PROMISE

Predictability and variability of monsoons, and the agricultural and hydrological impacts of climate change

Final Report

Contract number:	EVK2-CT-1999-00022
Project reporting period:	March 2000 to February 2003
Sections included:	Section 3
Workpackage co-ordinator:	Max Planck Institute for Meteorology, Hamburg (MPG.IMET)
Workpackage number:	WP2000

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3.1 Objectives

The objective of this work package is to evaluate the future impacts of anthropogenic climate change on monsoon climates using control and transient GCM model integrations, including regional and high-resolution models.

3.2 Methodology and scientific achievements

In addition to the existing standard control and transient climate change integrations of the modeling centers, higher-resolution model integrations are included to study changes in the characteristics of monsoon climates, in particular extreme events, and to provide the higher spatial resolution needed for the impact studies involving agriculture and hydrology. These higher-resolution simulations are performed using regional models and/or time-slice experiments with global AGCMs. In the 'time-slice' setup, the output from standard transient simulations is used as boundary conditions for high-resolution atmospheric GCMs that are run for relatively short present-day and future time periods.

CNRM (MF): Possible future changes of the monsoon climate have been analyzed in transient climate simulations performed with the coupled atmosphere-ocean-sea ice version of the ARPEGE-Climat atmospheric model (including the OPA ocean and GELATE sea ice models) at a T63 (~2.8°) horizontal resolution. Two new 150-year simulations starting in 1950 have been used: a control simulation in which the greenhouse gas concentrations and aerosols are kept fixed at their 1950 observed value, and a scenario simulation in which the greenhouse gas concentrations are changed annually according to the IPCC scenario SRES-B2. No flux adjustment is used. The control simulation gives a realistic representation of the current climate with only a small drift. The simulated change of the hydrological cycle has been analysed in detail. As expected, a general increase of precipitable water was found to be associated with the atmospheric warming. This positive feedback to the greenhouse effect also contributes to the global hydrological cycle by increasing the water holding capacity of the atmosphere and providing more water vapour to precipitating systems. However, as precipitation increases less than the precipitable water the residence time of atmospheric water increases. The horizontal transport of water vapour is generally increased, and changes in moisture convergence and divergence are enhanced. The stronger warming of he upper atmosphere by convection leads to a strengthening of the Hadley circulation, with a corresponding increase of subsidence and drying on the winter hemisphere subtropics. This is accompanied by a northward shift of the ITCZ. The annual cycle of precipitation over the monsoon areas is thus amplified with higher precipitation during the wet season. The increase in the summer monsoon rainfall is particularly strong over Sahel and India. A comparison of the relative contributions of moisture transport and surface evaporation to precipitation has been made. Precipitation efficiency is increased in the Sudan-Sahel, weakly decreased over India, and decreased over Amazonia. The increase in summer monsoon rainfall over Sudan-Sahel is due to stronger moisture advection, combined with a larger precipitation efficiency in July, and is reinforced by surface evaporation showing the importance of precipitation recycling in the region. The increase in the African summer monsoon leads to positive soil moisture anomalies in JJA, and the anomalies tend to persist during the dry season due to slower evaporation in the absence of vegetation and to stronger water recycling. Over India, where the soil reservoirs are saturated during the monsoon season, the increase of rainfall leads to a larger runoff and only to a small change in evaporation. The river routing model TRIP has been used to simulate streamflow and compute discharges over the large river basins. The trends in annual mean discharge simulated over recent decades have been compared with the river flow measurements available from the Global Runoff Data Centre. These trends are fairly consistent with the instrumental record in the northern hemisphere mid-latitudes. In the monsoon regions (Ganges and Niger river basins), the trends are less consistent (weak in the model, but negative in the observations). The response of the annual discharge is stronger at the end of the 21st century, due to the significant increase in the monsoon rainfall combined to a weaker increase in surface evaporation.

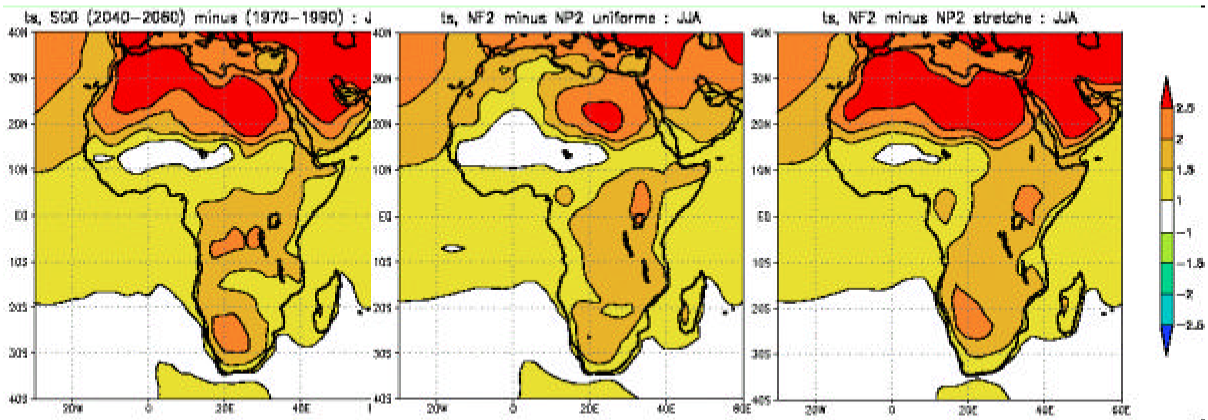
A more thorough analysis of the response of the Indian monsoon and its teleconnections with ENSO has been performed. A second transient coupled simulation similar to the first with only minor modification in the computation of ozone destruction and cloud albedo over sea-ice, has been used to check the robustness of the results. A validation of the present-day monsoon climate over India for the 1950-1999 period and its teleconnection with ENSO with observed datasets. The climate anomalies for the second half of the 21st century, when compared to the second half of the 20th century, show a significant increase in the mean annual surface air temperature over India of 2K with a maximum in winter, and of about 9-10% in monsoon rainfall due to increased moisture convergence. A northward shift of the westerly monsoon flow over the Arabian Sea and India, along with a relative weakening of the zonal monsoon circulation is simulated, together with a strengthening of the regional meridional Hadley circulation. The increase in precipitation has been attributed to the large increase of total precipitable water over India in the warmer climate, which plays a more important role than the circulation changes. Large multi-decadal fluctuations are found in addition to the long-term increase in simulated precipitation. The simulations show a Nino-like warming in summer, but no systematic change in SST variability in the Pacific. A strong correlation of Indian monsoon rainfall with east equatorial Pacific SST is found during summer and fall. The simulated ENSO-monsoon teleconnections have a strong modulation at the multi-decadal time scale but no systematic weakening in response to global warming.

A detailed analysis of the scenario for the impact over Africa has been performed. A validation of the climate for the recent period with comparison to ECMWF reanalyses and climatological data shows that this version is able to reproduce the main features of the west African summer monsoon climate. Some biases are found with excessive precipitation over the Gulf of Guinea caused by a positive bias in SSTs in the coupled model. A strengthening and northward displacement of the Hadley circulation is found over Africa, and is consistent with the intensification of the hydrological cycle. The zonal wind response shows a decrease of the intensity of the AEJ and a northward and upward displacement of its core. This is due to the response of the meridional temperature gradient which shows a reduction of the positive temperature gradient in the lower troposphere and an increase in the middle troposphere over the continent. By thermal wind relationships this leads to a reduction and higher extension of the easterly wind shear explaining the weakening and upward displacement of the AEJ. Maximum warming is stronger over land than over ocean. Precipitation is increased over Sudan and Sahel, which corresponds to a northward shift of the summer monsoon system. Soil moisture increases in JJA over most of the West African region, which produces increased evaporation.

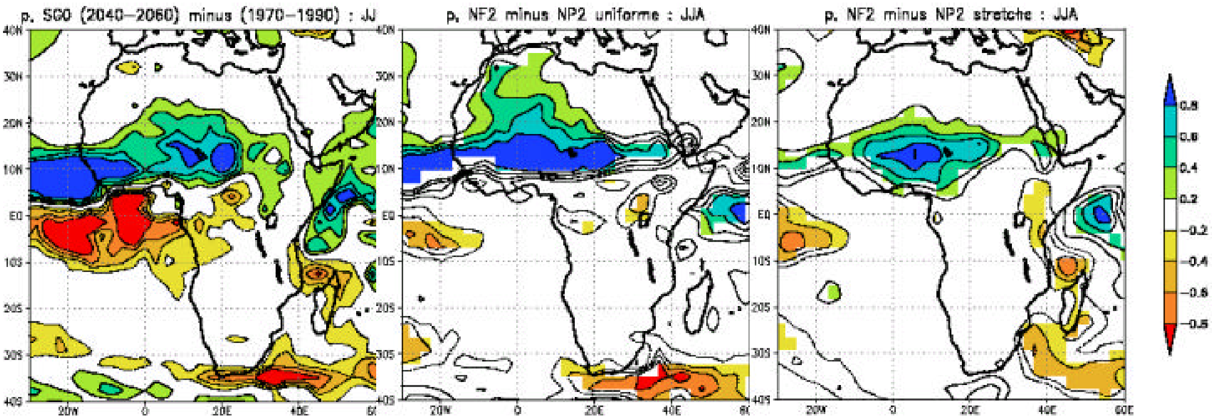
The scenarios over Africa have been improved by performing complementary simulations in “time slice” mode with the variable resolution version of ARPEGE-Climat (T106, with stretching factor of 2.5) with the pole of stretching over the Gulf of Guinea, in which the grid stretching allows to reach a resolution of about 100 km over Africa. A control simulation for the current climate has been made using observed climatological monthly mean SSTs averaged over the period 1970-1990. The description of the land surface has also been improved by updating the land-surface fields used in the soil-vegetation model ISBA on the basis the ECOCLIMAP database. A time-slice simulation has also been made for the period 2040-2060 with the averaged greenhouse gases concentrations averaged over this period and the computed SSTs from the coupled scenario, but with a correction of the bias of the coupled model. The comparison of the time slice simulations with the coupled simulations shows several improvements in the simulations of the African monsoon. The improvements are due to the use of more realistic observed SST climatology which allow to remove the bias in SSTs produced by the coupled model, in particular the excessively warm SSTs in the Gulf of Guinea. This warm bias produces excessive convection above which is causes a broadening of the ITCZ and excessive precipitation without a second dry season on the Guinea Coast region. Recently similar “time slice” simulations have been repeated with a uniform resolution (T63). The comparison of the variable resolution and the uniform resolution simulations shows broadly similar deficiencies in their climate, with only a small improvement with the increased resolution. The patterns of response to greenhouse warming are also very similar.

The greenhouse gas response in African temperature and precipitation for the coupled, uniform T63 and variable-resolution T106 models are compared in Fig. 1.

Temperature



Precipitation



coupled **uniform** **stretched**

Figure 1: Response of summer (June to August) 2m-temperature in °C (top) and precipitation in mm/day (bottom) for 2040-2060 with respect to 1970-1990 in scenario B2 simulated by ARPEGE-Climat in the coupled mode (left), and in time-slice simulations without the SST bias at the same uniform resolution T63 (middle), and with the variable resolution T106 with a stretching factor of 2.5 (right).

CNRS-LMD : The change of the hydrological cycle in anthropogenic climate change is of paramount importance for monsoonal climates and the water recources in monsoon regions. In a warmer climate the evaporation rate during summer will be enhanced with consequences for the storage of soil moisture. But the most important and difficult effect to assess is precipitation range. Many studies have suggested that, in an enhanced CO^2 atmosphere, rainfall could be more intense because the land-sea temperature contrast increases and induces a strong monsoon flow. However, as was also noted in the observed interannual variability of Indian monsoon regime, the low-level circulation is not well correlated with the precipitation changes and some studies have shown that a weakening of low-level flow can come with an increase of rainfall.

The results obtained with the LMD GCM are an example of such a paradox. We have conducted time-slice experiments to analyse the effect of doubling CO_2 on the Indian monsoon system. SST anomalies were prescribed using results from a transient experiment of the Hadley Centre. Two versions of land surface schemes were used in the time-slice experiments : one was carried out with a "bucket" scheme and the other with the Sechiba scheme. Two main points may be underlined in the results from the two experiments. The simulated increase of rainfall over South India is not clearly correlated with the 850 hPa wind changes (see figure) and the land surface scheme used in the model has an important effect on the anomaly of the monsoon regime that we simulate in the model.

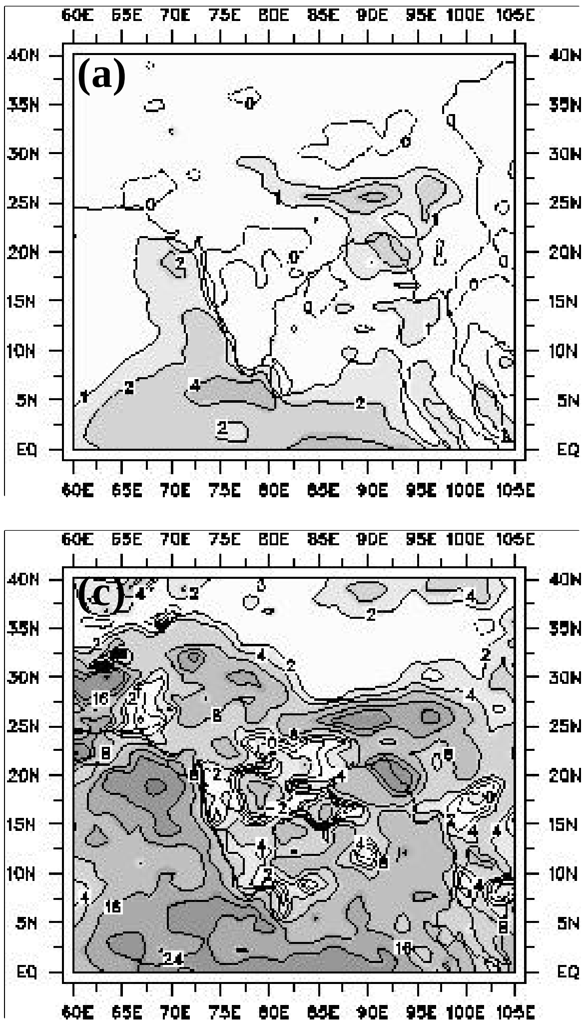
DMI: The potential future change of various aspects of the Indian summer monsoon as a consequence of the anticipated increase in the atmospheric greenhouse gas concentrations was investigated. This was done on the basis of a global time-slice experiment with the ECHAM4 atmospheric GCM at a high horizontal resolution of T106. The first time slice (period: 1970-1999) represents the present-day climate and the second one (period: 2060-2089) the future climate. The investigation includes aspects of the large-scale flow as well as of the hydrological cycle, in particular the day-to-day variation and the extremes of daily rainfall during the monsoon season. The time-slice experiment (period 1970-1999) simulates many aspects of the Indian summer monsoon very well, and due to the fine horizontal resolution of about 120 km many regional details of the rainfall pattern are well captured. Therefore, the time-slice experiment is quite suitable for assessing the potential future change of the Indian summer monsoon.

Despite a weakening of the large-scale monsoon flow in the future, the time-slice experiment predicts an increase of the mean rainfall during the Indian summer monsoon over most of the Indian region (Fig. 2a). The strongest increases occur in those regions, where the monsoon rainfall is rather strong, namely along the west coast of the Indian peninsula, over the tropical Indian Ocean, over the Bay of Bengal, and in Bangladesh and in the foothills of the Himalayas. Decreases, on the other hand, are found in the central part of the Indian peninsula and over the adjacent part of the Bay of Bengal, in Pakistan, in Tibet, and in southeast China, namely in the regions with rather weak monsoon rainfall. Apparently, the regional pattern of the monsoon rainfall is more pronounced in the future, due to an intensification of the atmospheric moisture transport into the Indian region in the future.

The future changes in the mean monsoon rainfall are only to a small extent due to changes in the frequency of days with rainfall, the so-called wet days, defined as days with precipitation exceeding 0.1 mm. There is, however, a general tendency of wet days occurring more often over the Indian Ocean and the Indian peninsula and occurring less frequently elsewhere. As a consequence, the future changes in the intensity of daily rainfall mainly account for the changes in the mean monsoon rainfall, and, hence, the distribution of the future change of the mean rainfall on wet days, giving the so-called rainfall intensity (Fig. 2b), has various features in common with the changes in the mean monsoon rainfall (see Fig 2a). But for the rainfall intensity, some of the areas with a reduction of the rainfall are smaller than for the mean monsoon rainfall, namely over the eastern part of the Indian peninsula, in Pakistan, in Tibet, and in southeast China.

One way to capture the heavy monsoon rainfall is by the 95%-percentile of the precipitation on wet days. That is, more precisely, the average amount of precipitation occurring on the 5% of the wet days with the strongest rainfall. For the future, the time-slice experiment predicts an increase of the amount of precipitation associated with heavy rainfall in most of the area (Fig 2c). The strongest increases occur over the northern end of the Bay of Bengal, in the Himalayan foothills, over the Indian Ocean south of about 10° N, and over the Arabian Sea. Except for the region over the northern part of the Arabian Sea and, to a small extent, over the eastern Indian Ocean, these are the regions where also the maxima of the 95-percentile are located. But the values of the 95%-percentile are markedly reduced in the northeastern part of the Indian peninsula and over the adjacent part of the Bay of Bengal.

The comparison with the future changes in the rainfall intensity (see Fig 2b) reveals a number of differences: As for the quantity, the changes in the 95%-percentile are considerably stronger than the corresponding changes in the rainfall intensity. In some regions, such as over the northern part of the Arabian Sea, in Pakistan, over the centre of the Indian peninsula, and in Indochina, the change in the 95%-percentile is up to 20 times as strong as for the intensity. As for the quality of the changes in the 95%-percentile, two regions with different signs of the respective changes stand out. In southeast China (Pakistan) the heavy rainfall, i.e., the 95%-percentile, is increased (reduced) in the future, while the rainfall intensity is reduced (increased). Further, in the central part of the Indian peninsula the area with a decrease of the heavy rainfall is larger than the corresponding area with a reduction of the rainfall intensity.



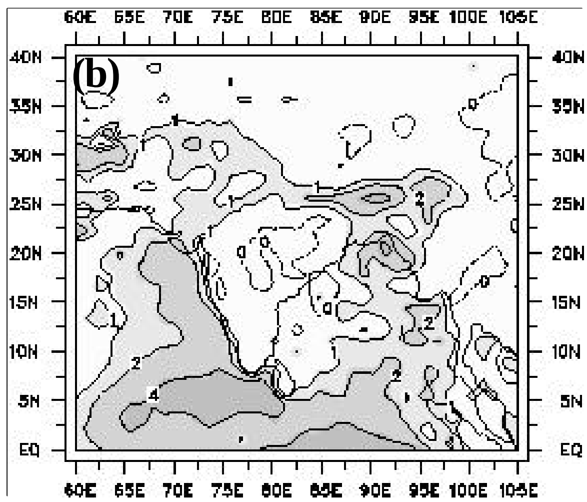


Figure 2: Climatic change, defined as the difference between the time-slice for the future climate and the time-slice for the present-day climate, for (a) the seasonal mean rainfall (June to September), (b) the intensity of rainfall, defined as the mean rainfall on wet days (days with precipitation exceeding 0.1 mm), and (c) the 95%-percentile of rainfall on wet days. Units are [mm/d]. The contour lines shown are at 0, ±1, ±2, ±4, ±8, ±12, ±20, ±28 and ±44 mm/d (a, b) and at 0, ±2, ±4, ±8, ±16, ±24, ±40, ±56 and ±88 mm/d (c), respectively. The 0-contour line is marked by the short dashes and the negative contour lines are marked by the long dashes. The different shades of grey indicate the magnitude of the changes.

Another focus of our work has been the sub-seasonal variability, i.e., active/break cycles of the Indian summer monsoon, considering both the large-scale circulation and precipitation in the Indian region. Both the re-analyses and the simulations reveal several distinct modes, which describe the day-to-day variations of both the horizontal wind field and precipitation. As for the horizontal wind field, these modes are associated with two preferred time-scales, one at 10-20 days and one at 30-60 days. For precipitation such time-scales could, however, not be found. These day-to-day variations are affected by interannual variations of the Indian summer monsoon and, hence, possibly by the El Niño/Southern Oscillation phenomenon.

MPG.IMET: The response of the Asian summer monsoon, including the mean monsoon and its variability, to global warming was studied by analysing a control and a transient greenhouse gas warming integration with the ECHAM4/OPYC3 AOGCM. In the transient greenhouse gas experiment, the atmospheric concentrations of greenhouse gases were prescribed as observed from 1860 to 1990, and according to IPCC scenario IS92a from 1990 onwards. In the control run, the concentrations were kept at their 1990 values. The broad-scale aspects of the Asian monsoon precipitation are reasonably well simulatd by this model, although the precipitation is somewhat underestimated over land and overestimated over the tropical Indian Ocean. The results show that increases of greenhouse gas concentrations lead to an intensification of the Asian summer monsoon and its variability. The intensified monsoon precipitation is confined to the Indian peninsula and its vicinity and results mainly from an enhanced land-sea contrast, a northward shift of the convergence zone and a westward shift of the ascending branch of the Walker circulation, as the land heats up more rapidly than the ocean in this run. In addition to this enhanced mean monsoon precipitation, a gradual increase of the monsoon variability was simulated from year 2030 onwards. It seems to be connected with the corresponding increase of the sea surface temperature variability (ENSO) over the tropical Pacific.

<u>Met Office</u>: Control (pre-industrial) and increased-CO_2 experiments (2041-2060) have been completed for both regional (RCM) and global (GCM) models and their time averaged responses to climate change have been assessed. The models' intraseasonal variabilities have been investigated via the active and break cycles of the summer monsoon, and the mechanisms which give rise to the distinctive precipitation anomalies associated with these events have been seen to be more realistically represented in the RCM compared to the GCM. In the warmer future climate, the change in particular intraseasonal precipitation anomalies can be attributed to the change in the frequency of cyclones, originating in the Bay of Bengal, which track over southern India, as opposed to along the normal position of the monsoon trough. These changes to the cyclone frequency, however, do not appear to be significant. This is not surprising as the historical record shows variability on decadal timescales, and we only have a twenty year integration from each period.

3.3 Socio-economic and policy implications

Obviously, improved projections of future monsoon climates, in particular for extreme precipitation events and surface hydrology, based on regional and high-resolution global climate models is important for the impact assessment of anthropogenic climate change on the Asian and African monsoon regions. The needs for water resources are increasing with the growth of the population and intensification of agriculture and a good prediction of monsoon variability is of paramount importance to plan ahead and limit climate-induced socio-economic problems. The simulations performed have confirmed a large impact of global warming on the monsoon rainfall in Africa and India, both in the mean change and the increase of extreme events.

3.4 Discussion and conclusion

A couple of control and climate change scenario integrations with global (GCM and higher resolution time-slice) and regional models have been carried out and analysed to evaluate the impact of anthropogenic climate change on the characteristics of the Asian and Indian monsoon systems, including seasonality, interannual and intraseasonal variability, and extreme events. The results obtained indicate an intensification of the Indian and Sahelian summer monsoon in a future warmer climate due, for example, to the enhanced land-sea contrast and a northward displancement of the intertropical convergence zone. For the increase in Indian monsoon precipitation, the increase of precipitable water in a warmer climate seems to be more important than circulation changes. An increase of the Indian summer monsoon interannual variability was also simulated from 2030 onwards, possibly related to an accompanying increase of ENSO variability. Overall, the effect of anthropogenic climate change on the Indian monsoon is an enhancement of the spatial patterns of rainfall intensity as well as extreme (i.e. heavy) precipitation. There are indications for changes in the intraseasonal precipitation anomalies of the Indian monsoon system due to changes in the frequencies of cyclones over southern India. All these results contribute directly to deliverable D2001.
Deliverable D2002 consists of an assessment of the value of high resolution regional models simulations for impact assessment. Naturally, regional high-resolution model simulations are very important since they provide the higher spatial resolution needed for impact studies involving agriculture and hydrology. It has been shown that the representation of the land surface, which will be better in higher resolution and regional models than in low-resolution GCMs, is important for the simulated monsoon climates in climate change scenarios.The results of this work package also suggest that the mechanisms responsible for Indian summer monsoon intraseasonal variability are more realistically represented in a regional model compared to a GCM. Using a higher resolution in time-slice GCM simulations of the African monsoon resulted only in limited improvements due to the resolution change alone, while the main improvement was due to a better representation of the SST boundary as compared to the coupled GCM runs.