in selected areas. It is important that climatologies based on volunteer ship data be systematically related to present operational analyses which, for this purpose, will inevitably be derived primarily from satellite observations. The identification of systematic biases or other differences between the two data sets must be an on-going effort. Serious attention to this activity is of the greatest importance if we are to realize the full potential of incorporating SST anomalies into Stream 1 forecasts.
- All future SST observations from ships should include specific information on method (bucket or intake) which must not be removed arbitrarily during data management procedures. Wind information should also be included with bucket measurements so that those temperatures taken during light wind can be removed, or analysed separately.
- Records of all intake temperature observations should include the ship identification. Ships, or at least selected key ships, should be calibrated so that systematic biases can be removed
- The volunteer ship programme should be augmented primarily by careful selection of ships traveling important routes and known to have personnel who will take very careful observations. Indiscriminate augmentation will only increase the contamination problem.
- Ship observations should be annotated with respect to day-night observational times.
- Implicit in the use of SST anomalies is the extrapolation of the SST itself for the duration of the forecast. Given our present knowledge, the most appropriate technique should be to allow SSTs to regress to a climatological mean, for that location and season, with a time constant determined empirically. The statistical basis for suitable regression formulas must come primarily from historical SST data. This will require a substantial analysis effort, based on at least 30 years of data. It should be noted that serious forecast errors may result if new procedures are then introduced (e.g., based on satellite observations plus calibration data) which have different biases or time resolution from the old. To avoid this problem, both 'old' and 'new' procedures would need to be continued independently and carefully intercompared on a month-by-month basis, until satisfactory 'new' regression formulas have been established. This will probably take at least 10 years.
- Satellites offer the best hope of providing homogeneous and timely data sets, with adequate sampling. Present operational information extraction procedures for satellite observations fall far short of their potential. The operational data management system needs to be upgraded considerably for Stream 2 use.
- Satellites observe the skin temperature, which is conceptually quite a different aspect of SST than that from point observations (ship, buoy or XBT). Corrections for the difference should be made in intercomparisons. Because of mesoscale eddies, precise location is also necessary in intercomparisons. Quality control (not surface truth) procedures of the kind needed for climate studies are not at all obvious to design and straightforward to conduct. Serious attention is needed to develop and implement satisfactory procedures to improve the operational SST for climate use.
- The dual-angle radiometer to be flown on the European earth resources satellite (ERS-1) is a potentially important advance in instrumentation. Plans need to be made for extensive comparisons with the split-

window AVHRR (which also contains a 4-micrometre channel). Intercomparison programmes should include observations taken from research and weather ships, perhaps carefully selected volunteer ships, and moored and drifting buoys.

- Volunteer selected ships, with carefully controlled observations, some perhaps with automatic packages to relay data via satellites, will continue to be valuable for spot measurements, as part of the quality control procedures, and as an indispensable means to accomplish a smooth transition from the historical SST data set to the future data sets for climate studies and predictions which will be largely based on satellite observations.
- What special areas in the tropical oceans will require SST analyses (monthly means) as good as the technique can be pushed, e.g., well under ± 1°C? For what other areas might a good seasonal climatology suffice to monitor long-range trends?

2.1.4 Proposed actions

Based on the above considerations, some explicit actions can be identified to improve SST operational and research information. These relate both to the development of a system using satellite observations and, on the other hand, the use of the conventional system.

- The accuracy requirements must be determined by region, with particular emphasis on isolating regions where better than ± 1°C is needed.
- The best possible algorithms for estimating SST from satellites must be implemented operationally.
- Because of uncertain atmospheric corrections, residual contamination from clouds and instrumental degradation, satellite-derived SSTs will need to be calibrated against in-situ measurements for the foreseeable future. Consideration should be given to a network of buoys (moored and drifters), and specially instrumented ships of opportunity deployed particularly for this purpose.
- Preparations should be made for careful validation and intercomparison programmes for the experimental dual-angle infrared sounder to be flown on ERS-1.
- Stream 1 will require a much improved operational data management system. A pilot programme covering both volunteer observing ship SST and wind data in the tropical Atlantic should be devised in the context of experimental precipitation forecasts in Brazil and in the Sahel.
- SST analysis and data management procedures should be adjusted to take into account different biases and limitations of various data sources.
- A careful evaluation is needed of complete system performance.
- An analysis of the historical record is needed to establish to the extent possible regression formulas and to identify what additional observations will need to be made to improve these estimates.

There are a number of other points which should be noted here and which eventually will have to be translated into action.

- A systematic difference in the long-term mean climatology based on the satellite observations and the long-term mean climatology based on the volunteer ship data will lead to systematic errors on the regression forecast.
- It is essential that there be an on-going effort of reevaluating the regression formulas in the light of the accumulating experience with satellite observations.

In summary, it is clear that very careful attention will be needed regarding the use of SST data in the WCRP if useful results are to be achieved.

2.2 Mean sea level

2.2.1 WCRP requirements.

- Stream 1 will not require MSL observations.
- Stream 2 will require that networks in the Indian Ocean and tropical Atlantic and Pacific be augmented to support TOGA. Existing networks in the Pacific must be maintained. Eventually, patterns of MSL change derived from satellite altimetry will be a powerful ongoing tool for observing the interannual variations, but until this capability is established beyond all doubt, conventional methods will be required.
- Stream 3 will require that good MSL analyses be available also for the middle and high latitudes, especially in the Southern Hemisphere to support WOCE. Adequate ties to geodetic leveling will also be required. Global MSL will have to be monitored to a high absolute accuracy for studies of ice cap melting and possible changes in MSL arising from large-scale changes in heat storage. A minimum but high-quality reference network will be needed as control and validation for satellite altimeter observations, and to detect long-term changes in basin-scale circulation.

2.2.2 Background

Changes in large-scale patterns of MSL are related to changes in atmospheric forcings, large-scale ocean circulation patterns, the heat storage in the ocean, and the global water/ice partition. Until some of these relationships can be understood in more detail than at present, we will not be able to identify all of the critical places where long-term observations of MSL are needed and thus define in detail the minimum required networks.

The historical tide gage networks have been implemented for a number of purposes, primarily for the study of tides and coastal shipping needs. However, some of these stations also are the primary source at the present of information on MSL, but it is not known now which are the most useful stations, and which are the most needed new locations to meet requirements of climate studies. Maintenance of the present networks and augmentation in certain areas now covered too sparsely will be the best means to provide the information base needed to address such questions. Thus, we must at the outset design the MSL network needed for climate studies along an empirical, step-wise approach. Nonetheless, we know enough now to define the goals of a minimum high-quality network: to define the large-scale changes in the east-west direction near the equator and the north-south changes in those regions associated with the important equatorial current systems, and to provide adequate supporting and control observations for future satellite-precision altimetric observations.

2.2.3 Issues

2.2.3.1 Station selection

For the purposes of climate studies, considerations in the selection of surface tide gage sites must include, besides general location, feasibility of installation and maintenance, corrections for isostatic adjustment, ties to high-quality geodetic leveling nets, and also assessment of the ability to relate the local observations to what is happening in the open ocean. It is anticipated that the filling in of the large-scale patterns will be done by high-precision satellite altimetric measurements, using the minimum MSL network for data quality control on the satellite data as well as for key tie points to geodetic leveling. Considerable progress in selecting such sites and designing programmes for training key personnel has already been made in studies undertaken under the auspices of the Scientific Committee on Oceanic Research (SCOR) and CCCO.

Stream 2 issues are to increase the network in the Indian Ocean and to maintain at the least the present network in the Atlantic and Pacific to assure adequate information for TOGA. For Stream 3, the issues involve identification of requirements for detection of long-term large-scale (i.e., basin) changes in atmospheric circulation. Some information will follow from the TOGA implementation, if maintained, but additional efforts for Stream 2 will be needed to improve the networks in middle and high latitudes, particularly in the Southern Hemisphere. In addition, to measure changes in global average MSL anticipated from a CO_2 induced warming, the stability of selected tide gage stations in all aspects of the observing and recording procedures will have to be maintained to within a few centimetres over several decades. This will require very careful planning and quality control. In addition, to correct for the local rates of isostatic adjustment, such stations need to be tied in to a global geodetic net. The satellite-based techniques for doing these are developed but will need to be implemented.

2.2.3.2 Data management

Timeliness of data collection, processing and availability is an issue that must be addressed in terms of the kinds of time averages needed for Stream 2. Can existing telecommunications (e.g., GTS) be utilized for key stations?

2.2.4 Proposed actions

CCCO has already initiated an inventory of existing tide gauge stations and their working status, and the various TOGA panels have developed or are developing requirements for augmentation. Studies in the USA related to implementation of a tropographic experiment (TOPEX) have also developed a list of specific studies that need to be carried out to clarify what in-situ observations will be needed to support this satellite programme. Similar studies need to be undertaken for ERS-1. These efforts should complete the definition of requirements.

- Based on TOGA requirements as already understood, existing stations should be maintained and new stations should be implemented in key tropical regions.
- Communication ties to selected key stations should be installed on a pilot basis to test feasibility of more rapid data collection.
- Selected stations should be tied to the global geodetic net.
- A qualified scientific group should be commissioned to undertake development of suitable information extraction algorithms. These should be reviewed as altimeter data becomes available.

2.3 Surface stress

2.3.1 WCRP requirements

- Stream 1 has no requirements for surface stress.
- Stream 2. Since the surface stress is a primary forcing of the oceanic circulation, without knowledge of it any attempt to predict oceanic thermodynamic and dynamic response to changes in the atmosphere will fail. Thus, for the predictability studies of Stream 2, using coupled ocean/atmosphere models, wind sets will be required with accuracy and sampling sufficient to derive mean monthly averages of stress equivalent to wind speed of ± 0.3 m/s, over the tropical oceanic regions.
- Stream 3 will require the same quality wind stress means as for Stream 2, but now over all oceanic regions of the globe.

2.3.2 Background

Until the operation of new satellite scatterometers, ship observations and surface winds inferred from low-level cloud tracking observations made from satellites will be the only information from which to derive surface stress. It is known that ship anemometer observations are contaminated by airflow around the ship, but it may be possible to model or calibrate the effects for different kinds of ships and wind directions. Anemometer data sets could also be improved by selecting only those observations for which the wind is from the quarter in which the instrument is mounted and there is no superstructure upwind; this would be possible only if the ship heading were also reported, and information were available on anemometer exposure aboard each individual ship.

Wind estimates based on visual observations of the sea state are apparently also biased. The estimates tend to be low in following winds and high in head winds; they also tend to be low at night. Coherence of wind data sets can be improved by selecting daytime estimates of sea state, and making empirical corrections for wind direction with respect to ship attitude. Existing observational data sets usually do not contain sufficient information to make such selections, and hence it may not be productive to attempt to do too much with the historical marine deck. To be useful for climate studies, future time series will need to be improved by inclusion of ships heading.

It has to be recognised that the standard for most ship-based wind observations is the Beaufort scale. While the present marine sea state observations are probably well standardized, it is also probable that the historical ship wind data set is based on a multitude of interpretations of the Beaufort scale. The calibration of the present standard in terms of surface stress is also in doubt.

While some ship reports are communicated by radio and some disseminated on the GTS, it is also true that much data are obtained on a much slower schedule, e.g., by examination of ship logs. Collection times of ship wind data need drastic shortening if the observations are to be useful in Stream 2 studies and predictions.

While the U.S. oceanographic satellite Seasat provided a credible demonstration of the scatterometer, it was only brief. Useful experience, however, was obtained in intercomparing the Seasat-derived winds with at least two extensive and carefully made surface observations (e.g., Joint Air-Sea Interaction [JASIN] experiment). Not all possible problems in interpreting the scatterometer measurements, however, could be addressed in the short Seasat operational time. Extensive preparations need to be made for quality control programmes to be in place during forthcoming scatterometer flights that will be more extensive and of longer duration than was possible for the Seasat scatterometer. Questions to be addressed include effects of sea state, temperature, atmospheric stability, and surface contamination. Central to achieving the requirements for both TOGA and WOCE is determining how much of the ± 2 m/s error claimed for Seasat is truly random, and hence reducible by averaging, and how much is systematic in ways which may vary with the region and the synoptic situation.

Looking to the future, the benefits will be enormous of having homogeneous data sets from a variety of measurements (be they wind, roughness of the ocean surface, or low-level cloud motions) that sample adequately the ocean surface. It will then be possible to assess whole new classes of measurements, e.g., their systematic errors, and their relationships to the quantity which is really needed, and which is impossible to measure directly on the scale needed for climate studies, the vector-averaged stress.

2.3.3 Issues

- Improved wind stress determinations are needed well before satellite scatterometers are in operation; hence, conventional methods must be exploited as much as possible to aid in model development and testing. The present observational system has very poor sampling, except in the midlatitudes of the Northern Hemisphere, and many kinds of random and systematic error problems.
- Investigation is needed as to how well wind stress can be inferred from low-level satellite winds, as now provided by tracking suitable targets in sequential cloud images taken from geostationary satellites.
- The current automated-operation information-extraction algorithm for cloud winds generally passes over scenes which the cloud-detector algorithm labels as 'mostly cloudy.' However, it was the experience in post-processing the data sets from the First GARP Global Experiment (FGGE) that human intervention could find numbers of suitable tracking targets in such scenes, and thereby increase dramatically the final density of wind observations. Thus, investigation is needed as to how to convert such experience into an operational possibility to up-grade significantly the operational image analysis system and thereby increase the density of derived winds.
- Future observational systems will place greater reliance on satellite-based techniques. However, these will become fully credible and useful only after long intercomparison of the satellite and surface-based techniques. Such intercomparisons will be required both (i) to establish the effectiveness and calibration of the scatterometer technique, and (ii) to establish a credible tie to the historical data set.
- ERS-1 will provide an opportunity to compare altimeter-derived wind estimates against the scatterometer observations, and against well maintained surface quality control networks.

2.3.4 Proposed actions

- WMO should implement as soon as possible new instructions for producing and procedures for collecting well annotated ship wind observations, so that the best subsets can be assembled. Also to be investigated, at least for some key routes, is how to speed up the data collection to near real time.
- A programme should be designed and implemented to establish effective calibration procedures for satellite scatterometers.

2.4 Subsurface heat storage

2.4.1 WCRP requirements

- Stream 1 will not use subsurface observations as input data for forecasts, but timely supply of these data will greatly facilitate diagnoses of experimental forecasts and the information will serve as useful monitors of the generic parameterizations in prediction models (e.g., climatological decay of SST anomalies).

- Stream 2 requires extensive XBT programmes in the tropical oceans to support TOGA. In addition, better assessment of variability on the various climatic scales is needed for all oceanic regions where this information is currently lacking, e.g., the Southern Ocean which may have feedbacks to the Southern Oscillation.
- Stream 3 will require good knowledge eventually of the seasonal, interannual, and secular variability of the oceanic heat content in the upper layers, building on the information gained in Stream 2.

2.4.2 Background

A considerable body of scientific, logistic, deployment and analysis experience exists in connection with XBTs. Scientifically, it has been shown for the Pacific Ocean that large-scale anomalies can be detected and tracked with XBT programmes. The spectrum of variability can also be defined with several years of XBT observations taken according to feasible sampling strategies. Other methods for determining heat storage anomalies (e.g. from satellite altimetry or acoustic tomography) are still only in development.

It has also been demonstrated that XBT programmes can be implemented reliably on selected ships of opportunity to meet specific scientific objectives, but it has not yet been demonstrated that observations can be collected quickly enough to be used for diagnostics in Stream 1 and forecasting studies of Stream 2.

Regular XBT programmes have been organised under the auspices of the Integrated Global Ocean Services System (IGOSS), paving the way for exploratory limited-duration observational programmes in some areas of key interest to TOGA and to obtain first-order large-scale variability as background for WOCE.

XBT observations also provide a good measure of SST and thus could contribute to routine quality-control procedures for satellite IR-based determinations of SST.

An inexpensive expendable instrument capable of measuring salinity at least to 0.03 parts per thousand would be a very important addition to present capability and would find wide application. Such an instrument is not currently available.

2.4.3 Issues

- It is known that there are more XBT data than are shown in the present data archives.
- Data collection methods need to be drastically improved. Conventional collection of data after the fact will not meet requirements of Streams 1 and 2. Data needed on critical routes could be relayed via satellite.
- Development of an expendable salinity probe needs to be encouraged, probably by making it clear that there is a substantial market for it.

2.4.4 Proposed actions

- An inventory needs to be assembled of all XBT data sets. Nations should be queried as to plans for XBT programmes for the next several years and requested to provide information on routes, sampling, data collection, data availability (when? from whom?), analysis products.
- Even before completion of the work above, however, a few key programmes need to be planned and implemented in regions important to Streams 1 and 2 and which are known to be lacking in good time-series observations. CCCO panels should be asked to develop recommendations and assign priorities to regions that should be explored with XBTs.
- IOC and WMO should implement fixed-duration XBT programmes in important tropical regions.
- The Scientific Committee on Antarctic Research (SCAR) and WMO should encourage member countries to make use of the antarctic supply ships to implement routine XBT observations in the Southern Ocean. After some five years of such pilot operations, a sensible assessment could be made of the need to continue operationally to obtain at least several decades of observations at some sampling density.

2.5 Sea ice

2.5.1 WCRP requirements

- Stream 1 will require sea ice extent as input to forecasts.
- Stream 2 has no known requirements at this time.
- Stream 3 will require long-term monitoring of sea ice extent.

2.5.2 Background

There are large variations in the timing and magnitude of the sea ice build-up from year to year. Numerical experiments have established that the atmospheric circulation is sensitive to changes in this lower boundary condition. For Stream 1 this is merely a matter of systematically observing the ice extent to low resolution in a timely manner. For Stream 2, the underlying question is potential feedbacks between variations in circulation and ice extent. The study of such feedbacks requires better understanding and ability to model the processes of ice formation and thickness. This is fundamentally a research issue which has, however, not been singled out for highest priority attention within WCRP. Within Stream 3, even though the ability to model the evolution of sea ice may be less than optimal, it is very important to keep track of any long-range changes in sea ice extent as an indicator of atmospheric circulation and the whole freshwater balance in the ocean at high latitudes. For a further discussion of research and ongoing observational issues relating to sea ice see the report of the WMO/CAS-JSC-CCCO meeting 'The Role of Sea Ice in Climatic Variations,' WCP-26, Geneva, June 1982.

2.5.3 Issues

- Present techniques for estimating sea ice extent rely on reports from shipping in critical channels and on images from microwave instruments on satellites. Currently available routine analyses are probably adequate for the purpose of Stream 1, though it is important that relatively high-resolution instruments such as Scanning Multichannel Microwave Radiometer (SMMR) continue to be available.
- For Stream 3 the issue is the long-term consistency of the data stream and analysis procedures. As satellite instruments change, and the mix of surface reports and satellite observations varies over a decade or more, does the derived quantity 'sea ice extent' mean the same thing in terms of what is actually happening? Such biases, if undetected, would vitiate the utility of the data stream and the analyses for long-range purposes.

2.5.4 Proposed action

- A study is needed of possible calibration procedures or baseline measurements that could alleviate this problem.

2.6 Surface heat flux

2.6.1 WCRP requirements

- Stream 1 has no known requirements at this time.
- Stream 2 and Stream 3 both need observations or estimates of heat flux through the ocean surface.

2.6.2 Background

Observations are needed from which the heat flux through the ocean surface can be inferred. This flux is the net of the incoming solar radiation, the outgoing infrared radiation, and the turbulent transfers of sensible and latent heat. Present estimates leave much to be desired. They depend almost entirely on the data from the volunteer observing ships (VOS). In the tropics and the Southern Hemisphere the sampling is inadequate for month-to-month anomalies, and everywhere the uncertainties in the parameterisation formulas being used and systematic errors in the data cause the meaning of the analysed product to be very much in question, at the level of several tens of W/m, even when averaged over many years. Yet this is the magnitude of the signal in most instances. The surface heat flux is a fundamental variable in the climate system, and our inability to measure it to a useful accuracy, or to infer it in a verifiable manner from other observations has profound implications for the credibility of efforts to model the climate system and to document significant fluctuation or changes in it. This deeply unsatisfactory situation is not likely to change quickly, and progress is going to require careful attention to a wide variety of possibilities, with no guarantee of results. The discussion here concentrates on those items with implications for the operational observing system.

Probably the most significant possibility for improvement would come from a conscious strategy for evaluating the performance of current atmospheric global climate models and operational weather analysis and prediction models from the point of view of the surface fluxes of heat, momentum and moisture. This does not avoid the measurement problem but brings different talents and methods of inference to bear on it. For example, credible simulations of atmospheric circulation associated with the Southern Oscillation must yield the correct regions of deep convection and seasonal average precipitation, and hence implies constraints on the regional evaporation rates, which are a major source of uncertainty in the heat flux, as well as the moisture budget. Parts of this calculation can be verified against existing data sets which are presently largely unexploited, such as satellite cloudiness retrievals and microwave estimates of total atmospheric precipitable water. In the long run, it is probably only by using atmospheric assimilation models and validating them for this purpose that sampling problems associated with present methods of estimating surface heat flux can be overcome. Indeed, long-range prediction models which do not correctly estimate the heat flux through the ocean surface are unlikely to make very good predictions.

2.6.3 Issues

In the short run, the following issues arise in connection with present approaches and data sources:

- The net solar radiation reaching the earth's surface is currently estimated using VOS estimates of cloudiness and applying parameterisation formulas originally derived from a few stations over land. There are sampling problems with the observations and many uncertainties about this parameterisation.
- Alternative schemes using data from geostationary satellites have been developed and look promising in research applications. Their ultimate utility is, however, limited by the lack of ship-borne radiation measurements which can be used for in-situ comparisons and calibration. If deployed on research ships of opportunity, existing trained technicians could probably make these measurements.
- The fluxes of sensible and latent heat through the ocean surface are currently estimated from parameterisations based on wind speed, atmospheric temperature, humidity, and SST. In general, the latent heat flux is the larger and more uncertain of these two contributions to the net. To increase sampling reliability, monthly averages of these quantities are computed separately, and then the average wind speed is multiplied by the air-sea temperature differences and by humidity to give fluxes of sensible and latent heat respectively. Some corrections are necessary for the day-

to-day correlations of these quantities, but in general they are fairly small. However, the accuracy of the product is directly proportional to that in the air-sea temperature difference and in the specific humidity. Recent analyses have exposed that there are probably major systematic errors in the observations of both wet- and dry-bulb air temperature, associated with inadequate exposure in the cramped conditions on board VOS. This problem could probably be mitigated if monthly mean temperatures, both atmospheric and sea surface, were estimated only from observations made at night, when contamination by solar radiation is absent.

- Unfortunately, though estimates of wind speed with adequate sampling over the globe will probably become available from scatterometers or satellite altimeters in the next decade, there are no prospects for the remote sensing of air-sea temperature differences or of near-surface humidity. Thus, alternative sources of data cannot be anticipated, and every means possible to improve existing sources and their utilization for this purpose should be explored. For example, there are indications of useful correlations between total atmospheric precipitable water and surface humidity. The former may be estimated from microwave instruments on current satellites and expected future ones, but this application has not been widely recognised and data processing and availability is in question. Though in the research stages at this time, such analysis technique development could have a major impact on the evolution of the OOSDP.

2.6.4 Proposed action

- Ship-board observations of air and sea temperatures should be annotated as to day or night observational times, so that a subset can be constructed of observations minimally influenced by solar radiation.

2.7 Ocean currents

2.7.1 WCRP requirements

- Stream 1 has no requirements.
- Stream 2 will require mapping and monitoring of ocean currents in the tropical regions.
- Stream 3 will require major investigations and mapping of the large-scale circulation patterns, and monitoring over a long period.

2.7.2 Background

In the long run, any ocean observing system for climate will have to relate to the circulation of water and the currents that accomplish it. However, at this time the basis of knowledge and experience for formulating the requirements from such a system and a means to achieving them is very limited. Most information about the large-scale subsurface circulation has been derived indirectly, from measurements of tracers such as temperature, salinity, nutrients, and various radioactive tracers, combined with dynamical influences based on geostrophic balance from the density distribution and from the surface wind stress. Because of the nature of this data set these studies have perforce been confined to long-term averages, with an emphasis on qualitative features or integrated quantities for which conservation provides additional constraints. Observations from current meters and floats have provided important additional information within the major current systems where the mean velocity is not obscured by the random fluctuations associated with mesoscale eddies, but have not so far been used for basin-scale inferences. New developments such as acoustic tomography promise a substantial increase in our capabilities, but for some time to come must be regarded as experimental. WOCE and TOGA will involve a very substantial observational effort using these methodologies. However, most of this activity is properly undertaken within research organizations, and is inappropriate for direct inclusion here. The reader is referred to the WOCE and TOGA planning documents for more specific information.

2.7.2 Issues

- For surface currents, data extending back over many years is available from ship drift, and, in a few special locations, by inference from tide gages. The difference between the actual path of a ship and that computed from its log is a measure of the surface current. This method has identified the intense current systems such as the Kuroshio and the Gulf Stream, and has spawned innumerable global atlases of dubious climatological value. The utility of this approach is severely limited by inadequate navigation and by sampling problems, quite apart from contamination by wind-induced motion. The island sea level observations have contributed greatly to documenting interannual variability of the horizontally integrated transports in those few locations where suitable island pairs have existed for many years.
- Given the present state of our knowledge in this area, the next steps toward developing a rational design for an observing system for both Streams 2 and 3 must be a systematic exploration of the magnitude of the large-scale time averages and the variability on various space and timescales, in order to establish the basis for judgment on which phenomena are most significant and what is a minimally adequate sampling strategy. This involves exploratory time series, undertaken in a consistent manner for a limited period (about 10 years) adequate to document the major high-frequency noise and to begin to identify patterns on the timescales of climatological interest, with the intention of using the experience gained to design a more cost effective system at the end of the period. Similar series are also appropriate in a few locations where major current systems are confined by straits or passages, and are accessible to special measurement techniques aimed at integrated transports. The patterns of variability will be compared to those predicted by numerical models, but the latter are not

sufficiently trustworthy to be used for system design in the absence of observational confirmation.

- For the surface layers of the ocean, the possible sources of information in the future are more varied. For the next decade or so, the most significant are likely to be:

  (1) MSL from satellite altimetry and islands;

  (2) Satellite-tracked surface drifters;

  (3) Acoustic Doppler current meters aboard ships of opportunity; and

  (4) Inferences from maps of subsurface heat storage.

  Of these, the only substantial body of operational experience extending over more than a few years is associated with the island tide gauges.

- A properly tracked satellite altimeter in an appropriate orbit, accompanied by the needed corrections for ionospheric electron density and tropospheric water vapour, should yield invaluable information on changes in surface geostrophic current over the globe (both the basin-scale velocities and the statistics of the mesoscale fluctuations), to an accuracy which is probably sufficient in most places to determine the major patterns of variability. With considerably more effort (including determination of the geoid) it should be possible to measure the time-average component of the surface current, where it is more intense or widespread. With appropriate orbit control, sampling during the satellite lifetime should be adequate. A separate in-situ effort is needed to test our ability to model the deep ocean tides, which could lead to significant errors or reduction of information. Present plans call for launching at least one such altimeter on ERS-1 in 1989, and possibly another on TOPEX. However, these will be expensive experimental systems, which are unlikely to be maintained consistently for long enough to meet the exploratory goals stated above. Thus, prudence dictates attention to possible alternatives.
- The best established technique is surface drifters, for which there was extensive deployment in FGGE, and there have been several development programmes since. Issues remain about the extent to which the buoy follows the water rather than being driven by the wind, and the interpretation due to the vertical shear of the current near the surface. The major problem with observing system design is achieving adequate sampling of the time-mean currents in the presence of fluctuations due to the mesoscale eddies. This can be achieved at moderate cost by deploying sufficient numbers. Drifters can also carry simple sensors to measure air and sea temperatures and surface pressure. A more detailed discussion, including proposals for action, is given in section 2.8.
- In recent years, an acoustic Doppler current meter has been developed which provides profiles of horizontal velocity relative to a ship (except for the upper 10 m or so which is blanked out) continuously in time throughout the upper 200 m. When combined with good navigational information, this provides absolute velocities along the complete section traversed. The error characteristics are still being determined, but experience aboard research vessels has demonstrated that the instruments are reliable and produce seemingly meaningful and significant data. They can be installed in selected merchant vessels, but this application is still experimental. Such a technique could provide an important complement to a drifter programme, and a pilot study should be undertaken to evaluate its potential.

2.7.4 <u>Proposed action</u>

- Drifting buoys programmes should be implemented in the topics to provide monitoring of surface currents and also air and sea temperatures.
- Drifting buoys should be implemented at higher latitudes, especially in the Southern Hemisphere, to observe the currents there for longer periods than was possible in FGGE, and also to obtain sea and air temperature and sea-level pressure observations.
- A pilot programme is needed to determine if acoustic Doppler velocity meters could be operated on volunteer ships of opportunity.

Because it has implications for several other variables, the proposed pilot programme for surface drifters will now be discussed in more detail.

2.8 Drifters

Several of the data needs discussed above can be met with a programme using satellite-tracked surface drifters. These are:

(1) a geographically dispersed network of well calibrated in-situ measurements of SST (equivalent bucket temperature) for intercomparison with simultaneous satellite IR observations;

(2) exploratory time series of large-scale surface currents and the statistics of mesoscale variability; and

(3) in the Southern Ocean only, surface pressure.

Several 10-year programmes in distinct geographic regions are needed, where major current systems are seeded with drifter buoys from a fixed location or locations. Candidate regions (in order of priority) are:

(1) Eastern equatorial Pacific;

(2) the equatorial Indian Ocean,

(3) the Southern Ocean (seeded from near South Africa or Australia);

(4) the equatorial Atlantic Ocean; and

(5) North Atlantic and north Pacific.

Though the purpose of this programme is to help present operational goals for SST and (in the Southern Ocean) pressure, and to obtain experience on surface currents necessary to design a better observing system for the future, the equatorial current and SST measurements are also needed for TOGA, and those in the Southern Ocean for WOCE. Because knowledge of the patterns of currents and mesoscale variability is fundamental to rational system design, and these vary widely, experience is needed in different regions over the globe.

In the equatorial Pacific there already exists a fragmentary time series of about five years. This shows that:

- acceptable coverage in that region can be achieved with a seeding rate of about 30/year;
- the normal flow pattern between 5°S and 5°N and major changes associated with the El Nino are clearly discernable, together with intermittent bursts of mesoscale activity; and
- 10 years is the minimum duration for a consistent time series to establish the existence and rough magnitudes of this type of interannual variability.

Unfortunately, this is the only region for which such multiyear time series have been analysed.

In the Indian Ocean, experience is much more limited, and, because of the annual reversal of the current systems, the situation is quite different. Almost any information is significant. The first issue is where drifters will tend to go from different launch locations at different times of year.

In the Southern Ocean, the signal/noise ratio (large-scale velocity divided by root mean square mesoscale eddy speed) is somewhat less favorable, but still relatively high; mapping the pressure field to FGGE specifications requires approximately 300 launches/year. However, substantial oceanographic information (and significant meteorological data) is likely to be obtained from launch rates of 30-100/year from a few selected locations. Learning how to interpret and use this information will require a 10-year time series. Questions to be addressed include:

- Are there major changes in the circulation pattern as would be indicated by nearly all the drifters launched from a particular location in different years ending up in quite different areas? What are appropriate measures of statistical significance for such changes?
- Does the strength of the Antarctic Circumpolar Current averaged over a sector of longitude change significantly from year to year or over the decade?
- What is the mesoscale eddy variability as a function of position?

Besides being fundamental to the design of a future observing system, these questions are also important to WOCE.

In the equatorial Atlantic, variations in surface currents are probably associated with anomalies in SST and atmospheric circulation which are predictors for droughts in northeast Brazil.

In the northern hemisphere midlatitudes, the proportion of drifters entering the subpolar as opposed to the subtropical gyre from the western boundary currents may be a sensitive indicator of interannual fluctuations in the circulation. Experience with this type of data is needed to decide this possibility.

Suitable pressure and temperature sensors exist, as does an adequate location and data relay system. Wind, humidity and subsurface heat storage measurements are still in the developmental stage, and should be included only on an experimental basis (if at all). There is considerable experience with several different hull designs and drogue technology (reflecting different compromises between a platform, on the one hand, to measure pressure and other atmospheric variables and, on the other hand, to provide a good measurement of ocean currents). This design will have to be substantially frozen for the duration of the exploratory time series.

Programme design issues which will need to be addressed immediately by a group of experts on drifters, augmented by individuals experienced in satellite SST retrievals and surface pressure analyses, include:

(1) The choice of hull design and sensor complement for each region.

(2) Data exchange and analysis procedures.

(3) Appropriate launch sites and frequency.

3. Action items

In the following table, the items introduced in the previous sections are listed in approximate order of importance within the four major categories of Major Programmes, Adjustments to Existing Procedures, Development and Pilot Programmes, and Design Studies and Homework. The named group is suggested as having lead responsibility for the implementation, in consultation with others as appropriate, of that particular item. IOC should be interpreted as acting primarily through IGOSS and the Working Committee on International Oceanographic Data Exchange (IODE), including Permanent Service for Mean Sea Level (PSMSL) for sea level. Where indicated, WMO should be interpreted as primarily through the corresponding oceanographic body. SOS is the joint CCCO/JSC working group on Satellite Observing Systems for Climate Research. CCCO should retain overall responsibility for the integrity and balance of the entire programme.

Major programmes

SST (data base for global, seasonal SST climatology and anomaly relaxation analysis) SOS

- Satellite (also initial conditions for Stream 1)
  - Update operational satellite algorithms
  - Establish in-situ calibration network
  - Quality control (sensor failure, volcanos, etc.)
  - Data exchange
- Conventional (also initial conditions for Stream 2) IOC
  - Adjust analysis procedures for different kinds of SST data
  - Assess system performance
  - Quality control (including interaction with producers)
  - Data exchange
- Anomaly analysis
  - Establish statistical regression formulae CCCO

MSL for Streams 2 and 3 (support TOGA, baseline for global MSL, validation for altimeters) IOC

- Maintain existing long-term, tide gauge stations
- Establish new stations
- Tie all long-term stations to geodetic net (Stream 3)
- Quality control
- Data exchange
- Analyse in-situ network performance in terms of variability fields from altimetry SOS

Establish exploratory time series of drifters (Streams 2 & 3) (determine typical tracks, variability and lifetimes, SST calibration, surface pressure (Southern Ocean), surface currents for TOGA, estimate mesoscale eddy energy for WOCE, variability (if any) in basin scale circulation) IOC/WMO

- Panel of experts on choice of hull design and sensors, data exchange and analysis, launch sites and frequency
- Maintain existing series in Eastern Pacific
- Initiate series in Indian Ocean
- Extend FGGE experience in Southern Ocean
- Plan for the Equatorial Atlantic and North Atlantic and Pacific CCCO
- Negotiate tariff agreement with Argos

Subsurface heat storage (Stream 2) (for TOGA, pilot for global ocean) IOC

- Maintain existing XBT ship-of-opportunity network in Pacific
- Extend network particularly in Indian Ocean
- Assess system performance
- Quality control
- Data exchange

Adjustments to existing procedures

Improved analyses of satellite observations of SST (Stream 1) SOS

- Implement highest quality cloud-clearance algorithms
- Design and implement long-term calibration system using selected in-situ measurements

Improved analyses of conventional SST (Stream 1), and monthly mean wind and air dry and wet bulb data (Streams 2 and 3) WMO

- Distinguish bucket, injection and skin SSTs in analyses and archives /IGOSS, IODE
- Distinguish day and night air and wet-bulb temperatures in analysis
- Maintain ship ID in all archives (Streams 2 and 3)
- Establish ship calibrations for injection temperature, anemometer height
- Consider reporting ships heading with wind data
- Improve quality control procedures
- Monthly mean analyses /IGOSS
- Data exchange

Improve yield for low-level cloud winds (for Stream 2)

- Develop automated retrieval algorithms to match Wisconsin winds in FGGE SOS

Development and pilot programmes

Pilot project on operational time voluntary observing ships (VOS) data transmission and assembly in tropical Atlantic (Stream 1) (forecast droughts in N.E. Brazil, data management)	WMO
- Identify suitable shipping lines	
- Install satellite communications	
- Establish analysis center and experimental forecast procedures	
- Assess utility and design extended programme	
Calibration and validation procedures for Scatterometer (Streams 2 & 3)	SOS
- Analyse SEASAT data for apparent biases	
- Support research on retrieval algorithm	
- Design and establish in-situ intercomparison stations	
- Assess scatterometer system performance	
Quality controlled subset of VOS surface data (Streams 2 & 3) (determine biases)	WMO/IGOSS
- Select routes and instrument packages	
- Install packages and communications systems on selected ships	
- Determine installation dependent corrections	
- Compare data with neighboring VOS data	
- Infer biases in historical VOS records	
- Assess potential impact of quality control and operational time communications on system performance	
Acoustic current meters on merchant ships (Stream 2) (surface currents)	CCCO
- Install a small number of instruments on selected ships	
- Exploratory time series in selected regions	
- Characterize variability of near-surface currents and profiles	
- Design surface current observing system	
In-situ radiation measurements (Stream 2 & 3) (calibrate satellite solar flux)	WMO
- Panel of experts on required sampling and quality control	
- Locate or train technicians	
- Observations from research ships of opportunity	
- Intercompare with satellite estimates	

Design studies and homework

Subsurface heat storage (Stream 2 & 3) (exploratory time series)	
- International inventory and exchange of existing data	IOC
- Complete analysis of existing data	CCCO
- Design extended ship-of-opportunity network	CCCO
Sea ice (Stream 3) (long-range changes in cover)	CCCO
- Design long-term calibration and validation procedures	
Assess performance of 4-dimensional assimilation models with respect to surface fluxes (all Streams) (improved analyses heat & freshwater fluxes)	JSC
- Analyse mean heat-flux divergences over continents	
- Compare output maps of surface stress with statistics of input data	
- Analyze surface heat- and moisture-fluxes for oceanographic consistency	JSC/CCCO

Glossary of acronyms and special terms

AVHRR	Advanced Very-High Resolution Radiometer.
Argos	French satellite-borne data relay and platform location system, which flies on USA NOAA operational, polar-orbiting satellites.
CAS	WMO Commission on Atmospheric Sciences.
CCCO	Committee on Climatic Changes and the Ocean, jointly sponsored by SCOR and IOC.
ERS-1	Earth Resources Satellite - 1.
FGGE	First GARP Global Experiment, conducted November 1978 through 1979.
GARP	Global Atmospheric Research Programme, organized jointly by ICSU and WMO.
GTS	Global Telecommunication System
HIRS	High-resolution InfraRed Sounder.
IGOSS	Joint WMO/IOC Working Committee for Integrated Global Ocean Services System.
IOC	Intergovernmental Oceanographic Commission of Unesco
IODE	IOC Working Committee on International Oceanographic Data Exchange.
IR	InfraRed.
JASIN	Joint Air-Sea Interaction Experiment.
JSC	Joint Scientific Committee (ICSU and WMO) for the WCRP.
MSL	Mean Sea Level.
OOSDP	Ocean Observing System Development Programme.
PSMSL	Permanent Service for Mean Sea Level.
SCAR	Scientific Committee on Antarctic Research.
SCOR	Scientific Committee on Oceanic Research.
Seasat	Oceanographic satellite (U.S.).
SMMR	Scanning Multichannel Microwave Radiometer.
SOS	Joint JSC/CCCO Working Group on Satellite Observing Systems for Climate Research.
SST	Sea Surface Temperature.
TOGA	Tropical Ocean and Global Atmosphere Experiment.
TOPEX	Topographic Experiment, using a precision radar altimeter.
VOS	Voluntary Observing Ship.
WCP	World Climate Programme.
WCRP	World Climate Research Programme.
WMO	World Meteorological Organization.
WOCE	World Ocean Circulation Experiment.
XBT	Expendable Bathythermograph.