2. VARIABILITY OF THE ASIAN-AUSTRALIAN MONSOON SYSTEM (G2)

2.1 INTRODUCTION

The Asian-Australian (AA) monsoon is a key component of the earth's climate system affecting the livelihood of more than 60% of the world population. Almost all facets of societal and economic activities in the AA-monsoon region are critically dependent on the variability of the monsoon. For example, Fig. 2.1 shows that a large part of the major crop production over south Asia can be accounted for by the fluctuation of Indian monsoon rainfall. Because of the strong linkages of the AA-monsoon region to the rest of the world through coupling with the global climate and economic systems, variability and major shifts in the AA-monsoon climate affecting economic productivity will have major global impacts. Therefore, better prediction of the AA-monsoon will greatly benefit the social and economic well-being of not only the population of the AA-monsoon region but also of the whole world. Improved predictions of the AA-monsoon require enhanced understanding of the monsoon system through well-co-ordinated international scientific research efforts. The CLIVAR AA-Monsoon Panel is charged by the CLIVAR Scientific Steering Group (SSG) with the responsibility of developing an implementation plan to provide scientific to promote international monsoon research including facilitating the co-ordination of existing national programmes. The Asian - Australian Monsoon Implementation Plan (AAMIP) as outlined in this document has evolved and will continue to evolve from inputs of panel members as well as international monsoon scientists and experts. The basic content of the AAMIP was formally adopted during the First CLIVAR AA-Monsoon Panel Meeting held in Goa, India, November, 1996 (CLIVAR, 1997).

2.2 SCIENTIFIC RATIONALE

The prediction of the monsoon is limited by the high frequency variability associated with its internal dynamics. As a working hypothesis, it is proposed that monsoon predictability can be enhanced by improving our understanding of how the slowly changing boundary conditions such as sea surface temperature, snow cover and other slow variables within the tropical climate system modulate the high-frequency behaviour. Past studies have shown that the AA-monsoon is linked to interannual variability of the tropical ocean-atmosphere system, in particular ENSO (Shukla and Paolino, 1983; Nicholls, 1989, and Li, 1990). There is now a body of scientific evidence indicating that the Asian monsoon may strongly influence ENSO (Yasunari, 1990, 1991; Webster and Yang 1992, and Lau and Yang, 1996). Other studies also suggest that the Asian monsoon may impact the climate outside the monsoon region, including extratropical North America (Yasunari and Seki, 1992, Lau, 1992). In view of these considerations, the CLIVAR AA-Monsoon Panel adopts the following primary goals for the CLIVAR Implementation Plan:

1. to explore and determine the limits of predictability of the monsoon climate system;
2. to quantify the relative contribution to monsoon predictability from the slowly varying boundary conditions and internal dynamics within the monsoon system;
3. to determine the role of the monsoon on the predictability of the global climate system, in particular those related to ENSO.

To achieve these goals, the effort will be focused on seven specific focus areas relating to interaction of the AA-monsoon with the annual cycle, intraseasonal oscillations, ENSO-monsoon coupling, tropospheric biennial oscillations, oceanic processes, land surface processes and tropical-extratropical interactions. The interrelationships among these subsystems and the monsoon climate are illustrated in Fig. 2.2. A brief scientific rationale for each of the focus areas follows.

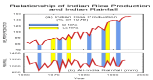

Fig. 2.1: Crop production vs. Indian monsoon rainfall. Notwithstanding the overall growth in rice production in India due to better farming practices and technological development, year-to-year fluctuations in production are determined largely by the success or failure of the summer monsoon which is in turn affected by the particular phase of the El Niño/Southern Oscillation phenomenon (from Webster et al. (1998), adapted from Gadgil, 1995).

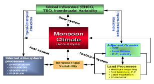

Fig. 2.2: Components of the AA-monsoon showing the interconnection between the various components discussed in the text (courtesy of K.M. Lau).

2.2.1 The annual cycle

First and foremost, the Panel recognises the need to better document and understand the mechanisms in the annual variations of the AA-monsoon. The annual variation of the monsoon is extremely complex, including sudden onset and breaks, abrupt transitions and strong interaction with SST in the adjacent and distant oceans and the surface hydrology of the Asian-Australian land masses (Meehl, 1987). The location of the maximum heat source during the Asian summer monsoon is far off the equator while that during the Australian summer monsoon is much closer to the equator, consequently, the fundamental dynamical regimes underlying these two monsoon components are quite different. For example, the response of the circulation to the Asian summer monsoon heating is mostly of the Rossby type where the rotational component of the wind and the b-effect (change of Coriolis parameter with latitude) are important. On the other hand, the near equatorial heat source during the Australian summer monsoon renders a stronger Kelvin type response, where gravity wave motions dominate. Moreover, the strong surface wind fluctuations over the maritime continent and the equatorial western Pacific associated with the Australian summer monsoon may exert a stronger influence on ENSO variability than its Asian counterpart. Recent studies suggest that the seasonal cycle can also influence the predictability of the ocean-atmosphere system (Torrence and Webster, 1998). For these reasons, both monsoon components need to be considered in studying the annual cycle of the overall monsoon system.

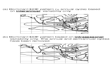

Fig. 2.3: Dominant spatial patterns of vorticity for (a) interannual and (b) intraseasonal variability of the Asian summer monsoon (Webster et al., 1998).

2.2.2 Intraseasonal Oscillations (ISO)

While the AA-monsoon is characterised by a very pronounced annual variation, it also possesses a wide range of variability from the intraseasonal, interannual to interdecadal time scales. ISO represent the strongest signal, with time scales from weeks to months, that permeate the monsoon land regions from India, Southeast Asia, East Asia and the Indian and western Pacific Oceans. A remarkable feature that should be noted is the strong similarity between spatial patterns of the intraseasonal and interannual variability (Fig. 2.3). While the basic physics of ISO is believed to originate from internal atmospheric moist dynamics, their interactions with the ocean and land surface processes are not very well understood; such interactions may be important in determining the characteristics of ISO over the monsoon region. Besides having a strong control on the monsoon active-break cycles, ISO may define a monsoon "attractor" that determines the evolution of the climate states of the monsoon. Considering the similarity between the ISO and interannual variability, it may be hypothesised that the monsoon attractor has multiple basic states and that it may be nudged to go from one state to the other under the influence of remote forcing induced by sea surface temperature anomalies, changes in snow cover or other external forcing functions (Palmer, 1994 and Webster et al., 1998). Moreover, it should be noted that the annual and the ISO time scales are arguably the most important time scales on which improved prediction will provide the greatest social and economic benefit. Hence, they warrant high priority for AA-monsoon studies.

Fig. 2.4: Composites of warm-minus-cold 850 mb winds and GPI rainfall seasonal anomalies based on the NASA-GEOS reanalysis for December-January-February (upper panel) and for May through August (lower panel) (courtesy of K.M. Lau).

2.2.3 ENSO-monsoon coupling

Many studies have documented that both the summer and winter components of the AA-monsoon can be affected by ENSO. The warm phase of ENSO has been linked to a weakening of the AA-monsoon, with overall reduction of rainfall over Southern India, Southeast Asia during May through August and northern Australia and Indonesian regions from December to February, with anomalous surface easterlies over the Indian Ocean and anomalous surface westerlies over the equatorial central Pacific (Fig. 2.4). Yet, not more than 40% of the strong and weak monsoons can be associated with ENSO. At the very best, less than 10-15% of the monsoon rainfall variance can be explained by SST variation in the Pacific. Therefore the monsoon-ENSO relationship is tantalising but incomplete. Several reasons may exist. First, the monsoon-ENSO relationship is likely to be non-linear. It has been suggested that the monsoon interacts with the Pacific trade wind system much more strongly in the warm phase compared to the cold phase of ENSO. Second, the monsoon-ENSO coupling may be non-stationary since the correlation between long-term records of Indian rainfall and Pacific SST has varied from 0.4 to 0.8 for different decades from 1900 through the present (Mehta and Lau, 1997). Hence the ENSO-monsoon relationship is subject to modulation by long-term climate variations. Third, other factors such as snow cover or soil moisture may exert impacts on monsoon variability, either directly and/or indirectly through feedback processes with the ENSO. Finally, the ENSO-monsoon system itself may be part of a chaotic climate system, which can generate variability on long-time scales internally through mutual interaction, even in the absence of external forcings. Clearly, the understanding of the dynamical underpinnings of the coupling of the AA-monsoon and ENSO is a scientific problem which lies at the heart of CLIVAR.

2.2.4 The Tropospheric Biennial Oscillation (TBO)

The TBO is a quasi-periodic oscillation found in a wide range of monsoon variables including rainfall, surface pressure, wind, SST and subsurface water temperature. The origin of the TBO is a subject of debate. Several theories exist. One contends that the TBO arises from air-sea-land interaction with the monsoon regions. This theory requires the long-term memory in oceanic as well as land variables such as soil moisture and snow cover (Meehl, 1993). Another theory is that the monsoon is an integral part of a tropical coupled ocean-atmosphere-land system, including at least the Indian Ocean and the Pacific basins. The TBO then arises as a subharmonic of the annual forcing from the monsoons and interacts with the ENSO system. This may be the reason for the strong phase locking between the annual cycle, TBO and ENSO (Shen and Lau, 1995). Recent modelling results have indicated that it is also possible to generate variance at the TBO time scale in atmospheric GCMs from annual atmospheric forcing alone and that intermediate coupled ocean-atmosphere models can generate TBO-like events without generating ENSO events (Goswami, 1996). Thus the origin of the TBO and its strong connection with the monsoon presents one of the most intriguing scientific problems for CLIVAR. Understanding the origin of the TBO may help to explain the scale selection and irregularities in ENSO cycles and in ENSO-monsoon coupling.

2.2.5 Oceanic processes

Even in simplified coupled ocean-atmosphere models with no land processes, an extremely rich ENSO-like dynamical behaviour can be found. The atmospheric response to SST anomalies is very indirect. According to statistical and AGCM studies, SST anomalies that influence the monsoon are found in very disparate parts of the ocean. Notably, the northern Indian Ocean is not a strong region of influence. Positive SST anomalies in the east Pacific and negative ones in Indonesia during ENSO influence the monsoon through different mechanisms (e.g. Soman and Slingo, 1997). Nicholls (1989) found that the major pattern of non-ENSO related Australian winter rainfall correlated with a dipole of SST anomalies in the Indian Ocean.

Other regions whose SST anomalies are known to influence the AA-monsoon are the southern Indian Ocean, the western Pacific, the South China Sea and the Indian Ocean region, but more remains to be learned regarding regions of SST influence on the monsoon. To predict the monsoon, these SST anomalies must be first predicted. This involves dealing with a range of oceanic processes, many still poorly known. Examples include the non-linear effects of currents in the western Pacific and the northern Indian Ocean (McCreary et al., 1993), the annual Rossby waves in the Southern Indian Ocean (Perigaud and Delecluse, 1992), tidal mixing and wind-driven upwelling in the waters of the Maritime Continent (Lukas et al., 1996 and Godfrey, 1996). Another critical issue confronting monsoon ocean research, and much of CLIVAR in general, is that the surface fluxes, which are key to the coupling of the atmosphere and the ocean and which are used to force ocean models, are all subject to large uncertainties (e.g. Weller and Taylor, 1993). Accurate estimate of surface fluxes are also critical to diagnostic and intercomparison studies of air-sea interaction in the Bay of Bengal, South China Sea and western Pacific. Two initial objectives of the ocean components of the AA-Monsoon programme have been identified (a) to understand the effects of SST anomalies in different regions on monsoon circulation, and (b) to determine the physical mechanisms governing SST changes in different geographic locations. A third objective is to improve the estimates of surface fluxes in the region, from both *in situ* and remote sensing methods, and from AGCMs and OGCMs when each is forced towards observed SSTs.

2.2.6 Land surface processes

Observational studies have suggested that the interannual variability of the Asian monsoon may be strongly affected by anomalous land surface conditions over the Eurasian continent (Shukla and Mintz, (1982)). The land surface anomalies may be due to snow cover, soil moisture or vegetation changes. It is believed that these land surface anomalies contribute to anomalies in the monsoons by modulating the surface heat budgets and therefore temperature and moisture contrasts between the continent and the adjacent oceans. For example, excessive snow during the antecedent winter and spring may lead to late melting thus keeping the ground temperature below normal and the mid-latitude westerly flow strong and persistent over the subtropics through early summer (Yasunari, 1991). These conditions reduce land-ocean contrast in early summer and prevent the northward migration of the monsoon westerlies and therefore favour a late onset and a weak monsoon (Webster and Yang, 1992). In this regard, the effect of the sensible heat flux in the elevated heat source over Tibet may be especially important in regulating the strength of the summer monsoon (Yanai and Li, 1994). Land surface processes may also impact intraseasonal variability, as evidenced in recent modelling results, suggesting that the feedback processes involving soil moisture, evaporation and convection over land may be important in the observed inverse relationship between the oceanic and land ITCZ (Lau and Bua, 1998). Possible feedback mechanisms involving the coupling of the land-atmosphere hydrologic and energy cycles under the influence of large-scale forcings are shown in Fig. 2.5.

2.2.7 Tropical-extratropical interaction

The importance of tropical-extratropical interaction in influencing AA-monsoon processes is well known. The onsets and breaks of the Indian monsoon are known to depend on the degree of meridional penetration of extratropical eastward moving troughs where the westerlies extend southward, and the position of the mid-tropospheric ridge over India during the boreal spring (Mooley and Shukla, 1987). These same ridge and trough systems are also responsible for the multiple onset and the discontinuous northward migration of the Mei-yu and Baiu fronts over East Asia. In particular, during the latter stages (July to August) of the East Asian monsoon, the influence of midlatitude baroclinic disturbances on the monsoon trough development is well known. Also documented are significant correlation of monsoon rainfall with the stratospheric circulation and in some cases the stratospheric QBO. Whether or not the latter is distinct or related to the TBO is an intriguing scientific problem that may have practical forecasting value. Strong extratropical influences associated with the winter monsoon cold surges from East Asia on near equatorial convection and possibly the austral summer monsoon have also been reported (Lau, 1982). The interaction of the winter monsoon over East Asia with convection over the South China Sea appears to be also important (Tomita and Yasunari, 1996). Because of their high frequency characteristics, extratropical influences may further limit the predictability of the AA-monsoon. An important scientific question is to determine in what ways the distribution of these high frequency signals interact with the large-scale stationary patterns induced by the slowly changing boundary conditions.

Fig. 2.5: Possible land-atmosphere feedback mechanisms under the influence of large-scale remote forcings in the AA-monsoon region (from Lau and Bua, 1998).

2.3 PROGRAMME OBJECTIVES

Under the guidance of the scientific rationale for an Asian-Australian monsoon programme outlined above and in pursuit of the goals of such a programme, CLIVAR will:

- Document the spatial structure and temporal variability of the AA-monsoon system from intraseasonal, annual, interannual to interdecadal time scales.
- Identify specific mechanisms for the complex evolution of the annual cycle in the coupled ocean -atmosphere-land system in the monsoon regions.
- Unravel the mechanisms of the intraseasonal oscillations (ISO) and the role of ISO in the interaction between monsoon and ENSO.
- Determine the fundamental modes and mechanisms in ENSO-monsoon coupling, including the tropospheric biennial oscillation (TBO) and interdecadal modulations.
- Identify regions where land surface and SST anomalies influence the monsoons, and quantify the underlying meteorological causes of these influences.
- Determine the relative contribution by internal dynamics vs. boundary forcing, as well as remote vs. local forcing to monsoon predictability.
- Quantify the physical mechanisms responsible for generating SST anomalies, emphasising ocean regions known to influence the AA-monsoon.
- Identify external influences including tropical-extratropical and tropospheric - stratospheric interactions affecting monsoon variations.

Numerical modelling activities now, and will continue to be, a major tool in addressing these objectives. However, there are a number or aspects of the monsoon where present models are known to be inadequate; and process studies are needed to tackle these issues. Furthermore, for practical real-time prediction the observing system will need to be addressed. These aspects are addressed in the following sections.

2.4 MODELLING AND PREDICTION

To meet the stated goals and objectives, the modelling component of the CLIVAR AA-monsoon programme effort will utilise a hierarchy of models, from simple through intermediate to fully fledged AGCMs and CGCMs (coupled global circulation models). Simple and intermediate models are important for providing a basic understanding of physical processes and a dynamical interpretation of observations and results from GCMs. In the initial phase of the CLIVAR AA-monsoon programme, modelling work will be guided by statistical studies of observed monsoon climate variability and its sensitivity to changing lower boundary conditions.

As monsoon climates are determined largely through processes coupling the ocean, atmosphere and land, coupled GCMs will ultimately be used to address the problems of monsoon predictability. However, fully coupled modelling studies aimed at predicting the AA-monsoon are premature at this stage. Nonetheless, it is encouraging that several state-of-the-art high resolution AGCMs and regional climate models nested in AGCMs have shown promise in realistically simulating the regional features of the monsoon. Much of the success is due to better parameterisation of physical processes such as cumulus heating, water vapour and cloud radiative processes and land surface processes. Submodel developments to better simulate the mean monsoon will be strongly encouraged. In particular, such efforts will be co-ordinated with the process studies discussed in Section 2.5 and with other WCRP programmes e.g. GCSS (GEWEX Cloud System Studies).

Ocean models can now reproduce the observed mean seasonal cycle of SST quite well in most of the tropical ocean (e.g. McCreary et al., 1993; Chen et al., 1994), although in the Indonesian region they do not perform very well. These models are now being used to simulate interannual variability. However, their ability to reproduce interannual SST anomalies when driven by observed fluxes is as yet unknown, due at least as much to problems with uncertainties in the fluxes as to model deficiencies.

In view of the above considerations, there is an urgent need to develop and assess the ability of state-of-the-art AGCMs driven by observed SSTs to simulate the seasonal mean, interannual variability and intraseasonal variability of the monsoon, and conversely, to assess the ability of OGCMs to simulate the observed SST anomalies, given interannually-varying surface flux estimates. These steps are prerequisites for making quantitative estimates of the predictability contributions from slowly varying boundary conditions versus those estimated from internal dynamics. Experiments with stand-alone AGCM and OGCM experiments will be carried out first, to be followed by coupled GCM (CGCM) experiments. Discussions and proposals of AGCM, OGCM and CGCM experiments are presented in the following subsections.

2.4.1 Experiments with AGCMs

2.4.1.1 Atmosphere Model Intercomparison Projects

This modelling activity aims at assessing the ability of AGCMs to simulate the seasonal cycle, interannual variability and intraseasonal variability of the monsoon. The model results will be validated against re-analysis products and *in situ* observations in the region, including satellite data. For re-analysis, the current efforts by the major centres have to be continued. For in-situ observations, data on daily precipitation, circulation over the South Asian, East Asia and Southeast Asian monsoon regions will be required. For satellite data, estimates of cloudiness, convective strength, water vapour and surface fluxes and derived precipitation data are needed (see discussion in Section 2.7.1).

Proposals:

In conjunction with AMIP-II (Geckler, 1996), a 15 year period of monsoon simulations from 1979 to 1994 will be investigated. This period includes the strong 82/83 and 1987/88 ENSO events, along with persistent El Niño conditions during 1992 and 1994. For validating the simulation of the monsoon, several monsoon indices based on area-averaged precipitation (e.g. All-India, Central China, and South China Sea) as well as circulation anomalies (e.g. Webster and Yang, 1992) will be applied.

2.4.1.2 Monsoon predictability

The objective of these experiments is to assess the predictability limit of the monsoon and to make quantitative estimates of contributions from slowly varying boundary forcings and internal dynamics.

Proposals:

Three sets of experiments are proposed.

Ensemble of AMIP simulations (5 or 9 members of 15 years each) which will give an estimate of contributions from slow boundary conditions and internal dynamics. Ensemble runs are started from different initial conditions but use identical boundary conditions of observed SST. AMIP simulations typically cover a 15 year period. If the experiments are done for the period 1979 to 1994 as in (2.4.1.1) the control simulation can represent one member of the ensemble. The uncertainty due to the chaotic nature of the atmosphere (noise) is determined from the range of the variability among the members of the ensemble in terms of rms values. The predictable part (signal) is estimated from the interannual variability of the ensemble mean. The signal to noise ration determines the level of predictability.

Dynamical seasonal prediction of the monsoon (again requiring ensemble of forecasts) for the summer seasons will provide measures of the influence from the initial conditions and the present skill of prediction.

Sensitivity and predictability experiments to see the impacts of land surface processes on the Asian monsoon with the use of the global soil moisture dataset during 1986-1995 which will be prepared in the 2nd phase of the ISLSCP.

Fig. 2.6: Illustration of three conceptual models of intraseasonal oscillation: a) Wave CISK, b) wind-induced surface heat exchange (WISHE), c) air-sea convective intraseasonal interaction (ASCII) (Flatau et al., 1997).

2.4.1.3 Intraseasonal variability

Some evidence is beginning to emerge that the intraseasonal oscillations of the monsoon play an important role in determining the seasonal mean and interannual variability. There is also evidence that there are similar intraseasonal oscillations in the upper ocean on a basin-wide scale. However, it is not clear whether coupling with the ocean is essential for the atmospheric ISO or they could be sustained purely by the atmosphere. Idealised AGCM studies have suggested that the coupling may be important. Fig. 2.6 (Flatau, 1997) shows a summary of the possible mechanisms of the ISO involving air-sea interaction and atmospheric dynamics and radiation. It is also possible that land processes also play a significant role in modulating the intraseasonal variability.

Proposals:

To establish the roles of the oceans and the land in monsoon intraseasonal variability, the outputs of model runs from (2.4.1.1) and (2.4.1.2) will be examined in detail to diagnose the structure and propagation of ISO in the models. Additionally, the following AGCM integrations for 5-10 simulated years are proposed:

1. AGCM experiments with observed daily or weekly 1^{o} x 1^{o} gridpoint SST versus monthly mean SST
2. AGCM experiments with prescribed soil wetness vs. variable soil wetness

These experiments are to be carried out with selected AGCMs whose monsoon climatologies are reasonably realistic.

2.4.1.4 Role of SST anomalies in influencing the monsoon

SST anomalies in different regions of the ocean influence the monsoon in different ways and through a variety of mechanisms. Thus ENSO-related SST anomalies in the east Pacific affect monsoon westerlies, while Pacific SST anomalies directly influence convection (Soman and Slingo, 1997). Positive SST anomalies in the south Indian Ocean and Arabian Sea are expected to enhance continental precipitation through enhanced moisture flux, whereas a positive SSTA over the equatorial Indian Ocean (Bay of Bengal) may cause a decrease (increase) in continental precipitation by favouring the oceanic ITCZ over the continental one. Up to now, very little modelling work has been done to delineate the dynamical underpinnings of these differences. To test mechanisms, AGCMs with realistic monsoon mean climatology should be used, and the experiments guided by statistical climate studies.

Proposals:

To meet these objectives, the following set of experiments will be carried out:

1. Observed SST anomalies over the global ocean will be used as control.
2. Observed SST anomalies will be prescribed over different portions of the Indian Ocean and western Pacific, while the rest of the ocean regions are kept at climatological SST.

Attention will be focused on regions where the SST anomalies are likely to produce different impacts, e.g. east Pacific, southern Indian Ocean, Bay of Bengal, equatorial Indian Ocean and the western Pacific/South China Sea region. To be effective, these experiments will be co-ordinated with a series of experiments with AGCMs proposed by CLIVAR NEG-1 to understand the dynamics of interannual variability of the monsoon.

2.4.2 Experiments with OGCMs

2.4.2.1 Ocean process modelling and intercomparison

The SST accuracy needed for monsoon studies may be as small as 0.2^{o}C; but presently, when OGCMs are run with realistic atmospheric boundary layer response to SST, they display SST simulation errors of order 2oC or more though the errors in SST anomalies will not be as large as those in absolute SST. The uncertainties in modelled SSTs are probably due to two major problems. First, most OGCMs have a significant thermocline drift in the tropics, especially the east Pacific. The development of OGCMs without such thermocline drift is thus a first priority. The other problem is related to the uncertainty in the net heat flux. Secondly, observed climatological net heat fluxes are uncertain to several tens of Watts/m2 (which can generate SST changes of several degrees in a few months). However, ocean models also have problems and flux estimates obtained by forcing OGCMs towards observed SST often lie outside these large error limits. Details of mixed layer dynamics are essential for improving the OGCM estimates of surface heat flux. Also, the roles of salinity and solar radiation penetration are likely to be important for SST change throughout most of the monsoon region, and nesting of high resolution submodels may be needed, e.g. in the

Indonesian region. The ocean modelling component of Asian-Australian Monsoon Implementation Plan will aim within the first five years to:

- Evaluate the performance of ocean models, driven by "state-of-the-art" observed fluxes, for simulating observed SST anomalies;
- Assimilate ocean subsurface data - and altimeter and SST data - into ocean models;
- Evaluate the performance of data-assimilating ocean models to reproduce observed high-quality surface flux measurements wherever these are available;
- Examine SST error growth rates when data assimilation is removed; and couple the resulting ocean models to atmospheric models for forecasting the monsoon.

Proposals:

To assess the performance of OGCMs in oceans in monsoon regions, the following four sets of experiments will be conducted:

1. OGCM simulations of the Pacific and Indian Ocean response to given surface stress products, and formulations of heat and freshwater flux boundary conditions ("OMIP" model intercomparison). These experiments will examine the mean seasonal cycle and anomalies of SST, ocean circulation and implied surface heat fluxes in several models, and will compare each with observations.
2. Studies of the sensitivity of OGCM simulations to different surface stress products, and formulations of heat and freshwater flux boundary conditions.
3. "Reanalysis" runs with data assimilating ocean models, forced towards observed SST. The surface flux data from these runs will be compared with high-quality surface heat flux observations, wherever these are available.
4. Studies of the "decay time" of model skill in simulating SST, following removal of data assimilation.

These experiments will be designed to complement AGCM experiments under Section 2.4.1.1 as closely as possible.

2.4.2.2 Evaluation of observed surface fluxes

To improve flux estimates for understanding monsoon mechanisms and for use in forcing ocean models, surface fluxes from AGCM reanalysis runs and operational models will be validated against all available high-quality, directly-observed flux data sets. Examples include the TOGA-COARE data, data obtained in recent process studies in the Arabian Sea, data to be collected in GAME, SCSMEX, PACS/VAMOS, satellite products from scatterometers (e.g. NSCAT, ERS-1) and radiation data collected in the equatorial central Pacific by the Atmospheric Radiation Measurement program (ARM). A comparison study by Weller and Anderson (1996) has suggested that the model fluxes may be seriously in error for the purpose of predicting short-term SST anomalies (Fig. 2.7).

Fig. 2.7: SST and flux variations over the TOGA-COARE region (Weller and Anderson, 1996).

Proposals:

1. In order to reduce the presently large errors in the model fluxes, modellers will employ the TOGA-COARE data set and those obtained from other suitable field programmes and satellite missions to pursue improvements to flux codes and parameterisations,
2. Special flux datasets will be compiled from field programmes, e.g. GAME and SCSMEX that can be used directly for monsoon diagnostic studies and/or the validation of model parameterisations (see discussion in Section 2.5.2).

2.4.3 Experiments with CGCMs

As coupled GCMs become more generally available to the monsoon research community and their capabilities over monsoon regions are proven, activities along the following lines will be considered:

Intercomparison of CGCMs simulations of the monsoon ocean-atmosphere-land system;

Sensitivity experiments with CGCMs to investigate ENSO - monsoon connections;

Assimilation of subsurface ocean data to improve the initialisation of ocean models for prediction with coupled models.

For sensitivity experiments, a multi-year control integration would first be carried out. The monsoon would then be perturbed (e.g. by increasing snow over Eurasia or by drying the land) and the impact on ENSO examined. Similarly, ENSO conditions could be perturbed, based on a knowledge of the interdecadal signals of the oceanic thermocline, and the impact on the monsoon examined. The ultimate objective is to couple data-assimilating ocean models to AGCMs, after it has been verified that both models generate realistic fluxes when each is forced by, or towards, realistic SSTs.

As discussed earlier, the modelling efforts will be closely co-ordinated with process studies (see Section 2.5) and future field campaigns. High resolution daily rainfall from both station data and satellite estimates will be needed for validation (see Section 2.7.1). Once such data sets become available, a "regional reanalysis" project will be launched that will use a good regional climate model nested in an AGCM or CGCM. This will establish a data set for detailed three dimensional studies of various processes related to monsoon variability. This work will be performed in close association with NEG-1 and the WOCE Modelling and Synthesis Group.

2.5 PROCESS STUDIES INCLUDING FIELD CAMPAIGNS

Process studies are focused research efforts, that may include field campaigns conducted over limited areas and duration. Such studies will be carried out within this initiative for the specific purpose of improving understanding of physical processes in the monsoon region. Process studies are an indispensable component of the CLIVAR AA-monsoon programme and will be carried out in close co-ordination with the modelling activities. Our understanding of the monsoon is developing rapidly, and we expect new proposals for process studies to emerge, and the present ones to evolve in the coming years.

2.5.1 Diagnostic studies

CLIVAR proposes five thrusts for conducting diagnostic studies. These are directed at elucidating the following:

2.5.1.1 Seasonal variations

- Mechanisms of the complex seasonal evolution (e.g. abrupt changes, onset and break) of the entire AA-monsoon.
- Role of air-sea interaction processes for different phases of the seasonal cycle over the western Pacific and the Indian Ocean.
- Processes associated with heating over Tibet, and large-scale land surface processes such as snow cover and soil moisture.
- Impact of winter monsoon on near equatorial convection and surface wind fields and SST.
- Maintenance and evolution of the maritime heat source over the Indonesian subcontinent preceding and during the austral summer monsoon.

2.5.1.2 Intraseasonal variations

- Relative importance of atmosphere/ocean interaction vs. land processes for the origin and propagation.
- Factors that govern the transition between active and break phases of the monsoon.
- Impact of intraseasonal variations on genesis of cyclones and monsoon depressions over the Indian Ocean and the western Pacific.
- Organisation of convection and interaction between convection and the large-scale environment over the Bay of Bengal and the South China Sea.
- Relationship with ENSO and the influence of ISO on interaction between the monsoon and ENSO.

Proposals for (2.5.1.1) and (2.5.1.2):

1. Support planned monsoon process studies and field campaigns in the western Pacific and East Asian regions i.e. GAME, SCSMEX, and other regional process experiments (e.g. KORMEX, Korea Monsoon Experiment).
2. Expand GEWEX/GAME regional experiment to the Indian subcontinent by the active involvement of Indian scientists, in particular, enhancement of radiosonde network over India for 1998 in conjunction with SCSMEX and GAME field experiments.
3. Initiate a pilot study of monsoon intraseasonal variability in the Bay of Bengal region, capitalising on the various observation platforms available from INDOEX in 1999 and activities planned under the National Indian Climate Research Programme.
4. Carry out feasibility and pilot studies for a focused field experiment on the Indian subcontinent and the surrounding oceans, which will provide data for the process studies of the seasonal march of the monsoon, including active and break periods associated with the intraseasonal variation of the South Asia monsoon and heat budget over the Indian Ocean (see Section 2.5.3 for specific proposals).
5. Expand the effort to process rainfall data to document the evolution of Indonesia rainfall on various time scales in conjunction with Indonesian scientists and research institutions.

2.5.1.3 Monsoon-ENSO coupling

Process studies addressing this issue will:

- Examine poorly understood ocean processes that may contribute to SST anomalies of importance for monsoon-ENSO coupling.
- Delineate the relative importance of land processes such as soil moisture, snow cover and continental ground temperature in amplifying or damping monsoon-SST coupling.

2.5.1.4 Tropospheric biennial oscillation

Process studies addressing this issue will:

- Identify the physical origin(s) of the TBO in monsoon regions, including local air-sea-land interaction, global-scale influence as well as internal dynamics.
- Identify the role of active convection during the boreal spring through summer, where interannual monsoon anomalies switch sign.
- Provide better understanding of the mechanism for interaction between processes with various time scales, i.e. 4-5 years, 2-3 years and others associated with the irregularity of ENSO-monsoon coupling.

Proposals for (2.5.1.3) and (2.5.1.4):

1. Conduct ocean process studies to illuminate the following subgrid scale processes in monsoon-affected oceans and marginal seas: diapycnal mixing near boundaries, especially the impact of baroclinic tides; epipycnal mixing in boundary regions (eddy statistics);

topographic influences (marginal seas, sills and straits); entrainment from the top of the thermocline and subtropical subduction.
2. Analyse outputs of high-resolution ocean models and observations to clarify large-scale oceanic processes: non-linear modifications of the reflection of Rossby waves from the irregular western Pacific boundary; bifurcation of the North and South Equatorial Currents and their variable impacts on low-latitude western boundary currents and effects of wind-driven upwelling on SST variations within the Warm Pool.
3. Analyse changes in land surface processes during warm and cold phases of ENSO to delineate possible impact of land surface processes in fostering or inhibiting the ENSO-monsoons coupling mechanisms, based on long-term integrations of CGCM (Section 2.4.1.4), satellite and reanalysis data.
4. Carry out process studies in conjunction with the development of special datasets and reanalysis projects for the monsoon regions (see discussion in Section 2.7).

2.5.1.5 Heat balance of the Indian Ocean

Process studies in this group will address the following issues:

- Understanding how the ocean dynamics can accommodate the anomalous heat flux into the North Indian Ocean.
- Identifying factors that inhibit organisation of deep convection over the Indian Ocean and unravelling causes for the small interannual variability in the Indian Ocean in contrast to the western and central equatorial Pacific.

Proposals:

1. Carry out diagnostic studies using satellite, reanalysis data and outputs from OGCM and CGCM as proposed in (2.4.2) and (2.4.3).
2. Investigate the feasibility of special observation platforms for the Indian Ocean (see Section 2.5.3).

2.5.2 Parameterisation of physical processes

- Several sub-grid scale processes are considered most important for understanding the AA-monsoon. CLIVAR will work closely with the relevant GEWEX subprogrammes to make improvements in parameterizing the following:
- Cumulus convection, including prognostic cloud water to better represent the monsoon moisture re-cycling and transport in the monsoon regions.
- Cloud-radiative processes associated with deep convection and cirrus shields that affect the water and heat budgets of the monsoon region.
- Coupling between vertical motions in deep convection and the boundary layer that modify surface fluxes at the air-sea and air-land interfaces.
- Improvement of land and ocean surface fluxes estimates based on information gained from prior and planned field campaigns and satellite missions. In addition, oceanic processes discussed in (2.5.1.3) need to be considered.

Proposals:

1. Exploit TOGA-COARE data fully to improve parameterisations of cumulus convection, heat and moisture surface fluxes, ocean surface layer and planetary boundary layer processes. CLIVAR monsoon scientists interested in this work will work within the TOGA-COARE research effort, which expects to yield its main results soon after the year 2000.
2. Develop, in association with relevant GEWEX subprogrammes, better techniques for representing in computer models, land and ocean surface processes and atmospheric mesoscale convection, employing data from planned field campaigns such as GAME,

SCSMEX.
3. Utilise regional climate models nested in GCMs to provide better and more detailed description of physical processes so as to improve parameterisation and the development of physical submodels in the monsoon regions.

2.5.3 Special observations and enhanced monitoring

Special observations over the eastern tropical Indian Ocean and western Pacific are required to understand better both the relationship between the seasonal variation of warm pool over the eastern tropical Indian ocean and the western Pacific, and the onset and variability of monsoon rainfall over South Asia, and also to improve model physics. The last international large-scale field campaign of the summer monsoon dates back to MONEX, 1979. Since then our knowledge of the regional monsoon has increased greatly, but knowledge of the monsoon as a climate subsystem is still lacking. Currently two major international monsoon field campaigns, i.e. GAME and SCSMEX are pending in 1998. GAME and SCSMEX will greatly enhance our understanding of the East Asian monsoon climate. Yet even with these special observations, knowledge of the structure of deep convection over interior India and Asia (morphology, heating distributions, etc.) and adjacent oceans and their role in the active and break of the monsoon is woefully lacking. CLIVAR will explore opportunities for continued special observations and enhanced monitoring over the South Asia and adjacent oceans. In this regard, three of the process studies described above are of particular relevance:

- Role of intraseasonal transitions (2.5.1.2);
- Monsoon-ENSO interactions (2.5.1.3);
- Heat balance of the Indian Ocean (2.5.1.5).

The use of existing observing platforms such as XBTs and drifting buoys must at least be continued at their present levels, and if possible enhanced. The use of well-instrumented oceanographic moorings is also essential. These are the only reliable means of obtaining *in situ* surface meteorology for accurate flux estimates. Mooring data will be intercalibrated with data obtained from other measurement platforms such as aerosondes and airborne remote sensors to provide estimates of near surface quantities and humidity profiles. Moorings also provide platforms for the deployment of emerging technologies such as acoustic tomography. Other activities including field programs and observations are being planned as national efforts and these are expected to contribute to project G2.

2.6 OBSERVATION SYSTEM REQUIREMENTS

2.6.1 Meteorological variables

Routine meteorological observations are the largest contributor to the observation systems for monsoon. Much of the detailed data derived from radiosonde and surface observations are either unavailable or are not digitalised for research use. For monitoring purposes, satellite data will play a critical role in the monsoon observing system. However, the moist and cloudy nature of the monsoon atmosphere may introduce large uncertainties in operational satellite retrieval algorithms. For example, various satellite-based rainfall estimates show major inconsistencies over the monsoon region, both in the mean and in the variance. Satellite-based surface winds fail during rainy periods, when it is critical to assess the impact of air-sea interaction on monsoon variability. While present satellite products provide good information on total water vapour content, they do not provide information on the vertical profile - of great importance for determining atmospheric stability and horizontal moisture fluxes. For all these variables, the failure during rain introduces the potential for aliasing - e.g. satellite estimates of SST may be systematically incorrect during the convective phase of ISO.

Proposals:

1. Make historical data and real-time satellite data (e.g. GMS, INSAT and others) available to the CLIVAR monsoon research community to enable effective coverage of the South Asian and Southeast Asian region.
2. Utilise rainfall products from TRMM and work closely with satellite algorithm developers to devise methods for improving satellite rainfall estimates and vertical profiling of water vapour.
3. Deploy rain gauges, incoming short-wave and long-wave radiation sensors and humidity sensors on ocean moorings; upgrade and install meteorological sensors on VOS (Volunteer Observing Ships); and instrument commercial aircraft for soundings during take-off and at flight-level.
4. Continue the development of new technology, such as aerosondes, i.e. autonomous atmospheric sounders (Holland et al., 1992), and explore its use strategically in monsoon-affected regions.
5. Maintain and expand on the existing network wind profilers in the monsoon region, e.g. in Indonesia, to provide continuous monitoring of boundary layer and upper wind conditions of the equatorial Pacific.

2.6.2 Oceanic variables

For monsoon oceanography, a serious difficulty arises from the fact that outside the equatorial Pacific, our understanding of the mechanisms that produce SST anomalies is quite limited. In much of the Indian Ocean, these mechanisms are complex and unique. Fluxes derived from models or from satellites contain serious errors. Salinity and other subsurface data in the monsoon oceans are almost non-existent.

Present routine SST products are based on satellite infrared estimates (AVHRR), which cannot see through clouds, and have to be corrected for vertical details of the water vapour profile to achieve the required 0.2^{o}C accuracy. As a result, SST estimates over the Bay of Bengal and the Indian Ocean ITCZ may be significantly in error during the monsoon season.

Proposals:

1. Maintain the current VOS XBT network, which was designed to meet WOCE/TOGA requirements, and expand it into the monsoon oceans (western Pacific and Indian Ocean) during the CLIVAR era and promote the continuation of the planned extension of TRITON (TRIangle Trans Ocean buoy Network) ocean moorings into the Indian Ocean (see 2.6.2.1).
2. Conduct or commission Observing System Sensitivity Experiments (OSSEs) to estimate the best use of existing resources, for purposes of understanding and predicting SST anomalies of relevance to the monsoon forecasting. Ideally these should be done with coupled models, but until these reach sufficient skill ocean-only models will be adequate. Based on the results of these OSSEs, it is further proposed to:
3. Vigorously pursue all opportunities for deploying TAO-type moorings, drifting buoys and profiling ALACE floats in the Indian Ocean in a fashion consistent results of the OSSEs and with effectively enhancing CLIVAR sustained observations and the initial observing system of GOOS/GCOS in the region. Although TAO-type moorings have yet to be justified as a requirement for operational monsoon prediction and inclusion in the GOOS/GCOS initial observing system, the research of G2 may easily do so.
4. Encourage the optimal use of the currently costly salinity sensors.
5. Utilise satellite data for SST and surface flux estimates, e.g. ADEOS/NSCAT, MODIS from EOS AM/PM Platforms.

2.6.2.1 The TRITON array

A new moored-buoy network named TRITON (TRIangle Trans Ocean buoy Network) has been developing at JAMSTEC for observing oceanic and atmospheric variabilities in the western tropical Pacific ocean and its adjacent seas as a part of CLIVAR observing system.

The principal scientific objective is to understand basin scale heat transports with emphasis on ENSO, Asian-Australian Monsoon showing large seasonal to interannual scale variations, and decadal scale variability that influence global climate change.

Fig. 2.8: The proposed TRITON buoy deployments (grey areas) and the TAO array.

The deployment will be started at four locations in the western tropical Pacific at TAO locations (Fig. 2.8). Subsurface ADCPs will be continually deployed along the equator as part of the Tropical Ocean Climate Study in conjunction with the TRITON buoy array. After establishing the network in the western tropical Pacific, two of buoys are planed to be extended in the eastern Indian ocean for the better understanding of heat and water budgets in the key area of Asian-Australian monsoon. Basically the sensors and those depths on the buoy are designed to be compatible with a standard TAO buoy in the western tropical Pacific. The TRITON buoys are also designed to measure the temperature and salinity in the full depth down to 750 m, and full surface meteorological parameters as wind speed/direction, temperature, relative humidity, atmospheric pressure, precipitation and short wave radiation. The buoy data are transmitted in real-time via GTS.

2.6.3 Land variables

In order to understand the predictability of the monsoon and the mechanisms of boundary forcing and internal dynamics, the continuous monitoring of land surface processes is necessary. Key land variables include soil moisture, river run-off, snow cover, surface heat budgets, including latent heat flux, sensible heat flux, long-wave and short-wave radiation. Currently, observations for these variables are mostly lacking. Many of the limited observations are being carried out under national or bilateral efforts within monsoon countries and regions.

Proposals:

1. Work closely with GEWEX, which has planned land surface programmes, e.g. GAME, GCIP to develop and share mutual needs for land surface atmospheric monitoring.
2. Create, in collaboration with GEWEX, an international framework to promote existing national and bilateral programmes for land surface monitoring.
3. The AAN/AWS network for GAME will be harnessed for long-term monitoring of surface heat budget and soil moisture to meet the CLIVAR AA-monsoon needs.
4. Make use of satellite estimate of land surface characteristics from land imaging sensors from ADEOS, EOS AM/PM and ENVISAT.

2.7 DATA SET AND PREDICTION SYSTEM DEVELOPMENT

2.7.1 Data set development and related studies

The most important parameter for describing the monsoon is rainfall. Yet the lack of rainfall data is very severe over the monsoon regions, in particular for the Southeast Asian region. Part of this is due to lack of observing stations and part due to data in local archives that is difficult to access. The lack of long-term rainfall and other critical datasets is a major impediment to progress in monsoon research. The following is a list of priority datasets that need to be developed:

- Long time-series (going back in time as far as possible) of daily rainfall data over the entire monsoon region.
- $1^o x 1^o$ daily precipitation data derived from INSAT, GMS and TRMM in the monsoon oceanic region.
- $1^o x 1^o$, weekly SST over the Indian Ocean and Western Pacific for the present and past decades.
- Daily surface temperature and soil moisture data from historical archives.
- Surface flux data over the monsoon oceans, including data from historical archives, satellites and *in situ* measurements.
- Upper air data from routine, operational radiosonde observations in monsoon regions.
- Datasets of dynamics, thermodynamics and physics fields from ongoing reanalysis efforts.

Proposals:

CLIVAR recognises that the development of historical datasets will entail major efforts and the full co-operation of many countries in the monsoon region. CLIVAR will collaborate with the data rescue projects of the World Climate Data and Monitoring Programme and other data rescue efforts to maximise the recovery and digitalisation of archived data sets in the monsoon region. Empirical studies will be conducted in parallel with the dataset development effort to ascertain the validity of the datasets. The following dataset development effort and related empirical studies will be carried out:

1. Establish and fund international programmes to retrieve, digitalise and archive historical daily rainfall data for the entire monsoon region.
2. Combine *in situ* and satellite data to develop gridded daily rainfall over the entire monsoon ocean and land region.
3. Develop appropriate monsoon indices based on rainfall and dynamical variables.
4. Construct high resolution maps of simultaneous and lagged correlation of monsoon rainfall and SOI or Niño area SST indices to quantify monsoon-ENSO relationships.
5. Identify SST regions in the Indian Ocean and western Pacific for which monsoon activities (as measured by the monsoon indices) are most sensitive to.
6. Conduct focused reanalysis effort in the monsoon regions in conjunction with special observations and field programmes for the validation of nested climate models.

2.7.2 Monsoon prediction system

A new thrust of the CLIVAR monsoon programme will be to take into account the applications and human dimensions of the predictability of the monsoon. Efforts towards the development of an end-to-end monsoon prediction system will be taken. These efforts will involve physical scientists, users and social scientists from the outset. This group will continue to work together throughout the process. Such an involvement promotes "ownership" of the products and optimises their usage. In this regard, CLIVAR will aid in the development of capacity building efforts in monsoon countries, with an eye towards the development of an end-to-end monsoon prediction system.

Proposals:

1. Establish a data network (internet based) to support users of monsoon data for the entire scientific community.
2. Develop capacity building programmes in monsoon countries for research and utilisation of research results for prediction in conjunction with APN/START (System for Analysis Research and Training) programme.
3. Expand activities of the IRI and related efforts, e.g. CLIPS, within national meteorological services to include a substantive monsoon component, with end-to-end prediction capabilities.

2.8 PROGRAMME LINKAGES

Because of the complexity of the monsoon problem and its linkages to many different subsystems of the earth's climate, the CLIVAR monsoon research programme must be carried out in co-ordination with other WCRP programmes. The major linkages are: Linkages with other CLIVAR components

- CLIVAR GOALS NEG-1 Panel: monsoon modelling and prediction experiments; development of coupled ocean-atmosphere model in monsoon regions.
- CLIVAR Upper Ocean Panel: studies of oceanic processes and response to monsoon forcings.
- CLIVAR/GCOS/GOOS TAO Implementation Panel (TIP): strategies of deployment of oceanic measurement platforms in the Indian Ocean for monsoon special observations. Linkages within WCRP
- GEWEX/GCSS: GEWEX Cloud System Studies for cloud ensemble and mesoscale models for development of nested regional climate models and improvement of physical parameterisation in AGCMs.
- International field campaigns: GEWEX/GAME, SCSMEX and other regional campaigns.
- COARE: model validation, flux estimation and description of atmosphere-ocean processes over the western Pacific warm pool that are related to the Asian-Australian-monsoons.
- WCRP/AMIP: Atmospheric model intercomparison over monsoon regions.
- WOCE (World Ocean Circulation Experiment): ocean circulation data from the WOCE Indian Ocean Expedition. Other Linkages
- International Pacific Research Center (IPRC): focused on basic research on Asian-Pacific climate, hydrologic cycle and related global changes issues.
- International Research Institute (IRI) & Climate Information and Prediction Service (CLIPS): end-to-end ENSO forecast system development and regional social and economic applications.
- International satellite missions: NASA/NASDA TRMM (rainfall); EOS (land surface characteristics and SST, clouds) ADEOS-1 and -2 and ERS-1 and -2 (atmospheric humidity and surface wind).

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To G3: Variability of the American Monsoon Systems

Last update: June 3, 1998 by Andreas Villwock