Impact of CO_2 Doubling on the Asian Summer Monsoon: Robust Versus Model-dependent Responses

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Abstract

The possible impact of anthropogenic climate change on the Asian summer monsoon is investigated in several time-slice experiments using prescribed sea-surface temperature (SST) and sea-ice anomalies. The study is carried out with four different atmospheric general circulation models (GCMs), each being involved in two pairs of experiments differing only by the treatment of the land surface hydrology. The objective is to assess the robustness of the simulated climate change, and its possible sensitivity to the land surface scheme. Despite the use of identical SST anomalies, the four GCMs do not predict similar monsoon responses on the regional scale. All models produce a stronger warming over the Asian continent than over the Indian Ocean, but this warming is not a good predictor of the monsoon response to increased CO_2 level. There is a significant spread in the summer precipitation anomalies despite a general weakening of the monsoon circulation, showing that the response of the monsoon rainfall is not solely related to the changes in the large-scale dynamics. In a warmer climate, the monsoon precipitation can increase despite a weakening of the monsoon flow, due to an increase in the atmospheric water content. For decades to come, the increase in the atmospheric water content could be more important than the increase in the land-sea thermal gradient for understanding the evolution of the monsoon precipitation. Though it does not represent a major source of uncertainty, the treatment of the surface hydrology is liable to affect significantly the regional response of the monsoon to CO_2 doubling. A slight change in evapotranspiration is enough to induce a significant change in precipitation. A simple analysis of the regional water budget indicates that this sensitivity is not only related to changes in the horizontal transport of water vapor, but also to changes in the precipitation efficiency, which depends on the treatement of the land surface hydrology.

1. Introduction

Due to the burning of fossil fuels and to large-scale deforestation, the atmospheric concentration of greenhouse gases has dramatically increased over the last few decades. The additional amount of heat energy trapped near the Earth's surface is likely to be responsible for the recent increase in the observed global surface temperature. This warming is anticipated to accelerate during the next century, possibly provoking significant modifications in the large-scale

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atmospheric circulation. The increase in the radiative forcing and the changes in the circulation patterns will also affect the hydrological cycle and have far-reaching consequences on human society, especially in the areas where water is already a major constraint for economical development. The south Asian countries are particularly concerned by the issue of climate change. They include more than half the world's human population and have predominantly agrarian economies that are critically affected by climate fluctuations. In this area, the seasonal reversal of the land-sea temperature contrast drives a large-scale circulation known as the Asian monsoon. The year is divided into two distinct phases: the dry and the wet seasons. During the wet season, warm, moist and disturbed winds blow inland from the tropical oceans and bring most of the annual precipitation. This rainy season is short (June to September) and unreliable, with large interannual variations leading to severe droughts or floods. South Asia could therefore strongly suffer from possible perturbations in the climate system, and predicting the sensitivity of the monsoon to anthropogenic climate change is a major and vital challenge.

Current generation atmospheric GCMs are able to simulate the main features of the present-day monsoon circulation, and to predict some aspects of its interannual variability (Webster et al. 1998, Stephenson et al. 1998). They have also been used to investigate the climatic impact of an increase in the atmospheric concentration of greenhouse gases (Melillo et al. 1995). Early studies suggested that the Asian summer monsoon could be more intense in an enhanced greenhouse climate. Comparing the response of five atmospheric GCMs coupled to a slab ocean model to CO_2 doubling, Zhao and Kellogg (1988) concluded that wetter summer conditions were likely to occur over both India and southeast Asia. With another coupled ocean-atmosphere model, Meehl and Washington (1993) also obtained greater summer monsoon precipitation in a doubled CO_2 climate, and also explained this increase by the stronger surface warming over the Asian continent than over the Indian Ocean. Bhaskaran et al. (1995) analyzed the results from a transient coupled experiment with a gradual increase of the CO_2 concentration, and found a northward shift and an intensification of the monsoon rainfall, which was also partly attributed to an increased difference between land and sea temperatures.

Despite this apparent consensus, the long-term evolution of the Asian summer monsoon is still a matter of debate. First, there is no evidence that the all-India monsoon precipitation would have changed significantly over the last few decades in the observational records (Pant et al. 1993). Moreover, the 40-year NCEP/NCAR reanalyses suggests a decrease in the large-scale wind shear monsoon indices between 1958 and 1998, at a rate of about 0.2 % per year (Stephenson et al. 2000). Finally, there are still large uncertainties in the numerical predictions. For example, in the preliminary study of Zhao and Kellogg (1988), only three models indicated an increase in soil moisture, while one produced a strong decrease and the last one gave a hybrid response. More recently, no clear evidence for a significant change in the monsoon rainfall was found either in the Max Planck Institut coupled model (Lal et al. 1994, 1995) or in various time-slice experiments performed with former versions of the Météo-France atmospheric GCM (Royer et al. 1996, Mahfouf et al. 1994, Timbal et al. 1995). Kitoh et al. (1997) noted an apparent paradox between the circulation and precipitation changes of the monsoon in a transient CO_2 experiment using the Meteorological Research Institute coupled GCM. Despite a weakening of the low-level monsoon winds over the Arabian Sea, summer rainfall increased over India, due to a larger moisture content in the warmer atmosphere.

The spread found in the GCMs' predictions can be explained by the high sensitivity and complexity of the monsoon phenomenon. Both observational and numerical studies have suggested that the Asian monsoon is affected by teleconnections involving both land and ocean areas. Two main large-scale forcings have been identified. The Eurasian snow cover was shown to influence the springtime temperature of the Asian continent and thereby the land-sea thermal contrast, which is believed to drive the monsoon circulation (Barnett et al. 1989, Yasunari et al. 1991, Douville and Royer 1996). The El Niño Southern Oscillation (ENSO) also shows significant correlations with the monsoon precipitation, due to the associated east-west shifts in the tropical Walker circulation (see for instance Webster et al. 1998). Although the ENSO seems to be the largest climatic forcing of the interannual monsoon variability, the relevance of snow was recently highlighted by Krishna Kumar et al. (1999). They suggested that the drop in the monsoon-ENSO correlation noticed over the latest two or three decades could be due to the simultaneous decrease in the Eurasian snow cover. The recent Eurasian warming, possibly related to anthropogenic effects, could therefore explain that no systematic decrease in the Indian monsoon rainfall was observed during the latest ENSO events, the SST impact being overriden by the influence of the stronger land-sea thermal gradient. However, their statistical analysis was based on climatological records that do not exceed a few decades. Numerical studies are needed to validate their results.

The LSPCR (Land-Surface Processes and Climate Response) project started in 1996 with the aim of determining the uncertainties linked to the land surface processes in climate change simulations (Polcher et al. 1998). A set of coordinated doubled-CO_2 time-slice experiments has been performed with different state-of-the-art atmospheric models using the same SST and sea-ice anomalies derived from a transient simulation using the HadCM2 coupled ocean-atmosphere global model (Johns et al. 1997). At least two experiments have been performed with each GCM, using both a reference and a modified land-surface scheme (LSS). This method enables us: i) to ignore the uncertainties related to the ocean response and, ii) to separate the uncertainties linked to the LSSs from those of the atmospheric models as a whole and compare them. It is found that: i) there is a significant spread among the models' predictions, even on the global scale, despite the use of identical SST and sea-ice anomalies; ii) the changes to their LSS carried out by the participants affect the global mean land surface temperature increase by only a small amount compared to the differences seen between the various GCMs, iii) the conclusion is different for global mean and regional precipitation, where the response to CO_2 doubling was shown to be more sensitive to the treatment of the land surface (Polcher et al. 1998).

In the present study, we further analyse the LSPCR experiments by focusing on the Asian summer monsoon. This region was chosen for two reasons. First, the monsoon response to increased CO_2 concentration is still a matter of debate. Second, the monsoon is expected to respond sensitively to changes in LSSs, since numerous studies have suggested that it is influenced by land surface anomalies (Sud and Smith 1985, Barnett et al. 1989, Meehl 1994, Douville and Royer 1996, Yang and Lau 1998). In the next section, the design of the LSPCR project is presented. Section 3 compares the results of the four atmospheric GCMs involved in the project. After a brief description of the monsoon simulated in the control experiments for present-day climate, we analyse the monsoon response to CO_2 doubling and its sensitivity to the treatment of the land surface hydrology. Section 4 investigates if the monsoon response can be influenced by the temperature response found over the Eurasian continent. It also pays particular attention to the effect of the local evapotranspiration on the regional hydrological cycle. The main conclusions of the study are given in Section 5.

2. Design of the experiments

Four climate modelling groups were involved in the LSPCR project: the Centre National de Recherches Météorologiques (CNRM), the Laboratoire de Météorologie Dynamique (LMD), the Hadley Centre for Climate Prediction and Change (HC) and the University of Reading (UR). Previous versions of the atmospheric GCMs used by these four modelling groups took part in the AMIP intercomparison project (Gates 1992) and produced reasonable simulations of present-day climate. We can thus consider that these four GCMs are a representative sample of current state-of-the-art atmospheric models. In the present study, each group was asked to provide 10-year time-slice experiments for both single and doubled-CO_2 climates, using a prescribed set of SST conditions and two different LSSs. The modifications which were done in the land surface parametrizations ranged from altering one parameter to the use of a substantially different scheme. The most extreme change is probably the replacement of the standard LSS of LMD (Ducoudré et al. 1993, De Rosnay and Polcher 1998) by a much simpler bucket hydrology (Manabe 1969). The first HC integration used the scheme described in Warrilow and Buckley (1989), while the second experiment used a recent parametrization developed by Cox et al. (1999), which includes major improvements in the soil hydrological properties and a stomatal resistance depending on the atmospheric CO_2 concentration. The UR, using the European Centre for Medium-range Weather Forecasts (ECMWF) GCM including the LSS developed by Viterbo and Beljaars (1995), halved the uniformly prescribed rooting depth in the second time-slice experiment.

At CNRM, three doubled-CO_2 experiments were performed with the ISBA LSS (Noilhan and Planton 1989, Mahfouf et al. 1995, Douville et al. 1995, Noilhan and Mahfouf 1996), in order to assess the relevance of possible vegetation feedbacks associated with changes in the plants' physiology and structure. In most climate change experiments, the vegetation properties are prescribed according to present-day satellite or in situ data. Yet, the rising CO_2 concentration may also have significant effects on the terrestrial biosphere (Melillo et al. 1995). Some plants could maintain the same intake of CO_2 for photosynthesis by reducing their stomatal openings, thus limiting the transpiration and providing a positive feedback to the surface warming. Other plants could benefit from the higher CO_2 level and the warmer climate to increase their productivity, which would, on the contrary, promote the transpiration. The relevance of these feedbacks has been investigated in the CNRM experiments. Besides a first doubled-CO_2 experiment, labelled A, with no modification of the vegetation properties, two other experiments have been performed. Experiment B explores the impact of increasing the stomatal resistance, while experiment C also considers an increase in the leaf area index. These simulations already have been described and analysed by Douville et al. (2000). The results showed that both vegetation feedbacks could be significant on the regional scale, but that they

Table 1. Description of the model configurations used in the LSPCR project.

Model	Exp.	Land-surface scheme
HC	A	Old land-surface scheme
	B	The MOSES scheme
LMD	A	The SECHIBA scheme
	B	A simplified hydrology
CNRM	A	The ISBA scheme
	B	Stomatal resistance was increased
	C	Leaf area index was increased
UR	A	The ECMWF scheme
	B	Rooting depth was reduced

partly cancelled each other in the ARPEGE climate model, due to their opposite impacts on evapotranspiration. For this reason, only experiments A and B will be discussed in Sections 3 to 5. Note also that CNRM carried out a single control experiment for present-day climate, while the other groups performed two pairs of control and future climate experiments.

The various simulations are summarized in Table 1. All GCMs were run with prescribed monthly varying SST and sea ice until the land surface reached equilibrium with the atmosphere before the 10 years of each experiment proper began. Temperature and sea ice changes for the doubled-CO_2 experiments were taken from the GHG transient simulation performed with the HadCM2 coupled model of the Hadley Centre (Mitchell et al. 1995, Johns et al. 1997). Average anomalies for each month were calculated over a 20-year period around the time at which CO_2 level doubled. These were then applied to climatological monthly average values over the period 1979 to 1988 as defined for the AMIP project (Gates 1992). The sea-ice distribution provided by the Hadley Center for the doubled CO_2 was not used directly because of deficiencies in the control climate. It was decided to transpose the simulated shift of the 10 % isoline of sea-ice fraction to the AMIP data. This solution was chosen because the 10 % isoline was very close to observations in the simulated present-day climate.

3. Intercomparison of the model results

3.1 Control simulations of the monsoon

Despite the focus of this study on climate change rather than on present-day climate, here it is important to describe briefly the control simulations, because patterns of the monsoon anomalies are likely to depend at least partially on the features of the control climate. The aim is not to evaluate and compare the skill of the various GCMs, which would need a much more detailed analysis, but rather to provide an insight of their control climates to better understand their response to CO_2 doubling. Even for state-of-the-art models like those considered in the present study, it remains a challenge to produce a realistic simulation of the present-day monsoon climate. Analysing the monsoon precipitation simulated by 30 atmospheric GCMs in the AMIP project, Gadjil and Sajani (1998) showed that the models fell into two main classes, the first comprising models with a realistic simulation of the seasonal migration of the tropical rainbelt over the Asia West Pacific sector, and the second comprising models with smaller amplitude of the seasonal migration than observed. In both classes, some models are able to capture the main features of the mean summer rainfall pattern over India.

The four atmospheric models developed at CNRM, LMD, HC and UR form a representative sample of GCMs, in which the seasonal migration of the Indian Ocean ITCZ (Inter Tropical Convergence Zone) shows a variable amplitude (strong for HC, weak for LMD). For the sake of simplicity, only JJAS (June to September) seasonal means are presented in this section. Figure 1 compares the 850 hPa horizontal wind simulated in the control A experiments of CNRM, LMD and HC (UR is not available) to the ECMWF reanalysis climatology (1979–1994). Alhough the large-scale summer monsoon circulation is captured by all models, the low-level westerly jet is generally too strong and continues too far eastward. Figure 2 shows the upper troposphere wind at 200 hPa. As is the case for the low-level westerly monsoon circulation, the upper-level easterly jet is generally overestimated and the center of maximum magnitude is not perfectly located.

Two indices have been proposed to summarize the large-scale Asian monsoon circulation. These are vertical shear indices between 850 and 200 hPa of the zonal (U-shear) and meridional (V-shear) winds. The U-shear index is computed over the domain 40–110°E/EQ-20°N (Webster and Yang 1992), while the V-shear index is averaged over a larger domain (40–140°E/15°S–25°N). The V-shear index was proposed by Goswami et al. (1999), who suggested that the U-shear index represents more a measure of the Walker circulation variability than a measure of the monsoon heat source. They showed that the V-shear index has a stronger correlation with the monsoon rainfall. Tables 2 and 3 show the indices obtained in all experiments A and B. Compared to the ECMWF reanalysis climatology, the models tend to overestimate both indices, which confirms the too-strong Walker and Hadley circulations in the control simulations.

Figure 3 shows the JJAS precipitation simulated in the control A experiments. The LMD and, to lesser extent, the CNRM experiments show maximum precipitation over India and Burma, but these two models underestimate the equatorial precipitation belt over the Indian Ocean. On the other

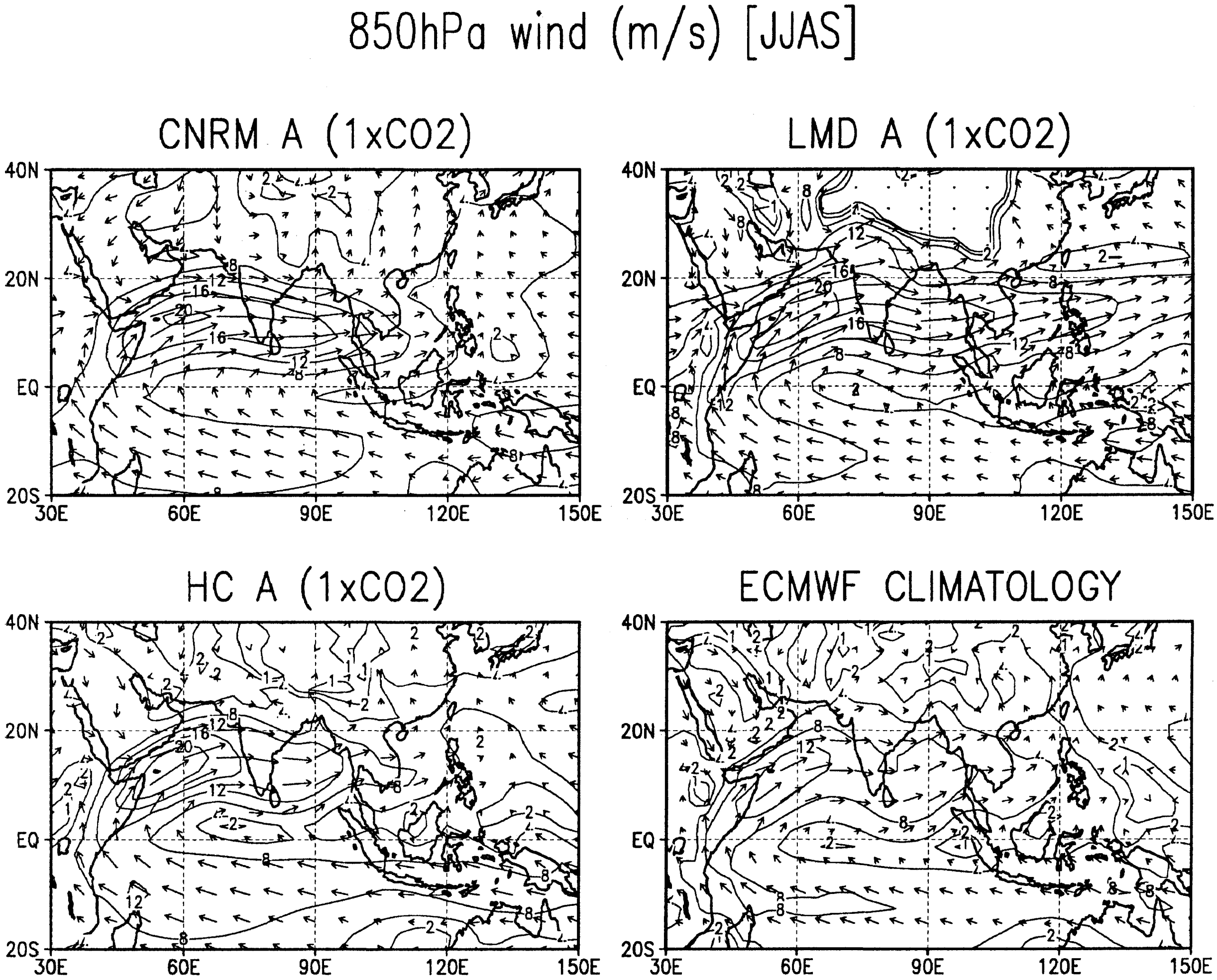

Fig. 1. Comparison between the JJAS 850 hPa wind field (m/s) simulated in the control A experiments (except UR) and the ECMWF reanalysis climatology (1979–1994).

hand, they simulate strong rainfall over the southern slopes of the Tibetan Plateau compared to the CMAP climatology (Xie and Arkin 1996). This feature has been noticed in several GCMs in the AMIP simulations (Gadgil and Sajani 1998). Note that CMAP does not correct the gauges for altitude, which can explain this apparent bias in the simulations. The recent CRU climatology (New et al. 1999) shows larger rainfall than CMAP over the Himalayan foothills, but still less than the CNRM and LMD simulations. In these models, the anomalous Tibetan convection might induce a subsidence over the Indian Ocean, which could explain the lack of precipitation in this area. The HC and UR simulations show more realistic precipitation patterns, though the monsoon rainfall is either too strong (HC) or too weak (UR). This is summarized in Table 4, showing the JJAS average precipitation over land in the domain 60–120°E/EQ-30°N, which encompasses the Indian and southeast Asian subdomains. The observed monsoon precipitation rate (6.3 mm/day according to the CMAP climatology) is clearly overestimated by the CNRM and LMD GCMs due to the Himalayan contribution.

Note that the control B experiments show basically the same features and shortcomings as the control A simulations, so that the changes in the LSSs have a limited impact on the control climate. In the continuation of this section, we will first concentrate on the monsoon response to CO_2 doubling (in experiments A) and then focus on the sensitivity of this response to the treatment of the land surface.

3.2 Monsoon response to CO_2 doubling

Tables 2 to 4 summarize the dynamical and hydrological response of the Asian summer monsoon to CO_2 doubling, through the wind shear and precipitation indices presented in Section 3.1. In the CNRM and LMD models, both U-shear and V-shear indices indicate a weakening of the monsoon circulation under enriched-CO_2 conditions. The HC model also shows a decrease in the Walker circulation, but no significant impact on the Hadley cell. The climate change experiments described in the literature do not give evidence of a systematic decrease in the

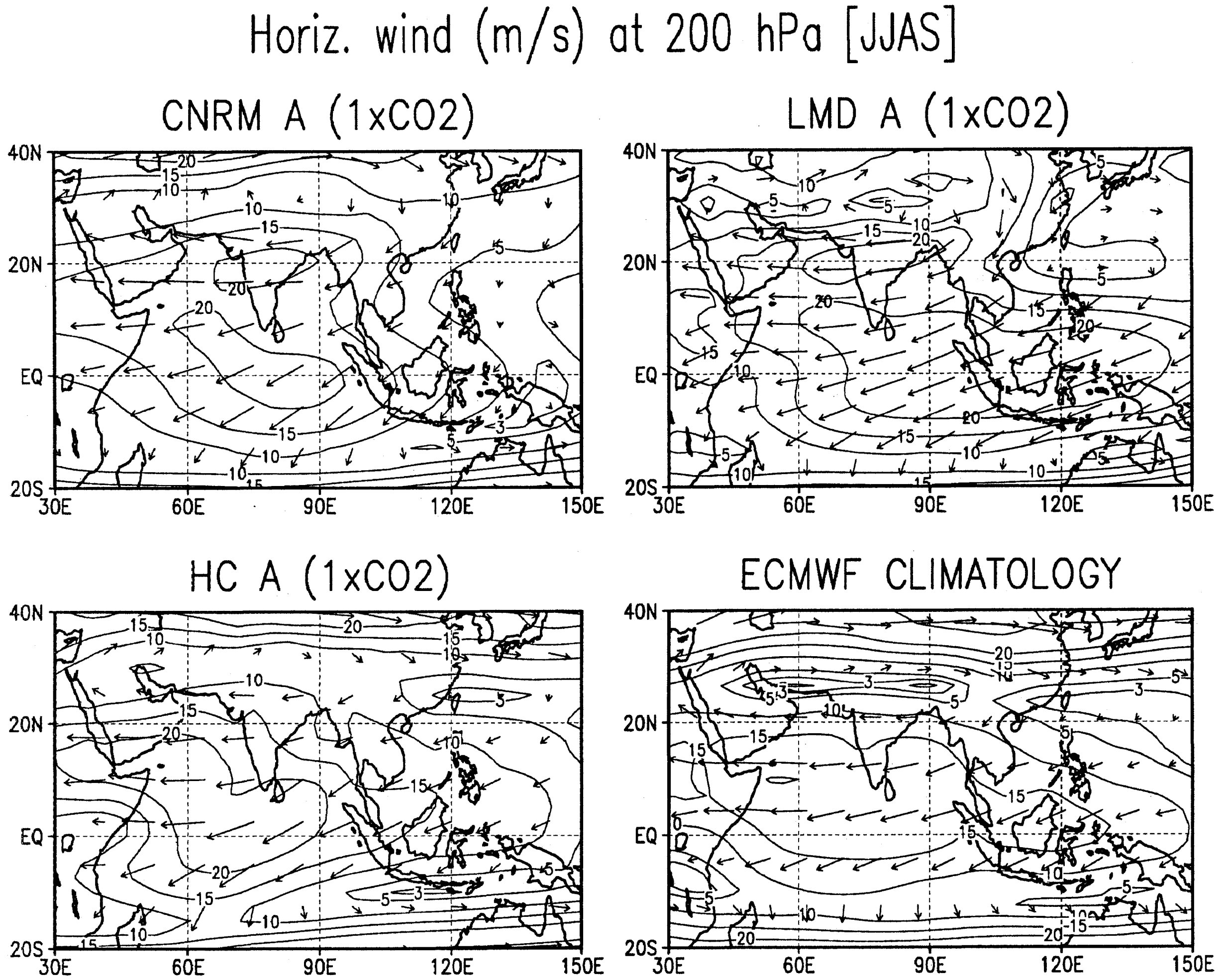

Fig. 2. Comparison between the JJAS 200 hPa wind field (m/s) simulated in the control A experiments (except UR) and the ECMWF reanalysis climatology (1979–1994).

Table 2. JJAS U-shear index U200–U850 (m/s) calculated over the domain 40–110°E/EQ-20°N.

Carbon dioxide	$1 \times CO_2$		$2 \times CO_2$	
Experiment	A	B	A	B
CNRM	27.5	-	24.4	24.9
LMD	29.6	27.3	28.4	26.7
HC	26.1	26.4	24.3	24.0
ERA clim.	21.9		?	

Walker circulation. In the present study, this consistent response could be driven by the prescribed SST anomalies (possibly by the weak El Niño signal appearing in the eastern equatorial Pacific), but a more detailed analysis would be necessary to verify this hypothesis.

The weakening of the Hadley circulation found between 40 and 140°E in the CNRM and LMD models is somewhat unexpected. Most GCMs predict an intensification of the Hadley cell in a warmer climate. As far as the CNRM experiments are concerned, this intensification is also observed on the global scale, with stronger precipitation over the ITCZ and weaker precipitation in the subtropics. However, Douville et al. (1997) showed that this zonal mean response was mainly associated with an enhanced convective activity over the equatorial oceans and disguised significant contrasts between land and sea. Negative rainfall anomalies were found not only over northern India, but also over western Africa, Indonesia and Amazonia, as if there was a competition between oceanic and continental convection.

Another robust feature of climate change experiments is a stronger warming over land than over sea. This increase in the thermal contrast between the Indian Ocean and the Asian continent has often been proposed as a possible explanation of the increased monsoon rainfall found in several GCMs (Zhao and Kellogg 1988, Meehl and Washington 1993). This differential warming is also found in the LSPCR experiments (cf Section 4.2), but it is not associated with an enhanced monsoon flow. This

Table 3. JJAS V-shear index V200–V850 (m/s) calculated over the domain 40–140°E/15°S–25°N.

Carbon dioxide	$1 \times CO_2$		$2 \times CO_2$	
Experiment	A	B	A	B
CNRM	7.02	-	6.69	6.93
LMD	7.12	7.19	6.79	6.39
HC	6.67	6.75	6.65	6.79
ERA clim.	4.80		?	

result suggests that a mechanism that is important for understanding the variability of the present-day climate (namely the relationship between land surface temperature anomalies over the Asian continent and monsoon circulation anomalies) is not necessarily relevant for predicting climate change.

Figure 4 compares the precipitation anomalies obtained in the first set of simulations (experiments A). Only anomalies significant at a 90 % level (two-tailed Student's t-test) have been represented. The control monsoon precipitation has been superimposed on the anomaly field to highlight the possible relationship between the future and present-day climates. All simulations produce a dipole pattern over the Indian Ocean and western Pacific, with positive anomalies around 10°N and negative anomalies over or slightly south of the Equator. This relative similarity in the large-scale precipitation anomalies can be explained by a consistent response of convection to the equatorial SST anomalies. The exact location of this dipole pattern is obviously influenced by the control simulation and is shifted northwards in the CNRM and LMD models compared to the HC and UR models, probably because of the underestimation of the equatorial precipitation belt in the first two models.

Focusing now on the Indian monsoon response, there is a large spread among the models, despite the use of identical SST anomalies. This result confirms that it is still a challenge for state-of-the-art GCMs to predict the regional hydrological consequences of global warming. The spread in the control climates is not the only explanation for the spread in the climate response. Over India, the anomaly fields simulated by the CNRM and UR models look relatively similar, despite significant differences in their control monsoon and in their large-scale precipitation response. The same remark applies to the results of LMD and HC models, which indicate an overall increase in the summer monsoon rainfall, whereas the CNRM and UR models predict decreased precipitation over India (except in the southern tip of the peninsula).

Once again, these results demonstrate the difficulty of achieving climate change predictions on the regional scale, as well as the need to use outputs from several models to distinguish between robust and model dependent predictions.

3.3 Sensitivity of the response to surface hydrology

In order to go one step further, the present section investigates the sensitivity of each model's response to the treatment of the land-surface. Comparing the results of the two sets of experiments A and B enables us to address the following question: do the LSSs contribute significantly to the variability of the monsoon response among the models?

Figure 5 shows the precipitation anomalies obtained in experiments B, which can be compared to the results of experiments A (Fig. 4). Not surprisingly, the large-scale feature of the anomaly fields, namely the dipole pattern over the Indian Ocean, is not much modified by the use of a different land surface parametrization. On the other hand, the precipitation change simulated over India is LSS dependent. As an example, the significant negative anomaly in CNRM A has nearly vanished in CNRM B, as a result of the increased stomatal resistance prescribed in the ISBA scheme. Similarly, the decrease in the rooting depth prescribed in the ECMWF scheme leads to a significant change in the rainfall anomalies predicted by the UR model.

Given the rather low horizontal resolution of the models, it is not surprising to find significant differences in the regional rainfall distribution. In order to suppress the details of the distribution, Fig. 6a is based on the rainfall index presented in Table 4, which is an average of the precipitation over the Asian continent south of 30°N. It shows the scatterplot of doubled CO_2 versus control monsoon rainfall for all experiments A and B. The main striking feature is the spread in the control precipitation which is discussed in Section 3.1. The rainfall index is not much affected by the treatment of the surface hydrology. Whereas the LSS is likely to affect the regional response of the monsoon precipitation, it is not important when averaging the results over the south Asian subcontinent.

Figures 6b and 6c show similar scatterplots for the U-shear and V-shear indices. The control monsoon is not very sensitive to the changes in the land surface hydrology, except the U-shear index simulated by the LMD model, which has been reduced (and thereby improved) in control B compared to control A. Both wind shear indices show a weakening of the monsoon circulation under enriched-CO_2 conditions. This weakening appears in both experiments A and B, except for the V-shear index in the HC model, where the response to CO_2 doubling is very weak. As for precipitation, the large-scale response of the monsoon circulation is not much sensitive to the LSS.

The regional analysis proposed by Polcher et al (1998) may be used to carry on the discussion about

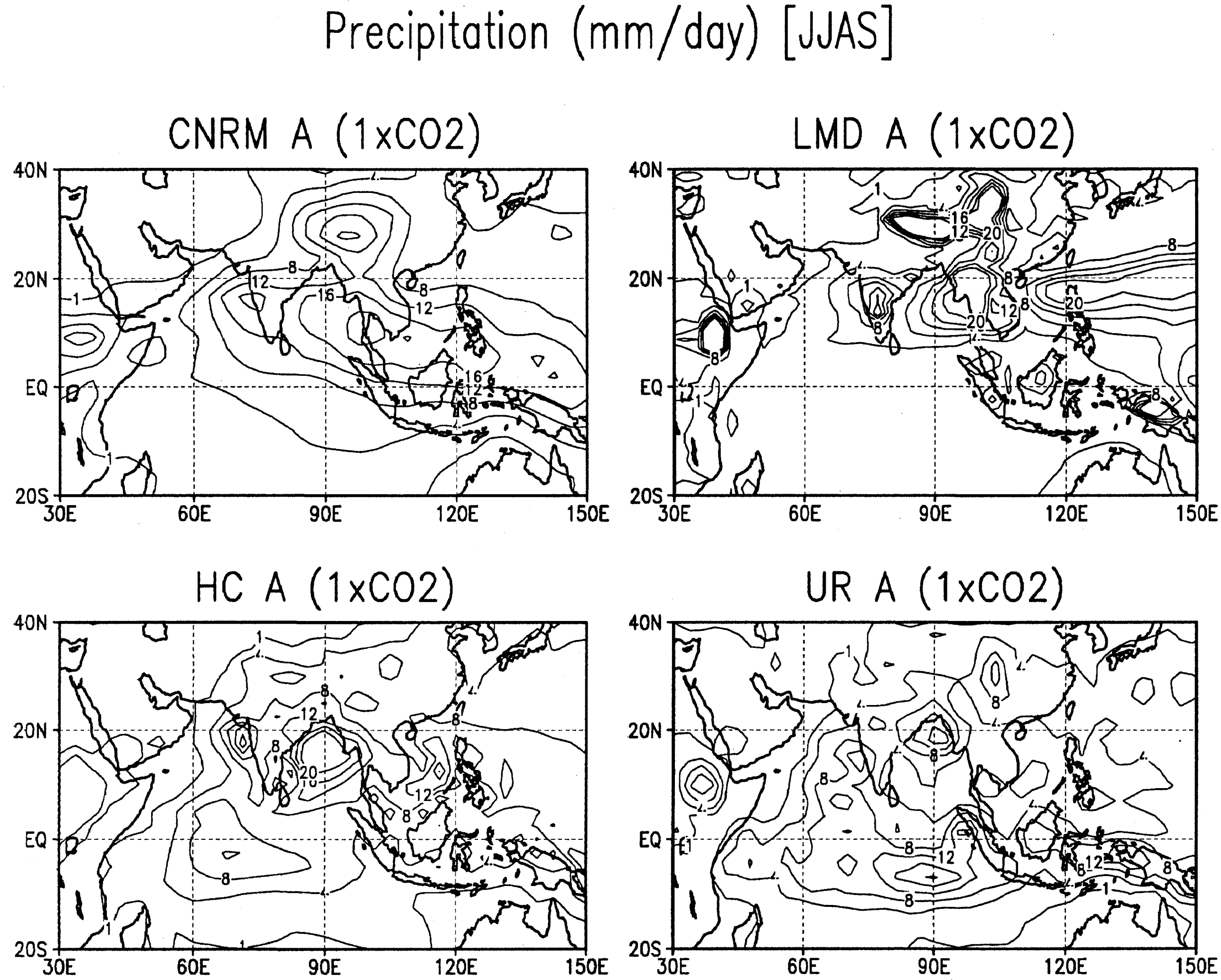

Fig. 3. JJAS total precipitation (mm/day) simulated in the control A experiments.

Table 4. JJAS rainfall (mm/day) calculated over land within the domain 60–120°E/EQ-30°N.

Carbon dioxide	$1 \times CO_2$		$2 \times CO_2$	
Experiment	A	B	A	B
CNRM	10.7	-	10.2	10.6
LMD	9.9	9.6	11.2	10.2
HC	7.6	7.7	8.1	8.3
UR	5.0	4.8	5.1	5.0
CMAP clim.	6.3		?	

the uncertainties generated by the land-surface. This analysis was conducted only over the Indian Peninsula, defined by the domain 68–92°E/5–30°N. Figure 7 shows the monthly evolution of the ratio between the variance due to the land-surface and the total variance mixing all years and experiments. The results are presented for 5 variables: precipitation, evaporation, screen-level temperature, cloudiness and solar radiation. The ratio is generally less than 0.4, indicating a rather weak influence of the land surface for all variables. Although this influence can be as large as the CO_2 impact, it is only marginally significant due to the strong interannual variability of the monsoon and the low significance of the CO_2 signal itself. However, the ratio in the control experiments shows a moderate peak in June for precipitation, cloudiness and solar radiation, suggesting that the land-surface parametrization has a significant influence on the onset of the monsoon. Looking at the anomalies, the June peak is also apparent for most variables, confirming that the largest uncertainty related to the land surface appears during the onset period.

4. Discussion

4.1 Linking temperature, circulation and rainfall anomalies

Early studies of the impact of increased CO_2 concentration on the monsoon focused on the temperature contrast between the Asian continent and the Indian Ocean. This contrast is assumed to drive the monsoon circulation and any increase in this gradient is expected to enhance the monsoon rainfall.

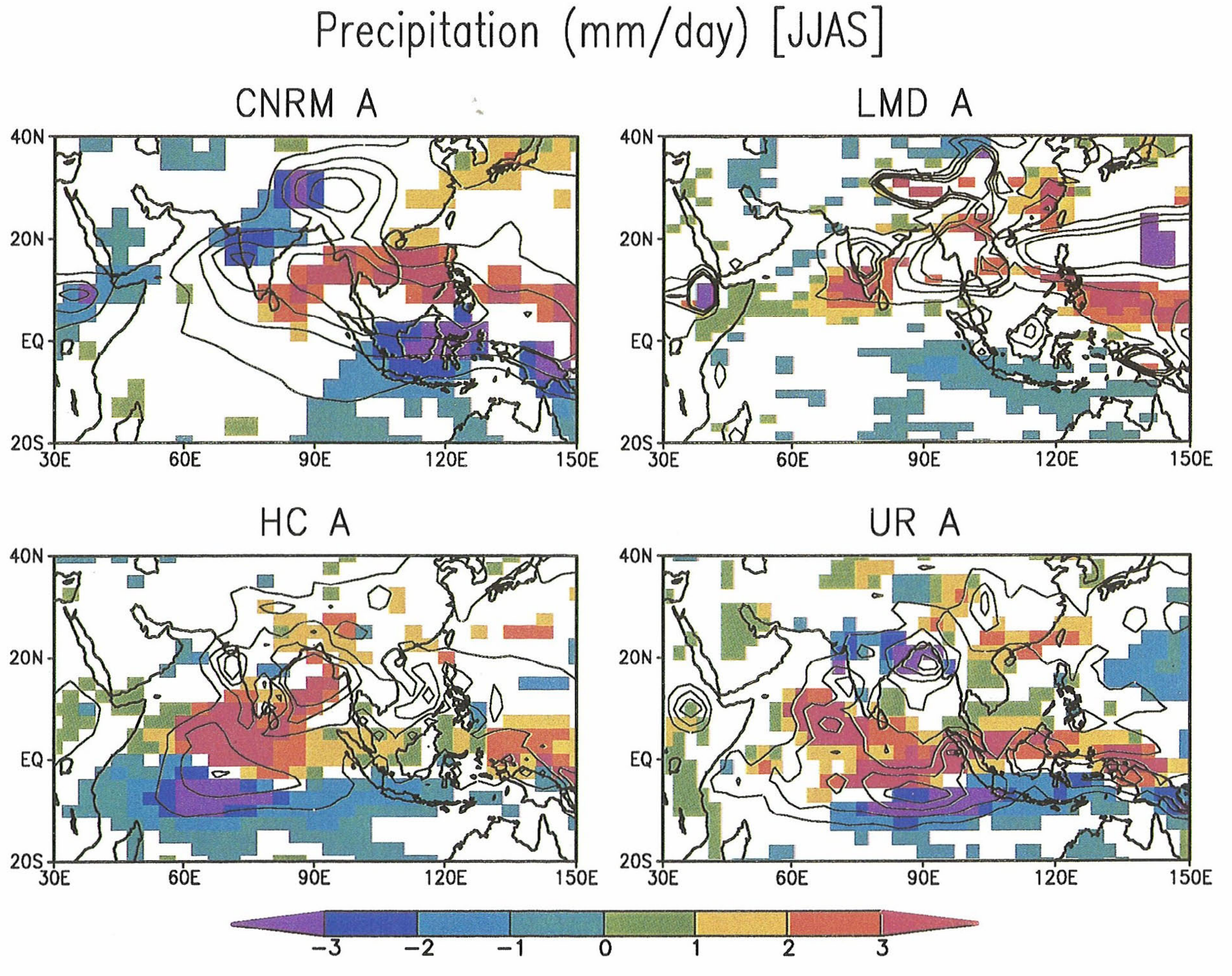

Fig. 4. JJAS precipitation (isolines) and precipitation anomalies (shading) simulated in experiments A; isolines are 4, 8, 12 and 16 mm/day; only significant anomalies at a 90 % level have been shaded.

According to this hypothesis, and given the fact that in the present study the prescribed SST anomalies are the same in all models, one might assume that a strong heating over the Asian continent will increase the land-sea contrast and therefore strengthen the monsoon circulation. This simple mechanism is not supported by Fig. 8, which shows the MAM (March-April-May) surface air temperature anomalies simulated in experiments A over the Asian sector. All models show a stronger warming over the Asian continent than over the Indian Ocean, but even the strongest warming over land (in the HC A experiment) is not associated with an increase in the wind shear indices.

Figure 9a shows the scatterplot of the summer anomalies in precipitation versus the MAM anomalies in surface air temperature, averaged over the land grid points in the domain 60–120°E/EQ-30°N. It confirms that the springtime temperature can not be considered as a reliable predictor of the monsoon intensity. In the CNRM and LMD models, changing the land surface hydrology affects the precipitation response to CO_2 doubling, but the temperature response is not much modified. Conversely, the temperature response is sensitive in the HC and UR models, whereas the precipitation response does not change. The results of experiments A suggest a possible consensus about the temperature anomalies, but a large spread in the rainfall anomalies. The results of experiments B lead to the opposite conclusion. This illustrates the difficulty of drawing robust conclusions from climate change experiments. It is not sufficient to compare the results of 3 or 4 models. The robustness of the response of each individual model should be also verified by testing different physical parametrizations. Another possibility is to use a larger number of models to explore a wider range of predictions.

Figures 9b and 9c show the scatterplot of the precipitation change versus the U-shear and V-shear anomalies respectively. Although all models predict a decrease in the U-shear index, the rainfall anomalies are either positive or negative. Similarly, there is apparently no link between the V-shear index

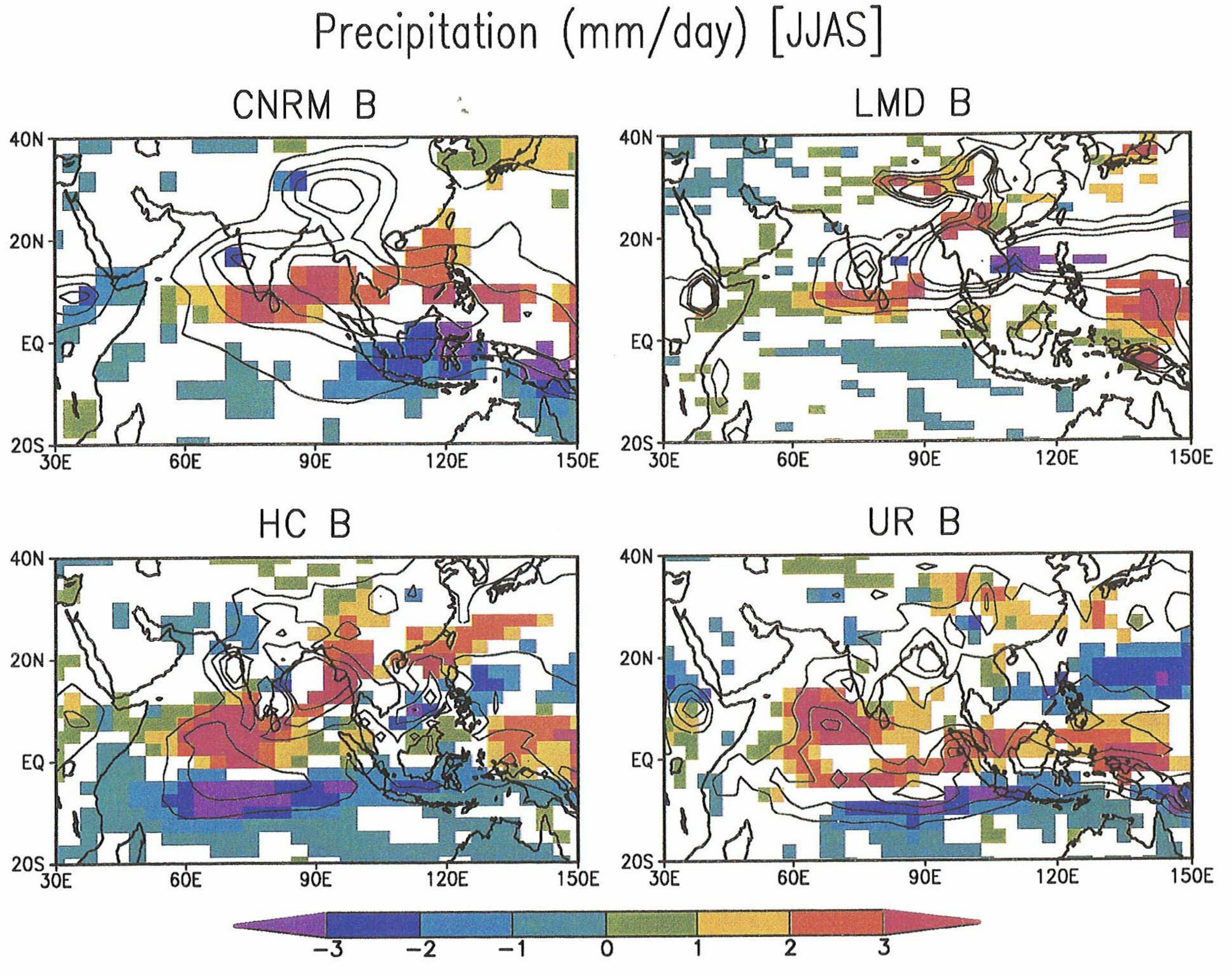

Fig. 5. JJAS precipitation (isolines) and precipitation anomalies (shading) simulated in experiments B; isolines are 4, 8, 12 and 16 mm/day; only significant anomalies at a 90 % level have been shaded.

and the rainfall anomalies when all experiments are considered together. However, such a relationship appears in each model when the LSS is modified. Moving from experiment A to experiment B leads to consistent changes in the CO_2 impact, a weaker Hadley circulation being associated with lower monsoon precipitation. In keeping with the finding of Goswami et al. (1999), the V-shear index seems to be a possible predictor of the monsoon precipitation in a given GCM and for a given CO_2 concentration. However, this relationship cannot be used to predict the precipitation change which could occur in a warmer climate simply as a function of the modification of the Hadley circulation. In keeping with the results of Kitoh et al. (1997), the monsoon precipitation can increase despite a weakening of the circulation, possibly due to a larger moisture content in the warmer atmosphere. This hypothesis can be verified by looking at the water budget of the monsoon area.

4.2 Regional water budget

The hydrological cycle over a limited domain depends on the amount of water which enters the domain, both at the lower boundary (surface evaporation) and at the lateral boundaries (horizontal advection). Horizontal advection can be considered as an external source of precipitation, as opposed to the internal source represented by local evaporation. Several studies have attempted to quantify the relative importance of internal versus external sources inside a region by defining suitable *recycling* parameters (Eltahir et al. 1996).

In the literature, there are various definitions under the name of *recycling rate*. If the focus is on the atmosphere, it is simply the inverse of the average residence time of water vapor inside the atmospheric reservoir, i.e., the ratio P/W_t between precipitation and precipitable water (Chahine et al. 1997). This ratio has been computed for the atmospheric column over the domain 68–92°E/5–30°N (including India and the surrounding ocean grid points) in the CNRM, HC and LMD models. All exper-

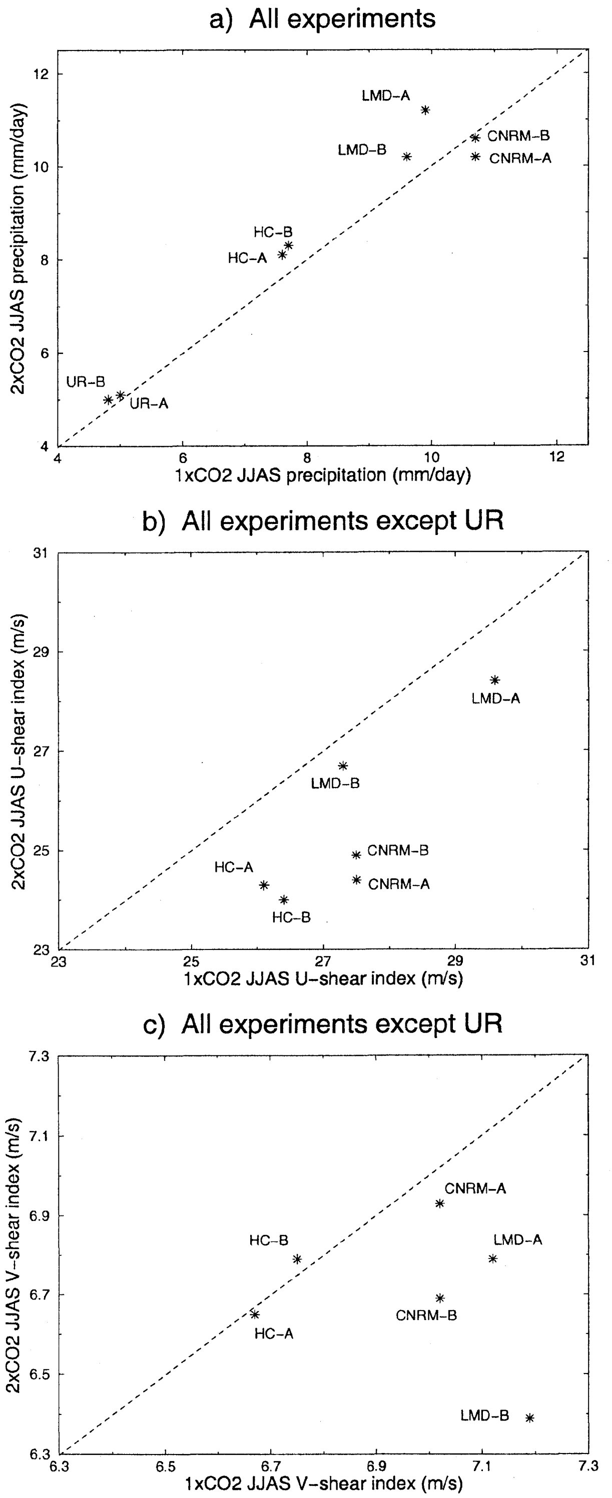

Fig. 6. JJAS doubled CO_2 versus single CO_2 values of the wind shear and precipitation indices: a) precipitation index (mm/day), b) U-shear index (m/s), c) V-shear index (m/s).

iments show a strong annual cycle in precipitable water with maximum values during the monsoon (Fig. 10a). The recycling rate exhibits a similar seasonality. The residence time of water vapor in the atmosphere suddenly decreases from about 20 days before the monsoon to less than 5 days during the monsoon.

All models indicate an increase in precipitable water in a doubled CO_2 climate, because a warmer atmosphere can sustain a larger amount of water vapor (Fig. 10b). This robust feature shows that the monsoon precipitation can increase despite a weakening of the monsoon circulation, in agreement with the results of Kitoh et al. (1997). The ratio P/W_t is not very sensitive to CO_2 doubling, and there is no clear signal indicating a systematic change throughout the monsoon season (Fig. 10d). The precipitation response is related to the change in precipitable water rather than to a modification of the atmospheric recycling rate.

Focusing now on the soil water reservoir, another recycling rate has been defined as the fraction of the precipitation inside the domain that originates from the local evapotranspiration. This definition has been introduced in regional scale studies by Budyko (1974) and is closely related to the soil-precipitation feedback discussed by Shukla and Mintz (1982). This feedback mechanism has been often put forward in order to explain that a change in precipitation can be amplified by the response in surface evaporation. This effect was recently analysed by Schär et al. (1999) in a regional climate model covering Europe and the northern Atlantic. Budget analysis of water substance were performed over selected subdomains. Following the ideas of Budyko (1974) and Brubaker et al. (1993), Schär et al. (1999) defined the precipitation efficiency, χ, as the fraction of water that enters a selected domain (either by evapotranspiration, ET, or atmospheric transport, IN) and subsequently falls as precipitation, P, within this domain:

$$\chi = \frac{P}{ET + IN}. \qquad (1)$$

With this simple method, Schär et al (1999) demonstrated that the sensitivity of the summertime European precipitation to soil moisture could not be interpreted with the classical recycling mechanism. The surplus of precipitation obtained over wet soils was not directly due to larger evapotranspiration, but derived from an indirect mechanism, whereby soil moisture increases the efficiency of the precipitation without any significant modification of the ambient atmospheric flow.

Such a budget analysis is obviously dependent on the size of the selected domain, and the computed precipitation efficiency has no universal meaning. However, this approach is useful for comparing the

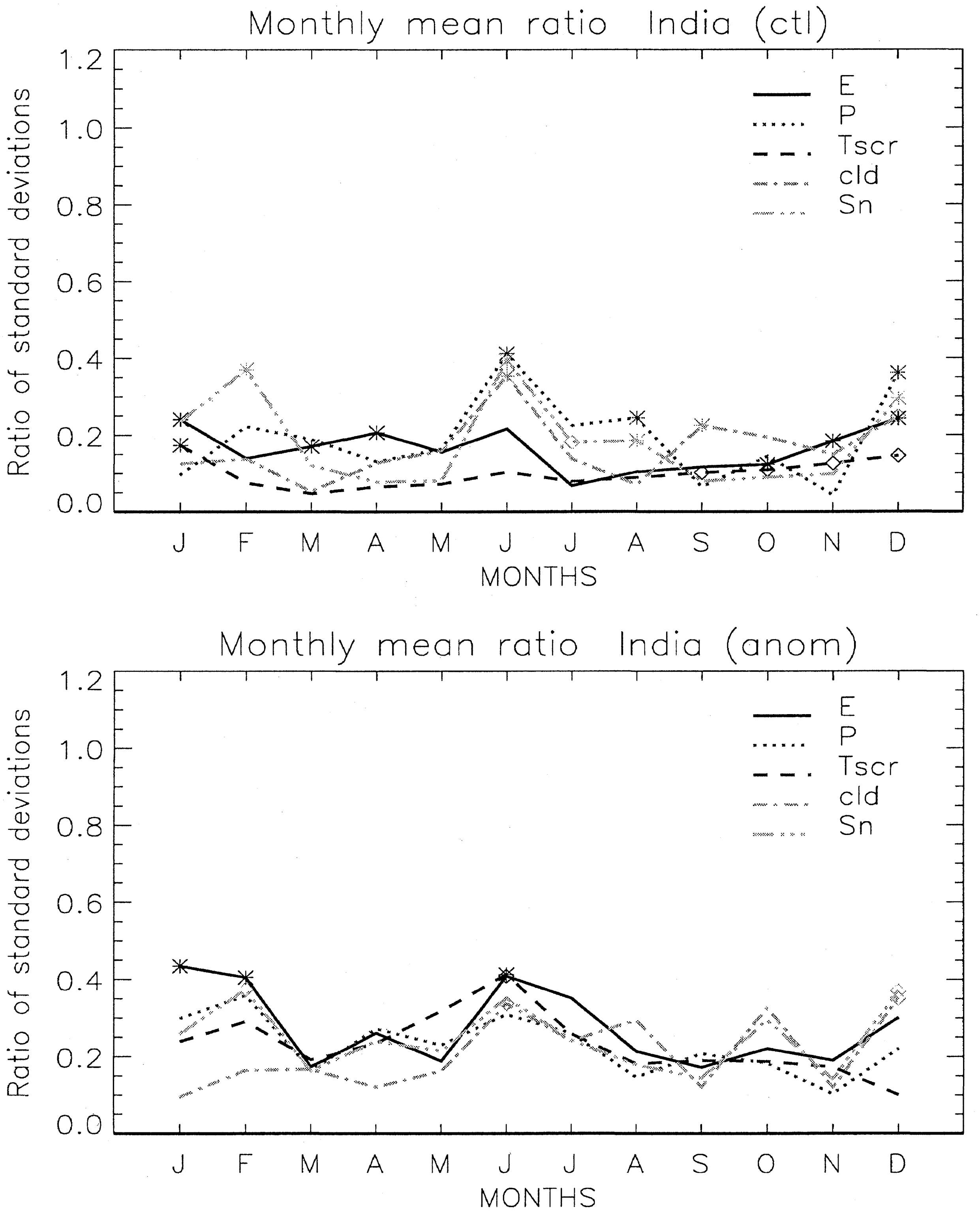

Fig. 7. Ratio between the variance due to the land-surface and the total variance mixing all years and all experiments over India (68–92°E/5–30°N); top: control experiments, bottom: anomalies. An asterisk indicates that the value is significant at 95 % and a diamond at 90 %.

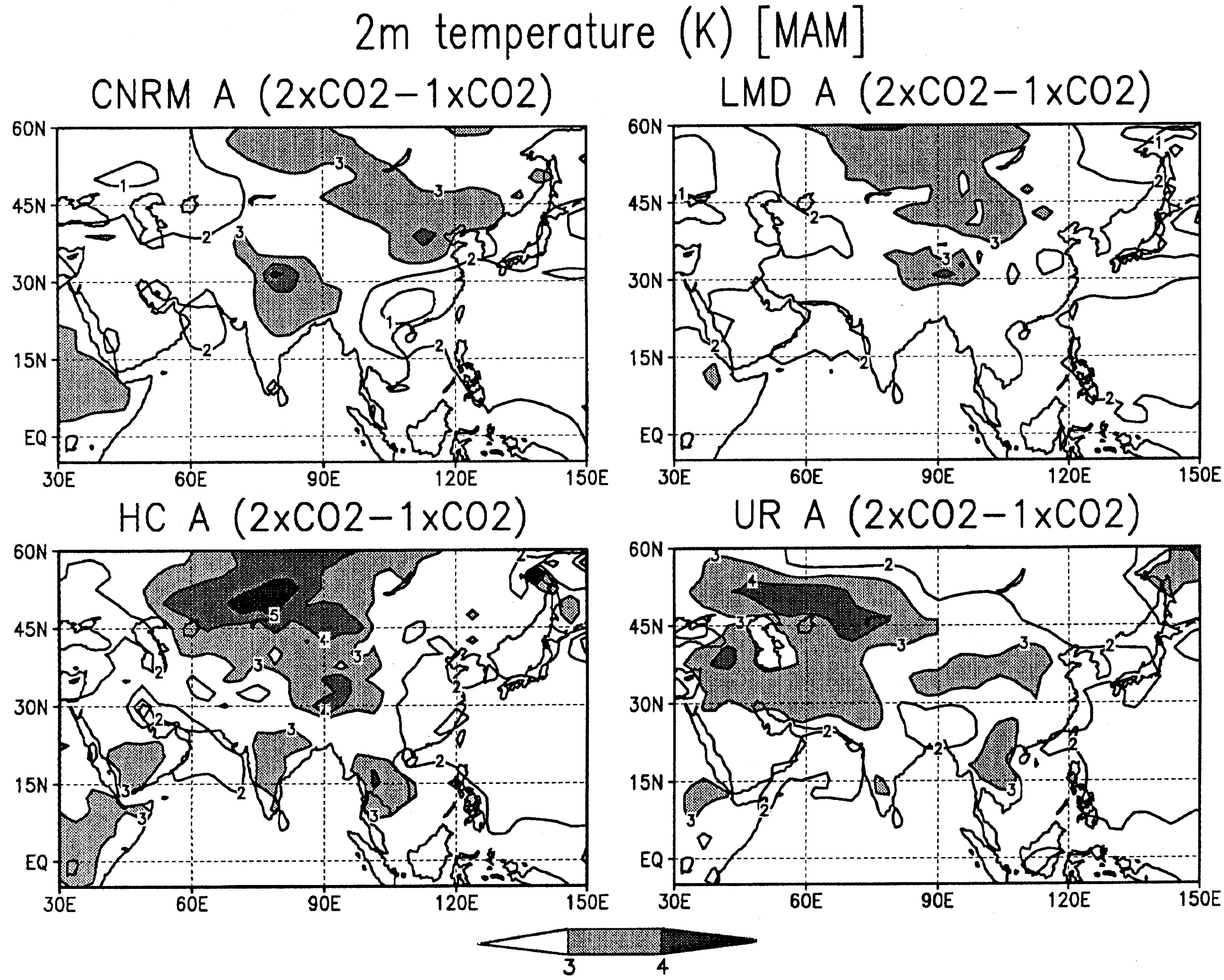

Fig. 8. MAM 2m temperature anomalies (degrees) simulated in experiments A.

results of different experiments averaged over the same domain. It provides some insight about the physical mechanisms that underlie the obtained precipitation change. Defining P_1 and P_2 as the average summer precipitation over northern India for present-day and doubled-CO_2 climates respectively, the precipitation anomalies can be expressed as:

$$\begin{aligned}\Delta P &= P_2 - P_1 \\ &= \chi_2(\Delta ET + \Delta IN) + \Delta\chi(ET_1 + IN_1),\end{aligned} \quad (2)$$

where the first term isolates the contribution associated with changes in evapotranspiration, ΔET, and atmospheric transport, ΔIN, while the second term isolates the contribution related to changes in the precipitation efficiency, $\Delta\chi$.

The zonal and meridional fluxes of moisture have been diagnosed at each model level in the LSPCR simulations, which enables us to compute IN_1 and ΔIN in Eq. (2). Precipitation and evapotranspiration are standard diagnostics of the models. It is therefore possible to assess the relative importance of the two contributions distinguished in Eq. (2). Figure 11 shows the annual cycle of these two quantities, and of the total precipitation anomalies, averaged between 68–92°E and 5–30°N in a cubic 3D domain. Note that the total anomalies are different from those shown in Fig. 10, which have been averaged only over land. The calculations have been done for the CNRM, HC and LMD experiments, the results of the various models being first interpolated onto the same horizontal grid.

In the CNRM experiments (Figs. 11a and 11b), the flux of water vapor into the 3D domain increases almost all year in a doubled CO_2 climate, and particularly between June and August. This response is consistent with the moistening of the atmosphere found in Fig. 10b. However, the precipitation anomalies are negative in June and July in experiment A, due to a significant decrease in the precipitation efficiency. In CNRM B, the summer rainfall anomalies are positive (except in September), since the increase in $(ET + IN)$ is now associated with a weak decrease in the precipitation efficiency. Therefore, the sensitivity of the rainfall anomalies to the increase in stomatal resistance, and thus to the change in surface evapotranspiration, is mainly explained by a modification in the efficiency of the

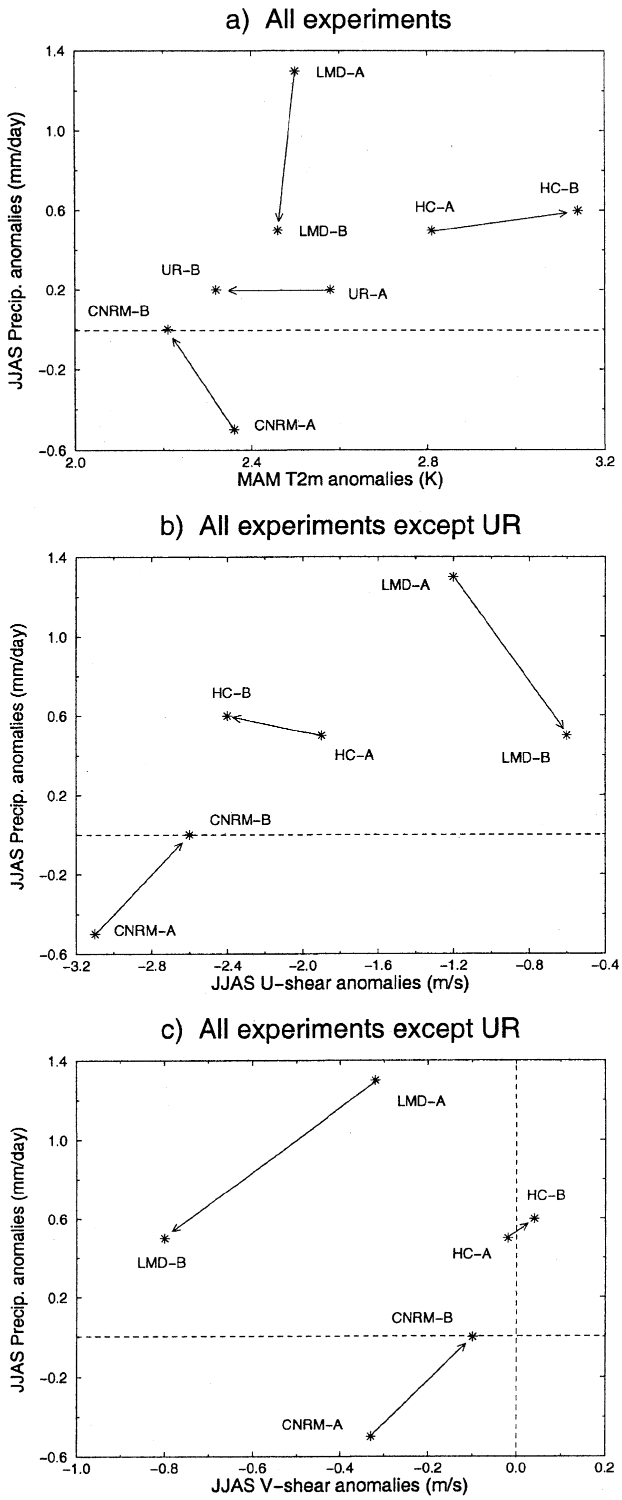

Fig. 9. JJAS precipitation anomalies (mm/day) versus anomalies of: a) MAM 2m temperature (K); b) JJAS U-shear index (m/s); c) JJAS V-shear index (m/s).

physical processes which lead to precipitation. This efficiency depends on the surface hydrology, which, according to the results of Schär et al. (1999) over Europe, is likely to affect the build-up of the boundary layer and the level of free convection.

The same analysis has been conducted for the HC and LMD models (Figs. 11c to 11f). All experiments predict an increase in the flux of water vapor into the 3D domain over India. As previously discussed, this is mainly due to a larger water content in a warmer atmosphere rather than to a stronger monsoon circulation or to a larger evaporation. However, the spread in the precipitation response between the models and experiments is only partly due to the variable intensity of the increase in the horizontal transport of water vapor. The variable response of the precipitation efficiency seems to play a major role. During the summer months, the associated precipitation change is generally negative, especially during the first half of the monsoon (June and July). However, the results are sometimes very contrasted: −3 mm/day in June in experiment B using the HC model, but +3 mm/day in July in experiment A using the LMD model. Clearly, the precipitation efficiency response to CO_2 doubling represents a significant source of uncertainty in the models, that is affected by the treatment of the land surface and the boundary layer.

5. Conclusions

Despite the increasing efforts of the scientific community, there is yet little consensus about the regional details of greenhouse gas-induced climate change. Because of its intrinsic complexity, the understanding of the Asian monsoon system and the prediction of its modification due to increased CO_2 level remain major challenges for years to come. Besides the major uncertainties related to the evolution of the anthropogenic emissions and their impact on the SSTs, there are also large uncertainties in the atmospheric models.

In the present study, different state-of-the-art atmospheric GCMs have been used to simulate the impact of doubling the present-day CO_2 concentration. At least two time-slice experiments have been performed with each model, using either a reference or a modified LSS. All models simulate a weakening of the Asian summer monsoon circulation (as indicated by the reduction in the U-shear and V-shear indices), in keeping with the slight trend found in the NCEP/NCAR reanalyses over recent decades (1958–1998). However, despite the use of identical SST anomalies and a certain similarity in the large-scale response, the results show a large spread in the regional precipitation anomalies. All simulations produce a large-scale dipole pattern over the Indian Ocean and western Pacific, but the all-India precipitation response depends on both the atmospheric

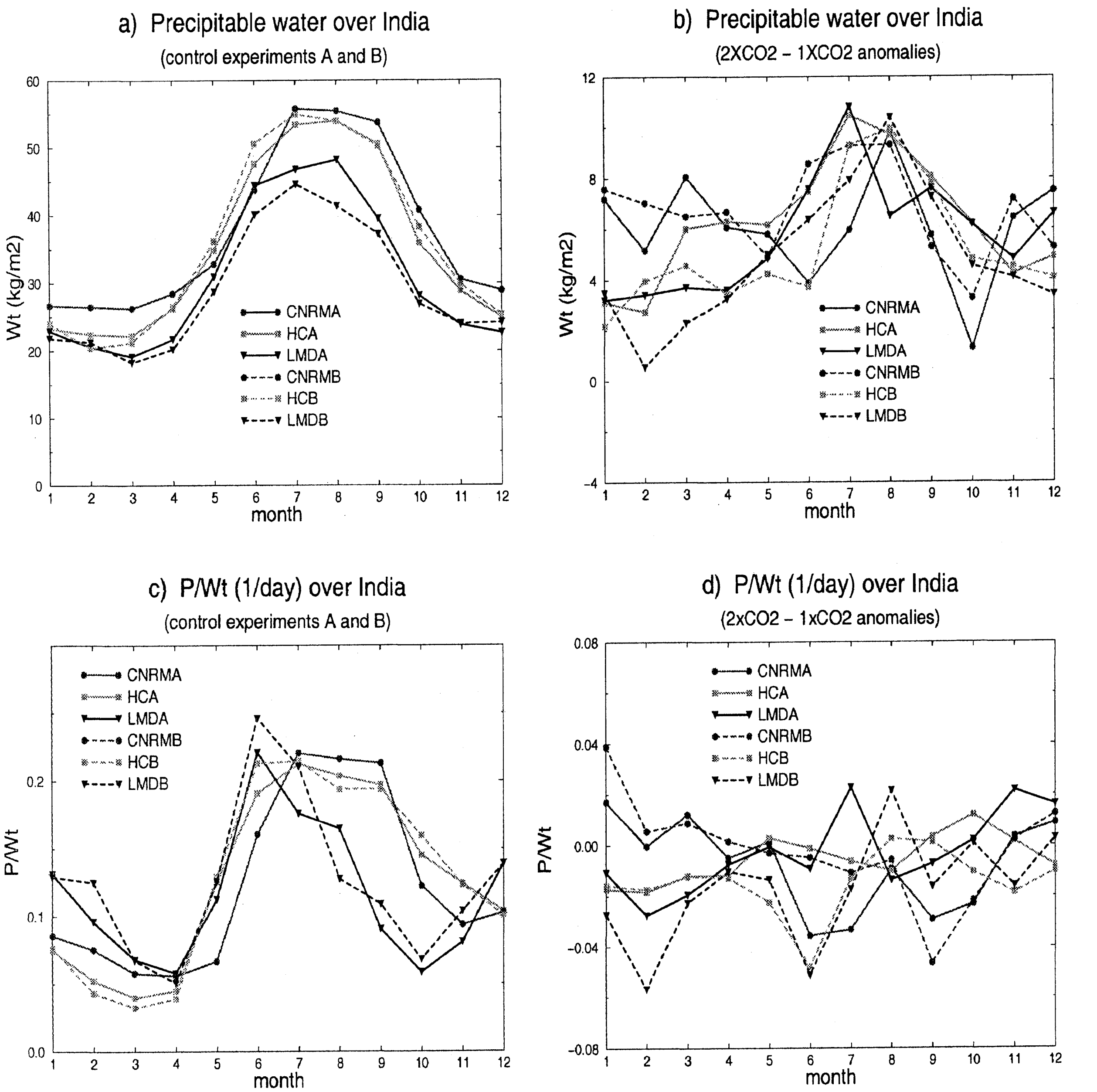

Fig. 10. Annual cycle of the precipitable water (kg/m^2) and of the ratio between precipitation and precipitable water (1/day) over the domain 5°N–30°N/68°E–92°E (both land and ocean grid points) in experiments A and B from CNRM, HC and LMD; a) and c) control values (note that CNRM-A=CNRM-B), b) and d) anomalies.

model and the LSS.

Using several models and LSSs makes it possible to verify the robustness of some mechanisms proposed in former numerical studies for explaining the monsoon response to an increased greenhouse effect. On one hand, our results indicate that the warming of the Asian continent is not a good predictor of the monsoon response to increased CO_2 level. All models simulate a stronger warming over land than over sea, but they do not all simulate a stronger monsoon. Convection is controlled by both temperature and humidity, and changes in the atmospheric humidity profile also must be considered in order to understand the monsoon response to climate change. On the other hand, the HC and LMD results confirm the finding of Kitoh et al. (1997). In a warmer climate, the monsoon precipitation can increase despite a weakening of the monsoon flow, due to an increase in the atmospheric water content, and therefore a contrasted response of the mass convergence and moisture convergence respectively.

As a consequence, the present study does not support the recent analysis of Krishna Kumar et al. (1999), which suggested that the surface warming

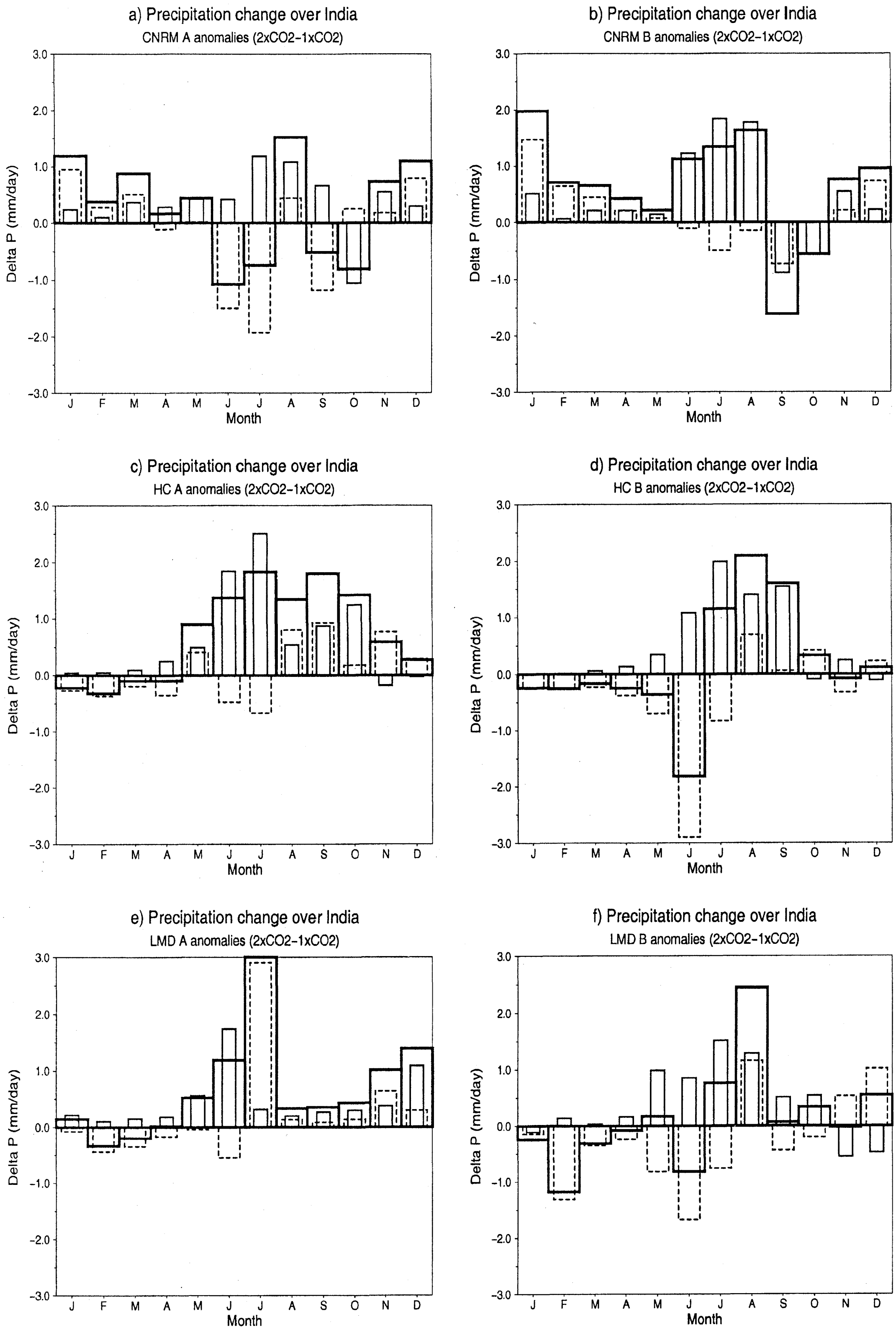

Fig. 11. Annual cycle of the precipitation change (mm/day) over the domain 5°N–30°N/68°E–92°E (land and ocean grid points) in experiments A and B from CNRM (a and b), HC (c and d) and LMD (e and f). Shaded bars : total precipitation change, thin bars : precipitation change due to variations in the flux of water vapor $(I+E)$ into the domain, thick bars : precipitation change due to variations in the precipitation efficiency (χ).

observed over recent decades in Eurasia could explain why no systematic decrease in the Indian monsoon rainfall was observed during the latest ENSO events, the SST impact being overriden by the influence of the land-sea thermal gradient. For decades to come, the increase in the atmospheric water content could be more important than the increase in this gradient. Even for recent decades, the drop in the monsoon-ENSO correlation emphasized by Krishna Kumar et al. (1999) could be partly explained by a possible increase in precipitable water as a result of the initial stage of the global warming. Note however that the atmospheric water vapor data derived from satellite measurements do not show any global increase in precipitable water between 1988 and 1994 (Chahine et al. 1997). Such an analysis should be repeated when longer time series of satellite data are available.

The link between the circulation and precipitation anomalies is complex and model dependent; further studies are necessary to investigate the physical processes that govern the interaction between the dynamics and the tropical precipitation within the GCMs. Among the numerous reasons for the spread in the rainfall predictions, the treatment of the land surface does not play a major role, but is able to affect the regional distribution of the anomalies and the onset of the monsoon. Even minor modifications, like the introduction of possible vegetation feedbacks in the CNRM experiments, are likely to have a significant impact (as strong as the direct radiative effect of CO_2 doubling) on the regional scale. In other words, a slight change in the surface evapotranspiration is enough to induce a significant change in precipitation. A simple analysis of the regional water budget indicates that this sensitivity is not only related to changes in the horizontal transport of water vapor, but also to changes in the precipitation efficiency. In the future, our efforts should focus on the mechanisms by which the land surface is liable to influence the precipitation. Particular attention should be paid to the interaction between the boundary layer and the deep convection, and to the sensitivity of the convective schemes to soil moisture anomalies.

Finally, it should be kept in mind that a single climate change experiment by no means represents a reliable prediction. Even comparing the results of four models using the same SSTs is not sufficient to achieve robust predictions on the regional scale. Producing long-term climate predictions rather than climate scenarios is still a challenge for years to come.

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夏のアジアモンスーンに対する CO_2 倍増の影響：モデルに依存する応答と依存しない応答

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夏のアジアモンスーンに対する人為的要因による気候変化の影響を、海面水温と海氷のアノマリを境界条件として与えたいくつかのタイムスライス実験によって調べた。実験は4つの異なった大気大循環モデル (GCM) を用いて行われた。各モデルで陸面過程の取り扱いを変えた2対の実験を実施した。目的は、モデルで再現された気候変化がモデルに依存しない確実なものであるかということと、陸面過程の取り扱いにどれだけ敏感であるかということを調べることである。実験ではすべて同一の海面水温アノマリを与えたにもかかわらず、4つのモデルのモンスーンに関する地域スケールの応答は異なっている。全てのモデルで、CO_2の増加によってアジア大陸の昇温がインド洋の昇温よりも大きくなっているが、このことはモンスーンの応答を予測するよい指標になっていない。モンスーン循環の強さはどのモデルでも弱くなっているが、降水量の変化はモデル間の差が大きい。このことはモンスーンの降水量の変化が、大規模な力学場の変化だけで決まらないことを示している。暖かい気候では、大気中の水蒸気量が多くなるために、モンスーン循環の弱まりにもかかわらず降水量が増加することが可能である。今後数十年のモンスーン降水量変化を理解する上で、海陸の温度傾度の増加よりも、大気中の水蒸気量の増加の方がより重要であると考えられる。陸面の水文過程の取り扱いは、モデルによる応答の違いの主要な原因ではないが、CO_2増加に対するモンスーンの地域的応答には少なからぬ影響を及ぼす。蒸発散のわずかな変化が、大きな降水の変化を引き起こす。簡単な地域水収支解析の結果によると、このような敏感さは、水蒸気の水平輸送の変化だけでなく、降水効率の変化にも関係している。降水効率は、土壌水分量に依存するので、モデル陸面水文過程の取り扱いに敏感である。