INTERNATIONAL COUNCIL FOR SCIENCE

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

UNESCO

WORLD METEOROLOGICAL ORGANIZATION

WORLD CLIMATE RESEARCH PROGRAMME

UNDERSTANDING THE ROLE OF THE INDIAN OCEAN IN THE CLIMATE SYSTEM — IMPLEMENTATION PLAN FOR SUSTAINED OBSERVATIONS

CLIVAR–GOOS Indian Ocean Panel and others

January 2006

WCRP Informal Report No. 5/2006

ICPO Publication Series No. 100

GOOS Report no. 152

Acknowledgements:

We gratefully acknowledge the assistance and comments received from P. Blouch, E. Charpentier, H. Cattle, M. Dengler, J. Gould, E. Harrison, H. Hendon, R. Lumkin, M. Merrifield, R. Molinari, S. Riser, B. Sloyan, N. Smith, A. Schiller, D. Walliser, J. Vialard, S. Wilson, K. Yoneyama, and the INSTANT group. Ray C. Griffiths carefully edited the final draft.

The work of the CLIVAR—GOOS Indian Ocean Panel is supported by the World Climate Research Programme, International CLIVAR Project Office, the Intergovernmental Oceanographic Commission Perth Regional Office, Indian Ocean GOOS, and the CSIRO Wealth from Oceans Flagship Programme.

CLIVAR is a component of the World Climate Research Programme (WCRP). WCRP is sponsored by the World Meterorological Organisation, the International Council for Science and the Intergovernmental Oceanographic Commission of UNESCO. The scientific planning and development of CLIVAR is under the guidance of the JSC Scientific Steering Group for CLIVAR assisted by the CLIVAR International Project Office. The Joint Scientific Committee (JSC) is the main body of WMO-ICSU-IOC formulating overall WCRP scientific concepts.

Bibliographic Citation

INTERNATIONAL CLIVAR PROJECT OFFICE, 2006: Understanding The Role Of The Indian Ocean In The Climate System — Implementation Plan For Sustained Observations. January. International CLIVAR Project Office, CLIVAR Publication Series No.100. (not peer reviewed).

Table of Contents

Executive Summary and Recommendations

The circulation and transport of heat in the Indian Ocean is unique in many respects, compared to the Pacific and the Atlantic. The Asian landmass blocks the ocean in the north so that currents cannot carry tropical heat to higher latitude as the Atlantic and Pacific do. It also receives extra heat from the Pacific via the Indonesian Throughflow. The movement of heat around the ocean and exchange with the atmosphere is highly variable in time. As a consequence, the Indian Ocean plays a unique role in the variation of regional and global climate systems. The monsoon, or seasonal cycle, of southern Asia, East Africa and northern Australia interacts strongly with the Indian Ocean. Whereas the monsoon reversals of wind and rain recur each year, they do so with sufficient variability to create periods of relative drought and flood in large parts of the surrounding tropics, while teleconnections carry the climate anomaly into higher latitude regions on a global scale. The societal and economic impacts of these climate variations affect the lives of nearly two-thirds of the world's population. The benefit to be derived from describing, understanding and predicting the coupled ocean–atmosphere behaviour in this region is potentially huge, but limited at the present time by a lack of observational data on the ocean.

The climate variations in the atmosphere are relatively well known due to the systematic collection of weather data on a global scale since World War 2. The related climate-processes in the ocean however are poorly documented, particularly in the Indian Ocean, where the development of the Global Ocean Observing System has lagged behind that of the Pacific and the Atlantic. This report is concerned with developing a rationale and a plan for implementation of sustained, basin-scale observations in this data-deficient region.

Realizing the potential benefits will require acceptance of certain fundamental principles from the outset:

- Implementing basin-wide observations is too large a task for any one nation or agency to accomplish alone. *A multi-national approach is required*. Agreement to use available national resources in a coordinated and cost-effective way is an essential part of achieving full implementation.
- *Data should be distributed openly in a timely manner*. There is a preference for communication of data in real time to make it available at climate analysis and prediction centers. Data management will follow the guidelines and policies of the Intergovernmental Oceanographic Commission and the World Climate Research Programme—CLIVAR project.
- *Satellite observations of oceanic surface properties provide a framework for the observing system.* The in situ observations are complementary and provide subsurface information that complements and enhances interpretation of satellite data. While this report is concerned with in situ observations, we note that the research issues identified in Part 1 cannot be resolved without satellite data and we strongly recommend continued measurement of sea-surface temperature, sea level, ocean colour, wind, rain and cloud. Likewise, in situ observations are used to maintain calibration of satellite data.
- *Development requires close coordination between the research and the operational-oceanography communities*. Some of the observations in this plan have already been partially implemented by operational programmes in the Global Climate Observing System (GCOS) and Global Ocean Observing System (GOOS); for example, the ship-of-opportunity expendable-bathythermograph programme and surface drifters. Full implementation requires close coordination among the Ocean Observation Panel for Climate (OOPC), the CLIVAR Global Synthesis of Observations Panel (GSOP), the International Argo Science Team (IAST) and the IOC–WMO Joint Committee for Oceanography and Marine Meteorology (JCOMM).
- *An integrated observing system using a variety of instruments is required to address the diversity of time- and space-scales of climate-relevant variability.*

The principle of open and timely sharing of data in the Indian Ocean requires some discussion. The Indian Ocean rim is a region with considerable potential for political instability and conflict. It is also a region where full agreement on the modes of access to exclusive economic zones has not been reached. The political realities have historically had an impact on data sharing. Nevertheless, the threat to countries in the region from natural hazards is recognized now, and may lead to rapid improvement. The global Argo programme and the TAO/Triton programme in the Pacific will serve as examples of appropriate data management for the Indian Ocean. Countries and research groups participating in Argo and TAO/Triton have agreed to the open exchange of data. This applies equally to the real-time (GTS and ftp) data stream (over 90% available within 24 hrs) and to delayed-mode data. It is recommended that these standards of timeliness and openness set by Argo and TAO/Triton be applied to all Indian Ocean observations.

While this report is primarily concerned with oceanographic measurements, the meteorological measurements (particularly at moorings) will be extremely valuable to data assimilation issues concerned with weather forecasting and reanalysis efforts. At present there are few such measurements in the Indian Ocean and this lack of information prevents accurate initial condition determination of weather forecasts and limits reanalysis efforts.

The rationale for the observing system from an oceanographic perspective is discussed in Part 1 of the report. The science-drivers are improved description, understanding, modelling and ability to predict:

- Seasonal monsoon variability and the Indian Ocean
- Intraseasonal variability
- Indian Ocean zonal dipole mode and El Nino–Southern Oscillation
- Decadal variation and warming trends in the upper Indian Ocean
- Southern Indian Ocean and climate variability
- Circulation and the Indian Ocean heat budget (including Indonesian Throughflow, shallow and deep overturning cells)
- Biogeochemical cycling in the Indian Ocean.

Also, operational oceanography will provide a range of products, including routine daily to weekly maps of temperature, salinity and currents to support maritime safety, fisheries and management of the marine environment, as well as initialization of coupled models for seasonal climate prediction. Part 1 reviews the present state of knowledge and recent progress for each of these topics, and identifies the science questions and issues that have to be addressed with new observations to improve capability for prediction.

The design and implementation of an integrated observing system is discussed in Part 2. The instruments available for large-scale ocean monitoring are moorings (for subsurface temperature, salinity and currents and surface weather variables that determine the fluxes of heat and fresh water), Argo floats for subsurface temperature and salinity, expendable bathythermograph (XBT) lines, surface drifters for sea-surface temperature and current and sea-level stations.

The key new element of the observing system is a basin-scale mooring array, which is essential to capture the seasonal monsoon variability and intraseasonal disturbances. The fast intraseasonal time-scale requires continuous time-series, which is only possible with mooring technology. The array provides well resolved data on the interannual variations, particularly with regard to mixed-layer dynamics. The array is made up of 34 moorings for measurement of temperature, salinity and basic weather variables; 5 Acoustic Doppler Current Profilers for equatorial and coastal boundary currents and 8 moorings for enhanced measurement of surface fluxes in different climatic zones. The array is designed to resolve the most energetic variations in the ocean and interactions with the atmosphere. The current profilers are located where geostrophy cannot be used to estimate currents. The flux moorings provide data to calibrate flux estimates from satellite data; and they are located in regions where flux climatology is poorly known. The report provides complete technical data for the design of the mooring array.

The Argo Programme to measure temperature and salinity profiles to a depth of ~1500 m every 10 days is progressing rapidly in the Indian Ocean. The standard sampling pattern requires 450 floats to cover the ocean to 40°S with one float per 3°×3° latitude/longitude. Sustained monitoring will require 125 deployments per year, assuming a float lifetime of 3-4 years. As a minimum the standard Argo array in the Indian Ocean should be completed and maintained. The Argo profiles are essential for research on the role of ocean circulation in climate variability and change, from interannual to multidecadal time-scales. Combined with satellite altimetry the data are essential for generating the products of operational oceanography. The intraseasonal time-scale is a challenge for monitoring the Indian Ocean. Model/observing system experiments suggest the sub-seasonal Indian Ocean temperature variation recovered from sampling at 5-day intervals does not represent a significant improvement over 10-day sampling. The effectiveness of 10-day Argo sampling combined with the continuous time-series from moorings for observing this time-scale remains to be assessed. This plan identifies areas of divergent surface currents and areas of particular relevance to climate where special attention is needed to maintain the array. The plan calls for an activity to identify deployment-opportunities and coordinate deployments.

Several merchant shipping routes were equipped with expendable bathythermographs (XBT) to measure temperature to a depth of 750 m during the 1980s as a component of individual research projects. The activity was transferred to national programmes after 1995, and is now coordinated by the Ship-of-Opportunity Implementation Panel (SOOPIP) under auspices of the IOC–WMO Joint Committee for Oceanography and Marine Meteorology (JCOMM). The XBT network in the Indian Ocean was never fully implemented. XBT lines are effective for monitoring specific ocean structures that affect climate, such as the upwelling zones off Java, Somalia, the Lakshadweep Dome and the thermocline ridge near 10°S. These are regions known to have strong ocean–atmosphere interactions. Combined with Argo floats the high-resolution XBT lines are effective to cut the upper ocean up into regions where the net transport, in or out, the interior heat and freshwater storage and the surface fluxes can be monitored, providing a method to understand the role of ocean dynamics in climate variations. The Indian Ocean Panel critically reviewed the XBT lines in preparing this report, with regard to scientific justification, potential impact on future research and feasibility of implementation. The high-priority lines were determined to be IX01, IX08, IX09N/IX10E, IX12, IX22 and PX-02 for the so-called frequently repeated (FRX) sampling mode; and IX1, IX15/IX21, and possibly IX10 for the high-density (HDX) sampling mode. The intraseasonal variation is strong at the north end of IX1 and the deployment of moorings is not advisable in this region, owing to intensive fishing activity; enhanced sampling to better resolve the fast time-scale is recommended for this line.

IOC and WMO through JCOMM sponsored an international workshop to organize implementation of the high-priority western Indian Ocean XBT lines in October 2005. The workshop was unique in that it brought together researchers, operators, shipping managers and customs officials. The outcomes were: improved protocols for shipping XBT's across national boundaries (which in the past was an impediment in the Indian Ocean region), identification of ships for presently unoccupied lines, a USA-India effort to occupy IX08, identification of a need for capacity building in the region and consensus to work toward full implementation of the XBT network.

The International Buoy Programme for the Indian Ocean (IBPIO) was formally established at a meeting in La Réunion in 1996. IBPIO is the primary body for coordinating multinational activities to implement surface drifting buoys. The number of drifters measuring surface velocity and SST in the Indian Ocean north of 40°N is typically about 60, whereas about 160 are required for full coverage at the standard sampling density. The primary uses of drifter data are reduction of the bias error in satellite SST measurements; documentation of large-scale surface current patterns and their role in heat transports; and, potentially, validation of surface currents in ocean models. Full implementation of the array at least at the standard sampling density is recommended. A well planned re-seeding programme will be required to maintain the array north of the equator because drifters are pushed out of the region by summer monsoon winds. The standard sampling density was determined with regard to the goal of calibrating satellite SST. A re-evaluation of the sampling density is required for measurement of surface current, particularly as forecasting of surface current in operational ocean models comes into common practice.

The international response to the Indian Ocean tsunami disaster in December 2004 is the rapid development of an Indian Ocean Tsunami Warning and Mitigation System. This development will potentially have numerous synergies with the development of the climate observing system discussed above, particularly if the warning system addresses the multiple hazards of tsunami, tropical cyclone, storm surge, coastal flooding and other potential marine hazards. The potential synergies include logistics of maintaining deep-sea mooring sites, shared ship time, protection from vandalism, coordinated development of instrumentation packages, fail-safe communication systems and a long-term commitment to maintain the sites in the open ocean. There is obvious synergy in the maintenance of real-time tide-gauge/sea-level stations. Maintenance of a long-term datum to observe sea-level rise is an essential requirement for the climate observing system and needs to be guaranteed in the implementation of tide gauges for tsunami warning. Real-time sea-level stations are needed to facilitate the maintenance of continuous sea-level records and to validate satellite altimetry data in operational ocean models.

The observational strategy for biogeochemical observations is coordinated through the International Ocean Carbon Coordination Project at IOC. Numerous national and international science plans developed in the past few years have identified the uptake and storage of CO_2 in all ocean basins and the biogeochemical responses to changes in environmental conditions (warming, acidification, circulation changes) as key issues that need to be addressed. Design of biogeochemical sampling is at an early stage compared to physical sampling. This report identifies initial ideas for Indian Ocean observations, including repeat hydrographic sections, recently developed instruments on ships of opportunity, and biogeochemical sensors on the basin-scale mooring array and Argo floats.

This report provides a survey of planned and future regional process studies that will be carried out within the background of the sustained basin-scale observing system.

Data management is not addressed explicitly here; however, an approach to developing a plan based on existing resources is recommended.

The report concludes with the idea that, in designing an integrated observing system for the Indian Ocean, and in particular in identifying the need for a basin-scale mooring array, focus has been placed on the Indian Ocean zonal dipole mode and the pronounced intraseasonal variation that exists in the tropics, features that have strong climatic impacts on the surrounding land masses. The proposed observing system calls for Argo floats, XBT lines and surface drifters in the subtropical southern Indian Ocean and at higher latitude; however, these observations alone are not likely to adequately capture all aspects of subtropical variability, particularly in the boundary currents and major frontal zones. Therefore an extension of the system, such as additional mooring arrays, may be needed in the future as more is learned from the initial, sustained observations and process studies.

Recommendations (numbered according to the section of the report where they appear)

Recommendation Intro.1 The agencies contributing to the integrated observing system accept, follow and further develop the principles given in the Introduction.

Recommendation 9.1 The agencies contributing to the mooring array agree to the mooring plan and, recognizing that implementation depends on national resources, agree to negotiate changes to the plan with the other agencies doing mooring work.

Recommendation 9.2 Recognizing that ship-time is the key resource needed to implement the array, the agencies agree to optimise the use of their vessels to maintain the array when they are available and to proceed to a multi-agency agreement on ship-time as soon as possible.

Recommendation 9.3 Increase the number of moorings deployed at recommended sites as soon as possible, with a view to full implementation of the array within five years.

Recommendation 10.1 As a minimum, the planned 3×3 Argo Programme in the Indian Ocean should be completed and maintained.

Recommendation 10.2 INCOIS identify and publicize deployment opportunities, including research-vessel opportunities during routine mooring-maintenance cruises and process studies, as well as contacts to enable air-deployment or deployments from chartered ships in remote regions that are not regularly crossed by commercial shipping.

Recommendation 10.3 Model/observing-system experiments suggest that the sub-seasonal Indian Ocean temperature variability recovered from sampling at 5-day intervals does not represent a significant improvement over 10-day sampling. Continuation of 10-day sampling is recommended until further studies of the integrated sampling strategy.

Recommendation 10.4 Actions should be taken to ensure that Argo floats are continuously maintained in key centres of action: e.g. Java/Sumatra upwelling region, SEC/SECC ridge (western region), Bay of Bengal, where divergent currents tend to disperse them.

Recommendation 11.1 Implement the full XBT network in accordance with the guidelines given below.

Recommendation 11.2 Increase sampling on IX1 to weekly sections to better resolve intraseasonal variability, including four high-density sections per year to measure Indonesian Throughflow; increase the number of thermosalinograph sections.

Recommendation 11.3 Restore frequently repeated sampling on IX8 to observe the thermocline ridge near 10°S and interactions with the atmosphere, as well as the inflow to the western boundary-current system.

Recommendation 11.4 Complete observing-system simulation experiments to determine the efficacy of IX10 and/or IX14 in HDX mode to monitor the transport of mass, heat and fresh water into/out of the Arabian Sea and Bay of Bengal.

Recommendation 11.5 Data from all the XBT lines should be submitted to JCOMM/OPS annually.

Recommendation 12.1 Full implementation of the surface drifter array at least at 5° latitude/longitude spacing for calibration of satellite SST data is strongly recommended, particularly with regard to the area north of the equator where clouds often interfere with passive measurements and where very active re-seeding is required to maintain the array, owing to strong southward surface currents.

Recommendation 12.2 A study to determine an appropriate sampling strategy for surface currents is needed.

Recommendation 13.1 The CLIVAR community needs to establish formal links with the tsunami community to take advantage of possible synergy in developing the Indian Ocean Tsunami Warning and Mitigation System and the Global Climate Observing System.

Recommendation 13.2 The IOTWS will be more robust and useful if it addresses the multiple hazards of tsunami, tropical cyclone, storm surge and coastal flooding. This will enhance links to GCOS.

Recommendation 13.3 Enhance the network of sea-level stations to allow real-time transmission of data to a tsunami warning centre, without diminishing the stations' capability to build a long-term record of a well maintained datum for the determination of sea-level rise.

Recommendation 14.1 Full implementation of repeat hydrographic sections for the Indian Ocean, with carbon, transient tracer and related biogeochemical measurements.

Recommendation 14.2 Instrumentation of all surface-flux reference sites in the Indian Ocean mooring array, with biogeochemical sensors and assessment of the need to instrument other surface moorings in the array.

Recommendation 14.3 Develop biogeochemical instrumentation on all suitable research ships and XBT lines in the Indian Ocean.

Recommendation 14.4 Work in collaboration with the biogeochemical community to assess and, where possible, deploy Argo floats with biogeochemical instrumentation.

Recommendation 14.5 Organize a workshop in 2006 to bring together the biogeochemical and physical interests in developing the Indian Ocean observing system.

Recommendation 16.1 INCOIS and APRDC write a joint implementation plan for Indian Ocean data management.

Introduction

Of the three major oceans – Pacific, Atlantic, and Indian – the Indian is the only one that is not open to the northern subtropical regions. This is a consequence of the presence of the Asian landmass restricting the Indian Ocean to south of about 25°N. The Indian Ocean is also the only ocean with a low-latitude opening in its eastern boundary. The unique geography has important implications for the oceanic circulation physics, and consequently for climate and the biogeochemistry of the ocean, giving the Indian Ocean many unique features. It cannot transport heat gained in the tropics to the higher northern latitudes, as the Pacific and Atlantic do, mainly via their western boundary currents. It gains additional heat from the tropical Pacific via the Indonesian Throughflow. Heat is carried southward along the western coast of Australia toward the southern subtropics. The Indian Ocean consequently has a unique system of three-dimensional currents and interactions with the atmosphere that redistribute heat to keep the ocean approximately in a long-term thermal equilibrium. The Indian Ocean interacts strongly with the surrounding land masses resulting in the well known monsoons, or seasonal cycle, of southern Asia, East Africa and northern Australia. Short-term imbalances and irregularity in oceanic heat storage give the climate system a tendency to vary at a broad range of time-scales from a few weeks (intraseasonal variation) to years and decades. The variation in the atmosphere is documented and at least partially understood, due to the longstanding collection of weather data. Sustained in situ data from the ocean are however scarce, and an understanding of the role of ocean dynamics in the regional climate system is consequently limited. In this report we will first review the scientific issues and questions concerned with regional ocean–atmosphere interaction, and then lay out an implementation plan for sustained, in situ oceanic observations to address these issues.

From the outset, we recognize the following principles:

- Implementing basin-wide observations is too large a task for any one nation or agency to accomplish alone. *A multi-national approach is required*. Agreement to use available national resources in a coordinated and cost-effective way is an essential part of achieving full implementation.
- *Data should be distributed openly in a timely manner*. there is a preference for communication of data in real time to make it available at climate analysis and prediction centres. Data management will follow the guidelines and policies of the Intergovernmental Oceanographic Commission and CLIVAR.
- *Satellite observations of ocean-surface properties provide a framework for the observing system*. The in situ observations are complementary and provide subsurface information that complements and enhances interpretation of satellite data. While this document is concerned with in situ observations, we note that the research issues identified in Part 1 cannot be resolved without satellite data and we strongly recommend continued measurement of sea-surface temperature, sea level, ocean colour, wind, rain and cloud. Likewise, in situ observations are used to maintain calibration of satellite data.
- *Development requires close coordination between the research and operational-oceanography communities*. Some of the observations in this plan have already been partially implemented by operational programmes in GCOS and GOOS; for example, the ship-of-opportunity expendable bathythermograph programme and surface drifters. Full implementation requires close coordination with the Ocean Observation Panel for Climate (OOPC), the CLIVAR Global Synthesis of Observations Panel (GSOP), the International Argo Programme's Science Team (IAST) and the IOC–WMO Joint Committee for Oceanography and Marine Meteorology (JCOMM).
- *An integrated observing system is required to address the diversity of time- and space-scales of climate-relevant variability*. This means that a variety of instruments will be used, each in an appropriate way considering the time-scale that has to be resolved and the physical or biological parameter to be measured.

More than anything else, international and inter-agency cooperation and good-will are required to successfully implement the Indian Ocean observing system. The above principles are intended to provide a basis for the common endeavour.

<u>Recommendation Intro.1</u> The agencies contributing to the integrated observing system accept, follow and further develop the above principles.

The principle of open and timely sharing of data in the Indian Ocean requires some discussion. The Indian Ocean rim is a region with considerable potential for political instability and conflict. It is also a region where full agreement on the modes of access to exclusive economic zones has not been reached. The political realities have historically had an impact on data sharing. Nevertheless, the threat to countries in the region from natural hazards is recognized now, and may lead to rapid improvement. The Argo Programme and the TAO/Triton Programme in the Pacific will serve as examples of data management for development of the Indian Ocean observing system. Countries and research groups participating in these Programmes have agreed to the open exchange of data. This applies equally to the real-time (GTS and ftp) data stream (over 90 per cent available within 24 h) and to delayed-mode data. It is recommended that these standards of timeliness and openness be applied to all Indian Ocean observations.

While this report is primarily concerned with oceanographic measurements, the meteorological measurements (particularly at moorings) will be extremely valuable to data assimilation issues concerned with weather forecasting and reanalysis efforts. At present there are no such measurements in the Indian Ocean and this lack of information prevents accurate initial condition determination of weather forecasts and limits reanalysis efforts.

Part 1 of this report updates the Indian Ocean research issues identified by Godfrey et al. (1995) and the CLIVAR Research Plan sections G2 and G4 prepared in 1997 (http://www.clivar.org/publications/wg_reports/index.htm). The science-drivers discussed here are improved description, understanding, modelling and ability to predict:

- Seasonal monsoon variability and the Indian Ocean
- Intraseasonal variability
- Indian Ocean zonal dipole mode and El Niño–Southern Oscillation
- Decadal variation and warming trends in the upper Indian Ocean
- Southern Indian Ocean and climate variability
- Circulation and the Indian Ocean heat budget (Indonesian Throughflow, shallow and deep overturning cells)
- Biogeochemical cycling in the Indian Ocean

Operational oceanography and programmes developing a capability for ocean-state estimation (e.g. Global Ocean Data Assimilation Experiment http://www.bom.gov.au/bmrc/ocean/GODAE/) also require in situ data. The uses of operational products range from initialization of coupled climate models for seasonal prediction to information for maritime safety, fisheries and management of the marine environment. With these applications in mind, all of the dominant space and time-scales of variation need to be observed. For the Indian Ocean the fast, upper ocean variability associated with intraseasonal disturbances is a challenge that has to be addressed by the observing system.

Part 2 is concerned with implementation of the elements that make up the basin-scale integrated in situ observing system. The planned basin-scale system is in Figure 1 (page 61), including fixed moorings, Argo floats, XBT lines, surface drifters and tide gauges, which are addressed in separate sections. Monitoring of boundary regions is not yet planned. It is worth mentioning here, although not covered in detail in this report, that multi-year regional monitoring is needed in the Arabian Sea (ASEA), the Bay of Bengal (BOB), the Indonesian Throughflow (ITF), the western (WBC) and eastern boundary currents (EBC) and deep equatorial currents indicated by a double arrow (⇔). Pilot projects in some of these regions are also discussed in Part 2.

The mooring array is the critical new element in Indian Ocean observations, required to understand the energetic intraseasonal variation in the upper-ocean, as well as mixed-layer thermodynamic processes in interannual variability. The array spans the tropical zone and provides well resolved time-series of surface weather parameters and upper-ocean temperature and salinity. A subset of the array will be equipped to measure equatorial currents and to estimate surface heat and freshwater fluxes. Argo floats, XBT lines and surface-drifters are already partially implemented in the Indian Ocean. This report sets out the plan for what we consider the full implementation required to understand the longer time-scales of variation, from seasonal climate to multi-decadal climate change.

The tsunami disaster in Asia in December 2004 has stimulated the rapid development of a tsunami warning system in the Indian Ocean. This will lead to a great improvement in the operation of regional tide gauges, probably including real-time or near-real-time transmission of sea-level data from most of the existing stations and additional required sites. The links between a tsunami warning system and the needs of a climate observing system are discussed in Part 2, particularly with regard to using some of the climate mooring sites for bottom-pressure measurements. A multi-hazard approach to the warning system can address a range of threats from the oceans (e.g. tsunami, tropical cyclones, storm surge and coastal flooding); and it will lead to a warning system that operates continuously, to the benefit of society. The collection of data for a multi-hazard warning system will have many overlapping elements with the climate-observing system. In particular, shared shiptime to maintain deep-sea data collection will be cost effective, and enhanced weather data will serve both hazard warning and climate research.

Part 1 Research Issues and Operational Oceanography

Background

The monsoon is the characteristic feature of Indian Ocean climate. The topography of the Asian landmass is dominated by the Tibetan Plateau which has an area of about a million square kilometres and an average height of about 5 km. The plateau acts as an elevated heat source for the atmosphere during the northern summer. The heating in spring, combined with a build-up of moisture over the northern Indian Ocean, triggers processes that lead to large seasonal changes in wind and out-going long wave radiation (OLR) indicative of precipitation in Asia (Fig. 2, page 61). During January the equatorial rain-band, i.e. the Inter-Tropical Convergence Zone (ITCZ), is located primarily in the southern hemisphere. The region north of the ITCZ then experiences northeasterly trade winds and that to the south, the southeasterly trades. This distribution of wind and precipitation is similar to that over other tropical regions of the world. During northern summer the ITCZ virtually covers the entire Bay of Bengal, the surrounding lands, and the eastern Arabian Sea. The winds in the north turn into strong southwesterlies, while the southeasterlies persist in the south. The wind speed is much greater than that during the northern winter. This seasonal reversal of winds and rainfall is the well known monsoon, a special feature of the region with profound implications for both the ocean and the people who live under its influence, about 60% of the population of the world.

Whereas the reversals of wind and rain recur each year, they do so with sufficient variability to create periods of relative drought and flood in large parts of southern Asia, East Africa and northern Australia. The societal impact of the variations is very large. The anomalies are often associated with strong, intraseasonal disturbances—weather patterns that evolve systematically over a period of three to four weeks—that can determine the character of an entire season of rainfall. A challenge for modern climate research is to understand how the ocean responds to the atmosphere and feeds back the heat and moisture that together govern the intraseasonal to interannual variation. This is the primary reason that sustained observations in the ocean are needed.

Process studies of relatively short duration in the past, and ocean models, together provide a qualitative view of the ocean's response to monsoon forcing (Schott and McCreary, 2001). The precipitation and wind stress depicted in Figure 2 bring about a response (Fig. 3a,b, page 62) that is distinctly different in the northern and southern parts of the Indian Ocean. A subsurface hydrothermal front near 10°S (Wyrtki, 1971) separates the monsoon-driven, northern region from the steadier southern region. The circulation in the North is strongly seasonal, and the currents experience a complete reversal from January–February (Fig. 3a) to July–August (Fig. 3b). During the transition between the monsoons, May and October, the equatorial Indian Ocean exhibits eastward jets, so-called Wyrtki Jets (Wyrtki, 1973). The highly seasonal circulation north of 10°S is a superposition of tropical and coastal locally and remotely forced waves with frequencies that range from intraseasonal to interannual. The waves lead to strong seasonally reversing currents, the most prominent being the following: the Somali Current along the coast of Somalia; the monsoon currents in the mid-basin (Shankar et al., 2002); and the West and East India Coastal Currents (Shetye and Gouveia, 1998).

South of about 10°S the direction of the currents remains approximately unchanged from season to season (Fig. 3a,b), and steady state ocean circulation theory (Sverdrup-theory), which takes Indonesian Throughflow into account (Godfrey and Golding, 1981), explains much of the structure of currents and density. The Agulhas Current, the Mozambique Current eddies and the East Madagascar Current form a complex western-boundary current system along the East African coast.

In summary, geography of the Indian Ocean sets the stage for a highly variable, 3-dimensional ocean circulation that responds to the monsoons. While the monsoons recur each year, their irregularity at a range of time-scales from weeks to years depends on feedback from the ocean in ways that are not fully understood. The geography also impacts the biogeochemistry of the region, leading to an ocean environment that has unique features.

Part 1 is concerned with the outstanding research issues that need to be addressed with observations to advance our understanding of the role of the Indian Ocean in the climate system and its predictability. The issues addressed in the next 8 sections are:

1. Seasonal monsoon variability and the Indian Ocean
2. Intraseasonal variability
3. Indian Ocean zonal dipole mode and El Niño–Southern Oscillation
4. Decadal variation and warming trends in the upper Indian Ocean
5. Southern Indian Ocean and climate variability

6. Circulation and the Indian Ocean heat budget (Indonesian Throughflow, shallow and deep overturning cells)
7. Biogeochemical cycling in the Indian Ocean
8. Operational oceanography

1. Seasonal monsoon variability and the ocean

Despite the critical need for accurate and timely monsoon forecasts, our ability to predict seasonal conditions has not changed substantially over the last few decades. Statistical methods have shown that while there are periods of high correlation between El Niño–Southern Oscillation (ENSO) and monsoon variation, there are decades where there appears to be little or no association at all (e.g. Torrence and Webster, 1999), making statistical prediction unreliable. Why this first-order predictability disappears for long periods of time is not known.

The critical need for seasonal prediction cannot at this time be filled by coupled, numerical modelling either. Dynamical prediction is still in its infancy and severely handicapped by the inability of models to simulate either the mean monsoon structure, or its year-to-year variation (Sperber and Palmer, 1996; Gadgil and Sajani, 1998), or the intraseasonal (20–50 day period) band which controls a very large percentage of the precipitation (Slingo et al., 1996; Waliser et al., 2003a, 2003b). What is the reason for the general failure of models to forecast monsoon variation? Clearly, there are model problems associated with characterization of convection. At the same time, it is apparent that many of the climate phenomena are coupled with ocean thermodynamics and hydrodynamics. This is clear for seasonal and interannual variability (e.g. Webster et al., 1998) and highly probable for sub-seasonal or intraseasonal variability (see section 2). Yet our current knowledge of the ocean–atmosphere interactions is limited by a lack of ocean data, particularly data relevant to the fast variability of temperature, salinity and currents in the mixed layer. In particular, for the Indian Ocean, incorporating the mixed-layer thermodynamics of thin, low-salinity layers at the surface into models is a challenge. Also, surface "weather" data such as near surface winds, temperature, humidity and radiation are lacking in the Indian Ocean, in comparison to the Pacific and Atlantic. Future research to understand the ocean–atmosphere interactions will place a high reliance both on model capabilities and the observations needed for understanding processes.

Despite the limited capability for prediction described above, recent progress increases our confidence that the capability can be improved (Walliser, 2005a). Better data for initialization of the numerical models will in itself improve predictions. Beyond that, there are physical reasons to expect improvement. Empirical schemes (Walliser et al., 1999; Lo and Hendon, 2000; Wheeler and Weickmann, 2001;Webster and Hoyos, 2004) have shown that regional precipitation characteristics are predictable with considerable accuracy 20–30 days in advance. Why models tend to show less skill than empirical techniques is less known, although there is some evidence that it is associated with problems in convective parameterization. For the interannual time-scale, a recent series of empirical studies have shown that the relationships between Indian Ocean SST and Indian rainfall are stronger than portrayed in earlier studies if the ENSO signal is properly addressed (Clark et al., 2000) The SST–monsoon relationship is apparent in the seasonally stratified persistence of SST anomaly across the tropical Indo-Pacific basin (Fig. 4, page 63). The Pacific Ocean has a strong persistent minimum in the boreal spring, known as the "predictability barrier", but shows persistence of several months after ENSO events begin, typically in June. The pattern in the Indian Ocean is quite different. Strong persistence occurs from the end of the boreal summer to the late spring of the following year, consistent with the idea that there is a biennial component in the Indian Ocean SST and monsoon rainfall in Asia and Australia (Meehl, 1997). The structure of persistence suggests that Indian Ocean thermodynamics is somewhat independent of the Pacific Ocean, in ways that are not yet simulated in coupled climate models.

A better physical understanding of ocean–atmosphere interaction is required to improve models. A key factor in the monsoon–ocean interaction is the small variation in SST between seasons (Fig. 2). The SST appears to increase little during the boreal spring over much of the northern Indian Ocean, despite weak winds and high insolation. Similarly, the winter SST in the northern Indian Ocean is only a degree or so cooler than in the fall or the spring despite significant reductions in surface heating. Understanding how the mean SST and the amplitude and phase of the annual cycle are established is very important in the Indian Ocean because of the close association of the magnitude of the SST with the vigour of the ensuing monsoon (e.g. Clark et al., 2000).

The small SST variation is thought to be related to advection by ocean currents. Despite biases (see below), the annual mean heat flux into the northern Indian Ocean has been estimated at about +50 to +70 Wm^{-2} in numerous studies in the past (Hastenrath and Lamb,1978; Hsiung et al., 1989; Oberhuber, 1988, Hastenrath and Greischar, 1993). After considering how this intake of heat can be balanced, Godfrey et al. (1995, p. 12) concluded:

"... on an annual average there is positive heat flux into the Indian Ocean, nearly everywhere north of 15° S. The integral of the net heat influx into the Indian Ocean over the area north of 15° S ranges between $0.5–1.0×10^{15}$ W, depending on the climatology. Thus, on the annual mean, there must be a net inflow of cold water (into the North Indian Ocean), and a corresponding removal of warmed water, to carry this heat influx southward, out of the tropical Indian Ocean. ..." Thus it is inferred that oceanic heat transport represents the only means that allows the large net annual surface heating of the northern Indian Ocean to be removed without raising the SST substantially.

Similarly, the annual cycle of net surface flux is large enough to cause a temperature change of 7°C during the year, if all the heat were stored in a 50-m mixed layer (Webster et al., 1998), but the large amplitude does not develop. A hypothesis based on models is that the unique 3-dimensional, basin-scale circulation of the Indian Ocean stabilizes the annual mean temperature and dampens the annual cycle (Loschnigg and Webster, 2000), as discussed further in section 7.

Clearly, knowing the climatological surface heat balance of the Indian Ocean is necessary to understand the monsoons. However, there are large differences (biases, 20–50 Wm^{-2}) between presently available estimates (Godfrey et al., 1995; L. Yu, personal communication). This should not be surprising as the surface heat balances are the relatively small sums of large terms, and data in the Indian Ocean are sparse. Furthermore, these large terms are obtained from empirical rules some of which are not precisely understood and which produce large errors in the estimates.

Given the problems in the prediction of monsoons, and in the light of the recent discoveries regarding the structure of Indian Ocean variation (see sections 2 and 3), a number of questions about the monsoons need to be addressed, and they will require an improved observing system:

(i) What factors determine the phase and the amplitude of the monsoon annual cycle? In particular, why is the amplitude of the SST variation so small?
(ii) What factors control the interannual rainfall variation of the South Asian monsoon so that the persistent multi-year anomalies and large excursions from long-term means are rare?
(iii) What factors produce the intraseasonal oscillation of the monsoon system which, in turn, produces seasons of drought or flood?
(iv) In particular, what is the role of ocean circulation and thermodynamics in the monsoon and the intraseasonal time-scale?
(v) To what extent is the monsoon a coupled ocean-atmosphere phenomenon? For example, do the correlations between Indian Ocean SST and monsoon rainfall indicate the existence of coupled modes?
(vi) What are the modes of interannual to decadal variability in the region and how do they interact?

2. Intraseasonal variability

The Monsoon Intraseasonal Oscillation (MISO) and Madden–Julian Oscillation (MJO) are long-lasting weather patterns that evolve in a systematic way for periods of four to eight weeks. They form over the western, central equatorial Indian Ocean, move eastward, interact with the centres of tropical convection near Indonesia, sometimes split into streams that affect East Asia or Australia, and move into the Pacific Ocean (Wang et al., 2005), where their impact can be felt as far away as the Americas. They have a very big impact on regional rainfall, and in some years determine the character of rainfall (drought or flood) for an entire season. The intraseasonal variations are now recognized as the elementary building blocks of the monsoons; hence, monsoon simulation and prediction hinges on the ability to simulate it. There is a growing body of evidence that successful simulation of MISO and MJO requires a coupled model with an active ocean that modulates atmospheric convection through intraseasonal SST fluctuations (Kemball-Cook et al., 2002; Fu et al., 2003; Zheng et al., 2004; Rajendran et al., 2004). While model simulation is not adequate at the present time, the skill of statistical predictions is evidence that models can be improved (see section 1), in part based on a better understanding and representation of oceanic upper-layer physics, and on a better choice of initial oceanic conditions by the modeller.

Progress in understanding the intraseasonal variability in oceanic structure and currents was recently reviewed in depth by Kessler (2005), in a volume that is dedicated to an extensive review of atmospheric MISO and MJO. He described the essential oceanic physics as follows, "[The events] affect the ocean through three main mechanisms: increased evaporation, the generation of equatorial jets and waves that produce advective changes remotely, and enhanced mixing and entrainment….these responses are proportional to the wind speed u, u^2 and u^3, respectively, and therefore depend very differently on the background wind and the structure of its variance. Much of the forcing by tropical intraseasonal oscillations…occurs over the warm pools of the Indian and west Pacific Oceans where the thermocline is usually deeper than the mixed layer. Thus, the near-surface density structure is relatively unconstrained by large-scale ocean dynamics and can easily be modulated by the winds and the heat and moisture fluxes…, providing the opportunity for air–sea feedbacks, nonlinear effects, and the retention of an oceanic memory of previous forcing. The dynamic response depends on the thickness of the accelerating layer, which is a function both of the background stratification and of local precipitation and mixing. Thus a principal focus…is the factors controlling the upper-ocean stratification under rapidly changing windspeed and precipitation sufficient for salinity variation to determine the mixed-layer depth. The correlation of intraseasonal variation of solar shortwave forcing with the wind fluctuations can also lead to significant effects on mixed-layer temperature structure."

The core, the most energetic region of global, interannual variability of MISO and MJO (Fig. 5 page 63, left panel) is in the central, eastern Indian Ocean near 90°E (Kessler, 2001) Whether or not intraseasonal variability in the core region plays an active, causal role in the ENSO cycle is still a matter of debate. Interannual indices of the variability indicate that the correlation over longer time-series is not high (Hendon et al., 1999; Slingo et al., 1999); however, activity in the core region was at a maximum just before the 1982 and 1997 El Niños (Fig. 5, right panel). Further discussion of the atmospheric side of intraseasonal variability is beyond the scope of this report; interested readers are referred to the comprehensive review by Lau and Walliser (2005).

The oceanic response to MISO/MJO is strongly affected by the boundary of the Indian Ocean. Strong westerly winds during intraseasonal events generate eastward currents in a ~300-km band on either side of the equator and the Kelvin waves that carry the response to the eastern boundary (Walliser et al. 2003c, 2004; Schiller and Godfrey, 2001; Masumoto et al., 2005). The Kelvin waves reflect as coastal waves and propagate around the Bay of Bengal into the Arabian Sea (Shetye and Gouveia, 1998). The regional currents and variations in oceanic structure are strong and have important societal impacts on the coastal communities, such as impact on fishing. The MISO in the atmosphere sometimes propagates northward into the Bay of Bengal, under the influence of SST patterns, affecting monsoon rainfall. There are very energetic responses in currents, salinity structure and subsurface fronts in the Bay of Bengal (Webster et al., 2002); however, the role of ocean dynamics in the northward propagation of MISO is not known.

The mean structure of the thermocline and the pycnocline (Fig. 6, page 64) sets the background state on which the basin-scale intraseasonal variability develops, and distinguishes the Indian Ocean from other regions. The thermocline in the eastern Indian Ocean is deep, in comparison to the Pacific and the Atlantic, primarily as a consequence of the opening to the Pacific through Indonesia (see section 6). Also, unlike the other oceans, the wind stress along the equator is predominantly eastward, giving the thermocline a downward slope toward the east. The deep thermocline shields the surface from thermocline dynamics and allows the formation of a large, deep pool of surface water with a temperature exceeding 28°C. Heavy runoff into the Bay of Bengal and rainfall over Indonesia form widespread, thin layers of low-salinity water, creating the so-called "barrier layer" (e.g. Qu and Meyers, 2005), within the thick surface isothermal layer. This structure leads to a complex mixed-layer dynamics that has to be documented, understood and modelled in order to predict SST (Slingo, personal communication; 2004 AAMP meeting).

The MISO and MJO are associated with strong fluctuations in surface heat fluxes, primarily evaporation and solar radiation, and they generate large (~1°C), well known fluctuations in SST (e.g. Webster et al., 2002; Harrison and Vecchi, 2001; Duvel et al, 2004). The role of horizontal advection on SST is more subtle, but has been observed at times in the western Pacific (Kessler, 2005), for which there are adequate data. The vertical mixing usually cools the surface layer, but can at times warm it in the presence of a barrier layer (Du et al., 2005). The challenge for future research on the intraseasonal time-scale in the Indian Ocean is to understand how oceanic processes generate SST and feedback to the atmosphere by modulating convection.

The need for accurate surface-flux products to support research on MISO and MJO cannot be overemphasized here. Weller et al. (1998) demonstrated the feasibility of the required measurements and their use to validate satellite-derived flux products. Likewise, temporally well resolved, basin-scale measurements of upper ocean temperature and salinity structure and direct measurement of equatorial currents are needed. The Japanese equatorial mooring program in the eastern equatorial Indian Ocean since November 2000 (Masumoto et al., 2005) has demonstrated that each new mooring brings about a quantum increase in description of the complex structure and time scales of variability in this region. Already the results provide us with a new perspective on importance of the energetic intraseasonal variability of currents, its strong correlation with the wind variability and other weather variables and the impact of wind-driven currents on structure of the mixed layer and barrier layer. A deeper understanding of the role of the ocean in MISO and MJO requires implementation of a basin-scale mooring array in the tropical Indian Ocean.

Some of the critical scientific questions that will be addressed by the observing system are:

- How much of the SST variation is controlled by local, surface fluxes and can be simulated with a 1-D (vertical) model of the mixed layer, including barrier-layer dynamics and the low-salinity water lenses?
- Under what circumstances do horizontal currents, baroclinic waves and mixing play a role?
- Which, if any, oceanic processes are related to the MISO and MJO convection?

3. Indian Ocean zonal dipole mode and El Niño–Southern Oscillation

A multitude of forces shape the structure of interannual SST patterns in the Indian Ocean, rendering it more complex than tropical SST variations elsewhere. Strong monsoons and intraseasonal events affect the tropical SST on a large scale, as discussed in sections 1 and 2. Also, coupled ocean-atmosphere modes of variability affect the SST pattern.

An important factor is ENSO. A typical El Niño signal in the Indian Ocean starts with warming in the western tropics during May/June and cooling in the Java upwelling zone. The warming spreads eastward covering the whole tropical Indian Ocean as far as the Indonesian Seas at the end of the year. The SST pattern is caused by thermodynamic and dynamic forcing through atmospheric (Reason et al., 2000; Alexander et al., 2002; Shinoda et al., 2004) and oceanic teleconnections (Meyers, 1996; Xie et al., 2002; Wijffels and Meyers, 2004). In particular, oceanic dynamics affect SST in the seas north of Australia (Wijffels and Meyers, 2004), particularly along the coast of Australia, and in the western Indian Ocean near 5°–12°S (Xie et al., 2002), at the so called "thermocline ridge". In turn, the SST controls the release of latent heat in the atmosphere and impacts regional climate, especially rainfall on all the continents around the Indian Ocean (Goddard and Graham, 1999; Nicholls, 1989; Reason et al., 2000). Formation of tropical cyclones in the southwestern Indian Ocean is influenced by the thermocline ridge (Xie et al., 2002). The role of ocean dynamics in the generation of Indian Ocean SST suggests a degree of predictability that has not yet been realized in seasonal climate-prediction systems. Sustained monitoring of the currents and structure of the Indian Ocean in response to ENSO and analysis of the surface-layer heat budget is required to understand and predict the monsoon–ENSO interaction. ENSO effects in the Indian Ocean as far as they are known have been summarized by Yamagata et al. (2004).

The recently identified Indian Ocean Zonal Dipole Mode (IOZDM) is another basin-scale SST pattern that affects the climate system. The phenomenon is called IOZDM here, combining the names used in the original papers in *Nature* (Saji et al., 1999; Webster et al., 1999). Yamagata et al., 2004) provide a comprehensive review of the many studies since 1999. ENSO is an important trigger for IOZDM events, but not the only one—about half the events having occurred in the absence of ENSO. The evolution of a positive IOZDM event (Fig. 7, page 64) starts with SST and wind anomalies in May–June, followed by growth during July–October and a rapid decay in November–December. In its well developed positive phase, SST is anomalously cool in the east and warm in the west, while the equatorial winds reverse direction from the normal westerlies to easterlies, blowing from a cool to a warm anomaly. The IOZDM has a major impact on seasonal climatic conditions in the Indian Ocean rim countries, sometimes even stronger than the impact of ENSO, and an impact on the global climate system (as discussed later). While great success has been achieved in synthesizing the phenomenology and climatic impacts of IOZDM from surface observations, important issues, such as its genesis, predictability and interaction with ENSO, have been hampered by a lack of systematic and sustained subsurface ocean observations. Nevertheless, some progress has been made in these over the last few years, aided by analysis of wind-forced ocean models (Rao et al., 2002; Shinoda et al., 2004) and coupled general circulation models (Fischer et al., 2005). These suggest that, as with ENSO, the predictability of IOZDM may lie in the slowly varying oceanic heat content and depth of the thermocline, shaped by coupled equatorial and planetary ocean-wave dynamics. Systematic and sustained observations are required to validate these theories and to exploit these findings for improved seasonal climate predictions.

The IOZDM pattern was first clearly identified in two seminal papers in *Nature* (Webster et al.,1999; Saji et al.; 1999), although aspects of it had been noted in earlier publications. The papers stimulated a vigorous, scientific debate concerning (1) whether or not IOZDM was a local, passive oceanic response to atmospheric ENSO teleconnections, and (2) whether or not IOZDM could maintain itself by positive feedback through ocean–atmosphere interaction within the Indian Ocean. At one extreme of the debate, some authors argued that IOZDM was a statistical artifact of the methods used to identify it. A summary of the debate is published in the CLIVAR Exchanges newsletter, (Allan et al., 2001; Yamagata et al., 2002). The proponents of IOZDM argued that it is a coupled mode inherent in the Indian Ocean, although at the time only one paper documenting observed variation in the thermocline had been published (Rao et al., 2002). Variation in the depth of the thermocline is a critical factor in coupled climate-modes because the slow dynamics of thermocline adjustment to changing wind conditions (such as Kelvin and Rossby waves) gives the mode persistence and predictability for lead-times of a few to several months. The thermocline process also allows the development of a delayed, negative feedback that returns the coupled ocean–atmosphere toward a normal state.

Subsequent observational studies increasingly clarified the role of thermocline variation in IOZDM and raised new, important research questions. These studies found that seasonal upwelling off Java played an important role in the formation of IOZDM SST anomaly (Fig. 8, page 65) (Wijffels and Meyers, 2004). Also like ENSO, thermocline depth anomalies propagate as Kelvin and Rossby waves and play an important role in the evolution of the SST anomalies (Rao et al., 2002; Feng and Meyers, 2003; Yamagata et al., 2004). Since thermocline variations have a consistent dipole structure in the tropical Indian Ocean, and the structure is often not evident in the SST anomaly, we need to study the surface-layer heat budget to understand why SST is sometimes decoupled from thermocline anomaly during extremes of IOZDM, in contrast to the more consistent relationship in the Pacific Ocean during ENSO extremes. Strong variation in depth of the thermocline is observed in both poles of IOZDM (Wijffels and Meyers, 2004; Xie et al., 2002), but it is not always the dominant factor in generating SST anomaly, particularly in the west.

Climate models suggest a hypothesis on the mechanism that allows IOZDM to grow. The relation between thermocline depth, SST, rainfall and surface winds during IOZDM, inferred from observational analysis is reproduced successfully (with some important caveats) in coupled climate models (e.g. Murtugudde et al., 2000; Gualdi et al., 2003; Fischer et al., 2005; Yamagata et al., 2004; Cai et al., 2005). The models suggest that upwelling and thermocline depth in the Java/Sumatra region are key processes that control ocean–atmosphere interaction during growth. Stronger upwelling increases the zonal SST gradient toward the west; and the SST gradient in turn feeds back to produce a stronger easterly wind.

Like ENSO, the IOZDM has climate impacts on regional and global scales. Rainfall anomaly in many of the Indian Ocean rim countries is correlated with IOZDM, with largest impacts observed over equatorial East Africa and Indonesia (Saji and Yamagata, 2003). Moderate impacts are noted over Sri Lanka (Lareef et al., 2003) and Australia (England et al., 2005). The IOZDM may affect the Indian monsoons (Ashok et al., 2001; Gadgil et al., 2003), but the relation is confounded in the presence of ENSO.

Recent studies have identified a global correlation to subtropical surface air temperatures in the southern hemisphere (Saji and Yamagata, 2003). Figure 9, page 65, depicts the correlation of IOZDM with temperature anomalies in the southern hemisphere. Interestingly, strong and significant correlations are found in the subtropical land-surface temperature of the southern hemisphere underlying the subtropical jet stream axis in accordance with the linear theory of Rossby-wave propagation. Further analysis by Saji et al. (2005) has shown that this relationship is indeed quite strong and statistically robust. It seems that both IOZDM and ENSO can generate Rossby-wave trains that affect South America, the South Atlantic and southern Africa (e.g. Kiladis and Mo, 1988; Mo and Paegle, 2001; Colberg et al., 2004). IOZDM may also impact temperature variation over parts of Europe, northeast Asia and North America (Saji and Yamagata, 2003). Guan and Yamagata (2003) found that the intense heat-wave conditions during the summer of 1994 over Japan and northeast Asia were related to a strong IOZDM.

Unlike ENSO, the present-day coupled dynamical prediction systems for seasonal climate cannot predict the SST anomaly of IOZDM with the same level of skill as for ENSO SST anomaly. This surprising result suggests that we need a much better understanding of the dynamics and thermodynamics of the observed IOZDM, the associated mixed layer and barrier layer dynamics and their representation in models. Key research questions that can be addressed with better ocean observations are:

- What role do ocean circulation and structure play in the monsoon–ENSO interaction? Is ocean circulation and structure involved in the waxing and waning of the correlation between monsoon rainfall and ENSO?

- What is the relationship between ocean circulation, depth of the thermocline, depth of the barrier layer, SST and surface fluxes during IOZDM episodes?
- What mechanisms control the triggering, growth and decay of IOZDM?
- Will the prediction skill in respect of Indian Ocean SST improve with better observations for the initialization of a prediction run?

4. Decadal variation and warming trends in the upper Indian Ocean

The CLIVAR Initial Implementation Plan in 1998 noted that the data base for Indian Ocean variability and change is so poor that knowledge of decadal, oceanic variability in the Indian Ocean was almost unknown. However, analysis of historical SST and SLP data sets (Allan et al., 1995) provided evidence of interdecadal variation in the strength and location of the southern Indian Ocean anticyclone. With improved processing of the historical SST data (Rayner et al., 2003; Smith and Reynolds, 2004; NOAA/CIRES Climate Diagnostics Center, 2003) and oceanographic data (Levitus et al., 2005), improved climate modelling and continuation of the WOCE repeat-hydrography sections, there has recently been progress in identifying regional decadal variability and trends. The Indian Ocean is recognized now as a centre of decadal to multi-decadal SST variation and change that has an impact on regional and global climate.

Human-induced climate change is debatably the most important environmental issue facing humanity in the twenty-first century, and is certainly linked to the great societal issues of our time—availability of water and energy. Increasingly, in the years and decades to come, governments and industries will have to make policies and management decisions that guide the societal response to future climate. Research on climate change has to provide a solid scientific foundation for these policies and decisions. A major uncertainty emerging at this time is the linkage between natural climate variability (monsoons, MISO, ENSO, IOZDM) and climate change as a result of fossil-fuel burning. It is now widely recognized that future climate change may express itself as changes in the physics of the natural modes of variability due to changes in the background state on which the natural variations develop. The change in background state in turn changes the frequency and intensity of extreme events. Perhaps more than any other reason, sustained ocean observations are needed to understand the linkages between climate variability and change, to model them appropriately and to produce reliable predictions of future climate for policy and management purposes.

Much of what is known at the present time about decadal to multi-decadal variation and change in the ocean comes from the SST records, which have been much better monitored, in the twentieth century, than any other oceanographic property. The tropical Indian Ocean and the subtropics off western Australia have warmed over this period, and the rate of warming has accelerated substantially during the last 30 years (Fig. 10, page 65). There is growing evidence that these changes play a key role in shaping important features of twentieth-century climate variability and change that have had huge impacts, from the drying trend of the African Sahel (Giannini et al., 2003) to the Pacific decadal variability (Deser et al., 2004) to the North Atlantic Oscillation (Hoerling et al., 2004).

Within the Indian Ocean region, the monsoon circulation has steadily weakened over the last 50 years (Sperber et al., 2000) and seems to be related to the Indian Ocean warming and the reduction in land–sea contrast in temperature. Also, the MISO/MJO have been more active in the last 20 years (Slingo et al., 1999), consistent with the tropical warming. Both the weakened monsoon circulation and the more active intraseasonal variability are supported by the new 40-year ECMWF reanalysis (Slingo, personal communication). Southwestern Australia has experienced a large decrease in rainfall and a 40 per cent reduction in inflow to the Perth water supply during the past 30 years (IOCI, 2001). Although research has not specifically related the reduction to Indian Ocean SST, the impact of the large-scale warming in the eastern Indian Ocean (Fig. 10) has not been tested in models, nor is its relationship to oceanic processes known.

The most important mechanism that generates SST—surface heat flux—is not known over the equivalent time periods of the SST record. Godfrey et al. (1995) noted that the problem of estimating surface fluxes, and their relationship with SST, was quite acute in the Indian Ocean. A decade later, good surface flux data still are lacking, because observing platforms measuring air–sea fluxes are extremely sparse. Although satellites are providing better estimates of surface wind stress and other measurements relevant to heat and freshwater fluxes, in situ data are still lacking to calibrate remote-sensing methods. The challenge for the future is to develop climate-change prediction models that accurately simulate mixed-layer thermodynamics and the advection and mixing that determine SST. Vastly improved, in situ estimates of surface fluxes—heat and fresh water—will be required, as well as sustained measurement of currents, mixed-layer and thermocline processes.

Levitus et al. (2005) have devoted a large effort during the past decade to assembling all the available subsurface ocean data. Their records show that world ocean heat content (0–3000 m depth range) has increased 14.5×10^{22} J between 1955 and 1998 (Fig. 11, page 66). Levitus et al. (2005) point out that the global ocean warming may be underestimated owing to insufficient ocean data in some regions. Their records also show cooling periods interrupting the warming trend, indicative of the interplay between human effects, natural variability and, possibly, volcanic effects.

The increasing heat content in the ocean leads to a measurable sea-level rise. A number of nations in the Indian Ocean region are particularly susceptible to sea-level rise, changing frequency and intensity of cyclones and the associated changes in the impacts of extreme sea-level (storm surge) events. These events will occur more frequently as sea level rises. The more severe cyclonic storms will lead to more frequent generation of devastating surges in sea level along the coastline. The Bay of Bengal is already one of the regions of the world most badly affected by coastal storm surges. The severe damage that has been caused here can be appreciated from the list given by Ali and Chowdhury (1997) of the worst storm surges on record anywhere in the world. Of the 34 disasters they listed in which death toll was 5,000 or more, 26 occurred along the coast of the Indian peninsula. Of these, 15 were along the coast of Bangladesh. An episode in 1970 killed 500,000 in Bangladesh; another in 1991 killed 138,000 in the same country. The loss of life in a 1994 event came down to ~200 because of improved early-warning methods based on better storm-forecast models together with the availability of elevated shelters that allowed people on low land to flee the flood waters. Yet still there is an increasing threat due to sea-level rise and climate change, and an opportunity to take greater protective measures.

Recent reconstructions of global and Indian Ocean sea level (Church et al., 2004, 2005) for the twentieth century were constrained by the very few long records available and their poor spatial distribution. These reconstructions suggested a minimum rate of sea-level rise in the central equatorial Indian Ocean and along the northwest coast of Australia in the latter part of the twentieth century and a maximum in the equatorial eastern Indian Ocean. The changing frequency of extreme sea-level events as a consequence of multi-decadal sea-level rise is an active area of research. The changing risk needs to be documented in particular for the Indian Ocean.

Model projections of sea-level rise for the twenty-first century reveal quite different patterns of regional sea-level rise (Gregory et al., 2001). However, as the different models have quite different regional distributions, sea-level data with adequate datum control are required. A better understanding of the oceanic mechanisms that produce warming of the subsurface and validation of these mechanisms in models are required to move toward consensus on the estimates of regional sea-level rise.

Decadal variability is superimposed on the multi-decadal trends discussed above. Much of the decadal variation in oceanic structure observed to date is often attributed to natural processes, but the relationship of these modes to human-induced climate change is not yet known. Decadal variation in the interannual correlations between the SST-based indices of IOZDM and ENSO has been documented by Clark et al. (2000) who found alternating decades of high (~0.5) and low correlation. Annamalai et al. (2005) investigated the decadal changes of interannual correlation using a suite of ocean-model experiments concentrating on the decadal variation of thermocline depth. They started from the hypothesis that preconditioning of stratification in the eastern equatorial Indian Ocean by the Indonesian Throughflow (an oceanic teleconnection) might play a role related to Pacific decadal variability. They concluded that the reason for IOZDM events to occur independently of ENSO events is that a decadal shallow thermocline in the eastern Indian Ocean favours the development of occasional cold (positive) IOZDM events. From singular value decomposition they showed that the thermocline was particularly shallow during 1952–1971 and 1990–1996, matching periods of strong IOZDM developed independently of ENSO. The shallow thermocline was transmitted from the Pacific through the Indonesian passages. Annamalai et al. (2005) proposed that this was an effect of advection by the Indonesian Throughflow. They also found an atmospheric teleconnection that produced wind over the equatorial Indian Ocean favouring the shallow thermocline in the East. It is, however, fair to state that the role of decadal ocean circulation in climate is still poorly understood and needs to be a focus of future research.

Decadal variation in the atmosphere is much better documented from weather data. Near Australia a change in pressure is associated with the decrease in winter rainfall in near Perth (Allan and Haylock, 1993; Ansell et al., 2000). Changes in the frequency of mid-latitude cyclones over the southern Indian Ocean also seem to be related (Smith et al., 2000) to the rainfall and pressure. Over South Africa and neighbouring countries, a nearly bi-decadal signal in rainfall has long been known (Tyson et al., 1975), but whose driving mechanism is not understood. Reason and Rouault (2002) showed that this rainfall variation was related to changes in atmospheric circulation and SST over the Indian Ocean that modulate southern African rainfall on decadal scales.

The heat content in the upper 300 m of the southern Indian Ocean, according to the compendium by Levitus et al. (2005), has relatively large decadal fluctuations super-imposed on the multi-decadal warming trend. In contrast, the variability in the northern Indian Ocean is much smaller on these time-scales, consistent with earlier analyses of wind and pressure data (Allen et al., 1995). The changes in the atmosphere seem to drive the heat-content variation. The shallow subtropical and equatorial overturning cells (see section 6) are important to the maintenance of the heat content in the upper few hundred metres of the southern and northern Indian Ocean, respectively. An important question is whether the southern overturning cell fluctuates more than the cross-equatorial overturning cell on decadal time-scales and thus contributes to the observed heat-content changes. It is necessary to examine the potential coupling of the tropical southern Indian Ocean with the atmosphere and its impact on decadal and longer-term variability. Based on satellite observations of wind stress and sea level, Lee (2004) suggested a near-decadal decrease of the overturning rate in the subtropical cell by about 7 Sv from 1992 to 2000, which is nearly 70 per cent of its average strength; yet no evidence of significant change in the cross-equatorial overturning cell was found during this period. Sustained in situ and satellite observations are indispensable to the assessment of the potentially important role of the Indian Ocean circulation in the regions' decadal and longer-term climate variability, as discussed further in section 6.

Analysis of historical hydrographic sections illustrates the need for sustained observations and the inadequacy of historical data to document decadal and longer-term trends in Indian Ocean circulation. A careful comparison of sections in the International Indian Ocean Expedition in the early 1960s with a transoceanic section in 1987 identified basin-wide changes in temperature, salinity and oxygen below the mixed layer near 32°S during the 25 years from 1962 to 1987 (Bindoff and McDougall, 2000). The changes are explained by a surface warming in the higher-latitude source regions of Sub-Antarctic Mode Water and by increased precipitation in the source region of Antarctic Intermediate Water. They seem to be consistent with the expected response to human-induced global warming (Banks and Bindoff, 2002). However a new trans-Indian section across 32°S reveals that thermocline mode waters have changed back toward the structure of the 1960's (Bryden et al., 2003). The shift back to the pre-1987 conditions again indicates the interplay between natural variability and global warming. These studies illustrate again the need for sustained in situ and satellite observation of subsurface properties to better understand and model natural decadal variation and its relationship to human-induced climate change.

5. Southern Indian Ocean and climate variability

The eastern and western boundaries of the southern Indian Ocean extend only to relatively low latitudes (about 34.5°S for South Africa and 43°S for Tasmania). This geometry has important consequences for the variability of circulation, since it implies efficient communication with the South Atlantic, South Pacific and Southern Oceans. The southern Indian Ocean is also linked to the tropics, and therefore is influenced by the Indonesian Throughflow, currents generated by the monsoons and the tropical modes of interannual variability (ENSO and IOZDM; see section 3). The unique currents and SST of the southern Indian Ocean in turn are related to climate variability and change over the surrounding continents.

The evolution of SST in the tropical Indian Ocean during an El Niño year (see section 3), is complemented by a tropical to mid-latitude SST anomaly pattern by the end of the year (Cadet, 1985; Allan et al., 1996; Reason et al., 2000). Although it has long been known that there are significant rainfall impacts on East Africa and southern Africa at this time (e.g. Ogallo, 1988; Lindesay, 1988), skill in forecasting the rainfall for individual events is less than in regions closer to the equatorial Pacific, pointing to the potential contribution of other factors, such as variability in the southern Indian Ocean or the South Atlantic Ocean and regional land–sea interactions.

Two unique features of the southern Indian Ocean are the Agulhas Current, the strongest western boundary current in the Southern Hemisphere, and the Leeuwin Current, the only poleward-flowing eastern boundary current in the world ocean. The Agulhas Current transports significant heat southeastwards into the mid-latitudes, some of this is shed into the South Atlantic via Agulhas rings, and some is transported back into the southern Indian Ocean after retroflecting as the Return Current. Heat loss to the atmosphere over the Agulhas retroflection region influences weather and climate in southern African (e.g. Jury et al., 1993; Rouault et al., 2002, 2003; Reason, 1998) and potentially also downstream in southern Australia (Reason, 2001). Heat transported southward by the Leeuwin Current and lost to the atmosphere influences the climate of Western Australia (e.g. Gentilli, 1991; Reason, 1996), creating a region quite different from the west coasts of other continents by its lack of significant coastal upwelling and a hyper-arid coastal desert. While Chile and southern Africa have significant coastal upwelling and coastal desert, Western Australia has a relatively moist climate and no upwelling.

Although early work (Walker, 1990; Jury et al., 1993) showed the importance of SST variation in the Agulhas Current region for South African summer rainfall, recently a larger, dipole-like SST anomaly pattern in the subtropical southern Indian Ocean has been found to be associated with rainfall variation over large parts of southern Africa poleward of about 15°S (Reason, 2001; Behera and Yamagata, 2001). The pattern is oriented SW–NE, with one pole south of Madagascar and the other west of Western Australia. Analysis of these events using a coupled model (Suzuki et al., 2004) showed the importance of wind-driven latent-heat flux anomaly for their generation which tends to be confined to the summer, since that is when the mixed layer is sufficiently shallow. Sometimes a similar dipole-like pattern also exists simultaneously in the South Atlantic (Fauchereau et al., 2003; Hermes and Reason, 2005) pointing to a near-hemispheric atmospheric forcing pattern that involves shifts in the wave-number (3 or 4) circulation pattern in the mid-latitude southern hemisphere and in the Antarctic Oscillation (Fig. 12, page 66). Analysis of an OGCM forced by 1948–1999 NCEP re-analyses (Hermes and Reason, 2005) suggests decadal variations between the patterns in the Atlantic and Indian Oceans (Fig. 13, page 67). When the South Atlantic and southern Indian Ocean events are in phase, there may be a link to the ENSO-induced Pacific South America (PSA) pattern. The SST anomaly appears to arise mainly from surface heat-flux anomaly driven by the atmospheric forcing, with contributions to the western pole also coming from Rossby waves generated by the anomalous winds and from modulations of the South Equatorial Current.

Further modelling work (particularly with coupled models) is needed to fully understand and assess the predictability of the observed rainfall variation over southern Africa and southern Australia. The oceanography of the southern Indian Ocean during phases of ENSO, IOZDM (and their teleconnections to higher latitude), the Antarctic Oscillation (or Sub-Antarctic Annular Mode) and the dipole-like SST patterns in the subtropical southern Indian Ocean needs to be documented by sustained observations. Ultimately the impacts of regional ocean-atmosphere modes on the climate of neighbouring land-masses need to be better understood, and predicted if possible.

The scientific questions and issues that need addressing by the observing system include:

- Determining the relationships between the regional atmospheric forcing (modulations of barometric pressure in the southern Indian Ocean) and the larger-scale modes, such as ENSO and the Antarctic Oscillation
- Does the southern Indian Ocean have a particular tendency (e.g. due to its geometry or the relationship of the hemispheric atmospheric circulation to the land-masses or the unique ocean currents) to evolve dipole-like SST patterns in the subtropics–mid-latitudes?
- What are the feedbacks between these SST patterns and the atmosphere?
- What is the predictability of these SST patterns?
- What is the relationship between the southern Indian dipole-like SST variation and that occurring in the South Atlantic and the South Pacific?

6. Circulation and the Indian Ocean heat budget

Embedded within the system of upper-layer currents, as described in the Background to Part 1 (Fig. 3a,b), is a unique, three-dimensional circulation that plays an important role in the surface-layer heat budget, and consequently a role in the climate system (Schott and McCreary, 2001). The annual average circulation is illustrated in Fig. 14, page 67. The seasonal variation was shown in Fig. 3. Subduction in a large region south of 20°S (Fig. 14, *blue*) feeds water into the Indonesian Throughflow and the South Equatorial Current, primarily within the depth range of the thermocline. Part of this water crosses the equator in boundary currents near East Africa and joins the circulation in the northern Indian Ocean. Thermocline water comes to the surface in as many as seven upwelling zones (Fig. 14, *green*) in the tropical zone. Ekman currents in the surface layer (Fig. 14, *red*) carry water back across the equator to near 20°S.

Upwelling is a cooling process critical to the Indian Ocean climate. By all estimates, the heat flux into the surface layer of the northern Indian Ocean is positive (Godfrey et al., 1995), and the upwelling is required to balance the surface heat budget. Fluctuations in the circulation, particularly at longer time-scales may be expected to affect the heat budget and generate sea-surface temperature and climate anomalies.

The major components of the three-dimensional circulation are the so called Cross-Equatorial Cell (CEC) and the Subtropical Cell (STC) joining the regions of subduction and upwelling (Fig. 14), as well as the Indonesian Throughflow (ITF) from the Pacific to the Indian Ocean.

The cross-equatorial cell

Upwelling occurs predominantly in the northwestern Arabian Sea and, to a lesser degree, around the Indian subcontinent, while subduction occurs predominantly in the southern hemisphere. The result is a shallow Cross-Equatorial Cell (CEC) connecting both regimes (Schott et al., 2002, 2004; Miyama et al., 2003). The northward cross-equatorial flow at thermocline depth occurs as part of the Somali Current, and the southward upper-layer return flow is carried by Ekman transport in the ocean interior directed southward in both hemispheres. In the southern Indian Ocean, strong upwelling at 3–12°S drives a hemispheric Subtropical Cell (STC).

The meridional transports in these cells have marked monsoon variability. During the northern summer, the winds north of the equator have an eastward component and south of it (in the Southeast Trade Wind zone) they have a westward component; that is, they drive southward Ekman transport on both sides of the equator (Fig. 14). However, the equatorial winds are directed primarily northward, *against* the off-equatorial Ekman transport, in both hemispheres, and they are strongest in the western Indian Ocean. Upwelling in the CEC is strongest at this time. During the northern winter, the Southeast Trades are confined to south of 10°S, and there is a belt of eastward wind stress between 10°S and the equator. Ekman divergence and thermocline doming along the northern edge of the Trade Wind zone are largest at this time, causing maximum upwelling in the STC. The mean zonal stresses are westward north of the equator and eastward south of it. Thus, the Ekman transport is directed northward on both sides of the equator: the opposite situation to that in summer. On the equator, the meridional stress is (weakly) southward in winter, again against the Ekman transport.

The annual mean cross-equatorial transport has been estimated as 6±1 Sv ($10^6 m^3 s^{-1}$), using moored-station observations in the Somalia Current, as well as wind stress data (Schott et al., 2002; Miyama et al., 2003). The summer-monsoon pattern of wind dominates the annual mean wind-stress distribution. The zonal component of the wind stress nearly vanishes at the equator during both monsoons, and it is roughly proportional to the distance from the equator on either side. For such a wind field, the geostrophic component vanishes and the Sverdrup transport equals the Ekman transport. Thus, the cross-equatorial Ekman/Sverdrup flow is very shallow, providing the driving force for the Cross-Equatorial Cell (CEC).

Estimates of the rates of subduction and upwelling

Subduction in the Indian Ocean occurs predominantly in the southeastern subtropical Indian Ocean (Fig. 14). Karstensen and Quadfasel (2002) estimated that a total of 36 Sv is subducted into water in the 23–27 kg m^{-3} density range in that region. Of this amount, 12 Sv enters into water at a density less than 25.7 kg m^{-3}, corresponding to an upwelling depth off Somalia of about 150 m. A small amount of subduction, estimated to be only about 0.5 Sv in the annual mean by Karstensen (personal communication, 2003), also happens in the northern Arabian Sea (Fig. 14) during the winter monsoon.

Subducted water masses are carried westward within the South Equatorial Current (SEC). The SEC bifurcates at the Madagascar coast, with part turning southward and the rest eventually joining the East African Coastal Current (EACC) to flow to the equator (Fig. 14), with a fraction also entering the Mozambique Channel. The denser waters do not participate in the CEC. They supply the southward flows west and east of Madagascar and then either leave the basin in the Agulhas Current or recirculate to the subduction region.

Upwelling off Somalia typically occurs in wedge-shaped areas, formed by offshore advection along the northern flanks of two prominent summertime gyres, the "Southern Gyre" at 3–5°N and the "Great Whirl" at 8–10°N (Fig. 3b; Schott and McCreary, 2001). Although upwelling densities as high as σ_θ=26.8 kg m^{-3} have been observed off Somalia, the typical upwelled water is lighter than 25.7 kg m^{-3}. Along the Omani coast, coastal upwelling is associated with filaments that are connected to topographic features and carry the upwelled waters far into the interior Arabian Sea (Fig. 3b).

The various model solutions that were analysed by Miyama et al. (2003) all produce similar values for the net annual mean upwelling in the northern hemisphere of about 6 Sv, a consequence of its being determined by the cross-equatorial Ekman/Sverdrup transport and, hence, solely by the winds. In contrast, the solutions differ markedly in the division of transport between *individual* upwelling regions, indicating that local upwelling is a highly model-dependent process. This concerns particularly the role of open-ocean upwelling in the northern Indian Ocean during the summer monsoon. The northern upwelling has been emphasized in several modelling studies with regard to cyclonic domes east and west of southern India and Sri Lanka (Figs. 3b, 14) (McCreary et al., 1993; Miyama et al., 2003).

Vertical structure at the equator

Model studies with realistic wind fields and high near-surface vertical resolution suggest that there should be a small vertical meridional overturning circulation, or equatorial roll, within a narrow band around the equator, with northward (southward) surface currents on the equator during the summer (winter) monsoon and subsurface counterflow underneath. This counterflow connects the southward (northward) Ekman transports from one side of the equator to the other during the summer (winter) monsoon. The JAMSTEC model streamfunction of Miyama et al. (2003) shows a particularly well developed equatorial roll (Fig. 15, page 68).

Based on shipboard ADCP sections taken during the summer monsoon in the western basin, where strong northward winds exist on the equator, Schott et al. (2002) reported observational evidence for the subsurface flow of the roll at speeds exceeding 20 cm s^{-1}. Evidence for the reverse circulation during the winter monsoon was also found, but the roll was not as well developed at that time.

Whether the rolls cause diapycnal fluxes depends on whether they penetrate the bottom of the mixed layer. In the observations, however, the evidence points to the roll being predominantly restricted to the surface mixed layer or at least the uppermost part of the thermocline, leading Schott et al. (2002) to the conclusion that the equatorial roll has small diapycnal effects and is therefore of little consequence for the meridional heat transport. This conclusion was confirmed by the Miyama et al. (2003) model study.

The subtropical cell

In the southern hemisphere, the annual mean upwelling at the northern rim of the Southeast Trade Wind zone causes a zonally extended open-ocean upwelling regime, the thermocline ridge (Fig. 14), which is apparent in isopycnal doming in the 3°–12°S band. Ekman divergence estimates for the region are almost 10 Sv (Schott et al., 2002), driving a shallow Subtropical Cell (STC), which is supplied by southeastern subduction, by return flow from the higher-latitude western subtropics and by the Indonesian Throughflow (Schott and McCreary, 2001). In addition to doming of the thermocline, enhanced chlorophyll concentrations in the surface layer along the northern edge of the Southeast Trade Wind zone indicate upwelling in the region. Miyama et al. (2003) obtained upwelling transports of 5–8 Sv for the upwelling band northeast of Madagascar (2°–12°S, 50°–90°E), depending on model type. This upwelling regime points toward the existence of a second shallow overturning circulation, the Indian Ocean southern subtropical cell (STC). The subsurface pathways associated with this cell have not been determined from observations, but should connect the possible sources for the thermocline water that supplies the upwelling, including subduction in the southeastern Indian Ocean, recirculation from the western Indian Ocean, and the Indonesian Throughflow.

Interannual variability and climate relevance of the CEC and STC

An interesting mechanism for a role of the CEC in interannual SST and monsoon variability was suggested by Loschnigg and Webster (2000) who proposed that a strengthened monsoon in one season would drain more heat from the Arabian Sea through southward Ekman transport, thus leading to a reduced meridional SST gradient which in turn might cause a weaker monsoon in the following season. Interannual to decadal covariation between variation in the Somali Current transport and shallow cross-equatorial return-flow anomalies in the interior have indeed been found in assimilation-model products, suggesting a role of the CEC in cross-equatorial heat transport variation.

In the southern STC, drastic changes in the upwelling northeast of Madagascar have been documented in association with ENSO and IOZDM (see section 3) particularly in 1994 and 1997 (Feng and Meyers, 2003) leading to extended periods of deep mixed layer and high SST. Close relations exist between these anomalies and cyclogenesis. Remote forcing by Rossby waves from the east plays a role in the generation and modification of the thermocline ridge anomalies, giving rise to the hope that ocean dynamics may provide some degree of predictability for these phenomena (Xie et al., 2002).

For the longer time-scales, Lee (2004) has reported a drastic decrease in zonal wind stress over the southern hemisphere STC during 1992–2000, leading to a decrease in the southward Ekman transport by about 7 Sv, almost 70 per cent of the mean, accompanied by drastic changes in the Sverdrup transport in the subtropics.

Such changes are much stronger than those found in the northern hemisphere and are of significance for the upper-ocean heat balance and preconditioning of IOZDM events.

Another important factor for the southern STC appears to be the variability of the Indonesian Throughflow. Annamali et al. (2005) found in a series of model studies that Pacific Decadal Variability (PDV) can affect Indian Ocean stratification by advecting more or less stratified upper-layer water through the Indonesian passages and thus modulate Indian Ocean thermocline variability (and with it, the STC) at decadal time-scales (see section 4).

Indonesian Throughflow

The Indonesian Throughflow (ITF) is an important source of water mass, heat and salt for the Indian Ocean (Fig. 14). It also is a choke-point in the global distribution of heat and freshwater in the climate system. Consequently it has important impacts on both regional and global climate. A large effort has been devoted to measuring the ITF transport of water mass, heat and salt since its importance was first recognized (Godfrey and Golding, 1981), and oceanographic studies were initiated (Fieux et al., 1994; Molcard et al., 1994; Fieux et al., 2005); but characterizing the ITF was difficult due complex topography and a highly variable current system. The ongoing INSTANT process study (see Part 2, section 15) will directly measure the transport over a three-year period. The challenge for developing the observing system is to find a way to measure the transport by proxy methods calibrated by the INSTANT results, so that the transport can be monitored at time-scales relevant to climate variability and change.

The ITF exists because the southeast trade winds over the Pacific pile up the warm equatorial waters against Indonesia, creating a pressure gradient between the western Pacific boundary and the eastern Indian Ocean. The gradient is maintained between the two sides of the Indonesian archipelago and it drives a flow through numerous passages, between thousands of islands, that connect the Pacific and Indian Oceans and the internal Indonesian seas. As the ITF leaves the Indonesian archipelago, it merges with the Indian Ocean South Equatorial Current, joining the overturning cells discussed earlier. The ITF is known to be highly variable on intraseasonal to decadal time-scales, making it a particularly difficult process to observe.

The warm water piled up against Indonesia is the largest heat reservoir of the global ocean. Consequently the region is often called the “maritime continent”, its role in the global climate system being recognized as a centre of intense atmospheric convection similar to that of the Congo Basin and the Amazon region. Unlike the continents, Indonesia is mostly water and the variable ITF and regional currents affect SST and the overlying convection, with time-scales influenced by oceanic variability. Consequently, its importance in regional and global climate is recognized (e.g. Schott and McCreary, 2001); and it has been the target of intensive observational and modelling research. Some of the detailed results in recent years are summarized below.

The ITF (as recently reviewed by Gordon, 2001) is composed mostly of North Pacific water flowing through Makassar Strait (Gordon and Fine, 1996). A small part enters the Indian Ocean through Lombok Strait while the rest turns eastwards through the Flores and Banda Seas and enters the Indian Ocean around Timor (Fig. 16, page 68). A small amount of deeper water of South Pacific origin flows through the eastern passages, via the Maluku and Halmahera Seas, with dense water overflow at the Lifamatola Passage. From the Banda Sea there are two deep passages to the Indian Ocean with sills at 1200–1300 m: the Ombai Strait and the Timor Passage. The Lombok Strait is ~350 m deep and passes only the upper layer.

Within the Indonesian Seas the ITF water is subject to strong tidal currents and atmospheric conditions which lead to significant modification of its water-mass characteristics as well as of its SST anomalies (Gordon 2001; Field and Gordon, 1992, 1996). The tidal mixing is the mechanism that links the long time-scales of ocean dynamical variation to regional convection over the maritime continent.

The mean transport of ITF is now believed to be about 10 Sv and it has a marked seasonal cycle with a maximum in August–September. These conclusions are based on various data collected before INSTANT, including year-long time-series in Makassar Strait, flow through the passages of the Lesser Sunda Island chain, repeated XBT sections between Java and Australia, direct deep-current measurements and WOCE sections between Australia and Indonesia (e.g. Gordon et al., 1997; Meyers et al., 1995; Molcard et al., 1996; Wijffels et al., 2002; Sprintall et al., 2002). Large-scale section analyses and global inverse studies yield estimates of the ITF transport of 10–15 Sv, depending on the selection of sections used and model constraints applied (McDonald, 1998; Ganachaud et al., 2000; Bryden and Beal, 2001).

In addition to the seasonal cycle, the early measurements show that the time-scales of variability range from intraseasonal to interannual. Pressure gauges, for three years in the Lesser Sunda outflow passages (Hautala et al., 2001), currentmeters, for one year in Lombok Strait, Ombai Strait and the Timor Passage, and tide gauges in Indonesia (Clarke and Liu, 1993, 1994) all show significant energy at the intraseasonal time-scale. Westerly wind bursts, in some cases associated with MJO and MISO, in the equatorial Indian Ocean force downwelling Kelvin waves which are much larger than the annual cycle of ITF transport (Walliser et al., 2003c). The disturbances turn poleward as they reach the Sumatra coast and radiate Rossby waves westward into the Indian Ocean (e.g. Birol and Morrow, 2001). The remotely generated disturbances are associated with strong reversals of the regional coastal currents (e.g. Quadfasel and Cresswell, 1992; Sprintall et al., 2000). The Indonesian region is also a confluence of the Indian and Pacific equatorial and coastal wave guides (Wijffels and Meyers, 2004), giving the region a complicated interannual variability. Rossby waves from the Pacific enter the Indonesian seas north of Papua New Guinea, propagate into the Indian Ocean and ultimately play an important role in the variability of the ITF (Potemra, 1999) and currents along the coast of Australia (Morrow et al., 2003).

Direct measurement during 1997 indicated that ITF varies in strength with the phase of ENSO (Susanto and Gordon, 2004). The ITF transport is thought to be as small as 4 Sv (and larger than 12 Sv) during El Niño (La Niña). The internal energy “heat” transport varies from 0.39 PW during El Niño to 0.63 PW during La Niña (Meyers, 1996; Fieux et al.,1998; Gordon and McClean, 1999; Potemra et al., 2002). More recent studies have shown that ITF variability is influenced by variation in the winds over both the Indian and Pacific Oceans, obscuring a simple relationship to ENSO (Wijffels and Meyers, 2004).

The effects of the ITF on global climate have been studied by contrasting stand-alone ocean and coupled climate with open and closed Indonesian passages between the oceans. The ITF is found to affect the time mean as well as seasonal-to-interannual variation of SST and upper-ocean heat storage, both in the Pacific and the Indian Ocean (Hirst and Godfrey, 1993; Verschell et al., 1995; Murtugudde et al., 1998; Lee et al., 2002; Gordon et al., 2003). The impacts of the ITF on Indo-Pacific circulation and tropical–subtropical exchange in the Pacific Ocean have also been discussed (Lee et al., 2002). Schneider (1998) reported the influence of the ITF on ENSO characteristics in a coupled ocean–atmosphere model. Annamalai et al. (2005) pointed to the role of Pacific Decadal Variability in Indian Ocean stratification and climate and associated it with advection by the ITF.

Numerical models of the archipelago face the problem of a very uneven bathymetry with a multitude of islands and straits. However, as the mean ITF transport is primarily dependent on the large-scale wind-driven transports of currents in the Pacific (Godfrey, 1996; Wajsowicz, 1996), models lead to mean values which fall near the range of those estimated from measurements. The numerous possible paths with different passage depths and bottom mixing effects result in variable residence times, vertical structure and water-mass composition of the outflow. Many open questions need to be answered before realistic numerical models of the ITF will become available (Potemra et al., 2002).

Ongoing research on ITF is focussed in the INSTANT process study (see Part 2). The challenge for developing the observing system is to monitor ITF in the long term and be able to validate the role it plays in models that predict climate variability and change.

Deep Meridional Overturning Cell (MOC)

Deep-ocean circulation is relevant to the very long-term (multidecadal) state of the climate system, particularly to storage of CO_2. The vertical structure of a deep overturning cell in the Indian Ocean was documented during WOCE, but little is known about its change in time.

As has been long known, Antarctic Bottom Water (AABW) and Circumpolar Deep Water (CDW) enter the Indian Ocean in the west off Madagascar and southeastern Africa, and in the east along the Ninety-East Ridge. From an analysis of a hydrographic section along about 32°S, Toole and Warren (1993) concluded that there was a very strong, deep, meridional overturning cell (Fig. 17, page 69), consisting of an inflow of 27±10 Sv below a depth of about 1800 m, and a corresponding outflow above that, augmented by an Indonesian Throughflow of 6.6 Sv. Subsequently, Robbins and Toole (1997) found that this solution would transport too much silica into the northern basin, and arrived at a reduced deep inflow of 12±3 Sv from that same section, which was accomplished through a decrease in the net northward inflow in the eastern basin. Both solutions are, however, based on a large volume transfer from CDW into shallower levels, above neutral density 28.1 kg m^{-3}, corresponding to a depth of about 2800 m.

A renewed analysis of the 32°S section was presented by Bryden and Beal (2001) who applied directly measured western boundary currents from an Agulhas Current moored array, reducing the earlier Agulhas transport estimates of Toole and Warren (1987) from 85 Sv to 70 Sv, with the consequence of a much reduced deep cell which now only transports 10 Sv of CDW into the Indian Ocean; the Indonesian Throughflow is estimated at 12.3 Sv in this analysis.

Evaluation of the deep overturning transport, using box inverse model calculations yielded different results for the magnitude of the overturning and of the deep upwelling. Ganachaud et al. (2000) used sections along 32°S, 20°S, 8°S, the Mozambique Channel, and the Indonesian Throughflow and in both hemispheres of the other oceans. They obtained a much reduced deep inflow of 11±4 Sv (Fig. 17) across all three zonal Indian Ocean sections, with an ITF of 15±5 Sv. By contrast, Sloyan and Rintoul (2001), who used the same 32°S section and an earlier 18°S section in the Indian Ocean, as well as other, partially different, sections in the other two southern oceans, obtained a much larger deep inflow of 23±4 Sv. Their solution included a lower ITF result, of 10±3 Sv. The latest inverse models continue to estimate differences in the strength of deep overturning. Although the models use the same data, the differences can be attributed to differences in the physical formulation of the models, such as how water is transferred between density layers.

Despite their large deep inflow, Sloyan and Rintoul (2001) were able to balance the silica budget because the southward return flow occurs at greater depths than in the Warren and Toole (1993) calculation, as can be seen from a comparison of the transport functions shown in Figure 17 in density classes. The Sloyan and Rintoul (2001) solution has a transport-function profile similar to that of Robbins and Toole (1998), with upwelling to fairly shallow layers. The large discrepancies between both inverse-study results, which lead to correspondingly large differences in the estimated deep-upwelling velocities, have so far not been satisfactorily explained. As an issue in climate-change research, a better understanding of how CO_2 and heat will be transported over several centuries is required.

Two recent studies yield updates on these earlier inverse results. First, Sloyan and McDougall (2005) re-evaluated the Sloyan and Rintoul (2001) solution. Using mean deep currents in the Perth Basin obtained from a year-long deployment of a moored currentmeter array, they estimated the deep inflow into the Perth Basin, below the neutral density surface of 28.1 kg m^{-3} , at between 4.4 and 5.8 Sv, down from the 7±2 Sv of the Sloyan and Rintoul (2001) calculation, but still much larger than the corresponding estimate of 1±8 Sv of Ganachaud et al. (2000). Second, a new global inverse calculation carried out by R. Lumpkin and K. Speer (personal communication, 2005) with somewhat similar assumptions to those of Ganachaud et al. (2000), but using the Bryden and Beal (2001) Agulhas transport estimates as a constraint, yielded again an Indian Ocean overturning rate at the low end compared to existing estimates, of 9.0±2.8 Sv, with an ITF of 12.4±2.1 Sv.

Deep mixing is a critical process in the overturning circulation. The large deep overturning transport shown in Figure 17 requires diapycnal upwelling velocities ranging from 2 to 10×10^{-7} ms^{-1} (Sloyan and McDougall, 2005). Based on an assumed vertical advective–diffusive balance, large basin-wide diffusion rates result, ranging from 4 to 12×10^{-4} m^2s^{-1} for Indian Ocean inverse studies (Wunsch and Ferrari, 2004). These required diffusivities are more than a magnitude larger than the typical diapycnal eddy diffusivity in the abyssal ocean, away from rough topography, which was estimated to be about 1×10^{-5} m^2s^{-1}, from a variety of sources (Munk and Wunsch, 1998).

Although such high mixing coefficients have been shown to occur locally over rough topography, the basin-averaged mixing levels determined from dissipation calculations are so far still significantly below what is required to maintain the upwelling balance. On the other hand, tidal dissipation calculations from T/P altimetry (Egbert and Ray, 2000) found that the area around the Mascarene Ridge and south of Madagascar accounts for more than 10 per cent of the estimated tidal dissipation for the global abyssal ocean, so that a revision of the basin-averaged mixing toward higher values may be forthcoming. Furthermore, the new calculations of the advective–diffusive balance for the weakly stratified southern Perth Basin by Sloyan and McDougall (2005) showed that the diffusive heat fluxes were not anomalous. The high diffusivities of $1.3–1.5\times10^{-3}$ m^2s^{-1} for that region, combined with the low stability of the water over the AABW inflow, yielded a diffusive heat flux of 1.2–1.4 Wm^{-2}, only about half the value determined over the AABW in the Brazil Basin in the Atlantic.

Not much is known from observations about seasonal differences of basin-wide transport. Stramma et al. (2002) and Brandt et al. (2002) analysed the 8°N section across the Arabian Sea for both monsoon seasons and concluded that there was a deep northward flow below 2500 m in both monsoon seasons of about 5 Sv and a reversing shallow overturning cell in the upper 500 m. They explained the overturning variability by the annual cycle of a Rossby wave crossing the Arabian Sea.

Numerical-model solutions (e.g. Lee and Marotzke, 1998 and Stammer et al., 2002) show large MOC reversals between the monsoon seasons (Fig. 18 a,b, page 69). The largest seasonal changes occur near 10°N and 10°S, where the seasonal wind-stress differences are also largest. Lee and Marotzke (1998) carried out an analysis of the processes involved in the seasonal changes and concluded that the largest contribution to the seasonal variability (and, correspondingly, also to the seasonal heat transport cycle) was due to the Ekman component and its compensation by barotropic motion, yielding an apparent seasonal overturning reversal greater than 20 Sv. The seasonal streamfunctions of the ECCO model of Stammer et al. (2002) in Figure 18 give the impression that there is large variability in the strength and structure of the deep overturning circulation. Physically, however, the variability mostly represents an adiabatic sloshing back and forth of water masses, not diabatic flow across isopycnals. Thus, it is mostly indicative of adiabatic changes in heat storage, rather than in cell strength.

7. Biogeochemical cycling in the Indian Ocean

From a biogeochemical perspective, the Indian Ocean is one of the least studied and most poorly understood ocean basins in the world. Although intensive process studies have been carried out in the Arabian Sea in recent years (e.g. the JGOFS process studies in the mid-1990s), integrative analyses of the Bay of Bengal are just beginning to appear (Madhupratap et al., 2003). Most of what we know about the large-scale biogeochemistry of the basin, including storage of carbon generated by human activities and the air–sea exchange of carbon dioxide (CO_2), comes from a relatively small number of hydrographic sections and underway surface observations. Ocean-colour satellites provide the only observations of basin-scale biological variability. Our understanding of the biogeochemical dynamics of the Indian Ocean is so primitive that we lack the ability to predict biogeochemical response on interannual scales to the most energetic phenomena like the El Niño–Southern Oscillation and the Indian Ocean Zonal Dipole Mode (see section 3). On the decadal scale, the biogeochemical response to phenomena such as the multidecadal warming of the Indian Ocean (see section 4), and the impact of feedback mechanisms (Gruber et al., 2003) on the carbon storage and air–sea CO_2 fluxes are poorly known.

The evolution of the storage of human-produced carbon in the ocean is a critical climate-change issue. The ocean is the dominant long-term sink for man-made CO_2, with about 40 per cent of the global ocean inventory of man-made carbon stored in the mid-latitudes of the southern hemisphere (Sabine et al., 2004). The technique used to quantify the man-made CO_2 concentrations needs to distinguish relatively small concentrations of this CO_2 from the large background concentrations of dissolved CO_2. The various methods produce similar man-made CO_2 distributions on a basin-scale, but the details and absolute amounts vary (Coatanoan et al., 2001; Hall et al., 2004). Estimates of the inventory for the Indian Ocean range between 14.3 and 20.5 PgC down to the Antarctic coast (Hall et al., 2004) with a maximum in the 20°S to 50°S latitude band (Fig. 19, page 70). The global inventory for the open-ocean water is about 106 PgC (Sabine et al., 2004).

The ventilation of thermocline waters is a major factor in determining the man-made CO_2 uptake rate and inventory for the ocean (Caldiera and Duffy 2000; Sabine et al., 2004). The large inventory of man-made CO_2 in the mid-latitudes of the southern Indian Ocean (Fig. 19) results from high uptake of human-produced carbon by the surface water of the Southern Ocean, the transport of the water into the region, with the contribution of cooled subtropical water, and the eventual subduction of the water as Mode and Intermediate Waters. The subduction of nutrients in the Mode water is also believed to be important in maintaining long-term biological export production in the tropics and subtropics (Sarmiento et al., 2004). The relevance of subduction in the subtropical region of the eastern Indian Ocean (Karstensen and Quadfasel 2002) and the contribution of Indonesian Throughflow water to the human inventory are currently unknown. The amount of stored human-produced carbon in the northern Indian Ocean is also uncertain. Sabine et al. (2004) calculated a relatively large inventory of 2.9 PgC in the thermocline water between about 300 m and 1500 m depths and concluded that a large component of the inventory in this depth range was from inputs of Persian and Red Sea Intermediate Waters. Other estimates (Coatanoan et al., 2001; Hall et al., 2004) have not found such high concentrations. Repeat hydrographic sections are planned (see implementation section) to determine how the inventory is evolving and to better understand the uptake pathways for the CO_2 and feedback mechanisms that will impact on the future storage.

Improved estimates of air–sea carbon exchange on seasonal to interannual scales are needed to constrain regional and global carbon budgets and to understand the drivers of ocean CO_2 uptake. The first large-scale climatology of net air–sea fluxes of CO_2 (Takahashi et al., 2002) indicates that the Indian Ocean north of 50°S takes up about 0.33 PgC annually, or about 20 percent of the global-ocean CO_2 uptake. This includes the flux driven by increasing atmospheric concentrations of man-made CO_2 and the underlying natural or pre-industrial flux. The 0.33-PgC annual uptake for the whole ocean is the net-balance of 0.52 PgC uptake in subtropical and sub-Antarctic waters south of 14°S, and out gassing of 0.19 PgC in the tropical and northern Indian Ocean.

The net air–sea CO_2 fluxes in the region are largely determined by the variation in the air–sea gradient of CO_2 partial pressure (ΔpCO_2), which is mostly affected by changes in surface pCO_2 values. Large seasonal changes in ΔpCO_2 occur in the southern Indian Ocean and the coastal upwelling regions of the northern Indian Ocean (Fig. 20, page 70). The ΔpCO_2 variation in nutrient-poor subtropical water from 14°S to 40°S is primarily due to seasonal temperature changes with cooling over winter months producing lower pCO_2 and a greater flux into the ocean (Jabaud-Jan et al., 2004; Sabine et al., 2000). South of 40°S, the subtropical water grades into the sub-Antarctic Zone (SAZ) where seasonal changes in stratification and biological production dominate the surface pCO_2 signal (Takahashi et al., 2002). Surface waters north of 14°S are on average a small annual source of CO_2 to the atmosphere. High surface ΔpCO_2 values are found at upwelling sites (Fig. 14) off the coasts of Somalia, the Arabian Peninsula and Sri Lanka during the summer monsoon (Fig. 20). The high ΔpCO_2 values in these locations are averaged over a 4×5-degree grid and the high values are likely to be more localized than is shown in the figure (Sabine et al., 2000). The Bay of Bengal also has locally high pCO_2 values, but this region is strongly influenced by freshwater and nutrient inputs that support biological drawdown of CO_2 and produce regions of uptake, particularly during the winter monsoon (Kumar et al., 1996). Other regions of upwelling along 5°S–10°S and sites off northwestern Australia and Sumatra (Schott et al., 2002) appear to be small seasonal sources of CO_2 to the atmosphere. It is not clear at present if upwelling signals in these regions are poorly characterized, due to a lack of data, or the upwelling has little surface expression. A new effort is needed to better characterize the air–sea flux on a regional scale and to link the fluxes to the biogeochemical variability outlined below.

Compared to the Atlantic and the Pacific, our knowledge of the biogeochemical variability and dynamics that drive the air–sea flux of carbon and determine the biological activity is rudimentary, at best. The equatorial Indian Ocean is distinct from the other ocean basins. The thermocline is deeper in the east, where a "warm pool" is maintained by the semi-annual Wyrtki Jets (see section 2). The structure of the equatorial thermocline (and nutricline) leads to prominent phytoplankton blooms in the west while biological activity in the east is relatively low (Wiggert, personal communication). So in contrast to the Atlantic and the Pacific, equatorial productivity is significantly weaker under typical conditions. However, when the equatorial thermocline slope is reversed during manifestations of the IOZDM, notably enhanced biological activity appears in the eastern equatorial region (Murtugudde et al., 1999). The SeaWiFS-observed biological response to these anomalous conditions suggests that a major restructuring of seasonal biogeochemical variability occurs over the equatorial and northern Indian Ocean. This supposition is borne out by recent results from an interannually forced 3-D biophysical model (Wiggert et al., 2004), though much work remains to be done to fully characterize the IOZDM's impact on basin-wide biogeochemical processes and CO_2 exchange. In the southern tropical Indian Ocean, it has been demonstrated that satellite-observed surface-chlorophyll-*a* variation is affected by westward propagating Rossby waves (Cipollini et al., 2001; Kawamiya and Oschlies 2001). Southeast of South Africa, a linkage between eastward propagating atmospheric dust and offshore carbon-sink regions between 30ºS and 50ºS has been suggested (Piketh et al., 2000), while further south, in situ iron-enrichment studies in the Southern Polar Frontal Zone have revealed pervasive iron limitation (Gervais et al., 2002). However, the temporal and spatial extent of iron limitation throughout the Indian Ocean remains poorly understood.

Similarly, biogeochemical modelling studies to date have focussed largely on the Arabian Sea (McCreary et al., 1996; Ryabchenko et al., 1998; Hood et al., 2003). While these studies have given rise to important new insights into the factors that control biogeochemical variability in the Arabian Sea (see Wiggert et al., [2005] for a recent review), they have provided little information about the basin-scale biogeochemical response to seasonal, interannual or long-term forcing variability and none addressed carbon cycling and CO_2 exchange. One recent coupled-model study has suggested that, among other things, there is pronounced basin-wide spatio-temporal variation in bio-available iron concentrations, with surface waters in the western equatorial and southern tropical regions always tending to iron limitation, while the Bay of Bengal and the eastern Arabian Sea remain largely iron replete (Fig. 21, page 71, from Wiggert et al., personal communication). This study also describes the typical biogeochemical variability associated with the eastward propagation of the semiannual Wyrtki Jet, but does not address the biogeochemical response to the IOZDM. As indicated above, further basin-wide coupled-model studies of this sort will be needed in order to characterize and understand the interannual and interdecadal biogeochemical and carbon flux variation in the Indian Ocean, and the mechanisms and limitations that control them.

Recent observational evidence suggests that the Arabian Sea and the Bay of Bengal have remarkably different biogeochemical responses to fairly similar atmospheric forcing (Kumar et al., 1999; Kumar et al., 2004a; Kumar et al., 2004b). The differences between the two regions' biogeochemical regimes can be largely attributed to the large freshwater injections, and accompanying sediment loads, that seasonally occur in the Bay of Bengal (Ramaswamy and Nair 1994; Gomes et al., 2000). The biogeochemical environment is also complicated by strong intraseasonal variations in chlorophyll in response to MJO/MISO (Walliser et al., 2005b). The notorious difficulties in constraining biogeochemical models will only be magnified in these pelagic systems which are so egregiously undersampled. The scantiness of the synoptic and in situ data used in such studies only highlights the need for a more sustained observational effort in the Indian Ocean. These two regions will also provide excellent natural laboratories in which carbon export can be understood in response to climate variability and climate change in two contrasting semi-enclosed basins. This is consistent with WCRP/CLIVAR's overall goal of developing an Earth System approach to climate variability and prediction.

A biogeochemical sampling and modelling effort is needed to complement the physical observing system developed in this report. The specific response of the Indian Ocean to climate change may make an important contribution to the global biogeochemical variability. Thus, in addition to the need for detailed measurements of the physical structure of the ocean and for complementary physical modelling studies, it is important to obtain measurements related to ocean biogeochemical cycles and to carry out complementary biogeochemical modelling studies. The implementation of a moored ocean-observing system array in the tropical Indian Ocean, the establishment of ship-of-opportunity measurements, and planned repeat ocean sections would provide a useful framework for future biogeochemical observations and modelling.

8. Operational oceanography

Operational oceanography (according to the EuroGOOS website) can be defined as the systematic and long-term routine measurements of the seas, oceans and atmosphere, and their rapid interpretation and dissemination. Operational oceanography proceeds by the rapid transmission of observational data to data-assimilation centres. There, powerful computers using numerical forecasting models process the data. Important products derived from operational oceanography are:

- nowcasts providing a description of the present state of the sea, including surface and subsurface temperature, salinity, currents and eventually biogeochemical properties, on a daily-to-weekly time-scale
- accurate forecasts of the future condition of the sea as far ahead as possible
- hindcasts that combine long-term data sets with ocean models to provide data for the description of past states, and time-series showing trends and changes.

Operational oceanography in the Indian Ocean at the present time is heavily dependent on satellite observations of the surface, including sea level, SST, ocean colour and wind to represent the daily structure of eddies and fronts. The satellite data are recognized as the essential backbone of the observing system here. However, in situ data will be required to characterize the complex vertical temperature and salinity structure. Continuous time-series are required to resolve the fast-varying upper-ocean currents and structure. The shallow, fast variability of the Indian Ocean—from tropical cyclones to intraseasonal time-scales—has been identified as the most important societal issue to be addressed by the Indian Ocean observing system (according to a workshop of regional scientists http://www.marine.csiro.au/conf/socio/socio.html). The societal impacts ranged across many issues, including storm surge, safety at sea, maritime forecasts, transport, fisheries, environmental management, industrial operations and more. It is recognized that the shallow, fast variability will have to be observed by an integrated observing system that makes use of many different types of observation and that data assimilation and ocean state estimation will be the cross-linking theme that integrates the various data types, and yields the products for many different applications.

The benefits of operational oceanography are likely to be substantial in this region which is home to more than one billion people. The oceanic Kelvin waves generated by intraseasonal variation in the wind field (see section 2) reflects at the coast of Sumatra sending strong currents into the populated coastal regions of Indonesia and Bay of Bengal. The communities of these regions are very dependent on fishing and transport by sea. They are likely to be among the first beneficiaries of operational oceanography. Also, ocean-state estimation will provide an improved initial condition for seasonal and intraseasonal climate prediction, providing benefit to all the peoples of the Indian Ocean rim.

The Global Ocean Data Assimilation Experiment (GODAE) is in the later stages of providing a practical demonstration of the feasibility and usefulness of operational oceanography. The data, modelling and assimilation systems under development now are providing infrastructure and products serving a broad range of users and applications. The targeted applications include open-ocean forecasts, coastal and regional prediction, climate assessment and prediction, and reanalysis of historical data for scientific and other purposes.

The Indian Ocean observing system will provide key data for input into the assimilation systems of GODAE-type models (provided real time delivery is assured). Products in the Indian Ocean are presently based largely on satellite altimetry data and Argo floats which do not resolve the fast variability characteristic of this region (Schiller et al., 2004; Vecchi and Harrison, 2005). Enhanced in situ time-series from moorings are expected to greatly improve the accuracy and utility of these products.

The in situ observations on their own also provide metrics for the purpose of validating operational products. GODAE has defined a need for four classes of metrics:

- Class1—intercomparison of the 4-dimensional temperature, salinity and current fields generated by different models
- Class 2—direct comparison of model results and high-quality observations, such as time-series from moorings or well observed transects
- Class 3—comparison of integral properties, such as Indonesian Throughflow transport
- Class 4—statistical analysis of initial conditions and forecasts.

The Indian Ocean observing system planned in Part 2 will provide data for Class 2 and Class 3 metrics. Specifically, the mooring array will provide accurate equatorial currents and well resolved equatorial and extra-equatorial temperature and salinity time-series for Class 2 metrics. The equatorial currents cannot be measured by the geostrophic method, and small errors in the measurement of temperature and salinity can generate large errors in equatorial current in the data-assimilation models. The metrics from the mooring array will monitor the accuracy of re-analysis currents in this region. Likewise, the mooring array will provide meteorological measurements in a region where lack of information on the wind and flux fields limits reanalysis efforts. Additional Class 2 metrics will come from zonal and meridional structure of temperature and salinity derived directly from the mooring array and the XBT lines. Class 3 metrics will include the Indonesian Throughflow, total transport of the major currents as measured by high-density XBT lines and by the slope of the thermocline along the equator, a sensitive test of the wind field driving the assimilation models.

While the emphasis of operational oceanography is on products that resolve the small spatial and temporal scales of ocean-variability, another important application of the observing system is initialization of seasonal climate prediction models. The observing system has been designed to provide crucial information on upper ocean-structure and currents that will improve representation of intraseasonal variations below the sea surface. Also, the meteorological measurements will be extremely valuable. At present there are no such measurements in the Indian Ocean and this lack of information prevents accurate initial condition determination of weather and climate forecasts.

A number of operational products for the Indian Ocean are already available. Basin-scale currents and structure at 1° resolution (Fig. 22) are available at the UK Met Office (Bell et al., 2004) http://www.met-office.gov.uk/research/ncof/foam/browser.html. The US Naval Research Laboratory provides a number of products with resolution ranging from 1° to 1/32° (Fig. 23) http://www7320.nrlssc.navy.mil/global_nlom32/indian.html 1/32.

Part 2 Implementation of an Integrated Observing System

The following sections present plans for the implementation of a moored buoy array, Argo floats, XBT lines, surface drifters, sea-level stations and biogeochemical measurements. In addition to the technical details for each type of observation, the Indian Ocean Panel has made a number of key recommendations, which are underlined in the text and summarized at the end of the Executive Summary. The recommendations are intended to provide guidelines to the research bodies and operational agencies that ultimately will implement the observing system. Specific recommendations are directed to the Argo Programme. The agencies that have contributed to implementation of moorings so far are: Department of Ocean Development (India), Japan Marine Science and Technology Agency, and National Oceanic and Atmospheric Administration (USA). High level representatives of these agencies and potential, future contributing agencies reviewed the implementation plan at the Third Annual Meeting of the Indian Ocean GOOS Regional Alliance and agreed in principle to adopt the recommendations.

A complete and successful implementation of the observing system will require a high level of cooperation among a number of national agencies from around the world. The highest level goal of this plan is to provide a framework within which the agencies can work together toward the common goal.

9. The basin-scale mooring array

With regard to the research issues discussed in Part 1, the basin-scale array is essential for understanding the role of the ocean in the MISO and MJO phenomena and identifying their limits of predictability. The intense, long-lasting weather conditions associated with MISO and MJO interact strongly with the temperature and salinity structure of the ocean mixed layer, but the physics is not yet understood nor is it fully built into coupled models. The role of surface currents in the evolution of intraseasonal variation is not known. The air–sea heat and freshwater fluxes are poorly known. The array will provide vital information on these processes. It is also needed to understand the mixed-layer dynamics and the role of currents in interannual variation, such as IOZDM. Operational ocean-state estimation, such as the production of daily maps of currents and thermal structure for marine industry and defence, is not possible without the array. While this report is primarily concerned with oceanographic measurements, the meteorological measurements (particularly at moorings) will be extremely valuable to data assimilation issues concerned with weather forecasting and reanalysis efforts. At present there are no such measurements in the Indian Ocean and this lack of information prevents accurate initial condition determination of weather forecasts and limits reanalysis efforts.

Background

Deep ocean mooring programmes have been successfully developed in the tropical Pacific and Atlantic Oceans during TOGA and CLIVAR in support of seasonal-to-interannual and longer time-scale climate studies. The TAO/TRITON array in the Pacific, maintained by the USA (NOAA) and Japan (JAMSTEC), is the most mature of these arrays, dating back to the early 1980s. TAO/TRITON provides data in real-time for improved description, understanding, and prediction of ENSO warm and cold events (El Niño and La Niña) which represent the strongest year-to-year climate fluctuation on the planet.

The PIRATA array, supported by the USA (NOAA), France (IRD) and Brazil (DHN and INPE) is a more recent development, dating from the mid-1990s. The goal of PIRATA is to provide real-time data for improved description, understanding and prediction of tropical Atlantic climate variation related to Atlantic warm events and development of the inter-hemispheric SST gradients. These variations significantly affect rainfall in northeast Brazil and western Africa, and SST variations in the northern tropical Atlantic have an impact on the formation and the intensity of hurricanes.

Deep-ocean mooring programmes have also been implemented in the Indian Ocean in recent years as part of WOCE, JGOFS, CLIVAR, and of various national programmes. Examples include: moorings to study air–sea interaction in the Arabian Sea (Rudnick et al., 1997); moorings near the equator in the Central Indian Basin (Reppin et al., 1999) and in the Madagascar Channel to study ocean circulation; JAMSTEC moorings in the eastern equatorial Indian Ocean to study variation associated with the eastern pole of the Indian Ocean Zonal Dipole Mode (Masumoto et al., 2002, 2005); and moorings deployed in the Arabian Sea and Bay of Bengal as part of the Indian National Data Buoy Programme (Premkumar et al., 2000). Also, under the Ocean Observing System (OOS) Programme of India's Department of Ocean Development, an array of three subsurface moorings was progressively implemented along the equator (at 93°E, 83°E and 76°E) beginning in February 2000 (Murty et al., 2000; Sengupta et al., 2004). However, these efforts have been either short-lived or regional in scope. What is required to address systematically the scientific issues outlined earlier in the present plan, however, is a coordinated, multi-national, basin-scale sustained mooring array as exists in the Pacific and Atlantic Oceans. The Indian Ocean array is particularly important to understand and model basin-scale air–sea interaction at the intraseasonal time-scale, a key to useful prediction of seasonal monsoon impacts, as discussed in Part 1.

The following sections outline a strategy to implement a moored-buoy array for the Indian Ocean in support of climate studies. The focus is on the open ocean north of 30°S. Special efforts will be needed to address western and eastern boundary currents, the Indonesian Throughflow and coastal dynamics.

Principles

The moored-buoy array will be designed and implemented according to the following principles:

- Design of the array will build on the experience gained in developing previous and ongoing moored-buoy programmes in the Indian Ocean and on the experience gained during TOGA and CLIVAR in designing and implementing TAO/TRITON and PIRATA;
- The array will focus on those aspects of ocean dynamics, ocean–atmosphere interaction and climate variation that require high temporal resolution, multi-variate time-series, which moored measurements are uniquely suited to address;
- The array will complement other components (satellite, in situ) of the Indian Ocean Observing System;
- The array will be long-term and sustained;
- Implementation will rely on contributions by several agencies;
- Real-time data transmission will be a high priority in order to support operational climate analyses and forecasts;
- Data will be freely and openly exchanged via the GTS and the WWW.

Array Design

a. Variables

Moorings are capable of measuring some of the key variables needed to describe, understand and predict large-scale ocean dynamics, ocean–atmosphere interactions and the Indian Ocean's role in global and regional climate. Marine meteorological variables include those needed to characterize fluxes of momentum, heat and fresh water across the air–sea interface, namely, surface winds, SST, air temperature, relative humidity, downward short- and long-wave radiation, barometric pressure and precipitation. Physical oceanographic variables include upper-ocean temperature, salinity and horizontal currents. From these basic variables, derived quantities, such as latent and sensible heat, net surface radiation, penetrative shortwave radiation, mixed-layer depth, ocean density, and dynamic height (the baroclinic component of sea level) can be computed. The array design will focus on these marine meteorological and physical oceanographic variables, though not all moorings will measure all variables, as described below. The moorings can also support sensors to measure CO_2 concentrations in air and sea water, nutrients, bio-optical properties and ocean acoustics. Coordination with those programmes involved in ocean biogeochemistry (e.g. the International Ocean Carbon Coordination Project and the Integrated Marine Biogeochemistry and Ecosystem Research Programme) will be a priority in order to maximize the interdisciplinary potential of the array.

b. Geographic coverage and horizontal resolution

The array is intended to cover the major regions of ocean–atmosphere interaction in the tropical Indian Ocean, namely: the Arabian Sea, the Bay of Bengal, the equatorial waveguide, where wind-forced intraseasonal and semi-annual current variation is prominent; the eastern and western index regions of the Indian Ocean SST dipole mode (10°N–10°S, 50°–70°E; 0°–10°S, 90°–110°E); the thermocline ridge between 5°S and 12°S, where wind-induced upwelling and Rossby waves in the thermocline affect SST; and the southwestern tropical Indian Ocean, where ocean dynamics and air–sea interaction affect cyclone formation (Xie et al., 2002). The bulk of the array is concentrated in the area 15°N–16°S, 55°E–90°E (Fig. 22, page 71). The Pacific TAO/TRITON array is intended to be marginally coherent in latitude and longitude for defining the evolution of large-scale intraseasonal-to-interannual wind, SST, upper-ocean temperature and salinity variation. Scale analyses and various dynamical modelling studies (e.g. Han et al., 1999; Murtugudde et al., 2000; Feng and Meyers, 2003; Delcroix et al., 2004) argue for mooring elements nominally separated by 10°–15° in longitude. Latitudinally, resolution should be finest near the equator, so as to capture variability tightly confined to the equator. Elements at 0, 1.5°N and 1.5°S are required to capture meridional structures associated with prominent second-vertical-mode variations (e.g. Han et al., 1999). Coarser resolution, with elements at 4°N, 8°N, 12°N and 4°S, 8°S, 12°S, 16°S should be sufficient to capture large-scale patterns in upper-ocean thermal structure and salinity. All of the moorings will include sensors for ocean temperature and salinity profiles, wind speed and direction, air temperature, relative humidity and precipitation.

The flux reference moorings located in several key climatologically distinct regions, including:

- Bay of Bengal
- Arabian Sea
- Equator
- Region of subduction in the southeastern basin (see the CEC in section 6) (25°S, 97°E)
- The ridge in the thermocline near 8°S, where ocean dynamics affect SST
- Region of cyclone formation east of Madagascar
- Region of maximum rainfall south of the equator near 95°E.

These moorings will carry the full suite of sensors in Table 9.1 needed to determine surface turbulent and radiative fluxes, and storage of momentum, heat and fresh water in the mixed layer. As such, they will be more heavily instrumented than standard moorings, with additional surface meteorological sensors and oceanographic measurements with a higher vertical resolution, in the surface mixed layer. The flux reference sites will contribute to the International OceanSITES programme

(http://www.oceansites.org/OceanSITES/index.html).

Direct velocity measurements are required along the equator where geostrophy breaks down and where currents in the upper ocean undergo rapid time-variations. Subsurface ADCP moorings along the equator will address this requirement. These moorings should be juxtaposed with nearby surface moorings to provide information on local forcing and upper-ocean temperature and salinity variation. An additional subsurface ADCP mooring off the coast of Java is intended to monitor the Java upwelling zone where the SST dipole first develops. The Java mooring is located near the frequently repeated XBT line IX1, used in the past to study the Indonesian Throughflow, upwelling and SST at the eastern pole of the dipole.

The array, when fully implemented, will consist of 40 surface moorings, 8 of which will be enhanced for surface-flux and related oceanographic measurements. In addition, the array will include 5 ADCP mooring sites along the equator and the coast of Java. This configuration is deemed the minimal array necessary to meet CLIVAR and GOOS objectives for sustained moored measurements.

Recommendation 9.1 The agencies contributing to the array agree to the mooring plan and, recognizing that implementation depends on national resources, agree to negotiate changes to the plan with the other agencies doing mooring work.

c. Vertical sampling

Standard (i.e. non-flux reference site) moorings need to resolve the basic vertical structure of temperature in the mixed layer and thermocline down to at least 500 m. Thus, a vertical array of temperature sensors is needed at 1 m 10 m, 20 m, 40 m, 60 m, 80 m, 100 m, 120 m, 140 m, 200 m, 300 m and 500 m depths. The sensor at 1 m will provide a measure of bulk SST. This vertical array is similar to that of moorings deployed in the tropical Atlantic and eastern Pacific, but with a sensor at 10 m depth to provide additional resolution in the mixed layer.

The T/S relation is relatively stable in the thermocline, so priority is given to salinity measurements in the mixed layer. A minimal array of conductivity (salinity) sensors at 1 m, 10 m, 20 m, 40 m and 100 m depths is therefore required. This array is similar to that in the tropical Atlantic, except for an additional sensor at 10 m depth to improve resolution in the mixed layer. All other surface moorings should measure velocity at least at one depth in the surface mixed layer, preferably at 10 m depth. Flux reference sites will require higher-vertical-resolution temperature, salinity and velocity measurements in the mixed layer. Nominal measurement depths should be accurate to within ±1 per cent.

Velocity will be measured from surface moorings at discrete depths as well as from acoustic Doppler current profiler (ADCP) moorings. Upward looking ADCP moorings should be deployed so as to measure velocity variation in the upper 200 m with a vertical resolution of 10 m or higher. Discrete velocity measurements should be made from nearby surface moorings at a minimum of four depths: 10 m, 20 m, 40 m and 100 m. The 10 m and 20 m sensors will measure in the blanking zone where ADCP measurements are contaminated by backscatter from the surface. The 40 m and 100 m measurements will provide ongoing calibration with the overlapping ADCP measurements and a minimal amount of redundant data in the surface layer and thermocline, should the ADCP fail.

d. Temporal sampling

The transmission of data to shore in real-time mode is required for monitoring evolving climatic conditions, oceanic and atmospheric model-data assimilation and analyses, weather, climate and ocean forecasting, and forecast verification. Real-time transmission also allows for accelerated scientific analysis of the observations and provides backup in case moorings are lost. Real-time data should be disseminated as rapidly and as widely possible through the GTS and the WWW.

For studies of variation at intraseasonal to interannual time-scales, the minimum requirement in real-time mode is for daily average data, though for some purposes (e.g. resolution of the diurnal cycle in SST, computation of turbulent surface fluxes using bulk formulae, data for inclusion in numerical weather-prediction models), hourly resolution is optimum. The minimum requirement for delayed-mode data (i.e. after moorings are recovered and data stored in memory is read and fully quality controlled) is hourly resolution. However, for some research purposes (e.g. examining the details of particular short-period events), 10-minute resolution would be optimum.

Sensor accuracy and resolution requirements

To define the range of oceanic and atmospheric phenomena of interest with reasonable confidence, moored-buoy sensors must meet minimum accuracy and resolution requirements. These requirements, based on past experience in the study of large-scale tropical ocean dynamics and air–sea interaction, are listed below and can be met with present-day sensor technology.

Table 9.1. Minimum Requirements for Sensor Accuracy and Resolution

Parameter	Accuracy	Resolution	Range
Ocean Temperature	0.02°C	0.001°C	0-40°C
Salinity	0.02 psu	0.002 psu	0-40 psu
Current Velocity Speed Direction	 5 cm s^{-1} 5	 0.1 cm s^{-1} 0.1°	0-250 cm s^{-1} 0-359°
Pressure	±0.25% full scale	2068 Pa	0-6.89 MPa
Atmosphere Wind direction Wind speed	 5° 0.3 m s^{-1} or 3%	 1.4° 0.2 m s^{-1}	0-359° 0-35 m s^{-1}
Air temperature	0.2°C	0.01°C	0-40°C
Rel humidity	2%	0.4%	0-100%
Precipitation	0.4 mm hr^{-1}	0.2 mm hr^{-1}	0-500 mm hr^{-1}
S/W radiation	± 1%	0.4 W m^{-2}	0-1600 W m^{-2}
L/W radiation [downward]	± 1%	0.1 W m^{-2}	0-500 W m^{-2}
Surf air pressure	0.1 hPa or 0.01%	0.1 hPA	800-1100 hPA

Implementation issues

Ship-time: Ships with specialized equipment, adequate deck space and sufficient capacity to carry several moorings are required for recovery and deployment operations. The amount of ship time per year required to service an array of 40 surface moorings and 5 subsurface ADCP moorings will depend on the specific ships used, their cruising speeds, and ports of call. A rough estimate of the amount of ship time required is about 180 days assuming a one-year buoy-design lifetime and that each mooring site is visited twice per year. The semi-annual servicing schedule is similar to that in the Pacific and allows for routine repairs, lost-sensor replacements, and in situ calibration checks at mid-deployment. It also allows for mooring replacement in the event of mooring failure or loss.

Recommendation 9.2 Recognizing that ship-time is the key resource needed to implement the array, the agencies agree to optimise the use of their vessels to maintain the array when they are available and to proceed to a multi-agency agreement on ship-time as soon as possible.

International coordination: Funding for implementation of the moored-buoy array will come largely through national programmes. However, coordination of national efforts at an international level is essential to optimize the utilization of resources, ensure efficient use of ship time, coordinate deployment schedules and cruises, maintain measurement standards, and promote the free and open exchange of data. Initially the coordination is being achieved through the CLIVAR/GOOS Indian Ocean Panel and the Tropical Moored Buoy Implementation Panel. It is likely that the responsibility for coordination will pass to international bodies such as the Indian Ocean GOOS (IOGOOS) Regional Alliance and the Joint Committee for Oceanography and Marine Meteorology (JCOMM) as maintenance of the array becomes routine and operational.

Schedule: The pace of implementation will depend on the funding of individual national programmes. However, given the endorsement of this mooring programme plan by the international community, a 5-year implementation timetable should be initiated. This schedule would ensure that a significant fraction of the mooring array would be in place to overlap with satellite salinity-measurement missions scheduled for launch in 2007 (SMOS) and 2008 (Aquarius).

Recommendation 9.3 Increase the number of moorings deployed at recommended sites as soon as possible, with a view to full implementation of the array within five years.

Data availability and dissemination: Data collected as part of the Indian Ocean moored-buoy array developed under the auspices of CLIVAR and GOOS will be freely and openly available. To the extent possible, data will be available in real-time via the GTS and in near-real-time via the World Wide Web. Following the example of TAO/TRITON in the Pacific and PIRATA in the Atlantic, a Data Assembly Centre (DAC) will be established to allow for a single point of contact to obtain both real-time data and research-quality data in delayed mode from all contributing nations in a common format. The holdings of this DAC will be available via the Web and may be mirrored in more than one location. The free and open exchange of these data will ensure that they are incorporated into various operational weather, climate and ocean analysis and forecasting efforts as well as being widely available for research purposes.

Vandalism: Fishing-related activities are a major cause of data and equipment loss for TAO/TRITON in the Pacific and PIRATA in the Atlantic. These activities involve vandalism of moored buoys by tropical tuna-fishing fleets and gear conflict between mooring and fishing equipment. Traditionally, the regions hardest hit in Pacific are the far eastern and western margins of the array that are close to land. The upwelling zone in the Gulf of Guinea experiences the greatest losses in the Atlantic. The TAO and TRITON Project Offices have for many years attempted to educate and inform the fishing community about the negative consequences of these losses for research and for weather, climate and ocean-state forecasting. Likewise, engineering design strategies to discourage vandalism and mitigate its effects have been implemented. However, these efforts have met with only limited success. TRITON moorings and moorings of the Indian National Data Buoy Programme in the Indian Ocean have experienced similar problems with fishing vandalism. Planning for the development of a basin-scale Indian Ocean moored array should therefore factor in a percentage of loss in developing equipment inventories and likewise strive for a semi-annual servicing schedule so as to minimize the impact of these losses on data return.

Process-oriented field studies: It is expected that, within the framework of sustained moored-buoy measurements described above, additional moorings will be deployed for short periods of time in certain regions for process-oriented field studies (see section 2.12). The sustained moored array will provide a long-term, large-scale context for these process-oriented studies whereas the latter may provide guidance in terms of improved sampling strategies or new measurement technology. Thus, sustained and process-oriented measurements provide complementary approaches to describing and understanding oceanic and atmospheric variability in the Indian Ocean region.

10. Argo profiling floats

The Argo Programme with vertical temperature/salinity profiles of ~300-km resolution every 10 days is essential for research on the role of ocean circulation in climate variability and change. It provides a means of knowing regional heat and freshwater storage for the longer time-scales; and, combined with other measurements (moorings, XBT lines, satellite altimetry and ship-based hydrography), it provides the means to identify the transport of heat and fresh water by ocean currents. Argo data are also essential for operational oceanography and seasonal prediction. Examples of applications of data from the Argo Programme unique to the Indian Ocean include:

- Improve understanding (and hence determine predictability) of the coupled ocean–atmosphere system.
- Study of the thin, low-salinity surface-layers and barrier-layers (in Bay of Bengal and Indonesian Seas, for example), and how they affect the generation of sea-surface temperature.
- Study of the role of subduction and mode-water formation in meridional circulation variability and their interaction with other modes of Indian Ocean variability.

Background

The Argo Programme is a continuation of the exploratory float measurements made during WOCE. Information on the objectives, present-day status, benefits and technical information on Argo are available on the internet at www.argo.ucsd.edu.

Briefly, ARGO is a pioneering, internationally coordinated effort to establish a global array of temperature and salinity profiles every 10 days at a spatial resolution of 3° latitude/longitude. About 3000 floats are required and the array should be complete by 2007. The data from the Argo Programme are highly complementary with satellite altimetry data (also sampled at 10-day intervals) for research applications and operational oceanography. The array comprises the collective contributions of about 20 countries all of which adhere to the principles of the Argo Programme, most importantly free and rapid availability of data and maintenance of the global array. The present generation of Argo floats can operate for 3–4 years, providing a profile of temperature and salinity to as much as 2000 m depth every 10 days, thus delivering around 100-150 profiles during each float's life. The floats are deployed in the open ocean (deeper than 2000 m) and countries are encouraged to allow the deployment of floats and the free exchange of Argo data from within their EEZ.

<u>Recommendation 10.1</u> As a minimum, the planned 3×3 Argo Programme in the Indian Ocean should be completed and maintained.

With this implementation plan we are beginning to address complementarities with the other elements of the integrated in situ observing system—a basin-scale mooring array, repeated XBT lines, surface drifters and ship-based hydrography. Experimentation is required to determine to what extent the in situ and satellite data can provide a nearly dynamically complete description of the subsurface structure of the Indian Ocean, particularly for the faster time-scales of variation.

The Argo floats transmit the profile data to National Argo Data Centres (DACs) mostly through CLS Service Argos. The DACs make the data available to the global community in the form of TESAC messages on the Global Telecommunication System (GTS), so as to enable their use for operational forecasts within 24 h of collection. The full profiles are also available within 24 h from two Global Data Centres (GDACs) through ftp and http access. Fully quality-controlled data sets are starting to be available from the GDACs. Accuracy of the salinity measurements to ±0.01 may be achievable. The procedures needed to apply this delayed-mode quality control are still being refined, so as to ensure the consistency of data within ocean basins and globally. This application of delayed-mode quality control imposes a minimum delay of 12 months from data collection**.** The Global Data Centres manage the global data sets and distribute the latest and highest-quality data available at any time.

The global Argo data coverage can be extended backwards in time by the use of the more than 11,000 float profiles (mostly temperature only and to around 1000 m depth) from 217 floats deployed from 1995 onwards during WOCE.

(See http://woce.nodc.noaa.gov/wdiu/diu_summaries/woce-ssf/ind.htm)

A map showing the present-day status of the global array of Argo floats is available on the internet at http://w3.jcommops.org/cgi-bin/WebObjects/Argo and recent news of the Programme is at http://www.argo.ucsd.edu/ .

Status of implementation in the Indian Ocean

The Indian Ocean to 40°S requires 450 floats to meet the Argo design of one float per 3°×3° latitude/longitude and will require 125 deployments per year, assuming a float lifetime of 3–4 years. Figure 23, page 72 shows the latest available map of Argo float density at the time of printing. The most recent map is available at http://www.incois.gov.in/Incois/argo/argo_webGIS_intro.jsp#. The float density is not uniform throughout the region. A strategy will need to be developed for deployments in low-density and remote areas. This will be assisted by a continuously updated survey of all the available cruises by research and merchant vessels and advice for participants in the Argo Programme when the vessels are going to cross regions that need deployments (see below). A complete Argo Programme will require deployments from aircraft and chartered vessels for the most remote areas.

Almost 33 per cent of the active floats in the Indian Ocean sector on 31 March 2005 were deployed more than two years ago (Fig. 24, page 72). This highlights the need for a replacement-strategy while the float density is building up. The reliability/performance of floats has greatly increased recently, so that failure rates have been reduced by a factor of at least 2, giving the floats a longer average life-time.

Future deployment opportunities

A regularly updated deployment co-ordination page at http://www.incois.gov.in/Incois/argo/argo_webGIS_intro.jsp# gives the available floats that are ready to be deployed. Considering the future deployment plans known at the time of printing, 90 per cent of the required number will be deployed by the end of 2006. The map of Argo float locations at the time of printing and the future deployments for the year 2006 is shown in Figure 25. The web page also lists opportunities to deploy floats from merchant-ships.

Recommendation 10.2 INCOIS identify and publicize all deployment opportunities, including research-vessel opportunities during routine mooring-maintenance cruises and process studies, as well as contacts to enable air-deployment or deployments from chartered ships in remote regions that are not regularly crossed by commercial shipping.

Table 2: Principal investigators implementing the Argo Programme in the Indian Ocean

Country	**Agency**	**PI**	**e-mail**
Australia	CSIRO Marine Research	Susan Wijffels	susan.wijffels@csiro.au
France	CIRENE	Jerome Vialard	jerome.vialard@lodyc.jussieu.fr
	LEGOS/GRGS	Rosemary Morrow	rosemary.morrow@cnes.fr
Germany	IFM-GEOMAR	Juergen Fischer	jfischer@ifm.uni-kiel.de
India	INCOIS	Ravichandran M	ravi@incois.gov.in
Japan	JAMSTEC	Nobie Shikama	nshikama@jamstec.go.jp
	National Institute of Polar Research	Shuki Ushio	ushio@pmg.nipr.ac.jp
Korea	Korea Ocean R & D Institute (KORDI)	Young-Gyu Park	ypark@kordi.re.kr
U.K.	UK Met Office	Jon Turton	jon.turton@metoffice.com
USA	University of Washington	Stephen Riser	riser@ocean.washington.edu

In addition to the deployments of the countries above, small numbers of floats have been deployed in the Indian Ocean by Canada, Mauritius and China.

Sampling issues unique to the Indian Ocean

The Indian Ocean has a very strong variability at the intraseasonal time-scale, which was not considered in setting up the standard Argo sampling strategy—300×300-km sampling every 10 days. In a preliminary assessment of the Indian Ocean Schiller (2004) performed experiments using an Ocean General Circulation Model (OGCM) forced with three-day-average winds. The standard Argo spatial sampling failed to resolve the strong intraseasonal signals. The results indicated that 10-day sampling with a spatial resolution of 500 km in the zonal, and about 100 km in the meridional, direction was also not adequate, and the improvement was marginal with 5-day sampling. In another experiment with a 1/3° resolution OGCM forced with mean daily winds, and including a representation of tidal and internal wave aliasing (Vecchi and Harrison, 2005), the sub-seasonal Indian Ocean temperature variability recovered from sampling at 5-day intervals with Argo floats does not represent a signficant improvement over 10-day sampling. The improvement from 5-day sampling is marginal because the amplitude of the intraseasonal variability is similar to the sub-daily temperature noise (which was not included in Schiller's study), the spatial scales of the intraseasonal signal are relatively short (particularly in the meridional direction), and much of the Indian Ocean intraseasonal variability occurs on sub-monthly time-scales (e.g. Sengupta and Ravichandran 2001, Harrison and Vecchi 2001, Vecchi and Harrison 2002, Sengupta et al., 2004, Masumoto et al., 2005). Further, practically all of the horizontal displacement of simulated Argo floats occurred while they were at the surface. Halving the sampling interval (from 10 days to 5 days) increases the time floats are at the surface and doubles the rate at which they move away from regions of surface current divergence. This decreases sampling density in regions of upwelling, which are particularly important in ocean-atmosphere interaction.

The OGCM experiments to date on the intraseasonal time-scale show that there is negligible added value to a 5-day sampling strategy, and significant potential disadvantages (e.g. higher costs, shorter lifetimes), thus arguing for the standard 10-day sampling to be maintained for now throughout the basin. Further OGCM experiments are needed to determine how well the standard Argo sampling, combined with the daily averaged data from the basin-scale mooring array, will measure the intraseasonal variability.

The depth of sampling is also a factor in determining the sampling strategy. Riser (personal communication) calculated how the Argo APEX float consumes power with different cycles and varying depths. The results are summarized in terms of the maximum number of profiles attainable, and the float lifetime, assuming that the sole cause of float failure is draining of the batteries.)

(1) 10-day sampling, all profiles to 2000 m; 161 profiles possible (=4.4 yr)
(2) 5-day sampling, all profiles to 2000 m; 175 profiles possible (=2.4 yr)
(3) 10-day sampling, all profiles to 1000 m, every fourth profile to 2000 m; 224 profiles possible (=6.1 yr)
(4) 5-day sampling, all profiles to 1000 m, every fourth profile to 2000 m; 252 profiles possible (=3.4 yr)

These are theoretical maximum lifetimes using manganese–alkali batteries. Actual lifetime is likely to be about 20 per cent less.

Sampling to 1000 m depth is adequate for most of the research issues addressed in Part 1 (except deep overturning), particularly the variability with seasonal to interannual time-scales. It seems attractive to get the longer lifetime with protocol (3).

Recommendation 10.3 Model/observing-system experiments suggest that the sub-seasonal Indian Ocean temperature variability recovered from sampling at 5-day intervals does not represent a significant improvement over 10-day sampling. Continuation of 10-day sampling is recommended until further studies of the integrated sampling strategy.

Recommendation 10.4 Actions should be taken to ensure that Argo floats are continuously maintained in key centres of action: e.g. Java/Sumatra upwelling region, SEC/SECC ridge (western region), Bay of Bengal, where divergent currents tend to disperse them.

Other sensors

Argo's standard sensor package measures temperature, salinity and pressure. Other sensors that have been deployed successfully on profiling floats may be useful. These include sensors for:

dissolved oxygen (SBE and Aanderaa instruments)
particulate organic carbon (POC) (WETLabs transmissometer)
rainfall and wind speed (Experimental sensor UW Applied Physics Laboratory)
near-surface shear (E-M sensor Tom Sanford UW APL)

Implementation of biogeochemical sampling is discussed further in section 14.

Argo deployments and data access

The IOC Assembly XX: Resolution 6 requires that:
"Every concerned coastal state must be informed, in advance, through appropriate channels, of all float deployments which might drift into waters under their jurisdiction, indicating their exact deployment date and location..."

This deployment notification is sent to every National Focal Point (NFP) in the Argo Programme. A joint WMO–IOC Circular Letter has been sent to all Member States calling on them to designate NFPs.

Argo data are freely available without any restriction via the GTS of WMO and data centres of the Argo Programme. The data of all the floats deployed in the Indian Ocean are received by the respective national data centre (DAC) within 12 h of data acquisition. After the real-time QC scrutiny, these data are sent to two Global Data Assembly Centres (GDACs), one in the USA and the other in France. These are mirrored every 24 h, to ensure that the holdings are identical.

Users can obtain Argo profile, trajectory and technical data from either GDAC (http://www.ifremer.fr/coriolis/cdc/argo.htm or http://www.usgodae.org/argo/argo.html) in ASCII or NetCDF format.

At present approximately 25 per cent of all Argo data have been subjected to delayed-mode quality control (DMQC) by PIs and regional experts. A meeting to finalize agreed DMQC procedures was held in April 2005. The method of DMQC implies a minimum delay of 12 months in data availability from the GDACs.

11. Expendable bathythermograph (XBT)

XBT lines combined with Argo floats are effective in cutting the upper ocean up into regions where the net transport in or out, the interior heat and freshwater storage and the surface fluxes can be monitored, providing a method for understanding the role of ocean dynamics in climate variations. They also are effective for monitoring specific ocean structures that affect climate, such as the upwelling zones of Java, Somalia, the Lakshadweep Dome and the thermocline ridge near 10°S.

Background

The XBT network in the Indian Ocean was originally established as individual research projects under TOGA (1985–1994) and WOCE (1990–1997). The network is now largely operated by national agencies and is coordinated by the Ship of Opportunity Implementation Panel (SOOPIP) (http://www.ifremer.fr/ird/soopip/) under the Joint Committee for Oceanography and Marine Meteorology (JCOMM) (http://ioc.unesco.org/goos/jcomm.htm). The Upper Ocean Thermal (UOT) Expert Panel reviewed XBT sampling in 1999, with a view to the time when the Argo Programme will be fully implemented. The Panel's report recommended a shift from so called "broadcast sampling" (which is similar to Argo sampling) to "line sampling", focussing the XBTs on ships that travel over nearly the same route on each voyage and that enclose ocean regions and/or transect important phenomenological features of ocean structure. Indian Ocean line sampling is defined in two modes—high-density (HDX) mode (quarterly sections with 10–50 km between drops) and frequently repeated (FRX) mode (18 sections per year with 100–150 km between drops). The sampling modes are adjusted to ensure adequate resolution of boundary currents, fronts and rapid temporal variation, particularly at the intraseasonal time-scale. Details of the UOT recommendations are available on the internet from the SOOPIP page and are published in *Observing the Oceans in the 21st Century*, edited by C. Koblinsky and N. Smith. The recommended lines are shown in Figure 26, page 73.

Status

JCOMM maintains an excellent system for tracking the Ship-of-Opportunity (SOOP) XBT Programme (Etienne Charpentier, personal communication) at the following website: http://w4.jcommops.org/cgi-bin/WebObjects/JCOMMOPS.woa.

The XBT's submitted to JCOMM/OPS in January–June 2004 are shown in Figure 27, page 73. The sampling patter has not changed substantially since 2004. About 3000 drops are made in the Indian Ocean each year. Clearly the XBT network has been only partially implemented. In the following section we set priorities for completing it.

Recommendation 11.1 Implement the full XBT network in accordance with the guidelines given below.

Priorities for XBT implementation

The scientific justification and the logistical feasibility of the XBT lines recommended by the 1999 review for the Indian Ocean, and their potential impact, were evaluated by the Indian Ocean Panel. A set of "high-priority" XBT lines was identified using the following criteria: high-priority lines were those deemed to have significant scientific justification, to complement the other components of the proposed Indian Ocean Observing System, and a significant logistical feasibility of either maintaining a currently occupied line or restoring a previously occupied line. The Panel recognized the importance of maintaining long historical records. The high-priority lines were determined to be IX01, IX08, IX09N/IX10E, IX12, IX15/IX21, IX22 and PX02. These and the other UOT lines are discussed individually below.

IX01 was determined to be essential in monitoring the upwelling zone off the coast of Java/Sumatra, a key region for the zonal dipole mode, and in monitoring the transport of mass, fresh water and heat away from the Indonesian Throughflow region. Intraseasonal variation is very energetic in this region, largely due to remote wind forcing and reflected equatorial waves. It was suggested that IX01 be occupied weekly (in FRX mode) to minimally resolve the short time-scales, with a drop every 100 km. An extra drop each time the ship crosses the 200m depth contour approaching the continental shelf is essential. High-resolution (HDX) sampling is recommended on at least four of the IX01 sections. The basin-scale array of surface moorings was not recommended to be extended to this region because of the risk of damage by fishing, and only a subsurface ADCP is planned to be located here. Also, Argo floats are expected to move out of this region due to divergent currents. Thus the rapid XBT sampling complements the mooring and Argo arrays by providing temperature profiles in a mode that can be sustained. An experimental project to develop "glider-float" technology to monitor this region at least between Christmas Island and Sunda Strait is desirable.

Recommendation 11.2 Increase sampling on IX01 to weekly sections to better resolve intraseasonal variability, including four high-density sections per year to measure Indonesian Throughflow; increase the number of thermosalinograph sections.

IX08 monitors the western edge of the SECC thermocline ridge, also a key region for the zonal dipole mode. It can describe the zonal current structure in the western part of the Indian Ocean and could be used to constrain estimates of the mass flow into the western boundary current region. IX08 and IX01 give complementary transects on either side of the basin. The intraseasonal variability is also strong here. IX08 should be occupied 18 times per year with a drop at least every 100 km.

IOC and WMO through JCOMM sponsored an international workshop to organize implementation of the high-priority western Indian Ocean XBT lines in October 2005. The workshop was unique in that it brought together researchers, operators, shipping managers and customs officials. The outcomes were: improved protocols for shipping XBT's across national boundaries (which in the past was an impediment in the Indian Ocean region), identification of ships for presently unoccupied lines, a USA-India effort to re-occupy IX08 (not occupied since 2003), identification of a need for capacity building in the region and consensus to work toward full implementation of the XBT network. It was not clear if there will be sufficient resources to occupy IX08 18 times per year.

Recommendation 11.3 Restore frequently repeated sampling on IX08 to observe the thermocline ridge near 10°S and interactions with the atmosphere, as well as the inflow to the western boundary-current system

IX09N/IX10E together act to help constrain the total freshwater, heat and mass transport into the Bay of Bengal and Arabian Sea. The line also covers the Lakshadweep Dome in the thermocline, an oceanic feature that may be related to the onset of the monsoon rains on the west coast of India. The line has been maintained consistently since the late 1980s. Eighteen sections per year with a drop at least every 100 km is appropriate.

IX12 samples the SECC thermocline ridge in the central Indian Ocean, and has been occupied consistently since 1986. Eighteen sections per year with a drop at least every 130 km is recommended, so that there will be a drop approximately at each degree of latitude.

IX15/IX21 together closes the southern limit of the subtropical Indian Ocean. Scripps Institution of Oceanography and CSIRO operated the line in HDX mode until recently, but had to stop due to a change in merchant ship routing. A search is currently underway for a new ship. This line has to be sampled in HDX mode to produce results on transport into/out of the basin. Recognizing the difficulty of maintaining a ship on this line, continual contact with the port authorities in Perth, Mauritius and South Africa should be maintained so that opportunities to for quarterly sampling will not be missed. In late 2005 it seemed that regular shipping might be re-established on this line.

IX22 and PX02 are the only available means of sustained monitoring of subsurface temperature in the Banda and Flores Seas at this time. Very large interannual vertical displacement of the thermocline develops in this region and affects SST, due to energetic mixing associated with tides. The zone of deep convection in the atmosphere over Indonesia is one of the main sources of energy for the global atmospheric circulation. Until Argo floats can be deployed in this region, maintenance of IX22 and PX02 in FRX mode (18 times per year, 100 km spacing) is highly recommended. IX22 should extend at least to 2°N and PX02 from shelf to shelf so that the lines will help constrain estimates of Indonesian Throughflow. A drop is required every time the ship crosses the 200m depth contour.

IX14 is recognized as being feasible and potentially useful. It provides a transect from shelf to shelf across the southern Bay of Bengal. The data are useful for thermal mapping and estimates of transport into/out of the northern Bay of Bengal. Much of the line is within an Exclusive Economic Zone and consequently data are not sent in near-real-time to the Global Telecommunication System (GTS). The data should be made available to the research community and JCOMM/OPS as soon as possible, certainly with a delay not exceeding one year.

IX10 was recommended as an HDX line by the UOT review in 1999. It could provide a transect from the continental shelf at the northern tip of Sumatra to the shelf at the entrance of the Red Sea, thus providing a constraint on the net transport into/out of the Bay of Bengal and Arabian Sea. The Indian Ocean Panel expressed some doubts about the feasibility of heat-transport monitoring on this line because of: the need for salinity profiles in a region with a highly variable T/S relation; the high cost of XCTD; uncertainty that the Argo profiles would fill this need, given their 300-km spacing; non-geostrophic surface currents near the boundaries; and uncertainty about the vertical distribution of Ekman currents. A careful study of the feasibility of heat and freshwater transport monitoring by HDX is recommended. Clearly, testing and eventual implementation of IX10 as an HDX line will require the engagement of a Principal Investigator, firstly to address the issues raised above, and to operate the line.

Recommendation 11.4 Complete observing-system simulation experiments to determine the efficacy of IX10 and/or IX14 in HDX mode to monitor the transport of mass, heat and fresh water into/out of the Arabian Sea and Bay of Bengal

IX06 is not recommended by the Indian Ocean Panel for coverage because maintaining ships for FRX sampling is not logistically feasible, and it does not add substantially to coverage of the southern Indian Ocean obtained with IX08 and IX12. It could however be the only line in the northeastern part of the basin, if an appropriate ship is found.

IX07 is not recommended by the Indian Ocean Panel for coverage because it will not resolve the strong spatial and temporal variability along the western boundary.

Coverage of the high-priority lines will require about 5,000 XBTs, depending on details of how each line is implemented. As mentioned above, JCOMM/OPS accounts for about 3000 drops per year in the Indian Ocean.

Recommendation 11.5 Data from all the XBT lines should be submitted to JCOMM/OPS at least annually

12. Surface drifters

The key application of surface drifter data is reduction of the bias error in satellite SST measurements. Data are also used for documentation of large-scale surface-current patterns and identifying their role in heat transport and the generation of SST patterns and variability; and validation of surface currents in ocean models.

Background

The International Buoy Programme for the Indian Ocean (IBPIO) was formally established at a meeting in La Réunion in 1996. IBPIO is the primary body for coordinating multinational activities to implement drifting buoys. There are presently seven organizations formally participating:

- Australian Bureau of Meteorology (BoM)
- Global Drifter Center of NOAA/AOML (GDC), USA
- Météo-France
- National Institute of Oceanography (CSIR/NIO), India
- National Institute of Ocean Technology (DoD/NIOT), India
- Navoceano, USA
- South African Weather Service (SAWS).

There are two types of surface drifters commonly in use. The older model was developed during the First GARP Global Experiment (1979-1980) and is called a FGGE drifter. A later model was developed during the Tropical Oceans Global Atmosphere Experiment and is called a Surface Velocity Pressure (SVP) drifter. The SVP drifter took advantage of later technology to measure surface barometric pressure (SLP) and achieved better measurement of surface current using the so called "holey sock drogue". The two types of drifter provide the following in situ measurements:

FGGE: position, SST, SLP, 100-m drogue
FGGE-W: position, SST, SLP, 100-m drogue, wind speed and direction
SVP: position, SST, "holey-sock" drogue
SVP-B: position, SST, SLP, "holey-sock" drogue
SVP-BW: position, SST, SLP, "holey-sock" drogue, wind speed and direction.

The number of drifters measuring surface velocity and SST in the Indian Ocean north of 40°S is typically about 60 since 2000, whereas about 160 are required for full coverage at the standard sampling density.

Status

A majority of the buoys in recent years were in the southern Indian Ocean, leaving poor coverage of the tropical zone, particularly north of the equator (Fig. 28, page 73). The most recent map showing coverage is at http://www.meteo.shom.fr/ibpio/traject/traject.htm.

IBPIO's immediate plans may fill some of the major gaps. They plan air deployment of SVP-B drifters by Navoceano in the southern tropical area. Effor to fill the unsampled area north of the equator is strongly recommended. Apparently the lack of sampling in the northern Indian Ocean is partly due to problems of getting drifter shipments through customs in some countries. IOC organized a workshop in October 2005 that may have ameliorated this problem (Thurston, personal communication).

<u>Recommendation 12.1</u> Full implementation of the surface drifter array at least at 5° latitude/longitude spacing for calibration of satellite SST data is strongly recommended, particularly with regard to the area north of the equator where clouds often interfere with passive measurements and where very active re-seeding is required to maintain the array, owing to strong southward surface currents.

Scientific issues

The initial requirement for drifters was set about 20 years ago, calling for a spatial distribution of one drifter in every 5°×5° square. It is based on the sampling density required for reduction in the SST bias error from satellite (AVHRR) observations, which have an error-correlation scale of about 5° globally. Although the goal was to provide a boundary condition for atmospheric models, the drifters met much interest within the oceanographic community and were widely used for surface-current measurements. (An extensive bibliography of studies of the surface currents is available at the website http://www.aoml.noaa.gov/phod/dac/drifter_bibliography.html).

An analysis of the sampling strategy required for the measurement of surface currents has never been carried out. The analysis should be made as a part of the strategy to complete the drifter array in the Indian Ocean.

<u>Recommendation 12.2</u> A study to determine an appropriate sampling strategy for surface currents is needed.

Applications of surface-current drifter results may include validation of the surface currents in ocean models and characterization of the currents to asses their role in determining SST.

The area north of the equator is of particular interest. Surface drifters in this region can characterise the Ekman flow that is supposed to close the cross-equatorial cell (CEC) described in Part 1. At present there is no way to measure this Ekman flow at seasonal to interannual time scales.

The surface currents in equatorial regions in spring and fall (Wyrtki Jets) result in eastward-propagating Kelvin waves which, as trapped coastal waves, produce intraseasonal variation in the ITF transport. This area, in which geostrophy does not apply, needs direct velocity measurements throughout the year for altimetry calibration.

The doming of the thermocline and the related upwelling in the 5°–12°S latitude range play an important role in the air–sea fluxes. The region is one of the poles of IOZDM. The role of surface currents in interannual variability of SST needs more investigation. Advection of water that plays a role in determining the observed SST is likely to be important in many other regions where the surface current encounters strong SST gradients, as in the outflow from the Java/Sumatra upwelling zone and in the southern Indian Ocean. Studies of the role of surface currents in maintaining SST patterns can be based in part on drifter measurements.

An assessment of the measurement of surface salinities with drifters may be useful.

13. Collaboration with the tsunami warning system

The international response to the Asian tsunami disaster in December 2004 is the rapid development of an Indian Ocean Tsunami Warning and Mitigation System (IOTWS). This development will probably be synergic with the development of the Global Climate Observing System, discussed above. If, as suggested by many parties, the warning system addresses the multiple hazards of tsunami, tropical cyclone, storm surge, coastal flooding and possibly other marine hazards, it and the climate observing system will have common needs for data from continuously operating deep-sea moorings and coastal tide gauges.

An important synergy between the climate system and tsunami system concerns the logistics of maintaining deep-sea mooring sites, potentially including shared ship time, protection from vandalism, coordinated development of instrumentation packages, fail–safe communication system and a long-term commitment to maintain the sites. Measurement of sea-bottom pressure (indicating sea level) is an essential part of the tsunami warning system. Some of the required pressure sites are likely to be close to the mooring sites for climate (see section 9). The pressure and climate measurements could be made at the same or nearby sites, allowing shared ship time and other synergic logistics.

Upgrading the Indian Ocean sea-level stations (tide gauges) to ensure real-time data transmission to a tsunami-warning centre is an obvious synergy. Real-time monitoring is the best way to ensure that sea-level stations operate continuously and that instrument failures are quickly identified and repaired. From the climate perspective, this ensures the continuity of record that is missing in much of the historical data base. Real-time monitoring is also needed to support the products of operational oceanography (see section 8) which depend heavily on validation of the near-real-time altimetry data stream. Real-time data transmission will also be a step toward a more open sharing of data in the region (see section 16), even if sharing is initially restricted only to the tsunami warning system.

The capability to maintain a long-term sea-level record with a well established datum is a critical issue for the climate observing system. This is not a critical requirement for tsunami warning. In the rush to set up a tsunami warning system, the need for long-term records has to be addressed and this will require close links between the climate and tsunami communities.

A multi-hazard warning system will be significantly synergic with the climate observing system, in particular with regard to the measurement of surface weather parameters. There is potential for design of an instrumentation package that provides all the required data.

<u>Recommendation 13.1</u> The CLIVAR community needs to establish formal links with the tsunami community to take advantage of possible synergy in developing the Indian Ocean Tsunami Warning and Mitigation System and the Global Climate Observing System.

<u>Recommendation 13.2</u> The IOTWS will be more robust and useful if it addresses the multiple hazards of tsunami, tropical cyclone, storm surge and coastal flooding. This will enhance links to GCOS.

Status of the present real-time and near-real-time sea-level network

According to the University of Hawaii Sea Level Center, the real-time and near-real-time stations that are already operating are summarized in Table 13.1 (Mark Merrifield, personal communication).

Station	*Operator*
Colombo, Sri Lanka.	NARA/UHSLC
Hulhule (Gan), Maldives	UHSLC
Point La Rue, Seychelles	UHSLC
Port Louis, Mauritius	UHSLC
Rodrigues, Mauritius	UHSLC
Diego Garcia	UHSLC
St. Paul	IMG
Crozet	IMG
Kerguelen	IMG
Lamu, Kenya	KMFRI/UHSLC
Mombassa	KMFRI/UHSLC
Zanzibar	DS
Richard's Bay, South Africa	HO
Masira, Oman	CIVAIR/UHSLC
Salalah, Oman	CIVAIR/UHSLC
Tanjong Pagar, Singapore	MPSA
Ko Lak, Thailand	NHD
Ko Taphao Noi, Thailand	NHD
Darwin, Australia	NTC
Cocos Island	NTC

Table 13.1. Real-time and near-real-time tide gauges in the Indian Ocean. NARA: National Aquatic Resources Research and Development Agency. UHSLC: University of Hawaii Sea Level Center. IMG: Institut Mechanique de Grenoble. KMFRI: Kenya Marine and Fisheries Research Institute. DS: Department of Surveys. HO: Hydrographic Office. MPSA: Maritime and Port of Singapore Authority. NHD: Naval Hydrographic Dept. NTC: National Tidal Centre

Access to historical hourly observations is possible for only a few tide gauges in the Indian Ocean region. India has maintained a high-quality network of tide gauges around the subcontinent for decades. Availability of the hourly data from a few test sites is being arranged (Stan Wilson, personal communication). UHSLC (Pat Caldwell) will lead a training workshop on new hourly-data-processing software using the record from the Paradip station. Once it has been digitized (estimated late-2005) and made available for research, additional stations will be processed, with emphasis on the 115-year continuous record from Mumbai needed for the determination of long-term sea-level rise and the three stations (Chennai, Visakhapatnam, and Paradip) in the Bay of Bengal needed for evaluation of storm-surge forecasts.

Upgrading the existing stations to real-time data transmission and enhancing the number of stations around the Indian Ocean in data-sparse areas is a matter of great urgency in all the Indian Ocean countries at this time. Much of the work in South and Southeast Asia is coordinated by UHSLC (Mark Merrifield). Work in Africa is coordinated by IOC-ODINAfrica (Mika Odido). GLOSS (Phil Woodworth) is also coordinating some of the developments. All of these activities will be brought together in the tide gauge working group of IOTWS. The Indian Ocean Panel has established good links to these organizations and individuals to provide advice on the needs of climate research as the sea-level network is developed.

Recommendation 13.3 Enhance the network of sea-level stations to allow real-time transmission of data to a tsunami warning centre, without diminishing the stations' capability to build a long-term record of a well maintained datum for the determination of sea-level rise.

The real-time and near-real-time stations known to us at the present time (June, 2005) are in Figure 29, page 74.

14. Biogeochemical observations

Numerous national and international science plans developed in the past few years have identified the uptake and storage of CO_2 in all ocean basins and the biogeochemical responses to changes in environmental conditions (warming, acidification, circulation changes) as key issues that need to be addressed (e.g. Doney et al., 2004). The issues require quantification of major fluxes and stocks of carbon in the ocean, and a good understanding of the major physical, biological and chemical mechanisms driving biogeochemical cycling. The integration of biogeochemical observations into aspects of the CLIVAR Indian Ocean observational plan will be a major step towards addressing these research issues.

The observational strategy outlined below is coordinated through the International Ocean Carbon Coordination Project (http://ioc.unesco.org/ioccp) and CLIVAR. It includes interactions with GOOS (Global Ocean Observing System), GCOS (Global Climate Observing System), GCP (The Global Carbon Project), SOLAS (Surface Ocean and Lower Atmosphere Study) and IMBER (Integrated Marine Biogeochemistry and Ecosystem Research). The plan will provide a framework for IMBER and SOLAS to develop targeted process studies of biogeochemical cycling and will provide input to modelling studies to link the wide range of spatial and temporal scales sampled.

An Integrated Biogeochemical Observing System

No individual type of measurement or measurement platform can provide all the data that are needed to address the scientific issues. An integrated biogeochemical observing system should include a combination of moored biogeochemical sensors, remote satellite measurements, biogeochemical/hydrographic repeat sections, underway observations and targeted process studies. Some of these measurements are already available (e.g. satellite ocean colour), while others could be integrated into proposed mooring deployments or are being implemented on hydrographic repeat sections as a part of CLIVAR's Indian Ocean observing programme.

The observational strategy needs to be developed in parallel with biogeochemical modelling studies supported through IGBP and national programmes. Modelling studies are needed that focus on a wide range of questions and temporal scales; i.e., from seasonal, to interannual, to climate time-scales. To what degree is the larger Indian Ocean basin iron-limited and how does this limitation vary in space and time? How, for example, does climate variability from intraseasonal to interannual and longer time-scales impact spatio-temporal variability of biogeochemical cycles and particularly carbon uptake and export to the deep ocean? What are the likely impacts of upper-ocean acidification on biogeochemical cycling and ecosystem structure? These are just a few examples of major questions that can be at least partially addressed with basin-scale biogeochemical modelling studies.

The major components of the biogeochemical observing strategy that will benefit from integration with CLIVAR are outlined below.

Repeat hydrographic sections

The JGOFS–WOCE CO_2 survey of the oceans in the 1990s provided the first detailed assessment of the distribution of carbon in the ocean and allowed the amount of man-made CO_2 stored in the ocean to be estimated, based on direct carbon measurements (Sabine et al., 2004). The results provide a baseline for detecting changes in carbon storage and defining the transport of man-made CO_2 and related biogeochemical tracers (oxygen, nutrients, and dissolved organic carbon) into the ocean interior. A series of repeat sections have been planned to define the storage changes in each basin to ±20 per cent per decade (Bender et al., 2002). Repeating these sections on seven- to ten-year time-scales is crucial to defining how the large-scale storage of carbon is evolving and for understanding the long-term biogeochemical responses to climate variability and change for the entire basin.

Sections funded or proposed to date by various countries for the Indian Ocean are shown in Figure 30, page 74. The suite of biogeochemical parameters that should be supported on the sections include carbon, oxygen, nutrients, transient tracers, dissolved organic carbon and nitrogen, phytoplankton pigments, bio-optical measurements to characterize phytoplankton and particulate matter, and where possible bio-limiting trace nutrients like iron.

The zonal sections in the southern Indian Ocean have recently been completed by UK and Spain in 2003 (I5S), and Japan (I3/I4) in 2004. These sections are useful for establishing storage changes in relatively well ventilated waters of the subtropics and allow estimates of the net transport of carbon and other biogeochemical properties (oxygen, alkalinity, nutrients) across the sections. Australia completed the I9S section in 2005 in collaboration with Japan. France maintains annual coarse-resolution sampling for carbon in the southwestern Indian Ocean. The two meridional sections planned by the USA along I07 and I09 are critical for defining the total basin storage and will help resolve the amount of storage associated with the Persian and the Red Sea Intermediate Water. Key areas that would benefit from extra coverage are the central Indian Ocean and the Indonesian Throughflow region, where transport of water from the Pacific Ocean has the potential to alter both the Pacific and Indian inventories.

Recommendation 14.1 Full implementation of repeat hydrographic sections for the Indian Ocean, with carbon, transient tracer and related biogeochemical measurements.

Upper-Ocean Biogeochemical Observing System

Upper-ocean biogeochemical observations are required to quantify air–sea CO_2 fluxes on seasonal to interannual scales and to understand the associated biogeochemical drivers, which include production, ecosystem structure and export fluxes that influence the air–sea exchange. These observations are possible using a variety of platforms including ships of opportunity, research vessels, and moored time-series observations.

The existing upper-ocean coverage of the Indian Ocean is the poorest of all basins. France has a winter–summer sampling programme in the southwestern Indian Ocean, and India has also been active in making time-series and underway measurements in the Arabian Sea and Bay of Bengal. Australia maintains limited observations of nutrients and phytoplankton in the coastal waters off Western Australia. Apart from these and intermittent research cruises, there are no other biogeochemical observing systems in place. The proposed CLIVAR mooring array and XBT and the ARGO measurement programme provide a unique opportunity to develop good coverage over a large part of the basin. The key elements of such an observing system are outlined below.

Time-series moorings

The relatively long-term deployment of sensors that measure a wide variety of biogeochemical parameters on moorings is now feasible (Dickey et al., 2001; Martin et al., 2002). These parameters include pCO_2, chlorophyll concentration (fluorometry), light penetration (PAR sensors), nitrate concentration (UV-based nitrate sensors), particulate carbon concentration (via calibrated transmissometry), oxygen concentration and particulate export flux to the deep ocean (deep-ocean sediment traps). It is also possible to collect and preserve water samples from moored arrays for shore-based analysis. This small suite of biogeochemical parameters can provide a characterization of high- and intermediate-frequency (minutes to months) variability in air–sea CO_2 exchange, "new" nutrient fluxes, primary production response and export flux response associated with measured physical variability, due, for example, to thermocline/nutricline perturbations caused by waves and eddies, or atmospheric iron-deposition events.

The first stage of utilizing the mooring array should be to instrument the surface flux reference sites with CO_2 and other sensors (see Section 9). The surface-flux reference sites include sites in the tropical Indian Ocean, the Arabian Sea, the Bay of Bengal and the southern hemisphere subtropics. The benefit of instrumenting other moorings in the array with biogeochemical sensors also needs to be assessed.

Recommendation 14.2 Instrumentation of all surface-flux reference sites in the Indian Ocean mooring array, with biogeochemical sensors and assessment of the need to instrument other surface moorings in the array.

Ships of opportunity and research vessels

Surface underway biogeochemical observations are used to determine the variability in the air–sea flux of carbon on seasonal to interannual scales (Takahashi et al., 2002). These observations are often made in combination with physical (T, S), dissolved-oxygen, and bio-optical measurements (e.g. fluorescence, PAR, transmissometry). Current targets for air–sea flux observations are to resolve the net CO_2 uptake in each ocean basin to ±0.2 PgC/yr (e.g. Bender et al., 2002). The analysis of the 4×5-degree averaged pCO_2 data from Takahashi et al. (2002) indicates that monthly sampling in most ocean regions on 1000 km length-scales will be sufficient to resolve the annual net flux for most basins to ±0.2 PgC (Bender et al., 2002). The underway observations combined with the measurements on moorings may satisfy the sampling requirements for air–sea CO_2 exchange over much of the Indian Ocean. It is important to recognize that such a coarse underway sampling scheme is unlikely to resolve the all the variation in the concentrations of biological tracers, which can occur on much smaller time- and space-scales.

The instrumentation of ships on XBT lines, ships servicing moorings, and research ships for pCO_2 and other biogeochemical measurements should be a major aim in developing an observing system. Research ships often traverse regions off normal shipping lanes and could help fill gaps, including the coastal margins. Seawater supply lines are needed on the ships, and most of the instrumentation requires someone on board to check its functioning routinely.

Recommendation 14.3 Develop biogeochemical instrumentation on all suitable research ships and XBT lines in the Indian Ocean.

Argo-based measurements

Sensors for the measurement of particulate matter and oxygen are already available for profiling floats and have been used to investigate the rapid ventilation of deep water in the North Atlantic (Koertzinger et al., 2004) and the biogeochemical response to dust inputs in the North Pacific (Bishop et al., 2002). Other sensors, including a variety of bio-optical sensors, are being developed and over the life of CLIVAR are likely to be used routinely in the field. Carbon-dioxide sensors may also be deployed in future, but technical difficulties need to be overcome to allow their use on deep profiling floats. The use of Argo floats for biogeochemical observations would substantially enhance the biogeochemical observing system and help fill gaps in data coverage. The use of additional sensors on profiling floats requires extra power, adds to the cost of the floats and in some instances may require more rapid and shallower profiling than is routine in the ARGO programme. The usefulness and costs of integrating biogeochemical sensors on the ARGO array needs to be assessed.

Recommendation 14.4 Work in collaboration with the biogeochemical community to assess and, where possible, deploy Argo floats with biogeochemical instrumentation.

Ocean-colour measurements

Satellite-based ocean-colour sensors are a component of any biogeochemical observing system. They can provide synoptic, biogeochemical measurements spanning time-scales from days to years and spatial scales from several kilometres to basin-wide, but they can only detect biological signals emanating from the first optical depth of the surface ocean. Therefore, satellite colour measurements are best suited for addressing questions related to biogeochemical phenomena that have relatively large-scale surface manifestations. These include signals related to seasonal changes in biomass and production, biogeochemical impacts of the Indian Ocean Dipole Zonal Mode, and the impact of westward-propagating Rossby waves on primary production and export, to name just a few.

New ocean-colour sensors have recently been launched and still more are planned for the near future by several different space agencies, which can be utilized as part of an integrated Indian Ocean biogeochemical observing system. At present, MODIS (moderate-resolution imaging spectroradiometer, NASA) is the primary ocean-colour sensor available for making routine ocean-surface biogeochemical measurements. This sensor, which flies on board the Aqua (EOS PM) satellite, provides a view of the entire Earth's surface every 1 to 2 days, acquiring optical data in 36 spectral bands ranging in wavelength from 0.4 to 14.4 μm. Among other things, these data can be used to estimate near-surface chlorophyll-*a* ("pigment") concentrations, coloured dissolved organic matter (CDOM) concentrations, and the diffuse attenuation coefficient for photosynthetically active radiation (K_PAR). Additional ocean colour sensors planned for launch over the next decade include GOCI (KARI/KORDI, Korea, 2008), HES-CW (NOAA/NESDIS, USA, 2012), OCM-II (ISRO, India, 2007), S-GLI (JAXA, Japan, 2010) and VIIRS (NASA, USA, 2006/2009). The routine ocean-colour measurements will be available in conjunction with the planned CLIVAR/IGBP-related biogeochemical observations for many years to come. The Ocean Colour Coordination Group (http://www.ioccg.org/) are responsible for this aspect of the observing system.

Conclusion

The need for a biogeochemical observing system was recognized decades after pilot programs for physical measurements started. Momentum is gathering to move forward with sustained biogeochemical measurements and to develop a truly integrated observing system by collaborating with the physical interests.

Recommendation 14.5 Organize a workshop in 2006 to bring together the biogeochemical and physical interests in developing the Indian Ocean observing system.

15. Process studies and regional arrays

The ongoing and planned process studies and regional mooring arrays known at the time of writing are briefly described below. These activities will benefit from the background and longer term observations from the basin-scale observing system that are already implemented. Details and updated information on process studies and regional arrays are available at the CLIVAR website

http://www.clivar.org/organization/indian/IOOS/IOprocess.htm .

The process studies in 2005–2007 can be viewed as pilot studies for a major international study of intraseasonal variation as a basin-scale coupled process, to be carried out towards the end of the decade. The Indian Ocean Panel has also identified a need for future process studies to understand hydrodynamics and the freshwater flux of the Indonesian Throughflow in straits and nearby seas, the heat and freshwater budgets of the Bay of Bengal and the shallow overturning cells (see section 6).

INSTANT (2003–2006)

The goal of INSTANT is to accurately describe the Indonesian Throughflow (ITF) and its transport of mass, heat and fresh water by direct measurement with moorings and pressure gauges for a period of three years in all the deep passages in the Indonesian Archipelago (Fig. 16). INSTANT began in September 2003. Moorings were turned around in mid 2005 and the study will finish at the end of 2006. The countries involved in the programme are: Indonesia [Indroyono Soesilo, Jana T. Anggadiredja, Jan Sopaheluwakan] (BRKP, BPPT and LIPI); United States [Arnold Gordon, Janet Sprintall, Dwi Susanto, Amy Ffield] (LDEO, SIO); Australia [Susan Wijffels] (CSIRO); France [Robert Molcard] (LODYC); and the Netherlands [Hendrik van Aken] (NIOZ).

The INSTANT objectives are:

1. To determine the full-depth velocity and property structure of the Throughflow and its associated heat and freshwater flux.
2. To determine the annual, seasonal and intraseasonal characteristics of the ITF mass transport and fluxes of heat and salt.
3. To investigate the storage and modification of the ITF water within the internal Indonesian seas, from their Pacific source characteristics to the Indonesian Throughflow water exported into the Indian Ocean.
4. To contribute to the design of a cost-effective, long-term monitoring strategy for the ITF.
5. The training of Indonesian scientific and technical personnel in the acquisition, processing and analysis of state-of-the-art oceanographic data.

Goal 4 is particularly important for this Implementation Plan. INSTANT will provide high-resolution measurements of mass, heat and freshwater transport over a period long enough to capture a significant range of climate variation. The data will allow design of a long-term monitoring strategy using proxy methods. The proxy methods can be derived from ongoing sustained observations—e.g. altimeters, sea-level stations, XBT lines, Argo floats—model data-assimilation systems, and/or new deployment of cost-effective instruments, such as acoustic tomography. This strategy will be incorporated into future revisions of the Implementation Plan, after the INSTANT observations and analysis are completed.

The VASCO/CIRENE Experiment

VASCO/CIRENE is a project led by Dr. Jean-Philippe Duvel and Dr. Jerome Vialard (LODYC, France) on air–sea interaction at the intraseasonal time-scale in the western Indian Ocean, focussed on the SECC thermocline ridge in the 55°E–80°E, 10°S–3°S region. The CIRENE campaign aims at understanding ocean–atmosphere coupling at the intraseasonal time-scale, and to explain: (1) the processes governing SST variability; and (2) SST influence on the atmospheric evolution. This campaign led by Dr. Vialard with French RV *Suroit* will take place in early 2007 and will follow the Vasco intensive-observing period aimed at measurement of surface fluxes led by Dr. Duvel. During CIRENE, physical oceanographic, air–sea flux and atmospheric measurements will be made following the tracks of drifters carried by the current. Special care will be taken in measuring the diurnal cycle, since it is believed to play an important role in intraseasonal SST variability. The research vessel in the region may be used as an opportunity to deploy additional moorings for the basin-scale mooring array with a mooring from NOAA. Measurements of nutrients and pigments will also be made, because they can provide useful information on the physical processes at work. These measurements will be combined with those from Vasco and from PROVOR (Argo) floats deployed in 2004 and 2005.

MISMO

MISMO is a project led by Dr. Kunio Yoneyama (JAMSTEC, Japan) on the onset of convection in the Madden–Julian Oscillation (intraseasonal time scale) in the eastern Indian Ocean. The objective is to understand the characteristics of the atmospheric and oceanic variability in the near-equatorial region from 80°E to 100°E, during the season of the onset of convection in the MJO. Details with a map and updated information are available at the above CLIVAR website. The study will be carried out with RV *Mirai* during October 2006 to January 2007. Main measurement systems include:

- Scanning 5.3-GHz Doppler radar (1 volume scan = 7.5 min)
- Radiosonde (atmospheric sounding every three hours)
- SOAR (Shipboard Oceanographic and Atmospheric Radiation): a measurement system developed by BNL for downward radiation as well as general surface meteorological parameters)
- Mooring arrays ATLAS and TRITON
- Subsurface ADCP moorings; if possible, tentative deployment at 1.5°N,80°E, 1.5°S,80°E, 0,85°E, 1.5°N,90°E, and 1.5°S,90°E.

The experiment is coordinated with the existing moorings in the region and will take place within a region that has fair coverage by Argo floats.

LOCO Mozambique Channel

This is a sustained mooring array to measure currents, led by Dr. H. Ridderinkhof (NIOZ). After a trial mooring in 2000–2001, an array of moorings, with currentmeters, ADCPs and T–S sensors, was deployed at the narrowest section of the Mozambique Channel in November 2003. These subsurface moorings are serviced every 1.5 years and the observations will continue till 2008. The observations are being used mainly to quantify the variability of the meridional mass and heat transport, to relate this variability to Indian Ocean (or El Niño) climate modes and to study the relation between this variability and the "downstream" formation of Agulhas Rings.

Bay of Bengal and Arabian Sea Mooring Arrays

The Department of Ocean Development, Government of India, established the National Data Buoy Programme (NDBP) in 1997 at the National Institute of Ocean Technology (NIOT), Chennai, to collect systematic real-time meteorological and oceanographic observations necessary to improve oceanographic services and prediction of short- and long-term climatic changes. The main objective of the programme is as follows:

- To collect real-time met–ocean parameters in Indian seas
- To monitor the marine environment
- To generate and supply value-added products
- To improve the weather and ocean-state prediction
- To validate satellite data

A network of 12 data buoys has been established in the Arabian Sea and in the Bay of Bengal during the implementation period of the programme, from 1997 to 2002; this network has been subsequently increased to 20 and is poised to be maintained and possibly enhanced. The moored buoys are fitted with sensors to measure meteorological, oceanographic and water-quality parameters.

Deep Equatorial Currents

The Department of Ocean Development (DOD), Government of India, initiated the Ocean Observing System (OOS) programme in 1997 for long-term current measurements in the equatorial Indian Ocean. Under the OOS, three locations were selected along the equator for deploying the currentmeter moorings at 93°E, 83°E and 76°E. The responsibility of executing the project was given to the National Institute of Oceanography (NIO), Goa. This project was implemented at NIO in 2002 after developing a suitable mooring design and procuring the currentmeters and relevant hardware. The mooring was designed with six recording currentmeters (RCMs) at 100 m, 300 m, 500 m, 1000 m, 2000 m and 4000 m. The full array at three longitudes was established by March 2002. The array is maintained by regular crusies of ORV Sagar Kanya and will be maintained at least until March 2007.

Xue-Long (Snow-Dragon) Mooring in Java Upwelling Zone

Observation of upper-ocean currents in the Sumatra/Java upwelling region is under consideration through cooperation among: Dr. Weidong Yu, FIO/SOA (China); Dr. Gary Meyers, CSIRO (Australia); Dr. Mike McPhaden, PMEL (USA); and Indonesia. The fieldwork includes deploying a subsurface ADCP mooring and possibly T/S sensors off Java. This deployment will take advantage of the RV *Xue-Long*'s annual crossing of this region. The mooring will be located adjacent to the frequently repeated XBT line IX1 and within a region covered by Argo floats. The number of XBT transects per year will be increased following the priorities for XBT lines given in Section 11. The combined data will shed light on the role of the South Java Current and upwelling near the eastern boundary in the IOZDM and ENSO.

16. Data Management

The agencies contributing to the Indian Ocean observing system are committed to following the CLIVAR data policy (http://www.clivar.org/data/data_policy.htm) and agreed that the policy will guide the Panel's activities. Climate data serve the purpose of operational applications as well as research, placing a high premium on real-time accessibility of data from temperature, salinity and other sustained hydrographic observations for monsoon prediction. Nearly all of the presently available data are collected by national programmes, not CLIVAR per se; consequently, national needs also need to be taken into account. The CLIVAR data policy recognizes the need for real-time data and allows for a range of national perspectives.

The principle of open and timely sharing of data in the Indian Ocean requires special consideration. The Indian Ocean rim is a region with considerable potential for political instability and conflict. It is also a region where full agreement on the modes of access to Exclusive Economic Zones has not been reached. The political realities have historically had an impact on data sharing. Nevertheless, the threat to countries in the region from natural hazards is recognized now, and this may lead to rapid improvement. The global ARGO programme and the TAO/TRITON programme in the Pacific will serve as examples of data management for development of the Indian Ocean observing system. Countries and research groups participating in ARGO and TAO/TRITON have agreed to the open exchange of data. This applies equally to the real-time (GTS and WWW) data stream (over 90 per cent of GTS data are available within 24 h) and to delayed-mode data. It is recommended that these standards of timeliness and openness set by ARGO and TAO/TRITON be applied to all Indian Ocean observations.

Large resources and capabilities are available for Indian Ocean data management at the Indian National Centre for Ocean Information Systems (Hyderabad, India) and the Asia–Pacific Data Research Center (Honolulu, USA). These agencies have agreed to collaborate on regional data management, and will begin by writing a joint implementation plan for Indian Ocean data management.

Recommendation 16.1 INCOIS and APRDC write a joint implementation plan for Indian Ocean data management.

Conclusion

This report has reviewed the various research issues essential to a better understanding of the Indian Ocean and the role it plays in the global climate system. By virtue of its geography, the Indian Ocean is profoundly different in many respects from the Pacific or Atlantic Oceans and this difference has important implications for regional and global climate. It is also a basin that is not well observed by in situ instruments. In designing an integrated observing system for the Indian Ocean, and in particular in identifying the need for a basin-scale mooring array, focus has been placed on the monsoonal oceanic circulation, Indian Ocean zonal dipole mode and the pronounced intraseasonal variability that exists in the tropics, features that have strong climatic impacts on the surrounding land masses. The observing system in the subtropical southern Indian Ocean and higher latitude calls for Argo floats, XBT lines and surface drifters; as well as satellite observations of SST, sea level, ocean colour, wind, humidity and clouds. However, these observations alone may not capture adequately all aspects of subtropical variability, particularly in the boundary currents, major frontal zones and regions where subduction of waters into the thermocline occurs. Therefore an extension of the system, such as additional mooring arrays, may be needed in the future as more is learned from the initial suite of observations.

Appendix 1

References

Alexander M.A, I Blade, M Newman, JR. Lazante, N-C Lau, JD Scott, 2002: The atmospheric bridge: the influence of ENSO teleconnections on air-sea interaction over the global oceans. *J. Clim.* **15**, 2205-2231.

Ali A and MA Chowdhury, 1997: Tropical cyclone risk assessment with special reference to Bangladesh. *Mausam* **48**, 305-322.

Allen RJ, JA Lindsay, CJC Reason, 1995: Multidecadal variability in the climate system over Indian Ocean region during austral summer. *J. Clim.* **8**, 1853-1873.

Allan RD et al., 2001: Is there an Indian Ocean dipole, and is it independent of the El Niño–Southern Oscillation? *CLIVAR Exchanges* 21 **6(3),** 18-22.

Allan RJ, JA Lindesay, DE Parker, 1996: El Niño–Southern Oscillation and Climatic Variability. CSIRO Publishing: Collingwood, Victoria.

Annamalai H, JR Potemra, Murtugudde, JP McCreary, 2005: Effect of preconditioning on the extreme climate events in the tropical Indian Ocean. *J. Clim.* (in press)

Ashok K, Z Guan, T Yamagata, 2001: Impact of the Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophys. Res. Lett.* **28**, 4499-4502.

Banks H and N Bindoff, 2003: Comparison of observed temperature and salinity changes in the Indo-Pacific with results from the coupled climate model HadCM3: processes and mechanisms. *J. Clim.* **16,** 156-166.

Behera SK and T Yamagata, 2001: Subtropical SST dipole events in the southern Indian Ocean. Geophys. Res. Lett. **28**, 327-330.

Bell MJ, MJ Martin, NK Nichols, 2004: Assimilation of data into an ocean model with systematic errors near the equator. *Q. J. R. Met. Soc.* **130**, 873-893.

Bender M, S Doney, RA Feely, I Fung, N Gruber, DE Harrison, R Keeling, JK Moore, J Sarmiento, E Sarachik,, B Stephens, T Takahashi, P Tans, R Wanninkhof, 2002: A large-scale CO2 observing plan: in situ oceans and atmosphere (LSCOP). A contribution of the US Carbon Cycle Science Plan, US Global Change Research Program, Washington DC, 201pp.

Bishop JKB, R Davis, JT Sherma, 2002: Robotic observations of dust storm enhancement of carbon biomass in the North Pacific. *Science* **298**, 817-821.

Bindoff N and T McDougall, 2000: Diagnosing climate change and ocean ventilation using hydrographic data. *J. Phys. Oceanogr.* **30,** 1207-1222.

Birol F, and R Morrow, 2000: Source of baroclinic waves in southeast Indian Ocean, *J. Geophys. Res.* **106**, 9145-9160.

Brandt P, L Stramma, F Schott, J Fischer, M Dengler, D Quadfasel, 2002: Annual Rossby waves in the Arabian Sea from TOPEX/POSEIDON altimeter and in situ data. *Deep-Sea Res.* II **49**, 1197-1210.

Bryden H, E McDonagh, B King, 2003: Changes in ocean water mass properties: oscillations or trends? Science **300,** 2086-2088.

Bryden H and LM Beal, 2001: Role of the Agulhas Current in Indian Ocean circulation and associated heat and freshwater fluxes. *Deep-Sea Res.* I, **48**, 1821-1845.

Cadet DL, 1985: The Southern Oscillation over the Indian Ocean. J.Clim. **5**, 189–212.

Cai W, HH Hendon, G Meyers, 2005: Indian Ocean dipole-like variability in the CSIRO Mark 3 coupled climate model. *J. Clim.* **18**, 1449-1468.

Church JA, NJ White, R Coleman, K Lambeck, JX Mitrovica, 2004: Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. *J. Clim.* **17**, 2609-2625.

Cipollini P, D Cromwell, PG Challenor, S Raffaglio, 2001: Rossby waves detected in global ocean colour data. *Geophys. Res. Lett.* **28**, 323-326.

Clark CO, JE Cole, PJ Webster, 2000: SST and Indian summer rainfall: predictive relationships and their decadal variability. *J. Clim.* **13**, 2503–2519.

Clarke AJ and X Liu, 1993: Observations and dynamics of semi-annual and annual sea levels near the eastern equatorial Indian Ocean boundary. *J. Phys. Oceanogr*. **23**, 386-399.

Clarke AJ and X Liu, 1994: Interannual sea level in the northern and eastern Indian Ocean. J. Phys. Oceanogr. **24**, 1224-1235.

Colberg F, CJC Reason, K Rodgers, 2004: South Atlantic response to ENSO-induced climate variability in an OGCM. *J. Geophys. Res*. **109**, C12015, doi 10.1029/2004JC002301.

Deser C, AS Phillips, JW Hurrell, 2004: Pacific interdecadal climate variability: linkages between the tropics and north Pacific during boreal winter since 1900. *J. Clim*. **17,** 3109-3124.

Dickey T, S Zedler, X Yu, SC Doney, D Frye, H Jannasch, D Manov, D Sigurdson, JD McNeil, L Dobeck, T Gilboy, C Bravo, DA Siegel, N Nelson, 2001: Physical and biogeochemical variability from hours to years at the Bermuda Testbed Mooring site: June 1994-March 1998. *Deep-Sea Res. II* (Topical Studies in Oceanography) **48**, 2105-2140

Doney SC, R Anderson, J Bishop, K Caldeira, C Carlson, M-E Carr, R Feely, M Hood, C Hopkinson, R Jahnke, D Karl, J Kleypas, C Lee, R Letelier, C McClain, C Sabine, J Sarmiento, B Stephens, R Weller, 2004: Ocean Carbon and Climate Change (OCCC): An Implementation Strategy for U. S. Ocean Carbon Cycle Science. UCAR, Boulder, Colo. 108pp.

Du Y, T Qu, G Meyers, Y Masumoto, H Sasaki, 2005: Seasonal heat budget in the mixed layer of the southeastern tropical Indian Ocean in a high-resolution ocean general circulation model. *J. Geophys. Res*. **110**, C04012, doi:10.1029/2004JC002845.

Duvel JP, R Roca and J Vialard, 2004: Ocean mixed layer temperature variations induced by intraseasonal convective perturbations over the IndianOcean. *J. Atmos. Sci*. **61**, 1004-1023.

Egbert GD and RD Ray, 2000: Significant dissipation of tidal energy in the deep ocean inferred from satellite altimeter data. *Nature* **405**, 775-778.

Fauchereau N, S Trzaska, Y Richard, P Roucou, P Camberlin, 2003: Sea-surface temperature co-variability in the southern Atlantic and Indian Oceans and its connections with the atmospheric circulation in the Southern Hemisphere. *Int. J. Climatol*. **23**, 663-677.

Feng M and G Meyers, 2003: Interannual variability in the tropical Indian Ocean—a two-year time scale in the Indian Ocean dipole. *Deep-Sea Res*. II **50**, 2263-2284.

Ffield A. and A Gordon, 1992: Vertical mixing in the Indonesian thermocline. *J. Phys. Oceanogr*. **22**, 184-195.

Ffield A. and A Gordon, 1996: Tidal mixing signatures in the Indonesian Seas. *J. Phys. Oceanogr*. **26**, 1924-1937.

Fieux M, C Andrié, P Delecluse, A Kartavtseff, AG Ilahude, F Mantisi, R Molcard and J Swallow, 1994: Measurements within the Pacific-Indian Oceans throughflow region . *Deep-Sea Res*. **I 41**, 1091-1130.

Fieux M, R Molcard, AG Ilahude, 1996: Geostrophic transport of the Pacific-Indian Oceans Throughflow. *J. Geophys. Res*. **101**, 12421-12432.

Fieux M, R Molcard, R Morrow, A Kartavtseff and AG Ilahude, 2005: Variability of the throughflow at its exit in the Indian Ocean. *Geophys. Res. Lett*. **32**,DOI:10.1029/2005GL022836.

Fischer AS, P Terray, E Guilyardi, S Gualdi, P Delecluse, 2005: Two independent triggers for the Indian Ocean Dipole/Zonal Mode in a coupled GCM, *J. Clim*. (in press).

Fu, X, B Wang, T Li, and J McCreary, 2003: Coupling between northward-propagating boreal summer ISO and Indian Ocean SST: Revealed in an atmosphere-ocean coupled model. *J. Atmos. Sci*. **60**, 1733-1753.

Gadgil S and S Sajani, 1998: Monsoon precipitation in the AMIP runs. *Clim. Dyn*. **14**, 659–689.

Gadgil S, PN Vinayachandran, PA Francis, 2003: Droughts of the summer monsoon: role of clouds over the Indian Ocean. *Curr. Science* **85**, 1713-1719.

Ganachaud A, C Wunsch, J Marotzke, J Toole, 2000: The meridional overturning and large-scale circulation of the Indian Ocean. *J. Geophys. Res*. **105**, 26,117-26,134.

Gentilli J, 1991: Homologous peri-oceanic west coast climates in the southern hemisphere. *J. R. Soc. West. Aust*, **74**, 15-33.

Gervais F, U Riebesell, MY Gorbunov, 2002: Changes in primary productivity and chlorophyll-a in response to iron fertilization in the Southern Polar Frontal Zone. *Limnol. Oceanogr*. **47**, 1324-1335.

Giannini A, R Saravanan, P Chang, 2003: Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science* **302**, 1027-1030.

Goddard L and NE Graham, 1999: The importance of the Indian Ocean for simulating rainfall anomalies over eastern and southern Africa. *J.Geophys. Res*. **104**, 19099-19116.

Godfrey JS and TJ Golding, 1981: The Sverdrup relation in the Indian Ocean, and the effect of Pacific-Indian Ocean throughflow on Indian Ocean circulation and on the East Australian Current. *J. Phys. Oceanogr.* **11,** 771-779.

Godfrey JS, A Alexiou, AG Ilahude, DM Legler, ME Luther, JP McCreary, Jr., GA Meyers, K Mizumo, RR Rao, SR Shetye, JH Toole, S Wacogne, 1995: The Role of the Indian Ocean in the Global Climate System: Recommendations Regarding the Global Ocean Observing System. Report of the Ocean Observing System Development Panel, Texas A&M University, College Station, Tex, USA. 89pp.

Godfrey JS, 1996: The effect of the Indonesian Throughflow on ocean circulation and heat exchange with the atmosphere: a review. *J. Geophys. Res*. **101**, 12217-12,238.

Gordon A and R Fine, 1996: Pathways of water between the Pacific and Indian Oceans in the Indonesian seas. *Nature* **379**, 146-149.

Gomes HR, JI Goes, T Saino, 2000: Influence of physical processes and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal. *Cont. Shelf Res*. **20**, 313-330.

Gordon AL, S Ma, DB Olson, P Hacker, A. Ffield, LD Talley, D Wilson, M Baringer, 1997: Advection and diffusion of Indonesian Throughflow water within the Indian Ocean South Equatorial Current, *Geophys. Res. Lett*, **24**, 2573-2576.

Gordon AL and J McClean,, 1999: Thermohaline stratification of the Indonesian Seas—model and observations, *J. Phys. Oceanogr*. **29**, 198-216.

Gordon AL, 2001: Interocean exchange. In: Ocean Circulation and Climate, G Siedler, J Church and J Gould (eds.), Academic Press, pp303-314.

Gordon AL, RD Susanto, K Vranes, 2003: Cool Indonesian throughflow as a consequence f restricted surface layer flow. *Nature* **425**, 825-828.

Gregory JM, JA Church, GJ Boer, KW Dixon, GM Flato, DR Jackett, JA Lowe, SP O'Farrell, E Roeckner, GL Russell, RJ Stouffer, M Winton, 2001: Comparison of results from several AOGCMs for global and regional sea-level change 1900-2100. *Clim. Dyn*. **18**, 225-240.

Gualdi SE et al., 2003: The interannual variability in the tropical Indian Ocean as simulated by a CGCM. *Clim. Dyn*. **20**, 567-582.

Guan Z and T Yamagata, 2003: The unusual summer of 1994 in East Asia: IOD teleconnections, *Geophys. Res. Lett*. **30**, doi:10.1029/2002GL016831.

Harrison DE and GA Vecchi, 2001: January 1999 Indian Ocean cooling event. *Geophys. Res. Lett*. **28**(19), 3717-3720.

Hastenrath S and P Lamb, 1978: On the dynamics and climatology of surface flow over equatorial oceans. *Tellus* **30**, 436-448.

Hastenrath S and L Greischar, 1993: The monsoonal heat budget of the hydrosphere-atmosphere system in the Indian Ocean sector. *J. Geophys. Res*. **98**, 6869–6881.

Hautala SL, J Sprintall, J Potemra, AG Ilahude, JC Chong, W Pandoe, N Bray, 2001: Velocity structure and transport of the Indonesian Throughflow in the major straits restricting flow into the Indian Ocean. *J. Geophys. Res*. **106**, 19527-19546.

Hendon HH, C Zhang, JD Glick, 1999: Interannual variation of the MJO during austral summer *J. Clim*. **12** , 2538-2550.

Hermes JC and CJC Reason, 2005: Ocean model diagnosis of interannual co-evolving SST variability in the south Indian and South Atlantic Oceans. *J. Clim.* (in press).

Hirst AC and JS Godfrey, 1993: The role of the Indonesian Throughflow in a global ocean GCM. *J. Phys. Oceanogr*. **23**, 1057-1086.

Hoerling M, J Hurrell, T Xu, GT Bates, A Phillips, 2004: Twentieth century North Atlantic climate change. Part II: Understanding the effects of Indian Ocean warming. *Clim. Dyn*. **23**, 391-405.

Hood RR, KE Kohler, JP McCreary, SL Smith, 2003: A four-dimensional validation of a coupled physical-biological model of the Arabian Sea. *Deep-Sea Res*. II **50**, 2917-2945

Hsiung J, RE Newell, T Houghtby, 1989: The annual cycle of oceanic heat storage and oceanic meridional heat transport. *Q. J. R. Meteorol. Soc*. **115**, 1–28.

IOCI, 2001: Second Research Report—Towards understanding climate variability in south western Australia**.** Research reports on the Second Research Phase of the Indian Ocean Climate Initiative. ISBN: 0 7307 6679 9. Department of Environment, Water and Catchment Protection, Perth, Australia. 193pp.

Jury MR, HR Valentine, JRE Lutjeharms, 1993: Influence of the Agulhas Current on summer rainfall along the southeast coast of South Africa. *J. Appl. Meteorol*. **32,** 1282-1287.

Karstensen J and D Quadfasel, 2002: Formation of southern hemisphere thermocline waters: water mass conversion and subduction. *J. Phys. Oceanogr*. **32**(11), 3020–3038.

Kawamiya M and A Oschlies, 2001: Formation of a basin-scale surface chlorophyll pattern by Rossby waves. *Geophys .Res. Lett*. **28**, 4139-4142.

Kemball-Cook, S, B Wang, and XH Fu, 2002: Simulation of the intraseasonal oscillation in the ECHAM-4 model: The impact of coupling with an ocean model. *J. Atmos. Sci*. **59,** 1433-1453

Kessler, W.S., 2001: EOF representations of the Madden-Julian Oscillation and its connection with ENSO. J.Clim. **14**, 3055-3061

Kessler WS, 2005: Intraseasonal variability in the oceans. In: Intraseasonal Variability in the Atmosphere-Ocean Climate System. WKM Lau and DE Waliser (eds.). Praxis Publishing**,** 436pp.

Kiladis GN and KC Mo, 1998: Interannual and intraseasonal variability in the Southern Hemisphere. Chapter 8 in: Meteorology of the Southern Hemisphere. DJ Karoly and DG Vincent (eds.) American Meteorological Society Monographs, Boston, Mass. pp307-336.

Koblinsky C and N Smith, 2001: Observing the Oceans in the 21st Century. ISBN 0642 70618 2 GODAE Project Office, Melbourne. 604pp.

Körtzinger A, J Schimanski, U Send, DWR Wallace, 2004: The ocean takes a deep breath. *Science* **306**, 1337

Kumar A, FL Yang, L Goddard, S Schubert, 2004: Differing trends in tropical surface temperatures and precipitation over land and oceans. *J.Clim.***17**, 653-664.

Kumar KK, KR Kumar, RG Ashrit, NR Deshpande, JW Hansen, 2004: Climate impacts on Indian agriculture. *Int. J. Climatol*. **24**, 1375-1393.

Kumar KK, B Rajagopalan, MA Cane, 1999: On the weakening relationship between the Indian monsoon and ENSO. *Science* **284**, 2156-2159.

Lareef Z, AS Rao, T Yamagata, 2003: Modulation of Sri Lankan Maha rainfall by the Indian Ocean dipole, *Geophys. Res. Lett*. **30**, doi:10.1029/2002GL015639.

Lau, WKM, Waliser, DE, (eds.) 2005: Intraseasonal variability in the Atmosphere-Ocean Climate System. Praxis Publishing Ltd. 474 pp.

Lee T, 2004: Decadal weakening of the shallow overturning circulation of the South Indian Ocean. *Geophys. Res. Lett*. **31**, doi:10.1029/2004GL020884.

Lee, T., and J. Marotzke, 1998: Seasonal cycles of meridional overturning and heat transport of the Indian Ocean. *J. Phys. Oceanogr.* **28**, 932-943.

Lee T, I Fukumori, D Menemenlis, Z Xing, L-L Fu, 2002: Effects of the Indonesian Throughflow on the Pacific and Indian Oceans. *J. Phys. Oceanogr.* **32**, 1404-1429.

Levitus S, J Antonov, T Boyer, 2005: Warming of the world ocean, 1955-2003. *Geophys. Res. Lett.* **32**, L02604, doi: 10.1029/2004GL021592.

Lindesay JA, 1988: South African rainfall, the Southern Oscillation and a Southern Hemisphere semi-annual cycle. *Int. J. Climatol.* **8**, 17-30.

Lo, F and HH Hendon, 2000: Empirical extended-range prediction of the Madden-Julian oscillation. *Mon. Weath. Rev.* **128**, 2528-2543.

Loschnigg J and PJ Webster, 2000: A coupled ocean-atmosphere system of SST modulation for the Indian Ocean. *J. Clim.* **13**, 3342-3360.

McCreary JP, KE Kohler, RR Hood, DB Olson, 1996: A four-component ecosystem model of biological activity in the Arabian Sea. *Progr. Oceanogr*. **37**, 193-240.

McCreary JP Jr., PK Kundu, RL Molinari, 1993: A numerical investigation of dynamics, thermodynamics and mixed-layer processes in the Indian Ocean. *Progr. Oceanogr*. **31**, 181-244.

Madhupratap M, M Gauns, N Ramaiah, KS Prasanna, PM Muraleedharan, SN de Sousa, S Sardessai, U Muraleedharan, 2003: Biogeochemistry of the Bay of Bengal: physical, chemical and primary productivity characteristics of the central and western Bay of Bengal during summer monsoon 2001. *Deep-Sea Res.* II **50**, 881-896.

Martin D, L Atkinson, T Malone, W Nowlin, 2002: Building Consensus: Toward an Integrated and Sustained Ocean Observing System (IOOS). Ocean.US, Arlington, VA. 175pp.

Masumoto Y, VSN Murty, M Jury, MJ McPhaden, P Hacker, J Vialard, R Molcard, G Meyers, 2002: Tropical Indian Ocean mooring array: present status and future plans. In: Report of the First Conference of the Indian Ocean Global Ocean Observing System, November 2002, Grand Baie, Mauritius. IOC Regional Programme Office, Perth, Australia. (on internet at http://www.incois.gov.in/Incois/iogoos/documents.jsp)

Masumoto Y, H Hase, Y Kuroda, H Matsuura, K Takeuchi, 2005: Intraseasonal variability in the upper layer currents observed in the eastern equatorial Indian Ocean. *Geophys. Res. Lett.* **32**, L02607, doi:10.1029/2004GL021896.

Meehl GA, 1997: The south Asian monsoon and the tropospheric biennial oscillation. *J. Clim.* **10**, 1921-1943.

Meyers G, 1996: Variation of Indonesian Throughflow and the El Niño–Southern Oscillation. *J. Geophys. Res.* **101**, 12,255-12,263.

Meyers G, RJ Bailey, AP Worby, 1995: Geostrophic transport of Indonesian Throughflow. *Deep-Sea Res.* I **42**, 1163-1174.

Miyama T, JP McCreary Jr., TG Jensen, J Loschnigg, S Godfrey, A Ishida, 2003: Structure and dynamics of the Indian Ocean cross-equatorial cell. *Deep-Sea Res.* II **50**, 2023–2047.

Mo KC and JN Paegle, 2001: The Pacific-South American modes and their downstream effects. *Int .J. Climatol.* **21,** 1211-1229.

Molcard R, M Fieux, JC Swallow, J Banjarnahor, AG Ilahude, 1994: Low frequency variability of the currents in Indonesian channels (Savu-Roti and Roti- Ashmore reef). *Deep-Sea Res.* **I 41**, 1643-1661.

Molcard R, M Fieux, AG Ilahude, 1996: The Indo-Pacific Throughflow in the Timor Passage, *J. Geophys. Res.* **101**, 12411-12420.

Molcard R, M Fieux, F Syamsudin, 2001: The Throughflow within Ombai Strait, *Deep-Sea Res.* I **48**, 1237-1253.

Morrow R, F Fang, M Fieux, R Molcard, 2003: Anatomy of three warm core Leeuwin Current eddies. *Deep-Sea Res.* II **50**, 2229-2243.

Munk W and C Wunsch, 1998: Abyssal recipes II: energetics of tidal and wind mixing. *Deep-Sea Res.* I **45**, 1977-2010.

Murtugudde R, AJ Busalacchi, J Beauchamp, 1998: Seasonal-to-interannual effects of the Indonesian Throughflow on the tropical Indo-Pacific basin. *J. Geophys. Res.* **103**, 21425-21441.

Murtugudde RG, JP McCreary, AJ Busalacchi, 2000: Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997-1998. *J. Geophys. Res.* **105**, 3295-3306.

Murty VSN, A Suryanarayana, MSS Sarma, V Tilvi, V Fernando, G Nampoothiri, A Sardar, D Gracias, S Khalap, 2002: First results of Indian currentmeter moorings along the equator: vertical structure variability at equator, 93°E during February–December 2000. In Proceedings of Pan-Ocean Remote Sensing Conference (PORSEC), Bali, Indonesia, 3-6 December, 2002, Vol. I, 25-28.

Nicholls N, 1989: Sea surface temperatures and Australian winter rainfall. *J. Clim.* **2**, 965-973.

NOAA/CIRES Climate Diagnostics Center, 2003: Kaplan extended SST. (http://www.cdc.noaa.gov/cdc/data.kaplan_sst.html)

Oberhuber JM, 1988: An atlas based on the COADS data set: the budgets of heat, buoyancy and turbulent kinetic energy at the surface of the global ocean. Rep. 15, 20pp., 160 figures, Max-Planck Institut, Hamburg.

Ogallo LJ, 1988: Relationship between seasonal rainfall in East Afica and Southern Oscillation. *Int. J. Climatol.* **8,** 34-43.

Piketh SJ, PD Tyson, W Steffen, 2000: Aeolian transport from southern Africa and iron fertilization of marine biota in the south Indian Ocean. *S. Afr. J. Sci.* **96**, 244-246.

Potemra JT, 1999: Seasonal variations of upper ocean transports from the Pacific to the Indian Ocean via Indonesian straits. *J. Phys. Oceanogr.* **29**, 2930-2944.

Potemra JT, SL Hautala, J Sprintall, W Pandoe, 2002: Interaction between the Indonesian Seas and the Indian Ocean in observations and numerical models. *J. Phys. Oceanogr.* **32**, 1838-1854.

Premkumar K, M Ravichandran, SR Kalso, D Sengupta, S Gadgil, 2000: First results from a new observational system over the Indian seas. *Curr. Sci.* **78**, 223-330.

Quadfasel D, A Frische, G Cresswell, 1996: The circulation in the source area of the South Equatorial Current in the eastern Indian Ocean. *J. Geophys. Res.* **101**, 12483-12488.

Qu Tangdong and G Meyers, 2005: Seasonal variation of barrier layer in the southeastern tropical Indian Ocean. *J. Geophys. Res.* (in press).

Rajendran K, A Kitoh, O Arakawa, 2004: Monsoon low-frequency intraseasonal oscillation and ocean-atmosphere coupling over the Indian Ocean. *Geophys. Res. Lett.* **31**, L02210 doi:10.1029/2003GL019031.

Rao AS, SK Behera, YMasumoto, T Yamagata, 2002: Interannual variability in the subsurface tropical Indian Ocean, *Deep-Sea Res.* II **49**, 1549-1572.

Ramaswamy V and RR Nair, 1994: Fluxes of material in the Arabian Sea and Bay of Bengal: sediment trap studies. Proc. Ind. Acad. Sci. – Earth Planet. *Sci.* **103**, 189-210.

Rayner NA et al., 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* **108,** 4407.

Reason CJC, RJ Allan, JA Lindesay, TJ Ansell, 2000: ENSO and climatic signals across the Indian Ocean basin in the global context. Part I, Interannual composite patterns. *Int. J. Climatol.* **20**, 1285-1327.

Reason CJC, 1996: Topography and the dynamical response to easterly flow in southern hemisphere subtropical west coast regions. *Meteorol. Atmos. Phys.* **61**, 187-199.

Reason CJC, 1998: Warm and cold events in the southeast Atlantic/southwest Indian Ocean region and potential impacts on circulation and rainfall over southern Africa. *Meteorol. Atmos. Phys.* **69**, 49-65.

Reason CJC, 2001: Subtropical Indian Ocean SST dipole events and southern African rainfall. *Geophys. Res. Lett.* **28**, 225-228.

Reason CJC, 2001: Evidence for the influence of the Agulhas Current on regional atmospheric circulation patterns. *J. Clim.* **14**, 2769-2778.

Reppin J, FA Schott, J Fischer, D Quadfasel, 1999: Equatorial currents and transports in the upper central Indian Ocean: annual cycle and interannual variability. *J. Geophys. Res.* **104**, 15495-15514.

Robbins PE and JM Toole, 1997: The dissolved silica budget as a constraint on the meridional overturning circulation of the Indian Ocean. *Deep-Sea Res.* I **44**, 879-906.

Rouault M, SA White, CJC Reason, JRE Lutjeharms, 2002: Ocean-atmosphere interaction in the Agulhas Current and a South African extreme weather event. *Weather and Forecasting*, **17**, 655-669.

Rouault M, P Florenchie, N Fauchereau, CJC Reason, 2003: South east Atlantic warm events and southern African rainfall. *Geophys. Res. Let.* **30**(5), 8009, doi:10.1029/2002GL014840.

Rudnick DL, RA Weller, CC Eriksen, TD Dickey, J Marra, C Langdon, 1997: Moored instruments weather Arabian Sea monsoons, yield data. EOS, *Trans. Am. Geophys. Union* **78**, 117, 120-121.

Ryabchenko VA, VA Gorchakov, MJR Fasham, 1998: Seasonal dynamics and biological productivity in the Arabian Sea euphotic zone as simulated by a three-dimensional ecosystem model. *Glob. Biogeochem. Cycl.* **12**, 501-530.

Sabine CL, RA Feely, N Gruber, RM Key, K Lee, JL Bullister, R Wanninkhof, CS Wong, DWR Wallace, B Tilbrook, FJ Millero, T-H Peng, A Kozyr, T Ono, AF Rios, 2004: The oceanic sink for anthropogenic CO_2. *Science* **305**, 367-371.

Saji NH, BN Goswami, PN Vinayachandran, T Yamagata, 1999: A dipole mode in the tropical Indian Ocean. *Nature* **401**, 360-363.

Saji NH and T Yamagata, 2003: Possible impacts of Indian Ocean dipole mode events on global climate. *Clim. Res.* **25**, 151-169.

Saji NH, T Ambrizzi, SET Simone, 2005: Indian Ocean Dipole Mode events and austral surface temperature anomalies, *Dyn. Atmos. Ocean.* (in press).

Schiller, A and JS Godfrey, 2001: Indian Ocean intraseasonal variability in an Ocean General Circulation Model. *J. Clim.* **16**, 21–31.

Schiller A, SE Wijffels, GA Meyers, 2004: Design requirements for an Argo float array in the Indian Ocean inferred from observing system simulation experiments. *J. Atmos. Ocean.* Tech. **21**, 1598-1620.

Schott F and JP McCreary, 2001: The monsoon circulation of the Indian Ocean. *Progr. Oceanogr*, **51**, 1-123.

Schott F, M Dengler, R Schoenefeldt, 2002: The shallow thermohaline circulation of the Indian Ocean. *Progr. Oceanogr.* **53**, 57-103.

Schott FA, JP McCreary Jr., G Johnson, 2004: Shallow overturning circulations of the tropical- subtropical oceans. In: C Wang, S-P Xie, JA Carton (eds.) American Geophysical Union: Geophysical Monograph, Washington D.C. pp261-304.

Schneider N, 1998: The Indonesian Throughflow and the global climate system. *J. Clim.* **11**, 676-689.

Sengupta D and M Ravichandran, 2001: Oscillations of Bay of Bengal sea surface temperature during the 1998 summer monsoon. *Geophys. Res. Lett.* **28,** 2033–2036.

Sengupta D, R Senan, VSN Murty, V Fernando, 2004: A biweekly mode in the equatorial Indian Ocean. *J. Geophys. Res.* **109**, C10003, doi:10.1029/2004JC002329.

Shankar, D, PN Vinayachandran, AS Unnikrishnan, et al., 2002: The monsoon currents in the north Indian Ocean. *Progr. Oceanogr.* **52**, 63-120.

Shetye SR and AD Gouveia, 1998: Coastal circulation in the north Indian Ocean. Coastal Segment (14, W-S). In: AR Robinson and KH Brink (eds.), The Sea, Volume 11. pp523-556.

Shinoda T, HH Hendon, MA Alexander, 2004: Surface and subsurface dipole variability in the Indian Ocean and its relation with ENSO. *Deep-Sea Res.* **51**, 619-635.

Slingo, JM, KR Sperber and 22 others, 1996 : Intraseasonal oscillations in 15 atmospheric general circulation models: results from an AMIP Diagnostic Subproject. *Clim. Dyn.* **12**, 325-357.

Slingo JM, K Rowell, KR Sperber, F Nortley, 1999: On the predictability of the interannual behaviour of the Madden-Julian Oscillation and its relationship with El Nino. *Q. J. R. Meteorol.* Soc. **125**, 583-609.

Sloyan BM and SR Rintoul, 2001: The Southern Ocean limb of the global deep overturning circulation. *Progr. Oceanogr.* **31**, 143-173.

Smith TM and RW Reynolds, 2004: Improved extended reconstruction of SST (1854-1997). *J. Clim.* **17**, 2466-2477.

Sperber KR, JM Slingo, H Annamalai, 2000: Predictability and the relationship between sub-seasonal and interannual variability during the Asian summer monsoon. *Q. J. R. Meteorol. Soc.* **126**, 2545-2574.

Sperber KR and TN Palmer, 1996: Interannual tropical rainfall variability in general circulation model simulations associated with the Atmospheric Model Intercomparison Project. *J. Clim.* **9**, 2727–2750.

Sprintall J, AL Gordon, R Murtugudde, RD Susanto, 2000: A semiannual Indian Ocean forced Kelvin wave observed in the Indonesian seas in May 1997. *J. Geophys. Res.* **105**, 17217-17230.

Sprintall J, S Wijffels, T Chereskin, N Bray, 2002: The throughflow in the southeast Indian Ocean. Part 2: Transport and velocity variability. *Deep-Sea Res.* II **49,** 1363-1390.

Stammer D, C Wunsch, R Giering, C Eckert, P Heimbach, J Marotzke, A Adcroft, CN Hill, J Marshall, 2002: Global ocean circulation during 1992-1997, estimated from ocean observations and a general circulation model. *J. Geophys. Res.* **107** (C9), 3118ff.

Stramma L, P Brandt, F Schott, D Quadfasel, J Fischer, 2002: Winter and summer monsoon water mass and heat transport changes in the Arabian Sea near 8°N. *Deep-Sea Res.* II **49,** 1173-1195.

Susanto RD and AL Gordon, 2005: Velocity transport of the Makassar Strait throughflow. *J. Geophys. Res.* 110, C01005, doi:10.1029/2004JC002425

Suzuki R, SK Behera, S Iizuka, T Yamagata, 2004: Indian Ocean subtropical dipole simulated using a coupled general circulation model. *J. Geophys. Res.* C109, C09001, doi:10.1029/2003JC001974.

Takahashi T, SC Sutherland, C Sweeney, N Metzl, A Poisson, B Tilbrook, N Bates, R Wanninkhof, R Feely, C Sabine, J Olafsson, Y Nojiri, 2001: Global sea-air CO_2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects. *Deep-Sea Res.* **49**, 1601-1622.

Toole JM and B Warren, 1993: A hydrographic section across the subtropical South Indian Ocean. *Deep-Sea Res.* I **40**(10), 1973-2019.

Torrence T and PJ Webster, 1999: Interdecadal changes in the ENSO-Monsoon System. *J. Clim.* **12**, 2679–2690.

Vecchi GA and DE Harrison, 2002: Monsoon breaks and sub-seasonal sea surface temperature variability in the Bay of Bengal. *J. Clim.* **15**(12), 1485-1493.

Vecchi GA and M Harrison, 2005: An Indian Ocean Observing System Simulation Experiment. *Submitted to J. Clim.*(in press)

Verschell M, J Kindle, J O'Brien, 1995: Effects of Indo-Pacific throughflow on the upper tropical Pacific and Indian Oceans. *J. Geophys. Res.* **100**, 18,409-18,420.

Wajsowicz RC, 1996: Flow of a western boundary current through multiple straits: an electrical circuit analogy for the Indonesian Throughflow and archipelago. *J. Geophys. Res.* **101**, 12295-12300.

Waliser, DE, C Jones, JKE Schemm, and NE Graham, 1999: A statistical extended-range tropical forecast model based on the slow evolution of the Madden-Julian oscillation. *J. Clim***. 12,** 1918-1939.

Waliser, DE, W Stern, S Schubert, and KM Lau, 2003a: Dynamic predictability of intraseasonal variability associated with the asian summer monsoon. Quart. *J. Royal Meteor.* Soc. **129**, 2897-2925.

Waliser, D E, K Jin, IS Kang, WF Stern, SD Schubert, MLC Wu, KM Lau, MI Lee, V Krishnamurthy, A Kitoh, GA Meehl, VY Galin, V Satyan, SK Mandke, G Wu, Y Liu, and CK Park, 2003b: AGCM simulations of intraseasonal variability associated with the Asian summer monsoon. *Climate Dynamics* **21**, 423-446.

Waliser DE, R Murtugudde, LE Lucas, 2003c: Indo-Pacific ocean response to atmospheric intraseasonal variability. Part I: Austral summer and the Madden-Julian Oscillation. *J. Geophys. Res.* **108**, 3160, doi.10.1029/2003JC001620.

Waliser DE, R Murtugudde, LE Lucas, 2004: Indo-Pacific ocean response to atmospheric intraseasonal variability. Part 2: Boreal summer and the intraseasonal oscillation. *J. Geophys. Res.* **109**, C03030, doi.10.1029/2003JC002002.

Waliser, DE, 2005a: Predictability and Forecasting. "Intraseasonal Variability of the Atmosphere-Ocean Climate System" WKM Lau and DE Waliser, Eds., Springer, Heidelberg, Germany, 474.

Waliser, DE, R Murtugudde, P Strutton, and J-L Li, 2005b: Subseasonal Organization of Ocean Chlorophyll: Prospects for Prediction Based on the Madden-Julian Oscillation. *Geophysical Research Letters*, In Press.

Wang B, PJ Webster, H Teng, 2005: Antecedents and self-induction of active-break south Asian monsoon unraveled by satellites. *Geophys. Res. Lett.* **32**, L04704 10.1029/2004GL020996.

Webster PJ, AM Moore, JP Loschnigg, RR Leben, 1999: Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997-98. *Nature* **401**, 356-360.

Webster PJ, EF Bradley, CW Fairall, JS Godfrey, P. Hacker, RA Houze Jr., R Lukas, Y Serra, JM Hummon, TDM Lawrence, CA Russell, MN Ryan, K Sahami, P Zuidema, 2002: The JASMINE Pilot Study. Bull. *Amer. Meteorol. Soc.* **83**, 1603-1630.

Wheeler, M. and K. M. Weickmann, 2001: Real-time monitoring and prediction of modes of coherent synoptic to intraseasonal tropical variability. *Mon. Wea. Rev.* **129**, 2677-2694.

Wiggert JD, RR Hood, K Banse, J Kindle, 2005: Monsoon-driven biogeochemical processes in the Arabian Sea. *Progr. Oceanogr.* (in press).

Wiggert JD, RG Murtugudde, JR Christian, 2004: Biogeochemical variability in the Indian Ocean: results of a coupled bio-physical model. 2004 Ocean Sciences Meeting. American Geophysical Union, Portland, Oregon, USA.

Wijffels S, J Sprintall, M Fieux, N Bray, 2002: The throughflow in the southeast Indian Ocean. Part 1: Water mass variability. *Deep-Sea Res.* II **49,** 1341-1362.

Webster PJ, T Palmer, M Yanai, R Tomas, V Magana, J Shukla, A Yasunari, 1998: Monsoons: processes, predictability and the prospects for prediction. *J. Geophys. Res.* (TOGA special issue) **103**, C7, 14,451–14,510.

Weller RA, MF Baumgartner, SA Josey, AS Fisher, J Kindle, 1998: Atmospheric forcing in the Arabian Sea during 1994–1995: observations and comparisons with climatology and models**.** *Deep-Sea Res.* II, **45,** 1961-1999.

Wijffels S and G Meyers, 2004: An intersection of oceanic waveguides—variability in the Indonesian throughflow region. *J. Phys. Oceanogr.* **34**, 1232-1253.

Wunsch C and R Ferrari, 2004: Vertical mixing, energy, and the general circulation of the oceans. *Annu. Rev. Fluid Mech.* **36**, 281-314.

Wyrtki K, 1971: Oceanographic Atlas of the International Indian Ocean Expedition. National Science Foundation, Publication OCE/NSF 86-00-001. Washington D.C. 531pp.

Wyrtki K, 1973: An equatorial jet in the Indian Ocean. *Science* **181,** 262-264.

Xie S-P, H Annamalai, F Schott, JP McCreary Jr., 2002: Origin and predictability of South Indian Ocean climate variability. *J. Clim.* **15**(8), 864-874.

Xie SP, H Annamalai, FA Schott, JP McCreary, 2002: Structure and mechanisms of South Indian Ocean climate variability. *J. Clim.* **15**, 874-878.

Yamagata T et al., 2002: The Indian Ocean dipole: a physical entity. *CLIVAR Exchanges* 24 **7**(2), 15-18.

Yamagata T et al., 2004: Coupled ocean-atmosphere variability in the tropical Indian Ocean. In: Ocean-Atmosphere Interaction and Climate Variability. Chunzai Wang, Shang-Ping Xie, JA Carton (eds.), American Geophysical Union Geophysical Monograph Series, Volume 147, ISBN 0-87590-412-2, AGU Code GM1474122. 414pp.

Zheng Y, DE Waliser, WF Stern, and C Jones, 2004: The Role of coupled sea surface temperatures in the simulation of the tropical intraseasonal oscillation. *J. Clim.* **17**, 4109-4134.

Appendix 2

CLIVAR-GOOS Indian Ocean Panel members in 2005:

Peter Hacker	University of Hawaii, Honolulu, USA
Yoshifumi Kuroda	JAMSTEC, Yokosuka, Japan
Yukio Masumoto	FORSGC, University of Tokyo, Japan
Mike McPhaden	NOAA, PMEL, Seattle, USA
Gary Meyers (chair)	CSIRO, Hobart, Australia
Robert Molcard	LODyC, Paris, France
M. Ravichandran	INCOIS, Hyderabad, India
Fritz Schott	IMR, University of Kiel, Germany
Satish Shetye	NIO, Goa, India
Lisan Yu	WHOI, USA
TBN	Indonesia
Jay McCreary (AAMP)	University of Hawaii, Honolulu, USA
Chris Reason (VACS)	University of Cape Town, South Africa
Bronte Tilbrook (IOCCP)	CSIRO, Hobart, Australia
Peter Webster (AAMP)	Georgia Institute of Technology, Atlanta, USA

Collaborators:

Safri Burhanuddin	University of Hasanuddin, Indonesia
Saji Hameed	University of Hawaii, Honolulu, USA
Raleigh Hood	University of Maryland, USA
Tony Lee	JPL, Pasadena, USA
VSN Murty	NIO, Goa, India
Laban Ogallo	Drought Monitoring Centre, Kenya
Gabe Vecchi	NOAA/GFDL, Princeton, USA
Weidong Yu	First Institute of Oceanography, China

Appendix 3

Figures

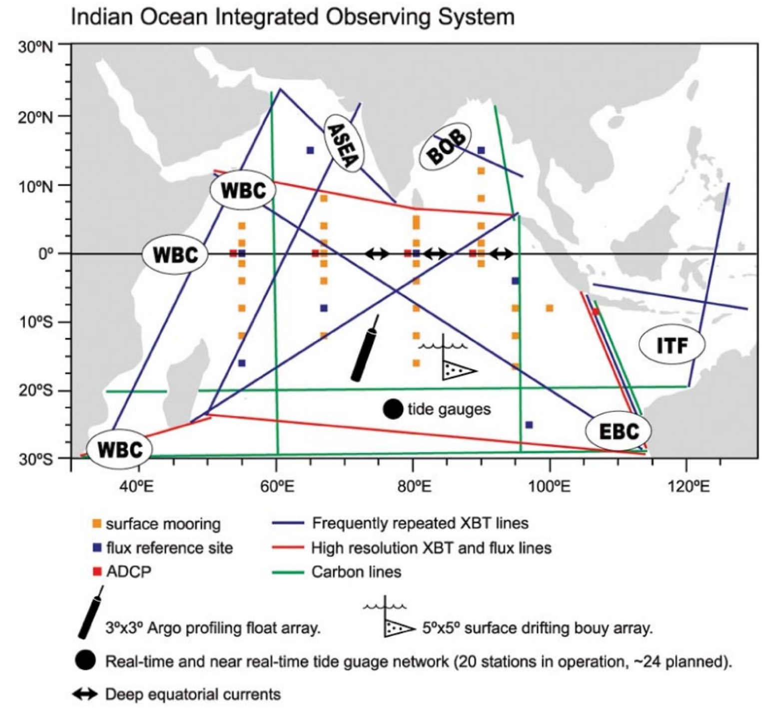


Figure 1. The integrated observing system, with basin-scale observations by moorings, Argo floats, XBT lines, surface-drifters and tide-gauges; as well as boundary arrays to observe boundary currents off Africa (WBC), in the Arabian Sea (ASEA) and Bay of Bengal (BOB), the Indonesian throughflow (ITF), off Australia (EBC) and deep equatorial currents.

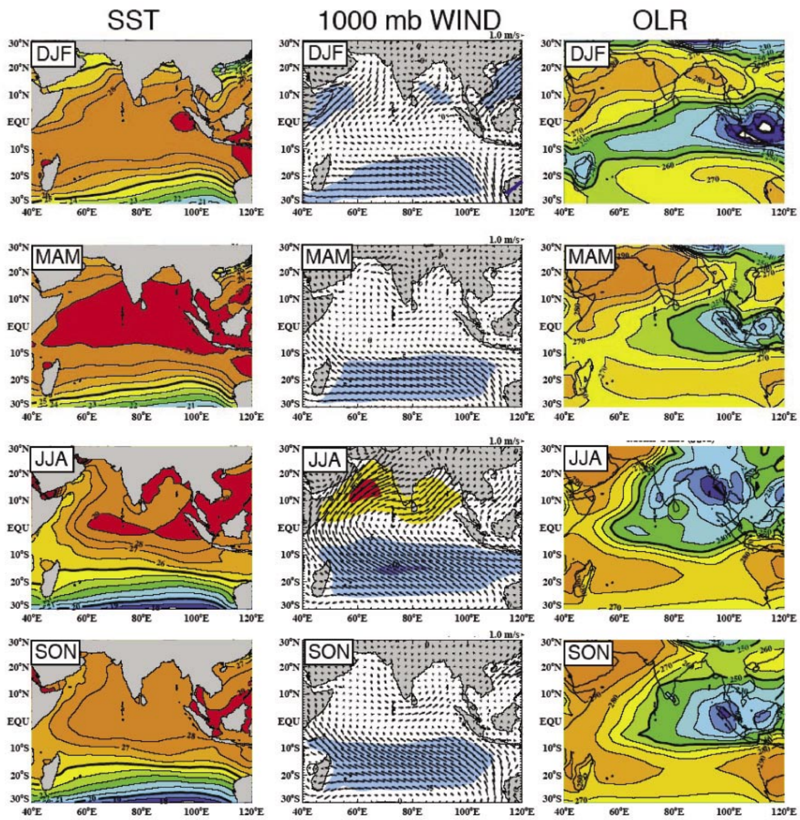


Figure 2. Mean annual climatology of SST (°C), near-surface wind vectors (m s^{-1}), and outgoing long-wave radiation (OLR, W m^{-2}). Low OLR is representative of high precipitation. Strong eastward (westward) wind is shaded yellow (blue) on the wind map. Data are plotted for the four seasons March, April and May (MAM), June, July and August (JJA), September, October and November (SON), and December, January and February (DJF).

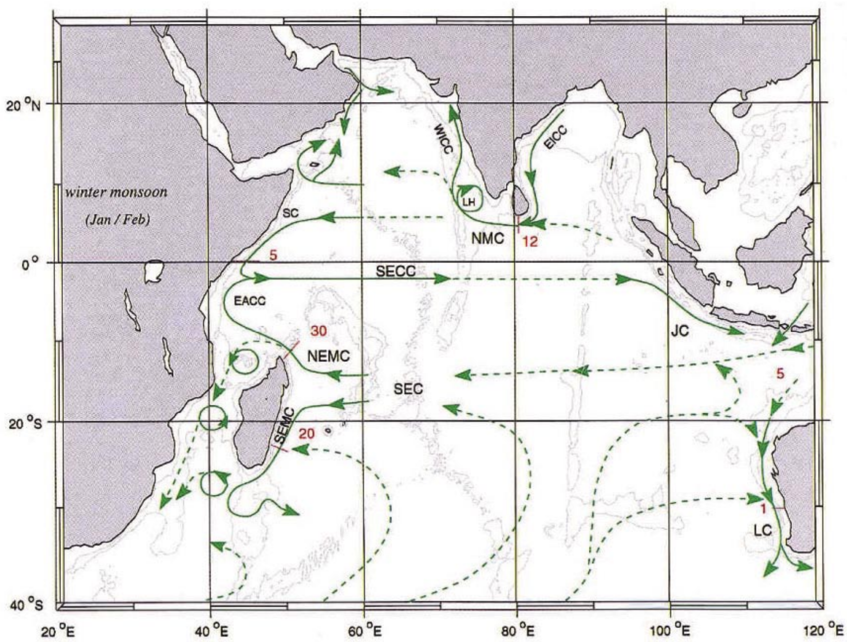


Figure 3. **a**. A schematic representation of currents observed during January–February. The currents identified are: South Equatorial Current (SEC); South Equatorial Counter-Current (SECC); the Northeast and Southeast Madagascar Currents (NEMC and SEMC); East Africa Coastal Current (EACC); Somali Current (SC), West India Coastal Current (WICC); Lakshadweep High (LH); East India Coastal Current (EICC); Northeast Monsoon Current (NMC); South Java Current (JC); and the Leeuwin Current (LC). Transport, in sverdrups (Sv: 10^6 m^3 s^{-1}) across sections is shown by *red lines*. The Indonesian Throughflow, which enters from the east, influences both the SEC and the LC. The figure is taken from Schott and McCreary (2001).

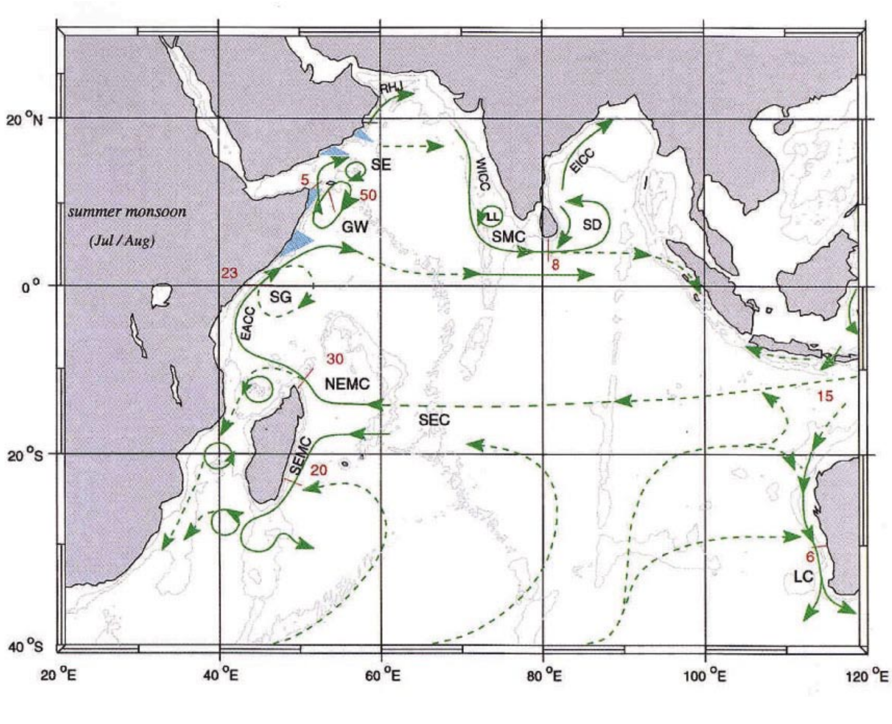


Figure 3 **b**. A schematic representation of currents (green) observed during July–August. The currents identified are: South Equatorial Current (SEC); Northeast and Southeast Madagascar Currents (NEMC and SEMC); East Africa Coastal Current (EACC); Southern Gyre (SG), Great Whirl (GW), and associated upwelling wedges (*in blue*); Socotra Eddy (SE); Ras al-Hadd Jet (RHJ) and an upwelling wedge off Oman; West India Coastal Current; Lakshadweep Low (LL); East India Coastal Current (EICC); Southwest Monsoon Current (SMC); Sri Lanka Dome (SD); and the Leeuwin Current (LC). Transport in sverdrups (Sv: 10^6 m^3 s^{-1}) across sections is shown by *red lines*. The Indo-Pacific Throughflow, which enters from the east, influences both the SEC and the LC. The figure is taken from Schott and McCreary (2001).

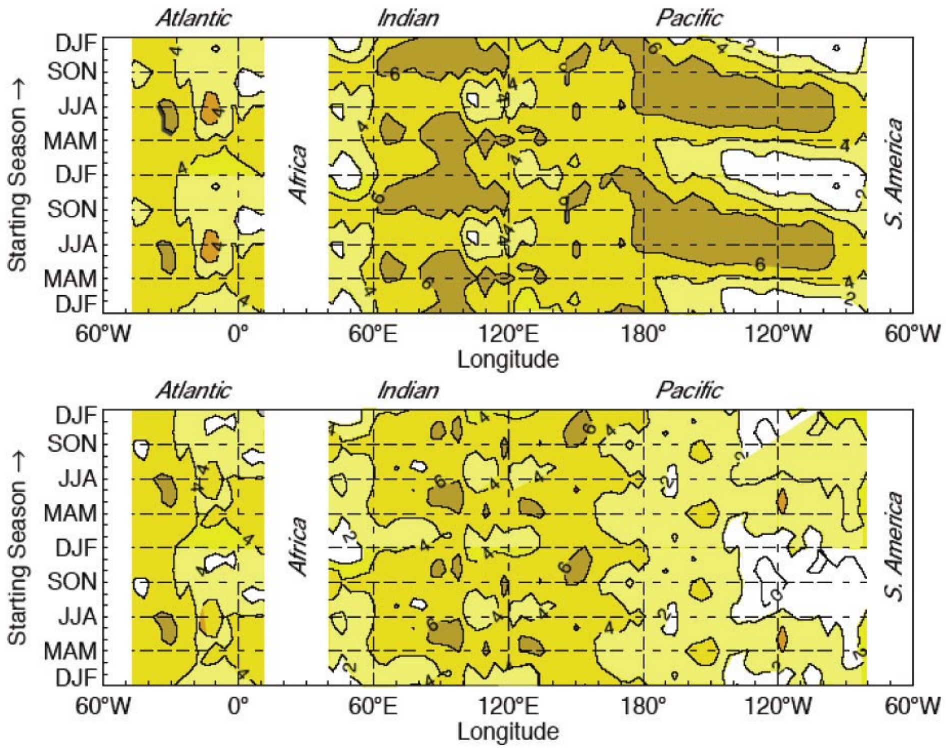


Figure 4. **Upper panel** Time sequence of the climatological persistence of SST anomaly along the equator for a two-year cycle. Persistence is plotted as the correlation coefficient times 10. **Lower panel** Persistence of SST anomaly with El Niño-3 influence removed by linear regression (Torrence and Webster, 1999).

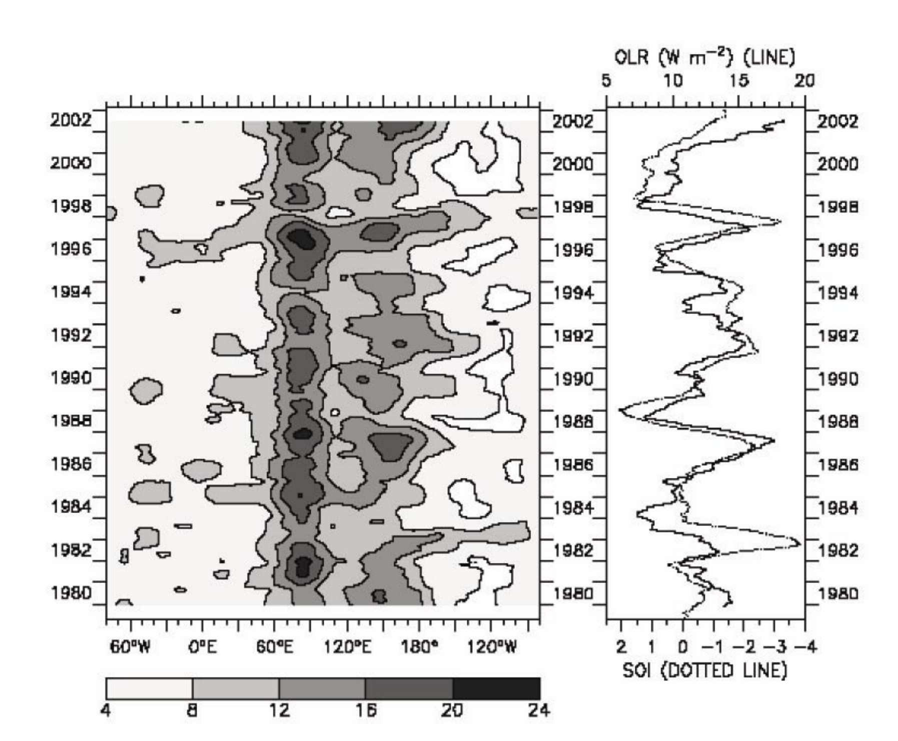


Figure 5. Interannual amplitude of intraseasonal OLR (5°S–5°N) (W m^{-2}), defined as the one-year running standard deviation of intraseasonally-bandpassed OLR. **Left** Amplitude in the global tropical strip, centred on the major region of variance at 100°E (the abscissa extends around the world, broken at the South American coast at 80°W). **Right** Time-series of OLR amplitude averaged over the western Pacific (150°E–180°E) (*solid line*, scale at top) in comparison with the SOI (*dotted line*, scale at bottom). Year ticks on each panel are at 1 January of each year, with year labels centred at mid-year (Kessler, 2005).

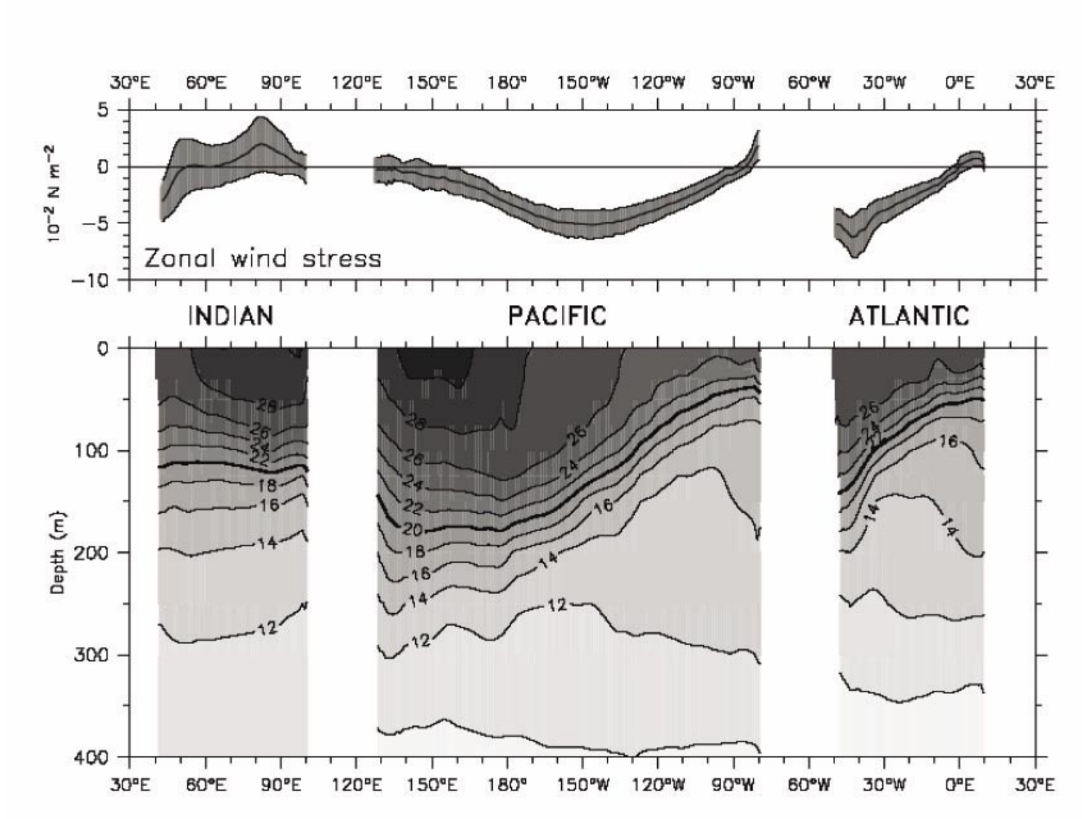


Figure 6. Mean zonal wind stress (**top**) and upper-ocean temperature (**bottom**) along the equator. The winds are from the ERS scatterometer during 1992–2000, averaged over 5°S–5°N. The *heavy line* shows the mean, and the *gray shading* around it shows the standard deviation of the annual cycle. The ocean temperatures are from the Levitus (1994) World Ocean Atlas, with a contour interval of 2°C, and a supplemental contour at 29°C (Kessler, 2005).

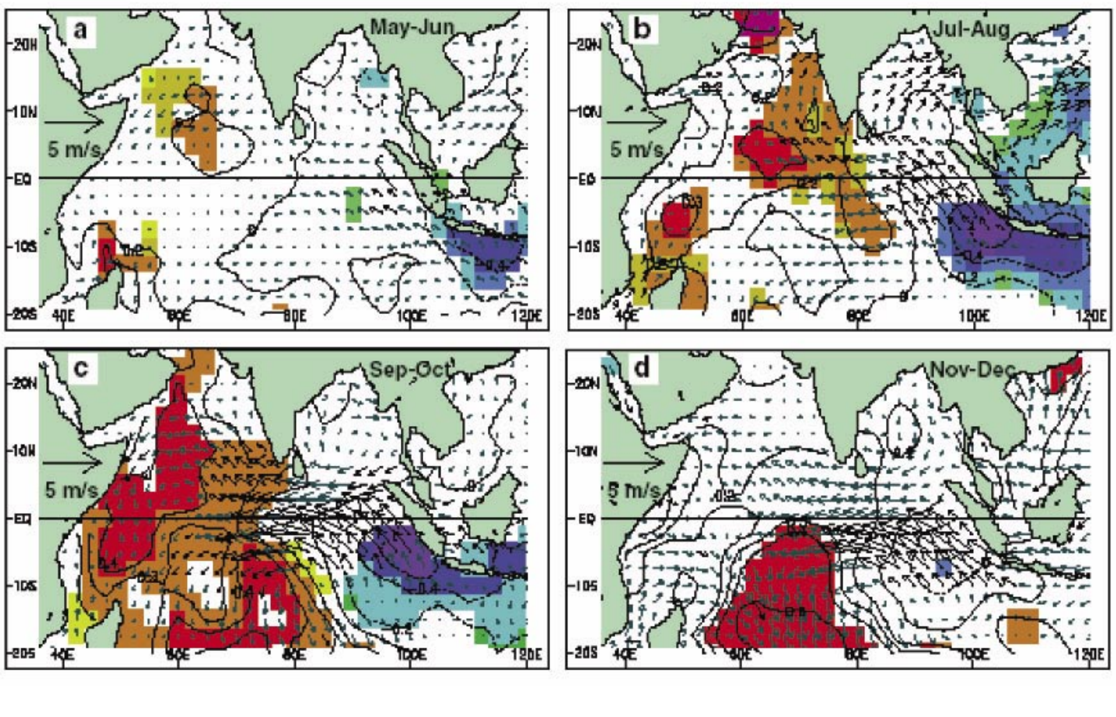


Figure 7. A composite dipole mode event. Frames **a** (from May to June) **b** (from July to August) **c** (from September to October and **d** (from November to December) show the evolution of composite SST and surface-wind anomalies (Saji et al., 1999).

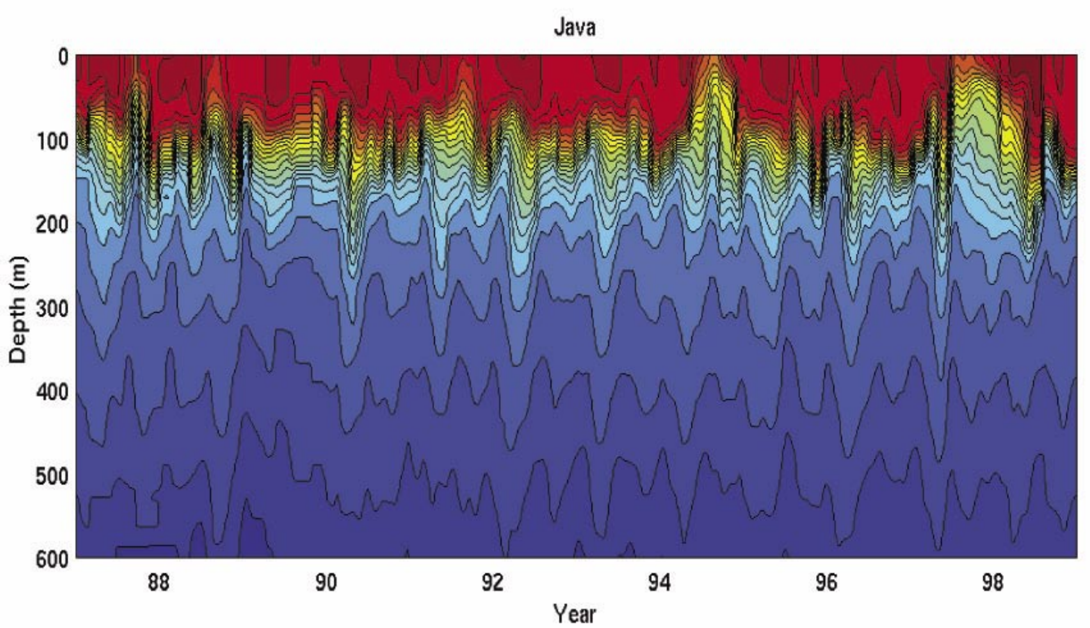
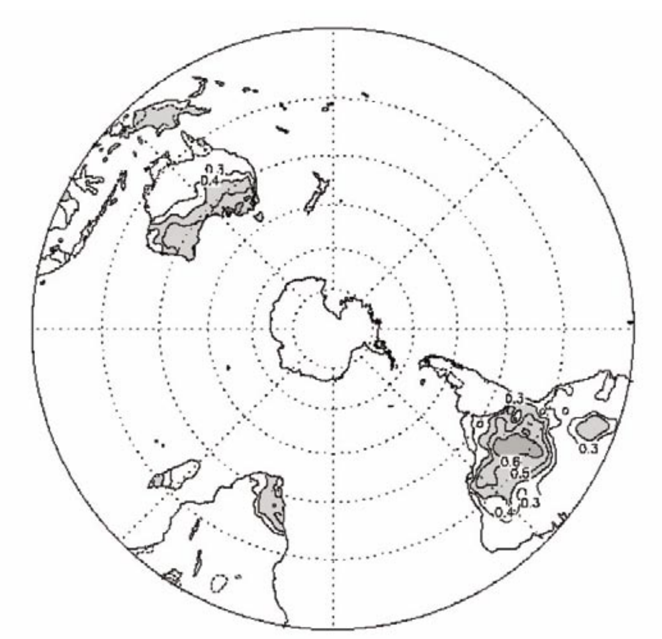


Figure 8. Subsurface temperature off Java observed on the expendable bathythermograph line IX1. Upwelling events occurred in 1988, 1991, 1994 and 1997.

Figure 9. The correlation of the land-surface temperature anomaly with the Dipole Mode Index during austral spring (SON). Values of the correlation coefficient <0.4 and .04 are shaded and are significant at ≥95 per cent level (Saji and Yamagata, 2004).



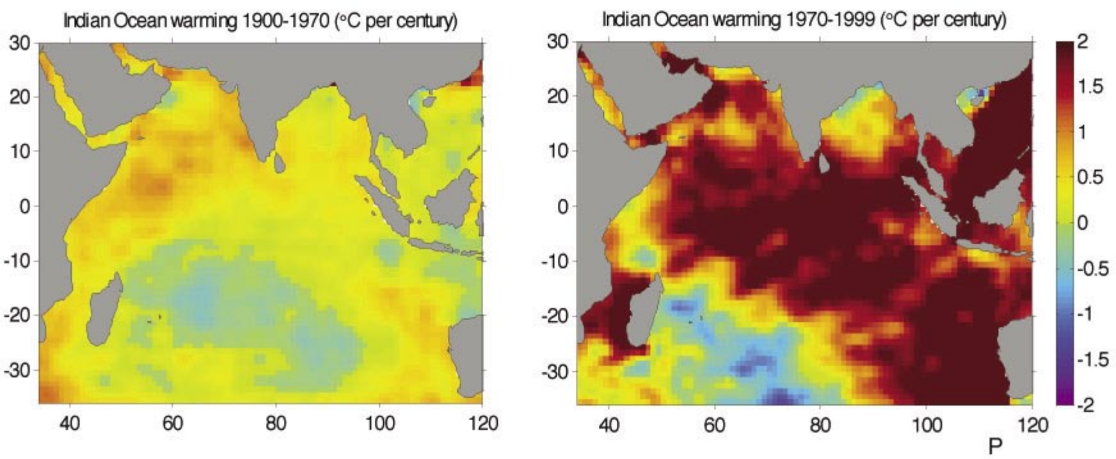


Figure 10. Estimate of the linear trend in SST during 1900–1970 (**left**) and during 1970–1999 (**right**), based on HadISST (after Rayner et al., 2003).

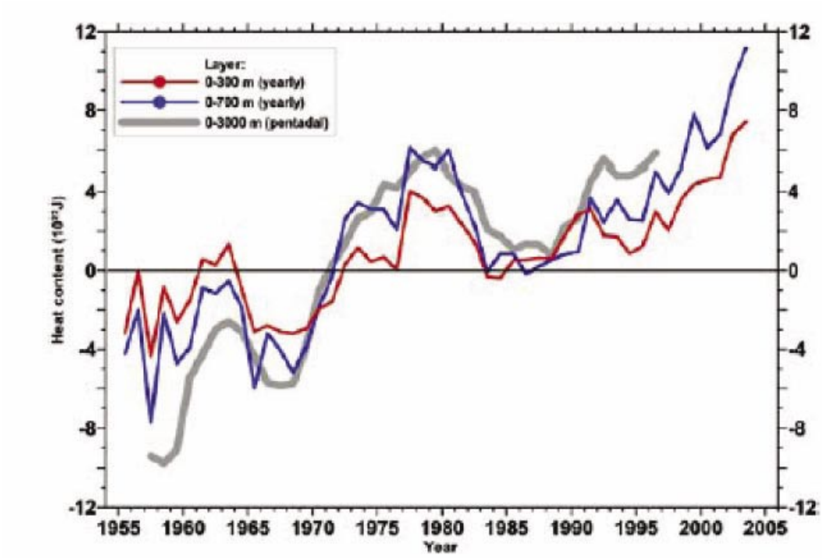


Figure 11. Time-series of yearly ocean heat content (10^{22} J) for the 0–300 m and 0–700 m layers and 5-year running composites of ocean heat content (10^{22} J) for the 0–3000 m layer for 1955–1959 through 1994–1998. Each yearly estimate is plotted at the midpoint of the year; each pentadal**[5-year]** estimate is plotted at the midpoint of the 5-year period. (after Levitus et al., 2005).

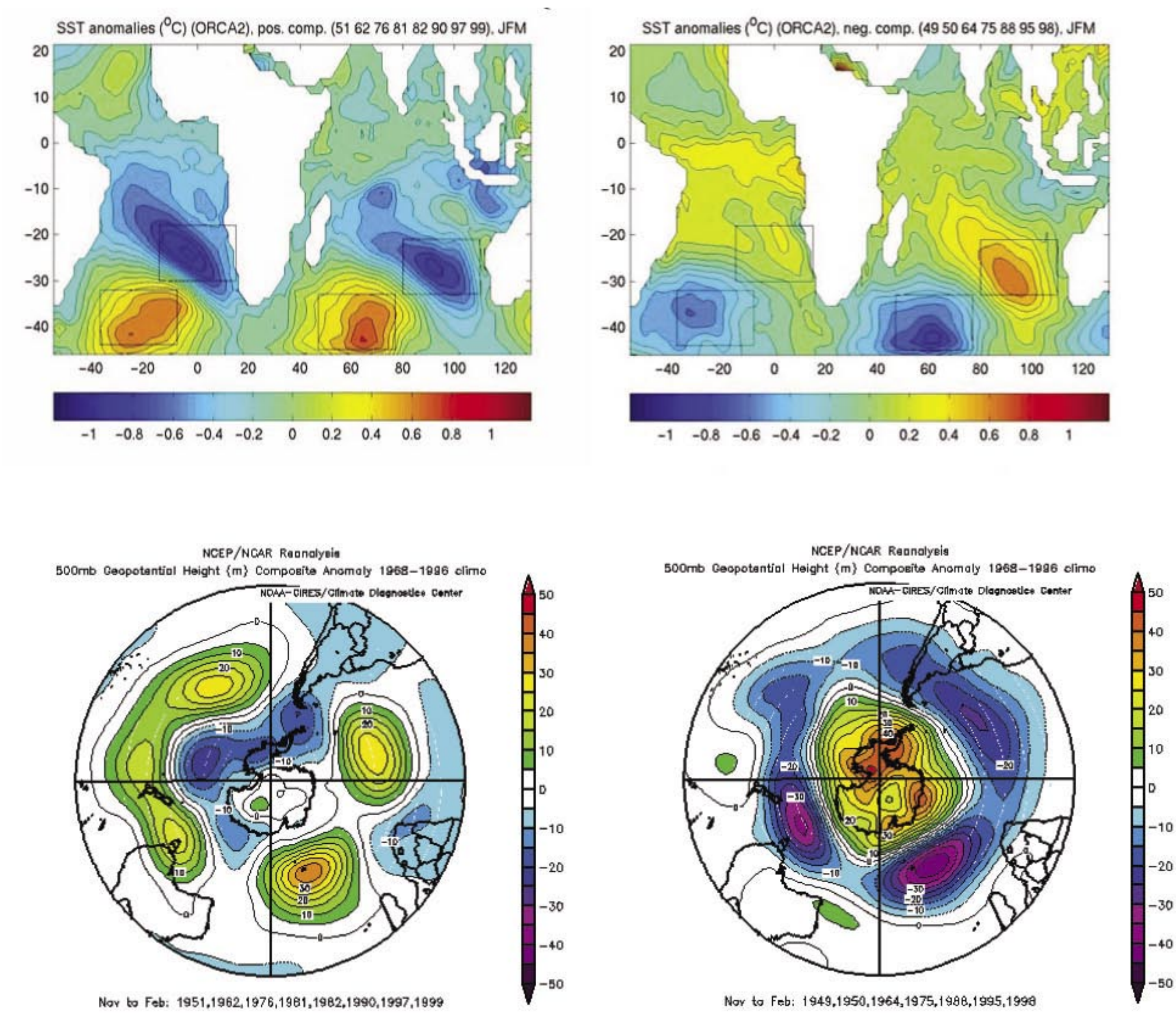


Figure 12. **Left** column shows composite of positive dipole event SST (**upper**) and 500 hPa height (**lower**) anomalies for austral summer. **Right** column shows the same fields for the negative event. (After Hermes and Reason, 2005).

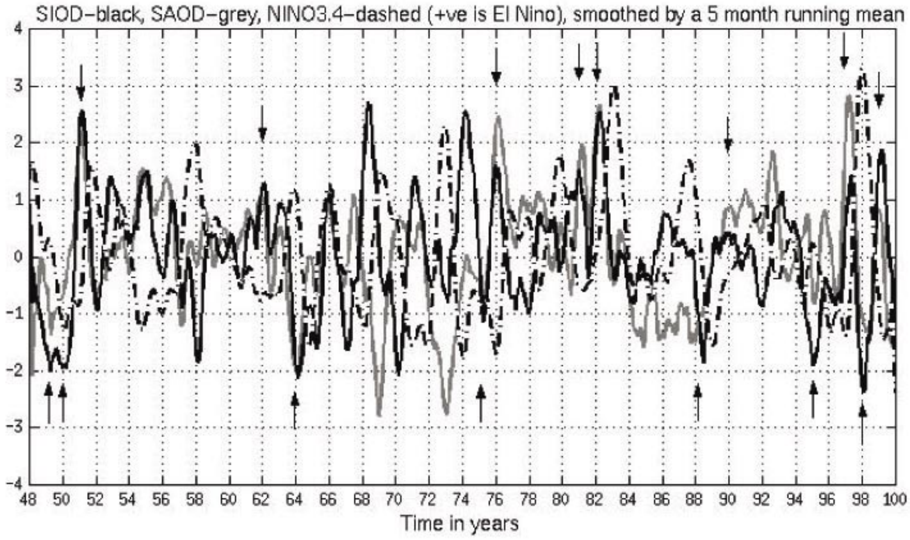


Figure 13. Time-series of the southern Indian Ocean dipole index (*black*), South Atlantic dipole index (*grey*) and El Niño-3.4 index (*dashed*). (After Hermes and Reason, 2005).

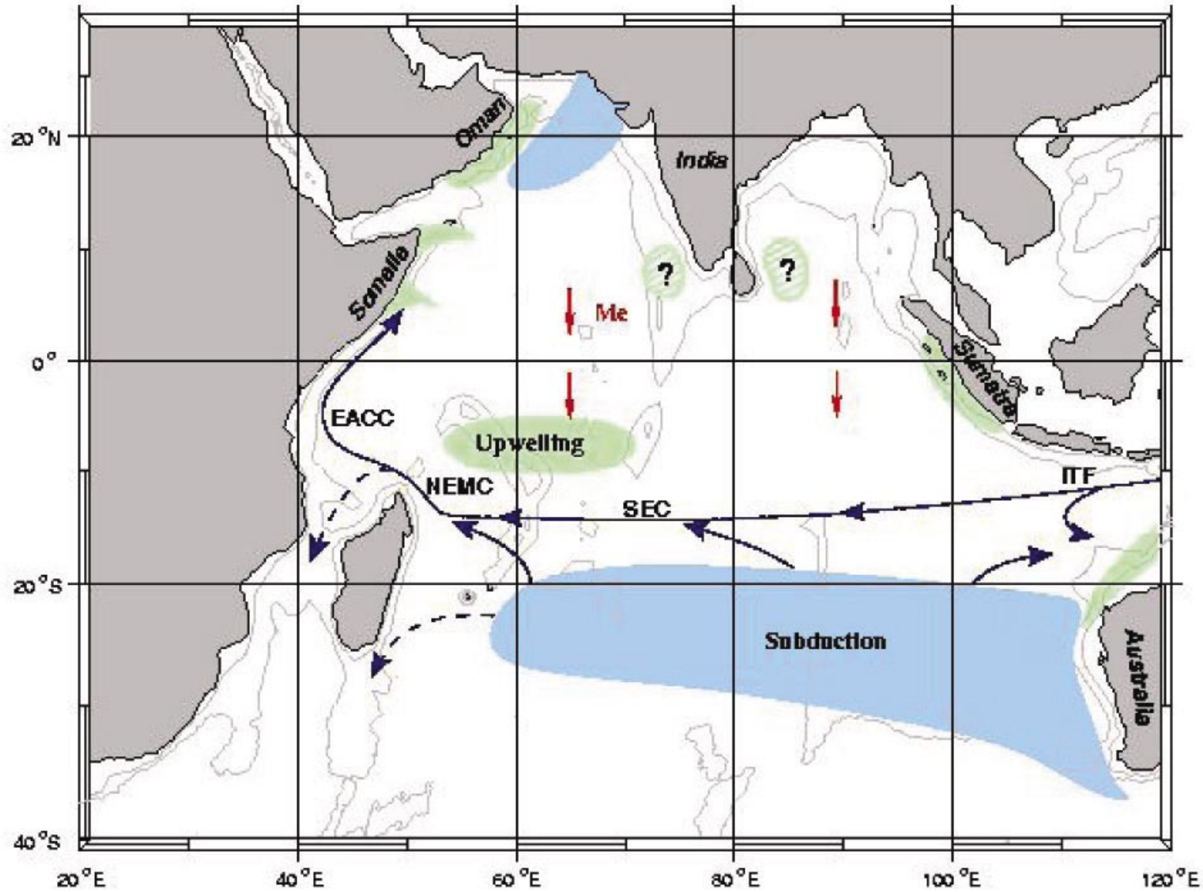


Figure 14. Schematic diagram of the Indian Ocean Cross-Equatorial Cell (CEC) with subduction (*blue*), upwelling (*green*) zones and circulation branches that participate in the CEC. The strength of the CEC has been determined to be 6±1 Sv from the cross-equatorial northward Somali Current transport at the level of the thermocline and from the southward Ekman/Sverdrup return flow across the equator (modified from Schott et al., 2002).

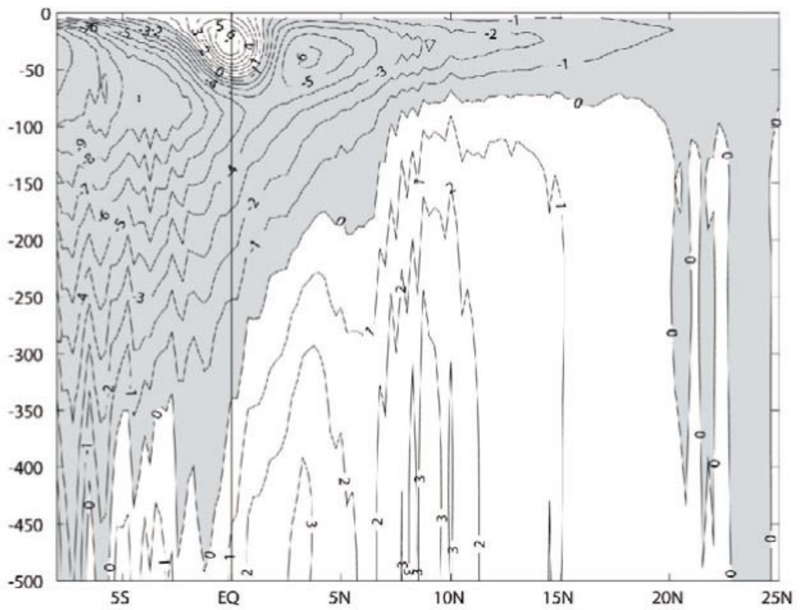


Figure 15. Meridional transport stream-function for the upper 500 m of the ocean from the model of Miayama et al. (2003) showing the CEC, equatorial roll in the upper 80 m and upwelling south of 3°S.

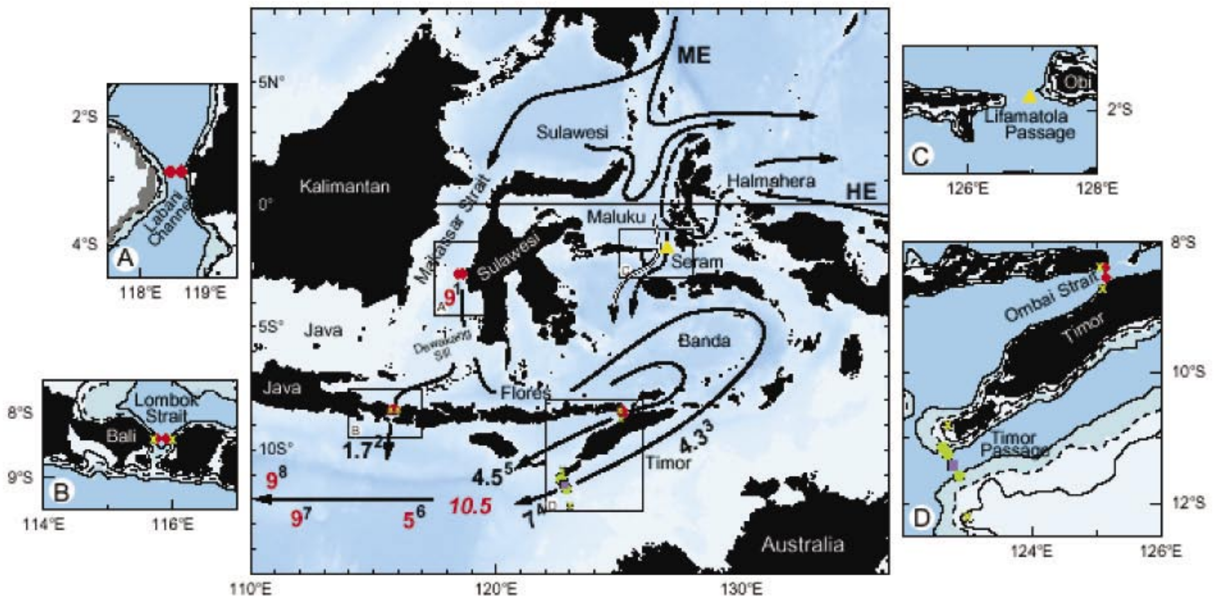


Figure 16. Schematic diagram of Indonesian Throughflow pathways (Gordon, 2001). The *solid arrows* represent North Pacific thermocline water; the *dashed arrows* represent South Pacific lower-thermocline water. Transport in sverdrups (Sv: 10^6 $m^3 s^{-1}$) is in *red*. The 10.5 Sv in *italics* is the sum of the flows through the Lesser Sunda passages. *ME* is the Mindanao Eddy; *HE* is the Halmahera Eddy. *Superscript* refers to reference source: 1: Makassar Strait transport in 1997 (Gordon et al., 1999); 2: Lombok Strait (Murray and Arief, 1988; Murray et al., 1989) from January 1985 to January 1986; 3: Timor Passage (between Timor and Australia) measured in March 1992 to April 1993 (Molcard et al., 1996); 4: Timor Passage, October 1987 and March 1988 (Cresswell et al., 1993); 5: Ombai Strait (north of Timor, between Timor and Alor Island) from December 1995 to December 1996 (Molcard et al., 2001); 6: between Java and Australia from 1983 to 1989 XBT data (Meyers et al., 1995; Meyers, 1996); 7: Upper 470 m of the South Equatorial Current in the eastern Indian Ocean in October 1987 (Quadfasel et al., 1996); 8: Average ITF within the South Equatorial Current defined by five WOCE WHP sections (Gordon et al., 1997). The *hollow arrow* represents overflow of dense Pacific water across the Lifamatola Passage into the deep Banda Sea, which may amount to about 1 Sv (van Aken et al., 1988). The 100-, 500-, and 1000-m isobaths are shown in the inserts.

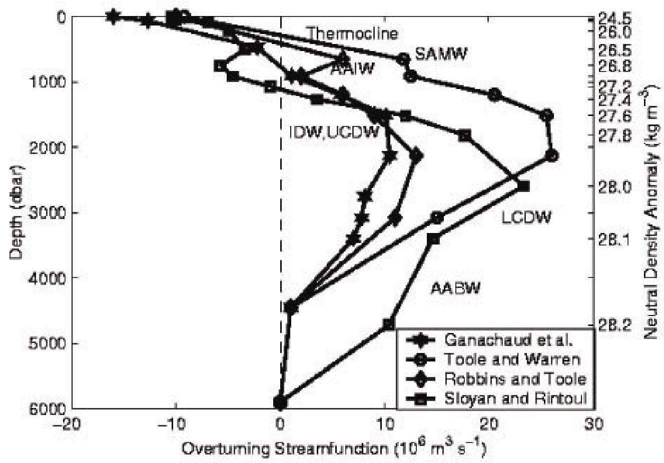


Figure 17. Overturning transport stream-function for the 32°S section, based on the analysis of Toole and Warren (1993), on the revised calculation of Robbins and Toole (1997) and on the inverse model results of Ganachaud et al. (2000) and of Sloyan/Rintoul (from Sloyan and Rintoul, 2001).

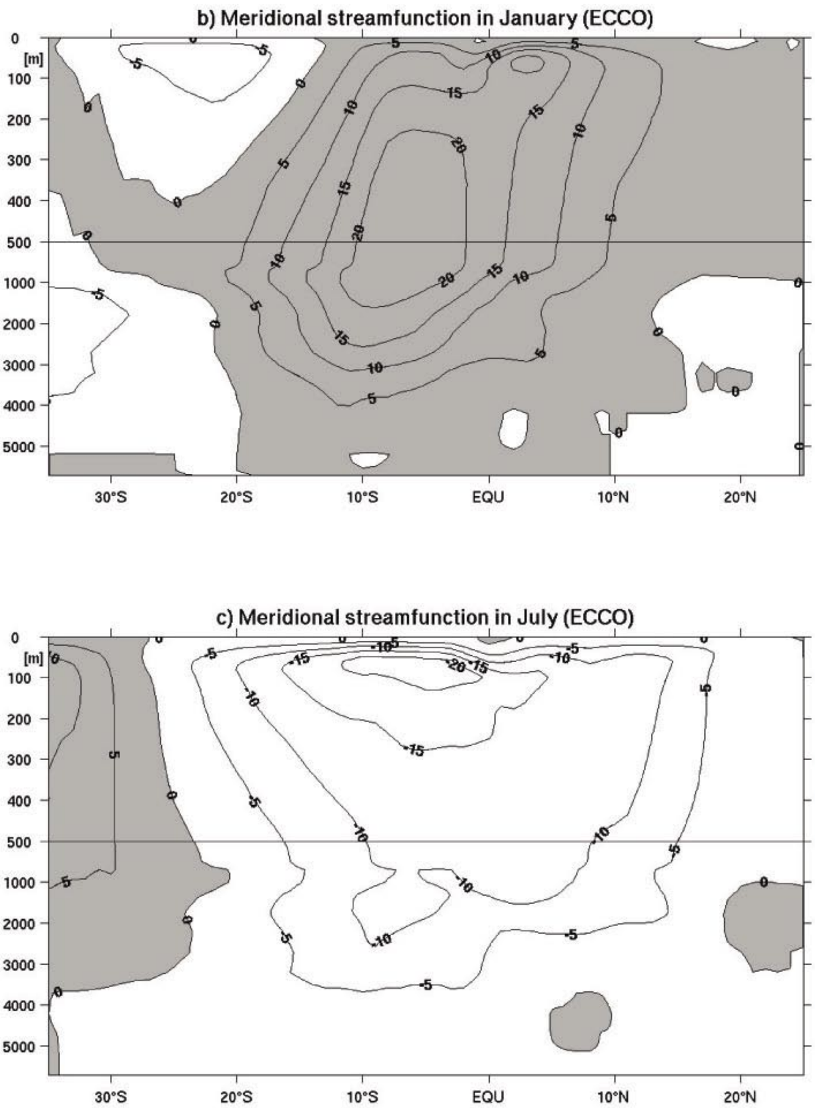


Figure 18. Seasonal meridional stream-functions of ECCO assimilation model of Stammer et al. (2002) for **a** January, and **b** July.

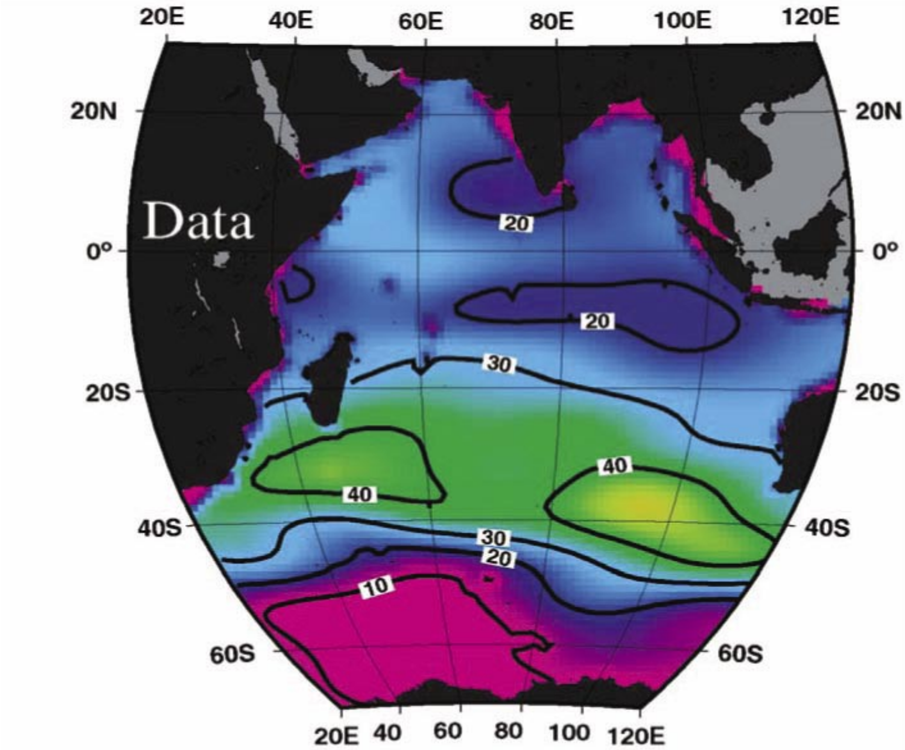


Figure 19. Man-made CO_2 column inventory (molC m^{-2}) from Sabine et al. (1999).

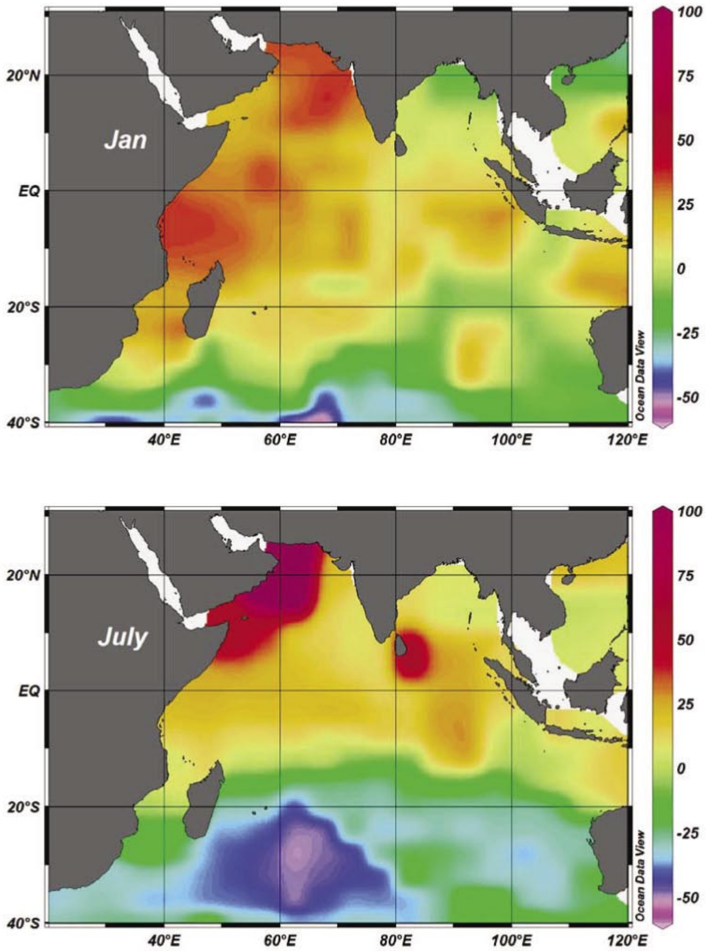


Figure 20; Air–sea pCO_2 gradient (*μatm*) for January and July from the climatology of Takahashi et al. (2002). Data are averaged over 4×5° areas and corrected to 1995. Regions with negative values are ocean sinks for atmospheric CO_2, and ocean sources occur in regions with positive values.

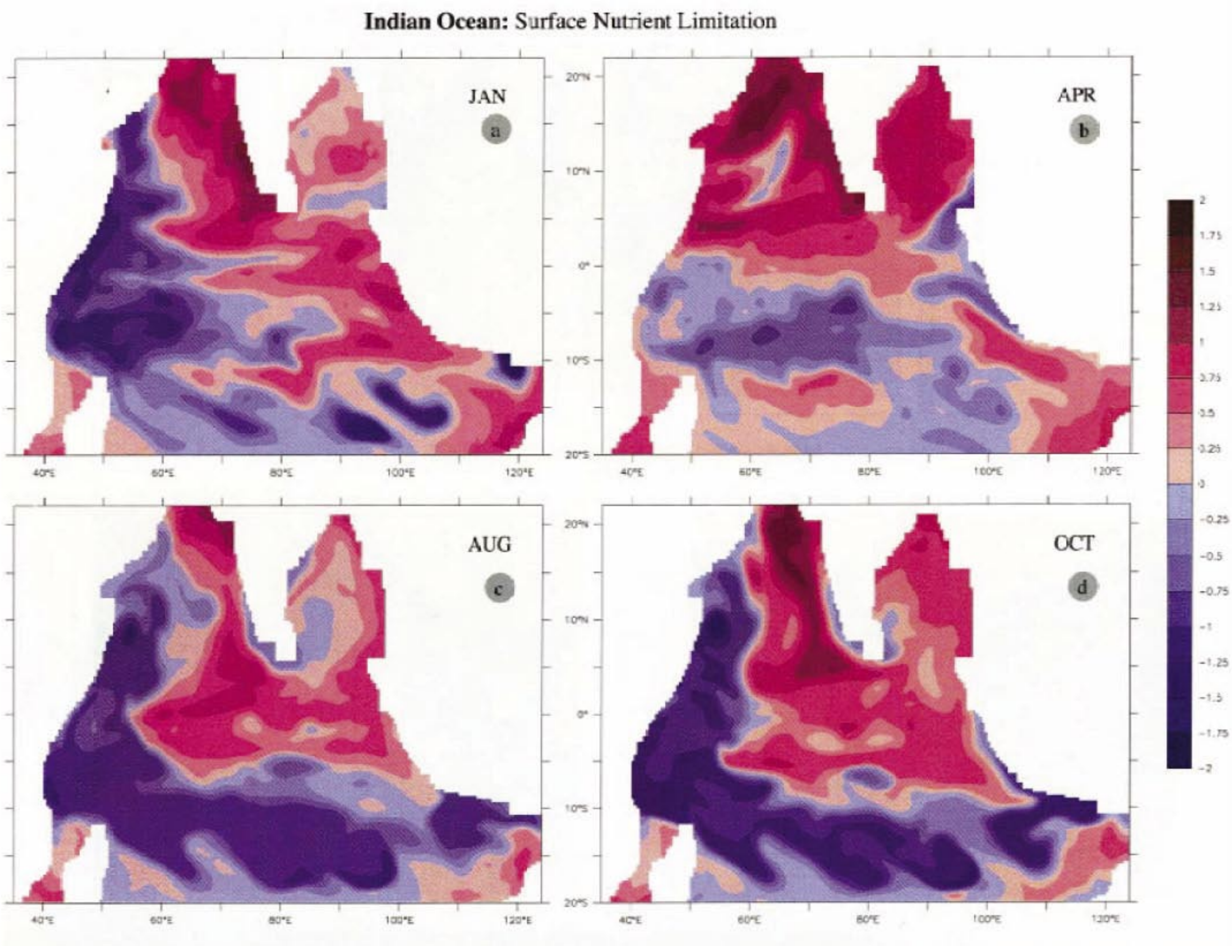


Figure 21. Model-estimated seasonal evolution of the most limiting surface nutrient from Wiggert (personal communication) *Blue shades* indicate iron limitation, whereas *red shades* indicate nitrogen limitation. The four seasons consist of **(a)** the northeast monsoon, **(b)** the spring intermonsoon, **(c)** the southwest monsoon, and **(d)** the fall intermonsoon.

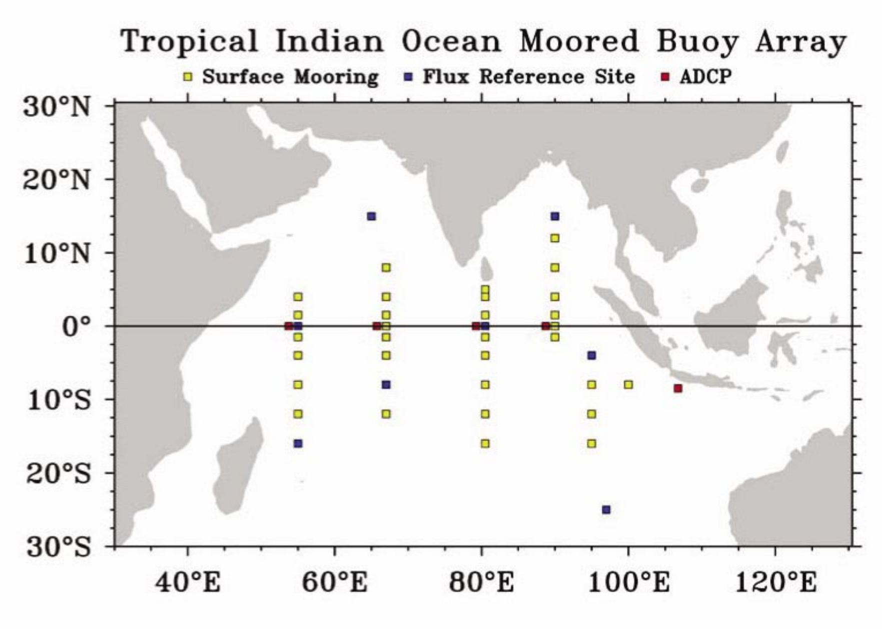


Figure 22. Tropical Indian Ocean moored buoy array. The surface moorings (*yellow*) are TAO or mini-TRITON as produced by NOAA and JAMSTEC. Upward looking ADCP's (*red*) are located on the equator where currents cannot be estimated by geostrophic methods. The ADCP off Indonesia is located in an area of heavy fishing where surface moorings are not recommended. The flux moorings (*blue*) will collect extra surface data to estimate heat and freshwater flues and calibrate satellite estimates.

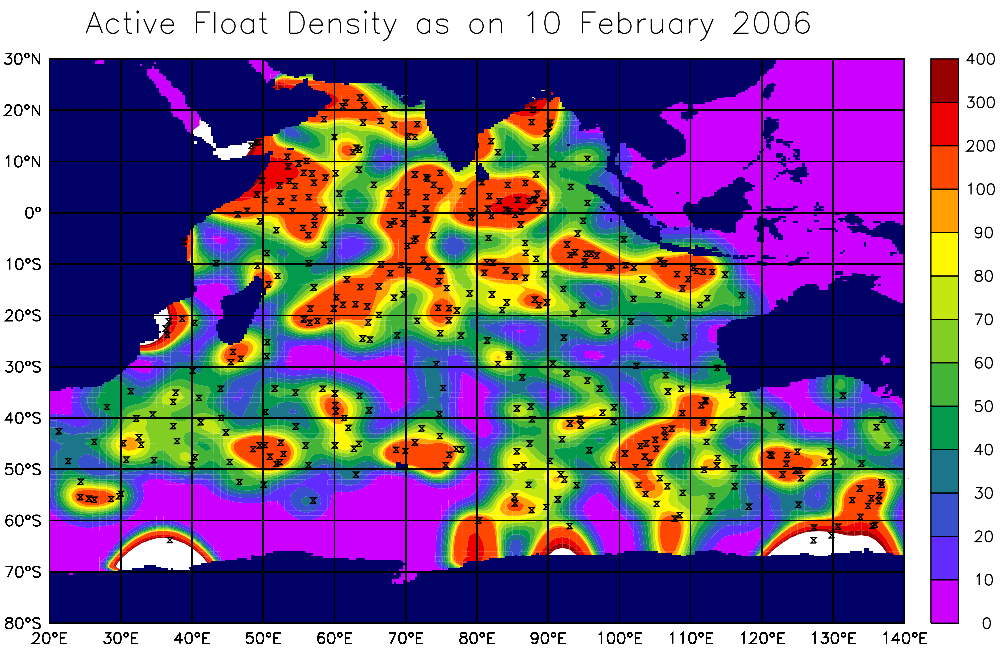


Figure 23. Active float density in percent on 10th February 2006; 10% represents one float per 3° latitude by 3° longitude area.

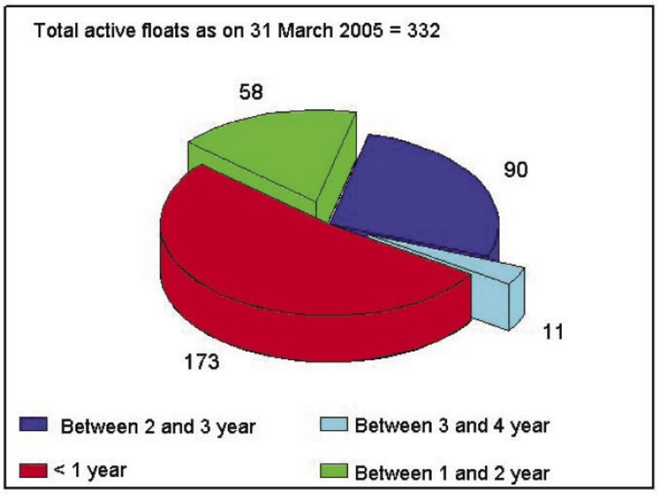
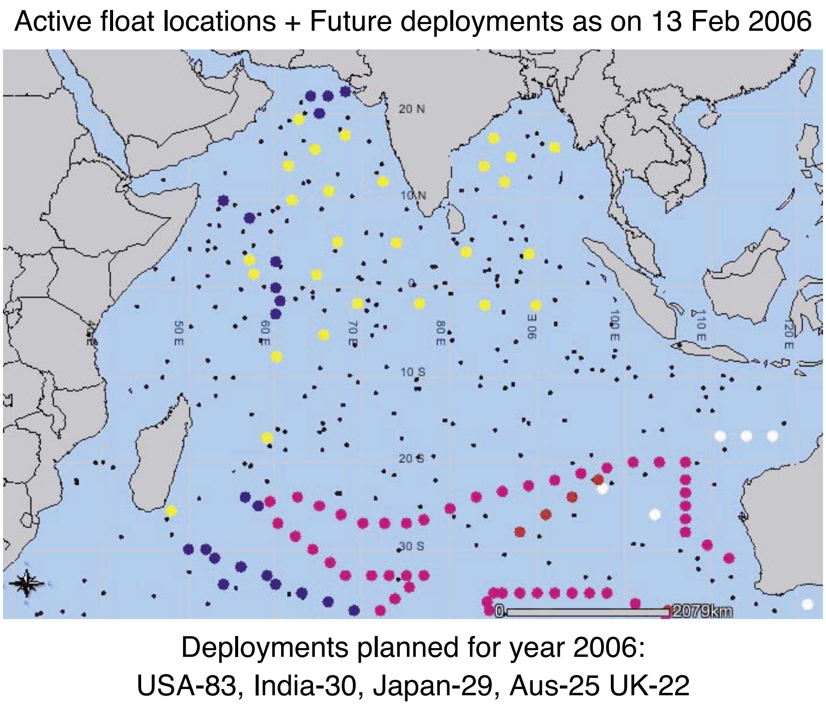


Figure 24. Life-time of the active floats in March 2005.

Figure 25. Location of active floats (black dot) as on 13 February 2006 and locations of future float deployments for the year 2006 (big coloured dots).



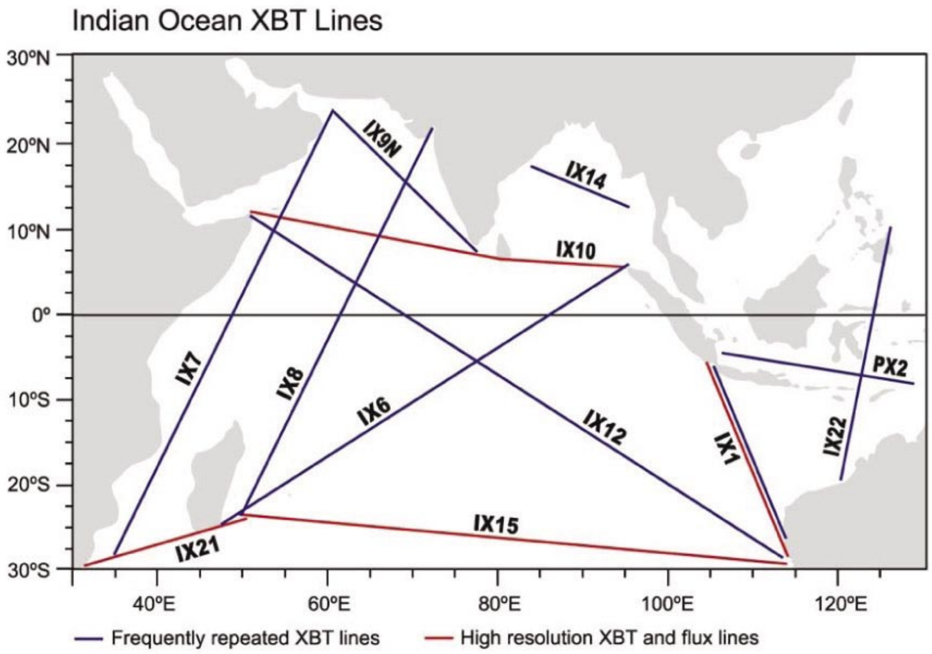


Figure 26. XBT lines recommended by the Upper Ocean Thermal Panel of Experts in 1999.

Figure 27. SOOPIP XBT drops for the period January–June 2004.

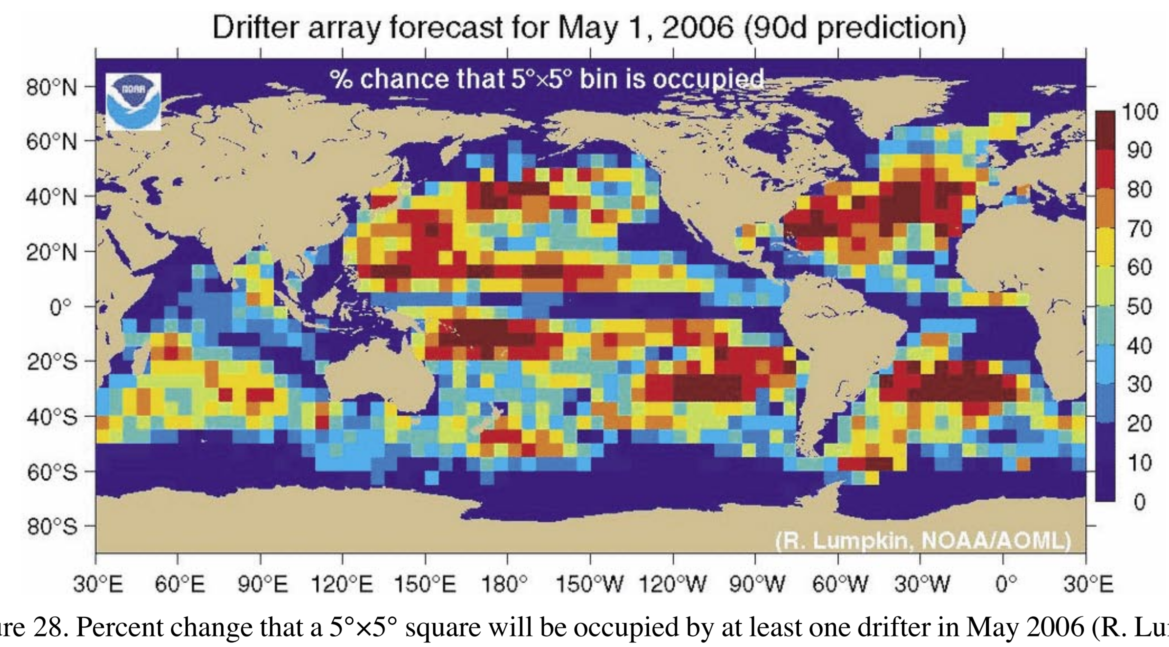


Figure 28. Percent change that a 5°×5° square will be occupied by at least one drifter in May 2006 (R. Lumkin, NOAA/AOML, personal communication).

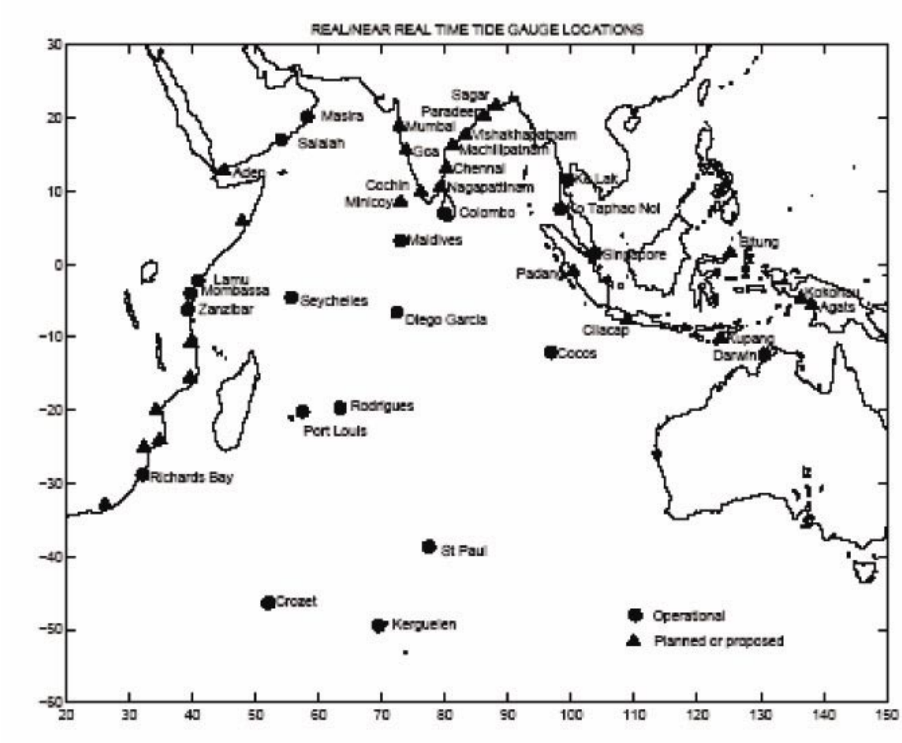


Figure 29. Planned and operational real-time and near-real-time tide gauges in June 2005. The number of stations is expected to increase.

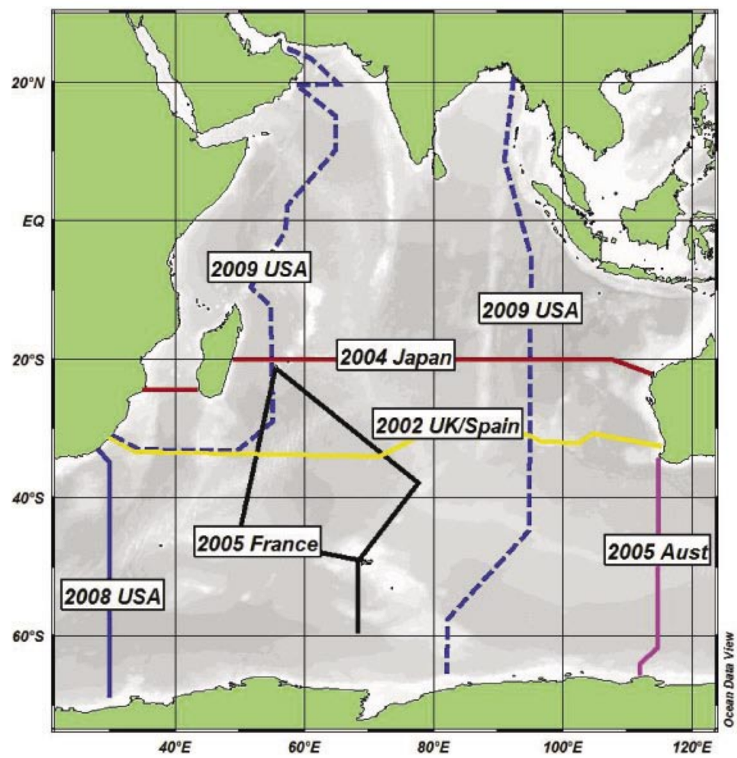


Figure 30. Planned or recently completed hydrographic sections in the Indian Ocean (source: http://ioc.unesco.org/ioccp).

International CLIVAR Project Office
National Oceanography Centre
Empress Dock
Southampton, SO14 3ZH, United Kingodom

email: icpo@noc.soton.ac.uk
tel: (0) 2380 596777
Fax: (0) 2380 596204
http://www.clivar.org