Changes in Global Monsoon Circulations Since 1950

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Abstract. We examined changes in several independent intensity indices of four major tropical monsoonal circulations for the period 1950–1998. These intensity indices included observed land surface precipitation and observed ocean surface pressure in the monsoon regions as well as upper-level divergence calculated at several standard levels from the NCAR/NCEP reanalysis. These values were averaged seasonally over appropriate regions of southeastern Asian, western Africa, eastern Africa and the Australia/Maritime continent and adjacent ocean areas. As a consistency check we also examined two secondary indices: mean sea level pressure trends and low level convergence both from the NCEP reanalysis.

We find that in each of the four regions examined, a consistent picture emerges indicating significantly diminished monsoonal circulations over the period of record, evidence of diminished spatial maxima in the global hydrological cycle since 1950. Trends since 1979, the period of strongest reported surface warming, do not indicate any change in monsoon circulations. When strong ENSO years are removed from each of the time series the trends still show a general, significant reduction of monsoon intensity indicating that ENSO variability is not the direct cause for the observed weakening.

Most previously reported model simulations of the effects of rising CO_2 show an increase in monsoonal activity with rising global surface temperature. We find no support in these data for an increasing hydrological cycle or increasing extremes as hypothesized by greenhouse warming scenarios.

Key words: Monsoon, Asia, Africa, Australia

1. Introduction

Tropical monsoonal circulations represent key regional components of the global circulation system, a large portion of the global hydrological cycle and a major avenue of communication between tropics and the extratropics (e.g., Webster, 1987). Monsoonal circulations would also be expected to be sensitive to a variety of environmental changes. The most important of these may include large scale tropospheric warming, changes in El Niño-Southern Oscillation (ENSO) cycles,

large-scale landcover changes or natural variations in the climate system including ocean circulations.

For example, greenhouse gas warming simulations generally show increased intensity of Asian summer monsoonal circulations (e.g., Meehl and Washington, 1993; Hirakuchi and Giorgi, 1995; Li *et al.*, 1995; Zwiers and Kharin, 1998; Chakraborty and Lal, 1994; Suppiah, 1995; Zhao and Kellog, 1988; Hulme *et al.*, 1998; Wang, 1994) though there are exceptions (e.g., Lal *et al.*, 1994). Whetton *et al.* (1993), Whetton *et al.* (1994) and Suppiah (1995) each found a general increase in Northern Australian precipitation during the austral summer season as a result of rising CO_2 in model simulations. Though no reports of effects on the African monsoons exist that we are aware of, a similar response might be expected for these regions given that the tropical atmospheric moisture content, latent heating and overall hydrological cycle have been hypothesized to increase with increasing tropospheric temperature (e.g., IPCC, 1996).

Paleoclimate simulations also indicate a relationship between global monsoonal intensity and warming temperatures. Several studies have found increased monsoon activity during simulated interglacial periods where overall summer temperatures were warmer and enhanced the land-ocean temperature contrast by heating land surfaces faster than ocean surfaces. Decreased monsoon activity was simulated during periods of decreased insolation and cooler summer temperatures (e.g., de Noblet *et al.*, 1996; Prell and Kutzbach, 1987; Kutzbach and Gallimore, 1988)

The inclusion of aerosols, however, seems to inhibit simulated monsoon circulations in southeast Asia in many (e.g., Lal *et al.*, 1996; Boucher *et al.*, 1998; Mitchell and Johns, 1997; Meehl *et al.* 1996) but not all (e.g., Roeckner *et al.*, 1998) general circulation model simulations. Again, the effect of aerosols on the smaller monsoon systems have not been widely reported.

It is also widely recognized that relationships between ENSO and all four tropical monsoon systems exist to differing degrees. These effects appear to be related to changes in the zonal Walker circulations which allow communication from region to region in the tropics (Camberlin, 1995). It has been shown that warm ENSO events are anti-correlated to the intensity of the Asian summer monsoon in both observational and modeling studies (e.g., Ji *et al.*, 1996; Zhang *et al.*, 1997; Krishnamurti and Surgi, 1987). However, more recent observations have shown that this relationship has deteriorated in recent decades (e.g., Kumar *et al.*, 1999).

McBride and Nicholls (1983) found little correlation between Australian monsoon rainfall and Southern Oscillation Index (SOI) at the height of the monsoon season though they did find significant relationships in other seasons. More recently, however, a relationship similar to that in Asia has been reported where El Niños are associated with weak monsoon troughs which are shifted towards the equator while La Nina is associated with stronger monsoon troughs situated more over the Australian landmass (e.g., Suppiah and Hennessy, 1996; Evans and

Allan, 1992). This relationship also appears to be in a state of flux since the 1970's (Nicholls *et al.*, 1996).

The relationship between the African monsoon systems and ENSO appears less coherent. Janowiak (1988) found a weak relationship between ENSO and African rainfall with regional changes in rainfall of both sign. Indeje *et al.* (2000) found ENSO effects on rainfall in eastern Africa to be variable by season and by region though they found an overall drying during the JJAS season, particularly in central Kenya and the northern parts of Uganda. Bhatt (1989), and Nicholson and Kim (1997) found significant correlations between decreased east African rainfall and El Niño events. Additionally, Camberlin (1997) found a strong correlation between eastern African rainfall and Indian summer precipitation and surface pressure indicating these systems are dynamically linked even apart from ENSO influences.

Rasmusson and Arkin (1993) reviewed model results and the general effects of landcover on changes in global precipitation and circulation though did not explicitly explore the role of monsoons. Model simulations of the effects of tropical/sub-tropical landcover change also indicate that changes in monsoon circulations might be expected (e.g., Eltahir, 1995, Zheng and Eltahir, 1996, Chase *et al.*, 1996; deRidder, 1998; Song *et al.*, 1996; Rowntree and Sangster, 1986) though these studies all showed diminished monsoonal circulations as a result of changes in landcover. Kutzbach *et al.* (1996) found that increased vegetation in the western Africa monsoon region substantially enhanced the monsoon circulation in a paleo-climate simulation. Additionally, changes in land surface conditions in the mid-latitudes such as changes in soil moisture, snowcover or vegetation might also be expected to affect some tropical monsoons (e.g., Blanford, 1884; Meehl, 1994; Bamzai and Shukla, 1999; Shen *et al.*, 1998; Xue, 1996). Changes in ocean circulation patterns would also have potential impacts on all regional monsoon systems. It is clear that the intensity and structure of monsoonal circulations are sensitive to a wide variety of sometimes competing mechanisms, all of which appear to be active at the present time.

Observed changes in monsoonal intensity have been reported in a variety of studies. For example, Longxun *et al.* (1994) find decreasing trends in southern China rainfall during both the summer and winter monsoon seasons since the 1950s which they attributed to decreased monsoonal intensity during both seasons. The east Asian winter monsoon has been shown to be significantly reduced during the period 1950–1989 in January by Shi (1996). Rao (1994), found no systematic trend in Indian JJAS rainfall in the last century though Subbaramayya and Naidu (1992) show a sharp decrease in all India rainfall from the period 1950 to the early 1980s (their Figure 10). Kothyari *et al.* (1997) found a regional decrease in Indian monsoonal rainfall since the late 1960s: an observation mirrored by Parthasarathy *et al.* (1994) who found that that 1960s, 70s, and 80s were periods of below average summer monsoon rainfall based on an 1871–1990 mean. Fu *et al.* (1999) related an observed increase in the Asian summer monsoon to abrupt global warming

in the 1920s and suggested a steady, positive relationship between hemispheric temperatures and monsoonal strength.

The west African monsoon has been the subject of much attention because of its observed weakening since the 1960s and concomitant decrease in Sahelian rainfall (e.g., Nicholson, 1980; Hulme, 1992a; Shinoda and Kawamura, 1994). This reduction of rainfall has been associated with both a general decrease in monsoonal intensity and with a southern shift of the rainfall belt (Shinoda, 1995). A significant portion of the low frequency variability in this region is associated with changes in SST (e.g., Rowell *et al.*, 1995; Folland *et al.*, 1986; Fontaine and Bigot, 1993).

Nicholls (1997) found increased precipitation in Australia since 1911 while Suppiah and Hennessy (1996) find mostly insignificant increases in heavy Australian tropical precipitation from 1910 to 1989 but note a decrease in heavy precipitation during the 1980s. Srikanthan and Stewart (1991) found no evidence of significant precipitation change during monsoon season though show a decrease in rainfall since the 1970s maximum associated, to some degree, with predominantly La Nina events shifting over to El Niños after the mid 1970s (Hennessey *et al.*, 1999). Lough (1997) finds the 1980s and 1990s were drier than previous decades in northeastern Australia. This, to some degree, matches with recent global precipitation estimates which show overall precipitation increases globally from early in the century though sharp decreases over most of the globe since the 1970s (Dai *et al.*, 1997).

While many have reported individual regional decreases in monsoonal intensity no attempt has been made to examine changes in all monsoonal circulations in a consistent manner as components and important drivers of the large-scale global circulation and hydrological cycle.

2. Monsoon Trends

Monsoons are quite variable in both time and space and are often the result of several interacting circulations so that simple indices of monsoonal strength frequently give contradictory indications of strength (Wang and Fan, 1999). Most indices of monsoonal intensity define a static area for averaging of some climate variable such as total precipitation or wind shear (e.g., Webster and Yang, 1992 , Goswami *et al.*, 1999; Wang and Fan, 1999 and references within).

We used several independent indices of monsoon strength for the period 1950–1998 and examined four regional monsoon systems in the tropics. These included southeast Asia, western Africa and eastern Africa for the months of June, July, August and September and the northern Australia/Maritime Continent (M.C.) in December, January, February and March.

For each major monsoon we prescribe a pre-defined region which is large enough to encompass the monsoon circulation's yearly variability. We begin with the definition of monsoonal regions proposed by Ramage (1971) and subsequently adopted by others (e.g., Hastenrath, 1985) and isolate 4 regional monsoon systems.

These regions are 0–30° N, 62–110° E for southern Asia, 30 S–10° N, 92–158° E for Australia/M.C., 0–28° N, 20 E–20° W for western Africa and 15 S–15° N, 27–55° W for eastern Africa.

The monsoon indices examined here are: (1) upper level divergence at several pressure levels derived from the NCAR/NCEP reanalysis, (2) land surface precipitation, and (3) surface pressure over oceans in the monsoon regions defined above. As a consistency check NCEP mean sea level pressure and NCEP lower level convergence at 850 mb were also calculated as secondary measures of monsoon strength. All conclusions from observational data must be treated with caution because errors and inhomogeneities will always exist. Consistency among independent data sets, however, adds confidence to the results.

2.1. 1950–1998 NCEP UPPER-LEVEL DIVERGENCE TRENDS

Dynamical monsoon indices derived from NCEP reanalysis derived from the east-west and north-south wind components at several pressure levels. These indices are upper-level divergence and low-level convergence fields calculated within the monsoon domains described above. Figure 1 shows each domain under consideration and the 925 hPa divergence field averaged over 49 monsoonal seasons from 1950–1998. Regions of convergence in these plots (negative contours) are an indication of the climatological position of the monsoon trough in that domain at 925 mb.

The NCEP reanalysis has been found to be reasonable for the study of monsoons in the past. Zhang *et al*. (1997) examined the east Asian winter monsoon using the reanalysis and found it adequate for that purpose. Annamalai *et al*. (1999) found that the reanalysis had a reasonable depiction of the Asian Summer Monsoon though compared somewhat less favorably to in situ precipitation observations overall than the ECMWF reanalysis product. The ECMWF reanalysis had a strong dry bias over India, however, and is available for only a limited period of time limiting its usefulness as a comparison.

In order to account for the monthly and year to year spatial variability of the monsoon and to isolate the active monsoon circulation within the domain, we average only the divergent portions of each domain each month and weight this average over the full area of the domain so that a consistent monthly area averaged divergence is obtained. These monthly averages are then formed into seasonal averages for each year. This results in a measure that is objective and undiluted by values in parts of the domain not directly associated with monsoonal circulations in a given year. This procedure accounts for the lack of regional coherence in the monsoon regions which would affect such measurements (e.g., Gadgil *et al*., 1993; Subbaramayya and Naidu, 1992). Divergence calculations are performed at 250, 200, 150 and 100 hPa.

Figure 2 shows the time series of upper-level divergence for each of the monsoon regions at four different levels. The slope of a linear regression line and
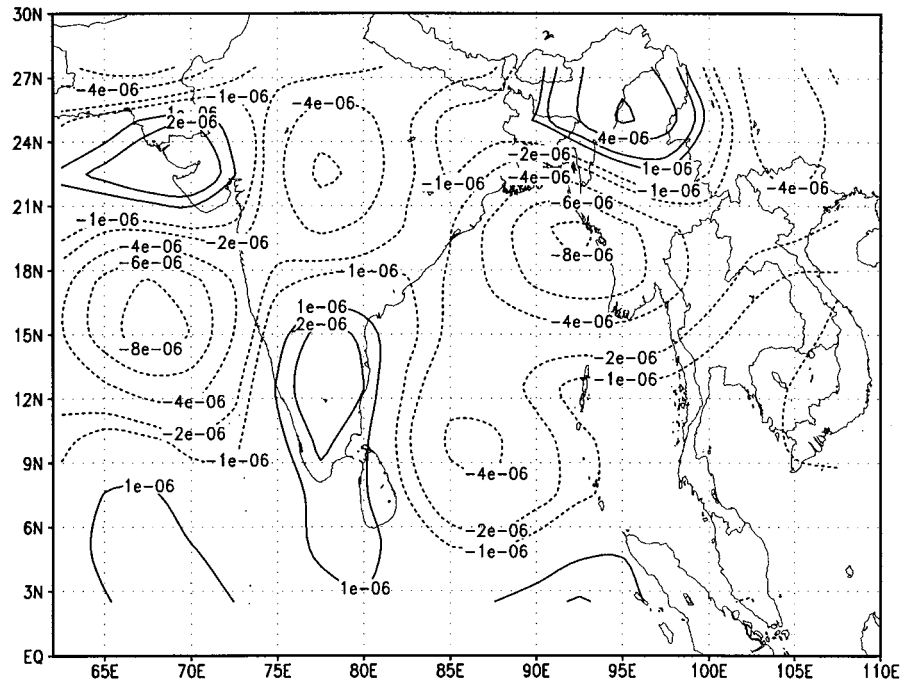
SOUTHEASTERN ASIA

Figure 1a.

Figure 1. Regional domains and climatological (1950–1998) seasonal divergence at 925 hPa. (a) southeastern Asia (JJAS) (b) Australia/Maritime continent (DJFM) (c) western Africa (JJAS), and (d) eastern Africa (JJAS).

associated p value using autoregression models with up to 4 year lags are given in Table I.

Negative divergence trends at upper-levels are indications of weakening monsoonal circulations and highly significant negative trends for all 4 levels occur in eastern Africa, western Africa and Australia/M.C. except at 100Pa. Southeast Asia shows significantly increasing divergence at the lowest two levels, no significant trend at 150Pa and significantly decreasing divergence at 100Pa. This is an indication that over the period of record the deepest monsoonal circulations in southeast Asia have diminished while more shallow circulations have increased. This result is suggestive of an overall decrease in the most vigorous monsoonal circulations in this region, an interpretation which is supported by additional observational data presented below.

We note here that temperature trends in the reanalysis data have been called into question in the past (e.g., Conference Summary, 1998) though winds (from which convergence and divergence are calculated) are among the most reliably analyzed variables (e.g., Kalnay *et al.*, 1996) and spurious trends in this field have
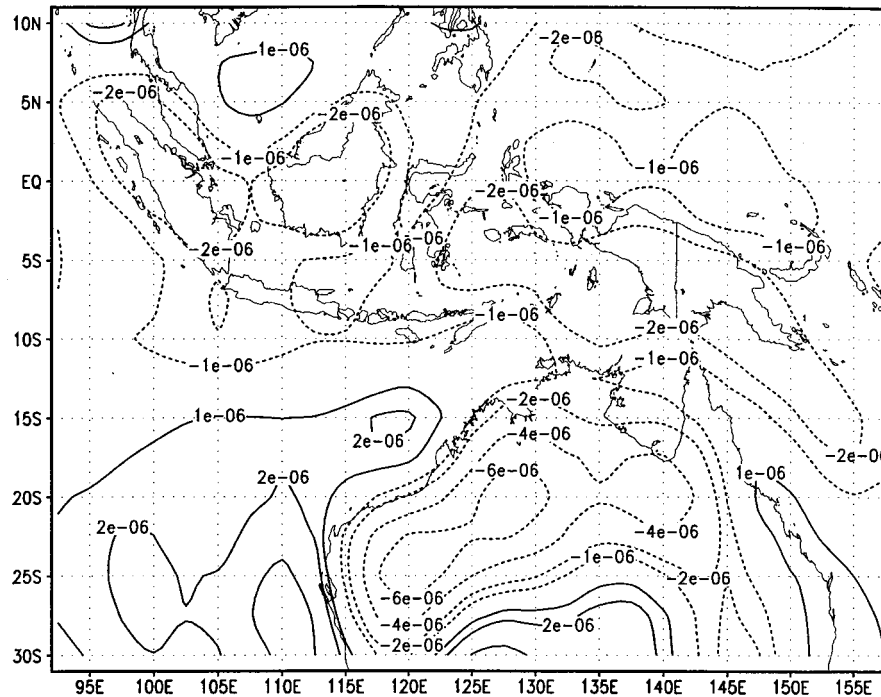
AUSTRALIA

Figure 1b.

not been demonstrated. However, as with all observational and meta-observational data, errors are likely to exist in the raw observations as are unrealistic model influences and these data should therefore be treated with caution. In the case of the reanalysis, the incorporation of satellite data in the late 1970s is one such possible source of error though time series from this dataset have been found suitable for analysis of trends in atmospheric heat content over the period (Levitus *et al.*, 2001). We did, however, examine trends over 1950–1978 (not shown), a period of homogeneous data sources in the reanalysis, and find little support for the possibility that downward trends are due to changes in data sources. For example, trends in both eastern and western Africa were downward at all levels during this period though were statistically significant at 100Pa in eastern Africa and for the three upper levels in western Africa which reflects the greatly reduced number of observations in this shorter period. Australian trends were significantly negative for all levels except 100Pa where an insignificant increase occurred. Southeast Asia had highly insignificant increases ($p > 0.4$) in the lower three levels and an equally insignificant decrease at 100Pa. Trends during the period 1979–1998, also one of homogeneous data inputs in the reanalysis, are examined in detail in Section 4 below.
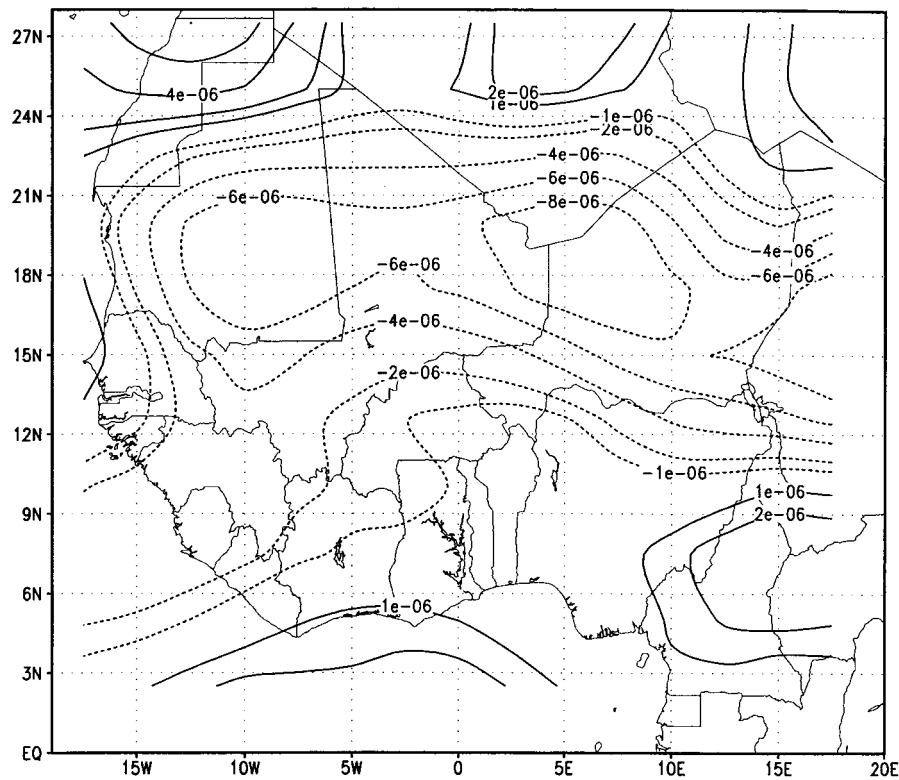
WESTERN AFRICA

Figure 1c.

2.2. LAND SURFACE PRECIPITATION AND SEA LEVEL PRESSURE OVER OCEANS

Few observational records applicable to the study of monsoon trends go back to the middle of the century. However, two additional directly observed proxies for monsoon strength are available. These are land surface precipitation observations (Hulme, 1992b) in the 4 monsoon regions defined above over the period 1950–1998 (Figure 3) and gridded sea level pressure over oceans from COADS, again in the 4 monsoon domains though for the period 1950–1997 (Figure 4). Unweighted area averages were applied to each dataset. These two quantities (SLP over oceans and precipitation over land) as measures of monsoon strength are significantly correlated (Australia/M.C 0.69; southeastern Asia 0.64; eastern Africa 0.65; western Africa 0.22) except in western Africa where a relatively weak correlation exists. Decreases in land surface precipitation and increases in surface pressure would be supportive of the results from the reanalysis data.
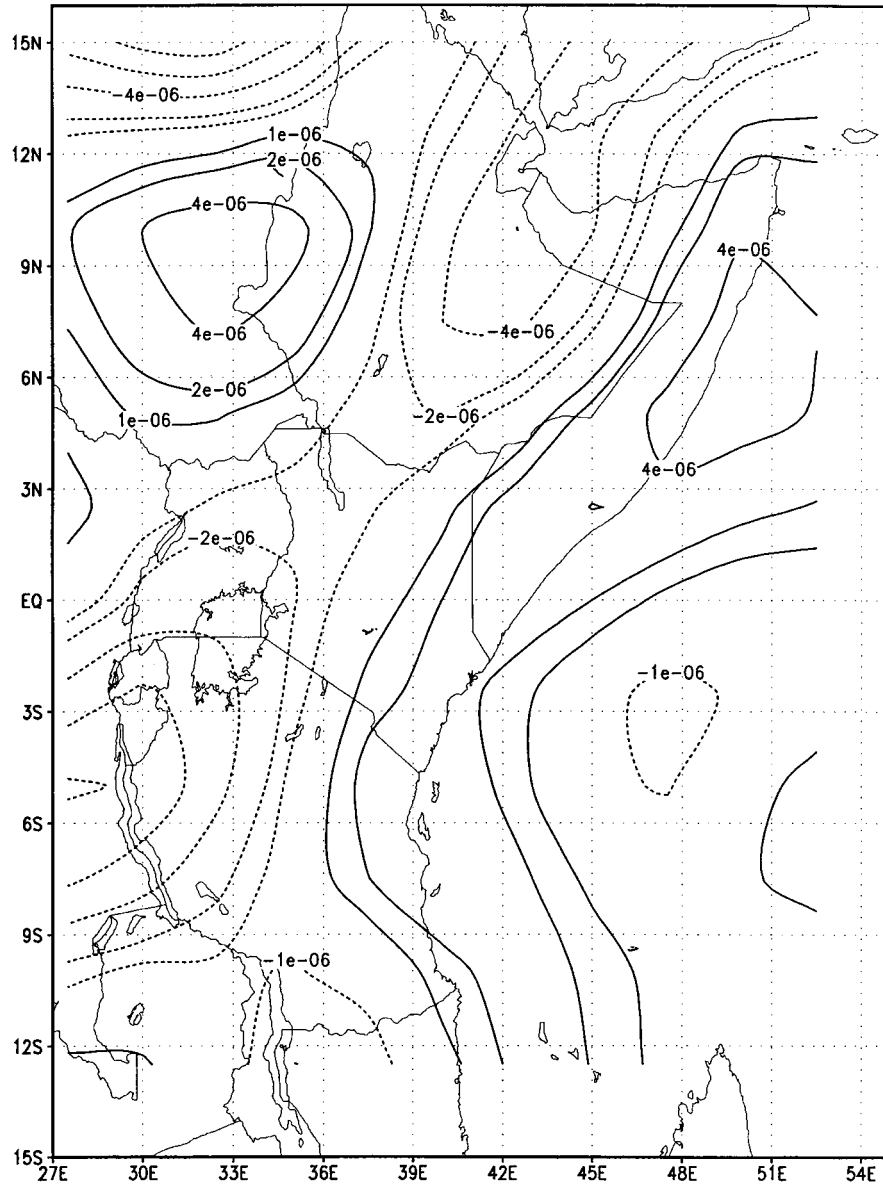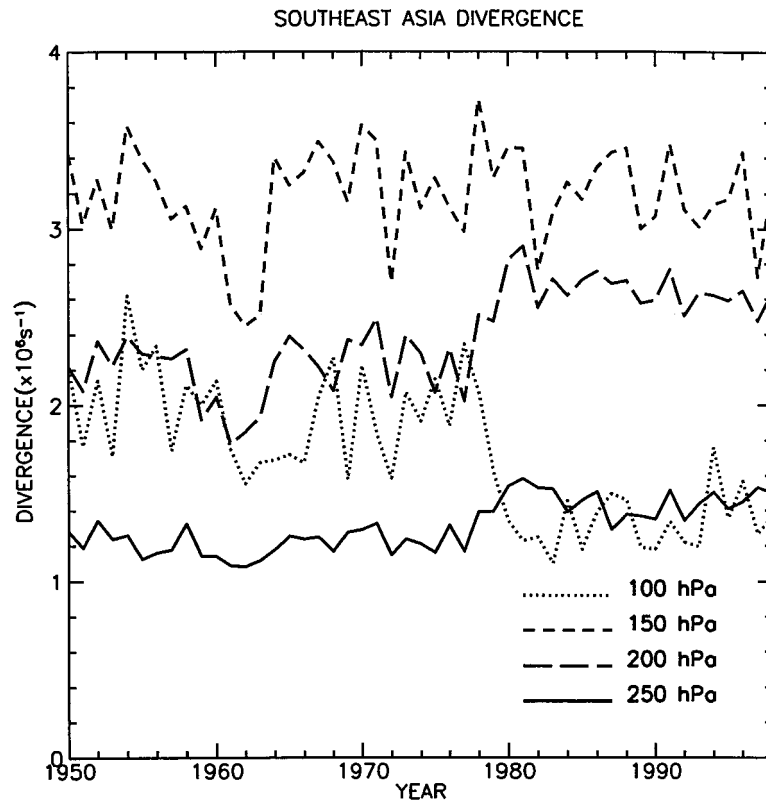
EASTERN AFRICA

Figure 1d.

SOUTHEAST ASIA DIVERGENCE

Figure 2a.

Figure 2. 1950–1998 Time series of upper-level divergence (s^{-1}) by monsoon domain. (a) southeastern Asia (JJAS) (b) Australia/Maritime continent (DJFM) (c) western Africa (JJAS), and (d) eastern Africa (JJAS).

Table I. Slope of the linear regression and significance p value for NCEP upper-level divergence by region and level(in units of s^{-1}/year).

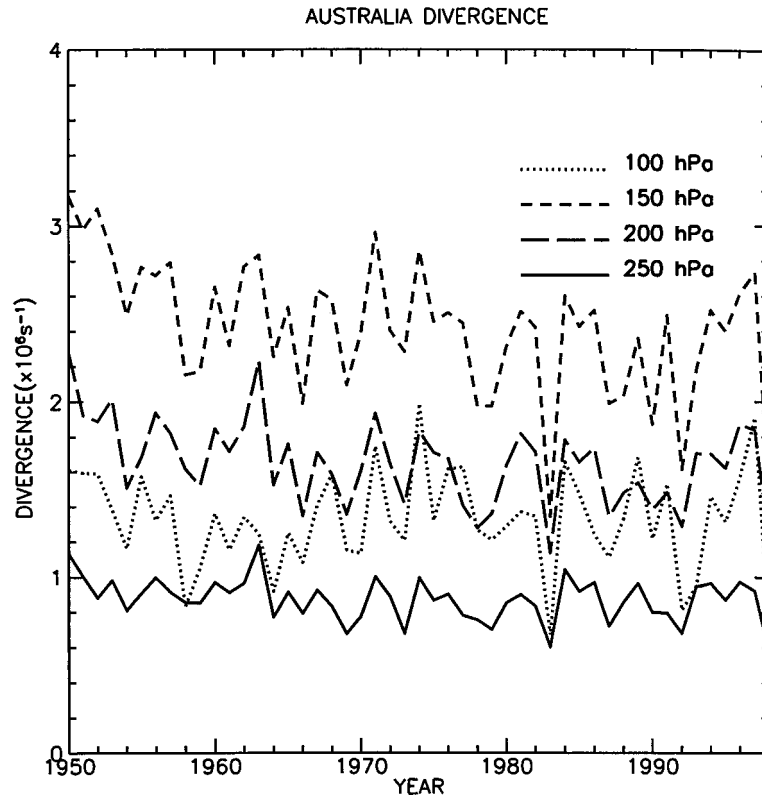|	250 hPa		200 hPa		150 hPa		100 hPa	
	Slope	p	Slope	p	Slope	p	Slope	p
S.E. Asia	6.73E-9	<0.01	1.21E-8	<0.01	1.18E-9	0.69	−1.81E-8	<0.01
Aust./M.C	−2.62E-9	0.03	−7.31E-9	<0.01	−1.36E-8	<0.01	−1.08E-9	0.71
W. Africa	−1.17E-8	<0.01	−1.49E-8	<0.01	−1.67E-8	0.04	−1.02E-8	<0.01
E. Africa	−9.42E-9	<0.01	−6.61E-9	<0.01	−1.48E-8	<0.01	−7.10E-9	0.02

AUSTRALIA DIVERGENCE

Figure 2b.

Linear regressions and significance values for these data are given in Table II and these data also indicate an overall decrease in monsoonal strength since mid-century. Exceptions to this are in Southeast Asia which shows a non-significant decrease in land precipitation though a significant increase in sea level pressure. Western Africa shows a well documented decrease of precipitation over land which is not mirrored with an increase of pressure over ocean surfaces in the region.

There was no significant autocorrelation in either the precipitation observations or in the SLP observations except in the case of eastern Africa ocean SLP where negative autocorrelation existed. In the case of east African SLP a second order autocorrelation model was found to be appropriate resulting in a slightly larger and more significant ($p < 0.01$) increase in the surface pressure trend.

2.3. 1950–1998 NCEP LOW-LEVEL CONVERGENCE AND SEA LEVEL PRESSURE TRENDS

As a consistency check we examined changes in low level convergence and sea level pressure in the monsoon regions. Lower level winds are subject to terrain effects and pressure surfaces can be extrapolated below ground. However, this
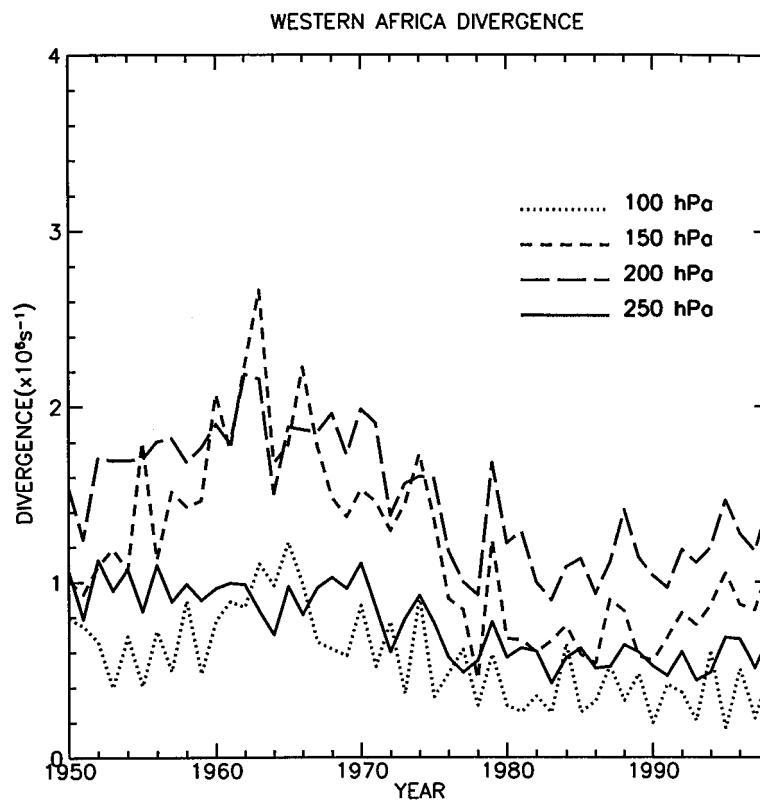
WESTERN AFRICA DIVERGENCE

Figure 2c.

Table II. Slope of the linear regression and significance p value for land Precipitation (1950–1998) in units of mm/year and ocean SLP (1950–1997) by region in units of Pa/year

	Land precipitaiton		Ocean SLP	
	Slope	*p*	Slope	*p*
Southeastern Asia	−0.10	0.53	1.30	<0.01
Australia/M.C.	−0.45	0.02	1.96	0.01
Western Africa	−0.62	<0.01	−0.26	0.64
Eastern Africa	−0.10	0.11	1.32	0.01

extrapolation is based on some useful information and therefore low level convergence trends are provided as a consistency check for previous indices which can be considered primary in this study. Convergence was calculated in the same manner as divergence. In all four monsoon regions 850 mb convergence decreased
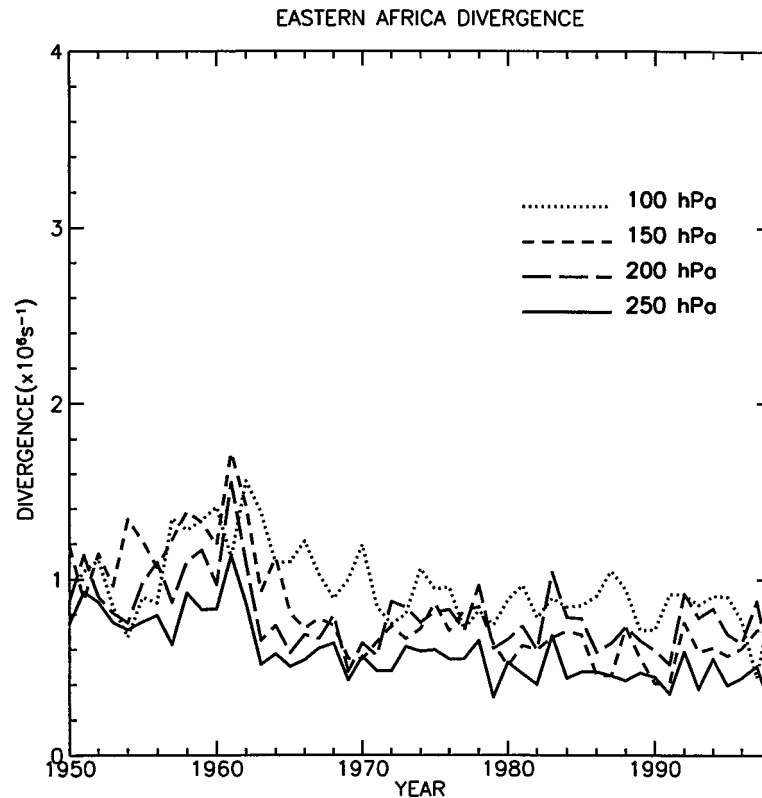
EASTERN AFRICA DIVERGENCE

Figure 2d.

significantly ($p < 0.05$) except in eastern Africa where the decreased convergence was insignificant ($p = 0.17$).

Reanalysis MSLP is heavily influenced by model calculations rather than primary observational data and for this reason is considered secondary. MSLP was averaged over the entire monsoon domain. Each monsoon region shows increasing surface pressure over the length of the record which is again an indication of weakening monsoons. MSLP trends are significant at higher than the 94% level in western Africa and Southeast Asia. Rising pressure trends in eastern and western Africa are insignificant for this variable.

For the monsoon indices presented here there is general agreement that all 4 tropical monsoon systems have weakened in the last half of the 20th century. Of the primary indices examined here (land precipitation, ocean SLP and 4 levels of divergence) 6 of 6 show a decreasing monsoon in Australia/M.C with 5 of these significant. Five of 6 show a decreasing monsoon in western Africa with 5 of these significant. Six of 6, all statistically significant, show a decreasing monsoon in eastern Africa. Southeastern Asia is more equivocal with a decreasing monsoon indicated in the direct SLP and precipitation observations. A significant decrease
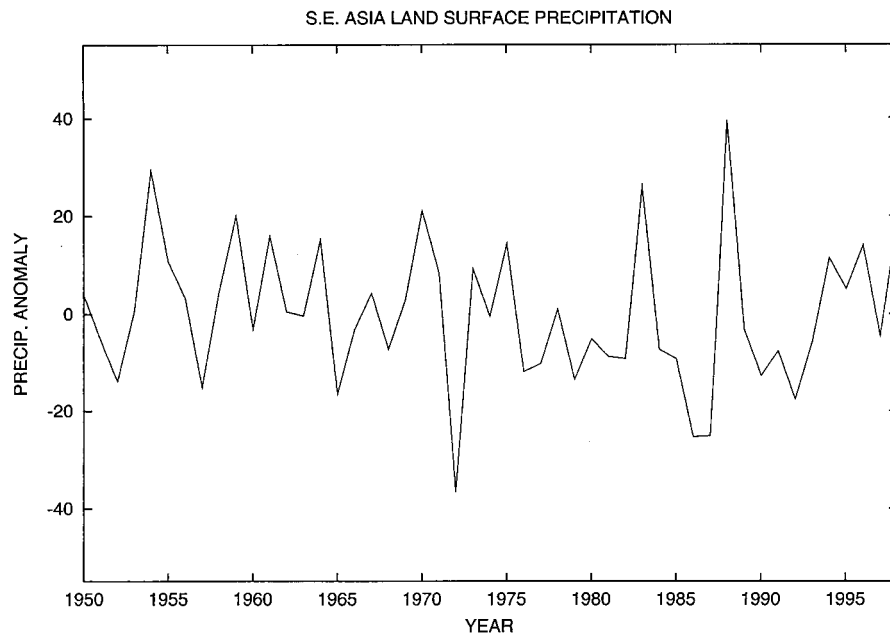
S.E. ASIA LAND SURFACE PRECIPITATION

Figure 3a.

Figure 3. 1950–1998 Time series of precipitation anomalies over land surfaces by monsoon domain. (a) southeastern Asia (JJAS) (b) Australia/Maritime continent (DJFM) (c) western Africa (JJAS), and (d) eastern Africa (JJAS).
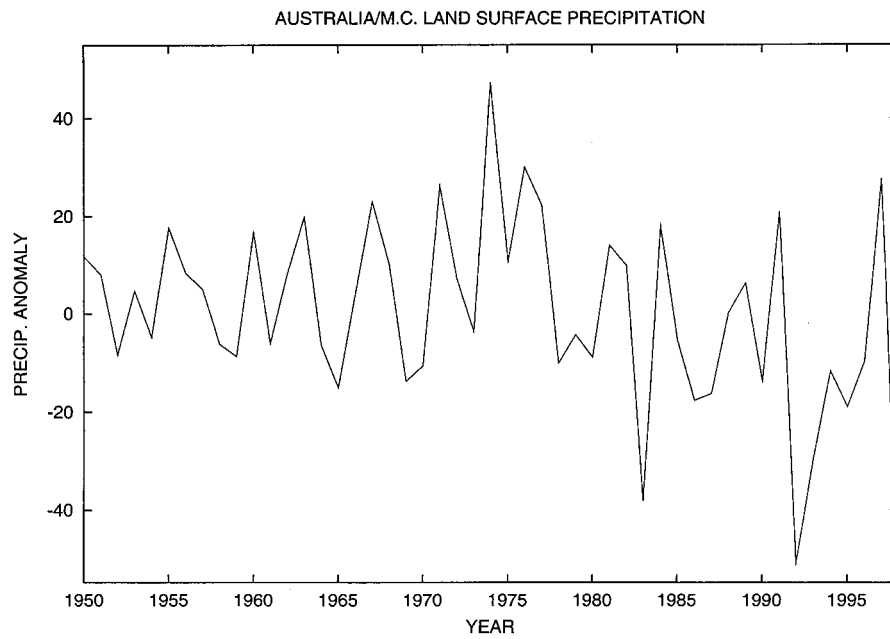
AUSTRALIA/M.C. LAND SURFACE PRECIPITATION

Figure 3b.

W. AFRICA LAND SURFACE PRECIPITATION

Figure 3c.

E. AFRICA LAND SURFACE PRECIPITATION

Figure 3d.

S.E. ASIA OCEAN SURFACE PRESSURE

Figure 4a.

Figure 4. 1950–1998 Time series of sea level pressure anomalies over ocean surfaces by monsoon domain. (a) southeastern Asia (JJAS) (b) Australia/Maritime continent (DJFM) (c) western Africa (JJAS), and (d) eastern Africa (JJAS).
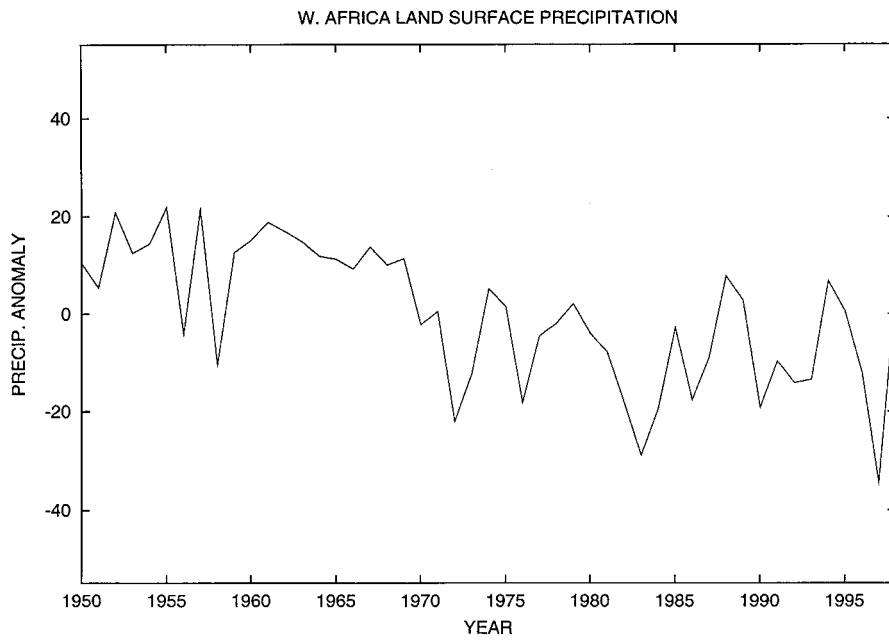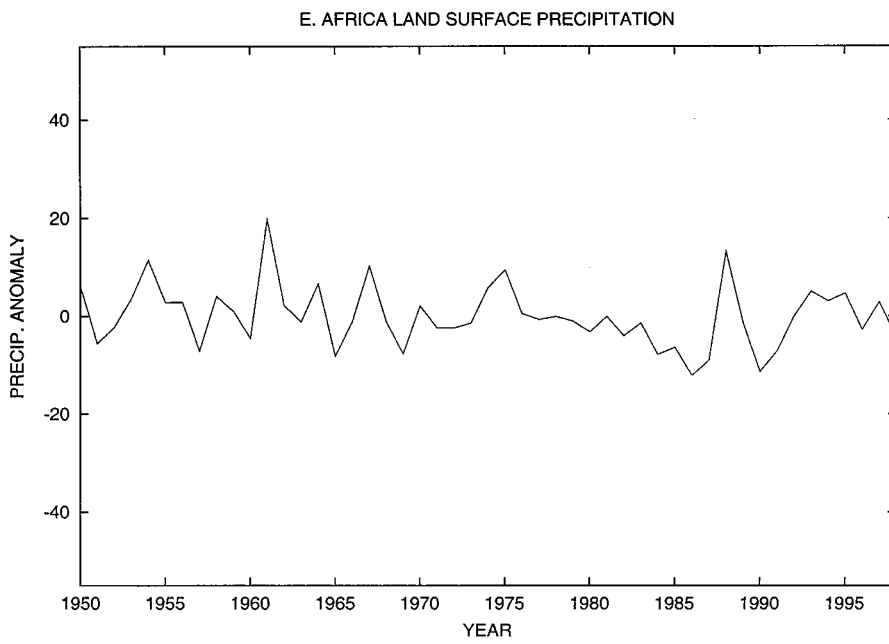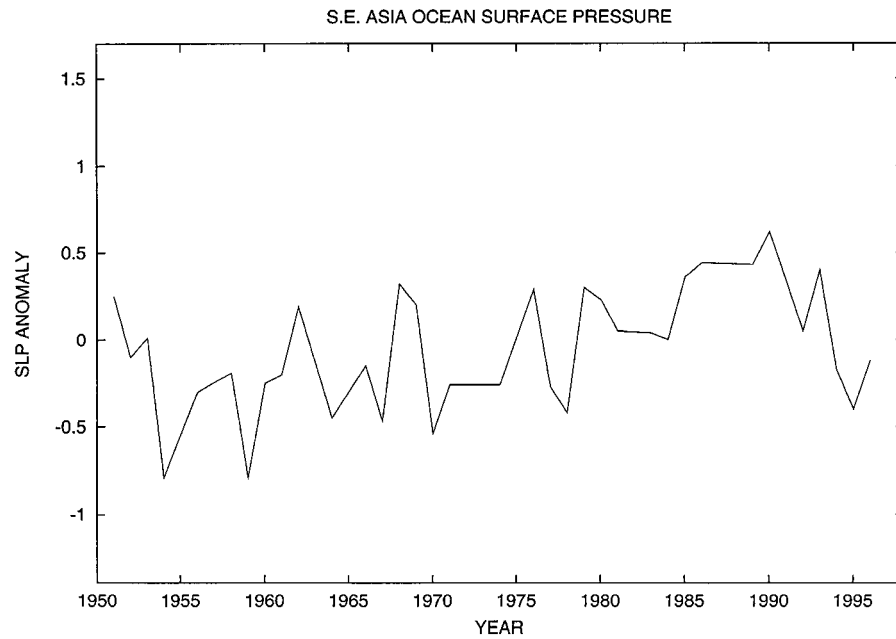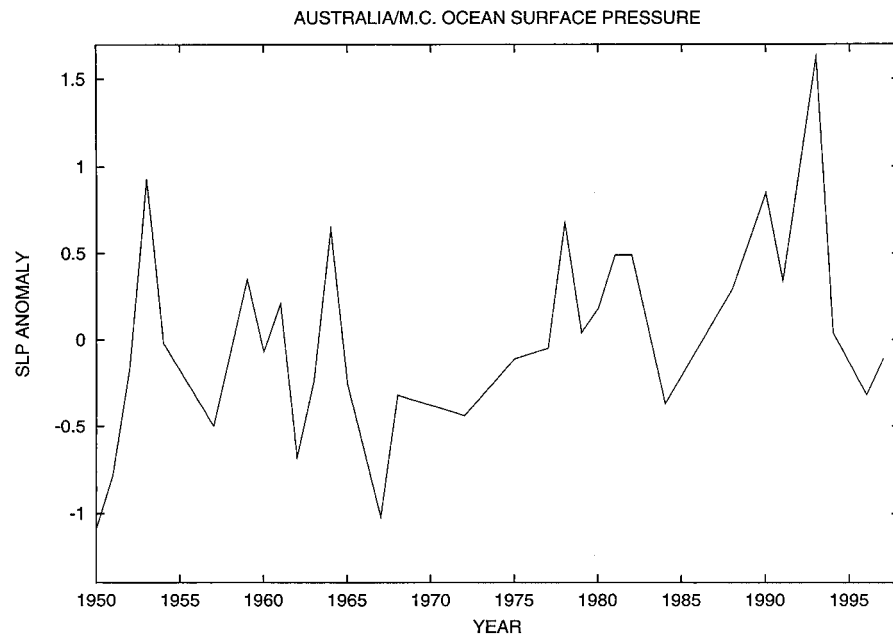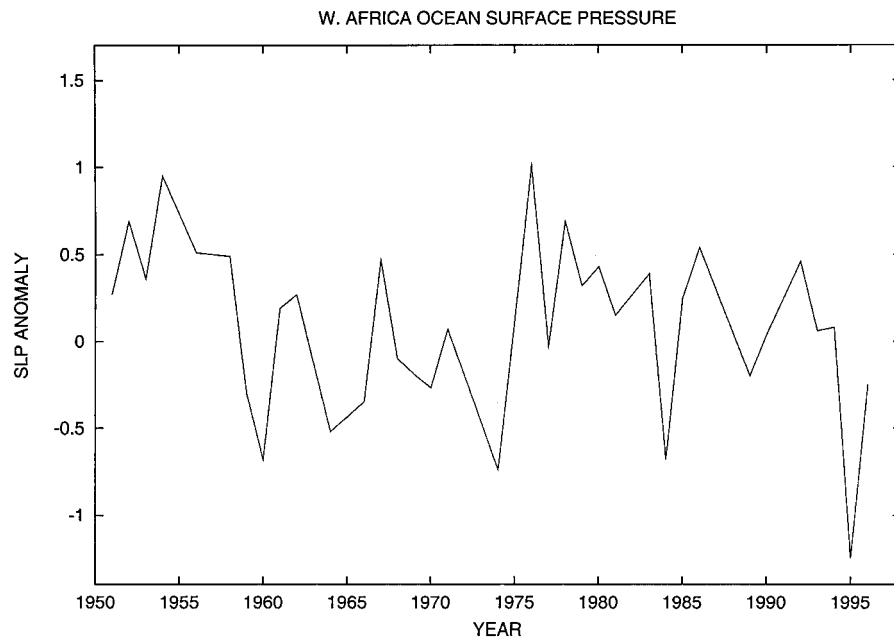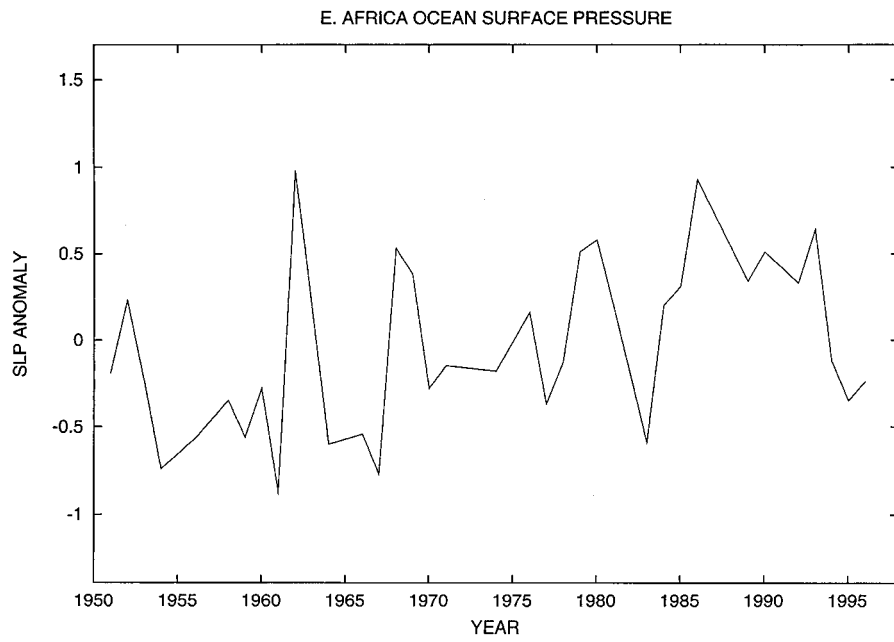
AUSTRALIA/M.C. OCEAN SURFACE PRESSURE

Figure 4b.

W. AFRICA OCEAN SURFACE PRESSURE

Figure 4c.

E. AFRICA OCEAN SURFACE PRESSURE

Figure 4d.

Table III. Trends in NCEP upper-level divergence by region for 1979–1998.

	250 hPa		200 hPa		150 hPa		100 hPa	
	Slope	p	Slope	p	Slope	p	Slope	p
S.E. Asia	−1.39E-9	0.67	−6.64E-9	0.13	−8.58E-9	0.34	3.19E-9	0.64
Aust./M.C.	1.00E-9	0.85	1.81E-9	0.84	1.59E-5	0.90	2.63E-9	0.84
W. Africa	−1.40E-9	0.71	3.35E-9	0.68	9.18E-9	0.22	−6.12E-10	0.84
E. Africa	−2.75E-9	0.22	−3.12E-10	0.96	1.96E-9	0.65	−5.63E-9	0.27

in divergence at the highest levels and an increase in lower levels is suggestive of less vigorous overall monsoon in southeastern Asia and is then consistent with the surface observations. Furthermore, the secondary observational indices presented here from the reanalysis also support an overall decrease of monsoonal strength since 1950.

3. Changes Since 1979

The globally averaged surface temperature record (Figure 5) reports that virtually all 20th century warming occurred in two discrete periods of steep increases. The first period was between 1910 and 1940 which was followed by a period of global surface cooling until the late 1970s. From about 1979 to the end of the record was a very large reported increase in global surface temperature. We are interested in comparing the effect of this apparant steep increase in surface temperatures since 1979 on the monsoon indices defined in previous sections. It might be exected that any circulation or hydrological cycle changes would be most evident during this period. This is also a period of homogeneous data sources for the reanalysis as discussed in Section 2.1.

The results of the regression analysis from 1979–1998 (Table III and IV) give little indication of a strong overall relationship between the reported surface warming since 1979 and monsoon activity as there is no significant trend of any sign in the main indices except for decreased SLP over in West Africa. A preponderance of indicators favor neither an increasing or decreasing trend in any monsoon region indicative of stagnant monsoon circulations over this time period.

4. The Effect of ENSO Fluctuations

In order to examine the effect of changes in ENSO on the observed decrease in monsoonal intensity we first remove all strong ENSO years from our time series and then repeated the analysis. We defined strong ENSO years as years when the average JJAS or DJFM | Niño3.4| anomaly is larger than 0.75. These specific years are listed in Appendix A.
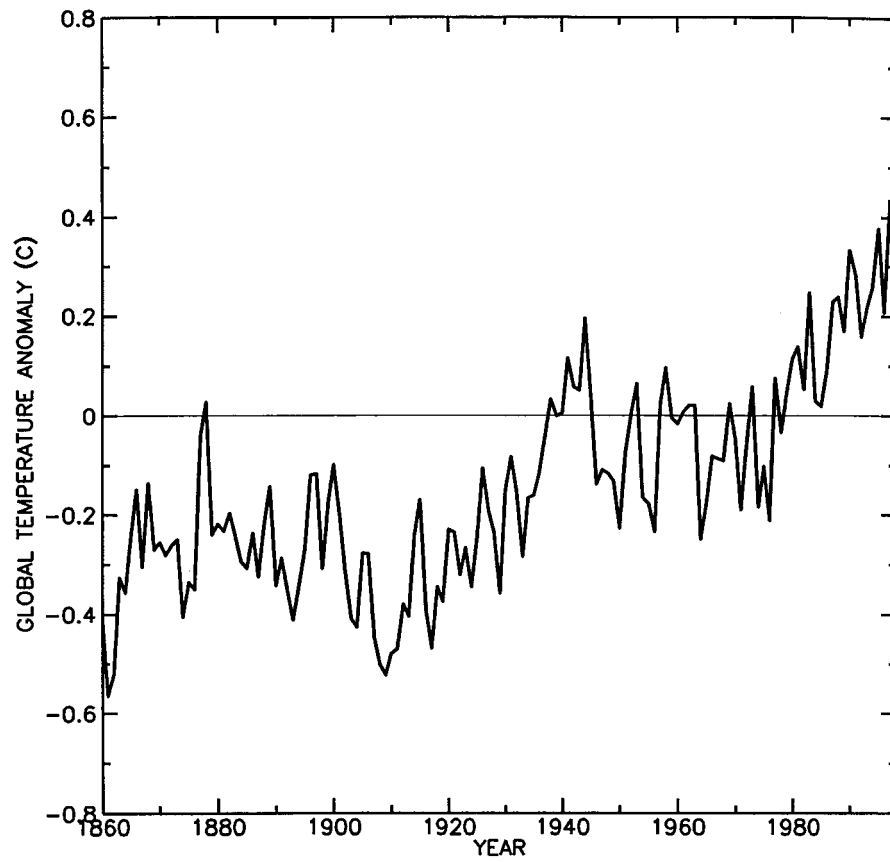
Figure 5. Global average surface temperature anomaly. Data described in Hansen *et al.* (1999).

Table IV. Trends in land precipitation (1979–1998) and ocean SLP (1979–1997).

	Land Precip.		Ocean SLP	
	Slope	p	Slope	p
S.E. Asia	0.78	0.24	0.000	0.98
Aust./M.C.	−1.04	0.25	0.007	0.81
W. Africa	0.08	0.87	−0.037	0.04
E. Africa	0.24	0.32	−0.015	0.41

Table V. As in Table I but with strong ENSO years removed from time series.

	250 hPa		200 hPa		50 hPa		100 hPa	
	Slope	p	Slope	p	Slope	p	Slope	p
S.E. Asia	6.65E-9	<0.01	1.36E-8	<0.01	1.90E-9	0.57	−1.94E-8	<0.01
Aust./M.C	−1.58E-9	0.22	−5.92E-9	0.03	−1.07E-8	<0.01	1.56E+9	0.56
W. Africa	−1.26E-8	<0.01	−1.58E-8	<0.01	−1.63E-8	0.08	−1.04E-8	<0.01
E. Africa	−1.02E-8	<0.01	−7.28E-9	0.04	−1.49E-8	<0.01	−7.34E-9	0.03

Table VI. As in Table II but with strong ENSO years removed from time series.

	Land Precipitaiton		Ocean SLP	
	Slope	p	Slope	p
Southeastern Asia	−0.23	0.15	0.01	0.02
Australia/M.C.	−0.11	0.52	0.01	0.03
Western Africa	−0.59	<0.01	−0.01	0.17
Eastern Africa	−0.14	0.08	0.02	<0.01

Upper-level divergence (Table V) show significant decreases in 3 of the four regions when ENSO fluctuations are removed. Southeastern Asia shows no significant trend in this measure over this time period.

Land precipitation and ocean SLP (Table VI) generally still indicate decreasing monsoon intensity over this time despite the removal of strong ENSO years. Apparantly, monsoonal intensity cannot be completely or directly attributed to changes in ENSO in the last 50 years though the possibilty of more complicated interactions between ENSO and monsoons affecting both cannot be ruled out.

5. Discussion and Conclusions

We have presented several differing and independent measures of monsoonal intensity and have applied them to all major tropical monsoons since 1950. Previously reported definitions of monsoonal intensity are varied and may give conflicting answers in differing situations. Our results, however, indicate a consistent reduction in intensity in all four tropical monsoon systems since 1950 and no trend in monsoon intensity since 1979, a time where strong surface warming has been reported. Sensitivity of these results to small changes in domain size, to changes in averaging period (monthly vs. seasonal) and to autocorrelation effects had no effect on our conclusions.

We also removed the direct ENSO signal from the time series of monsoon indices and found that there was still a significant tendency for diminishing global monsoon systems in all 4 regions since 1950. This is an indication that changes in ENSO are not completely or directly responsible for the observed trends in monsoon intensity.

Tropical deforestation has also been shown to affect monsoon circulations in a variety of modeling studies, most often by diminishing them. Because no transient model simulation of the effects of global landcover change has yet been performed we have not directly examined this possibility here though a detailed analysis will be undertaken in the future.

That monsoon indices since 1979 changed from a negative to neutral could possibly be construed as an indication that globally warming temperatures, as suggested by model simulations, are slowly overcoming some opposite trend in monsoonal intensity so that monsoons, and the entire hydrological cycle, will strengthen in the future. There is no evidence to back such a conclusion at this point. Regional temperature trends are also the dominant driver of recent globally averaged temperature trends (Chase *et al.*, 2000) and therefore may be a more pertinent measure of changes in monsoonal circulations as might other regional forcings such as snowcover change or changes in atmospheric or ocean circulation (e.g., Khandekar, 2000). However, current, state of the art, models of the climate system are generally unable to robustly simulate regional changes or changes in circulation regimes and generally simulate a strong relationship between globally averaged warming and increasing extremes in the hydrological cycle including monsoonal strength. We find no evidence to support this model hypothesis in these data indicating the possibility that unresolved or inadequately simulated processes are presently the dominant control over regional extremes in the tropical hydrological cycle.

Version 6, second edition). We thank Dr. Madhav Khandekar and Dr. T.S. Murty for their comments on this manuscript.

Appendix A

Years where seasonal average |Nino3.4| exceeded 0.75:

(a) JJAS
1950	−2.35
1955	−0.84
1957	0.82
1963	0.81
1965	1.27
1972	1.28
1973	−0.89
1975	−1.00
1982	1.39
1987	1.85
1988	−1.28
1991	0.83
1997	2.06
1998	−0.91
1999	−0.80

(b) DJFM
1955	−0.80
1956	−0.88
1958	1.67
1966	1.36
1969	1.08
1970	0.78
1971	−1.35
1973	1.56
1974	−1.50
1976	−1.21
1983	2.60
1985	−1.05
1987	1.40
1989	−1.60
1992	1.91
1995	0.96
1998	2.36
1999	−1.27

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