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Searching for a fingerprint of global warming in the Asian summer monsoon

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सार - इस अध्ययन द्वारा एशियाई ग्रीष्म मानसून को दर्शाने वाले कई बृहत्त अक्षांको की संभाव्य प्रवृतियों की जॉच की गई है। विश्वस्तरीय ऊष्णीकरण के प्रभावों से मानसून में आने वाले परिवर्तनों के कारणों का पता लगाने के लिए हाल ही के वायुमंडलीय सामान्य परिचालन के प्रयोगों से प्राप्त परिणामों का उपयोग किया गया है। इस अध्ययन की रोचक बात यह है कि जलवायु के कई वस्तुस्थिति निदर्शों के प्रयोग से यह पता चला है कि दुहरे CO_2 अनुकारो के साथ मात्रात्मक संमेल से प्राप्त हुए हाल ही के परिणामों के अनुसार पवन अपरूपण मानसून बृहत्त अक्षांकों में प्रति वर्ष 0.1-0.3 प्रतिशत की दर से (1958- 98 के दौरान NCEP/NCAR पर आधारित पुर्नविश्लेषणों) में कमी पाई गई है। तथापि, मानसून परिचालन के कमजोर पड़ने के बावजूद अखिल भारतीय स्तर पर वर्षा में न तो निदर्श के परिणामों के अनुसार और न ही 1958-98 तक के प्रेक्षित पुर्नविश्लेषणों के अनुसार कोई स्पष्ट प्रवृति दिखाई पड़ी है। अखिल भारतीय स्तर पर प्रेक्षित वर्षा सूचकांक से गतिकीय योगदान को पृथक करने के लिए बहुआयामी समाश्रयण का प्रयोग किया गया है। तत्पश्चात् बढ़ती हुई प्रवृति "अगतिकीय" अवशिष्ट में स्पष्ट रूप से दिखाई पड़ी है। इस शोध पत्र में मानसून के दौरान विश्वस्तरीय ऊष्णीकरण परिवर्तनों के मानीटरन के लिए एक सरल अविम बहुचर मानसून सूचकांक (एम.एम.आई.) प्रयुक्त करने का प्रस्ताव रखा गया है।

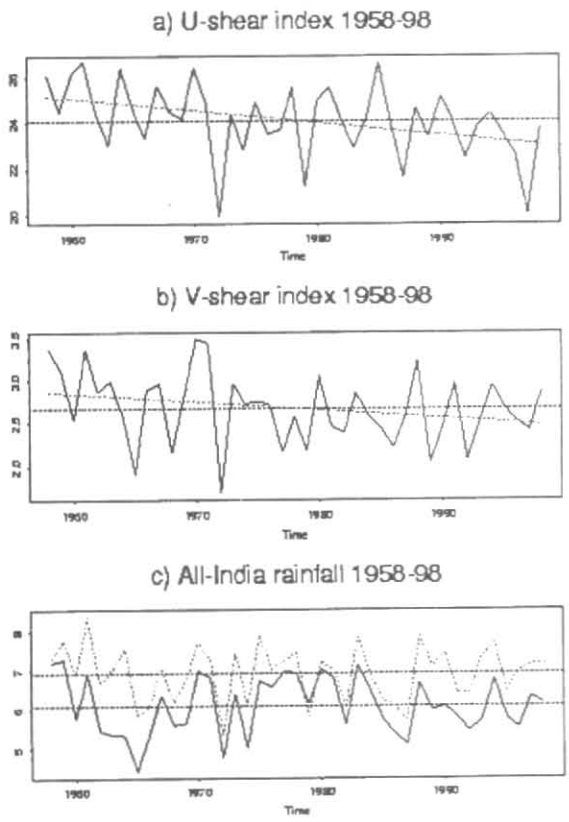
ABSTRACT. This study investigates possible trends in several largescale indices that describe the Asian summer monsoon. Results from recent atmospheric general circulation experiments are used to provide clues as to how the monsoon might be changing due to the effects of global warming. Interestingly, this study has found that the largescale wind shear monsoon indices have been decreasing at a rate of 0.1–0.3% per year (based on NCEP/NCAR reanalyses 1958–98) in quantitative agreement with recent results from doubled CO_2 simulations made using several state–of–the–art climate models. Nevertheless, despite the weakening of the monsoon circulation, all–India rainfall shows no clear trend in either the model results or in the observation reanalyses from 1958–98. Multiple regression is used to separate out the "dynamical" contribution from the observed all–India rainfall index, and a clear increasing trend then emerges in the "non–dynamical" residual. A simple dimensionless Multivariate Monsoon Index (MMI) is proposed that could be of use in monitoring global warming changes in the monsoon.

Key words – Monsoon, Climate change, Trends, Fingerprint, Multiple regression.

1. Introduction

Accelerated surface warming due to increasing greenhouse gas concentration could provoke significant modifications in the atmospheric general circulation. Changes in the radiative forcing and atmospheric circulation patterns may also impact the hydrological cycle and have far-reaching consequences on human society, especially in the areas where water is a major constraint on economical development. Asian region is particularly sensitive to perturbations in the climate system, and therefore predicting the sensitivity of the Asian monsoon to anthropogenic climate change is an important issue.

Despite its complexity especially on regional and smaller scales (Pant and Rupa Kumar 1997), many of the



Figs. 1.(a-c). Indices describing the large-scale Asian summer monsoon : (a) mean zonal wind shear index U = u_{200}-u_{850} (m/s) averaged over the domain 40°–110° E/EQ-20° N (Webster and Yang 1992), (b) mean meridional wind shear V = v_{200} – v_{850} (m/s) averaged over the domain 70° – 110° E/10-30 248° N (Goswami *et al.* 1999), (c) summer rainfall averaged over grid points covering India (solid line) and averged over 306 rain gauges (dashed line). Note the decreasing trends in both U and V but not in P

large-scale features of the monsoon circulation can now be captured by current generation atmospheric General Circulation Models [Stephenson *et al.* (1998) and references therein]. General Circulation Models (GCMs) have also been used to investigate the climatic impact of an increase in the atmospheric concentration of greenhouse gases (IPCC 1995). The GCM simulated monsoon response to increased amounts of CO_2 is complex and strongly model dependent. Nevertheless, because of the unprecedented nature of global warming, physically based climate models may be the only possible tools that can give some prior information on the possible changes that might occur in the monsoon.

Observational studies have found that there is little evidence of any significant trend in average Asian monsoon precipitation in the recent historical observations (Thapliyal and Kulshrestha 1991; Srivastava *et al.* 1992; Subbaramayya and Naidu 1992; Rupa Kumar *et al.* 1992). However, this does not preclude the possibility that the monsoon response to climate change may show up more clearly in either other variables than rainfall, or in special combinations of several variables. The GCM responses to increased CO_2 may provide useful clues that can help in the search for changes that may be taking place in the observable monsoon. For example, structural changes in monsoon correlations caused by movements in the descending branch of the Walker circulation (Krishna Kumar *et al.* 1999).

This article will briefly examine recent trends in several large-scale indices of the Asian monsoon. Changes simulated in recent model experiments will be used to interpret the observed trends. Multiple regression will be used to separate out the dynamical from the non-dynamical contributions to the all - India rainfall.

2. Large - scale monsoon indices

Fig. 1 shows three indices that are often employed in studying the large-scale behaviour of the Asian summer monsoon. For the sake of simplicity, this preliminary study will focus attention on these simple large-scale indices.

Monsoon convection over Asia is associated with strong vertical shears in both the zonal and the meridional winds. Webster and Yang (1992) demonstrated that a useful large – scale index is obtained by averaging the June - September mean zonal wind shear $u_{850} - u_{200}$ over the region 40 – 110°E / EQ – 20°N. This U – index measures the zonal circulation and is strongly related to changes in the Walker circulation (Ju and Slingo, 1995). Using the NCEP/NCAR reanalyses for the period 1958 – 98 we have calculated the U – index shown in Fig. 1(a). Despite a large amount of interannual variability, a clear decreasing trend can be noted in this index, most likely associated with the observed weakening in the Walker circulation (Trenberth and Hoar, 1996). Linear fits to the logarithm of the U - index show that the estimated trend is – 0.22% per year and explains R^2 = 0.15 of the total variance of the series.

Webster and Yang (1992) noted that there was "almost zero correlation" between the U index and variations in June – September rainfall averaged over India. To remedy this shortcoming, Goswami *et al.* (1999) proposed that a more appropriate monsoon index should be based on the meridional rather than the zonal circulation. They proposed a V index obtained by averaging the June - September mean meridional wind

TABLE 1

Correlations between various observed monsoon indices. Values above the leading diagonal give correlations between the raw series, whereas values below the diagonal give correlations between high – pass filtered de-trended series (year - to - year differences). Correlations above 0.403 are significantly different from zero at 99% confidence using a 2-sided Student t - test with 38 degrees of freedom

Index	U	V	AIRR	AIR
U	---	0.48	0.38	0.5
V	0.53	---	0.57	0.62
AIRR	0.52	0.71	---	0.76
AIR	0.63	0.68	0.9	---

shear $v_{850} - u_{200}$ over the region (70°-110°E / 10°S-30°N). Fig.1(b) shows this index calculated from the NCEP/NCAR reanalyses. The series is significantly correlated with the U index and also shows a decreasing trend. Linear fits to the logarithm of the V-index show that the estimated trend is – 0.32% per year and explains R^2 = 0.06 of the total variance of the series. The decreasing trends in the U and V wind shear indices are also present during both the earlier and later halves of this record suggesting that they are robust features that are not due to inhomogeneities in the reanalyses resulting from sudden changes in data availability (*e.g.* satellite irradiances).

Fig. 1(c) shows the average June–September rainfall over India estimated in two different ways. The solid curve gives the all – India Rainfall (AIRR) estimated by averaging rainfall at Indian grid points in the NCEP/NCAR reanalyses. The dashed curve gives the all – India rainfall obtained by directly averaging the measurements at 306 rain gauges over India (AIR). Despite a difference in mean value, variations in the two indices closely resemble one another which gives us confidence in using the NCEP/NCAR reanalyses for variability studies. A more detailed comparison of the two rainfall indices is presented in Rupa Kumar and Ashrit (1998). Unlike the dynamical U and V indices, there is no apparent trend in either rainfall index over the period 1958 – 1998. This is in agreement with previous studies that have also found no evidence for significant trends in the AIR even when using longer historical periods (Rupa Kumar *et al.* 1992).

Table 1 presents correlations between the various indices. Despite substantial correlations between the indices, most of the squared correlations do not exceed 0.5 suggesting that the time evolution of the indices can differ significantly from one another. Correlations have also been calculated between detrended series obtained by applying backward differences to each time series. Differencing is a simple and effective way of detrending short climate series and helps emphasize shorter period variations such as quasi – biennial signals (Stephenson *et al.* 1999). The correlations between the detrended time series are all larger than the correlations between the unfiltered series. For example, by filtering out the longer decadal trends the correlation between AIRR and AIR increases from 0.76 to 0.90. From Fig. 1(c) it can be seen that the AIRR derived from the NCEP/NCAR reanalyses has more decadal variability than the AIR derived directly from rain gauge observations. The inhomogeneous inclusion of upper air temperature and humidity data may partly account for some of these differences (*e.g.* differences in the MONEX year 1979, personal communication, M. Chelliah). Another noteworthy feature is that the reanalysis derived AIRR index has a much weaker correlation with the U – shear index (both raw and detrended) than does the AIR index. This suggests that the NCEP/NCAR reanalyses may be slightly underestimating monsoon rainfall teleconnections with ENSO perhaps because of model biases.

3. Model simulated monsoon response

As might naively be expected from enhanced warming over the Eurasian continent, several modelling studies have found that the simulated Asian summer monsoon becomes more intense in a world having increased amounts of CO_2 . In a comparison of doubled CO_2 response in five atmospheric GCMs coupled to a slab ocean model, Zhao and Kellogg (1988) concluded that wetter summer conditions were likely to occur over both India and south-east Asia. With another coupled ocean-atmosphere model, Meehl and Washington (1993) also obtained greater summer monsoon precipitation in a doubled CO_2 coupled model simulation, and also

TABLE 2

Model estimates of various summer monsoon indices (June – September). U is the mean zonal wind shear $u_{200} - u_{850}$ (in m/s) averaged over the domain 40° – 110°E /EQ – 20°N (Webster and Yang 1992). V is the mean meridional wind shear $v_{200} - v_{850}$ (in m/s) averaged over the domain 70° – 110°E/10° – 30°N (Goswami *et al.* 1999). P is the summer rainfall averaged over land points in the Asian domain 60° – 120°E/EQ – 30°N (Douville *et al.* 1999a,b)

Climate model	1 x CO_2			2 x CO_2		
	U	V	P	U	V	P
CNRM	27.5	3.71	10.7	24.4	2.93	10.2
LMD	29.6	5.78	9.9	28.4	5.73	11.2
UKMO	26.1	4.71	7.6	24.3	4.01	8.1
Mean	27.7	4.73	9.4	25.7	4.22	9.8

TABLE 3

Multiple linear regression fits to the all – India rainfall index using combinations of time and U and V wind shear indices as dependent variables. Coefficients in parentheses were obtained using all – India rainfall obtained directly by averaging 306 rain gauges instead of using NCEP/NCAR gridded reanalyses

FIT	β_1	β_2	β_3	R^2
TOO	0.0000 (-0.0002)	---	---	0.000 (0.002)
OVO	---	0.431 (0.397)	---	0.329 (0.397)
OOU	---	---	0.677 (0.769)	0.140 (0.255)
TVO	0.0007 (0.0004)	0.456 (0.413)	---	0.349 (0.408)
OVU	---	0.386 (0.318)	0.225 (0.397)	0.341 (0.449)
TOU	0.0008 (0.0006)	---	0.796 (0.869)	0.165 (0.280)
TVU	0.0009 (0.0008)	0.395 (0.326)	0.353 (0.504)	0.376 (0.483)

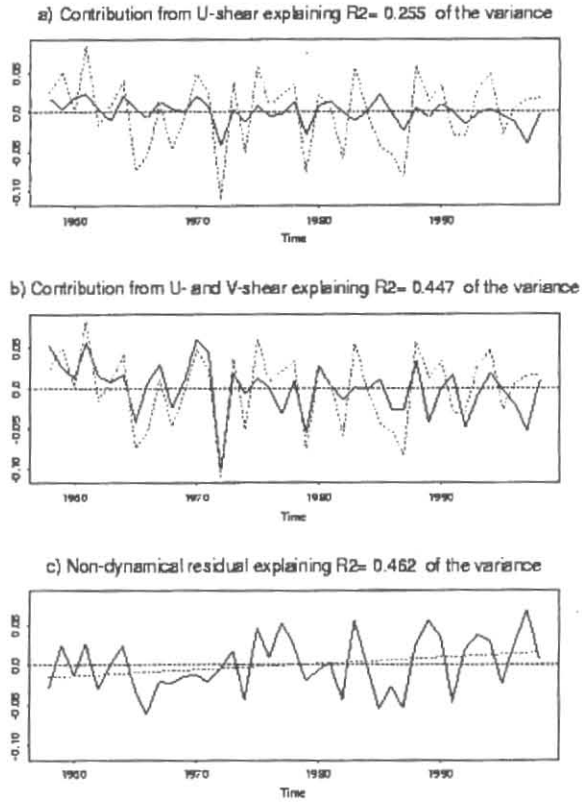
explained this increase by the stronger surface warming over the Asian continent than over the Indian Ocean. Bhaskaran *et al.* (1995) analysed the results from a transient coupled experiment with a gradual increase of the CO_2 concentration, and found a northward shift and an intensification of the monsoon rainfall, which was also partly attributed to an increased difference between land and sea temperatures. However, a later study showed a net reduction in area averaged monsoon precipitation when possible changes in sulphate aerosols were also prescribed (Bhaskaran and Mitchell 1998). Other studies without the inclusion of sulphate aerosols have also found decreases in mean monsoon precipitation. In the study of Zhao and Kellogg (1988), only three models indicated an increase in soil moisture over Asia, while one produced a strong decrease and the last one gave an unclear response. More recently, no clear evidence has been found for a significant change in monsoon rainfall either in the Max Planck Institute coupled model (Lal *et al.* 1994, 1995) or in various timeslice experiments performed with the Météo-France atmospheric GCM (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

coupled model experiment. Despite a weakening of the low–level monsoon winds over the Arabian sea, there was an increase in summer rainfall over India, which was speculated to be due to increased humidity in the warmer atmosphere.

Table 2 presents June – September means for indices obtained from both control 1 × CO_2 simulations and doubled CO_2 simulations made using three different atmospheric general circulation models that participated in the "Land – Surface Processes and Climate Response" (LSPCR) project (Polcher *et al.* 1998). The models were all run for 10 years for both the control simulations and for the doubled CO_2 simulations. For the doubled – CO_2 experiments, sea surface temperature and sea ice anomalies 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 of the year were calculated over a 20-year period around the time at which CO_2 levels were twice current values. These anomalies were then added to the climatological monthly average values over the period 1979 to 1988. For more details about the model simulations refer to Douville *et al.* (1999a,b).

All three models overestimate the strength of the U and V indices, which is a common problem in many GCM monsoon simulations (Stephenson *et al.* 1998). For all three models, there is a consistent decrease in both the U and V and dynamical indices with doubled CO_2 . The fractional decrease in the mean U and V indices is about 10% over a CO_2 doubling time of 70 years, which corres ponds to a net annual decrease of around – 0.15% per year. This is close to the rate of decrease noted in the pre vious section for the observed V – index over the period 1958-98. Some of this trend could be due to an ENSO-like monsoon response (Ju and Slingo 1995) to increased warming in sea surface temperatures in the equatorial Pacific in the UKMO coupled scenario run. It should be noted that in addition to the weakened zonal circulation, the local meridional circulation over Asia also weakens as seen in the weakened V index. This is contrary to the increase that might be expected to occur from simple arguments based on the increased temperature contrast between the Eurasian land mass and the Indian ocean. It is possible that increased humidity over the warmer tropical oceans may be favouring convection over such regions thereby weakening the off equatorial monsoon circulation (Stephenson 1995).

Table 2 also contains values for the mean June–September rainfall over land in the region 60°–120°E /EQ –30°N, which includes India and surrounding countries



Figs. 2(a-c). Decomposition of the observed P index obtained by performing multiple linear regression : (a) contribution to P from U-shear (solid) with P index (dashed), (b) contribution from both U and V-shears (solid) with P index (dashed), and (c) the residual precipition not explained by U and V which contains a linear trend (dashed).

in South East Asia. Because of the coarse resolution and systematic errors in models, a more trustworthy response is obtained by using a region slightly larger than just India. The rainfall index exhibits a less consistent response to CO_2 doubling than do the previous dynamical indices: it increases for UKMO and LMD whereas it decreases for CNRM (Douville *et al.* 1999a,b). The ambiguity in the rainfall response was also apparent in previous model studies, and there are several possible reasons for why the regional rainfall response may be harder to predict. Rainfall is the discontinuous result of complex physical processes that are often difficult to simulate using physically based models. Regional monsoon precipitation is often the delicate balance between both adiabatic and diabatic processes and is often prone to large sampling errors due to the presence of extreme events (Stephenson *et al.* 1999). Furthermore, local effects such as land surface properties also play an important role in determining the quantitative regional rainfall response (Polcher *et al.* 1998; Cox *et al.* 1999; Douville *et al.* 1999a,b).

4. Observed changes in all – India rainfall since 1958

Previous observational studies of monsoon climate change have tended to focus on trends in rainfall without considering in detail possible effects caused by changes in the atmospheric circulation (Thapliyal and Kulshrestha 1991; Srivastava *et al.* 1992; Subbaramayya and Naidu 1992; Rupa Kumar *et al.* 1992). The availability of longer analyses such as the NCEP/NCAR reanalyses now makes it possible to account for dynamical changes taking place throughout the depth of the troposphere. To better understand the changes in all – India rainfall, we have performed multiple regression using all – India rainfall as the dependent variable. Using a simple linear regression model, it is possible in principle to separate out the effects of dynamical processes related to changes in the large – scale wind shear from other effects such as changes in humidity *etc*. The regression model that we have used is given by :

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \qquad (1)$$

where $y = \log_{10} P$ is the dependent variable, and $x_1 = t$ (time in years), $x_2 = \log_{10} V$, and $x_3 = \log_{10} U$ are possible controlling factors. The beta parameters can be estimated most easily by minimising the sum of the squares of the residual (least squares). The parameter β_0 is identically zero because we center all variables (remove their means) before performing the regression. By using the logarithm of the indices, a "multiplicative" model is obtained, which is perhaps more appropriate for monsoon precipitation than is an "additive" model. For example, the total precipitation is the result of the convergence of moisture fluxes into the region, in other words, the product and not the sum of dynamical (*e.g.* wind) and non – dynamical (*e.g.* humidity) effects.

Table 3 gives the least square estimates of the beta parameters obtained for fits made with different combinations of factors. The right hand column gives the fraction R^2 of total variance explained by each fit. The best fits are obtained when the V index is included (*e.g.* OVU, TVO, OVU and TVU) confirming the claims made in Goswami *et al.* (1999). The best fit is obtained when all three factors (TVU) are included and can explain almost half the total variance of the gauge based AIR index. The inclusion of time in the fits does not substantially improve the fits, which confirms that linear trends explain only a small fraction of the total variance.

The various contributions to the gauge based AIR index obtained for the TVU fit are shown in Fig. 2. The contribution from the zonal wind shear $\beta_3 x_3$ explains only 25% of the total variance (Fig. 2a). By also including the contribution from the meridional wind shear $\beta_2 x_2$, it becomes possible to explain 45% of the total variance Fig. 2(b). This "dynamical component" of the all – India rainfall contributes substantially in certain years such as 1970, 1972, 1979, and 1980. By subtracting out the dynamical component, one can obtain a "non – dynamical" part that is more likely to be influenced by humidity and other diabatic effects. This is shown in Fig. 2c and can be seen to have a clear increasing trend and also more short – term interannual variability especially after the mid 1970s. A linear fit to the non – dynamical residual gives an estimated increase of 0.17% per year that explains $R^2 = 0.07$ of the variance of the residuals. This trend in the multivariate residual $\log_{10} P - \beta_2 \log_{10} V - \beta_3 \log_{10} U$ is the most significant of all the trends found in the various monsoon indices and is significant at 90% using a simple F – test. In addition, there is more variance in the later half of the record (*e.g.* 1974, 1983, 1997) due to the dynamical wind shear indices explaining less of the total precipitation variation as explained in Krishna Kumar *et al.* (1999).

Since β_2 and β_3 are both close to 0.5 for the TVU fits, the non–dynamical residual can be approximated by the logarithm of the dimensionless Multivariate Monsoon Index :

$$\mathrm{MMI} = \frac{\mathrm{P}}{\sqrt{\mathrm{UV}}} \qquad (2)$$

The MMI contains a marked increasing trend of 0.47% per year from 1958–98 significant at 95% confidence using an F – test (not shown). In addition, the MMI can be calculated for the model indices presented in Table 2 and also shows a consistent increase of between 14 – 20% for all three models. The MMI may therefore provide a sensitive multivariate fingerprint quantity for use in monitoring possible climate change in the large – scale Asian monsoon.

5. Concluding remarks

In this preliminary study of the largescale indices of the Asian summer monsoon, we have shown that :

(*i*) The observed all – India rainfall index contained no significant trend since 1958, and that there is also little consensus between various GCM studies concerning the possible trend in South East Asian rainfall.

(*ii*) The dynamical zonal and meridional wind shear indices based on NCEP/NCAR reanalyses both contain slow decreasing trends of 0.1–0.3% per year over the period 1958 – 1998 in agreement with expectations from recent time – slice simulations made with atmospheric general circulation models.

(*iii*) The combined zonal and meridional wind shear indices can account for almost 50% of the total variance in the all – India rainfall by using multiple linear regression.

(*iv*) The non – dynamical component of the precipitation exhibits a clear increasing trend from 1958 – 98 possibly caused by increases in atmospheric humidity.

(*v*) The dimensionless Multivariate Monsoon Index $P/(UV)^{1/2}$ provides a simple approximation to the non-dynamical component of the precipitation and could be useful for monitoring climate change in the monsoon.

Because of the complexity of the Asian monsoon, it is likely that the response of monsoon rainfall to increasing CO_2 will be difficult to interpret. Krishna Kumar *et al.* (1999) have speculated that the all – India monsoon rainfall has not increased significantly in recent years due to a compensation between weakening caused by warming in the eastern equatorial Pacific and strengthening caused by increased land temperatures over Eurasia. However, warming over Eurasia would be expected to lead to a strengthened meridional monsoon circulation which is converse to what can be seen in the observations and model results. Furthermore, most of the recent Eurasian warming can be accounted for by a strengthening in the mid – latitude westerly flow (the North Atlantic Oscillation) which is not known to be strongly correlated with all – India rainfall. It therefore seems likely that increasing atmospheric humidity or some other as yet unidentified factor may be compensating for the weakening all-India rainfall caused by increasing temperatures in the eastern equatorial Pacific.

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