Applications of an Indian Ocean Observing System to Climate Impacts and Resource Predictions in Surrounding Countries in the Context of ENSO-Monsoon Teleconnections

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Abstract

We explore the path between Indian Ocean observations and monsoon dynamics, the societal impacts of interannual climate variations and applications of resource predictions in southeastern Africa, the Mascarene Islands, India, southeast Asia and Australia. Recent progress in understanding ocean dynamics associated with SST variation is reviewed. The global El Niño-Southern Oscillation (ENSO) affects monsoon winds and ocean temperatures in a manner consistent with, but lagging, the Pacific. The ENSO influence often propagates across the tropical Indian Ocean from Africa to Indonesia, modulating the tropospheric moisture flux over the Indian Ocean and rainfall in surrounding continents. An east-west dipole in SST anomalies and monsoon rainfall is identified and related to the atmospheric Walker Cell. It appears partially in response to global ENSO conditions during build-up phase (July-Nov.). The eastern 'node' is confined near Sumatra, whilst the western centre of action extends from the Maldives to the Seychelles Islands. Correlations indicate that the strength of ENSO in the Indian Ocean region has decreased in recent decades, while large scale, spatial and temporal patterns suggest independent variations of the Indian Ocean. Apart from annual variations of the monsoon and year-to-year fluctuations of climate, short-term weather events have a dramatic impact on countries around the Indian Ocean. Recent floods in southern (2000) and eastern (1997-98) Africa and southeast Asia (1998) are related to SST patterns and localised atmospheric responses. Predictions of the future availability of food and water resources, and short-term forecasts of storm events are some of the decision tools that can be offered through information from ocean data. The close relationship between regional SST anomalies and impacts on the food and water resources of surrounding countries provides a strong motivation for sustained observations in the Indian Ocean. A specific design plan for the observational network is proposed, linking eastern and western efforts in an efficient manner.

Keywords: *Indian Ocean, Climate Impacts, SST patterns, ENSO responses*

1. Introduction

In comparison to the ocean observing network in the Pacific, the Indian Ocean is poorly sampled. Sustained observations for climate in the Indian Ocean include the VOS XBT network (Harrison et al., Oceanobs99), the sea level network (GLOSS), some drifters and floats and process studies such as the equatorial current meter array (Reppin et al., 1999). Reasons for this situation are two-fold: the center of global El Nino Southern Oscillation (ENSO) activity is in the Pacific Ocean; and many countries around the Indian Ocean have limited economies, hence government support for oceanographic endeavours is lacking. The economic importance of the phase of ENSO has attracted considerable investment by developed countries in recent decades, particularly the USA whose climate is strongly impacted by the Pacific (Leetmaa et al., Oceanobs99). The drivers for investment are expanding with the realisation that climate predictions can help mitigate fluctuations in global resources, in particular around the Indian Ocean where climate affects the lives of so many people. Also, scientific interest in the Indian Ocean has increased in recent years, as a ‘source’ of ENSO variability, both at interannual and intraseasonal scales, and as a 'source' of other predictable modes of climate variability (e.g. Saji et al., 1999; Webster et al., 1999).

Enhancing our understanding of the Indian Ocean and developing predictive applications in surrounding countries go hand-in-hand. Recent studies show it is insufficient to rely on prediction of SST in the Pacific as an indicator of ENSO uptake over the Indian Ocean. Even if the strength of the Pacific ENSO is accurately predicted, the resulting pattern of rainfall and storm events around the Indian Ocean varies markedly. For example the 1982/83 and 1997/98 El Nino events produced very different impacts. The former event induced devastating drought in southern Africa and Australia, yet the more recent episode produced floods in east Africa and drought across Indonesia: an east–west dipole pattern. More neutral conditions were observed elsewhere over the subtropics: India, Australia, and southern Africa. During the El Ninos of 1982, 87 and 97 the anomalies of the All India summer monsoon rainfall were -11.7%, -15.5% and +2% respectively. It can be expected that local climatic conditions around the Indian Ocean will depend not only on remote forcing, but also on local patterns of SST and the manner in which the atmosphere responds. Recent progress that underpins these concepts, and applications of this understanding are reviewed here. Based on that, a proposal is generated for sustained observations.

2. Climate Impacts and Ocean Applications

Climate variability directly affects the livelihoods of > 1 B people around the Indian Ocean. It has large impacts (+ and –) on all aspects of economic activity. Progress in understanding the role of oceans in climate and moderate skill in predicting seasonal rainfall is leading to an expansion in development of applications. Improved prediction offers potentially large benefits if annual gains and losses caused by climate are improved by a only small fraction.

African Region

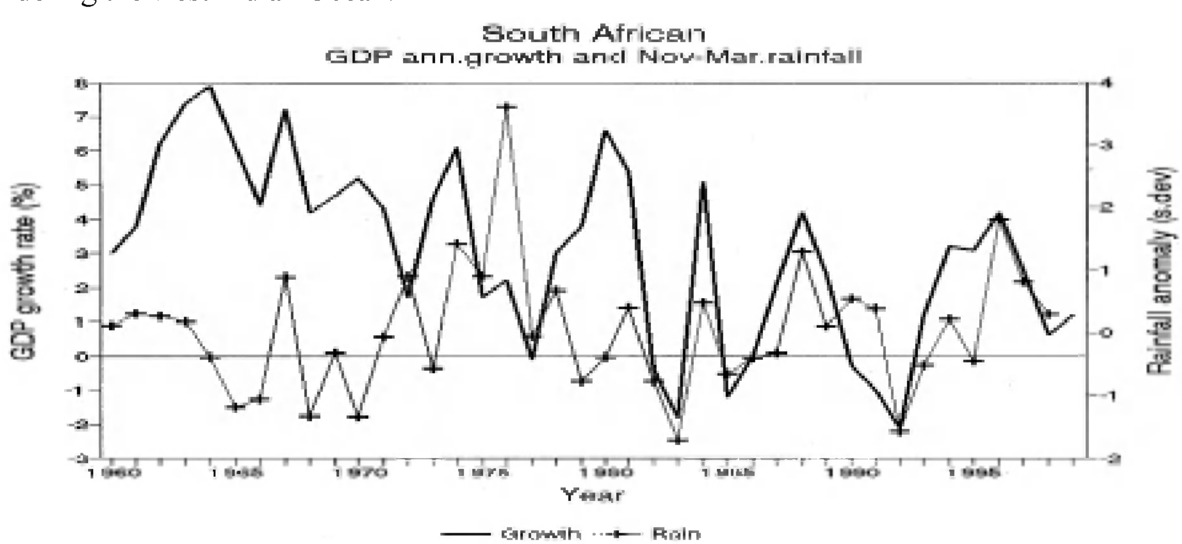
In the west Indian Ocean a number of developing countries can benefit from ocean applications. Mauritius is one example of an island nation with positive economic trends, which lies directly in the path of tropical cyclones. The GDP per capita is $ 3000 pa, and exports make up about 1/3 of this. Hence shipping plays a large role in the economy and reliable forecasts are essential. Economic growth slowed from +5.3% in 1998 to +2.5% in 1999 because of drought conditions. This drought was predicted but not mitigated because of uncertainty in the underlying science and its application. The drought was attributed to global La Nina conditions and locally cool SST, which reduced rainfall and sugar production. This led to a temporary increase in external debt from 8% to 30% of GDP.

Madagascar's economic situation is less positive, yet its natural resources are abundant and relatively unexploited. It is an island of area 587K km^2 with a population of 15 M. Malaria is a significant climate-related threat. GDP per capita stands at $265 pa, one of the lowest in the world. Local hydroelectric power could be developed to improve energy supplies. Rain-fed agriculture constitutes 34% of economic activity and main exports include coffee $40M, cotton $35M, vanilla $17M and prawns $17M. The GDP growth rate in 2000 is expected to decline because of drought in the south, and tropical cyclone damage in the north of the island. This is not the first time that severe weather has hampered economic growth – in 1994 three successive tropical cyclones made landfall near Tamatave harbour with 6 m storm surges putting the country's main oil refinery out-of-commission. Petroleum products were unavailable for most of that year, severely impacting economic activity. Was the unusual cyclone damage associated with the large scale mode of oceanic variability that year (Vinayachandran et al., 1999; Behera et al., 1999)?

In east Africa, Tanzania has seen upward growth in recent years. Its economy is dominated by agriculture which, in turn, is plagued by intermittent rains. Per capita GDP is $ 210 pa, half of which is attributable to rain-fed agriculture. Exports include coffee $117M and cotton $115M. The main destination for exports is India. In the early 1990s Tanzania was burdened by debt, high inflation and currency devaluation. More recently both Tanzania and Kenya have endured repeated drought conditions in 1996 and 1998-2000 related to La Nina conditions and cool SSTs in the west Indian Ocean. The droughts led to a collapse of subsistence crop production and food aid was needed. During the 1997 El Nino, SST warmed above 30 C resulting in coral bleaching along the coast. Economic growth declined, particularly in the tourism sector, as widespread floods occurred. Many of these climate aberrations were foreseen, but mitigating actions by government agencies were insufficient to prevent loss of infrastructure, life and economic hardship estimated at > $ 1 B. With greater underpinning knowledge, confidence in the application of climate predictions will grow.

South Africa offers an example where data from the Indian Ocean is already used to predict crop-yield to reduce vulnerability. With interest rates typically 20%, borrowings by commercial farmers are always at risk. The annual maize harvest generates $1 B and the yield is typically 4 tons per hectare. Differences from year to year exceed 2 tons per hectare. Following some years of research by a consortium of universities, statistical models were developed to predict food and water resources directly from environmental fields. The model that predicts South African maize yield relies on the contrast in SST to the northeast and to the south of Madagascar. Based on this model, predictions are made prior to planting in November. The predicted yield tracks the observed values closely, explaining half the variance. The statistical model is particularly good at forecasting low yields associated with El Nino conditions.

Beyond agriculture, accurate short-term forecasts for shipping are essential to safeguard trade, for coastal design and management, and for optimal exploitation of fisheries resources. Even for a diversified economy like South Africa (GDP $ 162 B), summer rainfall averaged over the country 'explains' 48% of GDP growth rate since 1980 as illustrated below. The rainfall is known to be driven by patterns of SST and monsoon circulations in the Indian Ocean (Cane et al., 1994; Jury et al., 1994; Jury et al., 1999; Reason, 1999, Reason and Mulenga 1999). If economic swings induced by climate are of order 5% ($10 B), and only 20% of this variability can be predicted and mitigated through strategic planning – then $ 2 B could be saved annually in African countries bordering the west Indian Ocean.



India and Southeast Asia

The agriculture sector in India is important for food security for the vast population, which recently crossed one billion. Over 60% of the people depend on agriculture for their livelihood. The phenomenal growth of the production of foodgrains during the green revolution made it possible for the country to move from a food deficit state to one which is by and large self-sufficient, despite the rapid growth in the population. The growth during the green revolution occurred with the introduction of new varieties (particularly of wheat and rice) in irrigated regions and enhanced investments in irrigation fertilizers etc. In contrast, the progress has been rather slow in rainfed areas which account for 65% of the area and about half the production. There are large fluctuations in the annual foodgrain production in response to the variability of the monsoon. With the fatigue of the green revolution setting in, the growth rates over the irrigated regions have decreased significantly in the last decade (Gadgil et al. 1999). Hence the problem of seeking strategies to enhance production of rainfed areas, in the face of the variability of the monsoon, has now become critical. Research programs in India are addressing the problem of identifying farming strategies for variable climate (Gadgil and Rao, 2000; Rao et al., 2000).

Predictions of rainfall on interannual and intraseasonal scales are required for identifying the appropriate strategies for a specific season. For generating such predictions an understanding of the coupling of the Indian monsoon to the warm oceans surrounding the Indian subcontinent as well as the Pacific ocean is a prerequisite. There are strong links between the interannual variation of the Indian monsoon and El Nino (Sikka 1980, Rasmussen and Carpenter 1983). However, recent studies have found that the correlation between Indian rainfall and ENSO phase is decreasing (Krishnakumar et al. 1999). The reasons for this are not immediately apparent. The variability of the monsoon is also linked to the variation of convection over the Arabian sea, the Bay of Bengal and the equatorial Indian ocean, since most of the synoptic and planetary scale systems responsible for the monsoon rainfall are generated over these warm oceans (Gadgil 2000). The Department of Ocean Development, Govt. of India has embarked on a programme of setting up a network of met-ocean buys in the Arabian Sea and the Bay of Bengal for continuous monitoring the surface met-ocean variables (Premkumar et al. 2000). An observational experiment, the Bay of Bengal Monsoon Experiment (BOBMEX) was carried out by Indian scientists during July-August 1999 (Bhat et al. 2000). Focussed observational experiments such as JASMINE and BOBMEX and enhanced ocean observations over the Indian seas and the equatorial Indian ocean can contribute towards unravelling the interactions with the oceanic ITCZ and generating predictions of the intraseasonal and interannual variations of the monsoon.

The impact of El Nino and La Nina events is considerable in Malaysia. During an El Nino event, Malaysia experiences severe drought particularly in East Malaysia and the eastern part of the Malay Peninsula (Tangang, 1999a). These areas also face severe floods during La Nina, particularly during the winter monsoon period (Oct to Mar). There are many socio-economic impacts in

Malaysia associated with the drought and flood. However, there has been no comprehensive study of socio-economic impacts of El Nino and La Nina in Malaysia. A problem that is getting serious attention lately is the occurrence of widespread haze due to forest fires in Indonesia, Malaysia, etc. Since 1980, six major haze episodes have been reported; September 1982; April 1983, June 1991, October 1991, August to October 1994, and July to October 1997 (Othman et al., 1998). These haze episodes are associated with outbreaks of forest fires in Indonesia and Malaysia caused by El Nino induced drought (Chow and Lim, 1994). Othman et al. (1998) studied the socio-economic impacts of the 1997 haze episode. The total cost of the 1997 haze was estimated to be > $ 200 M or 0.3% of GDP. Two types of damage contribute to these losses, productivity (49%) and tourism (39%). The air pollution was so severe that a state of emergency was declared in Sarawak from Sept.10-28, 1997. All economic activity ceased resulting in huge production losses. As expected, tourists diverted from the country during the haze period resulting in reduced consumption. The haze has a significant health impact, raising the incidence of respiratory diseases. In addition, the 1997 drought caused water shortages in many parts of the country, resulting in rationing and closure of many factories. Agricultural output also declined during the drought, as expected.

The climate fluctuation in Malaysia can be related to variability in the Indian and Pacific Oceans. Tangang (1999b) showed that on the quasi-biennial to ENSO (1.5 – 5 years) time scales, the Malaysian precipitation anomalies exhibit a large-scale coherence with changes of SST, SLP and surface wind over the tropical Indian and Pacific Oceans. It is believed that Malaysia will greatly benefit from a climate prediction scheme utilizing signals from the oceans. Recently, the Scripps Institution of Oceanography and the National University of Malaysia conducted a collaborative work on the influence of the eastward propagating signals of the global ENSO wave (GEW) and the Antarctic Circumpolar Wave (ACW) on the Southeast Asia precipitation (Tangang and White, 2000). This study formulated a climate prediction scheme for interannual precipitation anomalies in four regions. Significant hindcast skill was found at leads of > 1 year, with more than 60% of interannual rainfall variance explained for Sumatra and Borneo, as illustrated in the Scripps website (http://jedac.ucsd.edu/index_forecast.html).

Indonesia experiences significant ENSO impacts on agriculture. Rainfall records in eastern Indonesia exhibit a long dry spell during El Nino events (Sribimawati et al., 1996). The rainfall-SOI correlation is most significant near the Indonesian through-flow (Sribimawati and Durwandani, 1999). Rice production and value in these regions is ENSO-dependent (Amien at al., 1999), with marked decreases in 1982, 1987, 1991, 1994 and 1997. ENSO is less influential in western Indonesia (Sribimawati et al, 1997), because of locally independent SST patterns which modulate the atmosphere.

Australia

The total value of Australian crops is usually about $20 B, while the gains and losses from one year to the next are sometimes as large as $4 B (Nicholls, pers comm.). Many factors influence crop value, including market demand, farming technology and climate. Interannual fluctuations in crop value are correlated with SSTs north of Australia, in turn influenced by ENSO. Gains can be improved and losses minimised if accurate predictions of SST and rainfall were available to guide the management of farms. Already, statistical predictions based on the phase of ENSO are used to support management decisions in wheat farming (Hammar et al, 1996) mainly focusing on fertiliser use. A potential 10% gain in productivity is demonstrated when the SOI is used retrospectively. This capability is being extended to other industries and regions of Australia, but additional ocean data and research will be required to improve the skill and lead-time of predictions. The Oceans-to-Farms Project is developing applications of seasonal climate predictions to support farm-management decisions in five industries in different climate regimes around the country. An analysis of grazing livestock on rangelands in northeastern Australia showed that management decisions based on SST as a predictand can produce an increase of 16% in annual live-weight gain. Beyond farm management, the project is developing an integrated assessment of economic and policy tools, such as interest rates, taxation and drought relief.

Severe Weather Events

All of the countries around the Indian Ocean are affected by severe weather events, often associated with the intraseasonal oscillation (ISO). The intensity and path of these events depend on large scale ocean conditions that have a degree of predictability. The great flood in China in 1998 ranked as the most devastating economic loss due to climate in that year. Over 3700 deaths were reported, 223 M people were displaced, and property damage amounted to $30 B. Analyses from the South China Sea Monsoon Experiment (SCSMEX) show that the Yangtze flood came as a sequence of ISO pulses from the Indian Ocean. Its onset was characterised by a double cyclone structure and strong westerly winds over the Indian Ocean. Monsoon convection shifted to 30°N and persisted for almost two months. Warm SST over the eastern Indian Ocean during the growing phase of La Nina contributed to the intensity and stationairity of this event. In addition, high rainfall during the previous spring moistened the land surface, anchoring the monsoon trough over the Yangtze River. The ISO is clearly a key player in regional floods and drought, triggering monsoon onsets and breaks. A key issue is to understand the role of oceans in the ISO and to predict the occurrence of extreme events.

The first ISO of 1998 spawned a tropical cyclone over the Bay of Bengal, leading to the Bangladesh flood (30 M displaced, > $ 2 B damage). This is the latest example of storm surges on the coasts of southeastern Asia spawned by tropical cyclones. The most devastating event this century was in 1970, killing 300,000 people in Bangladesh. The damage due to storm surges in the Bay of Bengal in the period 1945-1975 has been estimated at $ 7 B. The frequency of these devastating events has been documented by Joseph (1994, 1995) and a 40 year oscillation has been identified. At present, we are in a low phase, with few cyclones being produced. It is not known if the ocean plays a role in the long time scale of this oscillation, or the long term shift in Monsoon ENSO correlation mentioned earlier, due to the unevenness of historical ocean data.

3. Regional Variability in the Indian Ocean and Teleconnections to Impact Areas

Basin-Scale Modes of Variability

Climate-impacts in Africa, Asia and Australia are partly controlled by basin-scale modes of variability in the tropical Indian Ocean. For the seasonal to interannual time scale, several studies within the past year have related large scale, regional variations of SST anomalies to oceanic processes. This is the first step toward improving the prediction of SST.

The past year has seen substantial progress in understanding the dynamics of the east-west Indian Ocean dipole (IOD) (Saji et al 1999; Webster et al., 1999). An index can be used to represent opposing SST anomalies across the tropical Indian Ocean and their relationship with wind anomalies and ENSO. Some dipole events appear to be independent of ENSO, while more are closely related. It is not clear whether there is an unstable, coupled ocean-atmosphere mode enabling the IOD to be strong and independent in some years, and forced more directly by ENSO in other years, particularly in the July – November season.

Simulations of oceanic structure during the 1994 dipole event using different 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 coast of Sumatra are well simulated and confirm the role of upwelling and evaporation in anomaly-formation. The east-west dipole experiences locally positive feedback (Behera et al. 1999). Anomalous moisture transports away from the cool anomaly feed enhanced convection over India, SE Asia, the west Indian Ocean and east Africa. An important lesson from the modelling studies is that significant errors arise in flux estimations. There is little scope for improving model physics until better flux fields are available - another challenge for the Indian Ocean Observing System.

In summary, considerable progress has been made recently in understanding basin-scale ocean-atmosphere interaction and dynamics of the Indian Ocean region.

Global and Regional Control of Rainfall

With increasing understanding of regional oceanic processes such as the east-west dipole and its seasonally-phase locked links to the Pacific, there is a need to quantitatively estimate the relative roles of the global ENSO phenomenon and regional processes in determining rainfall in countries surrounding the Indian Ocean. While empirical methods are employed to distinguish the various signals, further research with coupled models is needed. The results support the idea that a regional approach is essential.

Lau and Wu (1999) have separated regional and global ENSO effects by computing the dominant modes of covariability between rainfall and SST. For the JJA (northern) rainfall anomalies, the first mode is a global non-ENSO signal, explaining one third of variance. A number of secondary localised modes explain a similar amount of variance. For the DJF southern monsoon, the global ENSO mode yields a stronger control than the local modes. Weakening of the locally independent modes (eg. eastern Indian Ocean SST) during mature phase of ENSO (southern summer) was corroborated by Saji et al. (1999).

Teleconnections to Africa--the tropical gyre and thermocline ridge in the west

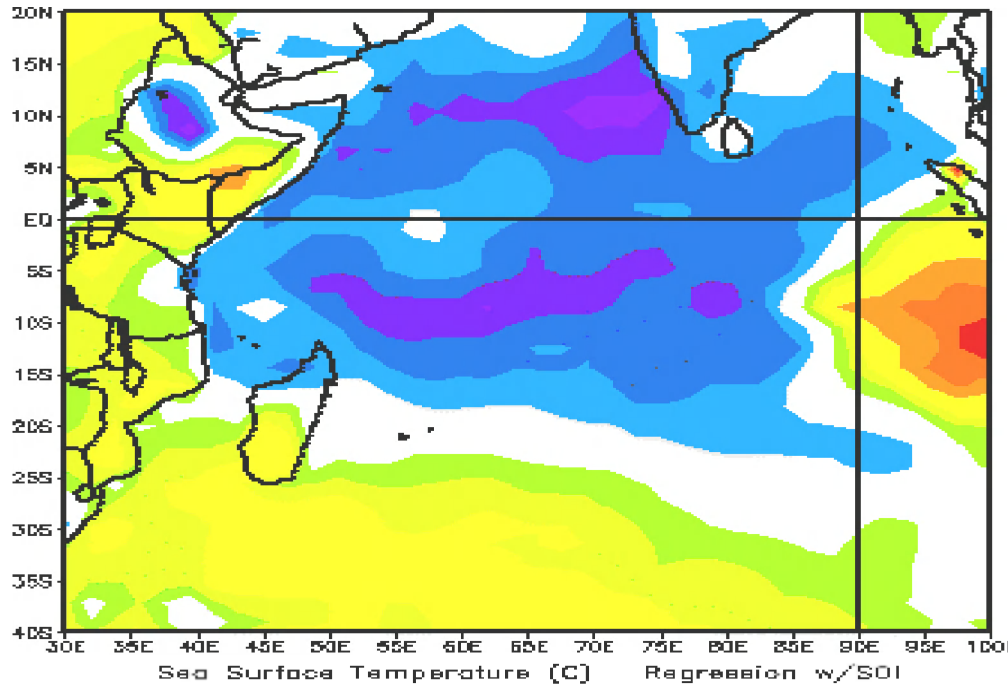
The western Indian Ocean has been considered a low priority region, yet for Africa, the Mascarene Islands and India, it plays a pivotal role in the annual cycle of the monsoon and the climatic impacts it can produce. There is growing evidence that it is a source region for, not only ISO, but the ENSO signal itself. An area of cyclonic circulation has been identified in ocean model studies of McCreary et al. (1993). It is referred to as the Tropical Gyre with a central radius near 8°S, 62°E. Woodbury et al. (1989) have demonstrated how the tropical gyre is driven by wind curl over the ocean interior. Cyclonic current shear around the tropical gyre is prominent in the analyses of Hastenrath and Greischar (1991). The ocean model of McCreary et al. (1993) describes potential variability of equatorial counter currents, whilst observations suggest a peak intensity in November and April at the initiation and decay of the NE monsoon when westward Ekman drift is reduced (Tomczak and Godfrey 1994). A zonally extensive thermocline ridge lies from 2.5°S to 10°S owing to persistent Ekman suction (McCreary et al. 1993). This feature imparts enhanced sensitivity to ENSO signals and coupling with the NE monsoon. South of 8°S, ocean circulations reflect the influence of the subtropical anticyclone which advects cooler water towards the tropics from west of Australia, and warm water away from the tropics along the east African coast. The south equatorial current connects these two regions, with steady westward flow along 10-15°S. Downstream mass and heat fluxes from the Agulhas Current feed the global thermohaline circulation, inducing decadal and long-term fluctuations in the global climate system (deRuijter et al 1999). It is therefore important to monitor these ‘choke’ points in a sustained ocean observing system, with a focus southwest of Madagascar.

ENSO - monsoon interactions over the west Indian Ocean cover a wide area ~ 10^{13} m^2. In warm events subtropical westerlies are drawn together and contribute to reduced rainfall over much of the continent (Jury et al 1996). The nature of ocean-atmosphere interactions can be analysed for composite warm and cool events in the west Indian Ocean (figure below). Chosen over the domain 10°N-15°S, 50-80°E in the period 1950-1995. Warm events start with a near zero SST anomaly and rise gradually to a minor plateau in months 4-7 (April-July) of the onset year (-1). During this time the wind field exhibits an increasing anticyclonic curl, thus depressing the oceanic thermocline south of the equator. Significantly the evaporative flux anomaly remains near zero, implying that ocean advection and mixing may be important then. A steep increase of SST occurs in months 8-10 as the evaporative flux declines and the curl continues its anticyclonic trend. The estimated shortwave radiation exhibits a negative tendency and plays a minor role until months 11-13 (Nov to Jan+1) when positive values occur. The anticyclonic curl and evaporative flux weaken at the mature stage of the warm event. The warm SST anomaly reaches a 2 sigma value from months 10 to 17 (Oct to May+1), a lengthy spell coinciding with the NE monsoon. Anticyclonic wind curl is re-established in months 16-18 (April to June+1) and the estimated shortwave radiation increases thereafter, inhibiting dissipation of the warm event, despite a positive flux anomaly. Finally SST anomalies begin to fall rapidly after month 20 (Aug+1) as the curl reverses sign.

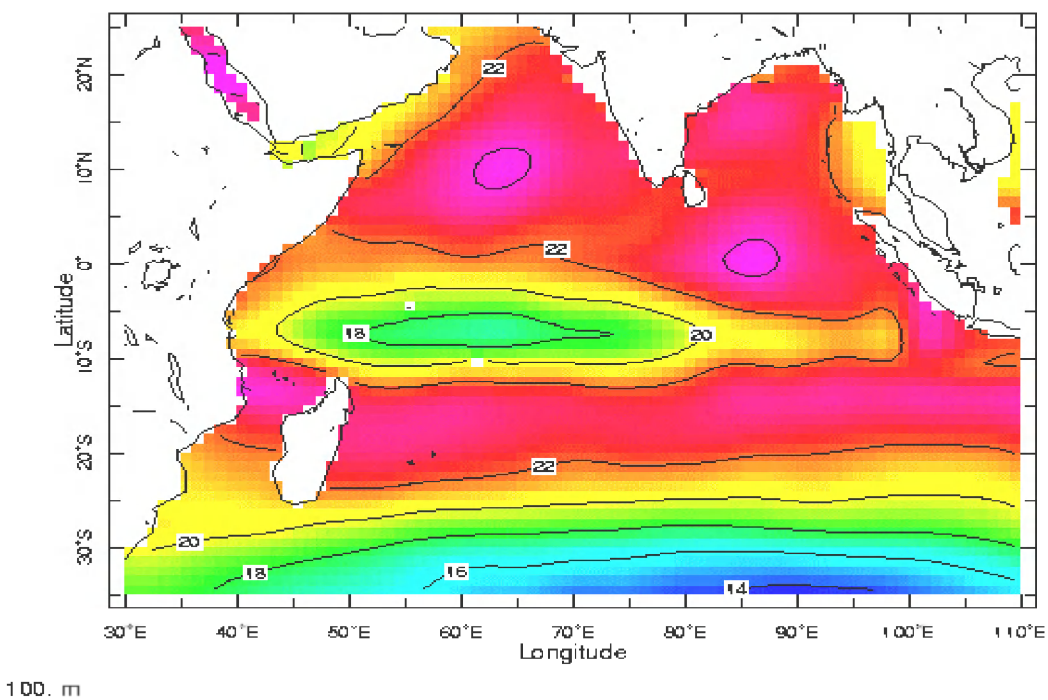
The cool event is somewhat different in character, suggesting a degree of non-linear behaviour for ocean-atmosphere coupling. SST declines to a minimum more symmetrically in months 11-15 (Nov to Mar+1). The onset phase displays a weak plateau for SST in the months 6-8, following a sharp increase in evaporative flux in month 5 (May). The wind curl remains neutral until months 8-10 when it takes a cyclonic tendency, promoting subsurface entrainment and thermocline uplift south of the equator. Fluxes remain above normal only through month 10 (Oct). The estimated shortwave radiation exhibits a sharp decline from month 8 to 11 (Nov) and remains below normal through much of the cold event (to month 22). SST anomalies begin to rise rapidly in months 16-20 (Apr to Aug+1) as the southwest monsoon prevails. The monsoon circulation exhibits anticyclonic curl and decreased fluxes from months 17-20 (May to Aug+1) which rapidly dissipate the cool event. Comparisons from a similar study over a longer time period can be found in Reason et al (2000).

Contrasts between the composite events can be found in the slow decay of the warm event and its greater amplitude (~ 4 sigma vs ~ 3). Evaporative flux and wind curl are constructively engaged as expected. However the curl leads the warm events whilst the flux leads the cool events, a significant result for predictive purposes. The estimated shortwave radiation is generally in-phase with the SST anomaly, and constructively supports the wind influence (eg. flux and curl). This is somewhat unexpected. In many tropical areas increased SST results in locally increased cloud and reduced radiative energy, a negative feedback which dampens extremes. This is confirmed by the ambiguous relationship between satellite outgoing longwave radiation (a proxy for cloud depth) and SST in the

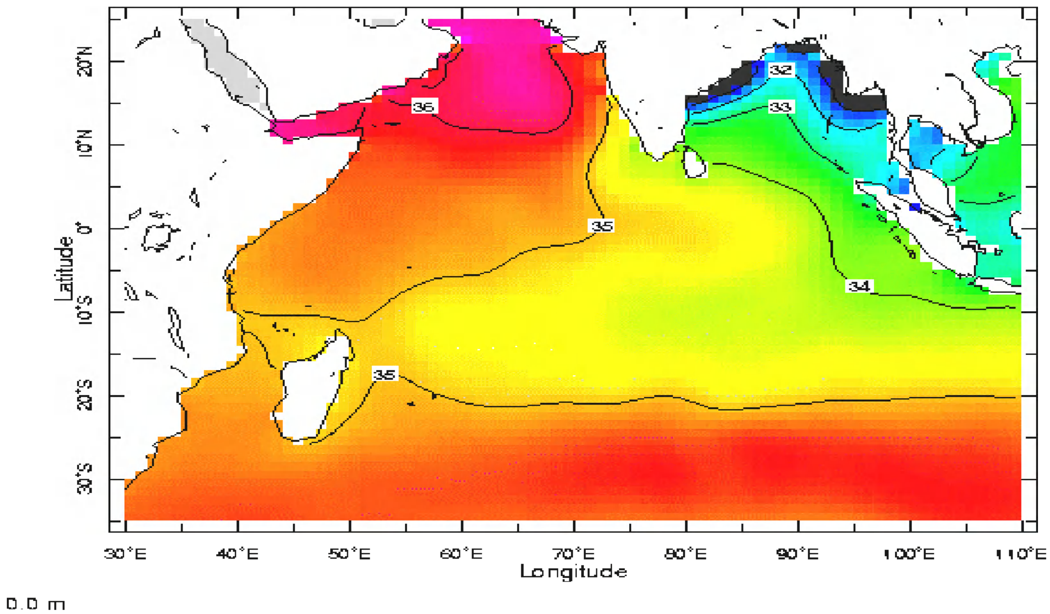
Indian Ocean. Further *insitu* information and analysis of the radiation budget would help clarify the coupling processes involved.



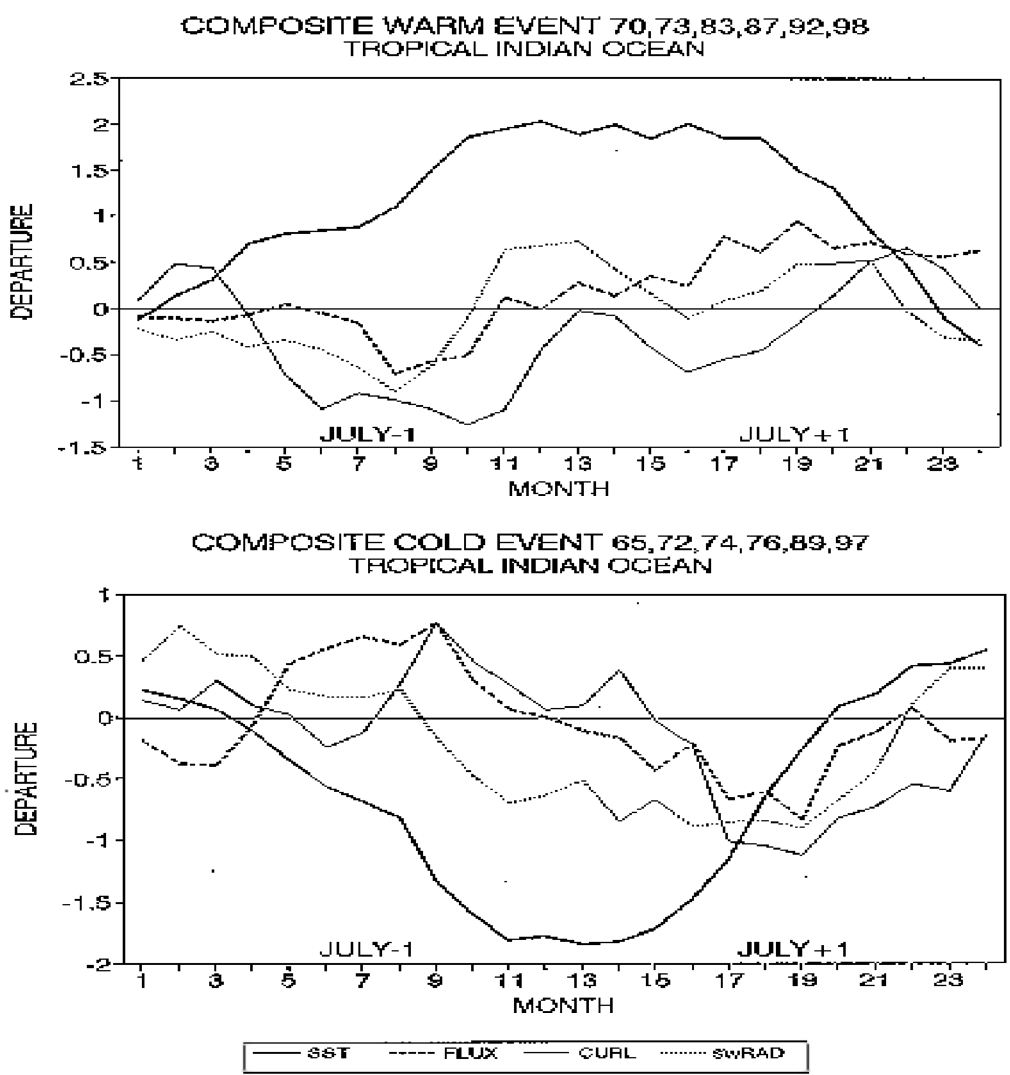
Regression of SST with SOI for the July-Nov. period 1958-1998. ENSO responses are clearly evident in this analysis, particularly the east-west dipole.



Annual mean temperature at 100 m depth.



Annual mean surface salinity.



Composite warm and cold event evolution in the tropical west Indian Ocean.

Teleconnections to India: Monsoon -Ocean Coupling

Tropical convergence zones (TCZ) appear intermittently over the equatorial Indian ocean in the summer monsoon season (June-September) of every year. The oceanic TCZ propagates northward onto the Indian subcontinent at intervals of 2-6 weeks throughout the season (Sikka and Gadgil 1980). These propagations play an important role in the large-scale monsoon rainfall. The onset phase of the monsoon and a large fraction of the revivals from weak spells or breaks in the monsoon are associated with such propagations. The other mode of revival involves genesis of synoptic scale systems over the Bay and propagation onto the subcontinent. Clearly predictions of genesis of TCZ over the equatorial Indian ocean and propagations onto the subcontinent are critical for the onset phase and the intraseasonal variation of the monsoon. It is also important to note that the equatorial TCZ is anomalously active in weak spells/breaks of the monsoon (Gadgil and Asha 1992, Webster et al. 1999) and also for seasons with deficit monsoon rainfall. Thus the relationship of the monsoon rainfall and the TCZ over the equatorial Indian ocean is complex. On the one hand the oceanic TCZ helps maintain the monsoon by northward propagations; on the other, excess activity of the oceanic TCZ is associated with anomalously low convection over the Indian monsoon zone. Understanding the mechanisms responsible for genesis of this oceanic TCZ, for its propagations onto subcontinent and its competition with the continental TCZ is critical for understanding and prediction of the variability of Indian monsoon on intraseasonal and interannual time-scales. For this, sustained observations of the critical atmospheric and oceanic variables over the equatorial Indian ocean is an essential pre-requisite.

It is important to note that the Indian monsoon is also strongly linked to convection over the Indian seas i.e. the Bay of Bengal and the Arabian sea. Understanding the variability of convection over these warm seas is therefore, extremely important for understanding and prediction of the variability of the Indian monsoon. For continuous monitoring of these seas and the atmosphere above, the Department of Ocean Development, Government of India has set up a network of met-ocean buoys (Premkumar et al. 2000). These will be complimented by a number of ARGO floats. In addition, observational experiments mainly from ships are planned of which the first over the Bay of Bengal -BOBMEX was successfully conducted during July-August 1999 (Bhat et al. 2000). Sustained observations over the Indian seas and the equatorial Indian Ocean and focussed observational experiments such as BOBMEX and JASMINE are essential for further progress.

Teleconnections to Malaysia

The Malaysian precipitation was shown to have year-to-year variability at QBO and ENSO times scales (Tangang, 1999a). Tangang (1999b). Malaysian precipitation anomalies lead the

Nino3.4 SST index by 6 - 8 months, consistent with the Southeast Asia monsoon anomalies leading the tropical Pacific SST anomalies by ~ 6 months (e.g. Shen and Lau, 1995). Tangang (1999b) showed that Malaysian precipitation anomalies exhibit a large-scale coherence with inter-annual changes of SST, SLP and surface wind over the tropical and Indian Ocean. Recently, SST anomalies in the Indian Ocean have been shown to be influenced by propagating climate phenomena. Tourre and White (1997) observed covarying SST and SLP anomalies in the tropical Indian Ocean propagating slowly eastward. Later, White and Cayan (2000) found this to be part of a global climate signal called the global ENSO wave (GEW) that conducts covarying SST and SLP anomalies from the tropical Indian Ocean into the tropical Pacific and on into the Atlantic oceans, and transiting Africa to come full circle. Earlier, Peterson and White (1998) found these covarying SST and SLP anomalies in the Southern Ocean associated with the ACW propagating slowly northeastward through the Indian Ocean, taking 1 to 2 years to reach Indonesia. Motivated by questions on the relationship between interannual Malaysian precipitation anomalies, Pacific SST anomalies and eastward propagation of the GEW and ACW, Tangang and White (2000) examined the evolution of various parameters including SST, SLP, meridional moisture flux (MMF). The study showed that the evolution of SE Asian precipitation on interannual time scales is strongly linked to the development of SST and MMF in Indian Ocean. Prior to peak dry (wet) periods, warm (cool) SST anomalies occupy the western (southeastern) tropical Indian Ocean in response to zonal teleconnections from El Niño; warm SST anomalies occur southeast of Madagascar associated with ACW. Subsequently during the transition from El Niño to La Niña, SST anomalies in the tropical Indian Ocean propagate eastward with the GEW, while SST anomalies southeast of Madagascar propagate northeastward with the ACW. Utilizing the slow eastward and northeastward propagation of these SST/SLP waves, Tangang and White (2000) constructed a statistical climate prediction system for the inter-annual variability in SE Asian rainfall. This prediction system was capable of producing significant hindcast skill at leads > 1 year.

Teleconnections to Australia - Northwest cloud bands and SST

An east-west dipole pattern of SST anomalies (closely related to the IOD discussed above) has been related to patterns of rainfall from eastern Africa to Australia (Nicholls, 1989, Ansell et al 2000). A statistical scheme for prediction of rainfall in Australia based on this dipole pattern and global indices of ENSO (Drosdowsky and Chambers, 1998) has better skill than a prediction based on SOI alone. Associated with the SST anomalies, there is a zonal 'see-saw' of the thermocline between Sumatra and the Seychelles (Meyers, 1996; Masumoto and Meyers, 1998). Cool SST anomalies develop in the eastern Indian Ocean off Indonesia in association with a shallow thermocline. Clearly, upwelling plays a role in maintaining the cool SST anomalies in this region. The thermocline variation is forced by the wind field over the equatorial Indian Ocean The

Indian equatorial wind is partly associated with teleconnections from the Pacific Ocean, with a correlation coefficient as large as 0.6 during the season of peak ENSO anomalies (R. Allan, pers. comm.). The Indian equatorial wind is not correlated to ENSO during May to August, when winds off Indonesia are favorable for upwelling. This seems to be the season when IOD grows rapidly. One of the synoptic weather patterns that brings rain to Australia is the so called northwest cloud band (Tapp and Barrel, 1984; Telcik., 2000). The cloud bands occur less frequently when the eastern Indian Ocean off Indonesia is cool. An ocean observing system in the Indian Ocean which supports prediction of the thermocline and SST anomalies is likely to lead to improved rainfall predictions for Australia.

7. Filling gaps in a Sustained Observing System

The regional, dynamical features of the Indian Ocean are the targets for sustained observation. A variety of scientific questions need to be addressed on issues from the physics of the ocean and atmosphere, to their coupling at basin-scale (Lau et al., 2000):

- How are the east-west dipole and ENSO related?
- How does the dipole interact with the ISO, local currents and monsoon circulations?
- Do these coupling processes govern rainfall in a predictable manner?

The key fields required for a better understanding of the physics on a basin scale are: precipitation and evaporation, surface heat and momentum fluxes, temperature and salinity structure of the upper ocean, circulation, horizontal heat and freshwater fluxes, the radiation budget and cloud forcing.

7.1 Satellite observations

Earth-observing satellites will provide a basis for estimating many of the key fields. Satellites already provide estimates of SST, precipitation, wind, sea level (barotropic currents) and color (productivity). Net surface heat fluxes can be derived from satellite data. For the Indian Ocean the satellite sea level data is crucial, because the existing in situ network to observe subsurface structure is sparse. Improvements to in situ data collection will come incrementally, leading in time to optimally tuned satellite estimates.

With the hydrological cycle as a central focus of future Indian Ocean studies, observations of sea surface salinity (SSS) are essential. Based on climatologies, the annual mean surface salinity (illustrated above) is low (< 35 psu) across the equatorial ITCZ, high (>36 psu) in the Arabian Sea and southern sub-tropics. In the Bay of Bengal salinity is below 32 psu and salinity fronts of 1-2 psu occur over horizontal scales of 100 km. The low salinity cap in the Bay of Bengal and the Indonesian region plays an important role in the surface layer heat budget. This barrier layer influences SST and flux exchanges across the basin. Remote sensing of SSS (Lagerloef et al., Oceanobs99) is an essential data set for description of spatial and temporal variability, and to optimise the use of altimeter data in model applications.

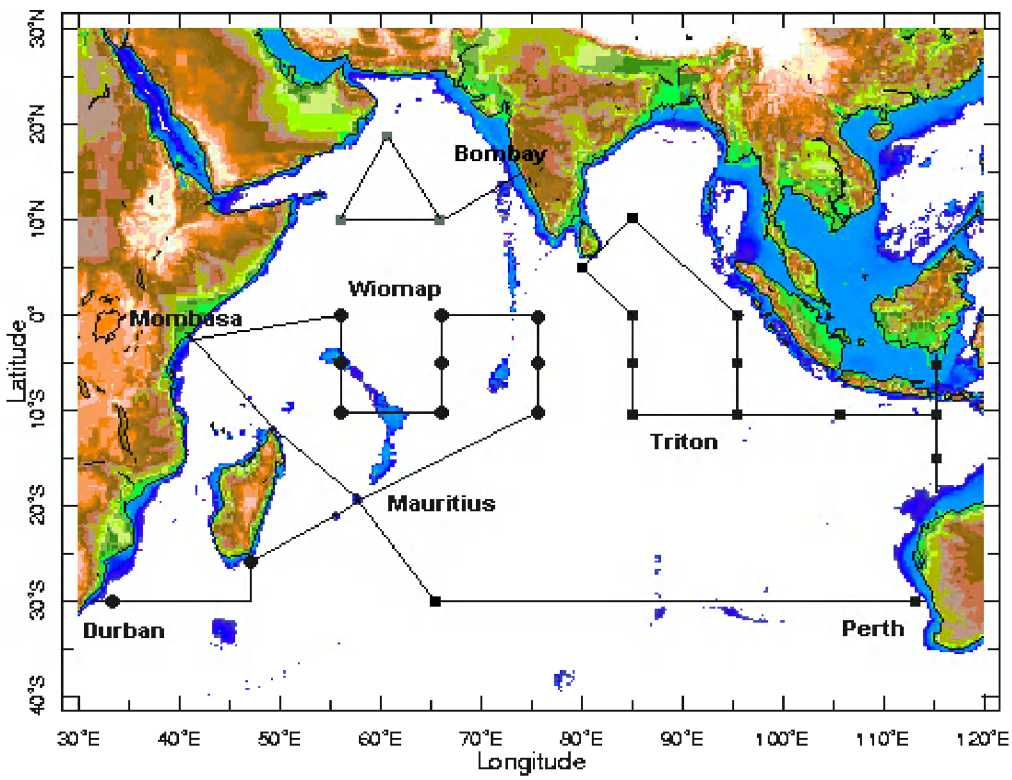
Maintenance and development of satellite remote sensing is an essential pre-requisite for sustained in situ observations in the Indian Ocean (Desai et al., 2000). Coupled models require spatially extensive information on sub-surface heat content. Altimeter data is often assimilated as a proxy, in the absence of an extensive moored array. However this procedure could impose errors in certain areas of the Indian Ocean where sea level gauge records and altimeter data do not concur. Particularly around the thermocline ridge illustrated above, errors of a few cm in geoid-corrected sea level slopes could lead to poor estimates of mass flux. This problem could be resolved with an appropriate mix of additional ocean data.

7.2 In situ observations

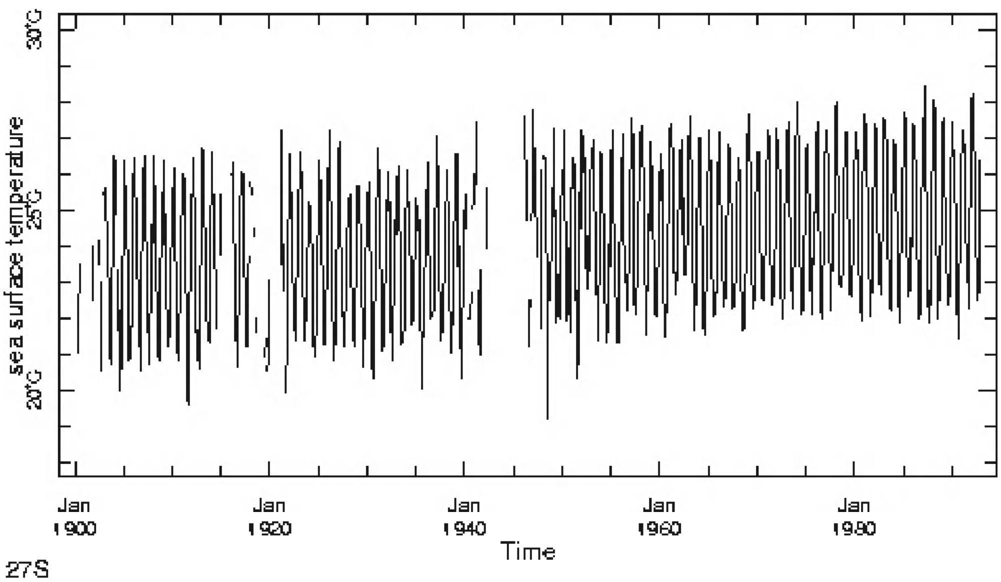
In situ ocean measurements are essential for the initialisation of coupled ocean-atmosphere models which will be used to predict climate anomalies across the Indian ocean and its surrounding continents. In situ observations will be needed for calibration, enhancement and optimal application of all forms of satellite data. In situ measurements provide details of the vertical density structure and enable estimation of ocean transport and entrainment processes. Important steps are being taken by Japan and Australia, with deployment of the Triton moorings and Argo floats in the east Indian Ocean. However to the west, the subsurface ocean is relatively unsampled. A plan for sustained in situ observations in the west Indian Ocean is presented below, which derives from a GOOS Africa initiative called WIOMAP, a partnership between southeastern Africa, the Mascarene Islands and the international scientific community.

While details of the sampling rates and location of the observations can only be proposed at this stage, the plan suggests what the west Indian Ocean observing system will look like by 2005. Data from the moored array will include sub-surface temperature and salinity, current meters, and IMET stations for surface weather conditions. The fixed in situ measurements will be complimented by microwave satellite data (altimeters, scatterometers, etc), Argo floats and frequently repeated XBT or CTD lines. This mix of observations will measure air-sea interactions, heat storage, freshwater inputs, and ocean transports. The continuous estimation of surface fluxes and shear in the monsoon wind field (curl) is a high priority. Similar automated measurements will be made in the Triton/TAO mooring array to the east, and together with a WIOMAP effort in the west, Kelvin and Rossby waves will be tracked to define intraseasonal to interannual variability. This vision is endorsed by inter-government institutions in southeast Africa and the Mascarene Islands and is actively promoted by the WMO, IOC, and its GOOS and CLIVAR panels. The observing system will grow incrementally according to new insights from research and experience from long term measurements.

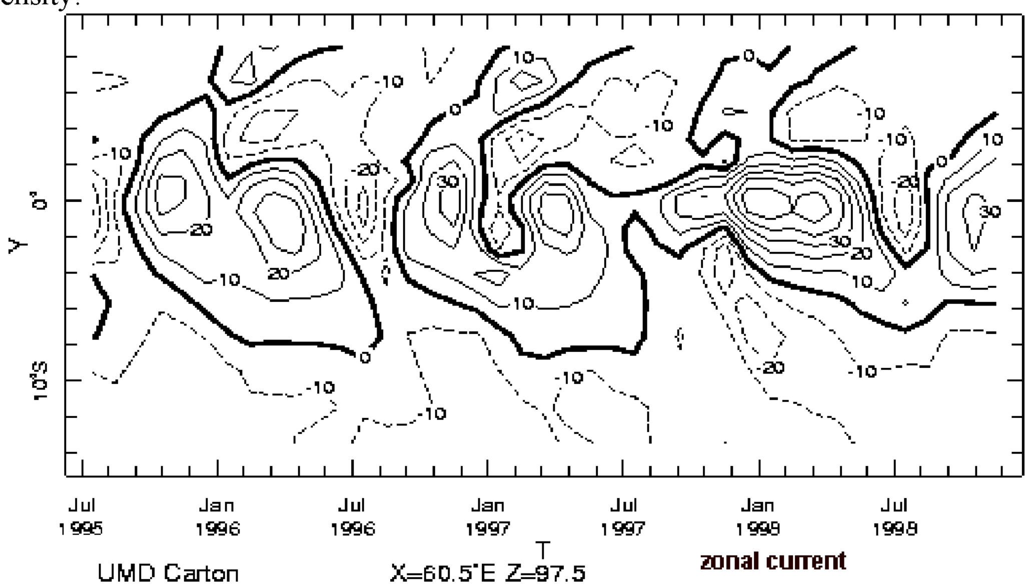
India has initiated a coordinated Ocean Observing System in the Indian Ocean, with the following four components: XBT operations on selected shipping lines, drifting buoy, research campaigns to validate meteorological and oceanographic data products, and current meter moorings at a few locations along the equator. The main objectives of the program include understanding deep sea current variability and climate change. Evidence for global warming of the Indian Ocean basin are widespread and ubiquitous.



Proposed Indian Ocean moored array and ship tracks for in situ measurements.



COADS-derived SST have increased 2 C in the past century in the Agulhas Current near Africa, coincident with similar increases in wind speed, vapour pressure and tropical cyclone intensity.



Zonal currents (cm/s) near 100 m depth estimated from an OGCM sliced along 60E, illustrating seasonal to inter-annual variability during the recent ENSO episode.

India has established an array of 12 buoys to monitor its nearshore marine environment. These buoys are equipped with meteorological and ocean sensors. The data collected from the buoys are transmitted through INMARSAT to improve the forecasting of tropical cyclones and ISO (Premkumar et al. 2000). Such an effort needs to be extended southward to the equator, to join the WIOMAP effort in the south. These data need to be made available to the international community in real-time via the internet for the purpose of global climate prediction.

7.3 Process Studies

Process studies are needed: to identify the role of ocean dynamics in SST variability, to improve understanding of air-sea coupling processes, to improve parameterization of surface fluxes, and to quantify the effect of internal waves on upper ocean mixing and evolution. Process studies usually take place in a limited area and season using ships and aircraft (eg. INDOEX). Sustained observations are required to provide a basin-wide framework within which the process studies can be interpreted. While process studies may be concerned with the physics of air-sea interaction in a limited area, sustained observations will yield a view of ocean-atmosphere coupling on the bains-scale.

8. Recommendations for implementation

8.1 Precipitation and evaporation, surface heat and momentum fluxes

Any observation network whose main benefit is climate prediction needs to place strong emphasis on obtaining accurate satellite and in situ surface fluxes. Climate 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 become clear when initialising an ocean model with 'observed' fluxes. It is necessary to add substantial flux corrections, otherwise model SSTs drift away from reality. 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. Methods to measure fluxes include the moored arrays Triton/Tao (McPhaden et al., Oceanobs99), IMET moorings (Send et al., Oceanobs99) and VOS with quality-controlled meteorological stations (Taylor et al., Oceanobs99).

Recommendation: Implement an appropriate flux array for the tropical Indian Ocean using moored platforms, emerging technologies and satellite data.

8.2 Upper ocean thermohaline structure

Little is known about the internal ocean dynamics that drives the SST anomaly patterns discussed above. 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 the Indian Ocean and an essential aspect of the surface heat budget. Enhancement of ongoing thermal monitoring with salinity measurements is necessary, particularly along the ship tracks proposed above. To adequately establish the basin-wide thermohaline structure of the Indian Ocean > 100 Argo floats need to be deployed (Roemmich et al., Oceanobs99).

Additional monitoring efforts will initially include the Bay of Bengal and eastern Indian Ocean where the state of readiness is advanced. A Triton/Tao line will soon be in place along 80°E and in the eastern upwelling zone. This effort must be extended to the thermocline ridge and choke points in the west. An overarching goal of sustained observations is to identify key indices of ocean dynamics and atmospheric coupling, to underpin climate predictions and support Process Studies.

Recommendation: Implement an appropriate mix of WIOMAP/Triton/Tao moorings, SOOP lines and Argo float deployments.

8.3 Circulation, horizontal heat and freshwater flux

The need to measure near-surface currents to identify process in the surface layer heat budget is crucial. Vertically integrated transports of mass, heat and freshwater are required to understand the role of the Indian Ocean in the climate system. With regular ship cruises and continuous ADCP measurements and high density CTD stations, basin-wide transport estimates can be inferred with addition of satellite altimeter fields (Harrison et al., Oceanobs99). Volume transport budgets need to be 'closed off' by regular sampling across the Arabian Sea, Bay of Bengal, South Indian Ocean, and western boundary. Satellite estimates of rainfall need to be validated with ship- and island-based gauges and coastal weather radar.

Recommendation: Implement high density CTD and ADCP measurements along specified lines. Ensure that marine meteorological services can provide validation data.

8.4 Capacity Building

Strengthening marine sciences and supporting institutions in developing countries surrounding the Indian Ocean would enable the uptake of new ocean data in predictive models. Unless a few key scientists have expertise in each country, much of the societal applications may not be realised. To support these applications, regional data assimilation centres are proposed to generate the necessary products tailored to local users. These centres will require enhanced communication facilities for data acquisition and product distribution. Although many countries around the Indian Ocean have internal resources for these purposes, more evenness would be of benefit to the developing countries whose populations are proportionately more vulnerable to climate impacts. This effort should be implemented phase-wise through GOOS, so that a wide range of the marine communities would benefit from the extension of ocean observations.

Take the west Indian Ocean as an example. Countries like Mozambique, Madagascar, the Comoros, and the Seychelles are limited by a shortage of suitably trained manpower. In others like Kenya, Tanzania, and Mauritius uneven funding has resulted in slow progress and a limited scope of activities. Capacity building through training and infrastructure development is an essential activity in parallel with enhanced observational systems. In that way, key institutions could reach a scientific level necessary to participate in GOOS and CLIVAR programmes.

Recommendation: Implement regional capacity building projects as part of an overall scientific mission, to ensure that the benefits of enhanced ocean observations reach local users.

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