A SOUTHERN HEMISPHERE PERSPECTIVE: MONSOON, SEASONAL AND INTERANNUAL APPLICATIONS OF AN INDIAN OCEAN OBSERVING SYSTEM

Gary **MEYERS**, Stuart **GODFREY**, Arnold **GORDON**, Peter **HACKER**, Mark **JURY**, Bill **LAU**, Satish **SHETYE**, Tien **SRIBIMAWATI**, Toshio **YAMAGATA**

ABSTRACT *- This paper explores the path between Indian Ocean observations and applications. Farming impacts of interannual climate variation in Australia and South Africa are associated with gains and losses of annual production and profit. Management of impacts is beginning to rely on timely, oceanic information and prediction from specific ocean-areas. Floods in Asia are related to intraseasonal oscillation over the eastern Indian Ocean. Recent progress in understanding ocean-dynamics in these areas is reviewed. An interannual Indian Ocean dipole (IOD) in SST anomalies and rainfall is identified and related to internal oceanic processes. Regional SST anomalies of IOD are located in the Indonesian-Australian Bight and the western tropical Indian Ocean. The impact of the global ENSO SST anomaly pattern on Asian/Australian Monsoon rainfall is compared to the impact of regional SST. Further research is needed to determine if IOD is a self-sustaining, independent mode of variability unique to the Indian Ocean. Intraseasonal oscillation (ISO) is associated with strong winds, heavy precipitation, and cool SST anomalies in the eastern Indian Ocean. Spatial and temporal scales of oceanic structure associated with ISO are reviewed. Warming transport of Indonesian Throughflow (ITF) into the region has recently been directly measured. Progress in understanding the regional SST anomalies provides a background for recommendations on sustained observations to monitor Indian Ocean structures such as IOD, ISO and ITF.*

INTRODUCTION

The present day sustained observations for climate in the Indian Ocean are the VOS XBT network (Harrison et al., OCEANOBS99), the sea level network, some drifters and floats and occasional long lasting process studies, such as the equatorial current meter array (Reppin et al., 1999). In comparison to sustained observations in the Pacific Ocean, the Indian Ocean is very weak. Probably the main reason for this situation is that El Nino is essentially a Pacific Ocean phenomenon. Besides intrinsic scientific interest, the economic importance of El Nino attracted a large investment of resources during the TOGA Programme. The drivers for investment are changing now, or at least expanding. Phenomena of economic importance like El Nino have been discovered in the Indian Ocean.

Enhancing our understanding of the Indian Ocean and beginning to develop applications is very import to countries in the Indian Ocean region. The global ENSO phenomenon (Leetmaa et al., OCEANOBS99) is important, no doubt. But, it is not enough to rely entirely on prediction of El Nino or La Nina. Even if the predictions are accurate, the resulting pattern of rainfall may be quite different in each episode. The two great ENSO's of the century, 1982/83 and 1997/98, are a good example. The 1982/83 episode produced a devastating drought in Australia, while the 1997/98 episode produced slightly below normal rainfall. A hypothesis is that seasonal climatic conditions in our region are very sensitive to details of the regional pattern of SST, as well as the global ENSO phenomenon. Recent progress that underpins this hypothesis, and applications of this understanding are reviewed here.

CLIMATE IMPACTS AND OCEAN-DATA APPLICATIONS

Climate variability is a strong feature of many countries. It has large impacts (both positive and negative) on agriculture, fisheries, tourism, mining, manufacturing, human health, natural environment and built environment. Progress in understanding the role of oceans in climate and much improved skill in predicting seasonal climatic conditions is leading to a rapid expansion in development of applications. Improved prediction will impact on the lives of almost 2/3 of the world's population living in the Asian-Australian Monsoon region. The economic importance of applications is potentially very large, even if annual gains and losses caused by climate are improved by only 1%. Potential savings have already been documented for the application of climate predictions in agriculture.

The total value of Australian crops is usually about $A30 billion, while the gains and losses from one year to the next are as large as $A6 billion (Fig. 1) (Nicholls, 1985, updated). Many factors influence the crop value, including market forces, technology, farm management decisions and climate. Differences from year to year are however correlated with the climate signal. May-October sea surface temperature (SST) anomalies in the seas north of Australia between 5°S and 15°S are influenced by the El Nino Southern Oscillation (ENSO) phenomenon from the Pacific Ocean, as well as the somewhat independent variations in oceans near Australia. The SST is correlated with crops because rainfall over Australia is very sensitive to the regional pattern of SST, as well as the global ENSO. The good correlation raises the question: could gains be improved and losses minimised if accurate predictions of SST were available to guide the management of farms? Already a statistical prediction based on the Southern Oscillation Index is used in Queensland, Australia to support the management of wheat farming (Hammar et al, 1996). The prediction is made in April/May prior to planting and a decision is made on how much fertiliser to use. A potential 10% gain in productivity can be demonstrated. While such a large improvement may not always be expected, this capability needs to be extended to other industries and other regions. This will require research to improve the skill and lead-time of SST prediction in all the oceans around Australia.

South Africa offers an example where data from the Indian Ocean is in operational use to predict crop-yield with a six-month lead-time, to reduce vulnerability in farm management. With interest rates typically 20%, annual borrowings by commercial farmers are particularly risky. The annual maize harvest generates US $1 billion on average, and variations of ± 80% are typical. Maize is planted during November and harvested during the following April. The yield during recent years is typically 4 tons per hectare) and differences from year to year are about 1 sigma or 2 tons per hectare (Fig. 2, dots). Half the variance of yield is explained by a liner relationship involving ocean and atmosphere parameters observed six months or more before the April harvest. The parameters are September-November SST anomaly in the subtropical Indian Ocean southeast of Madagascar, July-September meridional wind anomaly in the equatorial western Indian Ocean and the barometric pressure difference across the South Indian Ocean. The predicted yield (Fig. 2, solid line) tracks the observed values creating relatively small interannual differences, particularly in dry years associated with strong El Nino conditions in 1982/3 and 1991/2. The rainfall over southern Africa is related to both the global ENSO and regional SST patterns (Cane et al., 1994; Jury et al., 1994; Jury et al., 1999; Reason, 1999). The key SST areas that are believed to have the greatest effect include: the central and western tropical Indian Ocean, the Agulhas subtropical gyre and the tropical southeast Atlantic Ocean.

Application of climate predictions can extend beyond supporting farm-management decisions, into an integrated assessment of economic and policy tools, such as taxation or drought relief. A new CSIRO research project appropriately named “From Oceans to Farms: Integrated Management of Climate Variability” (A. Ash and M. Stafford-Smith, personal communication) will firstly investigate how ocean-data and long-term forecasts can be applied to improve agricultural gains in good years, and cut losses in bad years. New forecast methods will be developed and evaluated in conjunction with industry needs, across a range of industries including grains, extensive grazing, cotton and sugar. The forecasts will be assessed using agricultural models that simulate production under a range of management strategies in a way that can compare forecasts with no-forecasts. The output from the models will be used to assess economic impacts and to develop simple rules of thumb for adoption by industry. Then the project will ambitiously endeavour to integrate climate science and impact assessment to cover the complete pathway from climate inputs-to-impacts-to-economics and policy (Fig. 3). To achieve this vertical integration the project will foster a multidisciplinary team made up of CSIRO Divisions (Marine Research, Atmospheric Research, Wildlife and Ecology, and Tropical Agriculture), the Bureau of Meteorology, and state agricultural agencies. The project is partially supported by the Climate Variability and Agriculture Program (CVAP), a funding activity of rural research and development agencies.

Severe events and oceanic impacts are also associated with Intraseasonal Oscillation (ISO). The great flood over the Yangtze River Basin ranked as the number one in the category of most devastating economic loss due to natural disaster in 1998. Over 3700 deaths, 223 million people displaced, with property damage up to $30 billion. Analysis of the field data from the South China Sea Monsoon Experiment (SCSMEX), shows that the great flood of the Yangtze came partly as a sequence of ISO pulses coming from the Indian Ocean. The first ISO was detected, with a remarkable organization, complete with double cyclones, westerly winds and supercloud cluster structure over the Indian Ocean. The ISO spawned an intense monsoon depression over the Bay of Bengal, leading to the Bay of Bangladesh flood (30 million displaced, 3.4 billion damage), and then followed by the onset of the South China Sea Monsoon.

Most interesting, there is an inverse relationship between the South China Sea (SCS) monsoon convection and the rainfall over the Yangtze river region, on times scales of 30-40 days. The SCS monsoon onset occurred at about May 20, the major break occurred at about June 10-20, while a strong low level convergence zone developed over the Yangtze region. The monsoon convective zones jumped from the northern SCS to about 30°N and stayed more or less in place for the next 4-6 weeks. This phenomenon has been associated with a sustained synoptic to mesoscale development of the Mei-yu front, modulated by the ISO. In that sense, the 1998 events was not unusual, but the unusual aspects were the intensity and the longevity of the monsoon trough. SCSMEX will investigate two hypotheses. First, the warm SST over the eastern Indian Ocean and the subtropical western Pacific during the growing phase of La Nina may have contributed to the intensity and the stationarity of the Mei-yu rain pattern. Second, excessive rainfall during the previous spring may have moistened the land surface and further anchored the monsoon trough over the Yangtze river basin. The ISO is clearly a key player in the series and floods and droughts occurring over the Asian-Australian monsoon region during 1997-98. One may think of them as triggering extreme cases of regional monsoon onsets and breaks and revival, on intraseasonal time scale. A key issue is to understand the role of oceans in the ISO and if possible to predict the occurrence of extreme events.

REGIONAL VARIABILITY IN THE INDIAN OCEAN

Climate-impacts in Africa, Asia and Australia are at least partly controlled by oceanic structure in the Tropical Indian Ocean and Indonesian Seas. For the seasonal to interannual time scale, several studies within the past year have related regional variations of SST anomaly to oceanic processes. This is the first step toward improving the prediction of SST.

Earlier a pattern of SST anomalies, called Indian Ocean Dipole (IOD) was documented and related to patterns of rainfall as far away as eastern Australia (Nicholls, 1989). A well-known pattern of synoptic weather provides the link for the remote SST/rainfall teleconnection (Tapp and Barrel, 1984). A recent description of IOD is based on composites of SST anomaly for the upper and lower quartiles of rainfall in Victoria (southeastern Australia) (Figure 4) (T. Ansell, personal communication). A statistical scheme for prediction of rainfall throughout Australia based on regional IOD and global ENSO (Drosdowsky and Chambers, 1998) has better skill than the prediction based on a global index alone. Vertical heave of the thermocline is associated with the formation of SST anomalies in the poles. The thermocline depth is forced by both the ENSO wind field over the Pacific Ocean, and the regional wind field over the eastern, tropical Indian Ocean (Meyers, 1996; Masumoto and Meyers, 1998).

The past year has seen substantial progress in understanding ocean-dynamics within the IOD. Saji et al (1999) identified a simple index time series called Dipole Mode Index (DMI) to represent SST anomalies of the tropical Indian Ocean (Fig. 5, blue). It is the difference of SST anomaly between the tropical western Indian Ocean (50°E - 70°E, 10°S - 10°N) and the tropical southeastern Indian Ocean (90°E - 110°E, 10°S - Equator). The DMI time series is clearly related to wind anomalies over the equatorial Indian Ocean (Fig. 5, red) (70°E - 90°E, 5°S - 5°N). DMI is plotted with the NINO3 anomaly index (Fig. 5, black line) and is seen to be somewhat independent of ENSO. The strong, negative DMI events in 1961, 1967 and 1994 coincide respectively with no ENSO, a La Nina and a weak El Nino, while the strong DMI events in 1972 and 1997 coincide with El Nino. The correlation between DMI and NINO3 is 0.35.

The on and off coupling between SST anomaly patterns in the Indian Ocean and ENSO is a challenge to future research. It is not yet clear if the Indian Ocean mode represents a self-sustaining, independent mode of variation within the Indian Ocean. In order to better understand the development of Indian Ocean SST anomalies, Saji et al. (1999) composited the recent six extreme DMI events of 1961, 1967, 1972, 1982, 1994 and 1997 (Fig. 6). Seasonal phase locking is a key characteristic of the DMI time series. Significant cool SST anomalies appear around May-June in the Java upwelling zone with southeasterly wind anomalies. The pattern intensifies during July-August and September-October, as strong easterly anomalies develop along the equator and the western Indian Ocean develops a warm SST anomaly. Concomitant with the equatorial wind, winds along the coast of Indonesia tend to cool the ocean through enhanced seasonal evaporation and coastal upwelling. The anomalies die out rapidly after the monsoon transition season. Rainfall and surface pressure data show that convection is enhanced over the warm SST anomaly in the west (north of Madagascar) and suppressed over the cool anomaly in the east (off Indonesia). Saji et al. conclude, “Thus cooling, once initiated in the east, can be sustained and amplified through positive feedback between precipitation, surface wind and SST.” The idea that the Indian Ocean may contain a regional, self-sustaining mode of variability is an inviting idea for future research. Observation of the key dynamic and thermodynamic processes will be required.

Simulations of oceanic structure during the 1994 event using three different stand-alone ocean models (Behera et al., 1999; Vinayachandran et al., 1999; Schiller et al., 1999) are in good agreement with available (but scanty) oceanographic data. In particular, the cool anomalies along the coasts of Indonesia are well simulated and confirm the role of upwelling and evaporation in anomaly-formation. An important lesson from these studies is that the biggest errors in the stand-alone ocean models seem to come from uncertainties in the surface fluxes (wind stress, heat and moisture flux). There is little scope for improving model-physics until better flux fields are available. This is another challenge for the Indian Ocean Observing System.

Growth of IOD by regional, positive feedback was also suggested by Behera et al. (1999). They emphasised that anomalous moisture transports over the cool Indonesian anomalies feed enhanced convection over India and East Asia in June-July-August 1994, as well as the convection zone over the western Indian Ocean. They suggested that a meridional feedback between the enhanced convection in the Asian summer monsoon and suppressed convection off Indonesia maintain the anomalies, in addition to the zonal feedback suggested by Saji et al. (1999). The importance of the study by Behera et al. (1999) is the apparent interaction of ocean, land and atmosphere.

Considerable progress was made in 1999 in understanding ocean-atmosphere interaction and the dynamics of regional variability in the Indian Ocean. Compared to the gradual progress in the Indian Ocean during TOGA, it was a year of noteworthy breakthroughs. The key regions where dynamic processes were identified in the ocean are largely the same regions that seemed to be important in the earlier discussion of impacts and ocean-data applications.

GLOBAL AND REGIONAL CONTROL OF RAINFALL

With increasing understanding of regional oceanic processes such as IOD, there is a need to quantitatively estimate the relative roles of the global ENSO phenomenon and regional processes in determining rainfall in the Asian/Australian (AA) Monsoons. While the methods are still being developed and further research with coupled models is needed, the results seem to support the idea that regional processes may be significant in any attempt to predict rainfall.

Lau and Wu (1999) identified regional features of rainfall anomaly throughout the AA Monsoon region during the 1997/8 ENSO episode. During the Asian summer Monsoon there were alternating dry and wet bands extending from the equatorial Indian Ocean to subtropical East Asia and the western Pacific. During the Australian summer Monsoon coherent rainfall anomalies were concentrated over Indonesia and the tropical Indian Ocean.

Lau and Wu (1999) have separated regional and global ENSO effects by computing the dominant modes of covariability between rainfall and SST for a 19 year period, for two seasons May to September (Asian Monsoon) and the October to February (Australian Monsoon). The analysis is carried out firstly for the global data set, then for a subset covering only the AA-monsoon domain. The global analysis can only account for large scale features, which turn out to be the global ENSO signal. The first mode of the regional analysis is an expression of the global signal. Regional scale mechanisms appear in the higher modes of regional analysis. Correlating the regional modes to observed patterns of rainfall leads to an estimate of the amount of rainfall variance during Asian summer Monsoon captured by each mode, each year (Fig. 7). The result is that the global ENSO mode explains about 30-40 percent of the JJA rainfall anomalies over the entire region; while regional processes explain about an equal amount. For the Australian summer monsoon, the global ENSO mode seems to be a distinctly stronger control on DJF rainfall than the regional mechanisms. A possible reason for weakening of the regional effect of eastern Indian Ocean SST in January/February was proposed by Saji et al. (1999).

INTRASEASONAL OSCILLATION, FRONTS AND CIRCULATION FEATURES

The WOCE Hydrographic Program (WHP) expedition in the Indian Ocean provided high quality temperature, salinity and velocity data along several sections. As an example in the Bay of Bengal sector, the data provided almost synoptic snapshots of the vigorous circulation pathways and upper ocean temperature and salinity structure (Hacker et al., 1998) including previously unobserved detail. The paper identified strong across-Equator flow, a sharp salinity front in the central bay near 10°N, and large temperature and salinity signatures associated with the upper-ocean circulation. A weakness of the WHP sections is that they only provide snapshots of upper ocean fields which vary strongly in time. A moored current meter array south of Sri Lanka (Reppin et al., 1999) provided important temporal information on the exchange between the Bay of Bengal and the Arabian Sea resulting from the monsoon forcing. These papers, together with published climatologies, provide the space and time scale information needed for design of a monitoring system.

At intraseasonal time scales the boreal summer monsoon oscillates between active and break periods during its onset and evolution (Webster et al. 1998). The Joint Air-Sea Monsoon Interaction Experiment (JASMINE) began field work in 1999. Its goals are to study the intraseasonal modes, to quantify how the modes are coupled to annual and interannual variability, and to determine the degree to which the modes are the result of coupled ocean/atmosphere processes. The active and break period anomalies in precipitable water content (for example) are large-scale features spanning the Indian Ocean and neighbouring land masses (Fig. 8). The active composite (Fig. 8, top) shows a positive anomaly near 13°N, extending southeast to Indonesia and northwest Australia; near 80°E, from the Equator to 25°S, the anomaly is negative. The break composite (Fig. 8, bottom) shows a strong negative anomaly centered north of the Equator in the Bay of Bengal; south of this feature, from the Equator to 10°S, the anomaly is positive. (For additional figures, see the JASMINE web site at http://paos.colorado.edu/~jasmine/). These intraseasonal oscillations form in the central Indian Ocean, propagate eastwards, bifurcate along the equator and propagate poleward to the north and south as distinct vortices in the Bay of Bengal sector. The northward (and strongest) mode brings active periods of the monsoon to South Asia. The active periods are associated with strong winds, heavy precipitation, and cool SST anomalies. Prediction of the monsoon onset and the evolution of the active and break periods has important consequences for region-wide agriculture and water resource planning.

The JASMINE field work during April and May 1999 focused on observations of atmospheric convection, air-sea fluxes and the upper ocean response to atmospheric forcing. The ocean component's goals were to document: the meridional structure of temperature, salinity and velocity fields, the mixed layer and barrier layer structures, and the upper ocean heat, freshwater and momentum budgets as they vary during active and break periods within the Bay of Bengal sector. The 1999 field work successfully captured the active and break period variability, completed five meridional sections, and conducted two 5-day budget surveys in the fresh water lens region north of the Bay of Bengal front. Fig. 9 shows the current reversals associated with the strong intraseasonal forcing during the onset of the southwest monsoon and the meridional scales of the circulation features. Hacker et al. (OCEANOBS99) provides additional JASMINE results, especially the temperature and salinity structure of the mixed and barrier layers and the Bay of Bengal front.

The recent WOCE and JASMINE observations provide new detail on the oceanographic fields and facilitate the design of an ocean observing strategy in the Bay of Bengal sector. The complete lack of time series air-sea flux observations, such as exist for the Arabian Sea sector (Weller et al., 1998), is a critical void (Taylor et al., OCEANOBS99). Likewise, an ongoing program of ocean time series needs to be initiated (McPhaden et al. and Send et al., OCEANOBS99). Moorings to measure currents, temperature and salinity are needed near 80°E and 88°E to adequately address the horizontal heat and freshwater flux components of the hydrological cycle.

The mooring lines need to resolve the location of the Bay of Bengal front, the vigorous circulation pathways, and the close proximity of the eastern boundary.

INDONESIAN THROUGHFLOW

The Indian Ocean is associated with the monsoon system while the western tropics of the Pacific Ocean are strongly coupled to the ENSO climate phenomenon. The Indonesian Seas mark a transition from ENSO to monsoon prevalence. Observations and models indicate the presence of a significant flow of Pacific water into the Indian Ocean. This flow, referred to as the Indonesian Throughflow or ITF, is strongly modulated by monsoon and ENSO forcing. The ITF is an important, if not key element in the heat and freshwater budgets of both oceans, including the sea surface temperature (SST) which links the ocean to the climate system. Thus the ITF may act to link the ENSO and monsoon climate regimes. Estimates of the volume transport of ITF vary widely, but recent direct measurements by current meter moorings in Makassar Strait gave an average value of 9.3 Sv (Fig.12) (Gordon et al., 1999). The continuous measurements highlight variability of ITF at a broad range of time scales including intra-seasonal, seasonal and inter-annual, all at about the same amplitude. The energetic variability of ITF combined with complex topography will require an ambitious array of direct and indirect current measurements.

The Makassar Strait measurements indicate that the ITF is most persistent within the thermocline layer reflecting interocean forces, rather than within the surface layer which responds to the regional monsoonal wind forcing. This has important implications to regional SST patterns and climate. Some of the Makassar ITF transport flows through the Lombok Strait, but most passes through the Flores Sea into the Banda Sea, to enter the Indian Ocean by way of the passages on either side of Timor (Waworuntu et al., 1999). At deeper levels, additional transport derived from the deep eastern throughflow channels joins the ITF. While it remains to be conclusively shown, the 1997-1998 Makassar transport results compared to previously published ITF estimates based on Indian Ocean data, suggest that South Pacific water masses would provide only minor contribution to the ITF.

The Indonesian Seas are not a passive channel linking the two oceans, rather over its substantial area the ITF thermal and salinity stratification and the SST values are significantly modified by regional tidal induced mixing and by sea-air fluxes. Within the Indonesian Seas water masses are modified by sea-air fluxes acting on the general upwelling regime of the Banda Sea. The Banda Sea responds to ENSO, monsoon and higher frequency forcing of SST and sea-air fluxes. Changes in the depth of the thermocline associated with ITF (Ffield et al., 1999) are likely to be communicated to SST in the presence of strong tidal mixing. The ITF consequently will carry important feedbacks to convection over the “maritime continent”. Since it is one of the most active areas for deep tropical convection, there will be an impact on regional, if not global, climate.

RECOMMENDATIONS FOR THE OBSERVING SYSTEM

The regional, dynamical features of the Indian Ocean such as IOD, ISO and ITF are the targets for sustained observation. The key fields required for a better understanding and applications are: precipitation and evaporation, surface heat and momentum fluxes, temperature and salinity structure of the upper ocean including the barrier layer, circulation, horizontal heat and freshwater flux and river inflow.

In the future, earth observing satellites will provide a basis for estimating many of the key fields. Satellites already provide estimates of SST, precipitation, heat fluxes, wind and sea level. For the Indian Ocean the satellite sea level data is crucial, because the existing network to observe baroclinic structure is very sparse. Improvement of in situ data collection will come slowly in incremental steps. In the mean time, the satellite data must continue.

Recommendation: Long-term continuation of the satellite observations is essential, in particular for the Indian Ocean where resources for in situ measurements will always be scarce.

With the hydrological cycle as a central focus of future Indian Ocean studies, high resolution (space and time) observations of sea surface salinity (SSS) are essential. Based on published climatologies, the annual mean surface salinity increases by more than 1.0 psu from the Equator to 20N in the Arabian Sea sector and decreases by 3.0 psu on the Bay of Bengal sector over the same latitude range. In the Bay of Bengal sector vigorous circulation features produce surface salinity signals of 1-2 psu over horizontal scales of 100 km. Realistic model simulations suggest these features evolve over time scales from intraseasonal to interannual. Remote sensing of SSS (Lagerloef et al., OCEANOBS99) would provide an essential data set for description of spatial and temporal variability and model evaluation. It will be required for optimal applications of altimeter data.

In situ measurements will in turn be needed for calibration, enhancement and optimal application of all forms of satellite data. In some cases there is no substitute for in situ measurements, such as details of the vertical density profile (mixed layer depth, barrier layer depth, higher vertical modes of ocean circulation) and accurate measurement of the transport of currents. In this section we table recommendations primarily concerned with in situ measurements. A draft plan of sustained observations in the Indian Ocean and Indonesian Throughflow is presented in Fig. 11 for discussion.

INDIAN OCEAN--LARGE SCALE NETWORKS

Precipitation and evaporation, surface heat and momentum fluxes

Any observation network whose main “payload” is climate prediction needs to place strong emphasis on obtaining accurate surface fluxes. The predictions depend critically on surface heat and freshwater fluxes, and on ocean advection and upwelling, driven by wind stress. The uncertainties in present day flux-products are made painfully clear when driving an ocean model with “observed” fluxes. It is necessary to add substantial flux corrections. If this is not done, the model’s SST quickly drifts outside climatologically observed values. At present heat storage in the oceans can be measured more accurately than surface heat flux. This deficiency limits data analysis and diagnostic studies to identify ocean-climate processes. Proven methods to measure fluxes are the Triton/Tao array in the Pacific (McPhaden et al., OCEANOBS99), and carefully controlled Volunteer Observing Ships (VOS) with meteorological stations (Taylor et al., OCEANOBS 99). Process studies are essential to improve the parameterization of fluxes.

Recommendation: Extend the Triton/Tao array with meteorological instruments across the Indian Ocean. Selected VOS meteorological stations.

Temperature and salinity structure of the upper ocean including the barrier layer

Very little is known about the internal, oceanic structure of the Indian Ocean Dipole and the other SST features discussed in this paper. Observations of temperature and salinity are needed for research to identify the mechanisms that generate and maintain SST anomalies, and for operational modeling and prediction. Salinity is an essential feature of the surface layer of Indian Ocean and an essential aspect of the surface heat budget. Enhancement of ongoing thermal monitoring with salinity measurements is necessary. A recent Workshop to review the upper ocean thermal and salinity networks (Harrison et al., OCEANOBS99) recommended a shift from area-sampling to line-sampling for the VOS XBT, XCTD, thermosalinograph (T-S) network (Fig. 11). The arrangement of frequently repeated and high density lines recommended at the Workshop is strongly endorsed. Large gaps between the lines in the equatorial zone can be filled by the Triton/Tao array (McPhaden et al., and Send et al., OCEANOBS99). The thermohaline structure of the Indian Ocean requires deployment of Argo floats (Roemmich et al., OCEANOBS99). Especially areas that have a variable, low salinity cap such as the Bay of Bengal and the Indo-Australian Bight need floats to make optimal use of altimeter data and to understand the surface heat budget.

Priorities for large scale monitoring were discussed at the Asian-Australian Monsoon Workshop in St. Michaels, Maryland 29-31 July 1998. The Bay of Bengal and eastern Indian Ocean were given highest priority because of the lack of modern measurements in this region.

A high priority Triton/Tao line should be 80°E to study the coupling and transfer between the Arabian Sea and the Bay of Bengal. Upper ocean T-S and currents should be measured at 5°N, 2°N, 0°N, 5°S and 12°S. Complete air-sea fluxes should be observed at one of these sites (0°N). In the Bay of Bengal sector, upper ocean T-S and currents should be monitored near 88E (international waters). We recommend sites at 12°N (within the fresh water pool), 8°N, 5°N, 2°N, 0°N, 5°S and 12°S. (The 5°S and 12°S sites could be moved to 95°E to better sample a regional maximum of air-sea fluxes.) Complete air-sea fluxes should be observed at two sites, 12°N and 5°S and possibly at 0°N.

A Triton/Tao line is required in the Java upwelling zone of the Indian Ocean Dipole.

Recommendation: Extend the Triton/Tao array across the Indian Ocean with subsurface temperature and salinity. Current meters where the arrays meet the equatorial and coastal wave-guides and fronts. Selected VOS XBT/XCTD/T-S lines. Deploy Argo. Areas of highest priority are the Bay of Bengal and Indo-Australian Bight.

Circulation, horizontal heat and freshwater flux and river inflow

The need for near surface currents to identify process in the surface layer heat budget was mentioned above. Vertically integrated transports of mass, heat and freshwater are required to understand the role of the Indian Ocean in the climate system. Roemmich and colleagues have demonstrated the feasibility of sustained transport-measurements on transoceanic high density XBT/XCTD lines. A recent Workshop to review the upper ocean thermal and salinity networks (Harrison et al., OCEANOBS 99) recommended a set of high density XBT/XCTD lines (Fig. 11), which are strongly endorsed. The lines transect the Indian Ocean into large, closed regions - Arabian Sea, Bay of Bengal, South Indian Ocean, western boundary and Southern Ocean. IX1 monitors ITF. IX10 monitors flows in and out of the Arabian Sea and Bay of Bengal. IX2 monitors the subtropical gyre. IX7 monitors eddies of the western boundary current system.

Recommendation: Implement high density XBT/XCTD lines

INDONESIAN THROUGHFLOW

Oceanographers and climatologists are interested in determining not just the mean ITF from the Pacific to the Indian Oceans, but also its variability from intraseasonal to interannual scales, the resultant interocean heat and freshwater fluxes and air-sea interaction in the surface layer. An intense array of in situ measurements is required (Fig. 11, inset).

There are a number of methods that may provide cost effective indirect ITF information, such as sea level slope, temperature sensor moorings, repeat XBT/XCTD sections (which also provide important water mass information), deep pressure and inverted echo sounder sensors (PIES) and satellite remote sensing of sea level. For all of these approaches, assumptions are needed to link their data to ocean currents and the ITF. These methods may be considered as proxy ITF monitoring. Direct measurement of the ITF by current meter and ADCP moorings, or bottom moored ADCP instrumentation, may be needed for some period to help mould the required algorithm to convert the proxy data to ITF information. Hull mounted ADCP may help build the transport to isotherm depth or sea surface slope relationships, but strong tides characteristic of the region may make this a difficult task.

A long term plan should have as an operational objective to gradually replace the direct ITF monitor procedures with the most effective proxy measurements. In addition to what to measure is the question of where to measure it?

Recommended ‘what and where’:

1. Inflow between the Philippines and New Guinea: The inflow channels are complicated by the energetic Mindanao and Halmahera Eddies, with only a fraction of the water moved within these eddies ultimately contributing to the ITF. The inflow channels do not offer a convenient monitoring site. It is recommended that satellite altimetry data be used to track the variability of the Mindanao and Halmahera eddies, as they may be related to the ITF, and such data may eventually provide proxy information.

2. Interior Channels: Deep interior channels are found both east and west of Sulawesi Island.

[A] Makassar Strait: Recent measurements indicate the bulk of the ITF, strongly modulated by ENSO, is carried within Makassar Strait, as predicted by water mass analysis and models. The Makassar Strait has a convenient choke point: a 45 km wide 2000 m deep passage near 3°S (the shallow sill, about 600m, to the south is too wide with numerous channels to provide a direct monitoring site). A current meter mooring with upward looking ADCP at the deepest depth the ADCP technology allows (at sea floor?) within the Makassar choke point is recommended. The relationship of transport versus thermocline found in Makassar Strait if confirmed by a longer timeseries, may offer an efficient long term monitoring strategy for the Makassar Strait and perhaps other passages. Therefore repeat VOS XBT/XCTD lines in Makassar Strait is recommended.

[B] Lifamatola Passage: Significant ITF contributions through the eastern deep channels cannot be ruled out, mainly within the lower themocline and within the deeper layers. For density driven sill overlow the primary eastern channel is the Lifamatola Pasage. The thermocline layer in the eastern channels offer a very wide cross-sectional area, but water mass analysis suggests Lifamatola Passage is the main path for lower thermocline water. A current measurement mooring in the Lifamatola Passage is sugested. Repeat VOS XBT/XCTD with hull mounted ADCP within the eastern channels may provide proxy data applicable to the larger region, when calibrated to the Lifamatola mooring data. The XCTD data will provide water mass information, which is important as it appears that the ratio of North Pacific to South Pacific waters in the eastern channels varies with ENSO phase.

3. Export Channels: Export of Indonesian waters into the Indian Ocean occurs within the many passages within the Lesser Sunda Island Arc, primarily within the deep channels north and south of Timor and within the Lombok Passage, though seepage through the many other channels may

represent significant percentage of the ITF. The sea surface slope time series by the shallow pressure gauge array is promising, if well calibrated by a measured transport profile at each channel. Moorings to provide those data for the sea surface slope approach is recommended.

4. Australian-Indonesian Bight: The full ITF is collected and passes into the Indonesian-Australian Bight and into the South Equatorial Current of the Indian Ocean. The ITF is quite wide and a picket fence of moorings is not feasible, but it may be an ideal site for the proxy data approach, such as the ongoing repeat XBT (with added XCTD and hull ADCP) line. The XCTD data is very important as the ITF in the Bight is flanked to the north by an Indian Ocean thermocline “look-alike” to ITF waters, carried into the region by the South Java Current, that may confuse estimate of the ITF. Satellite altimetric data should prove a useful proxy monitoring procedure.

Recommendations for in situ ITF measurements:

Current Meter moorings with upward looking ADCP in Makassar Strait, Lifamatola Passage, the deep channels north and south of Timor and Lombok Channel.

Repeat (biweekly) XBT/XCTD with hull ADCP on the VOS in the Indo-Australian Bight, and in the interior Seas (Makassar, Banda).

Pressure gauges and inverted echo sounders across channels in the archipelago.

PROCESS STUDIES

Process studies are needed to improve parameterization of surface fluxes, to improve understanding of air-sea coupling processes in a region of large freshwater input and to quantify the effect of large-amplitude internal waves on upper ocean mixing and mixed layer evolution. Research ships transiting the region can provide ADCP/CTD sections to describe detailed structure of circulation and heat and freshwater pathways. An adequate description of these fields over the temporally evolving monsoon cycle does not exist.

Recommendation: Design a series of process studies based on intensive observing periods backed up by sustained monitoring.

REFERENCES:

[Behe 99] S.K. Behera, R. Krishnan, T. Yamagata: “Unusual ocean-atmosphere conditions in the tropical Indian Ocean during 1994”. *Geophysical Research Letters*, 1999 (in press).

[Dros 98] W. Drosdowsky and L. Chambers: “Near global sea surface temperature anomalies as predictors of Australian seasonal rainfall”. *BMRC Research Report No. 65*, 1998.

[Ffie 99] A. Ffield, K. Vranes, A.L. Gordon, R. Dwi Susanto: “Temperature Variability within Makassar Strait”. *Geophysical Research Letters*, 1999 (submitted).

[Gord 99] A.L. Gordon, R. Dwi Susanto, A.L. Ffield: “Throughflow within Makassar Strait”. *Geophysical Research Letters*, 1999 (in press).

[Hack 98] P. Hacker, E. Firing, J. Hummon, A.L. Gordon, J.C. Kindle: “Bay of Bengal Currents During the Northeast Monsoon”. *Geophysical Research Letters*, 1998, **25**, 2769-2772.

[Hamm 96] G.L. Hammer, D.P. Holzworth, R.C. Stone: “The value of skill in seasonal climate forecasting to wheat crop management in a region with high climatic variability”. *Aust. J. Agric. Res.*, 1996, **47**, 717-737.

[Jury 99] M.R. Jury: “Tropical Atlantic polarity with global ENSO: ocean-atmosphere response from statistical analysis and numerical simulation”. *Intl J Climatol*, 1999 (submitted)

[Jury 94] M.R. Jury, C.A. McQueen, K.M. Levey: “SOI and QBO signals in the African region”. *Theoretical and Applied Climatology*, 1994, **50**, 103-115.

[Lau 99] K.-M. Lau, H.T. Wu: “Assessment of the impact of the 1997-98 El Nino on the Asian-Australian monsoon”. *Geophysical Research Letters*, 1999, **26**, 12, 1747-1750.

[Masu 98] Y. Masumoto, G. Meyers: “Forced Rossby waves in the southern tropical Indian Ocean”. *Journal of Geophysical Research*, 1998, **103**, C12, 27,589-27,602.

[Meye 96] G. Meyers: “Variation of Indonesian throughflow and the El Nino - Southern Oscillation”. *Journal of Geophysical Research*, 1996, **101**, C5, 12,255-12,263.

[Nich 85] N. Nicholls: “Impact of the Southern Oscillation on Australian crops”. *Journal of Climatology*, 1985, **5,** 553-560.

[Nich 89] N. Nicholls: “Sea surface temperatures and Australian winter rainfall”. *Journal of Climate*, 1989, **2**, 965-973.

[Reas 99] C.J.C.Reason: “Interannual warm and cool events in the subtropical/mid-latitude South Indian Ocean region”. *Geophysical Research Letters*, 1999, **26**, 215-218.

[Repp 99] J. Reppin, F.S. Schott, J. Fisher, D. Quadfasel: “Equatorial Currents and Transports in the Upper Central Indian Ocean: Annual Cycle and Interannual Variability”. *Journal of Geophysical Research*, 1999, **104**, 15,495-15,514.

[Saji 99] N.H. Saji, B.N. Goswami, P.N. Vinayachandran, T. Yamagata: “A Dipole Mode in the tropical Indian Ocean”. *Nature*, 1999 (in press).

[Tapp 84] R.G. Tapp, S.L. Barrell: “The North-West Australian Cloud Band: Climatology, characteristics and factors associated with development”. *Journal of Climatology*, **4**, 1984, 411-424.

[Vina 99] P.N. Vinayachandran, N.H. Saji, T. Yamagata: “Response of the Equatorial Indian Ocean to an unusual wind event during 1994”. *Geophysical Research Letters*, 1999 (in press).

[Webs 98] P.J. Webster, V.O. Magana, T.N. Palmer, J. Shukla, R.A. Tomas, M. Yanai, T. Yasunari: “Monsoons: Processes, Predictability, and the Prospects for Prediction”. *Journal of Geophysical Research*, **103**, 1998, 14,451-14,510.

[Webs 99] P.J. Webster, J.P. Loschnigg, A.M. Moore, R.R. Leben: “The Great Indian Ocean Warming of 1997-1998: Evidence of Coupled Oceanic-Atmospheric Instabilities”**.** *Nature*, 1999.

.