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RESEARCH REPORT

# Impact of Climate Change on the Moisture Regime of Tropical Climates

M. Ravindranath

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***National Centre for Medium Range Weather Forecasting***
***Ministry of Earth Sciences***
**A-50, Sector 62, NOIDA – 201307, INDIA**

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| 10 | Abstract (100 words) | It is attempted to study the changes in tropical moisture keeping in view of the global warming as well as frequent occurrence of extreme weather events that are attributed to climate change. The IPCC generated global gridded mean monthly temperature and rainfall data for the period 1901-2006 is used to assess the global water balance using Thornthwaite's approach. The moisture decline over tropical land masses is clearly seen. The change point analysis suggested that the decline is statistically significant at a minimum of 90% confidence limit and this change has occurred around the year 1980. The indictors are so definite for land masses falling over and around equator singling out Africa as the major affected area. |
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# Contents

## Abstract

The climate change induced extreme weather events have been occurring at frequent intervals with alarming intensity for the last two decades all over the globe. The IPCC in its 2007 report suggested considering extreme events as well in defining the climate. The alarming situation has been affecting the mankind in many a form including loss of lives, crops, damages to structures etc besides physical discomfort due to persistent above average high temperature conditions.

In the present endeavor, it is attempted to study the climate change with reference to broad climatic classification as per Prof. C.W. Thornthwaite and his associates. This classification is simple with two major parameters that define the climate – Temperature and Rainfall – as input. The climate status quantified in terms of moisture index is further analyzed. The monthly/annual parameters in the land phase of hydrological for the years 1901-2006 are worked out using IPCC 0.5 degree global gridded data series on mean monthly temperature and monthly rainfall.

The moisture over tropics marginally declined for the past 3 decades staring 1980. The per-humid climates over Borneo, Malaysia and Sumatra islands suffered highest drop while humid climates depreciated the most over South America. The loss over Africa is very intense with high amplitude variations in moisture index and dwindled condition in all climates. The Indian region suffered moderate losses in its major dry sub-humid climates. China and Mexico falling in the outer edge of tropics did not exhibit significant features.

The change point analysis suggested that statistically significant changes in temperature and rainfall have affected the climate/moisture conditions over tropics since 1980. The indictors are so definite for land masses falling over and around equator singling out Africa as the major affected area. The rise in net moisture status since 2000 suggests that frequent extreme rain events are partially compensating the moisture loss over tropics.

# IMPACT OF CLIMATE CHANGE ON THE MOISTURE REGIME OF TROPICAL CLIMATES

## 1. Introduction:

The International Panel on Climate Change (IPCC) suggests that climate need be defined not only in terms of temperature and precipitation but also by the type, frequency and intensity of weather events (IPCC, 2007). The panel also contends that the archived data sets are not sufficient for determining long-term trends in extremes (Climate Change 2007: Working Group I: The Physical Science Basis). But a clear evidence was reported on the increasing severity of tropical storms, hurricanes and typhoons from category 4 to 5 since 1970 in which the power dissipation index (PDI) of the storms were examined to be on the raise.

The Palmer Drought Severity Index (PDSI), that uses monthly precipitation totals and temperature averages, calculated from the middle of the 20th century shows a large drying trend over many Northern Hemisphere land areas since the mid-1950s, with widespread drying over much of southern Eurasia, northern Africa, Canada and Alaska and an opposite trend in eastern North and South America. In the Southern Hemisphere, land surfaces were wet in the 1970s and relatively dry in the 1960s and 1990s, and there was a drying trend from 1974 to 1998.

Although the long-term (1901–2004) land-based precipitation trend shows a small increase, decreases in land precipitation in recent decades are the main cause for the drying trends, although large surface warming during the last two to three decades has likely contributed to the drying. Dai et al. (2004) showed that globally, very dry areas (defined as land areas with a PDSI of less than –3.0) more than doubled (from ~12 to 30%) since the 1970s, with a large jump in the early 1980s due to an ENSO-related precipitation decrease over land and subsequent increases primarily due to surface warming. However, results are dependent on the version of the PDSI model used, since the empirical constants used in a global PDSI model may not be adequately adjusted for the local climate.

Thus, the precipitation showed small rising trend in recent past whereas the temperature showed large surface warming during the last two to three decades along with a rise in the severity and longevity of extreme events. The impacts of severe weather conditions varied from region to region as well.

In the present work, it is attempted to assess the combined effect of temperature and rainfall on the land phase of hydrological cycle. For this purpose, the water balance procedure developed by Prof.C.W.Thornthwaite (1948) is used. According to him the climatic classification should be based on moisture regime since moisture availability is a net product resulting from temperature, rainfall and vegetation pattern. After making extensive lysimeter experiments measuring soil moisture, he developed a climatic classification scheme through water balance approach for which the mean monthly temperature and monthly total rainfall are the basic inputs.

The book-keeping procedure of Thornthwaite and Mather (1950a) assess the water available in various forms in the land phase of hydrological cycle. The moisture released into atmosphere to meet potential evapotranspiration (PE) depends on rainfall and soil moisture recession that has bearing on soil moisture holding capacity. The major components of water budget viz, the soil moisture storage, actual evapotranspiration, water deficit and water surplus are thus calculated by weighing the rainfall against PE that is estimated using mean monthly temperature. The procedure further deduces indices on aridity, humidity and moisture. Thorthwaite's contention was that the moisture index is a rational representation of the climate status at any point over earth since various demands for moisture due to temperature, vegetation and soil were addressed before arriving at the net moisture content in the soil. In the present work the moisture index according to Thornthwaite's procedure is considered for studying the geographical trends in moisture regime and the temporal variation over tropics. The required input data, mean monthly temperature and total monthly precipitation, at 1 degree global grid for the period 1901-2006 as provided by IPCC is used. The soil moisture holding capacity is according to GEWEX ISLSCP-II initiative.

The broad climatic classification basing upon the moisture index is given in six classes as shown in Table A. Although Thornwaite's scheme is very old, it is simple and easy to use for quick assessment of moisture status on annual basis with bare minimum input.

This approach has been extensively used for studying the floods, incidence and impact of droughts, soil moisture condition etc (Subrahmanyam, V.P. 1981, 1983, Mather, J.R. 1969, 1978, 1979, Legates, D.R., and Mather, J.R., 1992, Legates, D.R., and McCabe, G.J., 2005)

**Table A: Climatic Classification of Thornthwaite**

| Symbol | Climate Type | Moisture Index (%) |
|---|---|---|
| A | Per-humid | >=100 |
| B | Humid | 20 to <100 |
| C2 | Moist Sub-humid | 0 to <20 |
| C1 | Dry Sub-humid | -33.3 to <0 |
| D | Semi-Arid | -66.6 to -33.3 |
| E | Arid | <-66.6 |

## 2. Overview of Tropical Climates:

The mean annual rainfall, mean annual potential evapotranspiration (PE) and resultant climatic spectrum over tropics are shown in Fig.1, 2 & 3 respectively. The equatorial African region dominated by monsoon rainfall of the order of 1500-2000 mm is classified into three main categories of dry sub-humid, moist sub-humid and humid climates with a small pocket of per-humid climate over west coast. The high altitude regions over Ethiopia are classified into per-humid and humid climates due to reduced evapotranspiration although rainfall magnitude is comparable with that over equatorial sub-humid regions. Thus the climate status of the region is defined by the combined effect of rainfall and PE. The Sahara desert is classified into semi-arid type within which small pockets of arid climate exist.

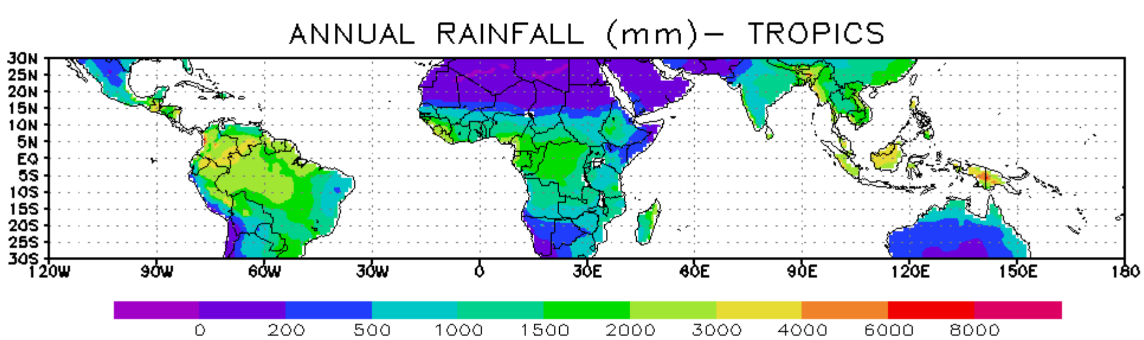



**Fig.1 Mean Annual Rainfall (mm) over Tropics**

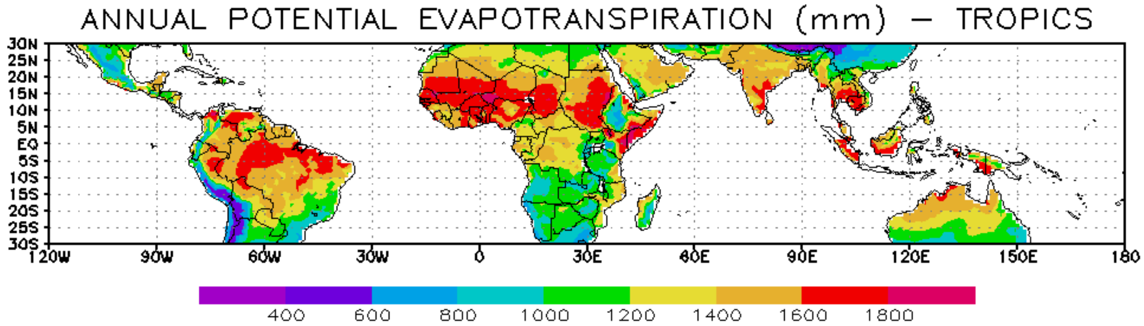



**Fig.2 Mean Annual Potential Evapotranspiration (mm) over Tropics**

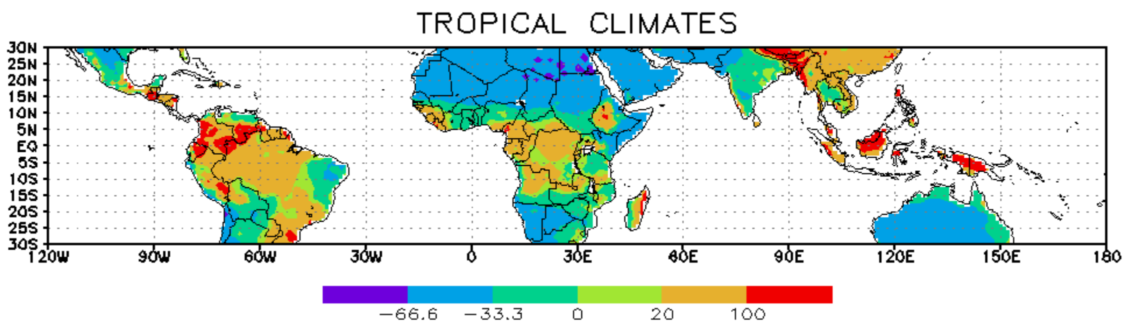



**Fig.3 Moisture Regime over Tropics**

Over the northern parts of South America both the annual rainfall and PE are of high order. These regions are blessed with per-humid climates due to rainfall domination over PE. The plains of Amazon river is characterized by humid climates to the east of which the climate status reduces to moist and dry sub-humid levels on moving close to coast. The hilly regions of west coast are characterized by low rainfall and low PE but the domination of PE over rainfall renders the hills to arid type climate.

The tropical Australia receives 500-1000 mm of rainfall along the coast. The orderly rain pattern gradually decreases towards interior lands. The potential evapotranspiration gradually decrease from around 1800 to 800 mm from coastal areas towards inland. The climate status in tropical Australia falls under dry sub-humid over coasts to semi-arid inland.

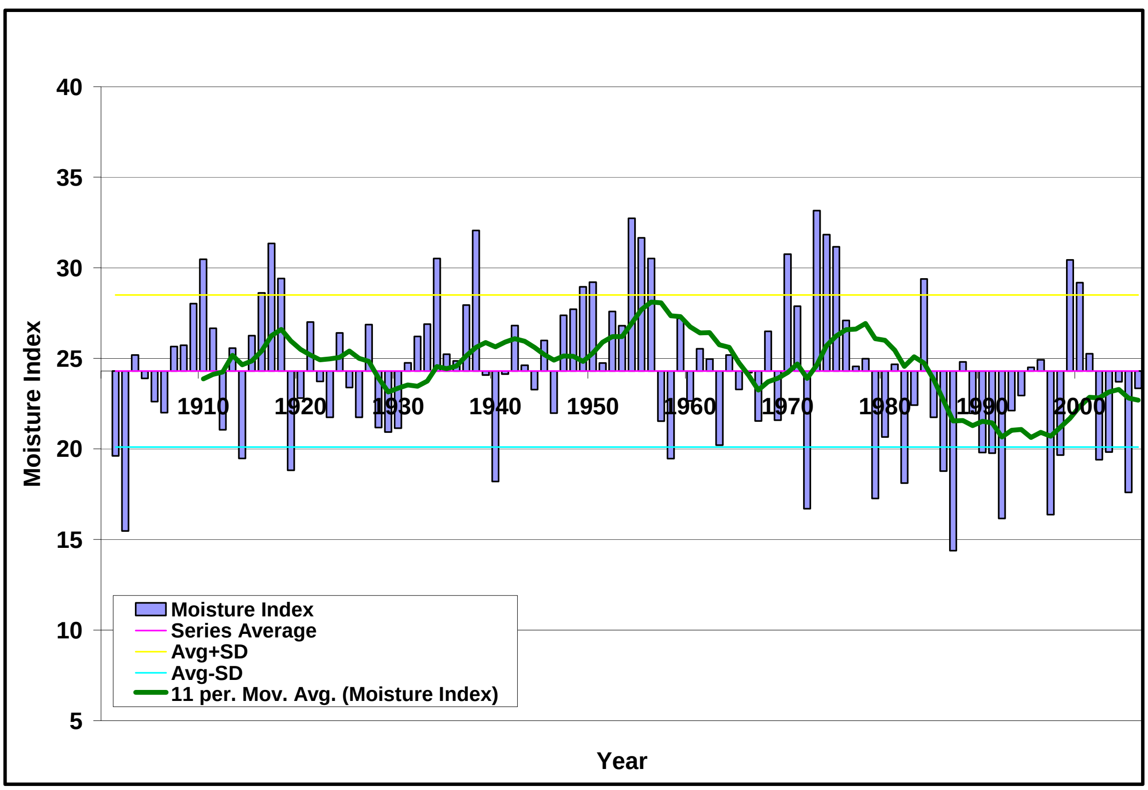
## 3. Temporal Distribution of Moisture Index:

The temporal distribution of area averaged Moisture Index falling within tropical land mass is discussed in this section. Further, in order to understand the area that is vulnerable / susceptible to moisture variation, the area average Moisture Index is estimated separately for nine different land areas namely, South America, Africa, India, Burma, Thailand, group of maritime islands Borneo,Malaysia,Sumatra (BMS), Australia, China and Mexico falling within tropics. The Himalayan region that is classified into per-humid category is omitted in this work since this high altitude, snow area is characterized by low temperature and more than equitable rainfall and as such a true comparison cannot be made with other per-humid areas that are characterized by high rainfall and temperature.

The temporal distribution of area averaged Moisture Index over tropics during 1901-2006 is shown in Fig.4a. The tropics (sans Himalayan region) categorizes into humid class with an index value of 24.3. The driest year 1987 register lowest moisture index value of 14.4 and the wettest 33.1 during 1973. The 11-year moving average pattern suggests that the Moisture Index varied moderately around the mean during the first four decades starting 1901. During the next three decades (1950-1970), wet moisture status is maintained most of the time. The moisture condition is mostly below average since late 1970s. The moving average line nearly touched one negative standard deviation during 1997. However, the individual year's data suggest that the deviation has gone below one standard deviation frequently since late 1970s. In the first 78 years of the series, there are seven occasions on which the deviations gone below one standard deviation. The frequency of negative deviations amplified significantly since late 1970s and is counted to 12 in just 28 years suggesting dominant dry weather conditions over tropics.

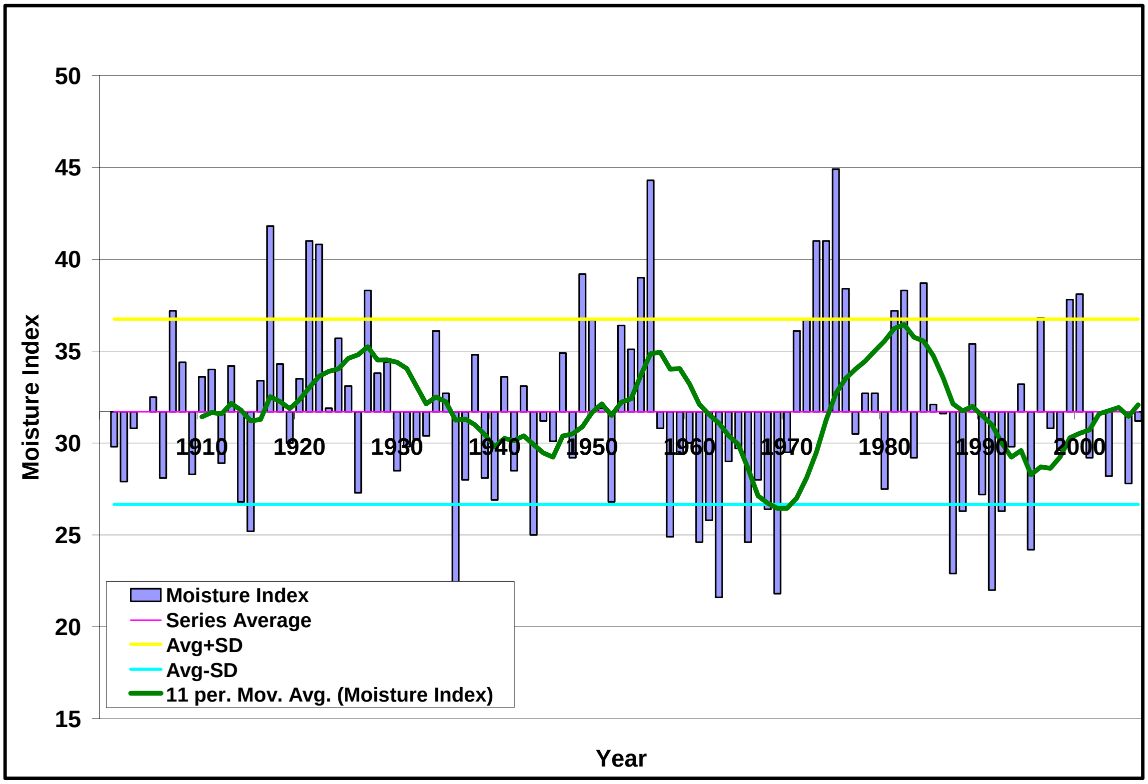
The Tropical South America is one of the highest rain zones and is blessed with dense rain forest adjacent to the equator. The moisture zones are mainly of per-humid and humid type. The overall climate status with a moisture index value of 31.7 is classified into humid category (Fig.4b). The driest and wettest years are 1963 and 1975 with an index value of 21.8 and 44.9 respectively. The 11-year moving average of Moisture Index varied moderately around mean during 1901 through mid 1950s. The 1960s are mainly dry and 1970s are wet in general. The moving average cycle amplified touching one standard deviation on the negative side during late 1960s to early 1980s on the positive side. The decade 1985-1995 is mostly dry with departures below mean. From mid 1990s the index exhibited improving trend.

The tropical Africa (Fig.4c) classifies into dry sub-humid category with an average index value of -26.5. The wettest year is 1961(-21.1) and the driest is 1983(-32.5). The distribution was close to mean till 1950 from which the amplitude of deviations magnified considerably on positive side with temporal continuity for 2 decades. The 1970s are mixed bag of departures on either side of mean followed by huge negative fluctuations with alarming frequency from 1980 onwards. The visual impression shows the distribution is unique with definite trend covering past 6 decades. During the recent 3 decades, the weather conditions are dry with alarming regularity featuring below the average moisture conditions. A very distinct feature of Africa Moisture Index is that the 11-year moving average line departed well over one standard deviation above mean during early 1960s followed by a steep fall upto mid 1990s covering 3 decades in one-go. The line has gone below mean during 1980.

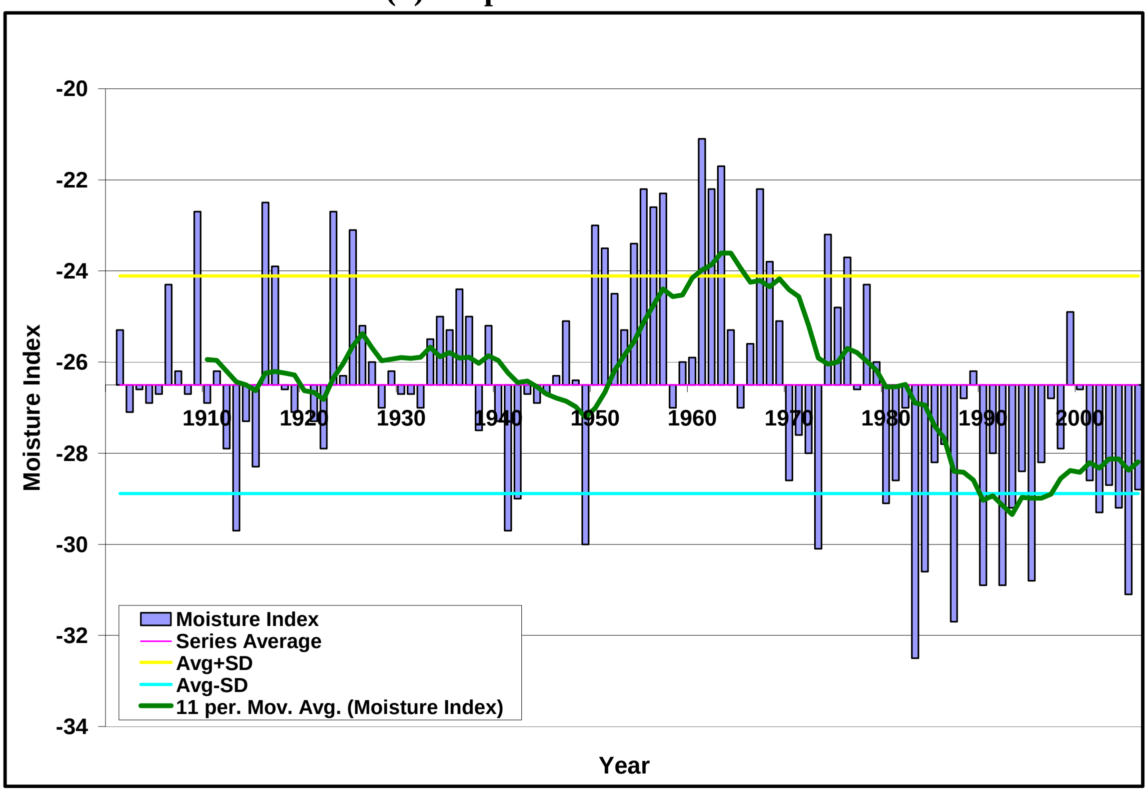



**(a) Tropics**

**Fig.4Temporal Distribution of Moisture Index**

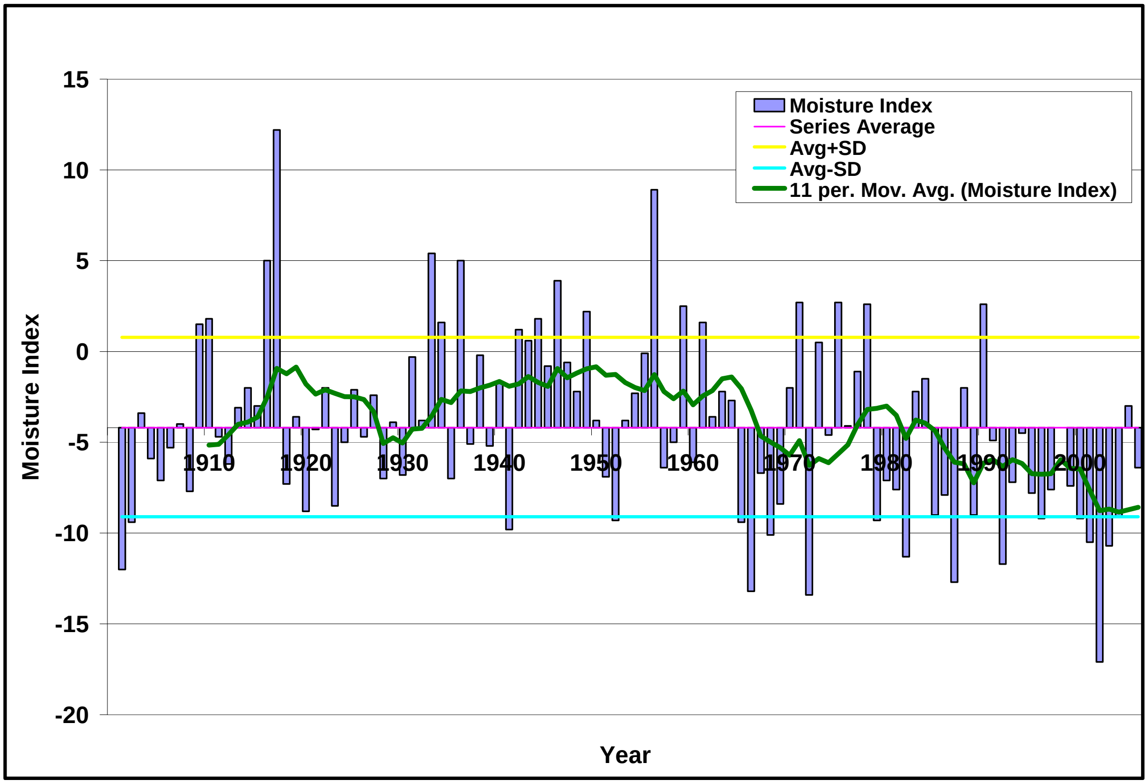



**(b) Tropical South America**

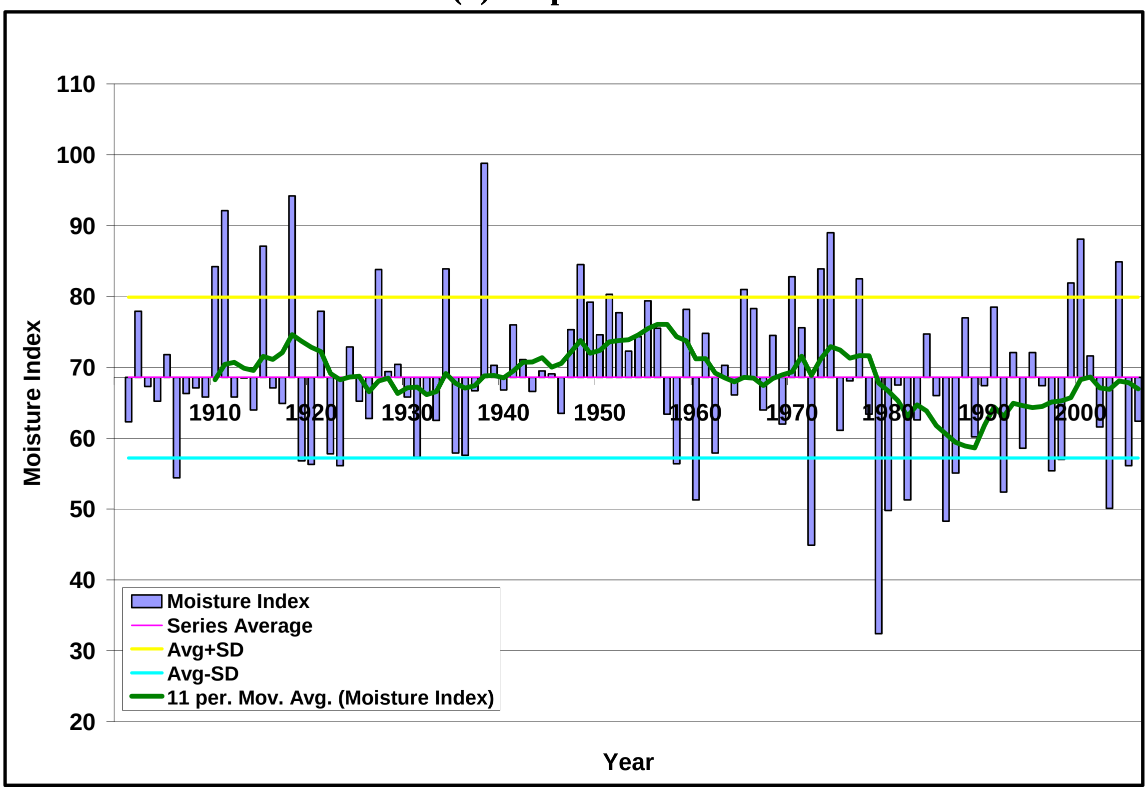



**(c) Tropical Africa**

**Fig.4 continued**

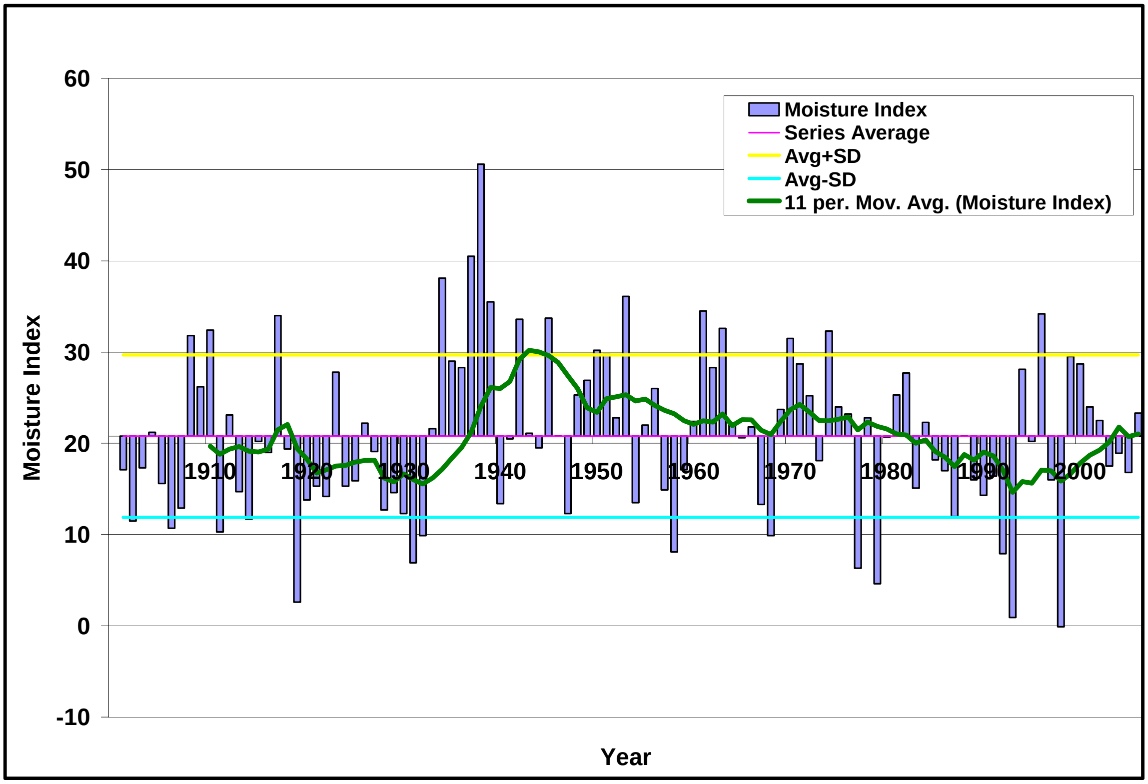



**(d) Tropical India**

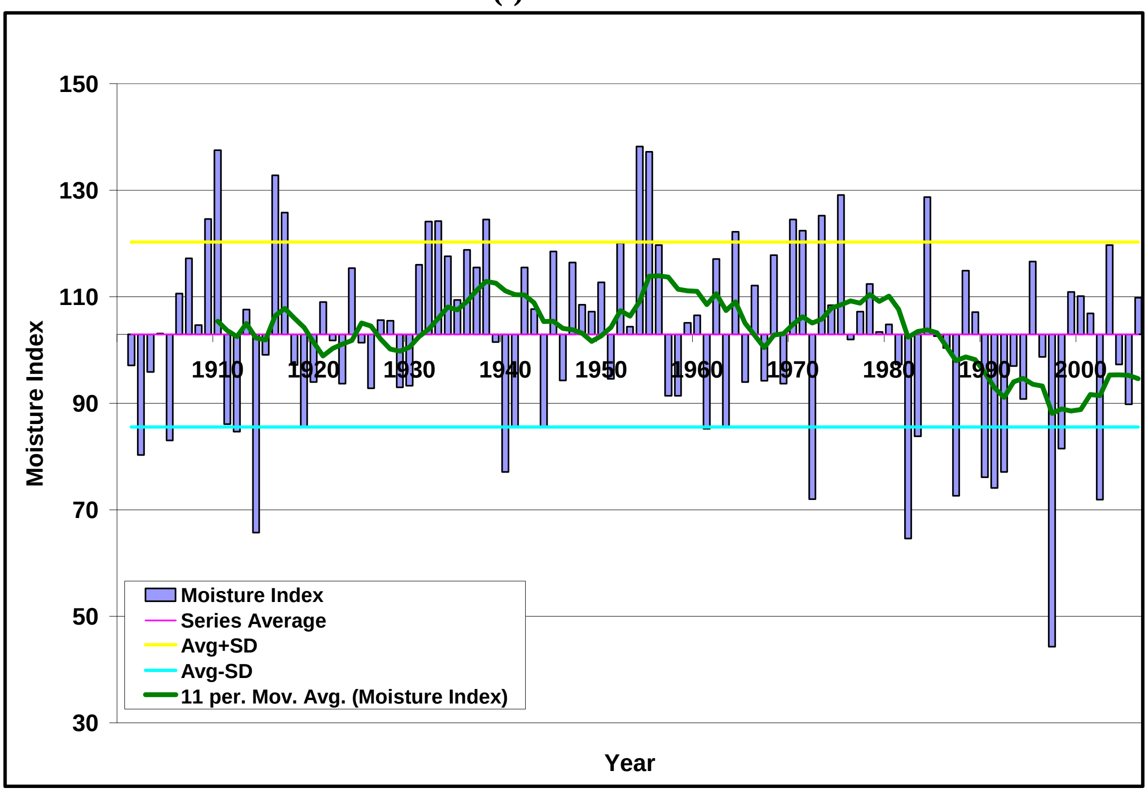



**(e) Burma**

**Fig.4 continued**

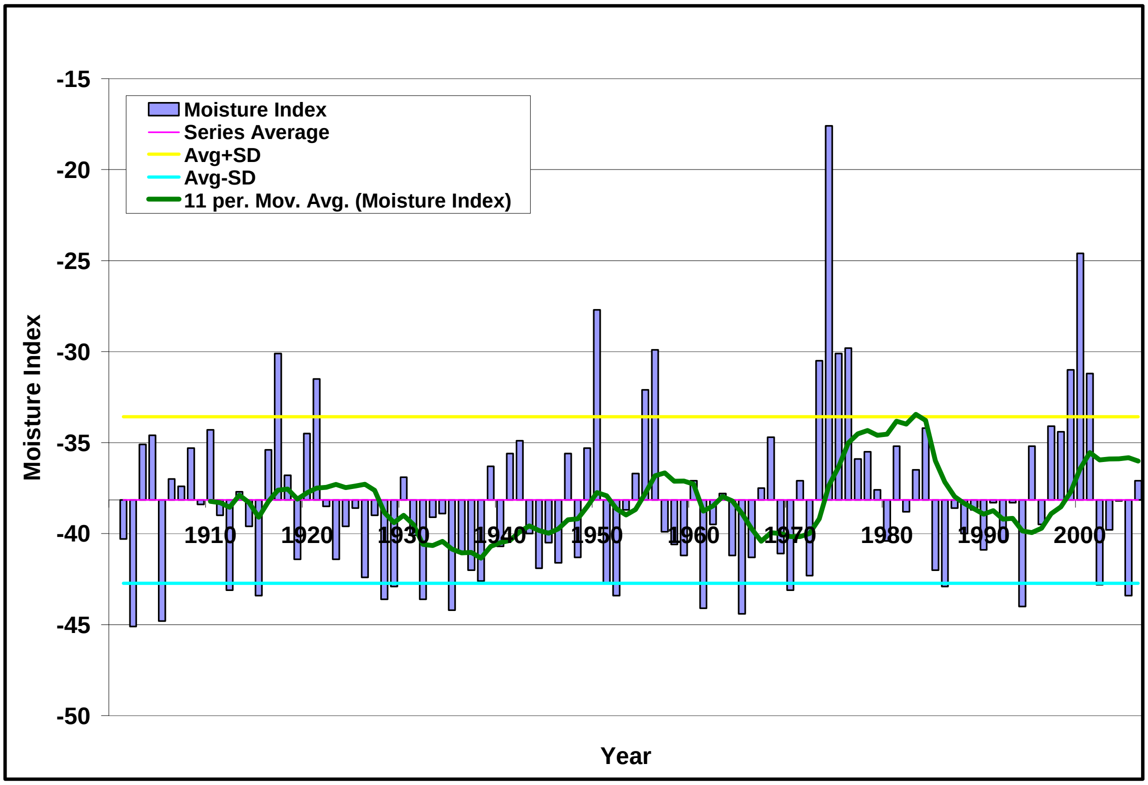



**(f) Thailand**

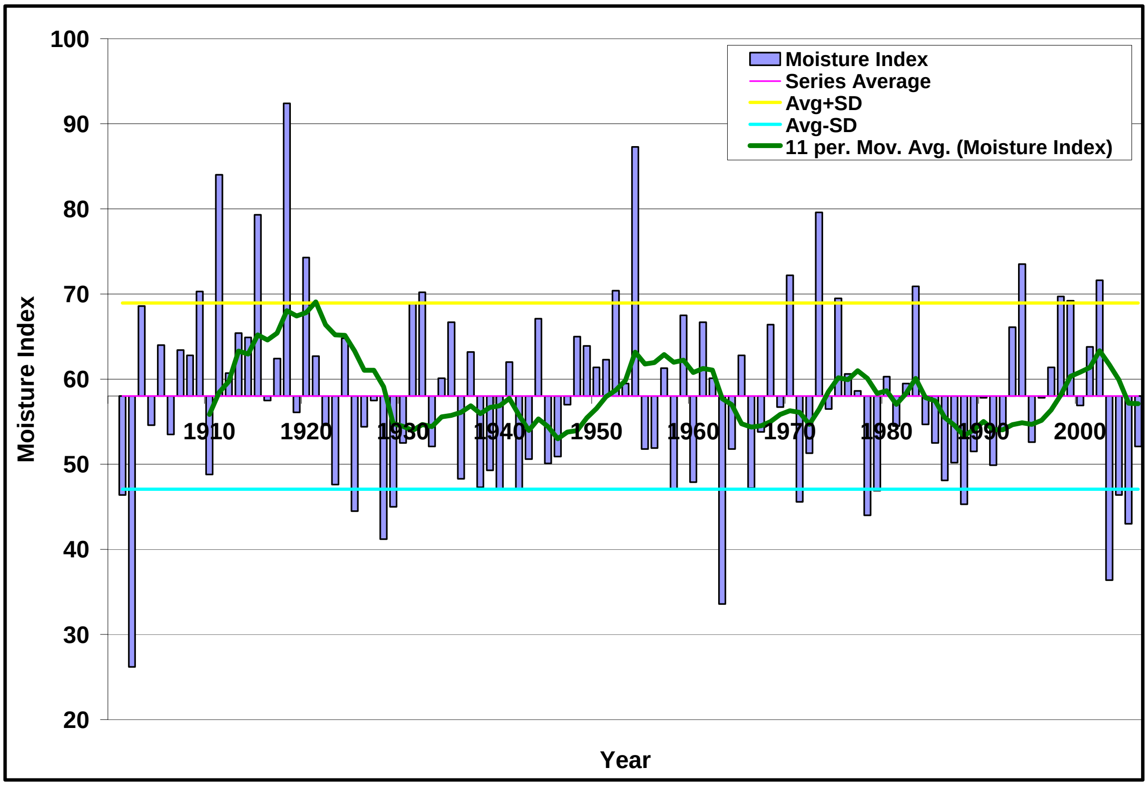



**(g) Borneo, Malaysia and Sumatra Islands**

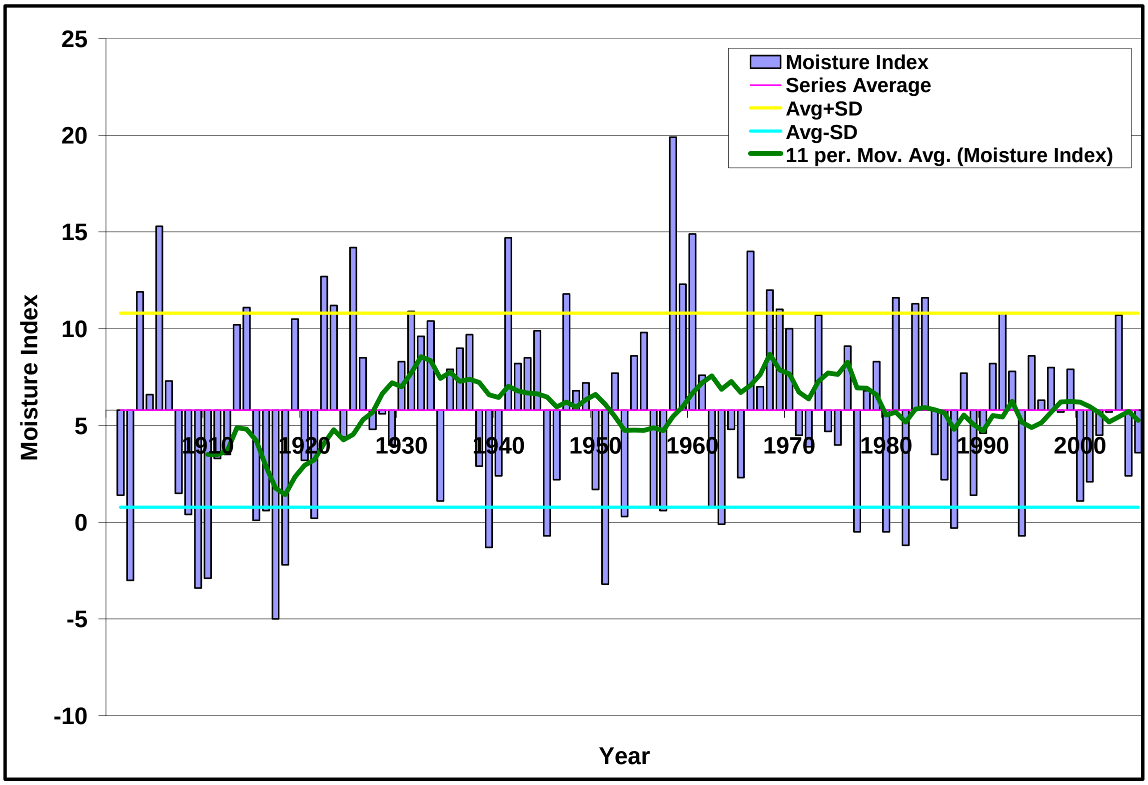
**Fig.4 continued**




(h) Tropical Australia




(i) Tropical China
Fig.4 continued




**(j) Tropical Mexico**
**Fig.4 continued**

The tropical India (sans Himalayan range) categorizes to be dry sub-humid with an index value of -4.2 (Fig.4d). The moisture index is at its lowest (-17.1) during 2002; the second lowest is -13.4 during 1972. According to India Meteorological Department (2002), the Year 1972 is the worst drought year in history of India in terms of country wide percentage departure of rainfall from the normal (-24%) whereas the drought years 1979, 1987 and 2002 are comparable with a departure of -19%. This classification is based on rainfall departure alone and thus does not truly reflect the net moisture status at the surface. The moisture index in the present work terms 2002 as the worst ever in the history of India with a departure of -12.9 from the mean relegating 1972 to second place with a departure of -9.2. The reason lies in significant rise in average temperature of the country since 1979 (discussed in Annexure-I). The countrywide temperature anomaly during 1972 was slightly below normal (0.09) whereas the year 2002 recorded positive anomaly to the tune of 0.87. Thus, the resultant evapotranspiration during 2002 dried up the soil more than that during 1972. The technique adapted in the present work assesses various indices in terms of net availability of moisture by weighing the incoming rainfall against outgoing due to evapotranspiration thereby classified 2002 as worst ever drought year in the history of India. The 11-year moving average line show a general falling trend in moisture since mid 1950s and from late 1970s the moisture status was mostly below average. The 11-year moving average line barely touched one standard deviation below mean in 2002 indicating alarming situation in the moisture status of India.

Burma classifies into humid category with an average moisture index value of 68.6 (Fig.4e). The wetness has gone down considerably during the year 1979 with the moisture index value of 32.4, a fall of 36.2 units below mean. The second worst situation occurred during 1972. The year 2002 is by far better than 1972 and 1979. The temporal distribution looks even with departures on either side of the mean through the series. But, 11-year moving average line suggests decline in moisture status from late 1970s to late 1980s. Thereafter the moisture exhibited improving trend but maintained below average.

The conspicuous features of Thailand's terrain are high mountains, a central plain, and an upland plateau. Mountains cover much of northern Thailand and extend along the Burmese border down through the Malay Peninsula. The central plain is a lowland area. The plains of Thailand categorize into dry sub-humid and the hills come under humid category. Both the classes prevail over almost equal area but the domination of high humid conditions assign humid status to the overall climate condition with an average moisture index value of 20.8. The temporal distribution of moisture index is almost similar to that of Burma. The wetness is at its worst in recent past during 1993 and 1998 (Fig.4f).

Over maritime islands BMS, situated over and around the equator, the moisture status is of highest order classifying the area to be per-humid with a value of 102.9 (Fig.4g). The temporal distribution is mostly above average till 1980 and then maintained below average status most of the years. The year 1997 is by far worst compared to any other year with an index value as low as 44.3, a fall of 58.6 units from the mean. The 11-year moving average line suggests declining moisture status since early 1980s.

The tropical Australia, classified into semi-arid category with an index value of -38.2, experienced almost opposite trend in moisture status compared to other countries in the present study. The 1970s and second half of 1990s are the wettest periods (Fig.4h). From mid 1980s to mid 1990s the moisture status is below normal. The recent past moisture is above normal.

Tropical China falls into humid category with its mean moisture index estimated to be 58.2. The 11-year moving average line suggests that the moisture status is evenly distributed around the mean since 1930s. The wettest and driest years are recorded in the first two decades of the time series. In recent past, the driest year is 2003 during which the moisture declined by 21.8 units below average.

Mexico classifies into moist sub-humid category with its mean moisture index standing at 5.8. The 11-year moving average line maintained above mean status during 1930-1980 where after average status is maintained till 2006. The departures are ideally on either side of mean in close intervals allowing the average moisture status to be stable at long term average since 1980. The driest year in the history of Mexico is 1917 followed by 1951, 1982 and 1994 but none of them experienced major departures from the normal.

## 4) Trends in Moisture Index:

### 4.1 The Decadal Variation

Decadal variation in Moisture Index with respect to long term average of 1901-2006 is shown in Fig.5.

During the first three decades starting 1901, the moisture index over the countries exhibited varying trend from each other by and large. In the next 3 decades (1931-1960) the whole of tropics and individual countries experienced above mean moisture conditions. Thereafter a tendency to fall below average is clearly demarcated for all regions. The overall scenario over tropics is below average moisture status during the last 3 decades starting with 1980s. Tropics exhibit a fall of 3 units below average during 1981-1990 and continued to remain more or less same till the end of series. The variation works out to be highest on either side of the mean in case of maritime climates BMS located over and around equator. In this region, the magnitude of deviations is much higher than other regions (countries).

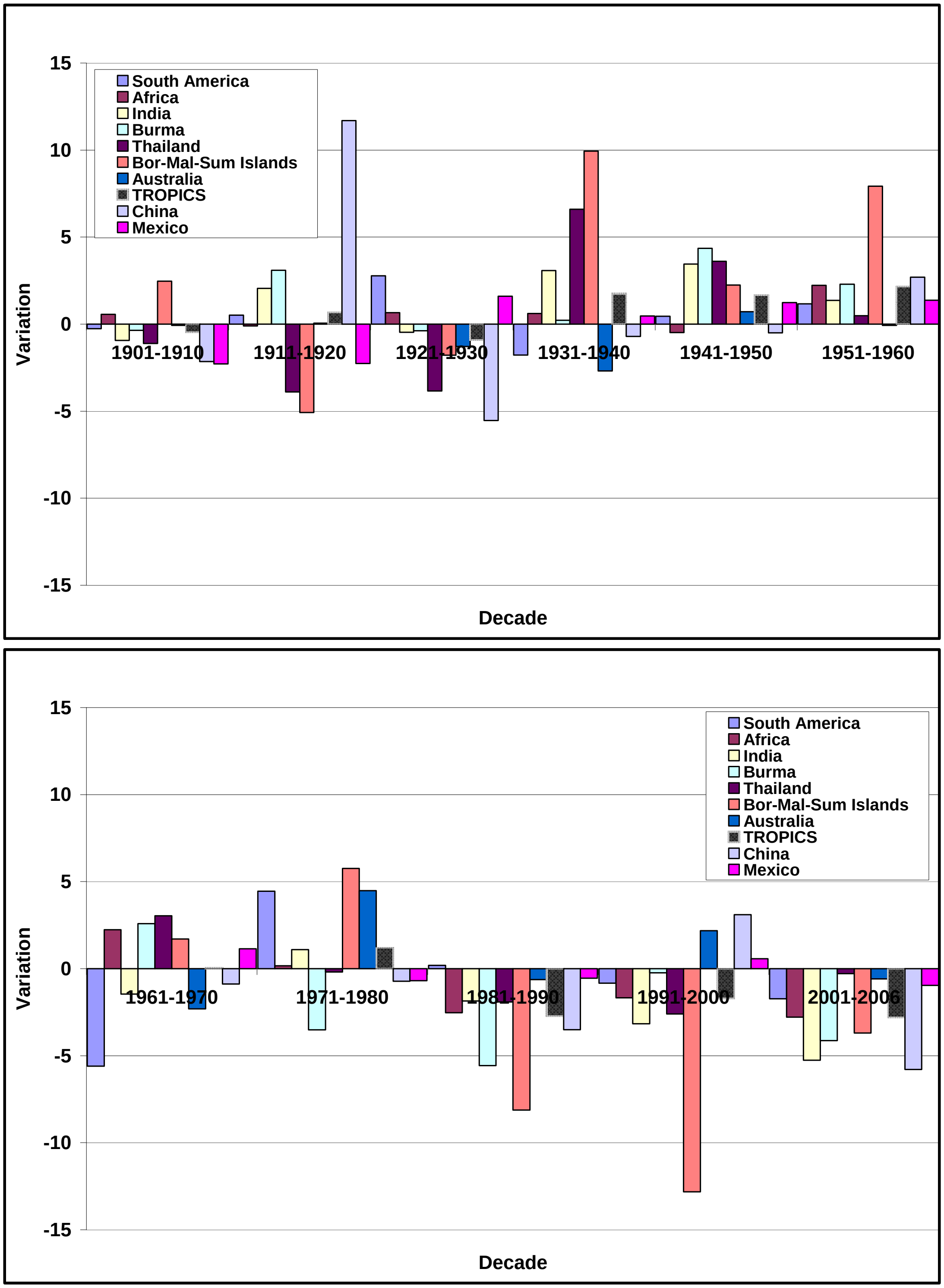



**Fig.5 Decadal Variation in Moisture Index**

**4.2 Standardized Moisture Index:**

As discussed above, the moisture index over tropics exhibited decline for long a period of three decades in recent past. In order to assess the country most vulnerable / susceptible to experience dry conditions, standardized Moisture Index is considered. The standard scores indicate how many standard deviations an observation is above or below the mean. It allows comparison of values from different normal distributions.

The standard scores have exhibited unique trend for each country up to 1950 (Fig.6). Thereafter, all counties exhibited comparable trend of moisture variation till the end of series implying prevalence of similar weather conditions over tropics from 1950 onwards. The variation is above mean or less than one standard deviation below mean till end of 1970s. A steep slump from 1980 crossed half the standard deviation below mean during mid 1990s.

The magnitude of standard scores is alike for all northern hemispheric countries except Africa over which highest amplitude to the tune of more than one standard deviation on either side of mean prevailed. All the countries experienced moisture decline to the tune of about one standard deviation (from +0.5 to -0.5) from mid 1970s until mid 1990s. The overshot trend over Africa lowered the trend over tropics to almost one SD below mean. It is inspiriting to note that the standard scores improved for all countries from the middle of 1990s. The mean deviation is becoming less and less; an indication for stabilizing/improving moisture conditions compared to preceding years. It may be noted that the standard scores of the two countries falling in southern hemisphere – the Australia and South America – have exhibited similar temporal trend and comparable standard scores.

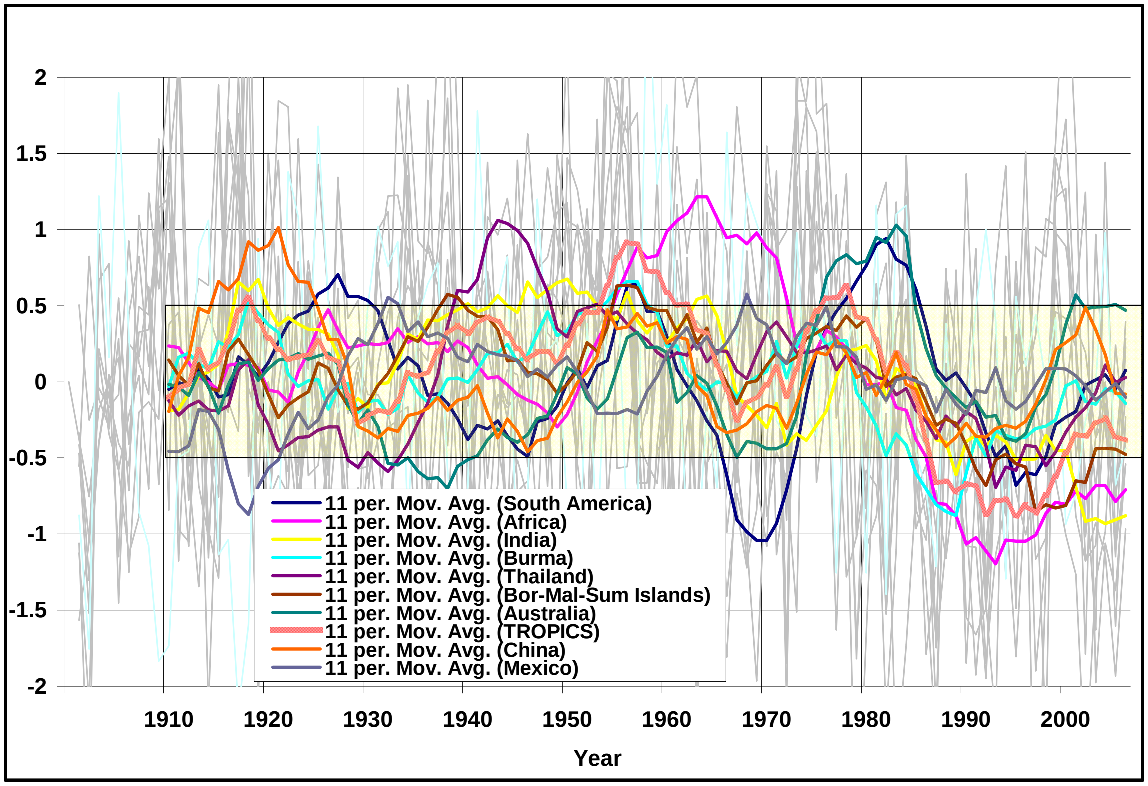



**Fig.6 Standardized Moisture Index**

### 4.3 Significant Changes in Moisture Index – The Change Point Analysis:

Change-point analysis is a powerful new tool for determining trend change in a time series. It is capable of detecting subtle changes missed by control charts. The technique used in this work is based on the procedure adapted by Taylor (2000). The analysis interactively uses a combination of cumulative sum charts and bootstrapping to detect changes. The cumulative sums (CuSum) are the cumulative sums of the difference between value and the average and hence an upward slope indicates a period when the values tend to be above overall average and vice versa. A shift in the direction of CuSum indicates a shift or change in the average. The confidence level for apparent change can be determined by performing bootstrap analysis that does not mimic the behavior of CuSum if change has occurred. Once change is detected, the time of change can be estimated using mean square error estimator in which the data is split into two segments and the averages and MSEs are worked out for the two separately. An iterative process continues till the minimum MSE is reached. The last value of the split series that estimate minimum MSE shows the time of change.

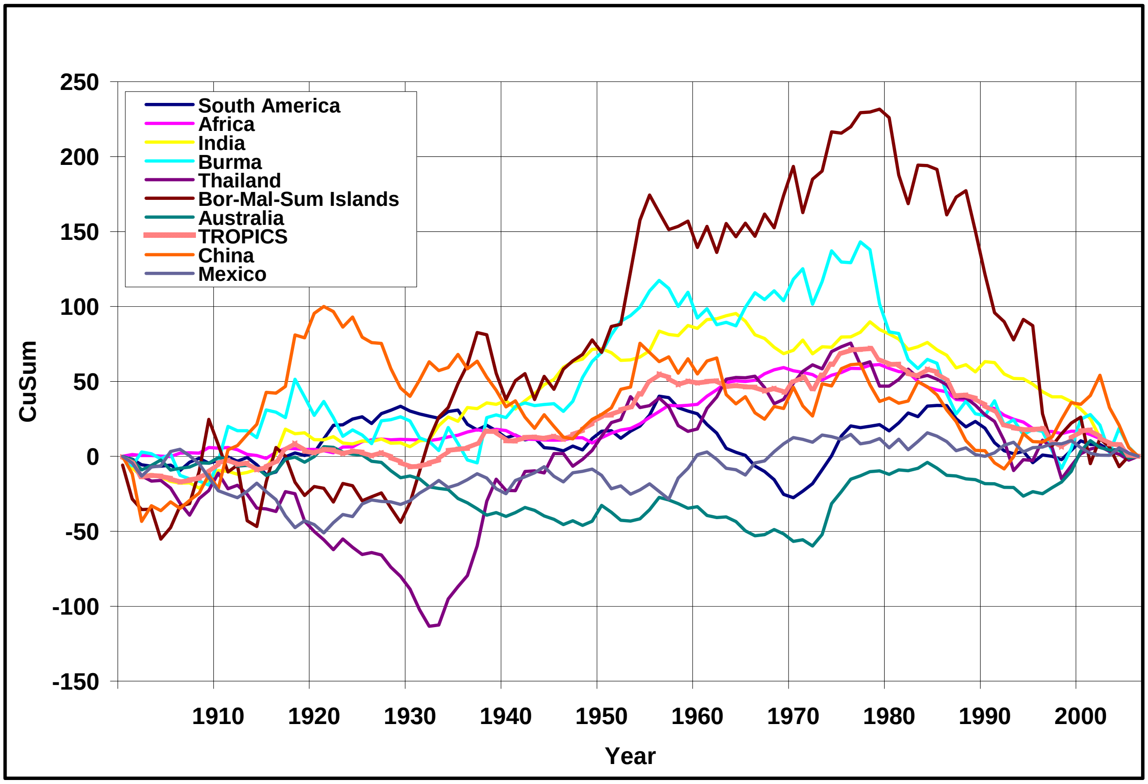



**Fig.7 Change Point Analysis**

Change point analysis is carried out for the average Moisture Index of all selected countries and is shown in Fig.7.

The trend in CuSum is similar for Australia and South America but different from other countries over which a clear rising trend in CuSum suggests that the Moisture Index was on rise from mid 1940s till late 1970s. The fall thereafter continued till mid 1990s followed by mild revival to end at zero in the year 2006. The maritime climate islands BMS and Burma experienced highest positive variations whereas the southern hemispheric areas – Australia and South America – dominated negative variations during 1960s suggesting a reverse trend.

In order to study the statistical significance of the variations and the apparent steep fall in CuSum from late 1970s, further analysis for each the selected countries is carried out setting the confidence level to 90%, confidence interval to 99% with 1000 bootstraps and without replacement mean square error (MSE) estimates. The upper and lower control limits are fixed following the principles of normal distribution (for normally distributed statistics, the area bracketed by the control limits will on average contain 99.73% of all the plot points on the chart).

The charts in the following sections show temporal distribution of Moisture Index and CuSum. The yellow color shaded area indicates the two years during which statistically significant changes have occurred.

***TROPICS:***

The CuSum chart for tropics shows that a statistically significant change in Moisture Index has occurred during 1979 (Fig.8a). The change is predicted at 100% confidence level (Table 1a). The mean moisture index is maintained at 25.1 till 1979 but fallen to 21.9, a drop of 2.4 units from its long term mean. The change continued through the time series for the past 27 years. The change is not immediately visible but occurred at level 4.

***TROPICAL SOUTH AMERICA:***

Three changes occurred during 1958, 1971 and 1977 (Fig.8b). The second change is pin pointed with zero confidence interval and 100% confidence level (Table 1b). The moisture index is improved by 13.1 units over a span of 6 years between 1971 and 1977. During 1977-2006 a fall of 8.7 units occurred at 96% confidence. The fall continued through the time series for past 29 years. It may be noted that the apparent fall after 1977 leveled the moisture status with the long term mean and thus nullified the advantage gained during 1971-1977.

***TROPICAL AFRICA:***

Africa had undergone two changes in moisture status, one in 1950 and the other in 1980 (Fig.8c). First change in not clearly visible but the second one is most visible (level 1) and supplemented by maximum confidence and narrow confidence interval (Table 1c) The first 50 years of the series maintained -26.3 units of moisture. The first change improved the condition marginally to -24.8 over thirty years. During 1980-2006, the average moisture status has fallen to -28.8, a drop of 4 units from previous high and a drop of 2.3 units from long term average. The continued fall for 26 years appear to be serious as the most visible changes are said to be certain.

***TROPICAL INDIA:***

The moisture status over India exhibited two changes of descent (Fig.8d). Both the changes have occurred at level 1 with 98% confidence in 1965 and 92% confidence in 1992 (Table 1d). From 1965, the moisture status is dropped to -5.4 in 27 years. The average dropped further to -8.4 in the last 14 years. The moisture decline has started in 1965 itself although the statistical significance segregates the change into two stages of drop by 2.7 and 3.0 units. The most recent and continued change is -4.2 units in comparison to long term average.

***BURMA:***

The Burma region (Fig.8e) exhibited no statistically significant changes in its moisture status during 1901-2006 and the prevailing climate is classified to humid category with an index value of 68.6.

***THAILAND:***

Thailand with an average moisture index of 20.8 experienced two significant changes in its moisture status way back in 1933 and 1940 (Fig.8f). No change has occurred in recent past as the case with Burma. During the first change, detected with 99% confidence at level 1, the moisture status rose to 34.8 from 17.2 and then dropped to 21.0 after second change at level 3 (Table 1f). In the last 66 years of the series (1940-2006) the moisture index is maintained at it long term average.

***BORNEO, MALAYSIA AND SUMATRA ISLANDS:***

The maritime climates that exist over and around the equator undergone a single change in average moisture status during 1981 (Fig.8g). The change has occurred 25 years ago at level 1 with 94% confidence as a result of which the moisture status declined by 14.8 units from 105.8 to 94.0. The decline is -8.9 compared to long term average (Table 1g).

***TROPICAL AUSTRALIA:***

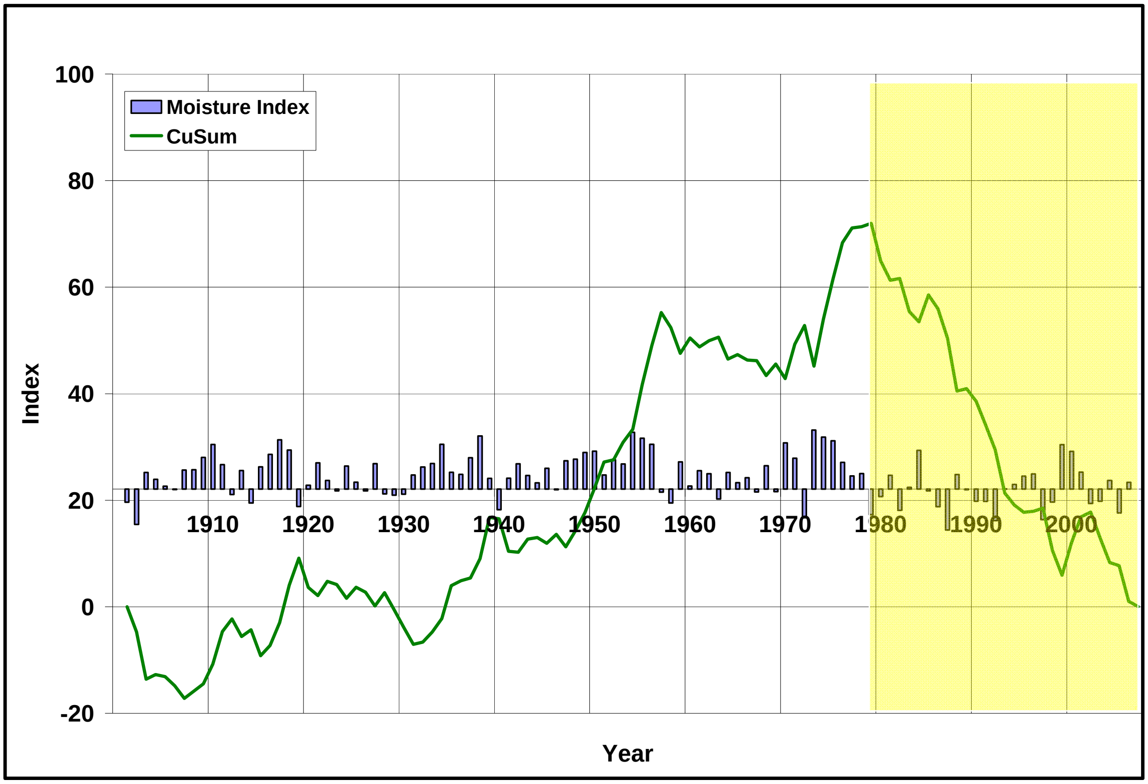
Australia (Fig.8h) experienced 4 changes in moisture status since 1970. The moisture status alternated during the 4 changes occurred in 1973, 1977, 1997 and 2002. The most recent change that occurred barely 4 years ago was pin pointed at zero confidence interval with 92% confidence limit. The moisture drop is a high -9.3 units from immediately previous high (Table 1h). However, the drop is a mere -2.1 units compared to long term average of -38.2.

***TROPICAL CHINA:***

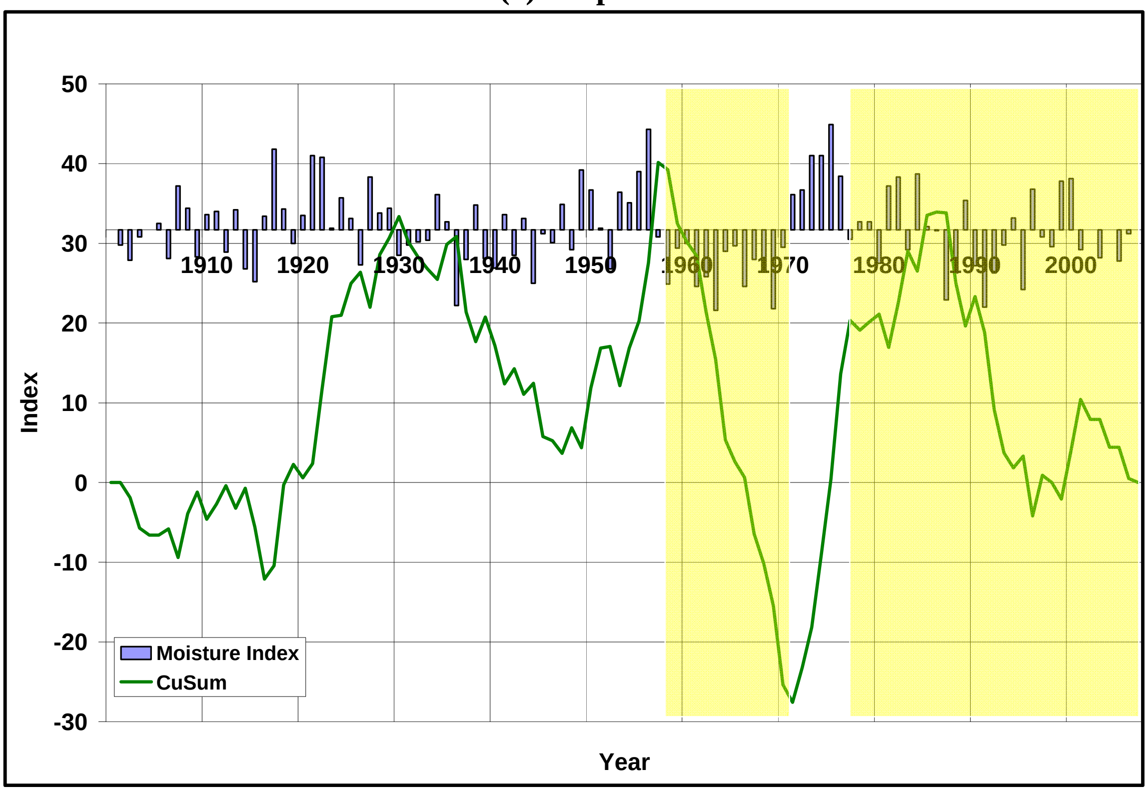
The change point analysis does not suggest any statistically significant changes in the moisture status of China during 1901-2006 (Fig.8i, Table 1i).

***TROPICAL MEXICO:***

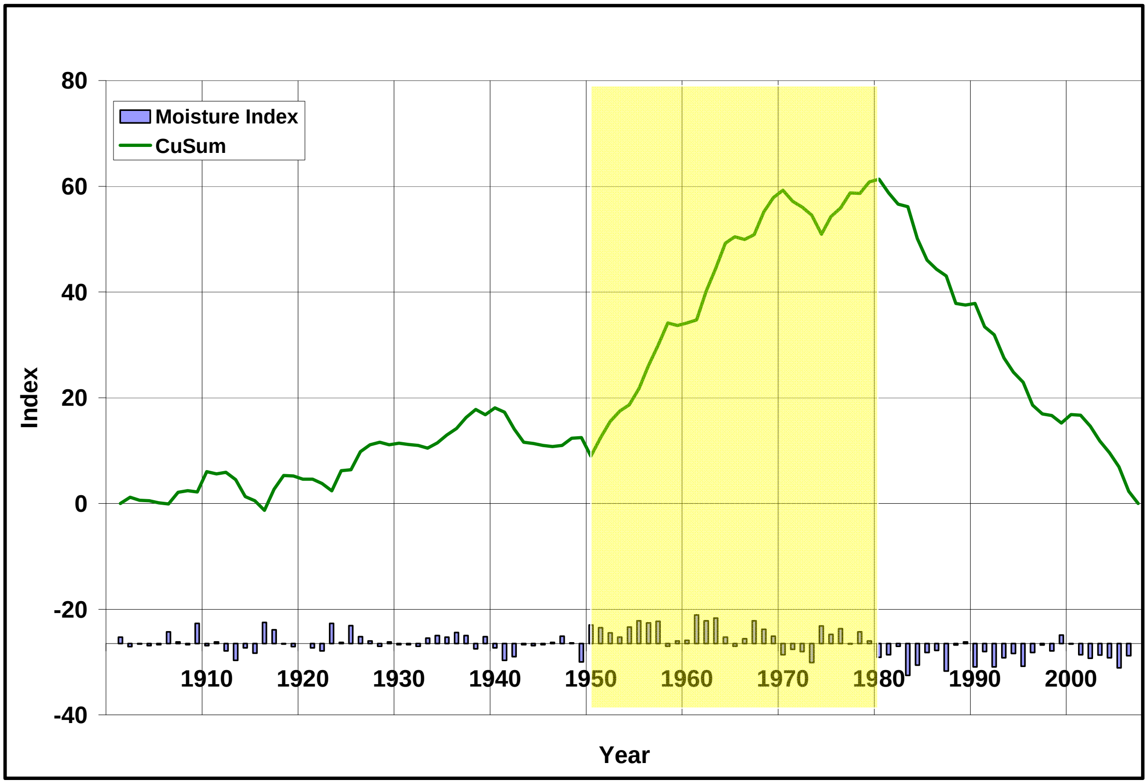
As is the case with China, the change point analysis does not suggest any statistically significant changes in the moisture status of Mexico during 1901-2006 (Fig.8j, Table 1j).



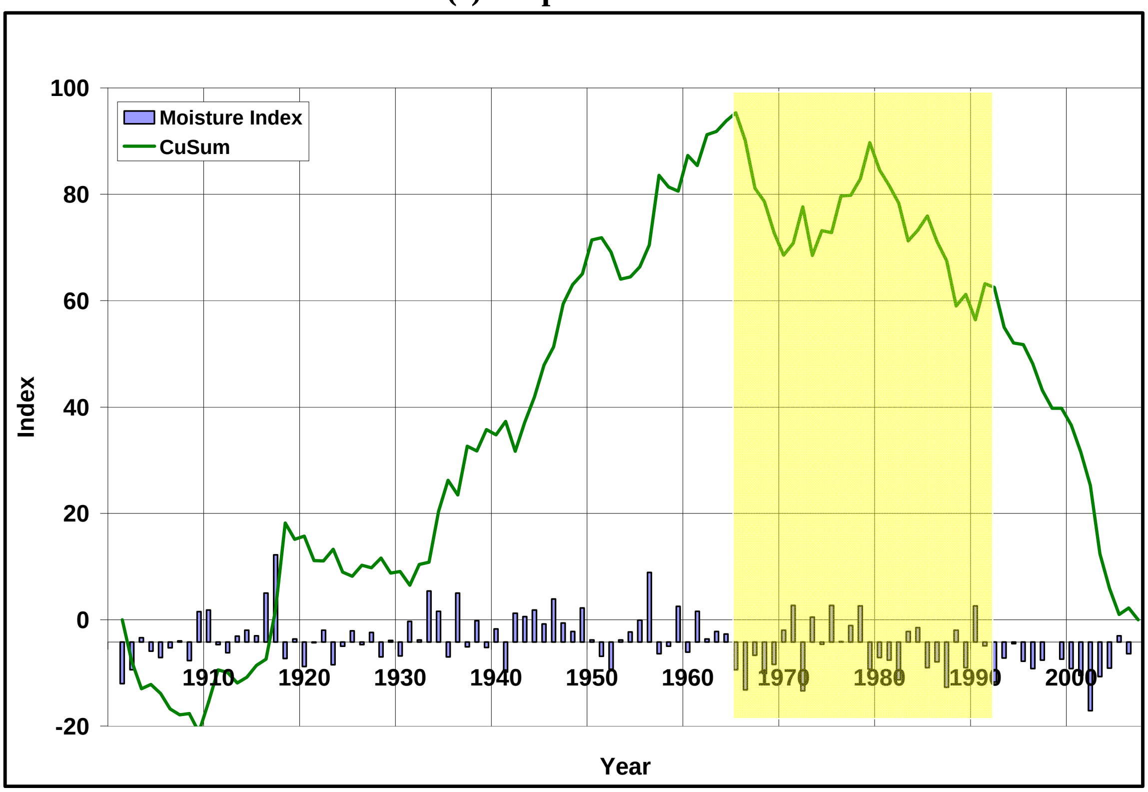

(a) Tropics



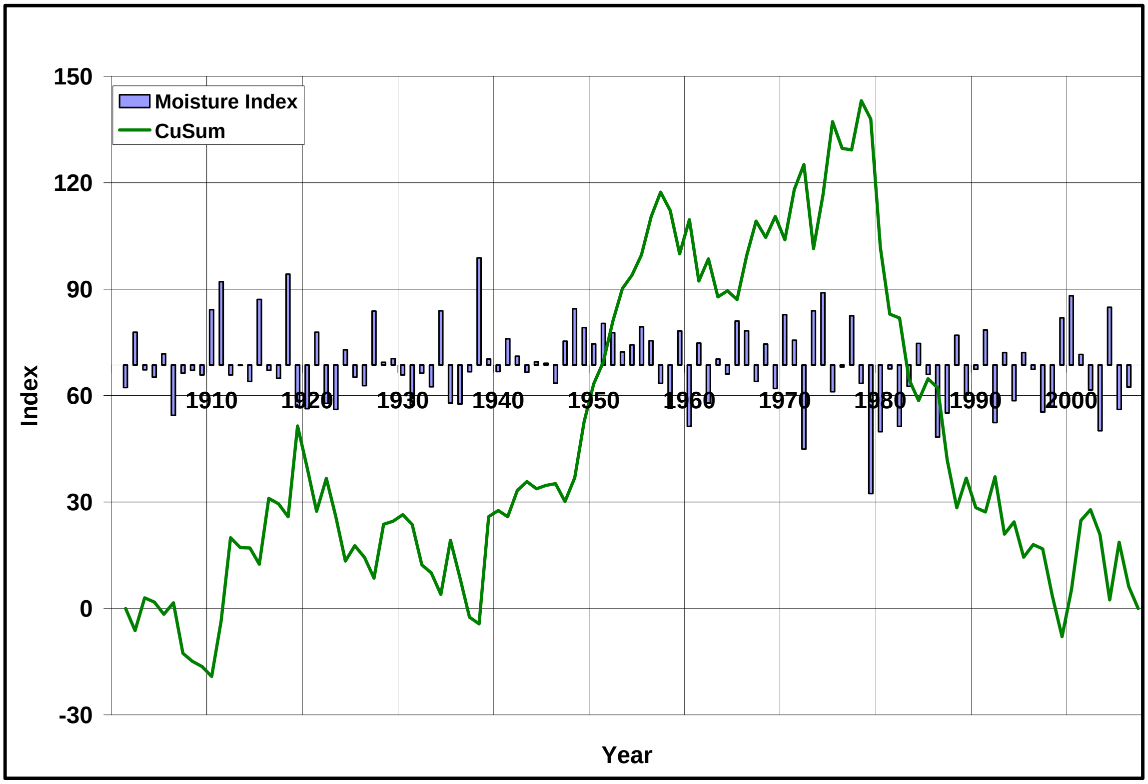

(b) Tropical South America
Fig.8 Change Point Analysis



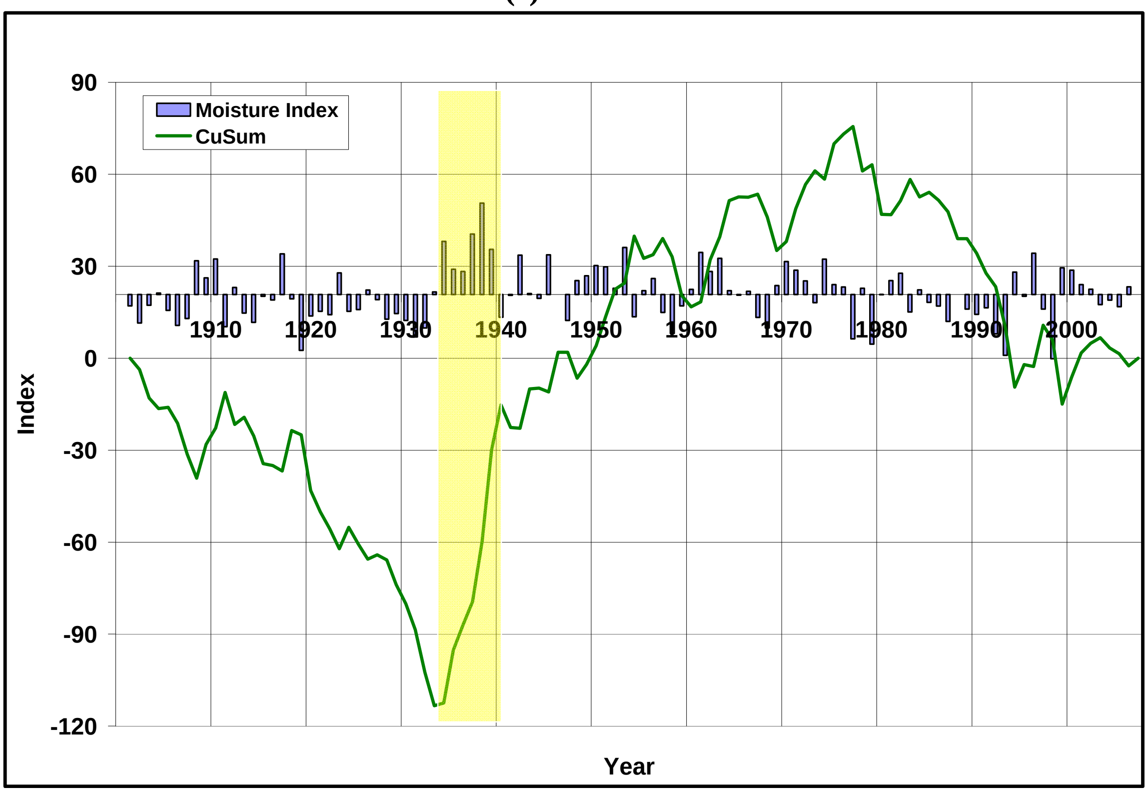

(c) Tropical Africa




(d) Tropical India
Fig.8 continued

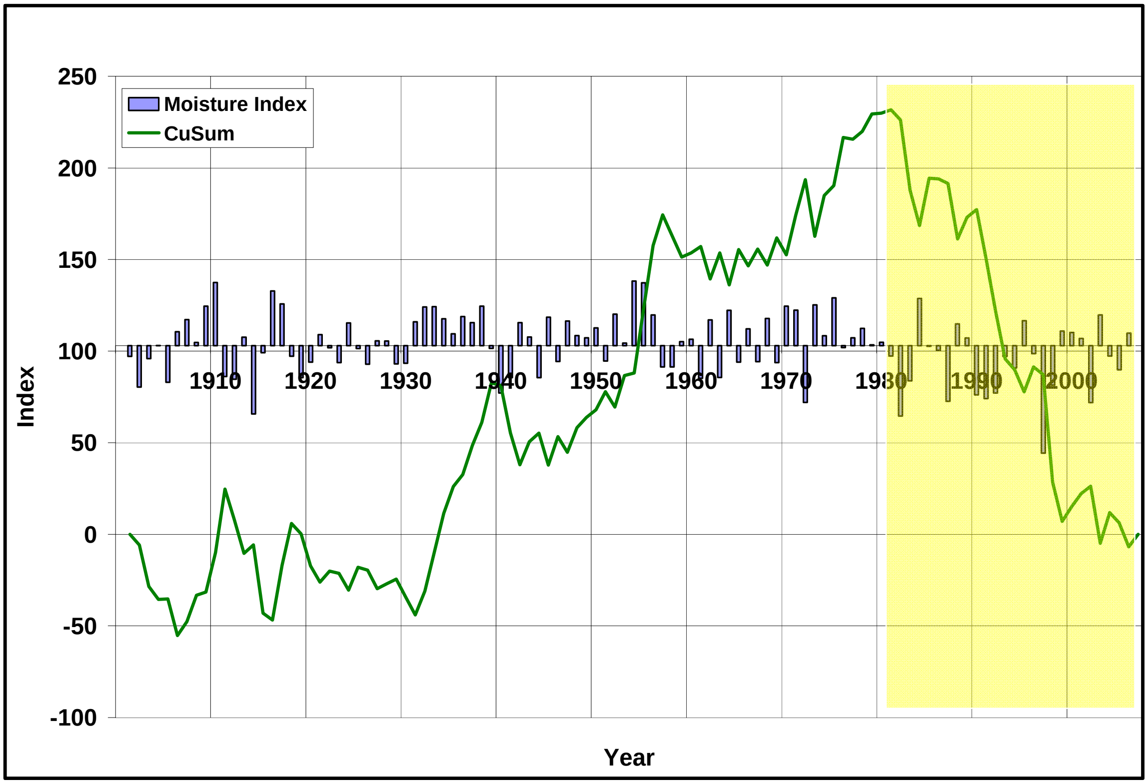



(e) Burma

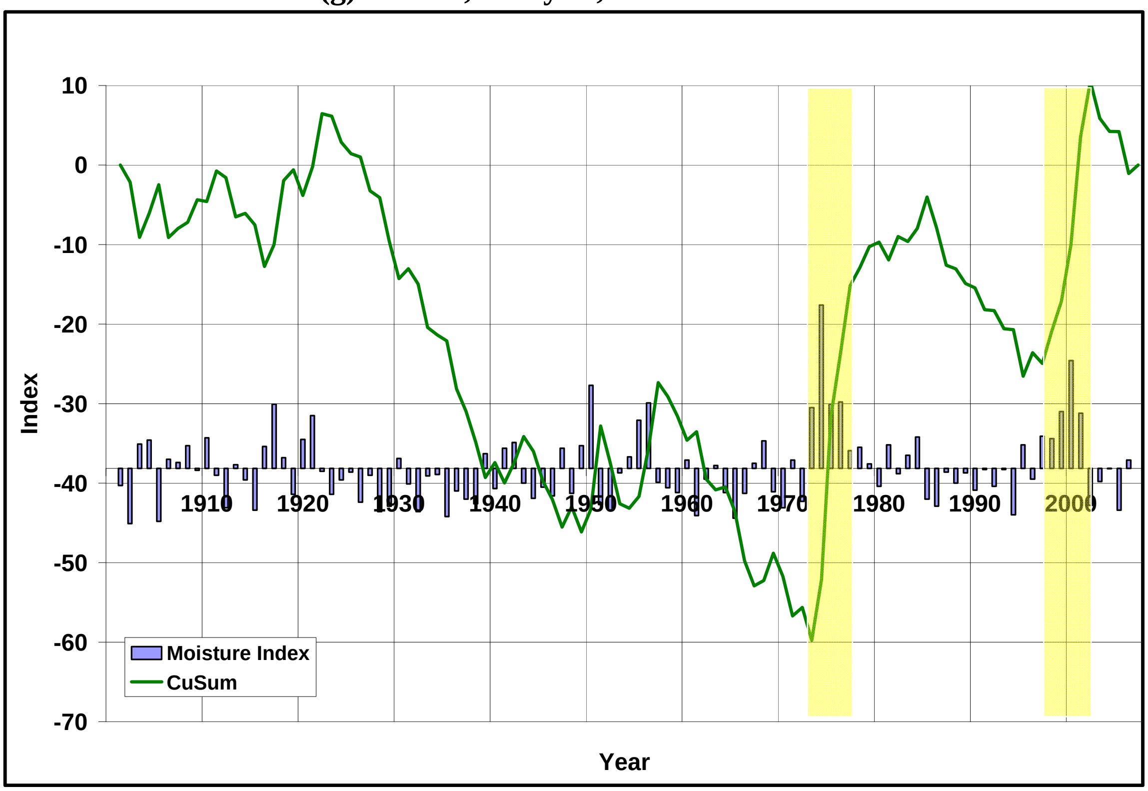



(f) Thailand

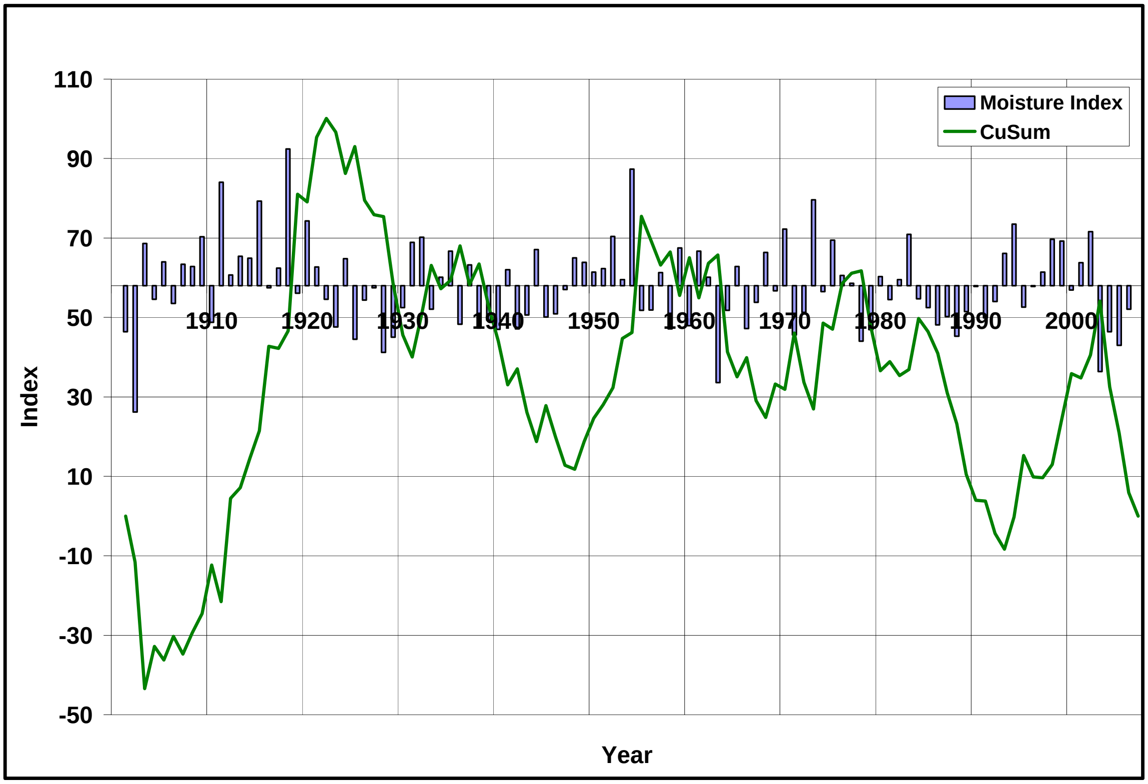
Fig.8 continued



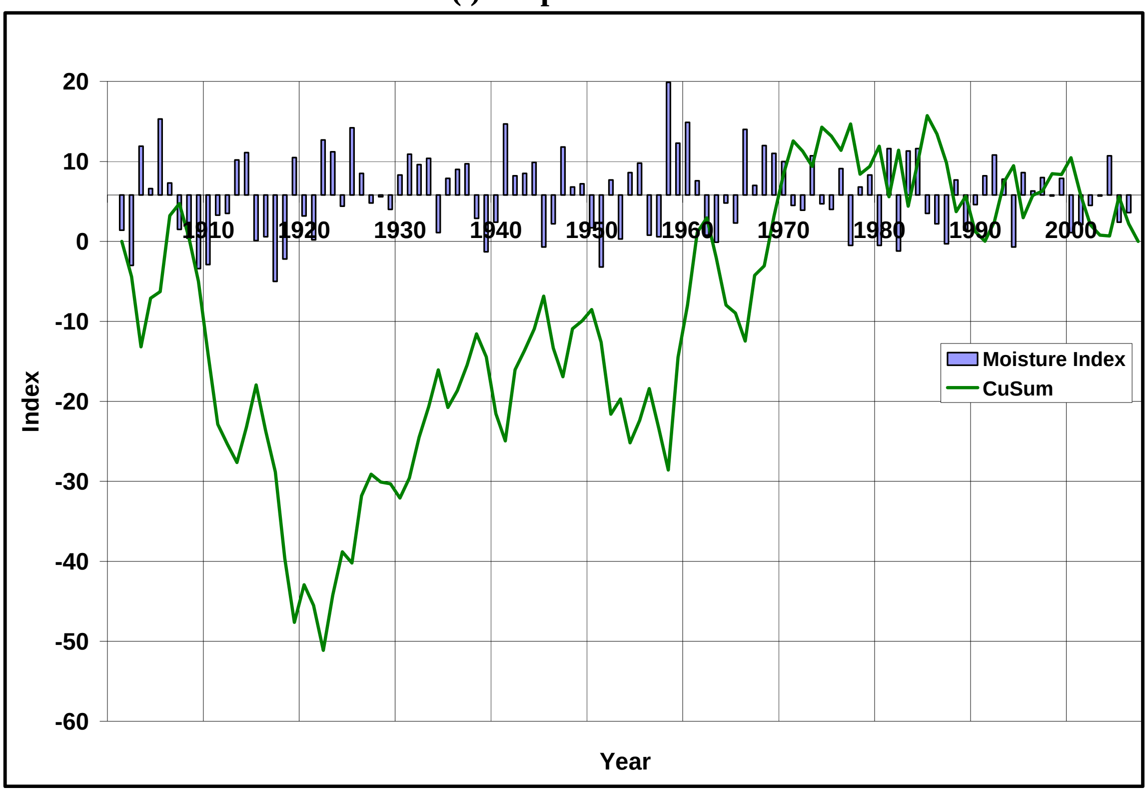

(g) Borneo,Malaysia,Sumatra Islands




(h) Tropical Australia
Fig.8 continued




(i) Tropical China




(j) Tropical Mexico

Fig.8 continued

## a) Tropics

| Year | Conf. Interval | Conf. Level | From | To | Level |
|---|---|---|---|---|---|
| 1979 | (1963,1993) | 100% | 25.1 | 21.9 | 4 |

## b) Tropical South America

| Year | Conf. Interval | Conf. Level | From | To | Level |
|---|---|---|---|---|---|
| 1958 | (1949,1960) | 99% | 32.4 | 26.6 | 5 |
| 1971 | (1971,1971) | 100% | 26.6 | 39.7 | 2 |
| 1977 | (1977,1981) | 96% | 39.7 | 31.0 | 3 |

## c) Tropical Africa

| Year | Conf. Interval | Conf. Level | From | To | Level |
|---|---|---|---|---|---|
| 1950 | (1935,1969) | 100% | -26.3 | -24.8 | 6 |
| 1980 | (1976,1982) | 100% | -24.8 | -28.8 | 1 |

## d) Tropical India

| Year | Conf. Interval | Conf. Level | From | To | Level |
|---|---|---|---|---|---|
| 1965 | (1903,1986) | 98% | -2.7 | -5.4 | 1 |
| 1992 | (1968,2004) | 92% | -5.4 | -8.4 | 1 |

## e) Burma

**Significant changes are not found**

## f) Thailand

| Year | Conf. Interval | Conf. Level | From | To | Level |
|---|---|---|---|---|---|
| 1933 | (1931,1935) | 99% | 17.2 | 34.8 | 1 |
| 1940 | (1936,1945) | 95% | 34.8 | 21.0 | 3 |

## g) Borneo, Malaysia, Sumatra Islands

| Year | Conf. Interval | Conf. Level | From | To | Level |
|---|---|---|---|---|---|
| 1981 | (1950,2003) | 94% | 105.8 | 94.0 | 1 |

## h) Tropical Australia

| Year | Conf. Interval | Conf. Level | From | To | Level |
|---|---|---|---|---|---|
| 1973 | (1971,1973) | 94% | -39.0 | -27.0 | 2 |
| 1977 | (1977,1977) | 100% | -27.0 | -38.6 | 4 |
| 1997 | (1995,1997) | 100% | -38.6 | -31.0 | 5 |
| 2002 | (2002,2002) | 92% | -31.0 | -40.3 | 4 |

## i) Tropical China

**Significant changes are not found**

## j) Tropical Mexico

**Significant changes are not found**

**Table 1: Data Showing Statically Significant Changes in moisture index**

## 4.4 Regional Variation in Moisture Classes:

The variation exhibited by the 6 classified climates over the nine countries considered in the present study is discussed in this section. The scores as per change point analysis for each climate type and for each country are shown in Table.2. The minus sign indicates no score or non-existence of particular climate type.

The tropics as a whole experienced statistically significant change during 1979 where from the moisture status started to drop below long term average (Table 1a). The per-humid climates, symbolic of rain forest regions with very high moisture status, demonstrated change occurred during 1977 at level 1 (most visible) with as high as 98% confidence (Table 2a). The humid climates, second in moisture richness, suggested change in 1978, with 100% confidence but at level 4. During 1979, both the moist and dry sub-humid categories experienced level 1 change with more than 94% confidence. The semi-arid climates did not undergo any significant change during entire length of data series but arid climate did show a level 2 change with 92% confidence as far back as in 1945. Overall it could be stated that moisture decline over tropics is decisive for all but arid climates in late 1970s.

Over South America the most recent change in moisture status occurred during 1977 (Table 1b). Humid is the only type of climate that showed change during 1977 at 90% confidence with a drop of 12 units (Table 2b). The moisture over per-humid climates did not show significant change during entire period of study. The sub-humid climates (C2 and C1) too dropped but much later in 1986. Thus, the overall change occurred in 1977 is mainly due to change in the humid climates occupying 49% of South America (Annexure-III).

Africa exhibited decline with 100% confidence at level 1 during 1980 (Table 1c). A drop of 14 units in per-humid climate took place starting 1976 (Table 2c) but the area affected was mere 0.9%. All the remaining climates dropped in moisture status after 1980 with more than 90% confidence. Thus the major rain bearing area of Africa (43% covering B, C2, C1 types) has suffered moisture drop since 1980.

The statistically significant decline in moisture status over India has occurred in 1992 in recent past (Table 1d). None of the individual climate experienced change during the same period (Table 2d) and this can be attributed to the vagaries of monsoon over India. Per-humid climates did show decline with a huge drop of 56 units at 91% confidence during 1979.

Burma did not undergo any change in overall moisture status (Table 1e). The per-humid and moist sub-humid types suffered marginally around 1979 (Table 2e).

Thailand is steady in its moisture status ever since 1940 (Table 1f). No significant changes in any climate took place in recent past (Table 2f).

The moisture decline over BMS islands is most visible having occurred at level 1 with 94% during 1981 (Table 1g). The islands, over which no dry climate categories exist, declined in all three humid categories at a minimum of 93% confidence (Table 2g). The decline in A and B climates (98% of area) started around 1980. The timing and the changes more or less matches with similar features seen over Africa, South America and India.

***a) TROPICS***

| CATEGORY | YEAR | FROM | TO | LEVEL | CONF. |
|---|---|---|---|---|---|
| A | 1977 | 149.9 | 140.4 | 1 | 98 |
| B | 1978 | 56.0 | 48.5 | 4 | 100 |
| C2 | 1979 | 16.8 | 9.4 | 1 | 94 |
| C1 | 1979 | -13.3 | -15.6 | 1 | 100 |
| D | - | - | - | - | - |
| E | 1945 | -155.5 | -157.4 | 2 | 92 |

***b) TROPICAL SOUTH AMERICA***

| CATEGORY | YEAR | FROM | TO | LEVEL | CONF. |
|---|---|---|---|---|---|
| A | - | - | - | - | - |
| B | 1977 | 61 | 49 | 3 | 90 |
| C2 | 1986 | 17 | 10 | 1 | 100 |
| C1 | 1987 | -10 | -14 | 3 | 95 |
| D | - | - | - | - | - |
| E | - | - | - | - | - |

***c) TROPICAL AFRICA***

| CATEGORY | YEAR | FROM | TO | LEVEL | CONF. |
|---|---|---|---|---|---|
| A | 1976 | 131 | 117 | 1 | 96 |
| B | 1980 | 38 | 32 | 3 | 91 |
| C2 | 1980 | 15 | 7 | 1 | 100 |
| C1 | 1980 | -16 | -20 | 1 | 99 |
| D | 1980 | -52 | -54 | 3 | 93 |
| E | 1946 | -156 | -157 | 2 | 93 |

***d) TROPICAL INDIA***

| CATEGORY | YEAR | FROM | TO | LEVEL | CONF. |
|---|---|---|---|---|---|
| A | 1979 | 194 | 138 | 3 | 91 |
| B | 1965 | 62 | 54 | 1 | 100 |
| C2 | 1950 | 14 | 7 | 1 | 100 |
| C1 | 1964 | -12 | -17 | 1 | 100 |
| D | - | - | - | - | - |
| E | - | - | - | - | - |

**Table 2: Change Point Analysis Scores for Different Climates**

***e) BURMA***

| CATEGORY | YEAR | FROM | TO | LEVEL | CONF. |
|---|---|---|---|---|---|
| A | 1978 | 178 | 162 | 1 | 93 |
| B | - | - | - | - | - |
| C2 | 1979 | 14 | 9 | 3 | 91 |
| C1 | 1999 | -9 | -5 | 2 | 96 |
| D | - | - | - | - | - |
| E | - | - | - | - | - |

***f) THAILAND***

| CATEGORY | YEAR | FROM | TO | LEVEL | CONF. |
|---|---|---|---|---|---|
| A | 1940 | 211 | 140 | 2 | 92 |
| B | 1954 | 61 | 47 | 3 | 98 |
| C2 | 1932 | 6 | 14 | 1 | 94 |
| C1 | - | - | - | - | - |
| D | - | - | - | - | - |
| E | - | - | - | - | - |

***g) BORNEO, MALAYSIA, SUMATRA ISLANDS***

| CATEGORY | YEAR | FROM | TO | LEVEL | CONF. |
|---|---|---|---|---|---|
| A | 1981 | 154 | 139 | 1 | 96 |
| B | 1982 | 63 | 54 | 1 | 94 |
| C2 | 1990 | 22 | 12 | 3 | 93 |
| C1 | - | - | - | - | - |
| D | - | - | - | - | - |
| E | - | - | - | - | - |

***h) TROPICAL AUSTRALIA***

| CATEGORY | YEAR | FROM | TO | LEVEL | CONF. |
|---|---|---|---|---|---|
| A | - | - | - | - | - |
| B | - | - | - | - | - |
| C2 | - | - | - | - | - |
| C1 | - | - | - | - | - |
| D | 1997 | -45 | -42 | 4 | 91 |
| E | - | - | - | - | - |

***i) TROPICAL CHINA***

| CATEGORY | YEAR | FROM | TO | LEVEL | CONF. |
|---|---|---|---|---|---|
| A | - | - | - | - | - |
| B | - | - | - | - | - |
| C2 | - | - | - | - | - |
| C1 | - | - | - | - | - |
| D | - | - | - | - | - |
| E | - | - | - | - | - |

**Table 2 Continued**

***j) TROPICAL MEXICO***

| CATEGORY | YEAR | FROM | TO | LEVEL | CONF. |
|---|---|---|---|---|---|
| A | 1971 | 191 | 168 | 1 | 100 |
| B | - | - | - | - | - |
| C2 | 1961 | 15 | 11 | 1 | 90 |
| C1 | - | - | - | - | - |
| D | 1993 | -40 | -43 | 3 | 92 |
| E | - | - | - | - | - |

**Table 2 Continued**

The scenario over Australia is in contrast with other countries. The overall climate has actually improved during 1997-2002 (Table 1h). The dominant climate (semi-arid) improved by 3 units at 91% confidence after 1997 (Table 2h). The timing is consistent with overall climate change. Analysis of individual climates did not capture the severe drop in overall status by 9.3 units after 2002 (Table 1h).

The average climate over China and Mexico did not change during the study period (Table 1i, 1j). A corroborative feature is seen in analyzing 6 climate types over China (Table 2i). The per-humid climates over Mexico suffered to the tune of -23 units at level 1 with 100% confidence after 1971. The major climates B and C1 (58% of area) did not exhibited any change through the series.

### 4.5 Recent Changes in Moisture Status:

Obviously, the most recent change in tropical climate has occurred around 1980 as seen from total tropical, countrywide and individual climates analysis. In this section, changes that have occurred since 1980 are discussed in three parts.

(a) How the average climate of a country varied since 1980 in comparison to the average up to 1980.
(b) In tropics, which climate exhibited maximum per unit area variation.
(c) In each region, which climate exhibited maximum per unit area variation.

*(a) Variation in mean climate since 1980:*

The threshold limit for climate type and the average moisture status in two parts of the series are shown in Fig.9. The most notable feature is depreciation of BMS islands climate from per-humid to humid category during 1980-2006. Thailand's borderline climate has fallen from humid to moist sub-humid category. The South America, Burma and China maintained humid status and Mexico maintained its moist sub-humid status despite decline. The tropics, on the whole, barely maintained its humid status. Thus, BMS islands are the only region actually suffered in status by climatic classification. Thus, all the countries suffered marginal depreciation of climate since 1980.

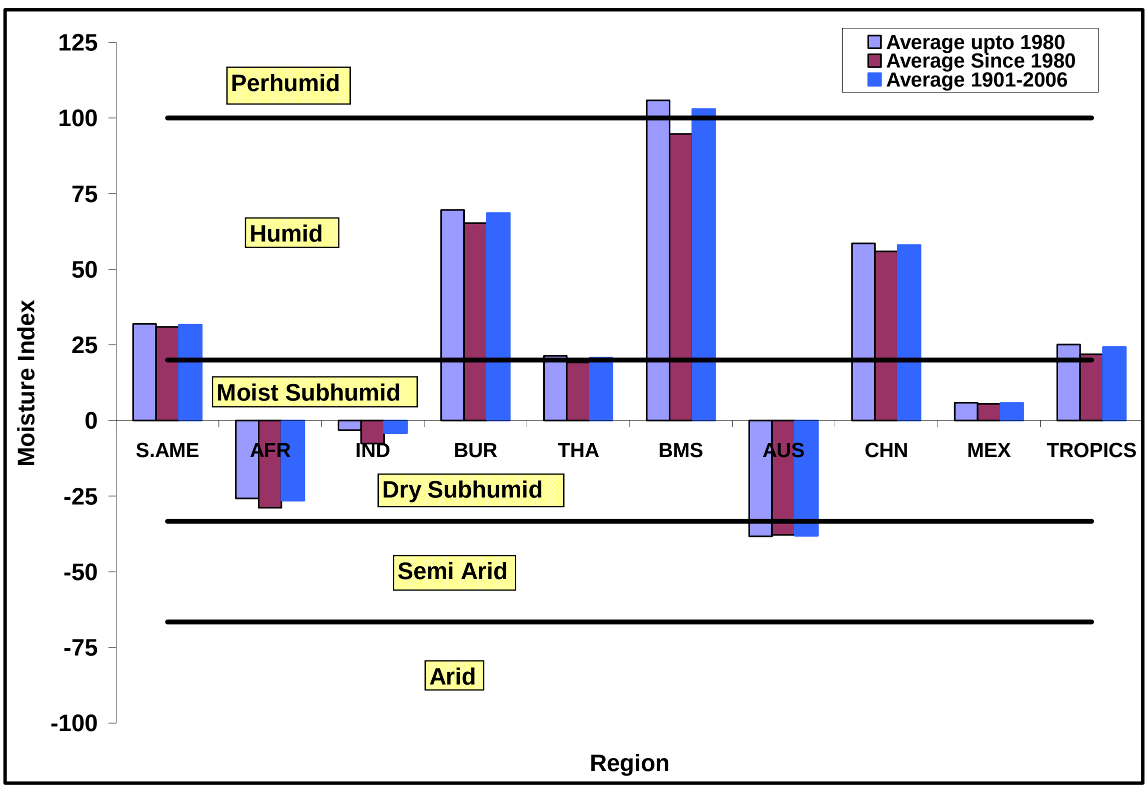



**Fig.9 Recent Change in Moisture Index**

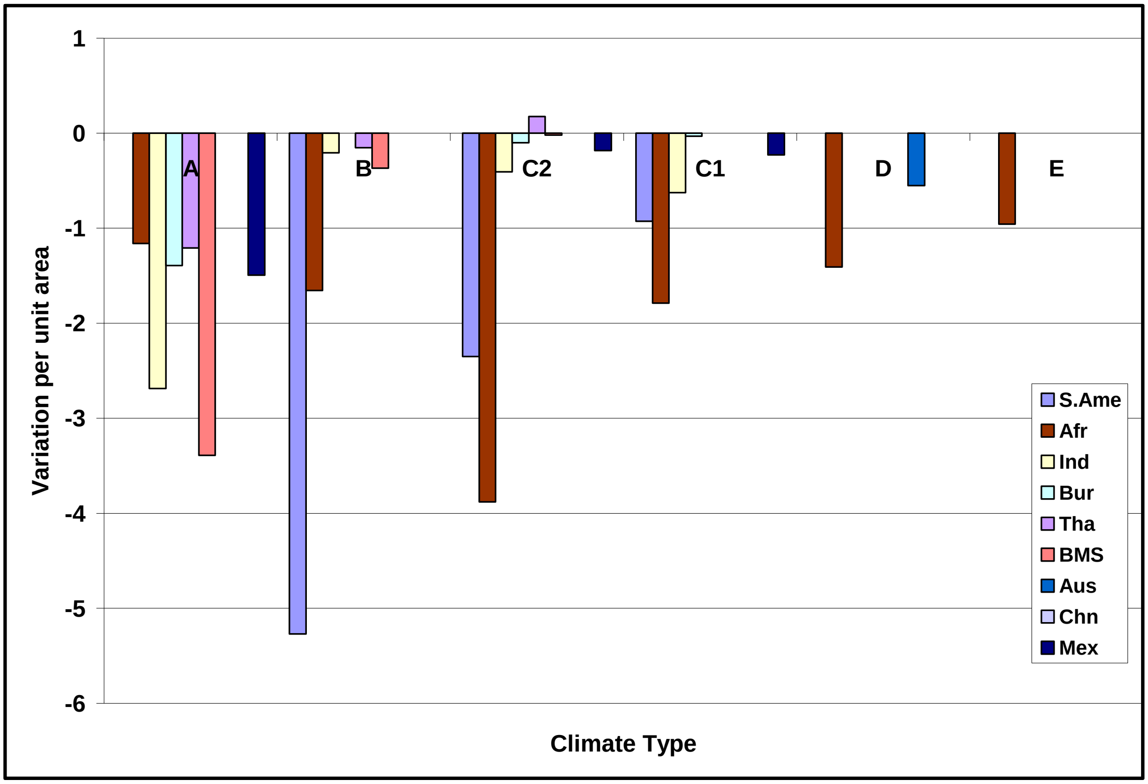



**Fig.10 Unit Area Variation in Moisture Index**

***(b) Variation in each climate over Tropics:***

The variation exhibited by each climate with reference to total geographical occupation in tropics is shown in Fig.10. The estimate is done from 1980-2006 since statistically significant change has occurred around the year 1980. The change with reference to long term average up to 1980 is negative for all climates in all regions but for an insignificant rise in C2 type over Thailand (Fig.10).

The maximum decline in Per-humid (A) climates is about 3.5 units per unit area over BMS islands followed by India with 2.7 units. Mexico has negligible area covering A climates (Annexure-III) hence the variation is insignificant. It is very striking that the 5.3 units loss of humid (B) climate over South America is much more compared to any other region. The C2 declined the most over Africa with South America coming next.

The BMS islands contain 22% total tropical per-humid climates and India has 5% (Annexure-III). South America is blessed with 44% of humid climates and Africa has 8%. The C2 are 48% and 34% over Africa and South America respectively. Thus vast area of wet climates suffered moisture decline. The magnitude of recession over dry climates (C1, D and E) is not as much as over wet climates and is mainly from Africa. Interestingly, China climates did not exhibit any change.

***(c) Region-wise variation in climates:***

In this section, the variation in each climate over a region with reference to total geographical area of respective region is discussed. We need to exercise some caution while interpreting the results for tropics since the temporal distribution of a particular climate over tropics as a whole is very likely to be different from the time distribution of the same climate over different countries. Thus, for a particular climate, the sum of changes shown over different regions does not necessarily match with the value shown for tropics.

The humid (B) climates over tropics suffered the most with near 2 units decline (Fig.11). The wet climates (A and B) occupying 98% of area over BMS island (see Annexure-III) have endured highest loss of moisture. Thailand faced similar scenario but less severe over 35% of area. For South America, the decline is highest over humid climates covering 48% of the area. All climates except type A suffered equally over Africa. The C1 (49%) and A (5%) climates went bad over India whereas adjacent Burma lost sheen in 18% area covered by type B climates.

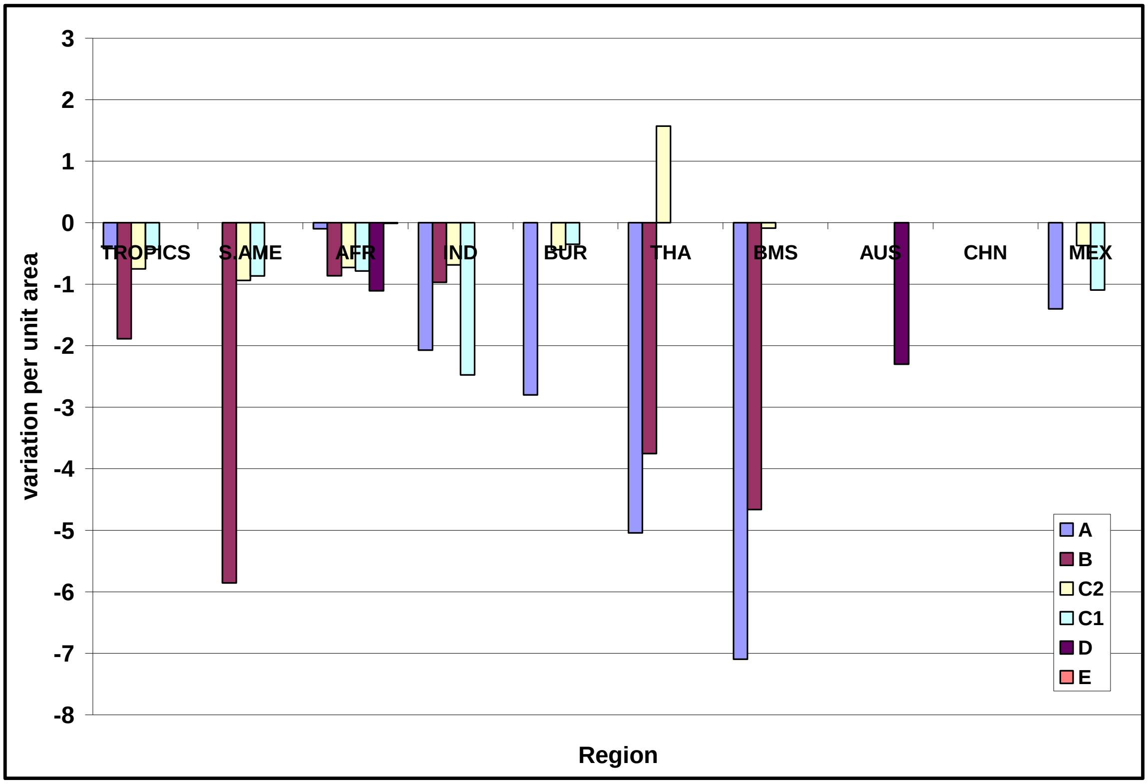



**Fig.11 Variation in Moisture Index – Country-wise**

The affected areas over tropics are shown shaded in Fig.12. The un-shaded dry climates too experienced changes of moderate magnitude but not immediately visible since desertification is a slow process. The regions affected not only by magnitude but also by size of area are termed as regions of 'Major Change'. The regions affected relatively low in magnitude are termed as regions of 'Minor Change'.

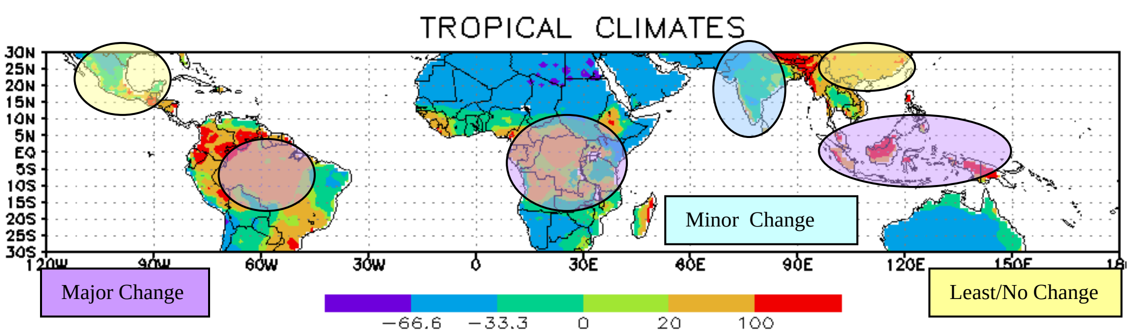



**Fig.12 Tropical Climates showing affected areas of moisture decline since 1980**

## 5. Conclusions:

A statistically significant change in moisture status has occurred at more than 90% confidence limit over tropics. The decline in moisture status started decisively around the year 1980 and that appears to be resulted from dominant dry weather conditions that occurred with alarming frequency due to combined affect of persistent positive temperature anomaly and negative rainfall anomaly since 1980 (Annexure-II). The status was partially compensated by extreme rain events since 2000. The African region covering 49% of tropics and where all climates dwindled at the same year (1980) with high intensity and in narrow confidence interval played major role in average moisture slump over tropics.

Over the South American region, per-humid climates are stable whereas the vast humid climate suffered highest drop since 1980. The per-humid climates over BMS islands demonstrated highest susceptibility for decline and so is the case with humid climates over Africa. Thus, the major change/decline is witnessed over wide geographic areas in close proximity to the equator. It appears that, around equator, discernible variations in major synoptic patterns that induce extreme weather conditions have come about since 1980 due excessive heat conditions overshooting stability threshold. Further north, over India, Burma, Thailand, Mexico and China the susceptibility for moisture decline is not as much as seen over equatorial region.

Over Africa the cyclical variations in moisture are of highest magnitude; much more than the deviations shown by other regions as evident from the standard scores. Among the regions that exhibited most visible change at level 1 (Africa, India and BMS), Africa is singled out to be more definite with narrow confidence interval and full 100% confidence limit. India and BMS islands exhibited more than 90% confidence limit. The statistical significance, thus, suggests that the African region is most susceptible to climate decline than any other region. Here, the moisture falling too low below the mean for three decades at a stretch is a matter of serious concern since the moisture status over desert climates does not exhibit much variation from year to year. It needs to be examined if 3 decades is significant even for slow desertification process.

All the 9 regions under study, suffered loss of moisture in past 3 decades in their respective dominant climate type occupying 50% or more of total geographical area implying that the moisture loss is not limited to few pockets but widespread.

It is heartening to note that since mid 1990s the moisture status over tropics is on the rise, as indicated by standard scores, although the overall status is below long term average. The rainfall anomaly rose since 1992-1993 with the temperature anomaly continued upward trend. It appears that the over heated conditions are thus compensated in the form of heavy rain events. According to World Meteorological Organization (WMO), the warmest 11 years in the record belong to the period 1995-2007 with 1998 being warmest with 0.52 degrees C rise above 1961-1990 global average. The temperature anomaly started rising since 2001 after a lull of 2 years from the warmest on record. WMO in its December 2010 document on "Weather Extremes in a Changing Climate: Hindsight on Foresight" listed out substantial rainfall extreme events alongside others asserting that the scale of occurrence of weather extremes have become more and more visible since 2000. But the rising net moisture status prior to 2000 indicates that discernible rainfall extremes perhaps started a few years earlier than 2000.

## Acknowledgements:

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**Annexure-I**

## Trends in Temperature and Rainfall over India

The temperature and rainfall anomaly over India with reference to long term mean (1901-2006) is shown in Fig.A1-1.

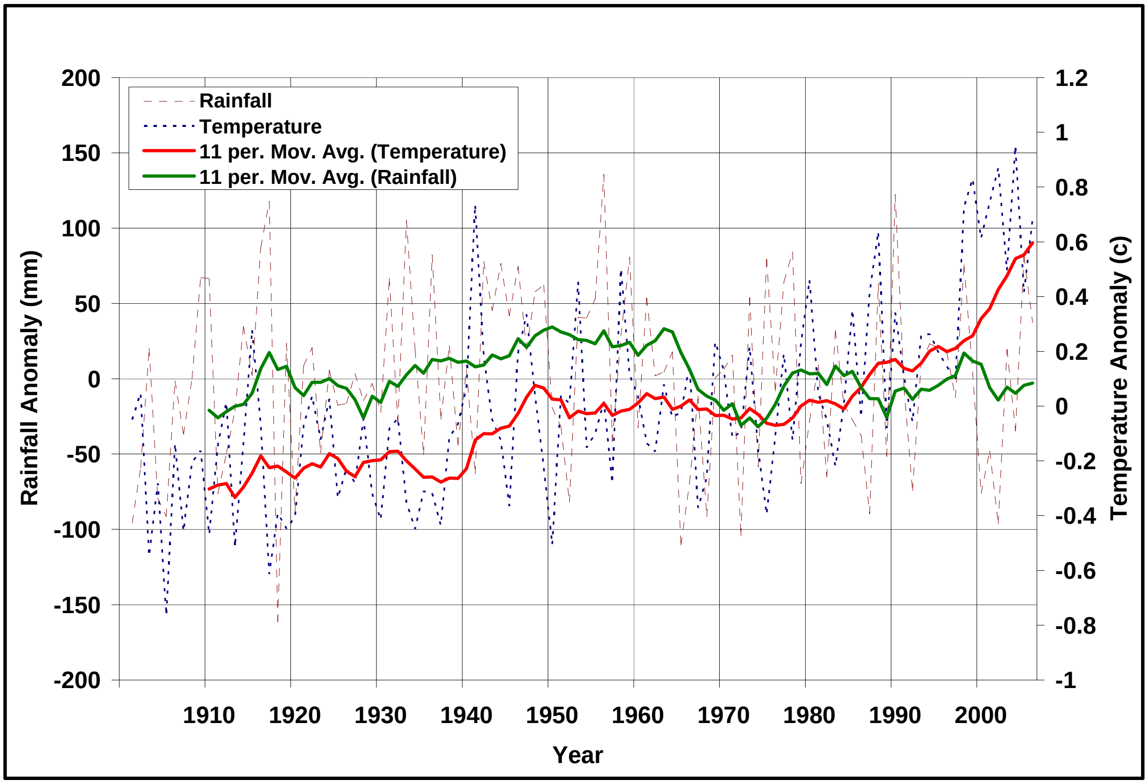
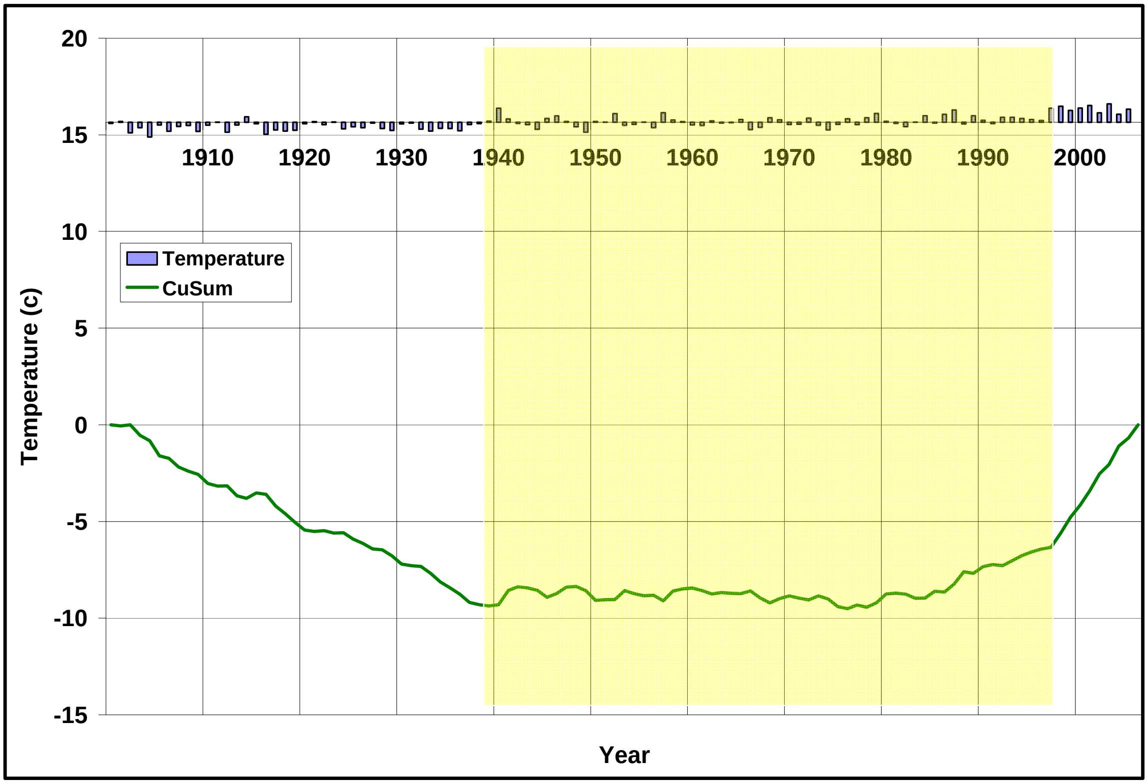


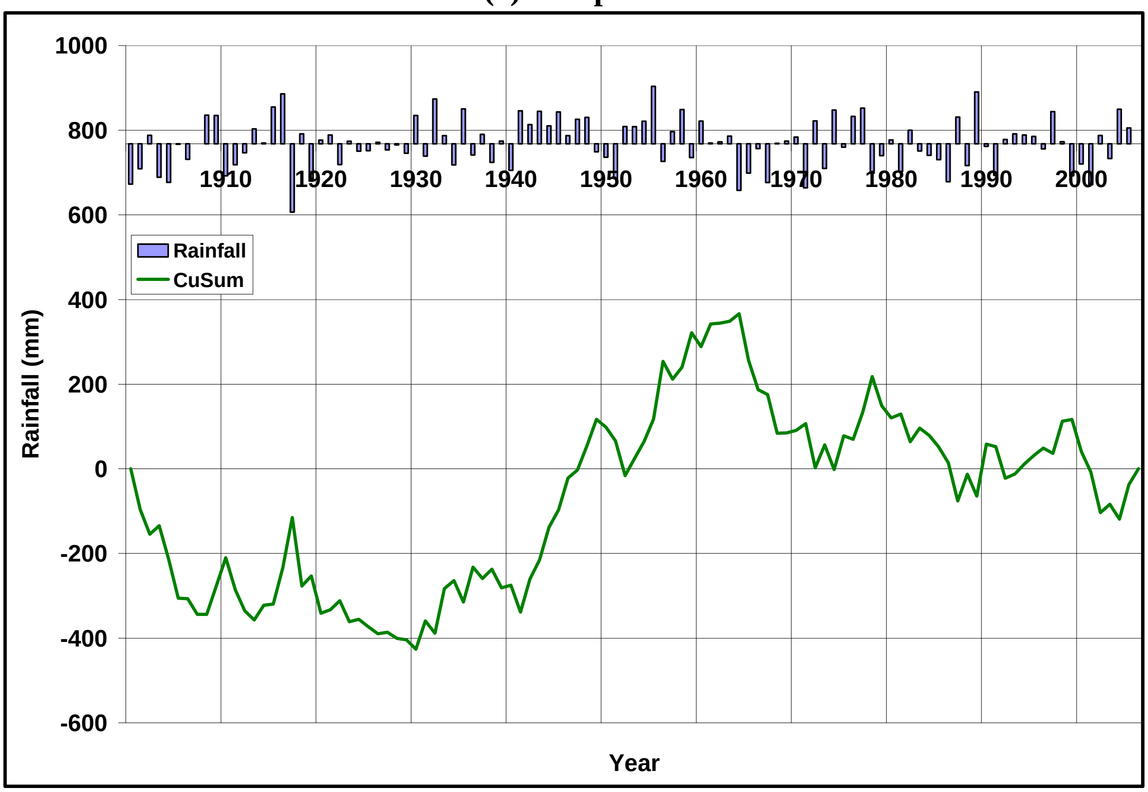

**Fig.A1-1 Temperature and Rainfall Anomaly over India**

The anomaly in temperature showed clear rising trend since mid 1970s and continued through the series whereas rainfall has not exhibited any definite trend during the same period. However, a sharp fall in rainfall from early 1960s to early 1970s is evident. Thereafter, rainfall maintained mostly a below average status.

The change point analysis for rainfall and temperature over India is shown in Fig.A1-2. The temperature had undergone two statistically significant changes during 1901-2006 (Fig.A1-2a). Both the changes have shown rising conditions at level 1 with 100% confidence. The first one occurred during 1938 from which till the next change in 1998, the temperature on average increased by 0.3 degrees C. From 1998 till 2006 the rise is 0.65 degrees C. Obviously the second rise is very sharp having occurred in just 8 years. The rainfall did not undergo statistically significant change during the study period (Fig.A1-2b). Although the cumulative sum exhibited undulated trend, the significance did not satisfy the 90% confidence limit set for the present analysis.




**(a) Temperature**




**(b) Rainfall**

**Fig.A1-2 Change Point Analysis for India**

**Annexure-II**

## Trends in Temperature and Rainfall over Tropics

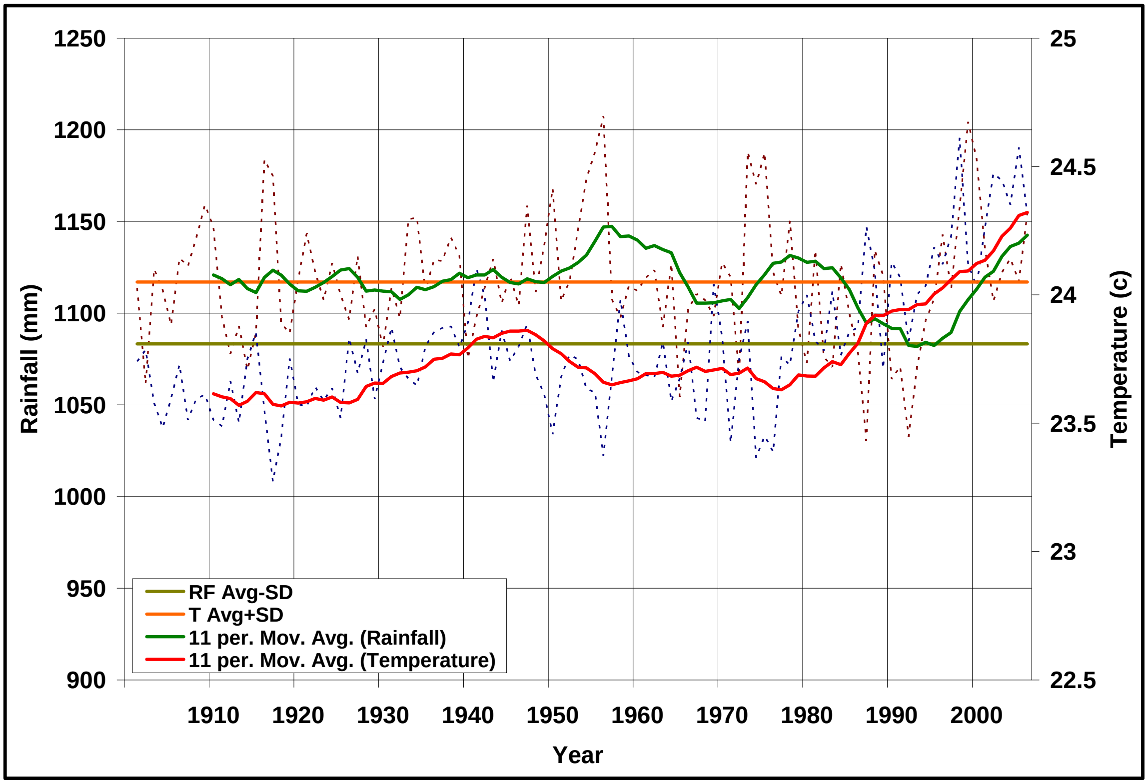
The temperature and rainfall moving average and the anomaly over tropics with reference to long term mean (1901-2006) is shown in Fig.A2-1.

The 11-year moving average rainfall line exhibited a falling trend since 1960s in general (Fig.A2-1a). The peak in late 1970s suggested improved conditions but a sharp fall thereafter till mid 1990s (for about 15 years) touched one negative standard deviation. The temperature on the contrary rose from late 1970s and continued crossing one positive standard deviation in late 1990s. It appears that large dynamical changes in atmospheric equilibrium have taken place during second half of 1990s.

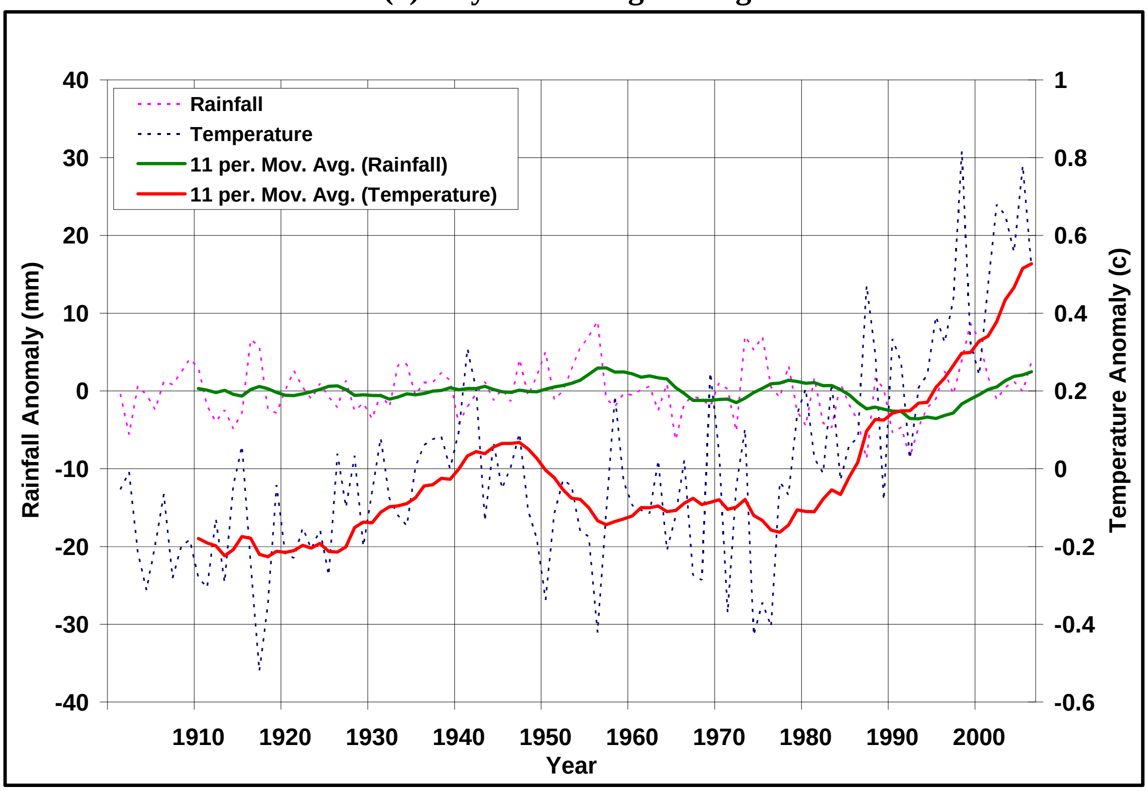
The temperature anomaly showed clear rising trend since late1970s and continued through the series whereas rainfall exhibited falling trend but up to mid 1990s (A2-1b). Rainfall has fallen below average, in general, since mid 1980s with mild rising trend since mid 1990s. It is interesting to note that the rainfall rose above average after the year 2000.

The change point analysis for rainfall and temperature over tropics is shown in Fig.A2-2. The temperature had undergone four statistically significant changes during 1926, 1948, 1979 and 1995 (Fig.A2-2a). The two most recent changes (1979, 1995) occurred at level 2 with 100% confidence limit suggesting that definite changes have been taking place since late 1970s. Between 1948 and 1979, temperature dropped by an average of 0.14 degrees C. From 1979, the average rise up to 1995 was 0.28 degrees C. The rise further compounded to 0.36 degrees C during the last 11 years. Thus, the temperature intensified since 1979 with two legs of statistically significant periods. The rainfall experienced 5 statistically significant changes during 1963, 1973, 1976, 1998 and 2001 (Fib.A2-2b) The change between 1976 and 1998, that witnessed rainfall decrease at an average of 86 mm, occurred at level 1 with 98% confidence.

The heightened rainfall activity during 1998 and 2001 was encouraging but short tenured as significant fall at an average of 54 mm at level 1 with 97% confidence occurred thereafter.

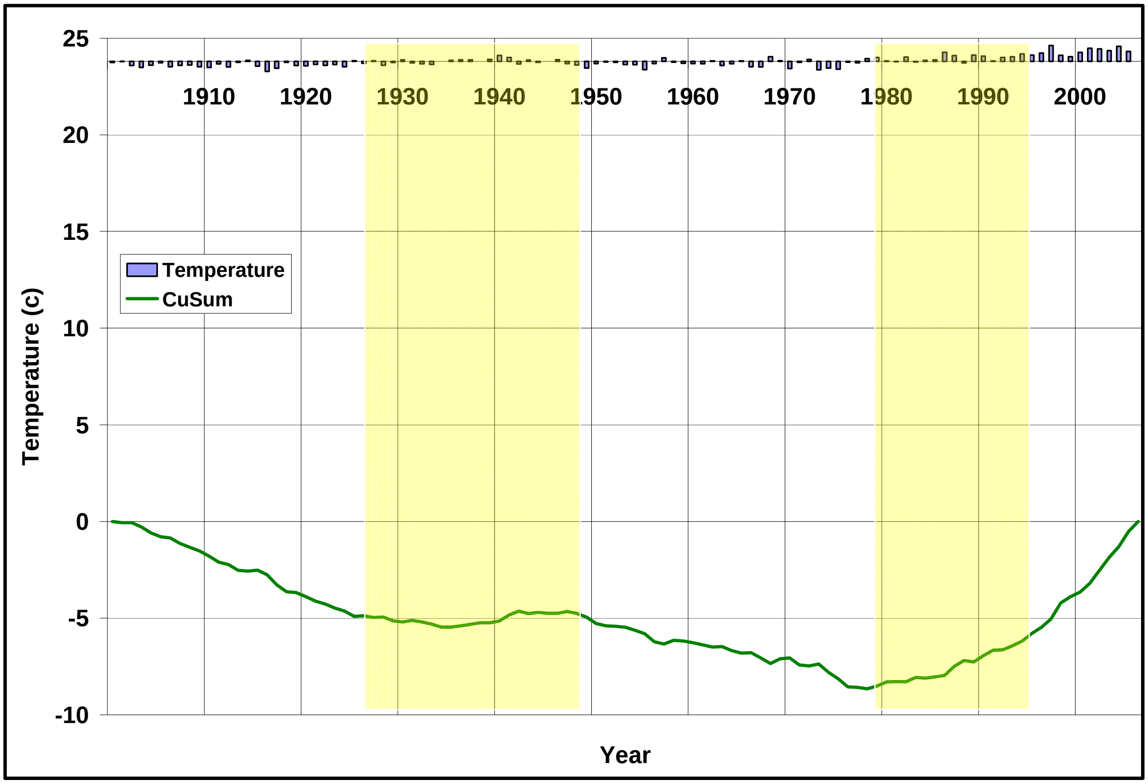



(a) 11-year Moving Average

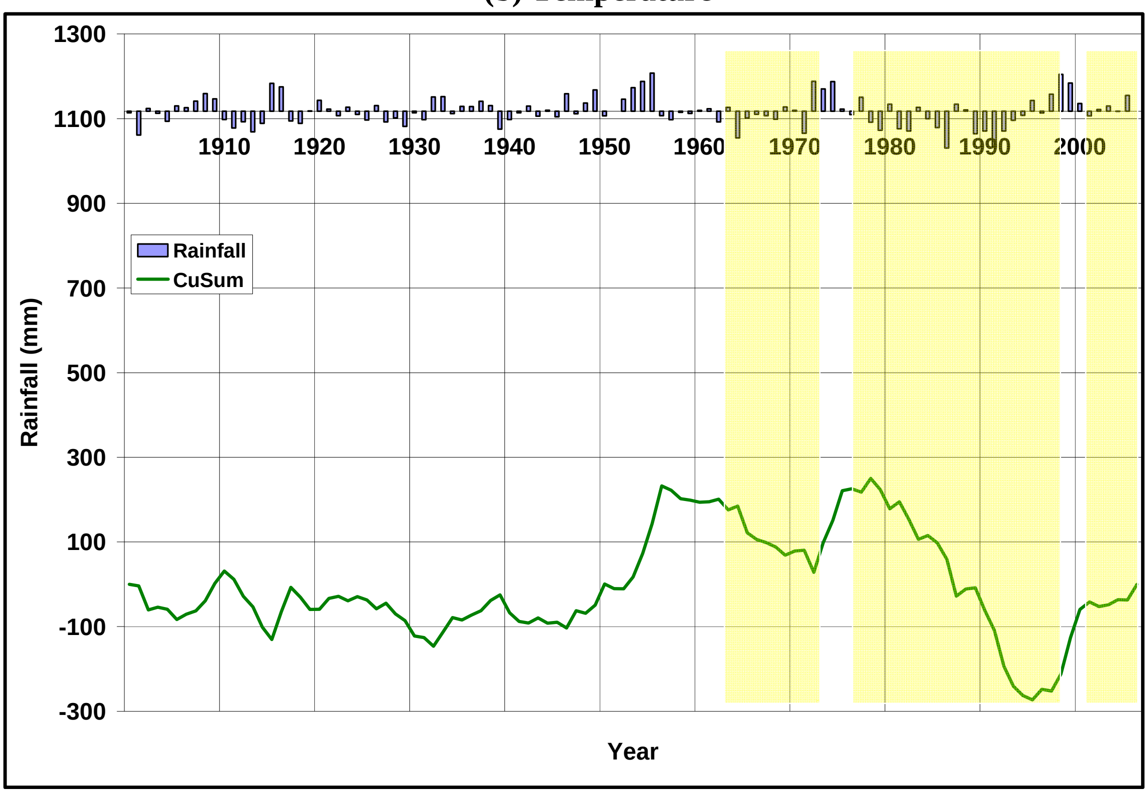



(b) Anomaly

**Fig.A2-1 Temporal Distribution over Tropics**




**(b) Temperature**




**(b) Rainfall**

**Fig.A2-2 Change Point Analysis for Tropics**

## Annexure-III

# Distribution of Climates by Area

***Distribution of climates within a region:***

In each of the nine selected countries, the percentage area occupied by each climate is estimated with reference to total area of the country. The climate occupying highest percentage area is the most dominant climate of the country.

The fractional area occupied by each climate for each country is shown in Fig.A3-1. The climate symbols are given in Table A in the main text.

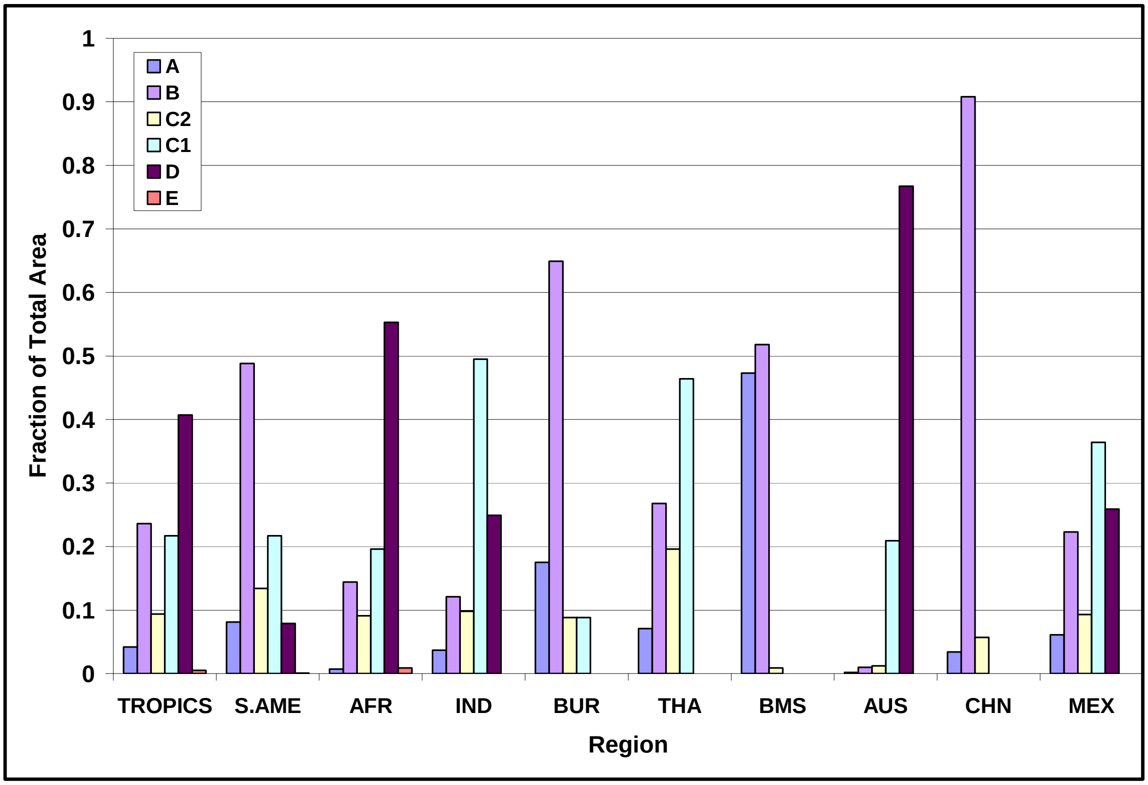



**Fig.A3-1 Distribution of Climate Types by Region**

The tropics are mostly dominated by semi-arid type with an occupation of 41% of total area. The next in the order are B and C1 types prevailing over 23% and 22% of the tropics. The C2 occupy 9.5% and type A, representing heavy rain zones, cover about 4% of total area. The arid climates are bare minimum at 0.5%.

The climate of China, Burma, South America and BMS islands is dominated by humid category covering 91%, 65%, 49% and 52% of their respective areas. Mostly dry climates (C1, D and E) exist with nearly 75% and 56% occupation respectively over Australia and Africa. The Indian region is covered by C1 (50%) and D (25%) climates over majority of area; and so is Mexico with 36% and 26%. Thailand has C1 at its highest at 47%. Only two climate types A and B exist over BMS islands and over Australia the climate is mostly semi-arid (77%). Thus each of the selected country has its own dominant climate type.

***Area-wise distribution of climates in tropics:***
This is worked out for each climate type. The percentage area occupied by a climate is estimated with reference to total area occupied by that particular climate in tropics. This gives the location of most dominating climate over tropics.

The fractional area occupied by each climate in tropics is shown in Fig.A3-2.

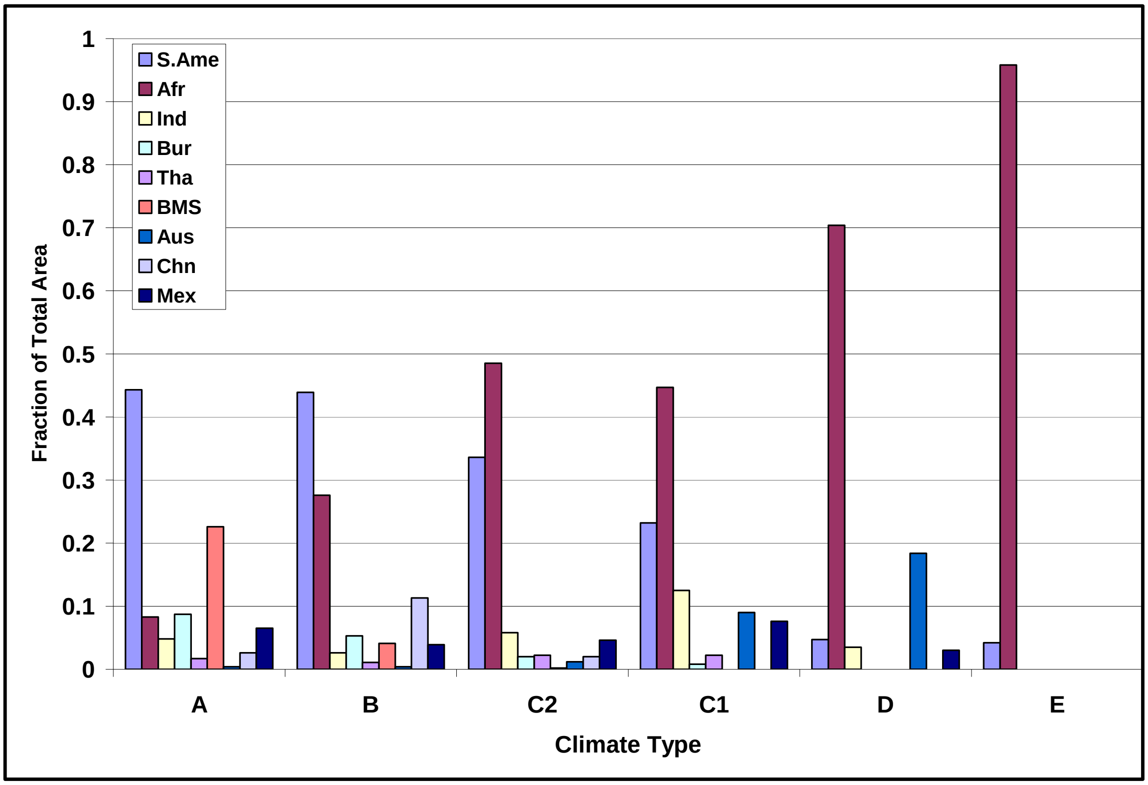



**Fig.A3-2 Distribution of Climate Types in Tropics**

As discussed in previous section, tropics are dominated by semi-arid (D) climates for which 70% of area is from Africa and 18% is from Australia. The C1 type is also mostly from Africa (44%) followed by India (23%). The B climates (second in domination over tropics) receives major contribution from South America (44%) followed by Africa (28%) and China (11%). Type A climates mostly exist in South America (44%) followed by BMS islands with 22% occupation. The rest of the regions occupy less than 10% of area. The C2, C1, D and E types have highest occupation in Africa with 49%, 44%, 70% and 96% respectively. The South America region follows Africa in C2 and C1 type occupation.