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Studies on some aspects of the intensification of Hydrologic Cycle over India

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ABSTRACT
It is widely reported that the intensified hydrologic cycle in the climate spectrum of the world is as a consequence of global warming which is not uniform over the world. In the present investigation, an attempt has been made to study and understand some of the aspects of hydrologic extremities in terms of prevalence of varied degrees of drought, humidness and climate shifts on All India basis through the revised water balance model during the monsoon period from 1901 to 1990. Trend aspects in seasonal All India aridity, humidness and climate shifts of the s-w monsoon period are studied compared to the march of Southern Oscillation (SO) Index and Sea Surface Temperature (SST) of NINO3 region. One of the important aspects of the present investigation is the appraisal of the modulation of the basic water budget elements of All India during extreme dry and wet shifts of the s-w monsoon compared to normal and in the context of ElNino – Southern Oscillation (ENSO) signal.

The paper also analyzes the mean monsoon seasonal flows of Krishna river basin at Vijayawada point along with its trend in relation to ElNino – Southern Oscillation (ENSO) and LaNina – Southern Oscillation (LNSO) signals.

A comparative study of the frequency of cyclonic disturbances and storms in the Indian region during distinct epochs compared to normal and in the context of global warming is made. The investigation also address not only in approximating a third order polynomial fit for the number of storms and cyclones in the Indian region, but also the trend aspects for the study period from 1901 to 1990 in relation to short term climate signal.

INTRODUCTION

The natural variations in the orbital forcing along with the worldwide anthropogenic forcing might be responsible in perturbing the world climate system and which in turn is manifested in modulating the world hydrological cycle in the context of global warming with regional implications that are not uniform in world climate spectrum (IPCC 1995). Apart from the climate variability due to the above factors in affecting the world hydrological cycle, the teleconnections among global climate systems might be also contributing (Shukla 1998) in triggering climate extremities in terms of droughts, floods, storms, heat and cold waves etc.

Globally it is reported that the broad geographic regions of cyclogenesis and the regions affected by tropical cyclones are not only expected no change significantly, but also little or no change in frequency. It is pertinent to note here that the north-east Pacific recorded an upward trend with an increased frequency of tropical cyclones where as the north Indian Ocean indicated a marked downward trend with a no appreciable long term variation in south-west Indian Ocean and south-west Pacific (Henderson Sellers et al. 1998). The results of De & Joshi (1995 & 1999), Srivastava, Sinha Roy & De (2000) and Bhaskar Rao, Naidu and Srinivasa Rao (2001) too pointed a decreasing trend in the frequency of tropical cyclones and monsoon depressions over the north Indian Ocean. De & Dandekar (2001) and De & Rao (2004) examined the urban climate trends in India in establishing the link between increased level of human activity and climate related global change. The large scale aspects of droughts and floods in relation to circulation pattern and their cyclic fluctuations compared to the double sunspot (Hale) cycle was reported by Bhalme & Mooley (1980, 1981). Chowdhury & Mhasawade (1991) studied the variability in meteorological aspects of monsoon floods. The hydrometeorological aspects of monsoon droughts and floods and the associated problems are reported by Sikka (1999, 2000). In the present investigation, some of the aspects of increased frequency of the extreme climate variability which is as a consequence of global warming is reported here through water balance model with reference to All India during monsoon period in terms of humidness, droughts, climate shifts, cyclonic disturbances, storms and river flows of Krishna river at Vijayawada point. The global warming and the teleconnection impacts of ENSO and LNSO on land based water cycle and river systems are global in nature (Simpson & Cane 1993; Houghton et al. 1995; Watson et al. 1996; SGCR 1999; Sarma, Padma Kumari & Srinivas 1999). The trends in All India climate indices including river flows of Krishna river basin are analyzed in an attempt to understand the interrelationship between the All India hydrological regime and the warm and cold phases of ENSO signal. The authors undertook the present investigation after having succeeded in coupling the annual moisture regime of All India with the trends in ENSO signal (Sarma, Srinivas & Karthikeya 2005).

MATERIALS AND METHODOLOGY

The revised water balance model (Thornthwaite & Mather 1955) is followed in obtaining the basic water budget elements for All India by taking the mean temperature and rainfall data on a monthly basis for a period of 90 years commencing from 1901 and is downloaded from the website of Indian Institute of Tropical Meteorology: tropmet.res.in. Climate indices of aridity, humidity and moisture are obtained for the s-w monsoon period. Percentage departures of these indices from the respective median determine the severity of the respective events such as drought, humidness and climate shift and these are normalized with respect to median for each of the index. To delineate the varied categories of these events standard deviation of the respective indices are used and the following schema are followed for identifying the events of drought, humid and climate shift for All India.

LIMIT	DROUGHT
0 – ½ s	Slight (SLD)
½ s - s	Moderate (MD)
s - 2s	Severe (SD)
≥ 2s	Very severe (VSD)

LIMIT	HUMID	CLIMATE SHIFT
0 - s	Moderate Humid (MH)	Moderate (M)
s - 2s	Very Humid (VH)	Large (L)
≥ 2s	High Humid (HH)	High (H)

In determining the moisture status of All India, the revised expression of moisture index (Carter & Mather 1966) is followed and is obtained on season climate concept. Stability of the climate type is determined following the season climate concept as was reported for year climate concept (Yoshino & Urushibara 1981; Sarma & Ravindranath, 1983).

The data for the cyclonic disturbances and storms from the Bay of Bengal and Arabian Sea are from the IMD publications of 1979 and 1996. Krishna river flows are obtained from Irrigation Circle, Vijayawada. The 3rd order polynomial fit is approximated for the climate indices, cyclonic disturbances, storms and for mean monsoon season flows of Krishna river basin at Vijayawada point while for the mean of June to Sept SOI, mean of Sept, Oct, Nov SSTs of NINO3 the 9th order is followed. The SSTs of NINO3 region are from Wright index (1989) values.

The statistical results of the present investigation in terms of occurrence of All India droughts, humid events and climate shifts are segregated not only for the periods of 1901-1990, 1901-1970 and 1971-1990 but also for 1901-1930, 1931-1960 and 1961-1990 with a view to study the variations not only in occurrence but also in frequency based on the report of PAGES News (1997), with reference to the commencement of the probable period of climate anomalies or increased frequency of extreme events globally.

RESULTS AND DISCUSSION

Occurrence of drought, humid and climate shift events

Among the three climate indices chosen for studying the hydrological regime of All India, aridity with its low values of mean and median registered the maximum standard deviation while the moisture and humidity occupied second and third places (Table 1a). The substantial high standard deviation in the aridity, humidity and moisture indices might be due to the high spatiotemporal and interannual variations in the strength and depth of the s-w monsoon circulation pattern over India and whose performance is governed by the teleconnections of the world climate system.

On All India basis during the s-w monsoon, for the study period of 1901 to 1990, it experienced a total of 15-slight, 11-moderate, 16-severe and 3-very severe droughts. The periods 1901-1970 and 1971-1990 recorded the same number that is a total of 5-droughts of all types per decade (Table 1b) (Fig.1a). However, there appears a slight increment in the frequency of severe and very severe droughts during 1901-1970 (2 per decade) as compared to 1971-1990 (1.5 per decade).

All India wise, the region harboured a total of 31-humid, 12-very humid and 2-high humid events. On

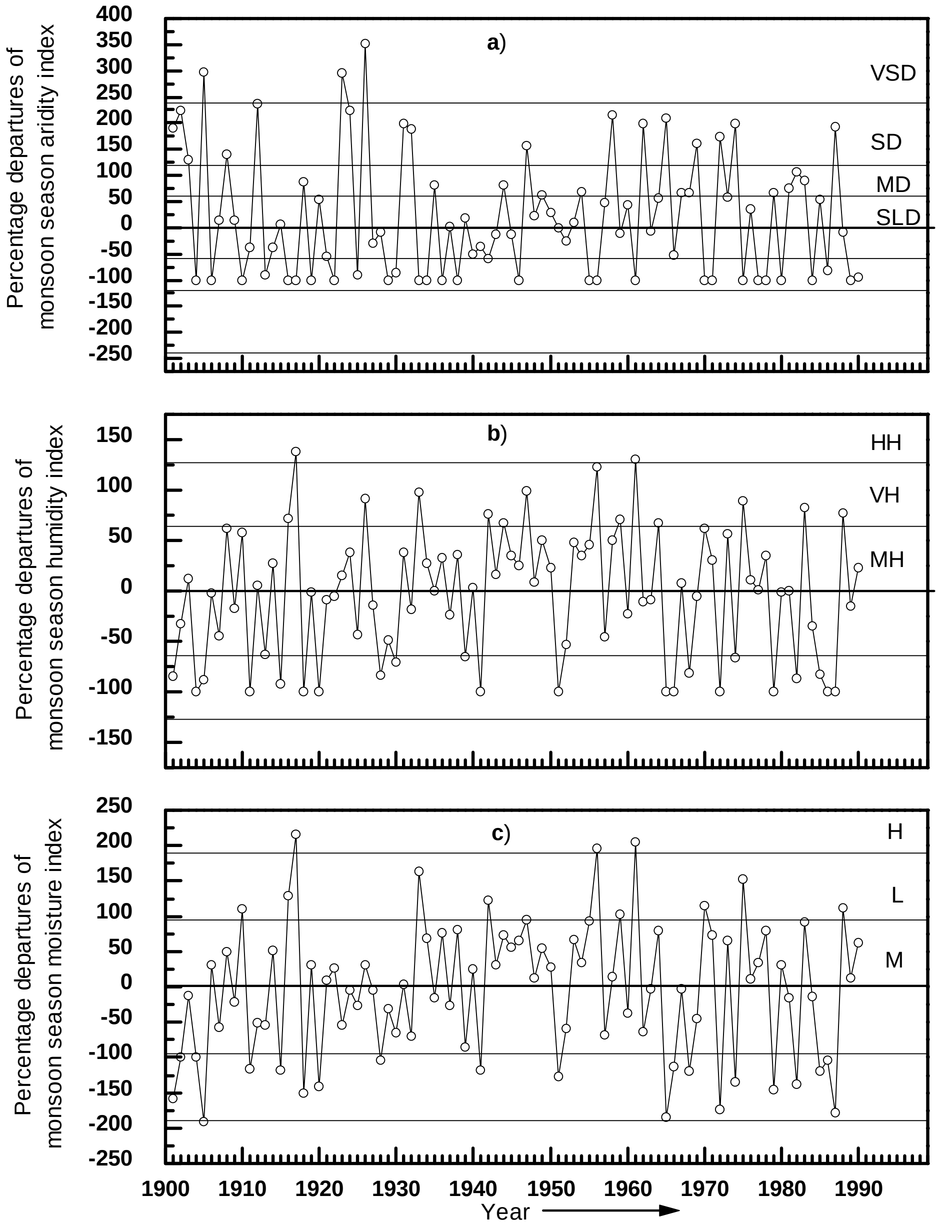

Figure 1. March of All India monsoon season's aridity, humidity and moisture indices.

Table 1a. Selected climate indices of All India - SW monsoon season

INDEX	MEAN	MEDIAN	SD
ARIDITY	2.8	3.5	119.2
HUMIDITY	13.6	17.6	63.8
MOISTURE	10.8	13.2	94.8

Table 1b. Climate statistic of All India drought events – SW monsoon season

PERIOD	SLIGHT DROUGHT (SLD)	MODERATE DROUGHT (MD)	SEVERE DROUGHT (SD)	VERY SEVERE DROUGHT (VSD)
1901-1990	15 (16.6%)	11 (12.2%)	16 (17.7%)	3 (3.3%)
1901-1970	12 (17.1%)	7 (10%)	13 (18.6%)	3 (4.3%)
1971-1990	3 (15%)	4 (20%)	3 (15%)	0 (0%)
DROUGHT PER DECADE	1.66 (1.84%)	1.22 (1.35%)	1.77 (1.96%)	0.33 (0.36%)

Table 1c. Climate statistic of All India humid events – SW monsoon season

PERIOD	MODERATE HUMID (MH)	VERY HUMID (VH)	HIGH HUMID (HH)
1901-1990	31 (34.4%)	12 (13.3%)	2 (2.2%)
1901-1970	25 (35.7%)	9 (12.9%)	2 (2.9%)
1971-1990	6 (30.0%)	3 (15.0%)	0 (0%)
HUMID PER DECADE	3.4 (3.82%)	1.3 (1.47%)	0.2 (0.24%)

Table 1d. Climate statistic of All India climate shifts – SW monsoon season

PERIOD	MODERATE SHIFT (M)	LARGE SHIFT (L)	HIGH SHIFT (H)
1901-1990	34 (37.7%)	8 (8.8%)	3 (3.3%)
1901-1970	25 (35.7%)	6 (8.6%)	3 (4.3%)
1971-1990	9 (45.0%)	2 (10.0%)	0 (0%)
CLIMATE SHIFT PER DECADE	3.7 (4.18%)	0.8 (0.97%)	0.3 (0.36%)

Table 2a. Epochal wise All India droughts – SW monsoon season

EPOCH	SLIGHT DROUGHT (SLD)	MODERATE DROUGHT (MD)	SEVERE DROUGHT (SD)	VERY SEVERE DROUGHT (VSD)	TOTAL NUMBER
1901-1930	4	1	6	3	14
1931-1960	7	4	4	-	15
1961-1990	4	6	6	-	16
TOTAL	15	11	16	30	45

Table 2b. Epochal wise All India humid events – SW monsoon season

EPOCH	MODERATE HUMID (MH)	VERY HUMID (VH)	HIGH HUMID (HH)	TOTAL NUMBER
1901-1930	7	2	1	10
1931-1960	16	6	-	22
1961-1990	8	4	1	13
TOTAL	31	12	2	45

Table 2c. Epochal wise All India climate shifts – SW monsoon season

EPOCH	MODERATE SHIFT (M)	LARGE SHIFT (L)	HIGH SHIFT (H)	TOTAL NUMBER
1901-1930	7	2	1	10
1931-1960	17	3	1	21
1961-1990	10	3	1	14
TOTAL	34	8	3	45

an average the period 1901-1970 had a higher (5.1) humid events compared to 4.5 events per decade of 1971-1990 (Table 1c)(Fig.1b).

All India hydrological regime witnessed 34-moderate, 8-large and 3-high shifts during the study period. On an average, the number of shifts per decade for the period 1971-1990 was 5.5, which was higher compared to 4.8 of 1901-1970 period (Table 1d)(Fig.1c).

The decreased and increased number of humid and climate shift events during the period 1971-1990 compared to 1901-1970 might be related to the seasonal performance of the monsoon in response to the ElNino – Southern Oscillation (ENSO) signal from southern tropical Pacific.

Table 2 presents All India wise, the probable prevalence of varied categories of drought, humidity and moisture type events for the southwest monsoon period in distinct epochs. The significance of 1961-1990 epoch was that it witnessed increased number of droughts and decreased number of humid events along with the decreased number of climate types compared to 1931-1960 (Table 2) and might be due to

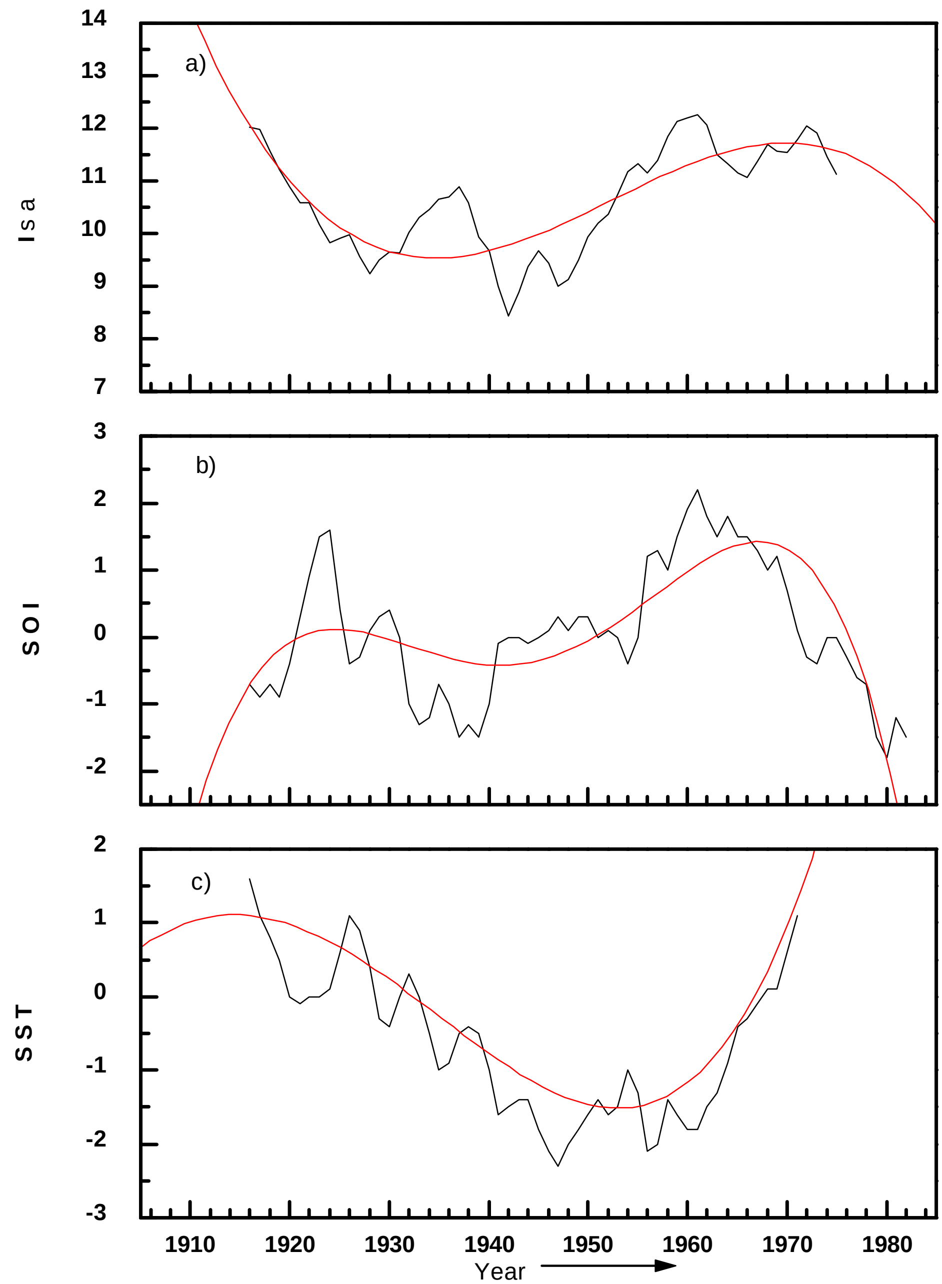

Figure 2. Polynomial fit for 30-yr normalized CMAS of All India aridity status of SW monsoon, SOI of June to September & SST of September to November of NINO3 region.

the frequent subnormal depth and intensity of monsoon current over India in relation to the short term climate signal of ElNino - Southern Oscillation. According to Sikka (2000), the anomalies in large-scale circulation features during the monsoon period might be responsible for the nature and the performance of weather during monsoon over India. Apart from antecedent factors, the prevalence of low-pressure systems and their tracks, the location of monsoon trough throughout the s-w monsoon season influences the intraseasonal monsoon activity. Regional atmospheric perturbations in response to one of the global teleconnections of short-term climate signal of ENSO/LNSO considerably contribute to the seasonal variability of monsoon on the regional scale, which interacts with the planetary scales of global monsoon controlled by surface conditions.

Table 3. All India SW monsoon period's basic water budget elements (mm)

EVENT	RAIN-FALL	WATER NEED	WATER DEFICIT	WATER SURPLUS	Im (%)
Normal Monsoon	846	631	18	86	10.8 (C2)
Extreme Wet Monsoon (1917)	1005	608	0	255	41.9 (B2)
Extreme Dry Monsoon (1905)	717	650	93	14	-12.1 (C1)
ElNINO (1987)	698	657	69	0	-10.5 (C1)
LaNINA (1988)	962	636	21	199	27.9 (B1)
Good Monsoon (1975)	963	612	0	204	33.3 (B1)

Anomalies in the basic water budget elements of the s-w monsoon season

Table 2 presents the basic water budget elements for the monsoon period during normal, extremities of dry and wet shifts, El NINO, La NINA episodes along with the good monsoon season. The extreme wet shift of 1917 monsoon generated a water surplus of greater than 3.7 times the normal while its extreme swing on to dry side in the year 1905 reduced the water surplus to more than six times the normal and might be responsible in elevating and deteriorating to first humid and dry subhumid season climate status to All India respectively. The years 1987 and 1988 witnessed worldwide El NINO and La NINA impacts and were not an exception to India wherein a water surplus of zero and greater than 2.3 times the normal occurred respectively. The good monsoon season of 1975 lodged a water surplus of 204mm to All India, which is about 2.4 times the normal.

All India's hydrological regime during the s-w monsoon period is moist subhumid but the analysis of composite El NINO and La NINA scenarios through the present investigation unfolds a dry subhumid and first humid status respectively to it in such cases.

Eventhough on long-term basis, All India's hydrological regime during monsoon period is moist subhumid, it recorded during the study period second humid status with 2.2%, first humid with 26.6%, moist subhumid with 48.8% and dry subhumid status with 22.2% of the time and there by indicating its regime is not stable.

Trends in aridity, humid and climate shift events - SOI and SST OF NINO3

The coupled mode of interaction of Ocean-Atmosphere from southern tropical Pacific Ocean influences the global hydrological regime in space and time with a lag. It is pertinent to note that the memory of the ocean is large compared to atmosphere. The 30-year centered moving averages (CMAs) in respect of derived season climate concept indices of All India in relation to the Southern Oscillation Index (SOI) and Sea Surface Temperature (SST) of September, October, November of NINO3 region points out the increased trend in both seasonal humidity (I_{sh}) and seasonal moisture (I_{sm}) indices for the period June to September from 1910 to 1955 of All India was in association with the overall trends of SOI and SST from 1910 to 1955 respectively while the decrease from 1956 to 1990 is accompanied by fall and rise in SOI and SST respectively. Figs 2, 3 and 4 clearly emphasize that it is the trend in SST of NINO3 that modulates the All India hydrologic regime compared to SOI.

A comparison of the trends of the normalized 30-yr centered moving averages (CMAs) of seasonal aridity, humidness and climate status of All India did show a lagged broad general agreement with the trends in the normalized 30-yr centered moving averages (CMAs) of June to Sept SOI and Sept, Oct, Nov SSTs of NINO3 region (Figs 2, 3 & 4). It is clear from the present study that while the seasonal aridity is decreasing, humidness and moisture status are improving with an increase of SOI and decrease of SST of NINO3 respectively and vice versa.

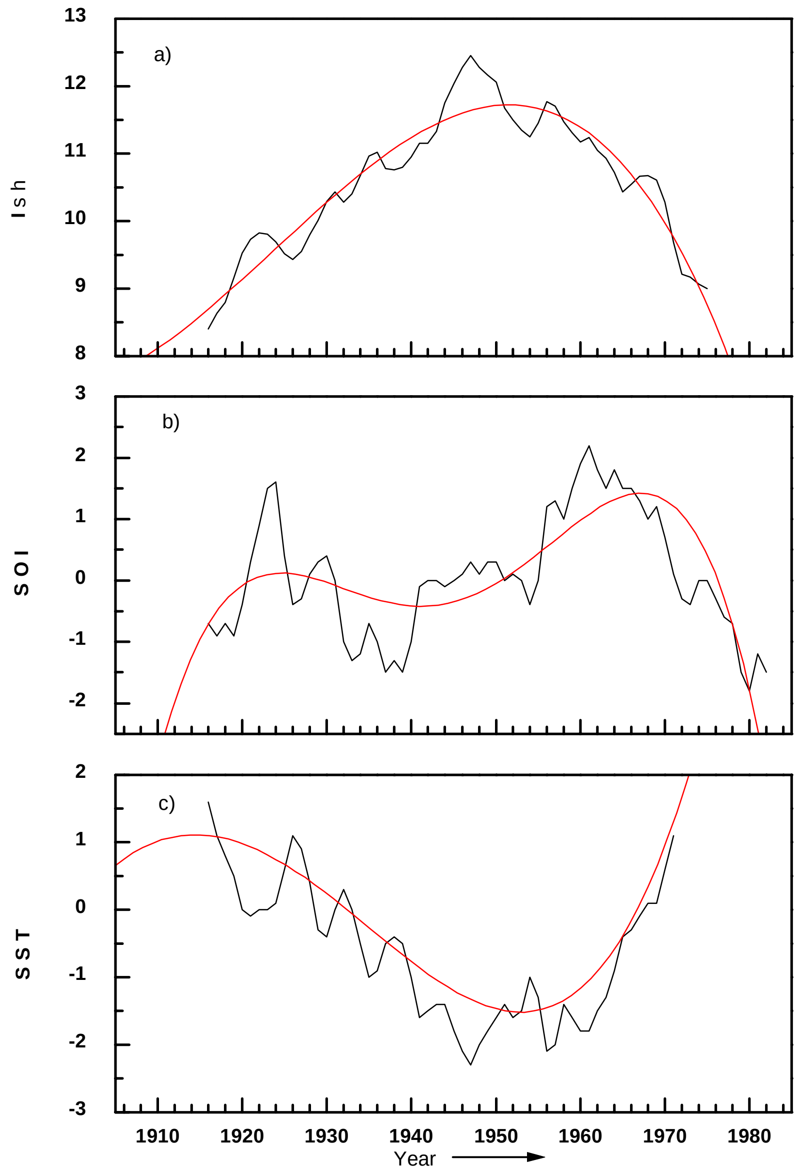

Figure 3. Polynomial fit for 30-yr normalized CMAS of All India humidity status of SW monsoon, SOI of June to September & SST of September to November of NINO3 region.

Trends in Krishna river flows - SOI AND SST

The river flows of Krishna river basin at Vijayawada point during the monsoon season is clearly indicating that there is a decreasing trend in its mean seasonal magnitude of 4,122Cumec during the period 1901-1970 to 1501Cumec for 1971-2000 (Fig.5).

The normalized 30-yr centered moving averages (CMAs) of mean seasonal flows at Vijayawada point is in agreement with the trends of SOI and SSTs of NINO3 region indicating the steady and slight increased flows till 1962 that are associated with increased SOI (with an exception to 1932 – 1940) and subnormal (cold) SSTs of NINO3, but the decreased trend might be attributed to negative SOI coupled with elevated SSTs of NINO3 region (Fig.6) as is reported Sarma, Padma Kumari & Srinivas (1999) in the case of annual flows.

Mean monthly frequency of cyclonic disturbances and storms & Trends

Based on 100-years of data (1891-1990), the average number of annual cyclonic disturbances is 15.65 from

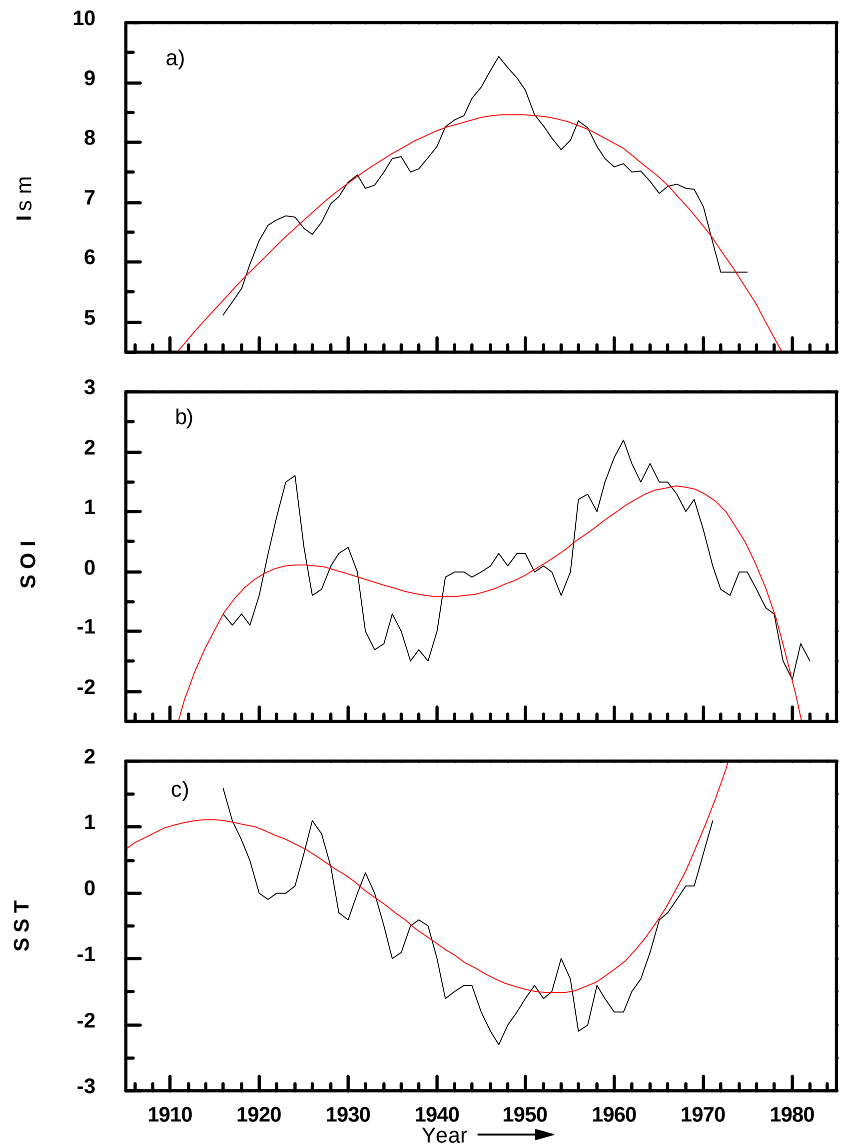

Figure 4. Polynomial fit for 30-yr normalized CMAS of All India moisture status of SW monsoon, SOI of June to September & SST of September to November of NINO3 region.

the Bay of Bengal and Arabian Sea. The period 1901-1930 is registered the maximum annual number (17.02) of cyclonic disturbances compared to 1931-1960 and 1961-1990 (Fig.7). It is observed that the mean monthly frequency of cyclonic disturbances is increased during the months of May, November and December of the period 1961-1990 compared to the periods 1901-1930 and 1931-1960.

From the Bay of Bengal and Arabia Sea, on an average per annum the frequency of storms is 5.52. The mean annual number of storms during 1961-1990 was a maximum of 5.44 compared to the epoch of 1931-1960 (Fig.8).

It is observed that the total number of storms during the months of May, September, November and December of the period 1961-1990 increased compared to the corresponding months of the periods 1901-1930 and 1931-1960 respectively (Fig.8).

The normalized 30-yr centered moving averages (CMAs) of cyclonic disturbances from the Bay of Bengal and Arabian Sea is indicating that the decrease has started from 1938 and continued till 1976 (Fig.9). The increased trend from 1906 to 1938 is in general agreement with the increased and decreased trends in SOI and SSTs of NINO3 region respectively. It is interesting to note that the falling trend in number

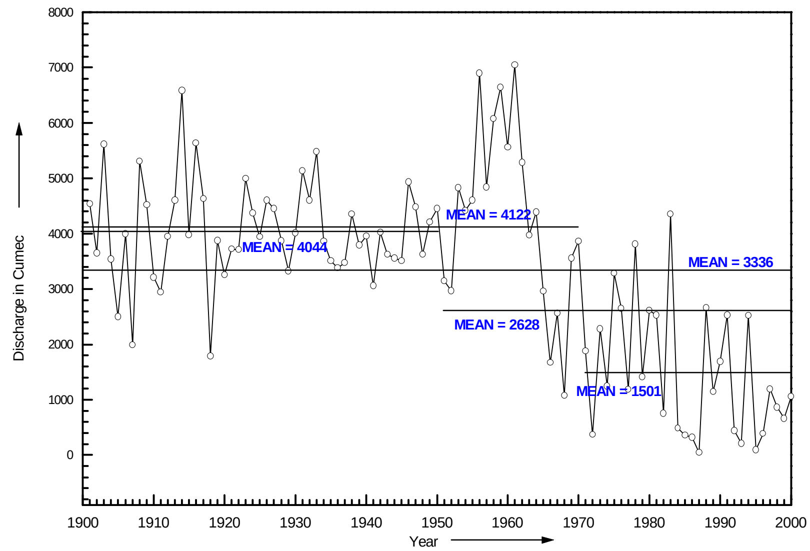

Figure 5. March of mean seasonal Krishna river flows - Vijayawada point.

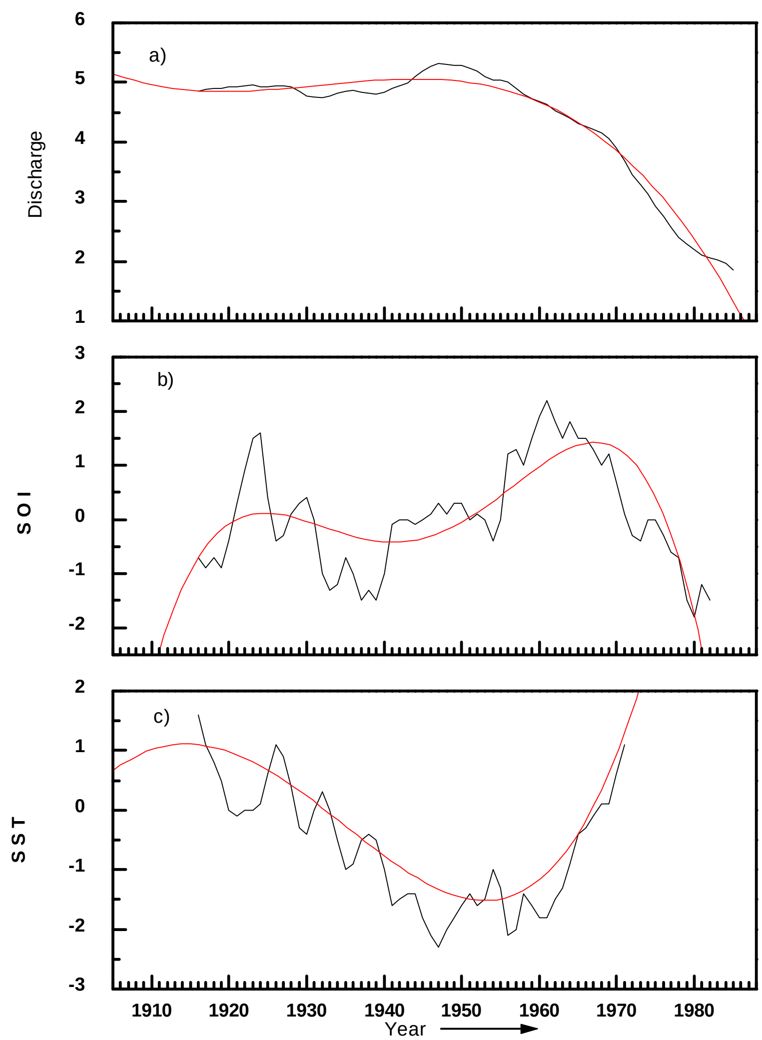

Figure 6. Polynomial fit for 30-yr normalized CMAS of Krishna river flows of SW monsoon at Vijayawada point, SOI of June to September & SST of September to November of NINO3 region.

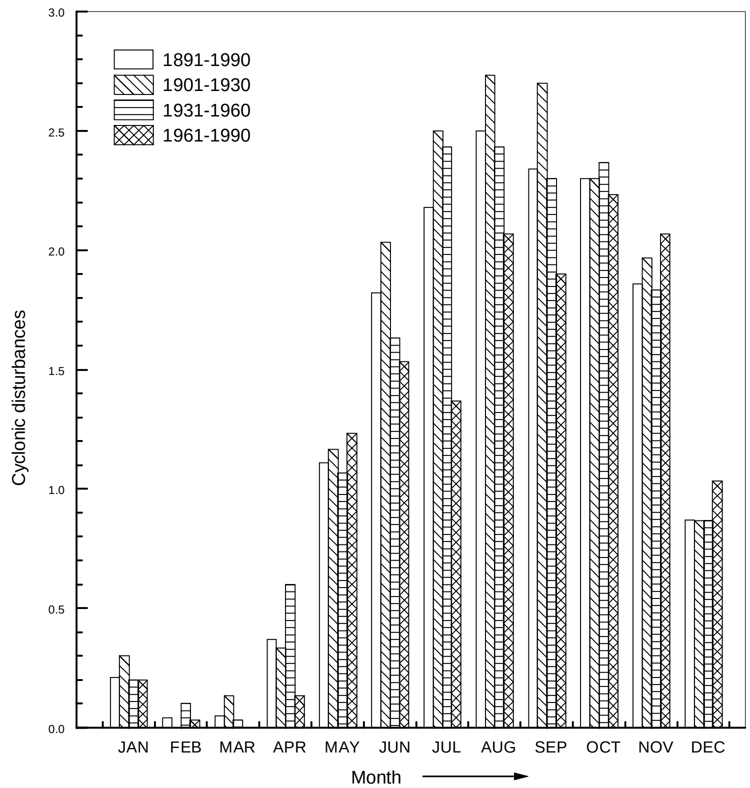

Figure 7. Mean monthly cyclonic disturbances - Bay of Bengal and Arabian Seas.

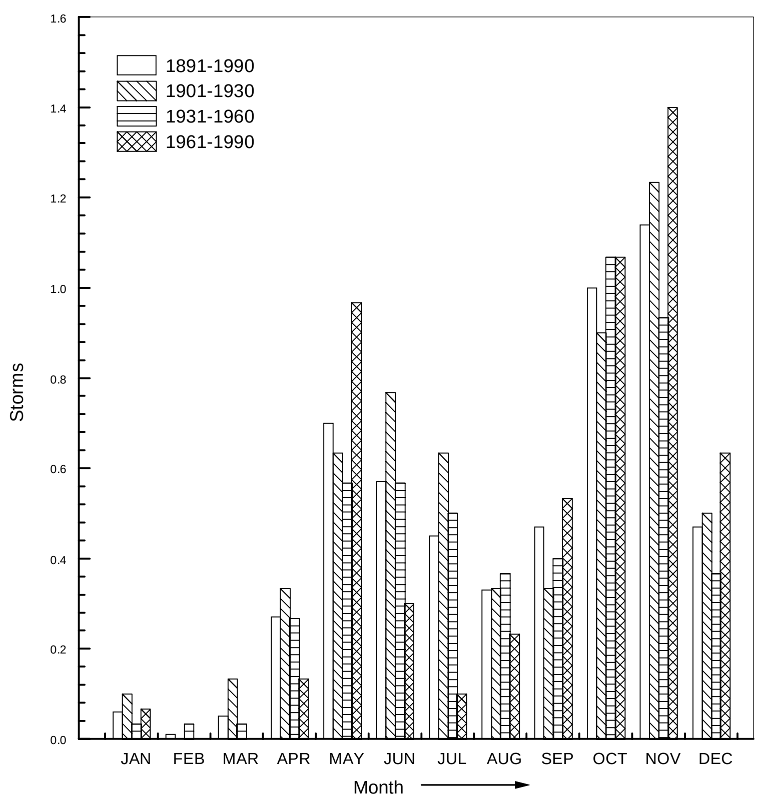

Figure 8. Mean monthly storms - Bay of Bengal and Arabian Seas.

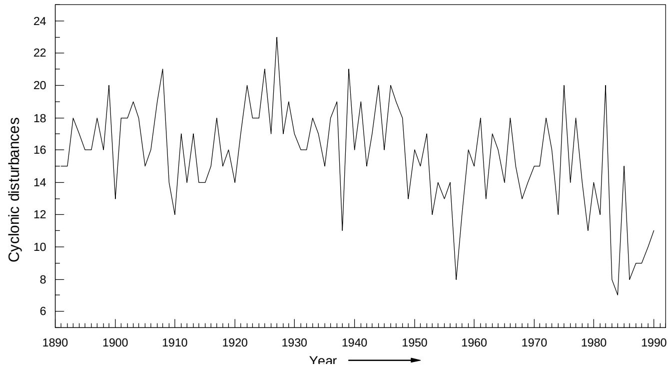

Figure 9a. March of cyclonic disturbances - Bay of Bengal and Arabian Seas.

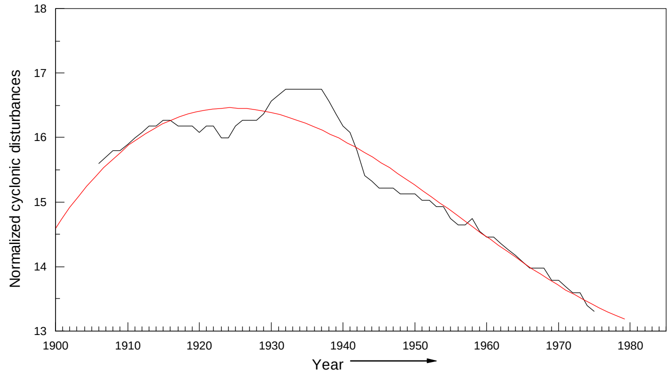

Figure 9b. Third order polynomial fit for normalized 30-year CMAS of cyclonic disturbances - Bay of Bengal and Arabian Seas.

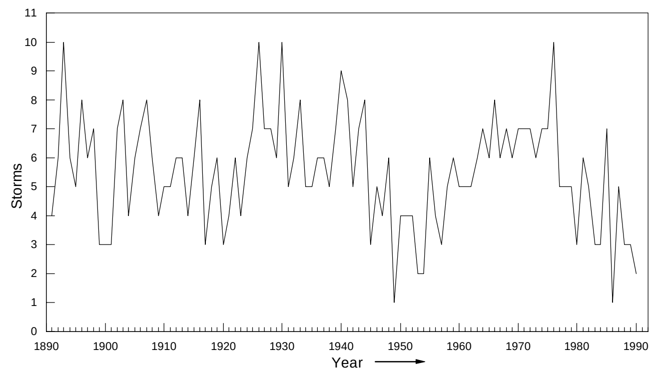

Figure 10a. March of storms - Bay of Bengal and Arabian Seas.

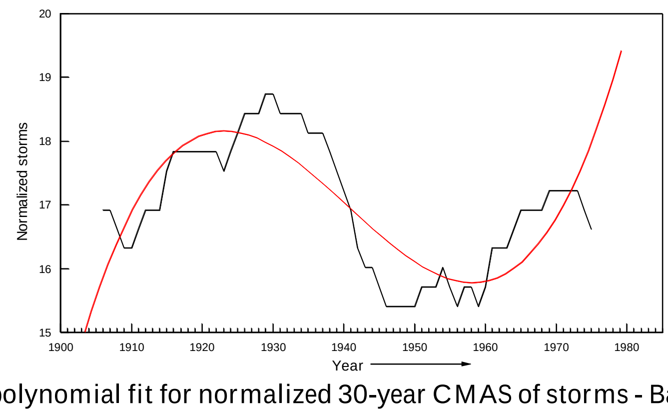

Figure 10b. Third order polynomial fit for normalized 30-year CMAS of storms - Bay of Bengal and Arabian Seas.

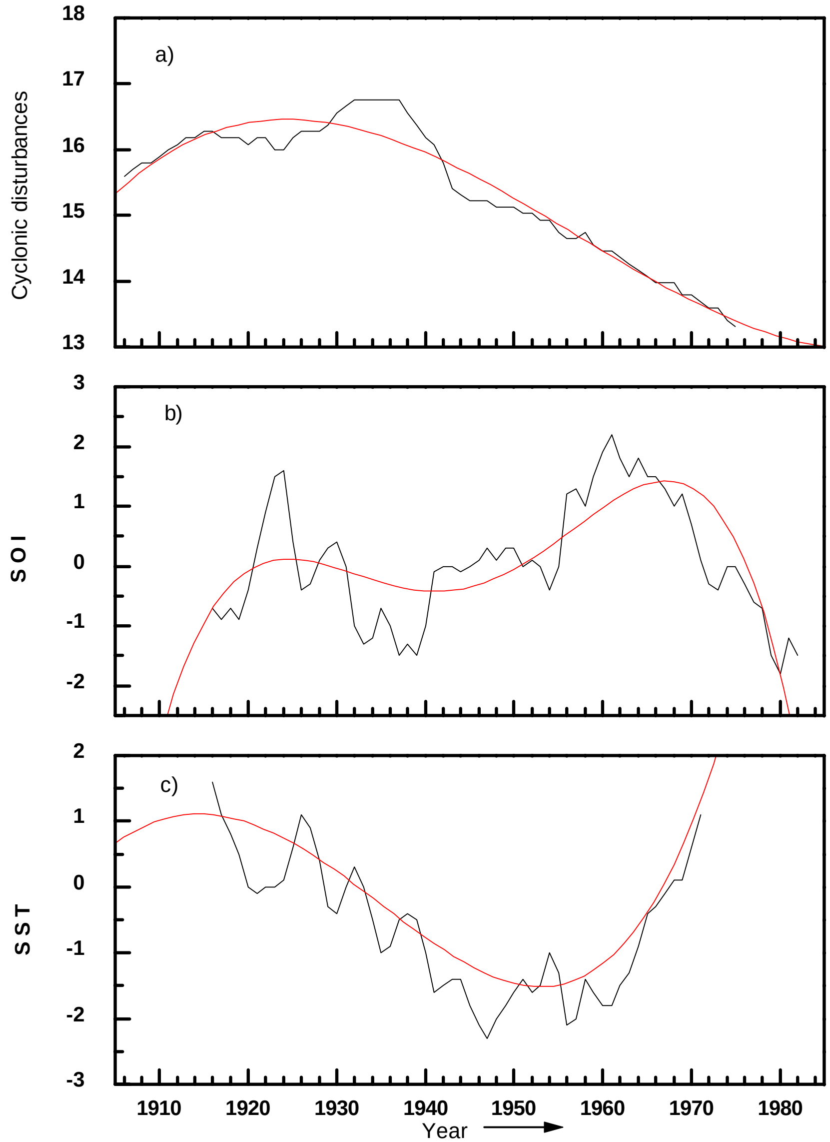

Figure 11. Polynomial fit for 30-year normalized CMAS of cyclonic disturbances of Bay of Bengal and Arabian Seas, SOI of June to September & SST of September to November of NINO3 region.

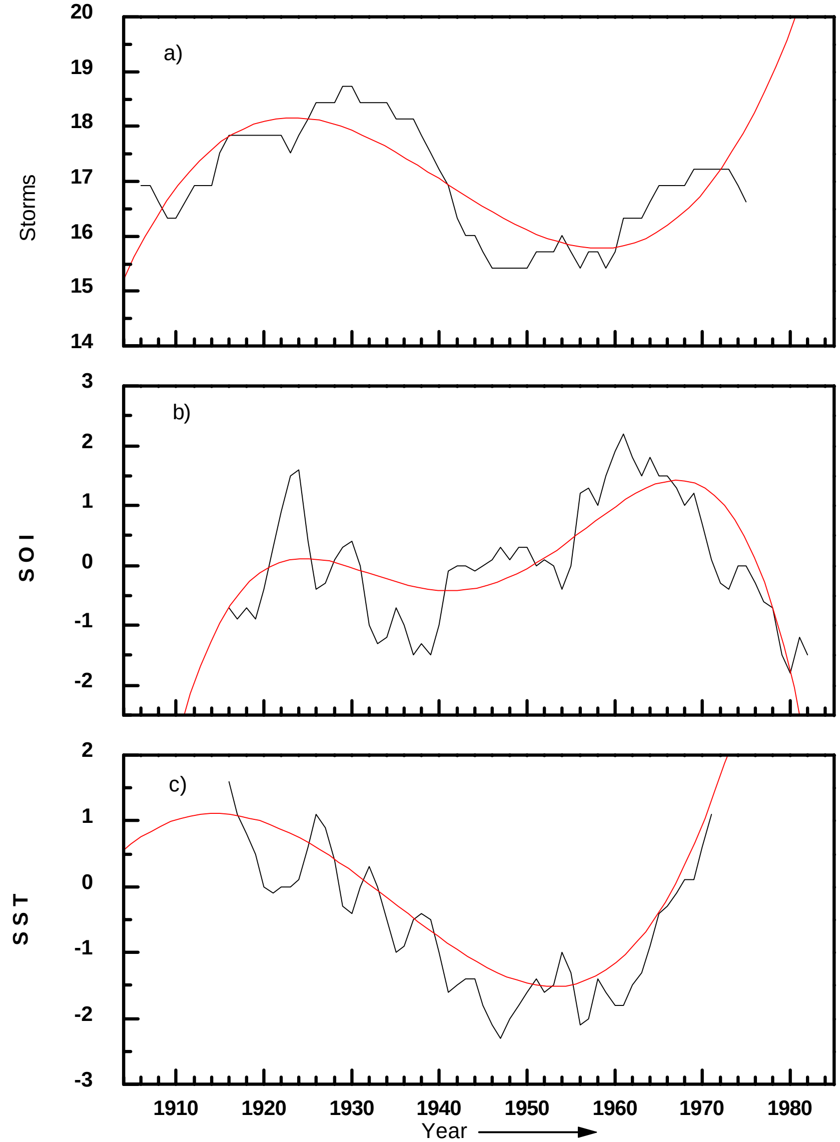

Figure 12. Polynomial fit for 30-year normalized CMAS of storms of Bay of Bengal and Arabian Seas, SOI of June to September & SST of September to November of NINO3 region.

of cyclonic disturbances is in association with negative SOI and increased SSTs of NINO3 region (Fig.10).

The overall trend in the march of normalized 30-yr centered moving averages (CMAs) of cyclonic disturbances is a general decreasing while in the case of storms an increase till 1930 followed by a decrease up to 1960 and thereafter the increase is associated with a decrease in SOI and a sharp rise in SSTs of NINO3 region (Figs 11, 12).

CONCLUSIONS

1. All India's hydrological regime during the s-w monsoon period is moist subhumid, but the analysis of composite El NINO and La NINA scenarios through the water balance model unfolds a dry subhumid and first humid status to it for such cases respectively. The consequences of subnormal performance of s-w monsoon along with the ENSO mode might be the causal factors for the decreased and increased number of humid and climate shift events during the epoch 1971-1990 compared to 1901-1970.
2. The trend analysis of the normalized 30-yr CMA's of seasonal climate indices of aridity, humidity and moisture status with the cold and warm phases of ENSO revealed that while aridity is decreasing with increase and decrease trends in SOI and SSTs of NINO3 region respectively, the humidness and moisture status are improving for All India. The mean seasonal flows of Krishna river basin at Vijayawada point is also indicated that increased flows are associated with increased SOI and subnormal SSTs of NINO3 while the decreased ones might be attributed to negative SOI coupled with elevated SSTs of NINO3.
3. On an average the annual frequency of cyclonic disturbances is 15.65 while that of storms is 5.52. The overall trend of cyclonic disturbances is a general decrease from 1938 onwards while in the case of storms an increase till 1930 followed by decrease till 1958 and later on increased with the general decrease associated with negative SOI coupled with increased SSTs of NINO3 region.

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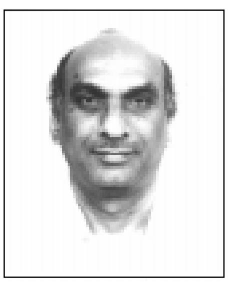

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