WP 1200 - Final Report

Objectives:
To investigate the influence of SST anomalies on the variability of monsoon climates, in particular the role of ENSO with the aim of raising awareness of the processes which must be well simulated by models before climate change predictions for the tropics can be judged useful.

Deliverables:
D1201: Assessment of the sensitivity of the tropical circulation and the associated hydrological cycle to regional anomalies, including idealized El Nino/La Nina integrations

D1202: Report on the causes of interannual variability of monsoon rainfall over tropical North Africa and the Caribbean

Summary
In general WP1200 has progressed well. The role of SSTs in controlling climate variability has been analysed for several regions and the simulation of SST anomaly teleconnections by both coupled and atmosphere only GCMs has been studied in detail (see individual reports from the partners for details). However, staffing changes at the Met Office meant that their work on the controls on Sahelian rainfall was terminated at the end of Year 1 and the analysis of Caribbean climate variability was not carried out. Instead, the Met Office undertook a study of the simulation of Asian summer monsoon teleconnections by several versions of their GCM.

In conclusion, with the exception of the study of Caribbean climate variability, all WP1200 deliverables have been achieved. Additional work, which is relevant to the work package objectives but not specified in the original work plan, has been carried out on the simulation of the Asian summer monsoon by both coupled and atmosphere only GCMS.

UREADMY

1. The relationship between Indian Ocean SST and East African rainfall

(Emily Black, Julia Slingo and Ken Sperber)

The identification of a mode of variability within the Indian Ocean (the Indian Ocean dipole or zonal mode) has raised questions about how Indian Ocean processes affect the climate of the surrounding continents. During IOZM events, the SST gradient in the Indian Ocean is reversed and the low level winds perturbed, with easterly anomalies in the central northern Indian Ocean weakening the climatological westerly flow. Observational and reanalysis data have been used to analyse the impact of the Indian Ocean Zonal Mode (IOZM) on the boreal autumn rainy season (the short rains) in coastal equatorial East Africa.

It has been found that strong IOZM events are associated with high rainfall in tropical, coastal East Africa, with the two strongest IOZMs of the last century (1961 and 1997) coinciding with the two rainiest autumns. Reanalysis wind and humidity data have been used to construct a dynamic scenario, in which sustained suppression of the climatological westerly winds in the northern, central Indian Ocean results in less moisture than usual being advected away from the African continent, and hence anomalously high rainfall in coastal East Africa.

The results of this study suggest that the relationship between Indian Ocean SST gradient and East African rainfall is, to some degree, non-linear. This conclusion is supported by two observations. Firstly, East African rainfall is only stronger than usual during the strongest IOZM events. Weaker events (moderate IOZMs), are not systematically associated with any rainfall anomalies at all. Secondly, during negative IOZM years, i.e. when the western Indian Ocean is anomalously cold and the Eastern Indian Ocean is anomalously warm, there is no significant effect on East African rainfall. If the system were linear, the positive rainfall anomalies observed in strong positive IOZM years would be matched by conversely strong negative anomalies during strongly negative IOZM years.

Determining the extent to which the IOZM is independent of ENSO is crucial to understanding the overall controls on East African rainfall. The relationship between the seasonal cycle of a developing El Nino and the onset of an IOZM event has been analysed using SST and low-level wind data. The dynamics of ENSO cause a cooling of the Indian Ocean off the north Australian and Sumatran coasts. Comparison of the evolution of IOZM and ENSO events suggests that when the ENSO forcing is strong during boreal autumn, the season in which the zonal gradient of SST in the Indian Ocean is weakest, the cooling in the Eastern Indian Ocean may be sufficient to reverse the zonal SST gradient in the Indian Ocean and trigger an IOZM. Hence, contrary to some published work, it is suggested that the IOZM cannot be regarded as independent of ENSO.

Analysis of the variability of Indian Ocean SST supports this hypothesis. Using NCEP reanalyses, the evolution of the IOZM was been studied using EOFs and regression analysis. Whilst the dominant pattern depicts the basin-wide warming associated with El Nino, the second mode captures the east-west structure described by the IOZM. However, the variance explained by this pattern is very high in the east

but negligible in the west, confirming that the IOZM is not an east-west SST anomaly dipole (as was originally suggested). Lag-lead regressions based upon the PC of this mode have shown that it develops in association with a growing El Nino and that the cooling in the east is linked to anomalous along shore winds off Sumatra which cause upwelling of cooler water.

A series of idealised experiments with the Hadley Centre atmospheric GCM, HadAM3, have been designed to investigate this relationship further. The model has been forced first with SST anomalies in the western Indian Ocean then by SST anomalies in the east and finally by symmetrical dipoles (anomalies of opposite sign in the east and west). These experiments suggest that, in the formulation of HadAM3 used, East African rainfall is linearly dependent on the SST of the western Indian Ocean. The zonal gradient in SST has been found to have no effect, independent of the SST in the western Indian Ocean. Comparison with observational and reanalysis data suggests that this behaviour is dissimilar to that observed - probably as a result of the model's poor representation of the mean state of October low level winds and rainfall.

2. Predictability of ENSO teleconnections *(Hilary Spencer and Julia Slingo)*

It is well known that the atmospheric circulation anomalies generated by the El Niño/Southern Oscillation (ENSO) can produce remote responses in the global oceans and land surface. However it is not clear to what degree these remote changes contribute to the memory and hence the predictability of the global circulation during and following ENSO. A series of idealised experiments with the Hadley Centre atmospheric GCM, HadAM3, have been designed to investigate these questions. The model is forced with a 4-year cycle of SSTs, typical of a fairly strong El Niño/La Niña, based on composites of many events from the observed SSTs for 1871 to 1999. These SST anomaly cycles are imposed either regionally in the tropical Pacific, or globally, and each experiment is run for 40 years, i.e. 10 cycles of El Nino/La Nina.

Preliminary results have shown that during the peak of El Niño/La Niña the global anomalies are primarily driven by the principal SST anomalies in the tropical Pacific, although the addition of the remote response to ENSO by the global oceans does lead to some changes in the structure of the teleconnections, particularly over the western Indian Ocean and Africa. However, several months later the remote, lagged response by the global oceans substantially affects the response in the model, particularly for the Asian Summer Monsoon. This suggests that the basin wide warming of the Indian Ocean, which occurs during the summer after El Niño, has an important influence on the behaviour of the monsoon. The model results show a damping of the precipitation anomalies associated with El Niño once the global SST anomalies are included. It is interesting to note the non-linearity of the response of the model to the Indian Ocean SST anomalies associated with El Niño/La Niña. Whilst the Indian Ocean warming in response to El Niño influences the monsoon, the corresponding cooling of the Indian Ocean in response to La Niña appears to have little effect.

Using a six member ensemble of the 19-level (L19) version of HadAM3, forced with observed SSTs, we have shown that the observed eastwards shift of the Aleutian Low during El Nino is not captured by the model. Instead the model's response is to produce an *in situ* deepening of the Aleutian Low with no high pressure anomaly west

of the dateline. This leads to errors in the downstream structure of the Pacific North American (PNA) pattern over North America with serious consequences for the skill of seasonal forecasts. We have attributed the poor extratropical response to errors in the response of the tropical convection to the SST forcing. Although the L19 model successfully captures the increase in precipitation over the central Pacific during El Nino, in *absolute* terms, the maximum heating remains in the West Pacific. Consequently the main forcing region for the extratropical Rossby waves is misplaced to the west. However, when this El Nino is modelled with 30 vertical levels, the precipitaion is highest in the centre of the tropical Pacific and correspondingly, tne North Pacific response is more realistic. The results from the L30 version of HadAM3 support the argument that the location of the absolute rather than the anomalous maximum in precipitation is crucial for the correct teleconnection patterns. The precipitation errors in the model have been traced to errors in the modelled sensitivity of precipitation to SST.

ICTP

Analysis of the variability and predictability of the Asian summer monsoon in an atmosphere only GCM forced with observed SST *(Franco Molteni and Susanna Corti)*

An analysis of the variability and predictability of the Asian summer monsoon, as represented by numerical simulations with observed SST performed in the context of the PRISM project (Predictability experiments for the Asian summer monsoon), was carried out by ICTP. The PRISM experiments consisted of a set of nine 10-member ensemble integrations performed with the ECMWF atmospheric GCM (cycle 16r2), with spectral truncation T63 and 31 vertical levels, using data from the ECMWF re-analysis (ERA) as initial and boundary conditions.

In these experiments, the dominant mode of interannual variability of the Asian summer monsoon consists of a zonally-coherent anomaly of 850-hPa wind in a latitudinal belt centred at 10°N, associated with a meridional shift of the TCZ from the equatorial Indian Ocean to the Bay of Bengal and south-east Asia. A similar variability pattern is found in observational data; however, the ECMWF model overestimates the fraction of variance explained by this mode, particularly of its wind component. The second mode of variability emerging from a singular-value decomposition (SVD) analysis of wind and rainfall fields also has a good correspondence with observed patterns of variability. In its positive phase, a cyclonic wind anomaly over the Indian subcontinent is associated with positive rainfall anomalies, while negative rainfall anomalies prevail over the Indian Ocean near the equator. A different degree of predictability characterizes the two leading modes of monsoon variability defined by the SVD analysis. While the association between the first SVD mode and SST anomalies is rather weak, leading to a poor predictability of its interannual variability, the second mode shows a clear relationship to the ENSO cycle. As a consequence, the interannual variations of the amplitude of SVD-2 anomalies are effectively simulated by the ensemble means, with a correlation of 96% between modelled and observed values of the associated rainfall index.

An EOF analysis of 5-day-mean rainfall revealed a strong similarity between the dominant patterns of rainfall variability on the interannual and intraseasonal scale. Although seasonal-mean values of the PC associated with the leading rainfall pattern shows no significant correlation with the ENSO index, the probability distribution of the leading 5-day-mean PC indices is turned from unimodal in the warm phase of ENSO to bimodal in the cold ENSO phase. These changes are suggestive of some sort of bifurcation in the monsoon properties, with a multiple-regime behaviour being established only when the zonal asymmetries in equatorial Pacific SST exceed a threshold value. Although an observational verification of this hypothesis is still to be achieved, the detection of regime-like behaviour in simulations by a complex numerical model gives a stronger support to this dynamical framework than simple qualitative arguments based on the analogy with low-order non-linear systems.

MPG.IMET.

The influence of tropical SST anomalies on Sahelian rainfall
(Mojib Latif, Jürgen Bader, Reiner Schnur)

The Sahelian region has a decadal variability being among the most pronounced identified in the historical climate records of the 20th century. The rainfall over the West Sahel shows a multidecadal drying trend from the 1950s (wet mode) to the beginning of the 1990s (dry mode), with a slight recovery in recent years. There is scientific agreement that this multidecadal trend is primarily induced by sea surface temperature anomalies (SSTA) and amplified and prolonged by local feedbacks, e.g. vegetation and soil moisture (see our contribution to WP1300). We investigated the impact of tropical decadal-scale SST forcing on West Sahelian rainfall using the ECHAM4 general circulation model. Two sets of sensitivity experiments with prescribed SST fields have been performed. In the first series, climatological SST was artificially enhanced or decreased by one Kelvin in different ocean basins to study the importance of the different regions for Sahelian rainfall. In the second set, more realistic SSTA composite fields were used to focus on the transition between the wet and the dry mode by perturbing the climatological AMIP2 SST from 1979-1995 ("dry control") with observed Reynolds SST from 1951-1960 ("wet") in all or certain ocean basins. The model response (perturbed sensitivity minus control experiment) to individual components and combinations of these tropical composite SST fields in the Atlantic, Pacific and Indian Ocean was then analysed.

The results show that decadal changes in tropical SST are able to produce a dry and wet mode in the Sahel. The tropical Atlantic is not responsible for the recent decadal change in West Sahelian rainfall; in particular, the inter-hemispheric Atlantic SST gradient is not the cause of the decadal drying trend over the West Sahel. The western tropical Pacific decadal SSTAs are more important for the eastern Sahel. Our experiments indicate that the warming of the tropical Indian Ocean that has been observed during recent decades seems to be most important for the recent decadal drying trend in West Sahelian rainfall (Figure 1). A large-scale atmospheric east-west pattern is associated with the warming of the Indian Ocean. As a result, a large-scale divergence response (accompanied by an intensified subsidence) occurs over West Africa in the dry mode. These model results are confirmed by observational results (e.g. Shinoda and Kawamura, J. Met. Soc. Jap., 1994). The experiments also show that the tropical SST warming, especially of the Indian Ocean, might have contributed to the recent decadal change of the North Atlantic Oscillation.

One of the leading modes of rainfall variability over West Africa is a dipole between Sahelian and Guinea Coast rainfall. The experiments show that this Guinea-Sahel rainfall dipole can be induced by simultaneous SST anomalies in the tropical Indian Ocean and in the eastern tropical Atlantic (Figure 1). This mechanism also explains why there is no significant anti-correlation between Guinea Coast and West Sahel rainfall. The SSTs in the tropical Indian Ocean and in the eastern tropical Atlantic evolve more or less independently.

In addition to the experiments described above, the influence of SST anomalies on precipitation over northeast Brazil was also investigated. Three sensitivity experiments have been performed where the climatological SST was increased

(decreased) by 1 K in the North Atlantic and decreased (increased) by 1 K in the South Atlantic, and increased by 2 K in the Nino3 region, respectively. All experiments caused significant changes over northeast Brazil, with an enhanced/reduced SST gradient in the Atlantic increasing/reducing rainfall. The response is nearly linear. The main effect of the enhanced Atlantic SST gradient was a shift of the ITCZ, caused by trade wind changes. The 'El Nino'–type perturbation caused a significant reduction in northeast Brazil rainfall. A significant positive sea level pressure (SLP) anomaly occurred over northeast Brazil, which may be associated with the descending branch of the Walker circulation. Also, a significant positive SLP anomaly over the Atlantic region between 30º S and 10º N occurred, resulting in a reduced SLP Gradient from the subtropical highs to the equator and a weakening of the trade winds.

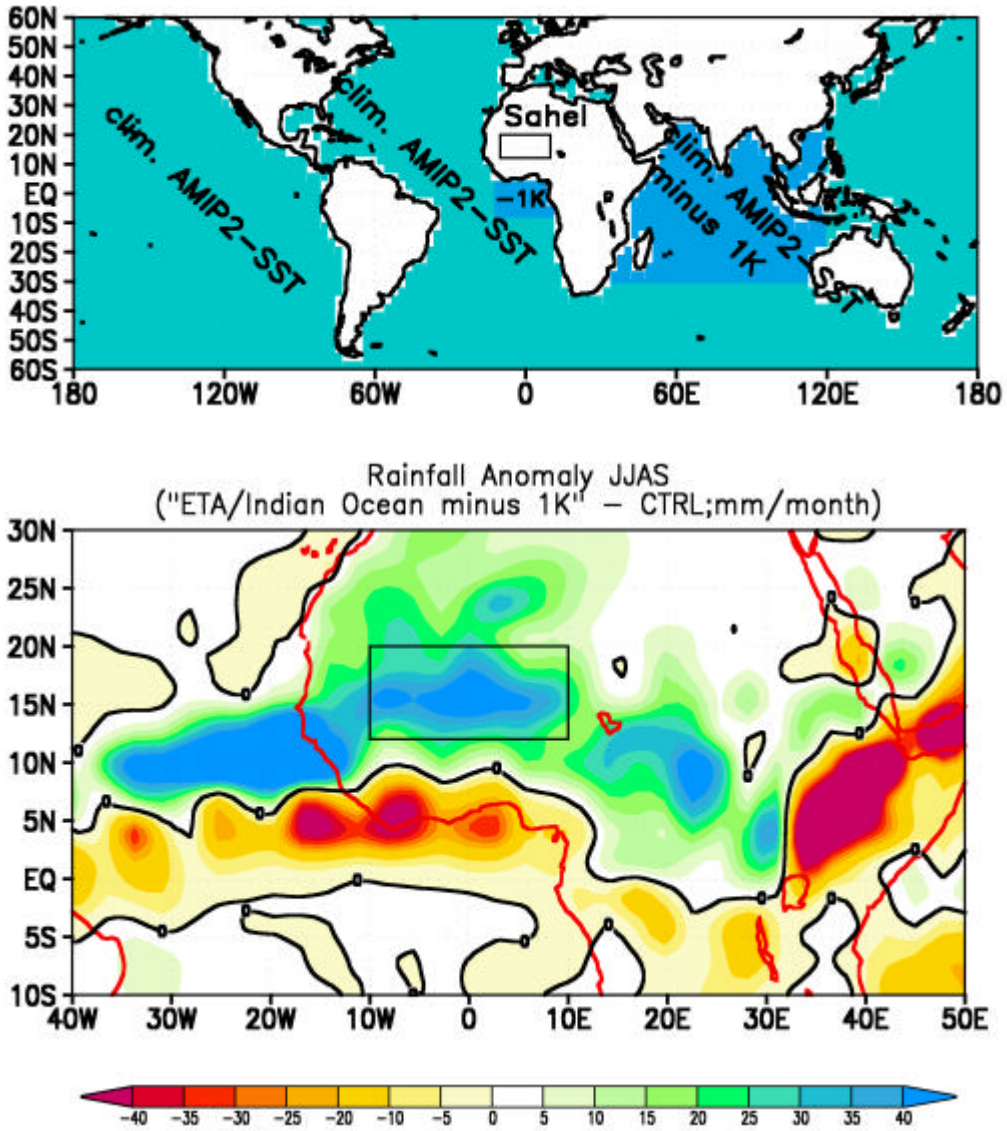

Figure 0: Combined effect of warming Indian Ocean and eastern tropical Atlantic SST on West African rainfall: a decrease of the climatological AMIP2 SST (1979-1995, representing the "dry" mode) by 1 K in these two regions (top panel) leads to a significant increase in West Sahel rainfall and is able to reproduce the dipole between Guinea Coast and Sahelian rainfall (bottom panel).

Met Office

1. The simulation of the teleconnection between global SST and the Asian summer monsoon in various versions of the Met Offices GCMs *(Gill Martin)*

During PROMISE, we have investigated whether development versions of the Met Office Unified Model show an improved simulation of the teleconnection between the Asian summer monsoon and global sea surface temperatures (SSTs). A secondary aim has been to assess the impact of coupling the atmosphere and ocean models on these teleconnections. We have compared four-member ensembles of atmosphere-only runs (each differing only in their initial conditions) covering the AMIP-II period (1979-1995), and several decades from runs of the coupled versions of each model. The standard model version is HadAM3/HadCM3 (atmosphere-only/coupled). The development version, HadGAM/HadGEM, is a new semi-Lagrangian, non-hydrostatic model which incorporates numerous changes to the physical parametrisations in both the atmosphere and ocean components, as well as to the model grid and vertical resolution, and includes additional processes such as the sulphur cycle and cloud aerosol effects.

Despite the vast differences between the two atmosphere-only models, their dominant modes of interannual variability are very similar. Easterly 850 hPa wind anomalies across east Asia and most of the Indian peninsula are associated with decreases in precipitation here, while increased convergence over Indonesia, western India and the Arabian Sea is associated with increased precipitation there. The coupled versions of the two models also show aspects of this mode, but both show additional anomalies over the southeastern equatorial Indian Ocean. The influence of the coupling on these modes is minimal, but appears to be slightly stronger in HadCM3 than HadGEM. In the latter model, the dominant mode is very similar to, and explains the same amount of variance as, the atmosphere-only model, whereas in HadCM3 the dominance of the primary mode is reduced compared with HadAM3.

Both the atmosphere-only and coupled configurations of HadAM3/CM3 show significant teleconnections between the dominant mode of interannual variability and SSTs in the central and eastern Pacific. Wind and precipitation anomalies in El Nino years are very similar to the dominant modes of variability in these models. This even extends to the additional wind anomalies over the southeastern equatorial Indian Ocean in the coupled model. These teleconnections are rather weak in HadGAM/GEM, suggesting that internal variability may be prevalent in this model. However, anomalies in El Nino years in HadGAM are quite similar to those observed, suggesting that strong SST forcing can outweigh the internal variability on some occasions. In contrast, HadAM3/CM3 responds too strongly to both local and remote SST forcing, such that teleconnections with SST, and anomalies in El Nino years, are less realistic than in HadGAM/GEM.

The appearance of anomalies over the southeastern equatorial Indian Ocean in the coupled models may indicate an improved representation of the Indian Ocean SST dipole mode when the atmosphere and ocean are allowed to interact. Both coupled models also show rather stronger teleconnections with SSTs than their atmosphere-only counterparts in this region. Distinct occurrences of an Indian Ocean SST dipole occur in HadCM3. Anomalies in these years are fairly realistic when compared with

observed anomalies from 1994. Occurences of the SST dipole in the HadGEM run are hard to identify, but a realistic representation of the associated atmospheric anomalies can be found in the second mode of interannual variability in HadGEM, and explains 12% of the variance. In the observations, this mode of variability is more prominent than in the models. We note, however, that tests carried out at CGAM (Reading University), where HadAM3 was run with the SST climatology from HadCM3, suggest that it may be the change in SST distribution, rather than the coupling, that improves the representation of this mode. It remains to be seen whether this is the case in HadGEM.

Preliminary analysis of the intraseasonal variability in the models shows a strong similarity between the second mode of intraseasonal variability and the dominant interannual mode in HadAM3. A bias towards positive/negative phases of this intraseasonal mode in El Nino/La Nina years is also apparent. This characteristic has been noted in other climate models. Conversely, there is little similarity between the intraseasonal and interannual modes in HadGAM, suggesting once again that internal variability dominates.

We conclude several things from this work. Different atmosphere-only models can exhibit very similar dominant modes of interannual variability, despite having quite different monsoon climatologies. However, in the case of HadAM3, the variability is strongly linked to SST forcing, while internal variability dominates in HadGAM. In spite of this, we find that strong SST forcing can outweigh the internal variability in HadGAM on some occasions. Coupling the models appears to improve the variability associated with the Indian Ocean SST dipole, although it is possible that this is associated with SST errors over Indonesia. However, links to ENSO are not altered much by the coupling of either model version. Neither model really captures the impact of global SST changes on the monsoon. This may be a result of remaining systematic errors which are common between the models, or it may suggest that the impact of SST forcing on the atmosphere is not represented properly in either model version. Investigation of these aspects should help to inform future model development.

2. The impact of Mediterranean SST on climatic variability in the Sahel

(David Rowell)

A series of sensitivity experiments designed to investigate the impact of the Mediterranean on the Sahel have been carried out. A pair of experiments has been performed with positive or negative SST anomalies throughout the Mediterranean, each simulating 20 annual cycles. The rainfall response over the Sahel is of the expected sign, and statistically significant, indicating that Mediterranean SST anomalies do indeed contribute to the forcing of climatic variability over the Sahel. These model experiments are now being used to explore the mechanism for this link. Finally, the possibility that Mediterranean SSTs may be used to improve seasonal forecasts of Sahel rainfall has been explored. However, the inclusion of an index of these SSTs unfortunately has no noticeable impact on the skill of multiple-linear-regression hindcasts of Sahel rainfall (with either a 2-month-lead or zero-lead). This is shown to be because Mediterranean SST anomalies lack sufficient persistence (or any other linear predictability) during the prelude to the Sahelian rainy season.

Because of difficulties (now overcome) in obtaining a good monsoon circulation with the latest version of the Met Office climate model, the idealised ENSO experiments planned for year one have not yet been completed. However, we have investigated whether improving the representation of boundary layer turbulent mixing and convective transport results in an improved simulation of the teleconnection between the Asian summer monsoon and Pacific SSTs in the Met Office Unified Model. The control is the standard climate version HadAM3, and the test run (including changes to the boundary layer and convection schemes plus an increase in vertical resolution) is referred to as NEWCONV. Both runs are 20 years long and forced with observed SSTs.

We find that the teleconnection pattern of All India Rainfall (AIR) with Pacific SSTs is much more realistic in NEWCONV than HadAM3, where the sign of the correlation is generally incorrect. The teleconnection pattern between the Dynamical Monsoon Index (DMI) and SST is also much more realistic in NEWCONV, and the agreement in terms of strength is better than in the teleconnection with AIR. Composite wind and precipitation anomalies in El Nino and La Nina years are quite realistic in NEWCONV in general, although less good in La Nina years especially at upper levels. Similar composites for HadAM3 show poor agreement with observations/reanalyses. These results suggest that improving the representation of boundary layer mixing and convection (along with increased vertical resolution) improves the links between surface forcing and the monsoon strength.