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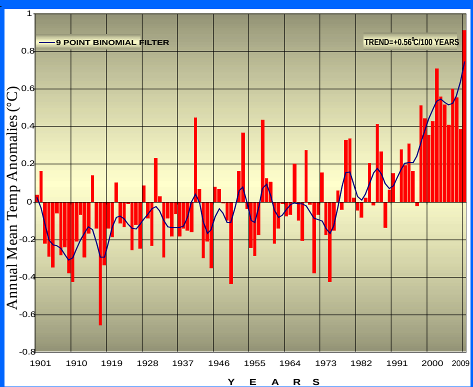
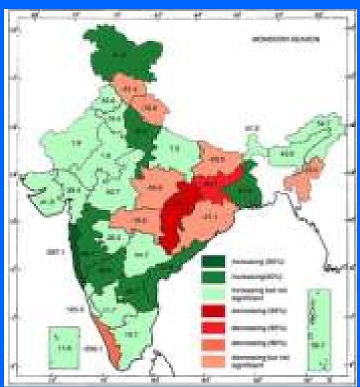
CLIMATE PROFILE OF INDIA

S. D. Attri and Ajit Tyagi





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CLIMATE PROFILE OF INDIA

**Contribution to the
Indian Network of Climate Change Assessment
(NATIONAL COMMUNICATION-II)
Ministry of Environment and Forests**

S D Attri and Ajit Tyagi

**India Meteorological Department
Ministry of Earth Sciences
New Delhi**

2010

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IMD is not responsible for any errors and omissions. The geographical boundaries shown in the publication do not necessarily correspond to the political boundaries.

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PREFACE

The beginnings of meteorology in India can be traced to ancient times from the philosophical writings of the Vedic period, contain serious discussion about the processes of cloud formation and rain and the seasonal cycles caused by the movement of earth round the sun. But, the Modern Meteorology is regarded to have had its firm scientific foundation in the 17th century after the invention of thermometer, barometer and the formulation of laws governing the behaviour of atmospheric gases. India is fortunate to have some of the oldest meteorological observatories of the world like those at Calcutta (now Kolkata) in 1785 and Madras (now Chennai) in 1796 for studying the weather and climate of India

India Meteorological Department (IMD) has progressively expanded its infrastructure for meteorological observations, communications, forecasting and weather services and it has concurrently contributed to scientific growth since its inception in 1875. One of the first few electronic computers introduced in the country was provided to IMD for scientific applications in meteorology. India was the first developing country in the world to have its own geostationary satellite, INSAT, for continuous weather monitoring of this part of the globe and particularly for cyclone warning. It has ventured into new areas of application and service, and steadily built upon its infra-structure during its history of 135 years. It has simultaneously nurtured the growth of meteorology and atmospheric science in India for sectoral services. Systematic observation of basic climate, environmental and oceanographic data is vital to capture past and current climate variability.

IMD has provided climatic observations and products to the national requirements including National Communication (NATCOM). To meet the future need, it is in process of augmenting its weather and climate-related observation systems that underpins analytical and predictive capability which is critical for minimising extreme climate variability impacts.

I am hopeful that this publication on “Climate Profile of India” will contribute to the “India’s National Communication-II” to be submitted to UNFCCC next year. The publication is based on the work mainly carried out by IMD scientists. I extend my sincere thanks to Sh. A K Bhatnagar, Dr A Mazumdar, Dr Y E A Raj, Sh B. Mukhopadhyay, Sh N Y Apte, Dr Medha Khole, Dr M Mohapatra, Dr A K Srivastava and Dr J Sarkar for providing requisite inputs.

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Director General of Meteorology

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16	Abstract	Normal climatic pattern and long term trends over India during last more than 100 years have been presented here. The publication contains studies with latest data on various aspects of important weather / climate systems viz. Monsoons, Cyclone, Drought, Floods and observational weather / climate mechanism in the country. Status and trends in parameters of atmospheric environment viz. radiation, ozone, precipitation chemistry etc has been depicted. The publication is also intended to provide requisite details for Indian Network of Climate Change Assessment (INCCA) to address climate change issues.
17	Key words	Climate Change, Cyclone, Monsoon, Drought, Flood, Environment

CLIMATE PROFILE OF INDIA

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Chapter - I

CLIMATE PROFILE

1. Introduction

India is home to an extraordinary variety of climatic regions, ranging from tropical in the south to temperate and alpine in the Himalayan north, where elevated regions receive sustained winter snowfall. The nation's climate is strongly influenced by the Himalayas and the Thar Desert. The Himalayas act as a barrier to the frigid katabatic winds flowing down from Central Asia keeping the bulk of the Indian subcontinent warmer than most locations at similar latitudes. As such, land areas in the north of the country have a continental climate with severe summer conditions that alternates with cold winters when temperatures plunge to freezing point. In contrast are the coastal regions of the country, where the warmth is unvarying and the rains are frequent.

The country is influenced by two seasons of rains, accompanied by seasonal reversal of winds from January to July. During the winters, dry and cold air blowing from the northerly latitudes from a north-easterly direction prevails over the Indian region. Consequent to the intense heat of the summer months, the northern Indian landmass becomes hot and draws moist winds over the oceans causing a reversal of the winds over the region which is called the summer or the south-west monsoon This is most important feature controlling the Indian climate because about 75% of the annual rainfall is received during a short span of four months (June to September). Variability in the onset, withdrawal and quantum of rainfall during the monsoon season has profound impacts on water resources, power generation, agriculture, economics and ecosystems in the country. The variation in climate is perhaps greater than any other area of similar size in the world. There is a large variation in the amounts of rainfall received at different locations. The average annual rainfall is less than 13 cm over the western Rajasthan, while at Mausiram in the Meghalaya has as much as 1141 cm. The rainfall pattern roughly reflects the different climate regimes of the country, which vary from humid in the northeast (about 180 days rainfall in a year), to arid in Rajasthan (20 days rainfall in a year). So significant is the monsoon season to the Indian climate, that the remaining season are often referred relative to the monsoon.

The rainfall over India has large spatial as well as temporal variability. A homogeneous data series has been constructed for the period 1901-2003 based on the uniform network of 1476 stations and analyzed the variability and trends of rainfall. Normal rainfall (in cm) pattern of the country for the four seasons and annual are depicted in Fig 1 and Fig 2 respectively. Normal monsoon rainfall more than 150cm is being observed over most parts of northeast India, Konkan & Goa. Normal monsoon rainfall is more than 400cm over major parts of Meghalaya. Annual rainfall is more than 200 cm over these regions.

For the country as whole, mean monthly rainfall during July (286.5 mm) is highest and contributes about 24.2% of annual rainfall (1182.8 mm). The mean rainfall during August is slightly lower and contributes about 21.2% of annual rainfall. June and September rainfall are almost similar and contribute 13.8% and 14.2% of annual rainfall, respectively. The mean south-west monsoon (June, July, August & September) rainfall (877.2 mm) contributes 74.2% of annual rainfall (1182.8 mm). Contribution of pre-monsoon (March, April & May) rainfall and post-monsoon (October, November & December) rainfall in annual rainfall is mostly the same (11%). Coefficient of variation is higher during the months of November, December, January and February.

India is characterised by strong temperature variations in different seasons ranging from mean temperature of about 10°C in winter to about 32 °C in summer season (Fig 3). Details of weather along with associated systems during different seasons are presented as under:

1.1 Winter Season / Cold Weather Season (January and February)

India Meteorological Department (IMD) has categorised the months of January and February in winter season. However, December can be included in this season for north-western parts of the country. This season starts in early December associated with clear skies, fine weather, light northerly winds, low humidity and temperatures, and large daytime variations of temperature . The cold air mass extending from the Siberian region, has profound influence on the Indian subcontinent (at least all of the north and most of central India) during these months. The mean air temperatures increase from north to south up to 17°N, the decrease being sharp as one moves northwards in the north-western parts of the country. The mean temperatures vary from 14 °C to 27°C during January. The mean daily minimum temperatures range from 22 °C in the extreme south, to 10 °C in the northern plains and 6 °C in Punjab. The rains during this season generally occur over the western Himalayas, the extreme north-eastern parts, Tamil Nadu and Kerala. Western disturbances and associated trough in westerlies are main rain bearing system in northern and eastern parts of the country.

1.2 Pre-monsoon season/ Summer season/ Hot weather season/ Thunderstorm season (March, April and May)

The temperatures start to increase all over the country in March and by April, the interior parts of the peninsula record mean daily temperatures of 30-35 °C. Central Indian land mass becomes hot with daytime maximum temperatures reaching about 40°C at many locations. Many stations in Gujarat, North Maharashtra, Rajasthan and North Madhya Pradesh exhibit high day-time and low night-time temperatures during this season. The range of the daytime maximum and night-time minimum temperatures in found more than 15 °C at many stations in these States. Maximum temperatures rise sharply exceeding 45 °C by the end of May and early June resulting in harsh summers in the north and north-west regions of the country. However, weather remains mild in coastal areas of the country owing to the influence of land and sea breezes.

The season is characterised by cyclonic storms, which are intense low pressure systems over hundreds to thousands of kilometres associated with surface winds more than 33 knots over the Indian seas viz. Bay of Bengal and the Arabian Sea. These systems generally move towards a north-westerly direction and some of them recurve to northerly or northeasterly path. Storms forming over the

Bay of Bengal are more frequent than the ones originating over the Arabian Sea. On an average, frequency of these storms is about 2.3 per year.

Weather over land areas is influenced by thunderstorms associated with rain and sometimes with hail in this season. Local severe storms or violent thunderstorms associated with strong winds and rain lasting for short durations occur over the eastern and north eastern parts over Bihar, West Bengal, and Assam. They are called norwesters or "Kal Baisakhis" as generally approach a station from the northwesterly direction. Thunderstorms are also observed over central India extending to Kerala along wind-discontinuity lines. Hot and dry winds accompanied with dust winds ("andhis") blow frequently over the plains of north-west India.

1.3 South-west Monsoon/ Summer Monsoon (June, July, August and September)

The SW monsoon is the most significant feature of the Indian climate. The season is spread over four months, but the actual period at a particular place depends on onset and withdrawal dates. It varies from less than 75 days over West Rajasthan, to more than 120 days over the south-western regions of the country contributing to about 75% of the annual rainfall.

The onset of the SW monsoon normally starts over the Kerala coast, the southern tip of the country by 1 June, advances along the Konkan coast in early June and covers the whole country by middle of July. However, onset occurs about a week earlier over islands in the Bay of Bengal. The monsoon is a special phenomenon exhibiting regularity in onset and distribution within the country, but inter-annual and intrannual variations are observed. The monsoon is influenced by global and local phenomenon like El Nino, northern hemispheric temperatures, sea surface temperatures, snow cover etc. The monsoonal rainfall oscillates between active spells associated with widespread rains over most parts of the country and breaks with little rainfall activity over the plains and heavy rains across the foothills of the Himalayas. Heavy rainfall in the mountainous catchments under 'break' conditions results flooding over the plains. However, very uncomfortable weather due to high humidity and temperatures is the feature associated with the Breaks.

Cyclonic systems of low pressure called ‘monsoon depressions’ are formed in the Bay of Bengal during this season. These systems generally form in the northern part of the Bay with an average frequency of about two to three per month and move in a northward or north-westward direction, bringing well-distributed rainfall over the central and northern parts of the country. The distribution of rainfall over northern and central India depends on the path followed by these depressions. SW monsoon current becomes feeble and generally starts withdrawing from Rajasthan by 1st September and from north-western parts of India by 15th September. It withdraws from almost all parts of the country by 15th October and is replaced by a northerly continental airflow called North-East Monsoon. The retreating monsoon winds cause occasional showers along the east coast of Tamil Nadu, but rainfall decreases away from coastal regions.

1.4 Post-monsoon or Northeast monsoon or Retreating SW Monsoon season (October, November and December)

North-East (NE) monsoon or Post-monsoon season is transition season associated with the establishment of the north-easterly wind regime over the Indian subcontinent. Meteorological subdivisions namely Coastal Andhra Pradesh Rayalaseema , Tamil Nadu, Kerala and South Interior Karnataka receive good amount of rainfall accounting for about 35% of their annual total in these months. Many parts of Tamil Nadu and some parts of Andhra Pradesh and Karnataka receive rainfall during this season due to the storms forming in the Bay of Bengal. Large scale losses to life and property occur due to heavy rainfall, strong winds and storm surge in the coastal regions. The day temperatures start falling sharply all over the country. The mean temperatures over north-western parts of the country show decline from about 38°C in October to 28°C in November. Decrease in humidity levels and clear skies over most parts of north and central India after mid-October are characteristics features of this season (NATCOM 2004, IMD 2010).

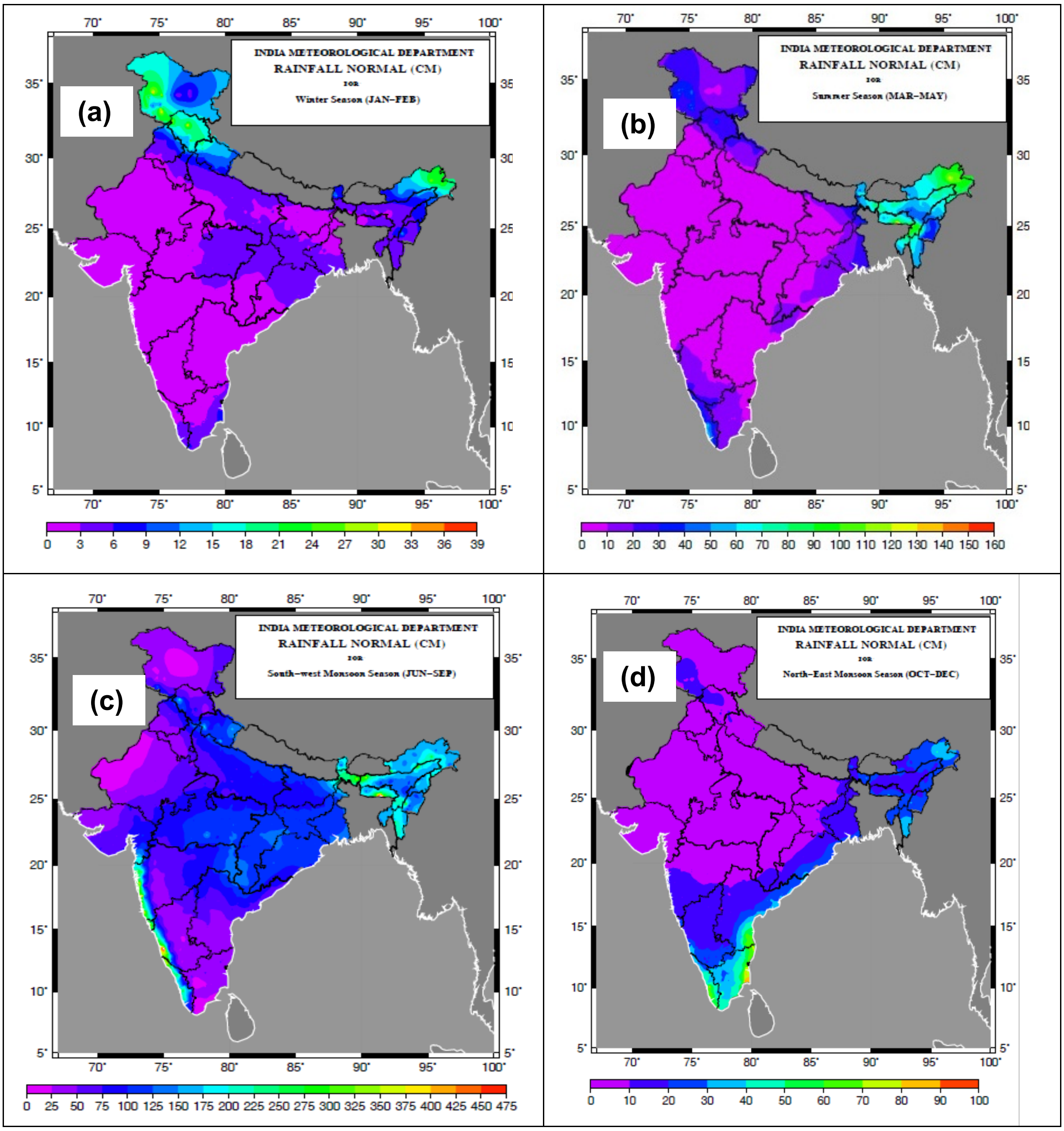


Fig 1: Normal rainfall pattern (cm) during (a) Winter (b) Pre-monsoon (c) Monsoon and (d) Post-Monsoon seasons for the period 1941-90

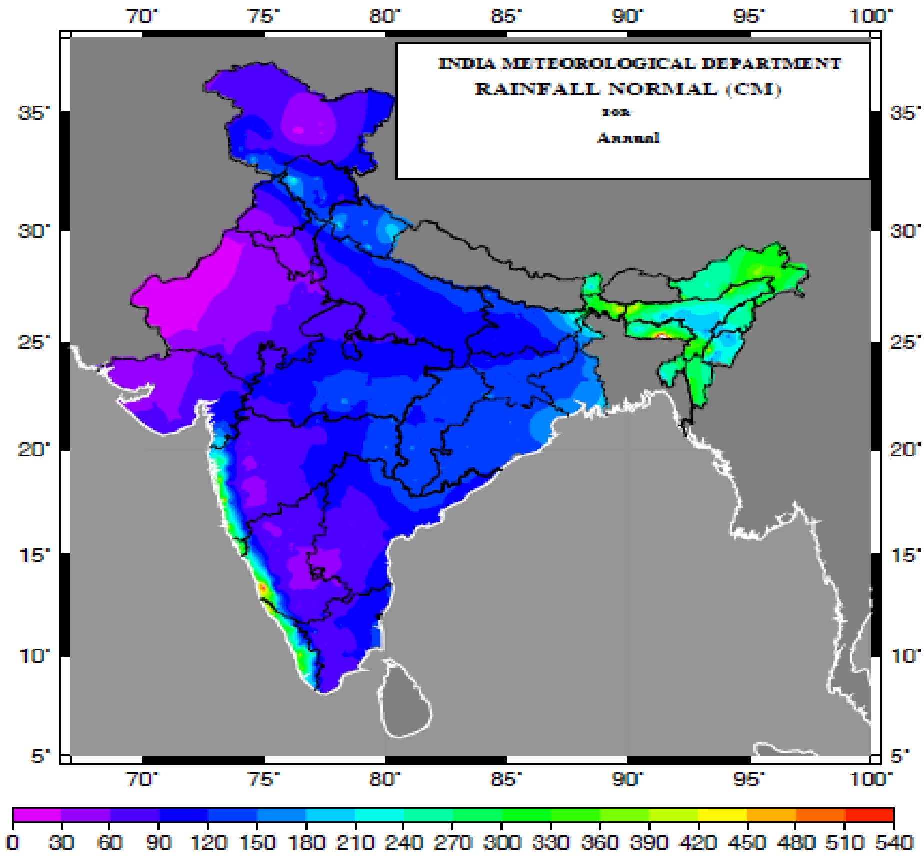


Fig 2: Annual normal rainfall pattern (cm) during 1941-90

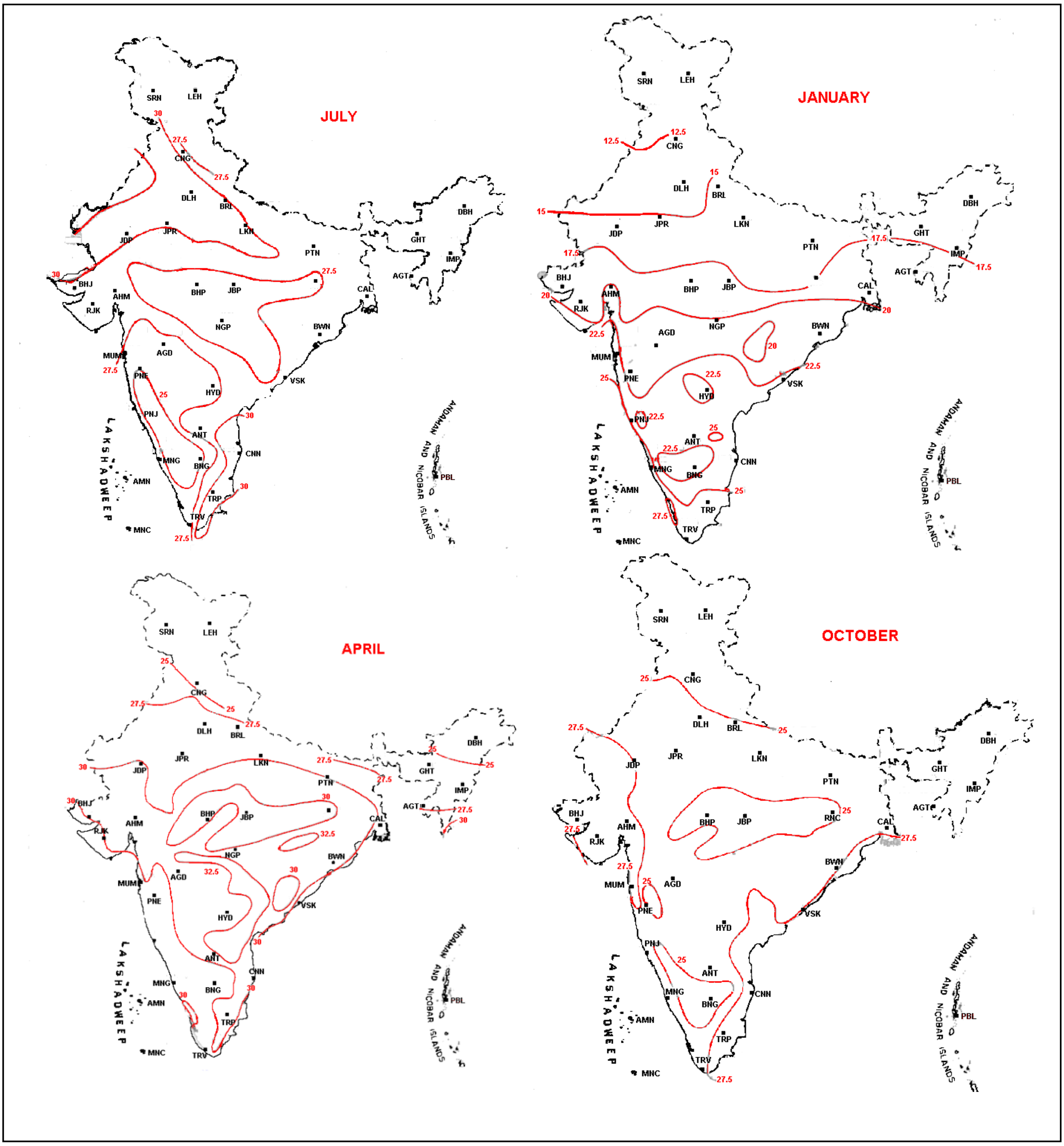


Fig. 3: Seasonal temperature distribution over India

Chapter - II

SYSTEMATIC OBSERVATIONS

Agriculture based economy under favourable climatic conditions of the summer monsoon has necessitated a closer linkage with weather and climate since the Vedic period. Ancient Indian literature by Varahmihir, the *'Brihat-Samhita'*, is an example of ancient Indian weather research. Modernized meteorological observations and research in India was initiated more than 200 years ago, since 1793, when the first Indian meteorological observatory was set up at Madras (now Chennai). IMD was formally established in 1875 with a network of about 90 weather observatories for systematic observation and research. Agricultural-meteorology directorate was created in 1932 to further augment the observation network. Many data and research networks have been added during the 135 years for climate-dependent sectors, such as agriculture, forestry, and hydrology, rendering a modern scientific background to atmospheric science in India. The inclusion of the latest data from satellites and other modern observation platforms, such as Automated Weather Stations (AWS), and ground-based remote-sensing techniques, has strengthened India's long-term strategy of building up a self-reliant climate data bank for specific requirements, and also to fulfill international commitments of data exchange for weather forecasting and allied research activities. The latest observational network in depicted in Table 1.

2.1 Institutional arrangements

The Ministry and Environment and Forests (MoEF), Ministry of Earth Sciences (MoES), Ministry of Science and Technology (MST), Ministry of Agriculture (MoA), Ministry of Water Resources (MWR), Ministry of Human Resource Development (MHRD), Ministry of Nonconventional Energy (MNES), Ministry of Defence (MoD), Ministry of Health and Family welfare (MoHFW), Indian Space Research Organization (ISRO) and India Meteorological Department (IMD) promote and undertake climate and climate change-related research in the country. The MoES, MoEF, MST, MHRD and MOA also coordinate research and observations in many premier national research laboratories and universities. The IMD possesses a vast weather observational network and is involved in regular data collection basis, data bank management, research and weather forecasting for national policy needs.

2.2 Atmospheric monitoring

There are 25 types of atmospheric monitoring networks that are operated and coordinated by the IMD. This includes meteorological/climatological, environment/ air pollution and other specialized observation of atmospheric trace constituents. It maintains 559 surface meteorological observatories, about 35 radio-sonde and 64 pilot balloon stations for monitoring the upper atmosphere. Specialized observations are made for agro-meteorological purposes at 219 stations and radiation parameters are monitored at 45 stations. There are about 70 observatories that monitor current weather conditions for aviation. Although, severe weather events are monitored at all the weather stations, the monitoring and forecasting of tropical cyclones is specially done through three Area Cyclone Warning Centres (Mumbai, Chennai, and Kolkata) and three cyclone warning centres (Ahmedabad, Vishakhapatnam and Bhubaneswar), which issue warnings for tropical storms and other severe weather systems affecting Indian coasts. Storm and cyclone detections radars are installed all along the coast and some key inland locations to observe and forewarn severe weather events, particularly tropical cyclones. The radar network is being upgraded by modern Doppler Radars, with enhanced observational capabilities, at many locations.

In another atmospheric observation initiative, the IMD established 10 stations in India as a part of World Meteorological Organization's (WMO) Global Atmospheric Watch (GAW, formerly known as Background Air Pollution Monitoring Network or BAPMoN). The Indian GAW network includes Allahabad, Jodhpur, Kodaikanal, Minicoy, Mohanbari, Nagpur, Port Blair, Pune, Srinagar and Visakhapatnam. Atmospheric turbidity is measured using hand-held Volz's Sunphotometers at wavelength 500 nm at all the GAW stations. Total Suspended Particulate Matter (TSPM) is measured for varying periods at Jodhpur using a High Volume Air Sampler. Shower-wise wet only precipitation samples are collected at all the GAW stations using specially designed wooden precipitation collectors fitted with stainless steel or polyethylene funnel precipitation collectors. After each precipitation event, the collected water is transferred to a large storage bottle to obtain a monthly sample. Monthly mixed samples collected from these stations are sent to the National Chemical Laboratory, Pune, where these are analyzed for pH, conductivity, major cations (Ca, Mg, Na, K, NH_4+) and major anions ($SO_4$2-, NO_3-, Cl-).

The IMD established the glaciology Study Research Unit in Hydromet. Directorate in 1972. This unit has been participating in glaciological expedition organized by the GSI and the DST. The unit was established for the: (a) determination of the natural water balance of various river catchment areas for better planning and management of the country's water resources; (b) snow melt run-off and other hydrological forecasts; (c) reservoir regulation; (d) better understanding of climatology of the Himalaya; and (e) basic research of seasonal snow cover and related phenomena. The IMD has established observing stations over the Himalayan region to monitor weather parameters over glaciers.

In view of the importance of data in the tropical numerical weather prediction, IMD has been in the process of implementing a massive modernization programme for upgrading and enhancing its observation system. It is establishing 550 AWS out of which about 125 will have extra agricultural sensors like solar radiation, soil moisture and soil temperature, 1350 Automatic Rain Gauge (ARG) stations and 10 GPS in 2009 and will increase these to 1300, 4000 and 40, respectively . In addition to this, a network of 55 Doppler Weather Radar has been planned of which 12 are to be commissioned in the first phase. DWR with the help of algorithms can detect and diagnose weather phenomena, which can be hazardous for agriculture, such as hail, downbursts and squall. A new satellite INSAT-3D is scheduled to be launched during 2011. INSAT-3D will usher a quantum improvement in satellite derived data from multi spectral high resolution imagers and vertical sounder. In addition to above, IMD is also planning to install wind profilers and radiometer to get upper wind and temperature data.

It is also augmenting its monitoring capability of the parameters of atmospheric environment. Trace gases, precipitation chemistry and aerosols will be monitored in the country on a long term basis at 2 baseline and 4 grab sample

GHG monitoring stations, Aerosol monitoring at 14 stations using sky radiometers, Black carbon measurement at 4 stations using aethelometers, Ozone measurements in NE and Port Blair in addition to existing stations in India and Antarctica, Turbidity and Rain Water chemistry at 11 stations and Radiation measurements at 45 stations. The data will be monitored and exchanged globally as per GAW / WMO protocols and quality control will be ensured as per international standards. Such data will be used in C-cycle models to accurately estimate radiation forcing and quantify source and sink potential for policy issues under UN framework.

The IMD, in collaboration with the NPL plays an important role for climate change-related long-term data collection at the Indian Antarctic base-Maitri. Continuous surface meteorological observations for about 22 years are now available for Schirmacher Oasis with National Data Centre of IMD.

The IMD collects meteorological data over oceans by an establishment of cooperation fleet of voluntary observing ships (VOF) comprising merchant ships of Indian registry, some foreign merchant vessels and a few ships of the Indian Navy. These ships, while sailing on the high seas, function as floating observatories. Records of observations are passed on to the IMD for analysis and archival.

2.3 Data archival and exchange

The tremendous increase in the network of observatories resulted in the collection of a huge volume of data. The IMD has climatological records even for the period prior to 1875, when it formally came into existence. This data is digitized, quality controlled and archived in electronic media at the National Data Centre, Pune. The current rate of archival is about three million records per year. At present, the total holding of data is about 9.7 billion records. They are supplied to universities, industry, research and planning organizations. The IMD prepared climatological tables and summaries/ atlases of surface and upper-air meteorological parameters and marine meteorological summaries. These climatological summaries and publications have many applications in agriculture, shipping, transport, water resources and industry.

The IMD has its own dedicated meteorological telecommunication network with the central hub at New Delhi. Under the WWW Global Telecommunication System, New Delhi functions as a Regional Telecommunication Hub (RTH) on the main telecommunication network. This centre was automated in early 1976, and is now known as the National Meteorological Telecommunication Centre (NMTC), New Delhi. Within India, the telecommunication facility is provided by a large network of communication links. The websites of IMD viz. *http://www.imd.gov.in* / http://www.mausam.gov.in operational from 1 June, 2000 contains dynamically updated information on all-India weather and forecasts, special monsoon reports, satellite cloud pictures updated every three hours, Limited Area Model (LAM), Global Circulation Model (GCM) generated products and prognostic charts, special weather warnings, tropical cyclone information and warnings, weekly and monthly rainfall distribution maps, earthquake reports, etc. It also contains a lot of static information, including temperature and rainfall normal over the country; publications, data archival details, monitoring networks and a brief overview of the activities and services rendered by IMD.

2.4 Augmentation of Weather and Climate forecasting capabilities (short, medium and long range)

In view of growing operational requirements from various user agencies, IMD has embarked on a seamless forecasting system covering short range to extended range and long range forecasts. Such forecasting system is based on hierarchy of Numerical Weather Prediction (NWP) models. For a tropical country like India where high impact mesoscale convective events are very common weather phenomena, it is necessary to have good quality high density observations both in spatial and temporal scale to ingest into assimilation cycle of a very high resolution non-hydrostatic mesoscale model. A major problem related to skill of NWP models in the tropics is due to sparse data over many parts of the country and near absence of data from oceanic region.

Data from AWSs, ARGs, DWRs, INSAT-3D and wind profilers are available in real time for assimilation in NWP models. A High Power Computing (HPC) system with 300 terabyte storage has been installed at NWP Centre at Mausam Bhavan. All the systems have started working in an integrated manner in conjunction with other systems, such as all types of observation systems, AMSS, CIPS, HPCS, synergy system etc., in a real-time and have greatly enhanced IMD capability to run global and regional models and produce indigenous forecast products in different time scales. It has also started running a number of global and regional NWP models in the operational mode . IMD also makes use of NWP Global model forecast products of other operational centres, like NCMRWF T-254, ECMWF, JMA, NCEP, WRF and UKMO to meet the operational requirements of day to day weather forecasts. Very recently, IMD has implemented a multimodel ensemble (MME) based district level five days quantitative forecasts in medium range.

Climate-related risks are likely to increase in magnitude and frequency in future. There is need to prioritize actions to improve monitoring of such extremes and refine models for their prediction and projection in longer scale. New levels of integrated efforts like Global Framework for Climate Services/ National Framework for Climate Services (GFCS/NFCS) are required to strengthen climate research at existing and newer institutions to:

- Develop improved methodologies for the assessment of climate impacts on natural and human system
- Characterize and model climate risk on various time and space scales relevant to decision-making and refine climate prediction skills
- Enhance spatial resolution of climate predictions, including improvements in downscaling and better regional climate models
- Improve climate models to represent the realism of complex Earth system processes and their interactions in the coupled system
- Develop a better understanding of the linkages between climatic regimes and the severity and frequency of extreme events
- Enable progress in improving operational climate predictions and streamlining the linkages between research and operational service providers.

IMD is taking initiatives for creation of Indian Climate Observation System (ICOS) to support such services in long run.

A dynamical statistical technique is developed and implemented for the real-time cyclone genesis and intensity prediction. Numbers of experiments are carried out for the processing of DWR observations to use in nowcasting and mesoscale applications. The procedure is expected to be available in operational mode soon. Impact of INSAT CMV in the NWP models has been reported in various studies. Various multi-institutional collaborative forecast demonstration projects such as, Dedicated Weather Channel, Weather Forecast for Commonwealth Games 2010, Land falling Cyclone, Fog Prediction etc. are initiated to strengthen the forecasting capabilities of IMD.

Table 1
Atmospheric monitoring networks

1	Surface observatories	559
2	Pilot balloon observatories	65
3	RS/RW observatories	3
4	Aviation current weather observatories	71
6	Storm detecting radar stations	17
7	Cyclone detection radar stations	10
8	High-wind recording stations	4
9	Stations for receiving cloud pictures from satellites	
	a Low-resolution cloud pictures	7
	b High-resolution cloud pictures	1
	c INSAT-IB cloud pictures(SDUC stations)	20
	d APT Stations in Antarctica	1
	e AVHRR station	1
10	Data Collection Platforms through INSAT	100
11	Hydro-meteorological observatories	701
	a Non-departmental rain gauge stations	
	i Reporting	3540
	ii Non-reporting	5039
	b Non-departmental glaciological observations (non-reporting)	
	i Snow gauges	21
	ii Ordinary rain gauges	10
	iii Seasonal snow poles	6
12	Agro-meteorological observatories	219
13	Evaporation stations	222
14	Evapotranspiration stations	39
15	Seismological observatories	58
16	Ozone monitoring	
	a Total ozone and Umkehr observatories	5
	b Ozone-sonde observatories	3
	c Surface ozone observatories	6
17	Radiation observatories	
	a Surface	45
	b Upper air	8
18	Atmospheric electricity observatories	4
19	*a Background pollution observatories*	10
	b Urban Climatological Units	2
	c Urban Climatological Observatories	13
20	Ships of the Indian voluntary observing fleet	203
21	Soil moisture recording stations	49
22	Dew-fall recording stations	80
23	AWS	550
24	ARG	1300
25	GPS	10

Chapter – III

CLIMATE CHANGE SCENARIO

India Meteorological Department (IMD) maintains a well distributed network of more than 500 stations in the country for more than a century. The salient findings of the IMD studies (IMD Annual Climate Summary, 2009, Tyagi and Goswami, 2009, Attri 2006) are summarized as under:

3.1 Temperature

Analysis of data for the period 1901-2009 suggests that annual mean temperature for the country as a whole has risen by 0.56^0C (Fig 4) over the period. It may be mentioned that annual mean temperature has been generally above normal (normal based on period, 1961-1990) since 1990. This warming is primarily due to rise in maximum temperature across the country, over larger parts of the data set (Fig 5). However, since 1990, minimum temperature is steadily rising (Fig 6) and rate of its rise is slightly more than that of maximum temperature (IMD Annual Climate Summary, 2009). Warming trend over globe of the order of 0.74^0C has been reported by IPCC (2007)

Spatial pattern of trends in the mean annual temperature (Fig 7) shows significant positive (increasing) trend over most parts of the country except over parts of Rajasthan, Gujarat and Bihar, where significant negative (decreasing) trends were observed (IMD Annual Climate Summary, 2009).

Season wise, maximum rise in mean temperature (Fig 8) was observed during the Post-monsoon season (0.77^0C) followed by winter season (0.70^0C), Pre-monsoon season (0.64^0C) and Monsoon season (0.33^0C). During the winter season, since 1991, rise in minimum temperature is appreciably higher than that of maximum temperature over northern plains. This may be due to pollution leading to frequent occurrences of fog.

Upper air temperatures have shown an increasing trend in the lower troposphere and this trend is significant at 850 hPa level, while decreasing trend (not significant) was observed in the upper troposphere (Kothawale and.Rupa Kumar, 2002).

3.2 Precipitation Trends

The country as a whole, the all India annual and monsoon rainfall for the period 1901-2009 do not show any significant trend (Fig. 9a & 9b). Similarly rainfall for the country as whole for the same period for individual monsoon months also does not show any significant trend. The alternating sequence of multi-decadal periods of thirty years having frequent droughts and flood years are observed in the all India monsoon rainfall data. The decades 1961-70, 1971-80 and 1981-90 were dry periods. The first decade (1991-2000) in the next 30 years period already experienced wet period.

However, during the winter season, rainfall is decreasing in almost all the sub-divisions except for the sub-divisions Himachal Pradesh, Jharkhand and Nagaland, Manipur, Mizoram & Tripura. Rainfall is decreasing over most parts of the central India during the pre-monsoon season. However during the post-monsoon season, rainfall is increasing for almost all the sub-divisions except for the nine sub-divisions (Fig 10).

The analysis for the monthly rainfall series of June, July, August, and September (% variation) for all the 36 subdivisions (Guhathakurta, P. and Rajeevan 2008) shows significant variations on the regional scale (Fig. 11) which are summarized as under:

- June rainfall has shown increasing trend for the western and southwestern parts of the country whereas decreasing trends are observed for the central and eastern parts of the country. Its contribution to annual rainfall is increasing in 19 subdivisions and decreasing in the remaining 17 subdivisions.

- The contribution of July rainfall is decreasing in central and west peninsular India (significantly in South interior Karnataka (95%), East M.P.(90%) Vidarbha (90%), Madhya Maharashtra (90%), Marathwada (90%), Konkan & Goa (90%), and North interior Karnataka (90%)), but has increased significantly in the northeastern parts of the country
- In August, four (ten) subdivisions have shown decreasing (increasing) trends in rainfall. It has increased significantly (at 95% significance level) over the subdivisions Konkan and Goa, Marathwada, Madhya Maharashtra, Vidarbha, West M.P., Telangana and west U.P.
- September rainfall is increasing significantly (at 95% level of significance) in Gangetic West Bengal and decreasing significantly (at 90% level of significance) for the sub-divisions Marathwada, Vidarbha and Telangana.

During the season, three subdivisions viz. Jharkhand (95%), Chattisgarh (99%), Kerala (90%) show significant decreasing trends and eight subdivisions viz. Gangetic WB (90%), West UP (90%), Jammu & Kashmir (90%), Konkan & Goa (95%), Madhya Maharashtra (90%), Rayalseema (90%), Coastal A P (90%) and North Interior Karnataka (95%) show significant increasing trends. The trend analyses of the time series of contribution of rainfall for each month towards the annual total rainfall for each year in percentages suggest that contribution of June and August rainfall exhibited significant increasing trends, while contribution of July rainfall exhibited decreasing trends.

However, no significant trend in the number of break and active days during the southwest monsoon season during the period 1951–2003 (Fig 12) were observed (Rajeevan et al 2006).

3.3 Extreme Rainfall events

A large amount of the variability of rainfall is related to the occurrence of extreme rainfall events. The extreme rainfall series at stations over the west coast north of 12°N and at some stations to the east of the Western Ghats over the central parts of the Peninsula showed a significant increasing trend at 95% level of confidence. Stations over the southern Peninsula and over the lower Ganga valley have been found to exhibit a decreasing trend at the same level of significance. Various studies on extreme rainfall over India have found the occurrences of 40 cm or more rainfall along the west and east cost of India, Gangetic West Bengal and north eastern parts of India. Country's highest observed one day point rainfall (156.3 cm) and also world's highest 2-day point rainfall (249.3cm) occurred in Cherrapunji of northeast India in the year 1995 (IMD 2006).

Significant increasing trend was observed in the frequency of heavy rainfall events over the west coast (Sinha Ray & Srivastava, 2000). Most of the extreme rainfall indices have shown significant positive trends over the west coast and northwestern parts of Peninsula. However, two hill stations considered (Shimla and Mahabaleshwar) have shown decreasing trend in some of the extreme rainfall indices (Joshi & Rajeevan, 2006). Increase in heavy and very heavy rainfall events and decrease in low and moderate rainfall events in India have been reported by Goswami et al (2006). Rao et al (2010) have assessed the role of Southern Tropical Indian Ocean warming on unusual central Indian drought of summer monsoon – 2008.

The recent exceptionally heavy rainfall of 944 mm over Mumbai (Santacruz) on 26th July, 2005 was very unprecedented in nature, which led to many more studies on frequency and variability of heavy rainfall events. The development of a high resolution (1° X1° lat./long.) gridded daily rainfall dataset for the Indian region by IMD is very helpful in undertaking such studies. Based on the amount of rainfall in a day, IMD has classified into six categories. However, for extreme event studies, rain has been regrouped into three broad categories viz. i) light to rather heavy rainfall ($0 < R \leq 64.4$ mm), ii) heavy rainfall ($64.4 < R \leq 124.4$ mm) and iii) very heavy to exceptionally heavy rainfall ($R > 124.4$ mm). Rainfall > 124.4 mm will be referred hereafter as extreme rainfall events (Pattanaik and Rajeevan, 2010).

The frequency of extreme rainfall (Rainfall ≥ 124.4 mm) shows increasing trend over the Indian monsoon region during the southwest monsoon season from June to September (JJAS) and is significant at 98% level (Fig. 13). It is also found that the increasing trend of contribution from extreme rainfall events during JJAS is balanced by a decreasing trend in category-i (rainfall ≤ 64.4 mm/day) rainfall events. Similarly on monthly scale, the frequency of extreme rainfall events show significant (95% level) increasing trend during June and July, whereas during August and September the increasing trend is not significant statistically (Fig. 14). Like the frequency of extreme rainfall events, the contribution of extreme rainfall to the total rainfall in a season is also showing highly significant increasing trend during the monsoon season from June to September and during June and July on monthly scale. It is observed that the mean monthly contribution of heavy and extreme rainfall events (rainfall > 64.4 mm in a day) during June-July is 5 to 6% higher than that during August-September and hence contributes significantly to the total rainfall during the first half of the season (June and July).

3.4 Cloud cover over the Indian Seas

Both total and low cloud cover over Arabian Sea and the equatorial Indian Ocean are observed to decrease during the ENSO events. However, cloud cover over Bay of Bengal is not modulated by the ENSO events. On inter-decadal scale, low cloud cover shifted from a "low regime" to a "high regime" after 1980 which may be associated with the corresponding inter-decadal changes of sea surface temperatures over north Indian Ocean observed during the late 1970s (Rajeevan et al., 2000).

3.5 Heat Wave and Cold Wave

A significant increase was noticed in the frequency, persistency and spatial coverage of both of these high frequency temperature extreme events (heat and cold wave) during the decade (1991-2000) (Pai et al. 2004).

3.6 Discomfort indices

It has been found that in general, there is an increasing trend (significant) in the discomfort indices from the last 10 days of April to June over most of the Indian cities (Srivastava, et al. 2007).

This publication is confined to observed climate change. However, future scenario of climate change in India have been brought out by Indian Institute of Tropical Meteorology, Pune (NATCOM 2004, Rupa kumar et al 2006, Krishan Kumar 2009, INCCA 2009)

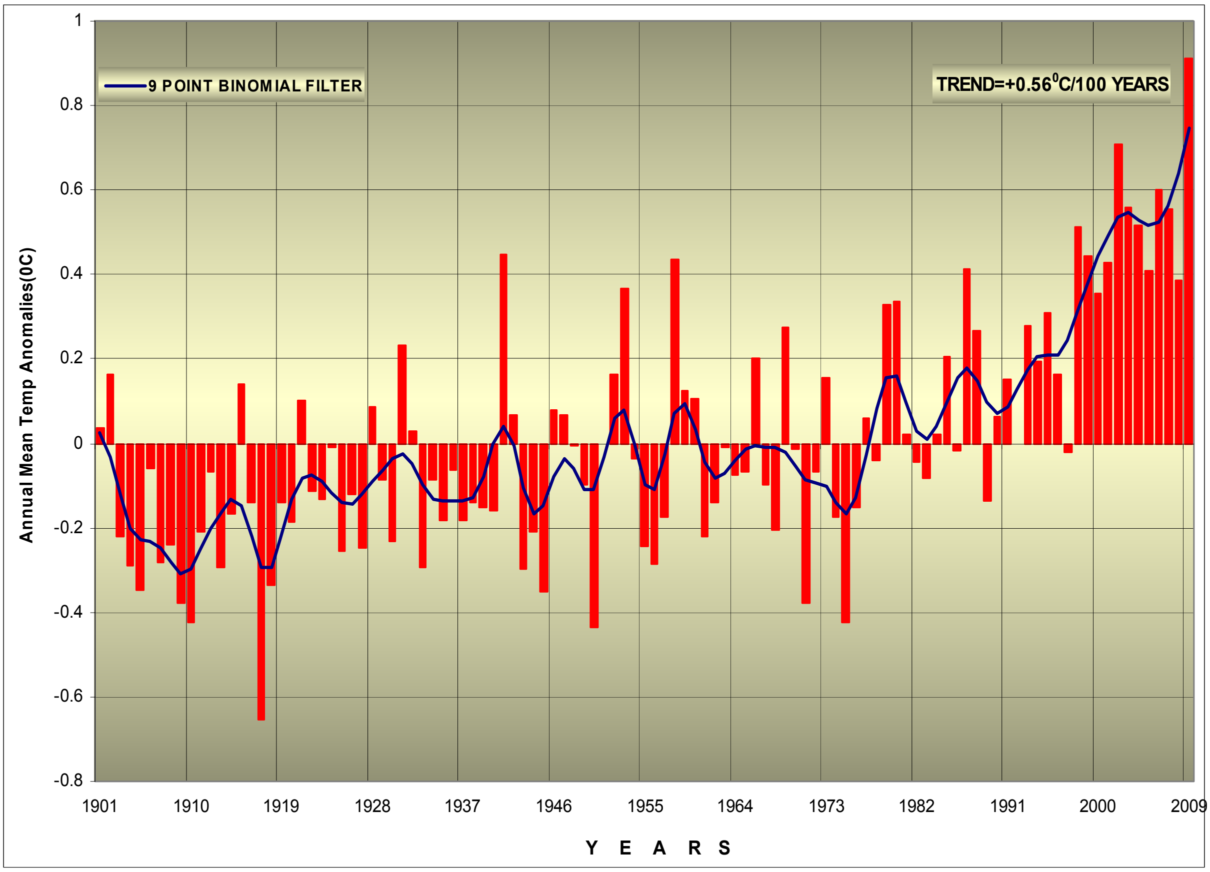


Fig 4: All India annual mean temperature anomalies for the period 1901-2009 (based on 1961-1990 average) shown as vertical bars

(The solid blue curve show sub-decadal time scale variations smoothed with a binomial filter)

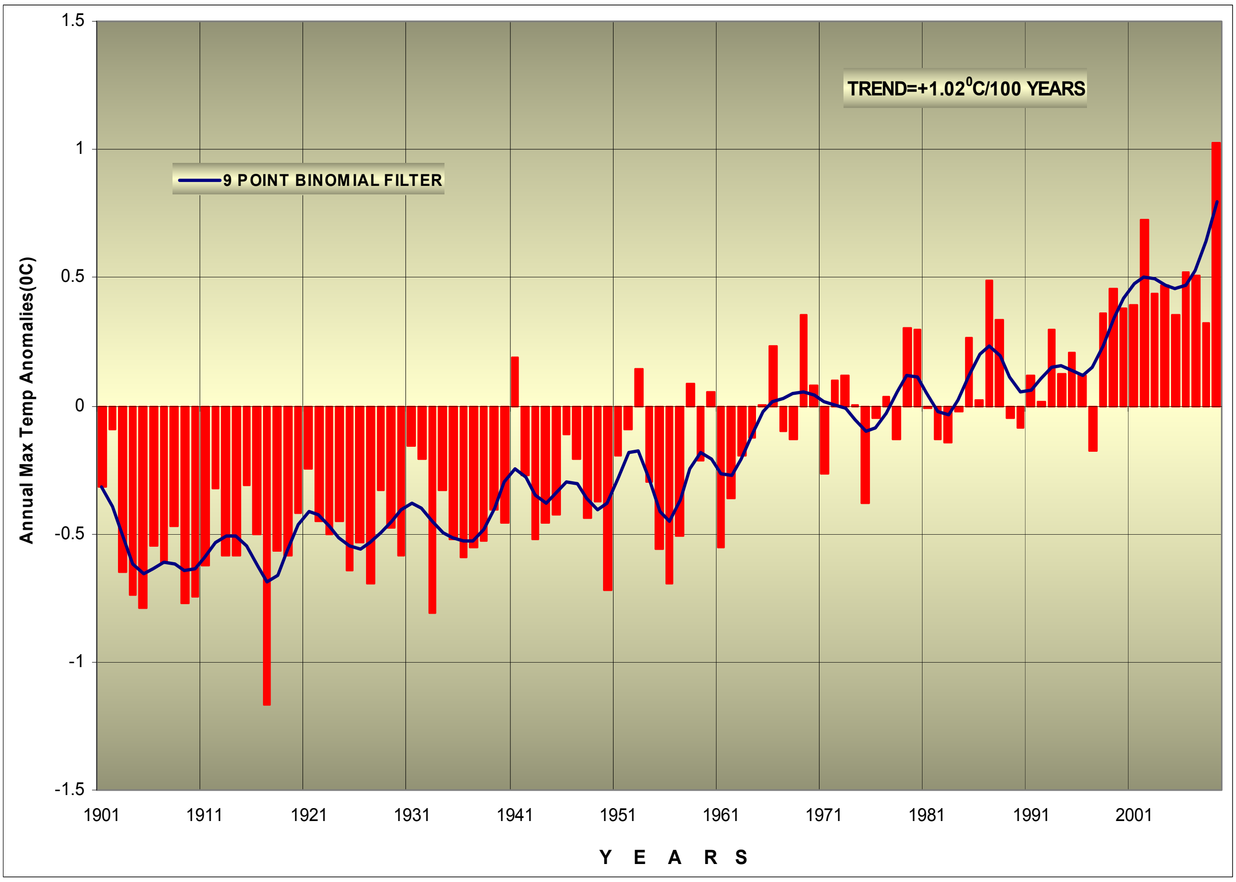


Fig 5: All India annual maximum temperature anomalies for the period 1901-2009 (based on 1961-1990 average) shown as vertical bars

(The solid blue curve show sub-decadal time scale variations smoothed with a binomial filter)

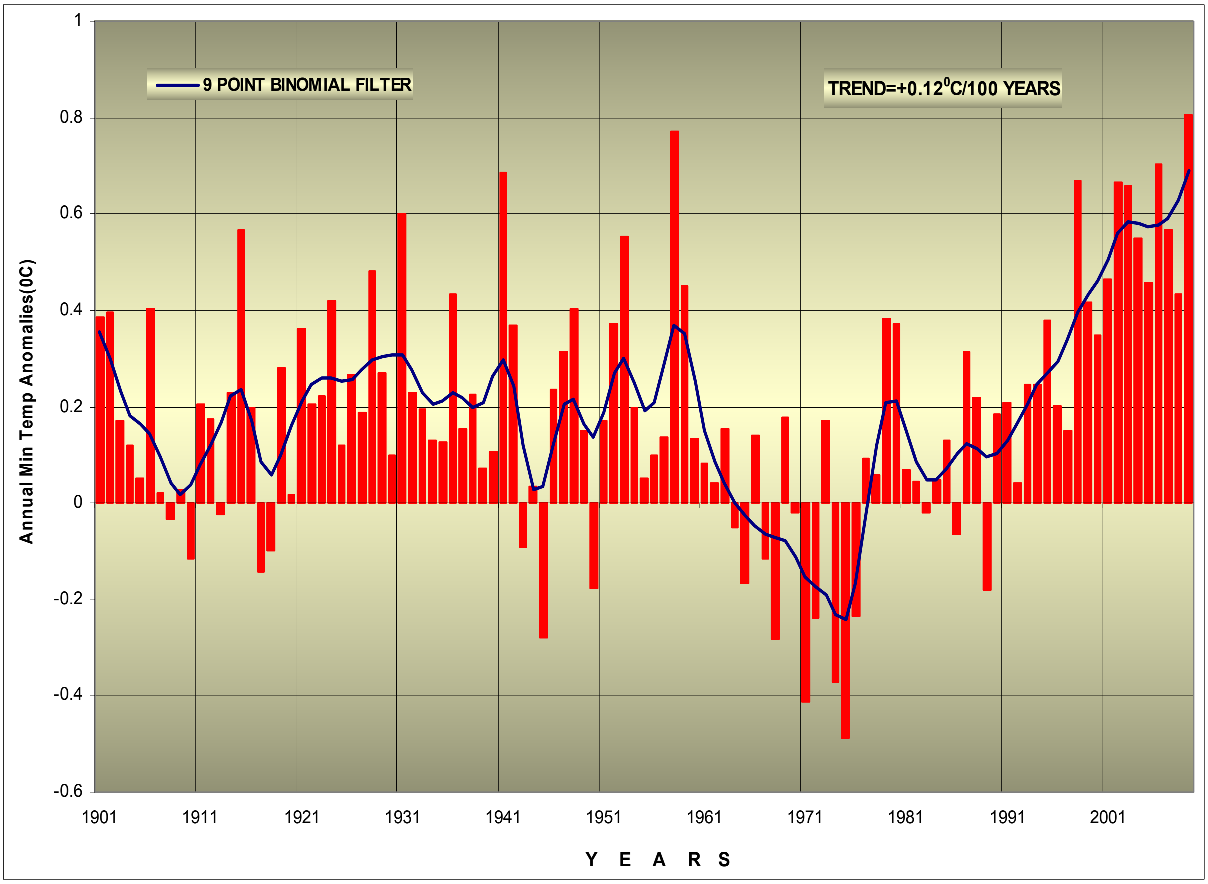


Fig 6: All India annual minimum temperature anomalies for the period 1901-2009 (based on 1961-1990 average) shown as vertical bars

(*The solid blue curve show sub-decadal time scale variations smoothed with a binomial filter)*

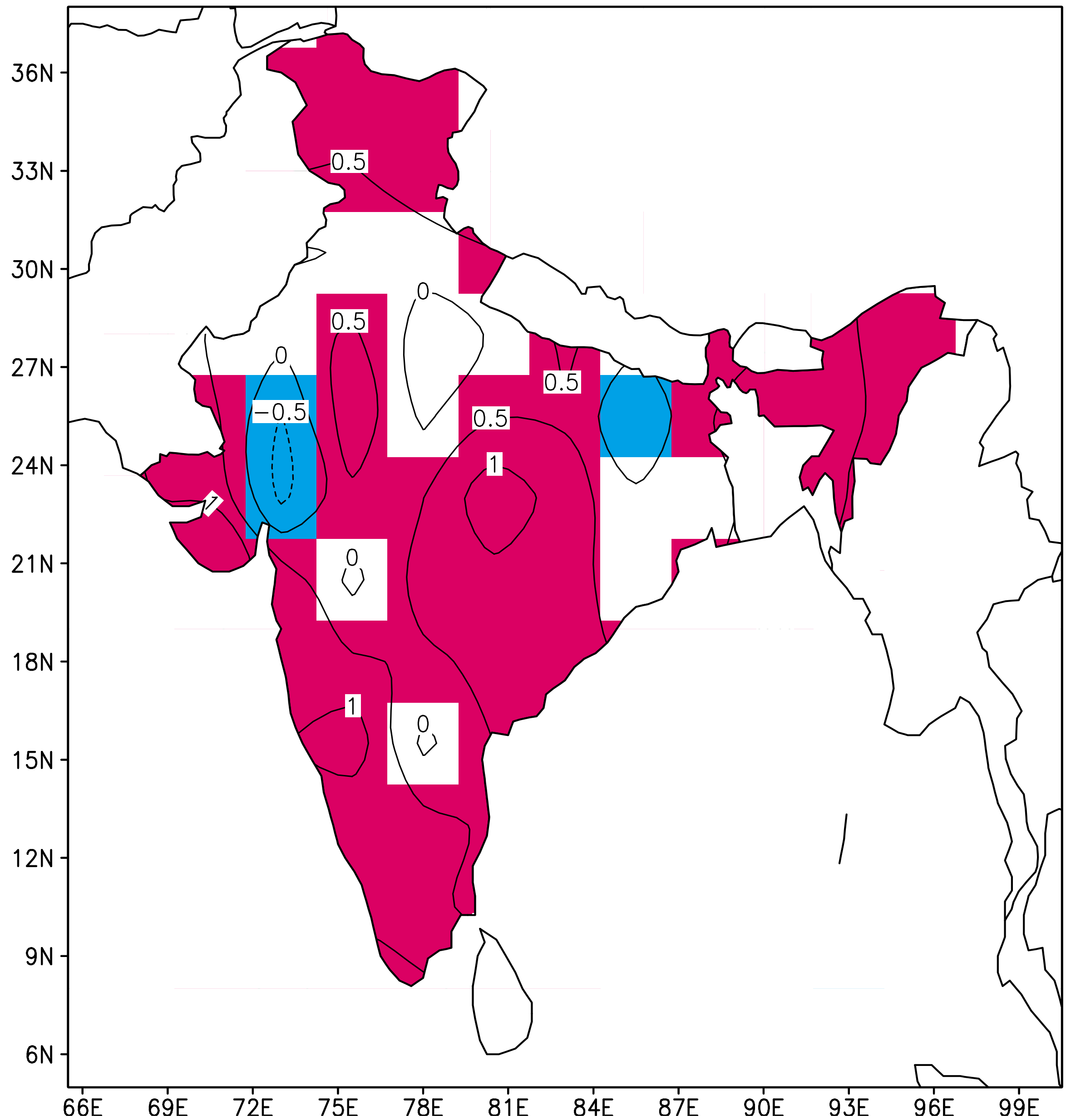


Fig 7: Spatial Pattern of Trend (^{0}c/ 100 years) in Mean Annual Temperature Anomalies (1901-2009). Areas where trends are significant are shaded (red : warming, blue : cooling)

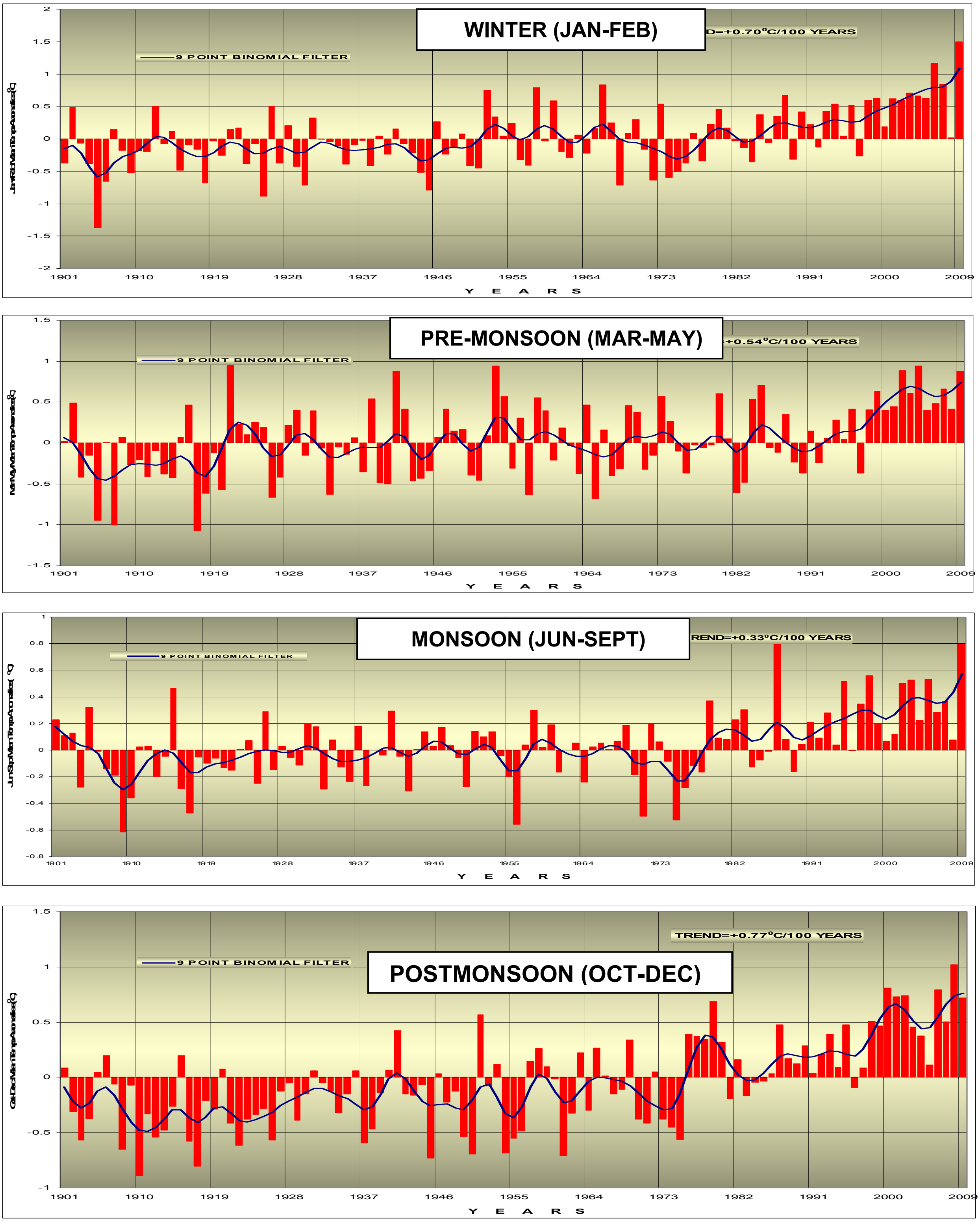
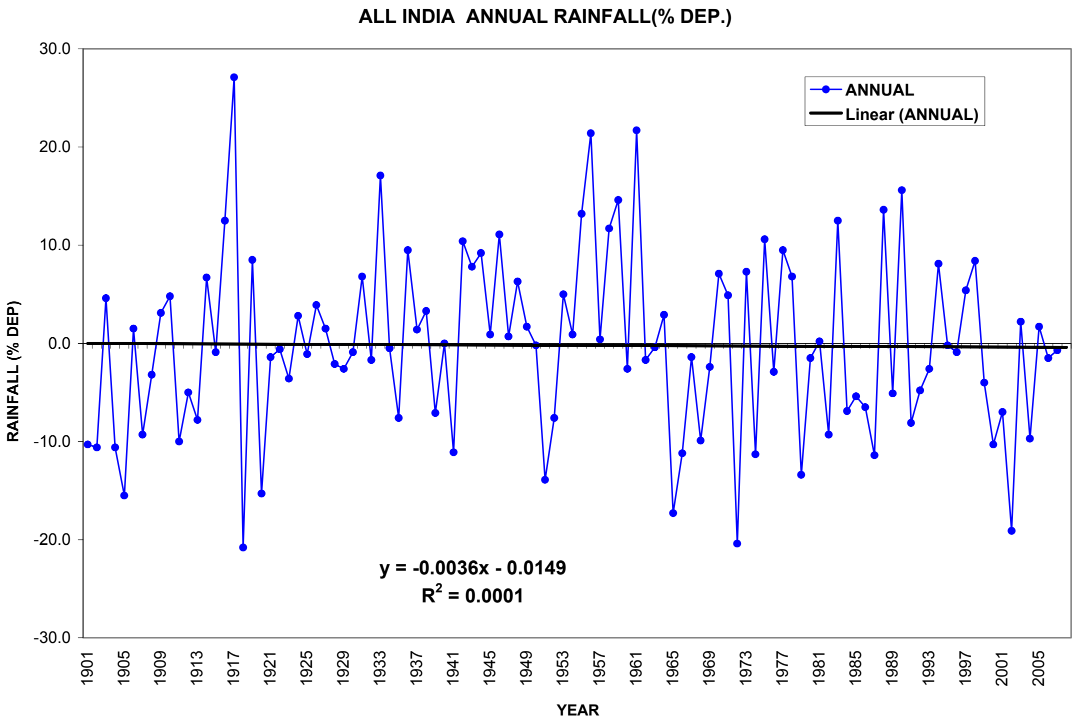


Fig 8: All India Mean Temperature Anomalies for the four seasons for the period 1901-2009 (based on 1961-1990 average)

(a)



(b)

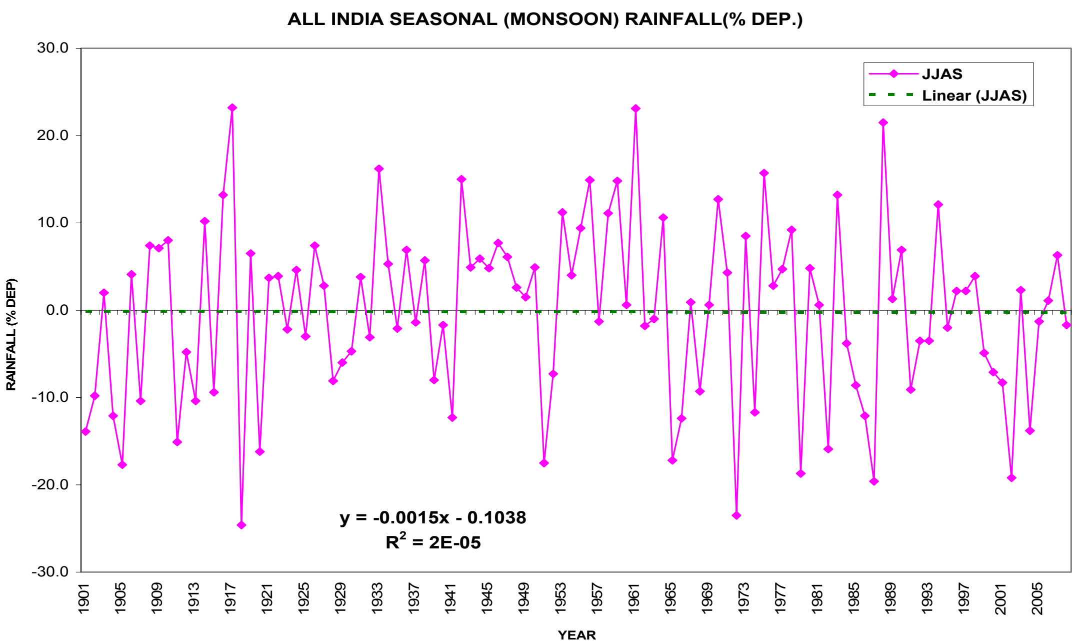


Fig 9: Trend in all India rainfall data for country as a whole, a) annual b) monsoon season, for the period 1901-2009.

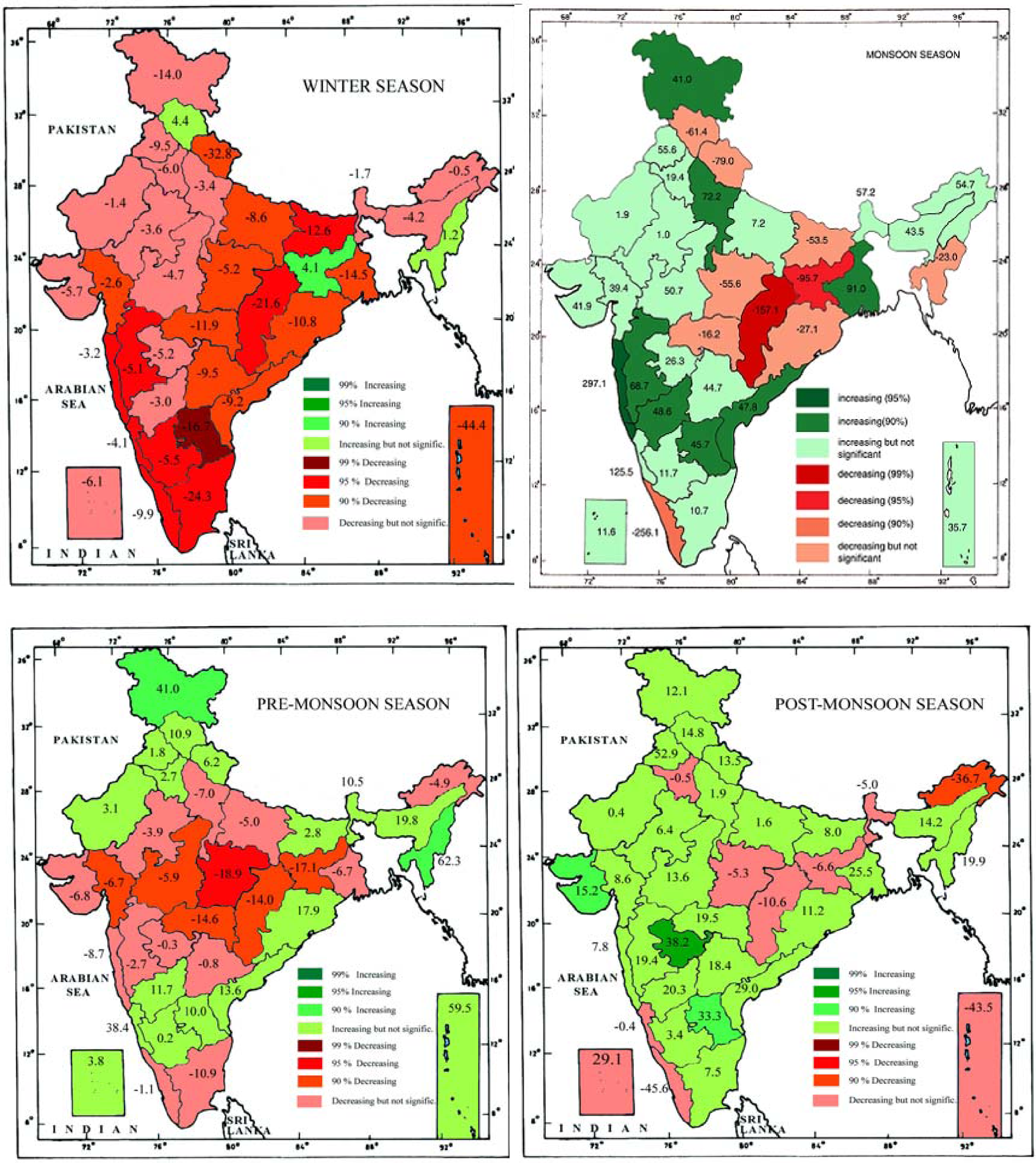


Fig 10: Trend in sub- divisional rainfall data (increase/decrease in rainfall in mm) for different seasons season (1901-2003). Different levels of significance are shaded with colors.

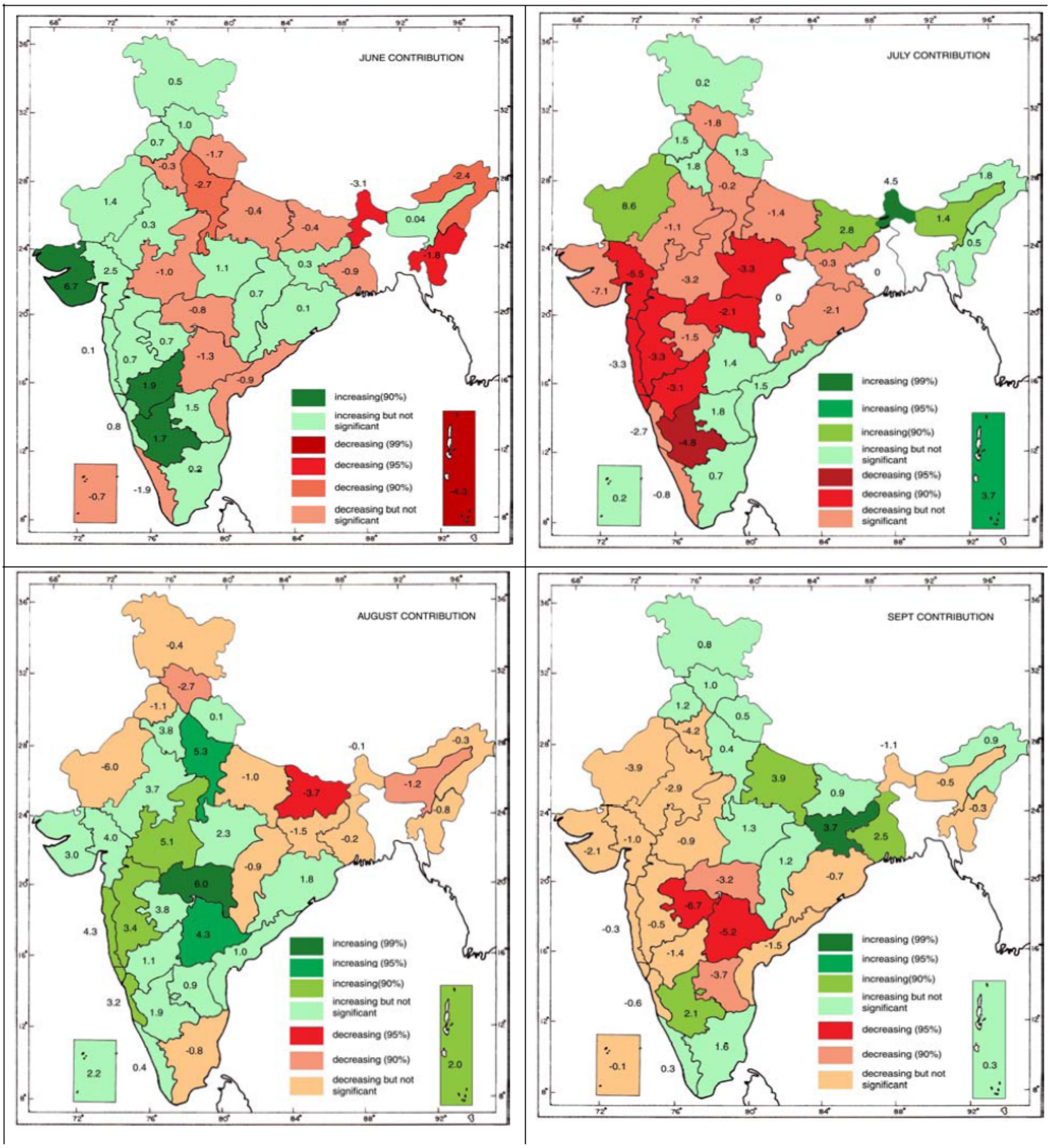


Fig 11: Trend in sub- divisional rainfall data of monsoon months (increase/Decrease in rainfall in percentage) to annual rainfall (1901-2003).

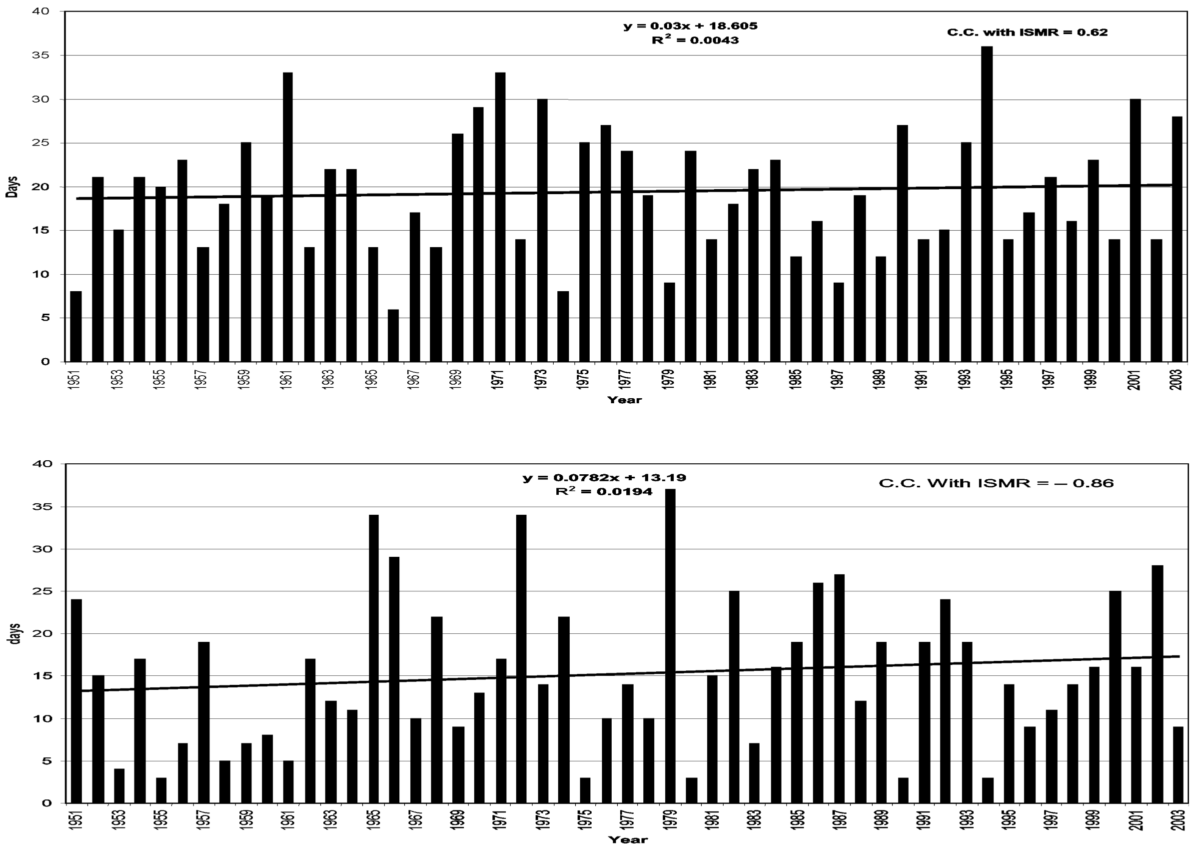


Fig. 12 : Time series of active days (*a*) and (*b*) break days during the monsoon season (1951–2003).

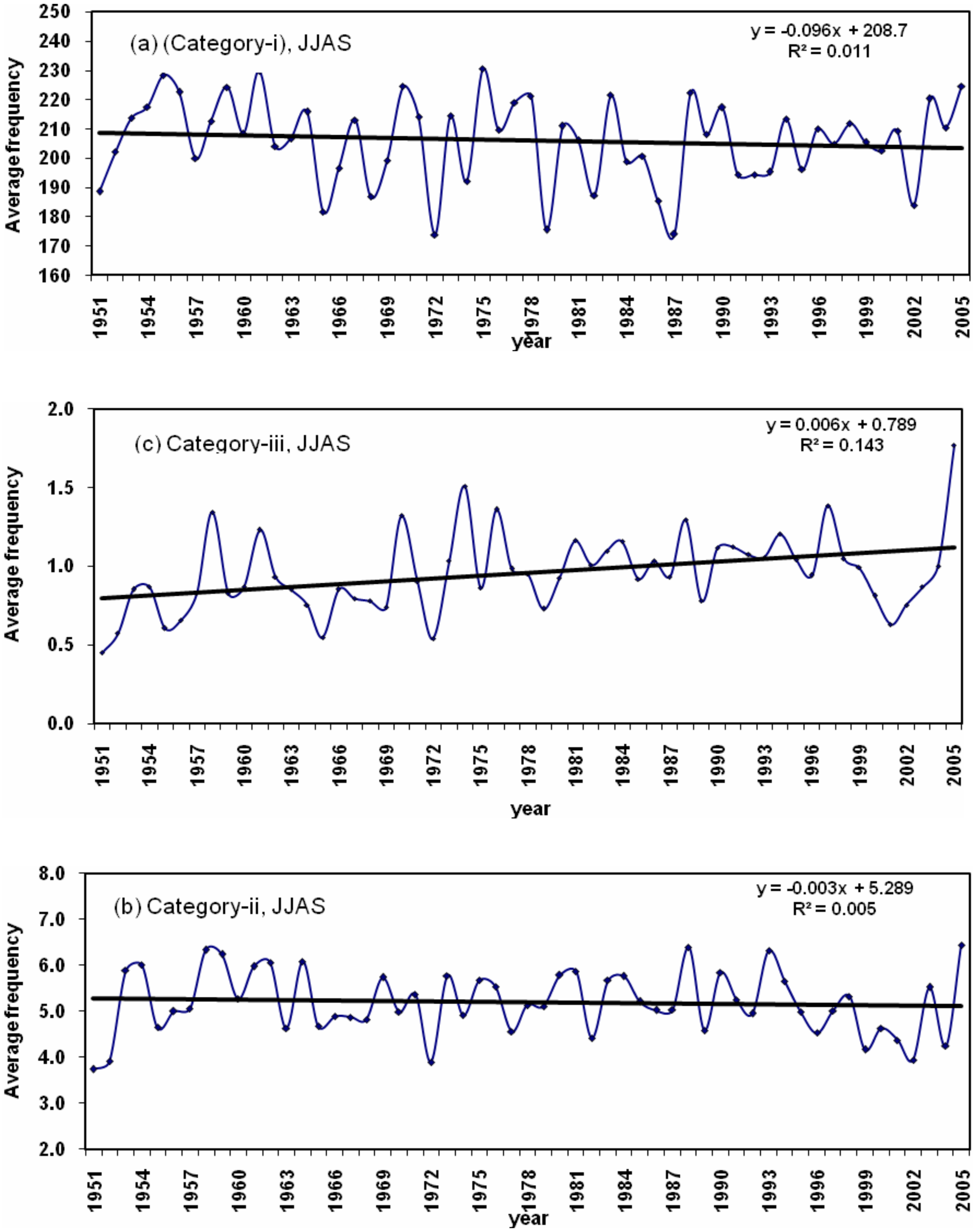


Fig. 13 : Average frequency (count per day) of occurrence of different rainfall (R) events during monsoon season (June to September) from 1951 to 2005. (a) Category-i with 'R' ≤ 64.4 mm in a day, (b) Category-ii with 64.4 < 'R' ≤ 124.4 mm in a day & (c) Category-iii with 'R' > 124.4 mm in a day.

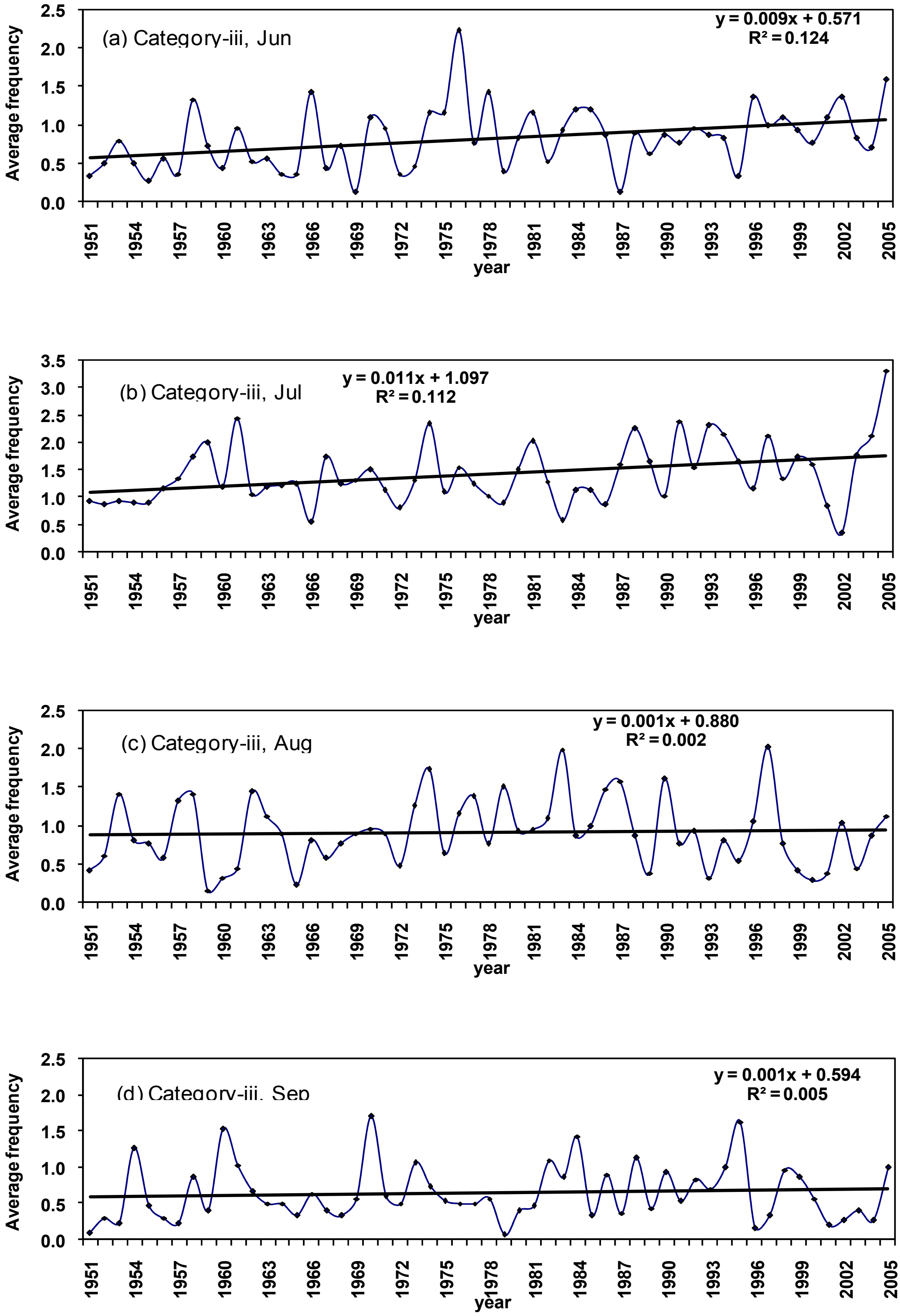


Fig 14: Average frequency (count per day) of occurrence of category-iii rainfall events (rainfall > 124.4 mm in a day) on monthly scale from (a) June to (d) September during the period from 1951 to 2005

Chapter - IV

BEHAVIOUR OF MONSOONS

Southwest / Summer Monsoon

The behavior of major features of Southwest Monsoon can be analysed for any characteristic trend exhibited by them over the period of years in terms of the following:

- Dates of monsoon onset, duration of monsoon over the country in terms of number of days and dates of withdrawal (Mazumdar et al 2001)
- Quantum of monsoon rainfall over various meteorological sub-divisions during June to September.
- Frequency of monsoon low pressure systems viz. Depressions, well marked lows, low pressure areas etc.

4.1 Variability in monsoon Onset and Withdrawal

A study of mean dates of onset of monsoon for the period 1941-2000 (Mazumdar et al 2001) revealed that the mean onset dates over majority of subdivisions have been later than normal in both the 30 years' time slots of 1941-1970 and 1971-2000.The magnitudes of late onset during 1941 – 1970 have been higher than those during 1971 – 2000. Some of these deviations are statistically significant. The maximum deviation being 11 and 7 days over Andaman & Nicobar Islands during 1941 – 1970 and 1971 – 2000 respectively. Since, for India as a whole, the commencement of onset starts from Andaman & Nicobar Islands, the SW monsoon had a late start by about a week during the period of study.

Based on 100 years (1901 – 2000) of data, the onset dates for the twentieth century, when compared to the existing normals, the differences for the period are marginal except for Andaman Nicobar Islands where it has been greater (late onset) by about 5 days.

The lowest Standard Deviation (SD) of date of onset of about 5 days is over Andaman & Nicobar Islands during 1971-2000 and the highest of 14 days is over Jammu and Kashmir. For every subdivision of India, the values of SD are higher during 1941-1970 as compared to 1971-2000. Generally, the SDs of onset dates are about one week over high rainfall area and North Eastern parts, increasing to one and half week towards low rainfall areas of West and North Western parts of India. Generally, decreasing trends are found over northern parts (North of 25ºN) and increasing trends over southern parts of India.

The mean withdrawal dates are found to be later than the existing normal, in both the 30 years slot of 1941 – 1970 and 1971 – 2000, by about one to one and a half week. A general late onset, as concluded earlier coupled with late withdrawal suggests a shift in the monsoon activity. The SDs of withdrawal dates range from 11 to 14 days during 1941 – 1970 and from 7 to 10 days during 1971 – 2000. This indicates that the variability in the withdrawal of monsoon has been greater during the first 30 years period as compared to the later half, not only in temporal but also in spatial scales.

The duration of southwest monsoon is found to be higher than normal almost in all meteorological sub-divisions in both the 30 years' period. The duration is much higher in the first half as compared to that during the second half. The SDs of duration of monsoon varies between 13 and 19 days and 7 to 15 days during 1941-1970 and 1971-2000, respectively. These results are shown in Fig. 15 and Fig. 16. Decadal and epochal variability indicates near 30 year's periodicity in onset, withdrawal and duration of the monsoon.

Trends in the sub divisional rainfall data for the individual monsoon months are depicted as under:

- June rainfall has shown significant increasing trend for the western and southwestern parts of the country, whereas significant decreasing trend is observed for the central and eastern parts of the country.

- July rainfall has significantly decreased for most parts of the central and peninsular India but has increased significantly in the northeastern parts of the country.
- August rainfall has increased significantly for the subdivisions Konkan & Goa, Marathwada, Madhya Maharashtra, Vidarbha, West Madhya Pradesh, Telengana and West Uttar Pradesh.
- September rainfall has shown significantly decreasing trend for subdivisions Vidarbha, Marathwada and Telangana and increasing trend for the subdivision Sub Himalayan Gangetic West Bengal (Guhathakurta and Rajeevan, 2008).

4.2. Trend in Withdrawal of monsoon

The mean withdrawal dates are found to be later than the existing normal, in both the 30 years slot of 1941 – 1970 and 1971 – 2000, by about one to one and a half week. A general late onset, as concluded earlier coupled with late withdrawal suggests a shift in the monsoon activity. The SDs of withdrawal dates range from 11 to 14 days during 1941 – 1970 and from 7 to 10 days during 1971 – 2000. This indicates that the variability in the withdrawal of monsoon has been greater during the first 30 years period as compared to the later half, not only in temporal but also in spatial scales.

4.3 Duration of SW monsoon

The duration of southwest monsoon is found to be higher than normal almost in all meteorological sub-divisions in both the 30 years' period. The duration is much higher in the first half as compared to that during the second half.

The SDs of duration of monsoon varies between 13 and 19 days and 7 to 15 days during 1941-1970 and 1971-2000, respectively.

Major findings of analyses of onset, withdrawal and duration of SW monsoon as during the period 1941-2000 are:

(i) Slight shift of monsoon activity with late onset and late withdrawal.

(ii) Increase in the duration of the monsoon by about a week, as compared to normal duration.

(iii) Decreasing trends in onset dates, roughly north of 25° N and general decreasing trends in both withdrawal and duration of the monsoon ;

(iv) Decadal and epochal variability indicate near 30 year's periodicity in onset, withdrawal and duration of the monsoon.

4.4 Monsoon Forecasting (Long Range/ Seasonal Forecasting)

4.4.1 History

IMD started issuing tentative forecasts from 1882 to 1885 utilizing the indications provided by the snowfall in Himalayas. The success achieved infused greater confidence and the first of the regular series of forecasts was given on the 4th June 1886 and is continuing practically till date but for changes in its format and content. In 1892, long range forecast (LRF) for the rainfall for the second half of the monsoon season (August-September) was also started. In December 1893, the first forecast for winter precipitation over the Northern and central India was issued. Various subjective methods such as analogue and curve parallels for the LRF of Indian Summer Monsoon Rainfall (ISMR). The efforts for better forecasts continued during the period during 1904-1924 and IMD started the forecasts based on objective techniques using correlation and regression techniques for preparing long range forecasts and discovered importance of Southern Oscillation, North Atlantic Oscillation and North Pacific Oscillation for monsoons. In 1922, India was divided into three main homogenous areas, namely, i) Peninsula ii) N.E. India and iii) North-west India. In 1935, forecast for NE India was discontinued. The issuance of forecast for two homogenous regions (NW India and Peninsula) was continued till 1987.

In 1988, IMD introduced operational 16 parameter power regression for issuing quantitative forecasts and parametric models for qualitative forecasts (whether normal/excess or deficient) for the southwest monsoon rainfall over the country as a whole. IMD introduced a new two stage forecast strategy in 2003 viz. the first stage forecast for the seasonal (June to September) rainfall over the country as a whole is issued in April and the update for the April forecasts is issued in June. Along with the update forecast, forecast for seasonal rainfall over broad homogeneous rainfall regions of India and July rainfall over country as a whole are also issued. During the period 2003-2006, the first stage quantitative and 5 category probabilistic forecast for the season rainfall over the country as a whole were issued using 8-parameter power regression (PR) model and Linear Discriminant Analysis (LDA) model respectively. Update for the first stage forecasts were issued using 10 Parameter PR and LDA models. In 2007, IMD introduced new statistical forecasting system based on ensemble technique for the south-west monsoon season (June to September) rainfall over the country as a whole.

4.4.2 Present forecasting system

At present, the forecast for the South-West monsoon rainfall is issued in two stages. The first stage forecast for the seasonal (June to September) rainfall over the country as a whole is issued in April and the update of the April forecast in June. Along with the update forecast, forecast for seasonal rainfall over four broad geographical regions of India and July rainfall over country as a whole are also issued.

For issuing the forecast for the seasonal rainfall over the country, a new statistical forecasting system based on the ensemble technique was introduced in 2007 using 8 predictors for the new ensemble forecast system as summarized in Table 2. The predictors used for the April forecast and the updated forecast in June are presented in Table 3 and table 4 respectively. The model error of the April forecast system is 5% and for the June forecast system, it is 4%. For developing the models, two different statistical techniques viz. Multiple Regression and Projection Pursuit Regression were considered

For the forecast of July rainfall over the country as a whole, a statistical model with 6 predictors was developed using Principal Component Regression (PCR) technique. The predictors used are: North Atlantic Sea surface temperature (December of previous year), NINO 3.4 Sea Surface Temperature (May +June), North Pacific mean sea level pressure (March), East Asia mean sea level pressure

(February + March), North Atlantic mean sea level pressure (May) and Equatorial Indian Ocean mean sea level pressure (November of previous year). The model error of the model for July rainfall is 9%.

For forecasting of South-West monsoon season rainfall over the four broad geographical regions of India (NW India, Central India, South Peninsula and NE India), multiple regression (MR) models based on separate set of predictors are used. All the four multiple linear regression models have model errors of 8% of LPA.

IMD also prepares an extended range forecast for the onset of southwest monsoon rainfall over Kerala. This forecast was first issued in 2005 using indigenously developed statistical model with 6 predictors (Table 5).

In addition, IMD prepares operational long range forecasts for the Winter Precipitation (Jan to March) over Northwest India and Northeast Monsoon rainfall (October to December) over South Peninsula. For this purpose, separate statistical models have been developed.

Table 2
Predictors used in new ensemble forecast system of Monsoon over India

S.N.	Predictor (Period)	Used for the forecasts in
1	North Atlantic Sea Surface Temperature (December + January)	April and June
2	Equatorial SE Indian Ocean Sea Surface Temperature (February + March)	April and June
3	East Asia Mean Sea Level Pressure (February + March)	April and June
4	NW Europe Land Surface Air Temperatures (January)	April
5	Equatorial Pacific Warm Water Volume (February+March)	April
6	Central Pacific (Nino 3.4) Sea Surface Temperature Tendency (MAM-DJF)	June
7	North Atlantic Mean Sea Level Pressure(May)	June
8	North Central Pacific Wind at 1.5 Km above sea level (May)	June

Table 3
Details of predictors used for the first stage forecast (April)

No.	Parameter	Period	Spatial domain	CC with ISMR (1958-2000)
A1	North Atlantic SST anomaly	December + January	20N-30N, 100W-80W	-0.45 **
A2	Equatorial SE Indian Ocean SST anomaly	February + March	20S-10S, 100E-120E	0.52 **
A3	East Asia surface pressure anomaly	February + March	35N-45N, 120E-130E	0.36 *
A4	Europe land surface air temperature anomaly	January	Five stations	0.42 **
A5	Northwest Europe surface pressure anomaly tendency	DJF(0) – SON (-1)	65N-75N, 20E-40E	-0.40 **
A6	WWV anomaly	February + March	5S-5N, 120E-80W	-0.32 *

* Significant at and above 5% level
** Significant at and above 1% level

Table 4
Details of predictors used for the second stage forecast (June)

No.	Parameter	Period	Spatial domain	CC with ISMR (1958-2000)
J1	North Atlantic SST anomaly	December + January	20N-30N, 100W-80W	-0.45 **
J2	Equatorial SE Indian Ocean SST anomaly	February + March	20S-10S, 100E-120E	0.52 **
J3	East Asia surface pressure anomaly	February + March	35N-45N, 120E-130E	0.36 *
J4	Nino-3,4 SST anomaly tendency	MAM(0) – DJF (0)	5S-5N, 170W-120W	- 0.46 **
J5	North Atlantic surface pressure anomaly	May	35N-45N, 30W-41W	-0.402**
J6	North Central Pacific zonal wind anomaly at 850 hPa	May	5N-15N, 180E-150W	-0.55 **

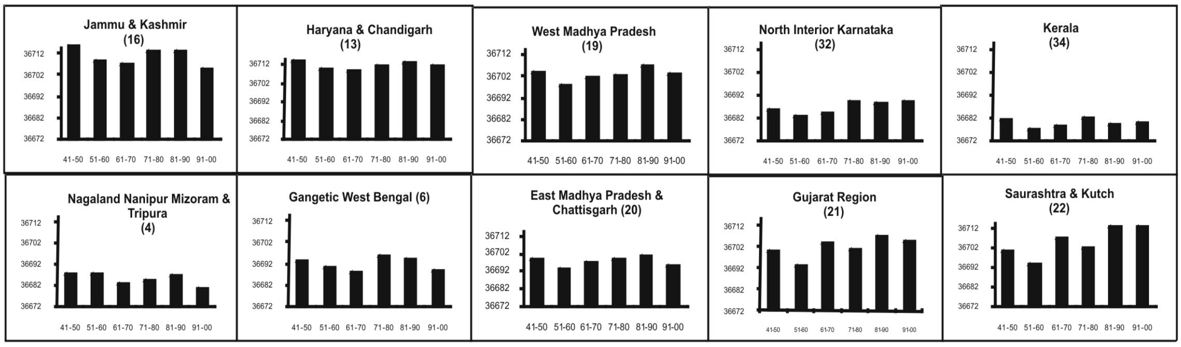
* Significant at and above 5% level
** Significant at and above 1% level

Table 5

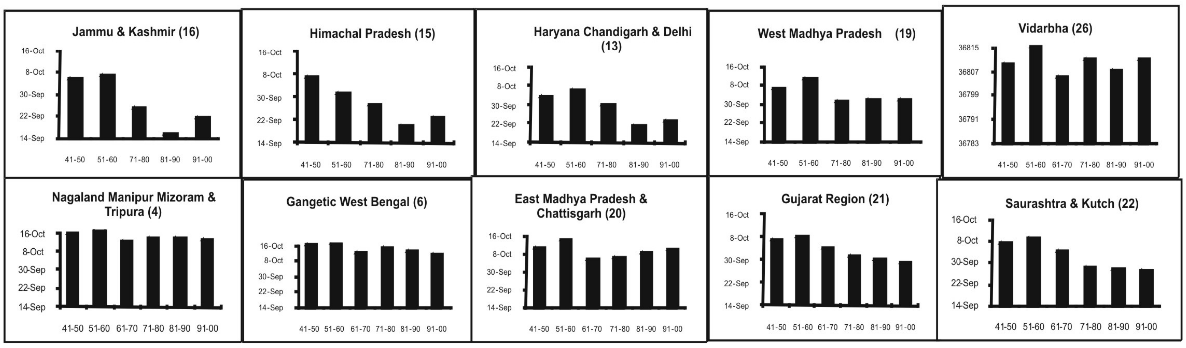
Prediction of monsoon onset date over Kerala

No	Name of Predictor	Temporal Domain	Geographical Domain	C.C 1975-2000
1	SE Indian Ocean SST anomaly	JAN	24S-14S, 80E-100E	0.41
2	NW India Minimum Surface air Temperature Anomaly	Deesa, Rajko, Guna Bikaner, Akola, Barmer	16th April to 15th May	-0.63
3	Zonal Wind Anomaly at 1000hpa over Equatorial South Indian Ocean	1-15may	10S-0, 80E-100E	0.52
4	OLR Anomaly Over Indo-China	1-15may	17.5N-27.5N, 95E-105E	0.43
5	OLR Anomaly Over Southwest Pacific	1-15may	30S,20S, 145E-160E	-0.54
6	Pre-Monsoon Rainfall Peak Date	Pre-monsoon	South Peninsula (8N-13N, 74E-78E)	0.65

ONSET



WITHDRAWAL



DURATION

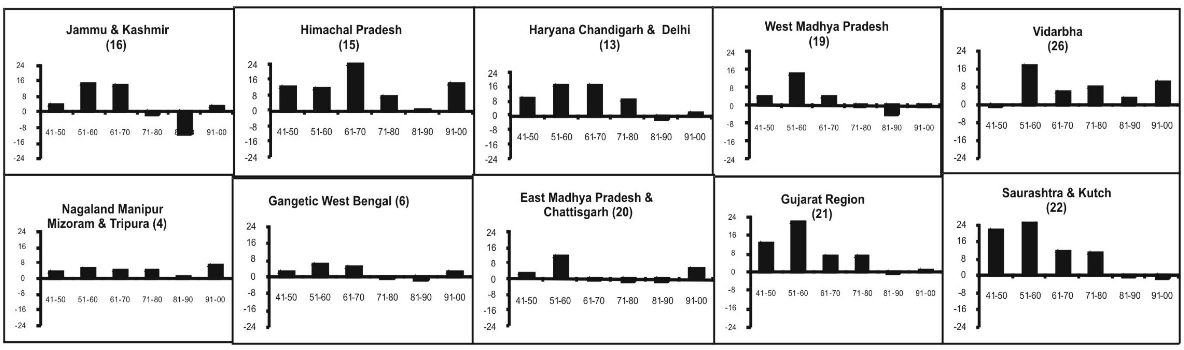
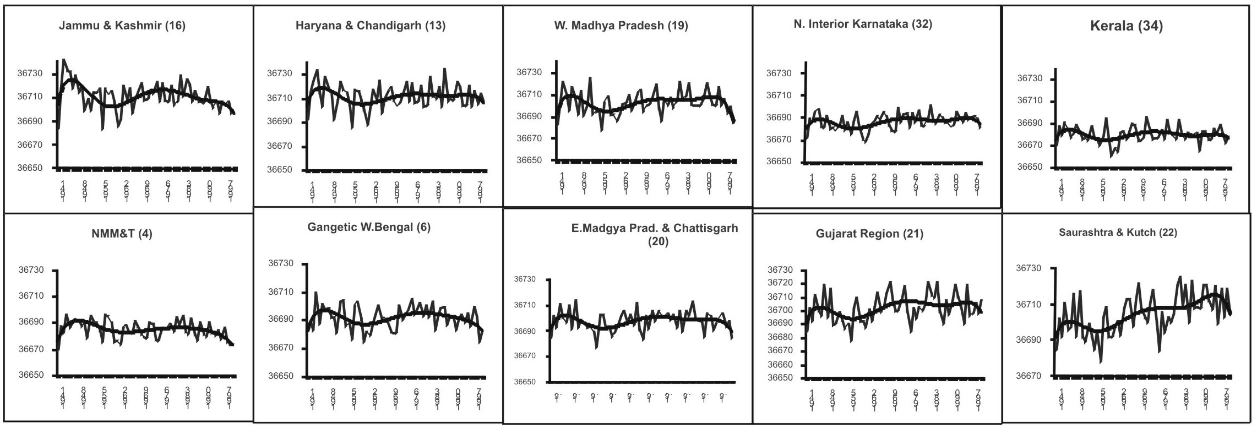
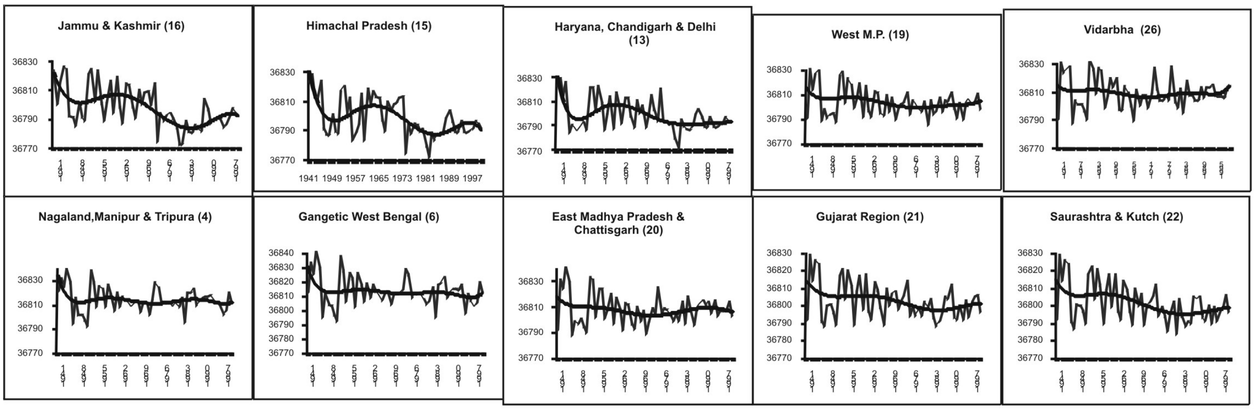


Fig 15: Decadal mean values of onset, withdrawal and duration of monsoon

ONSET



WITHDRAWAL



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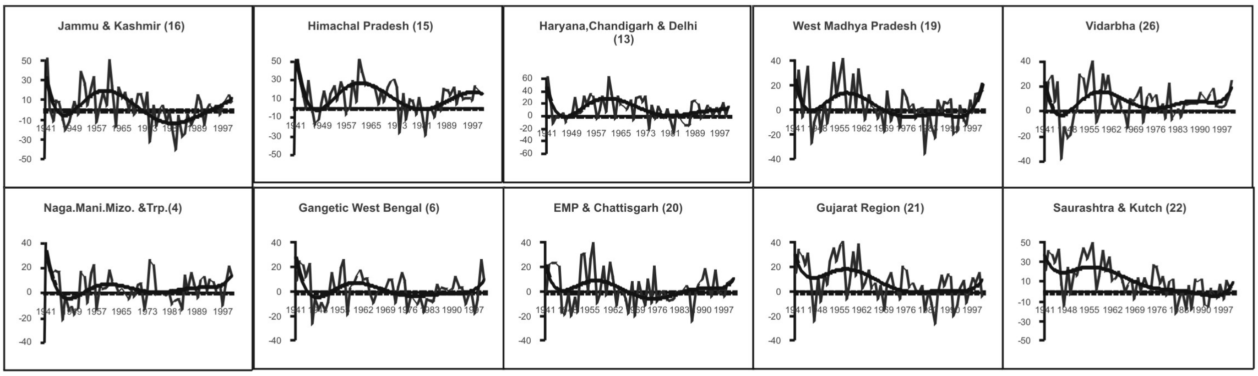


Fig 16: Epochal variation of onset, withdrawal and duration of SW Monsoon

4.5 Northeast Monsoon

The southeast peninsular India which falls under the rain shadow region during the summer season due to the presence of the Western Ghats receives rainfall from the subsequent northeast monsoon (NEM) which supplements the inadequate precipitation received during the SW monsoon. It is a small scale monsoon experienced by the southern peninsular India during October to December. Meteorological features associated with the NEM have been described in detail by IMD (1973). The onset of NEM is well defined with dramatic reversal of low level winds from southwesterly to northeasterly during mid-October followed by the commencement of fairly widespread rainfall activity along the coastal districts in about a week. The seasonal rainfall manifests high inter-annual variability characterised by the occurrence of years of large scale droughts and large scale floods. The intra-seasonal variation of NEM is frequently associated with long dry spells.

4.5.1 Climatology

The meteorological subdivisions of Coastal Andhra Pradesh (CAP), Rayalaseema (RYS), Tamil Nadu (TN), Kerala (KER) and South Interior Karnataka (SIK) are the beneficiaries of the northeast monsoon (Fig.17). These sub-divisions receive about 35% of their annual total during this season. Normal rainfall received by these 5 sub-divisions based on the long period (1941-1990) are presented in Table 6. All the 5 sub-divisions receive good rainfall in October. The sub-divisions of TN, KER and CAP receive good rainfall in November, while, the rainfall is confined to TN and KER during December. This season is the main rainfall period for TN during which nearly 47% of the annual total of 91cm is received. Further, the coastal districts of Tamil Nadu normally receive about 75-100cm of rainfall during this season thereby constituting nearly 60% of their annual total. Onset and the various features associated with the onset of NEM have been described by Raj (1992,1998 & 2003).

4.5.2 Trends in NEM rainfall

Seasonal and monthly linear rainfall trends in October, November and December (OND) over these 5 sub-divisions during 1900-2008 have been depicted in Fig.18 (a-e) and Figs.19 (i-v)(a-c) respectively. Actual linear increase or decrease in seasonal (OND) and monthly (OCT, NOV and DEC) rainfall per year during this period are presented in Table 7. The Salient findings are summarized as under:

(i) There is an increase in seasonal (OND) rainfall over the eastern sub-divisions of CAP (0.406mm/year), RYS (0.475mm/year) and TN (0.265mm/year) and a very modest decrease of OND rainfall over the western sub-divisions of KER (-0.19 mm/year) and SIK (-0.061mm/year). The increasing trend over RYS is statistically significant at 10% level.

(ii) The October rainfall shows a positive trend over all the five sub-divisions with rainfall over RYS and CAP increasing at the rate of 0.548mm and 0.490mm per year respectively. The increase over RYS is statistically significant at 1% level.

(iii) Excepting TN, all other sub-divisions show a negative trend in the November rainfall. The November rainfall over SIK, RYS and CAP has decreased at the rate of -0.153mm, -0.081mm and -0.099mm per year respectively.

(iv) The December rainfall over Kerala has decreased at the rate of -0.197mm per year.

(v) Overall, there is a modest increase in the NEM seasonal rainfall over the eastern sub-divisions of CAP, RYS and TN and a very modest decrease in the seasonal rainfall over the western sub-divisions of KER and SIK.

(vi) By and large, rainfall during October has increased and that during November has decreased.

(vii) There is a significant increase in the October rainfall of RYS.

Table 6
Normal seasonal / monthly rainfall during October-December (1941-80)

Sub-division	Month / Season	Normal rainfall in (mm)
TN	OND	431.8
	OCT	181.5
	NOV	165.3
	DEC	85.0
CAP	OND	326.2
	OCT	196.8
	NOV	103.5
	DEC	25.9
RYS	OND	212.1
	OCT	121.3
	NOV	66.3
	DEC	24.5
KER	OND	498.5
	OCT	291.6
	NOV	163.8
	DEC	43.1
SIK	OND	199.7
	OCT	138.6
	NOV	48.1
	DEC	13.0

Table 7
Trend in the seasonal / monthly rainfall of the 5 sub-divisions during 1900-2008

Sub-division	Month / Season	Increase/Decrease of rainfall per year in mm	Linear correlation coefficient (r)
TN	OND	0.265	0.063
	OCT	0.069	0.032
	NOV	0.112	0.032
	DEC	0.083	0.032
CAP	OND	0.406	0.089
	OCT	0.490	0.145
	NOV	-0.099	-0.000
	DEC	0.016	0.000
RYS	OND	0.475	0.164*
	OCT	0.548	0.251**
	NOV	-0.081	-0.045
	DEC	0.008	0.000
KER	OND	-0.190	-0.032
	OCT	0.081	0.000
	NOV	-0.075	-0.000
	DEC	-0.197	-0.152
SIK	OND	-0.061	-0.000
	OCT	0.111	0.045
	NOV	-0.153	-0.105
	DEC	-0.019	-0.032

*: significant at 1% level
**: significant at 10% level

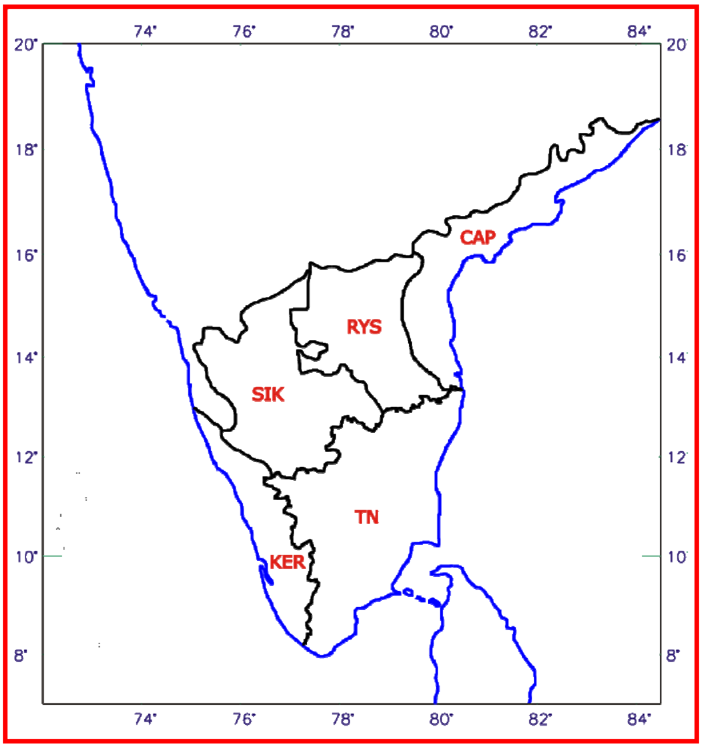
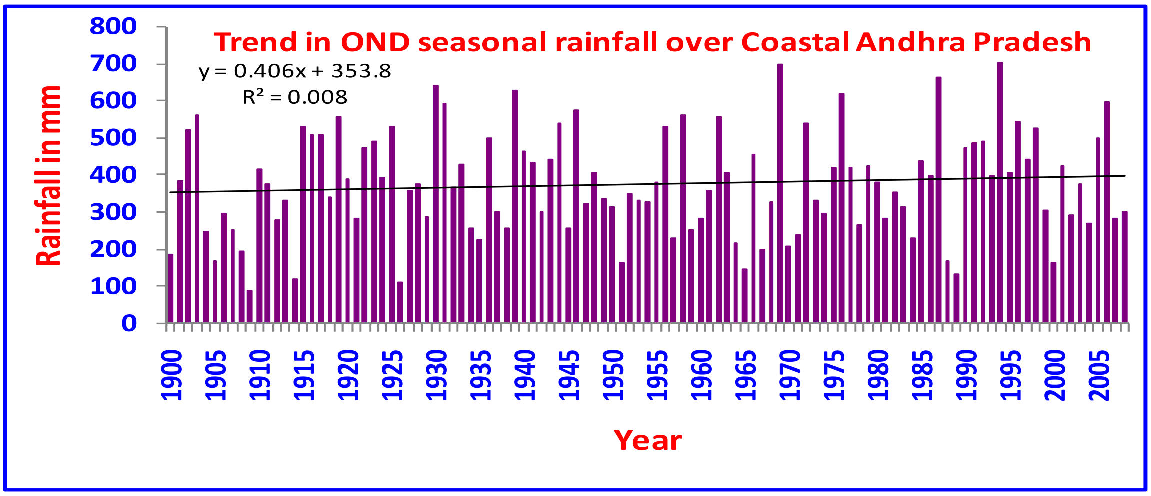
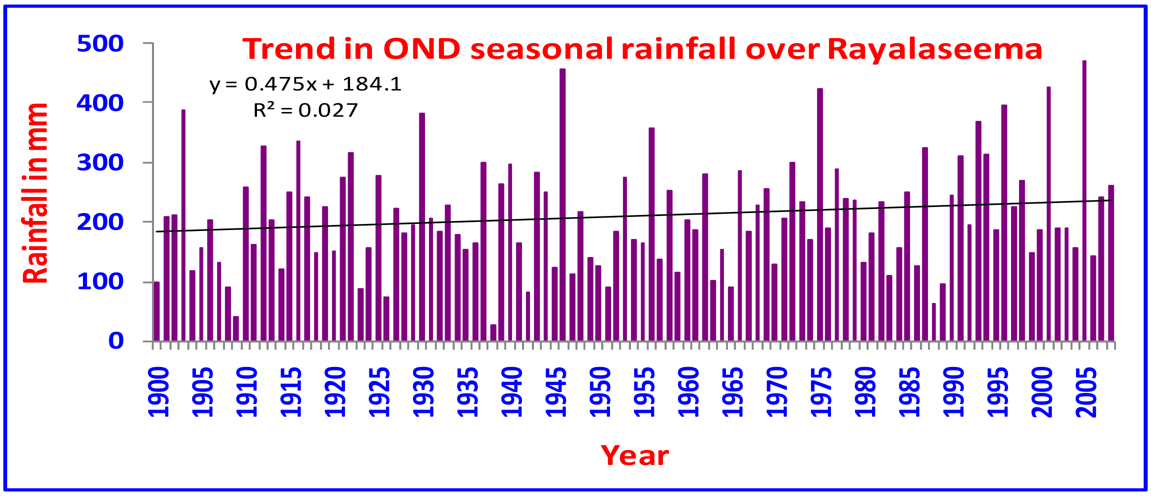


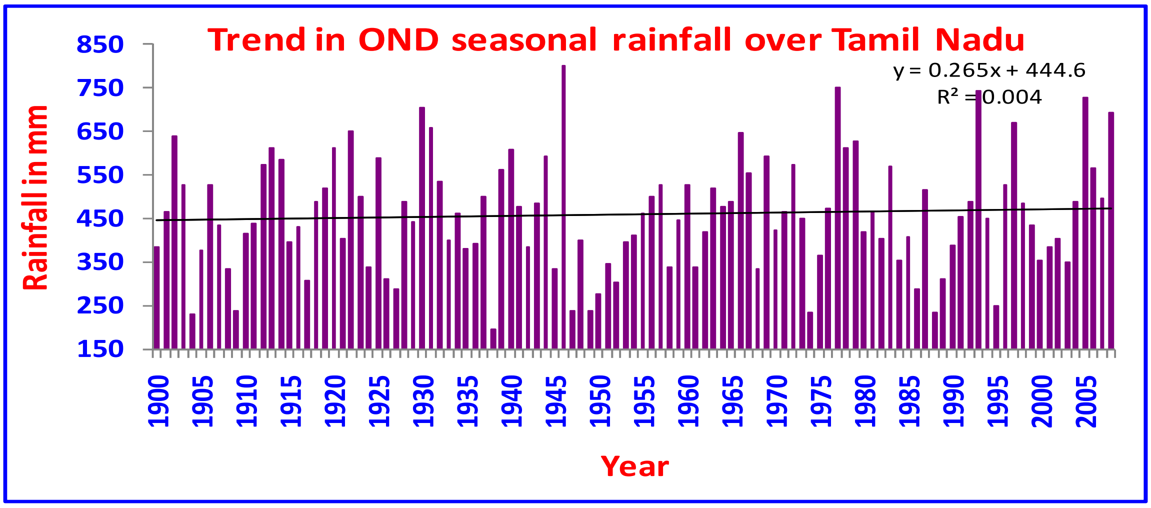
Fig. 17: The five meteorological sub-divisions of southern peninsular India influenced by the Northeast monsoon


Trend in OND seasonal rainfall over Coastal Andhra Pradesh
y = 0.406x + 353.8
R² = 0.008
Rainfall in mm
0
100
200
300
400
500
600
700
800
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year

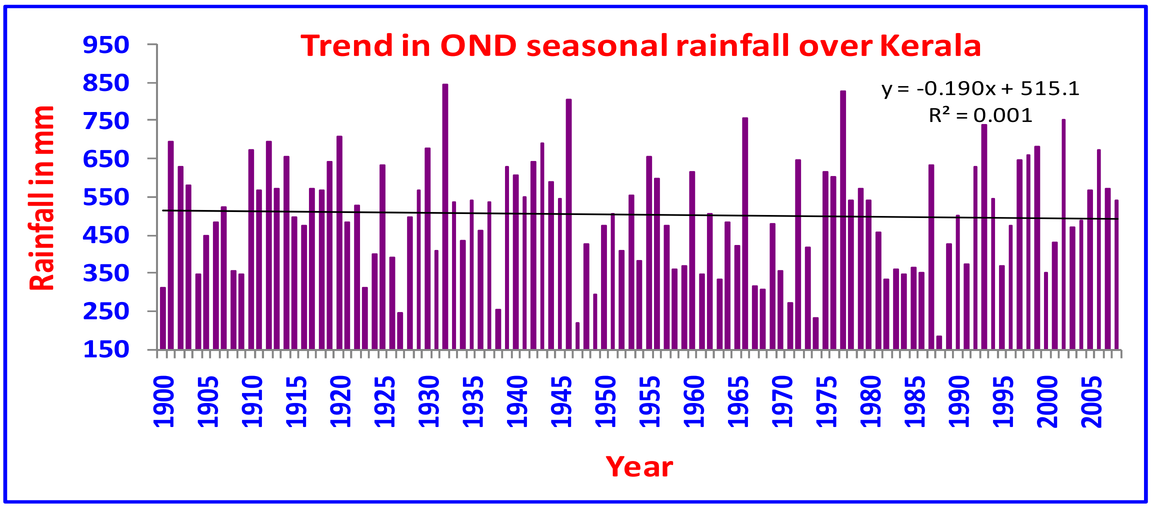
(18a)


Trend in OND seasonal rainfall over Rayalaseema
y = 0.475x + 184.1
R² = 0.027
Rainfall in mm
0
100
200
300
400
500
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year

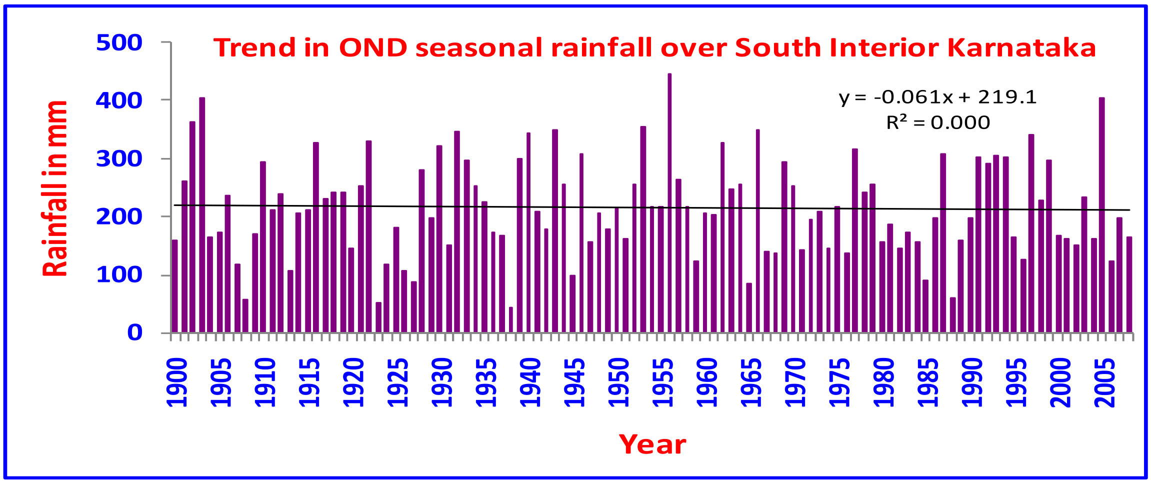
(18b)


Trend in OND seasonal rainfall over Tamil Nadu
y = 0.265x + 444.6
R² = 0.004
Rainfall in mm
150
250
350
450
550
650
750
850
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year

(18c)

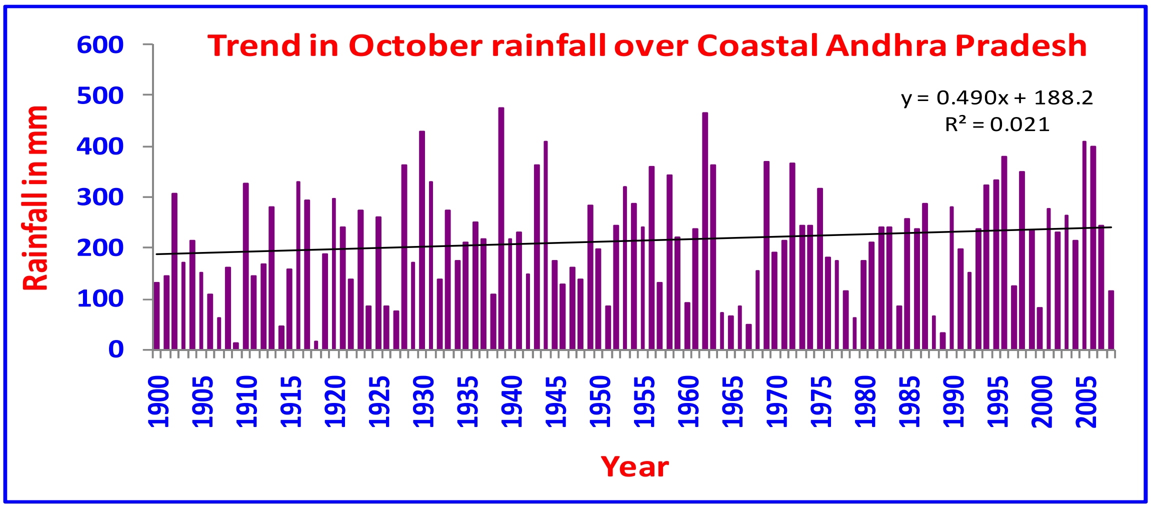


(18d)

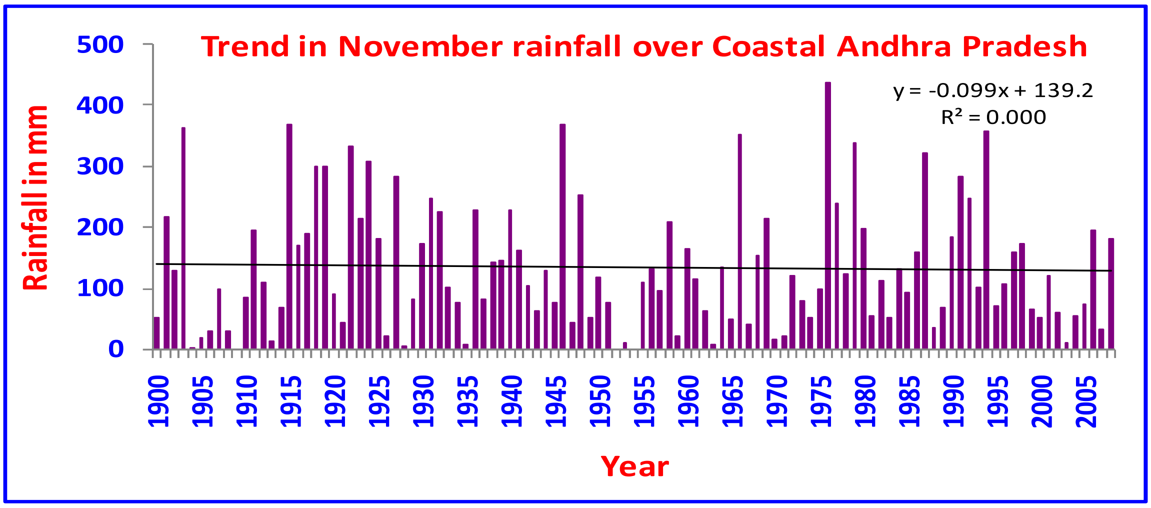


(18e)

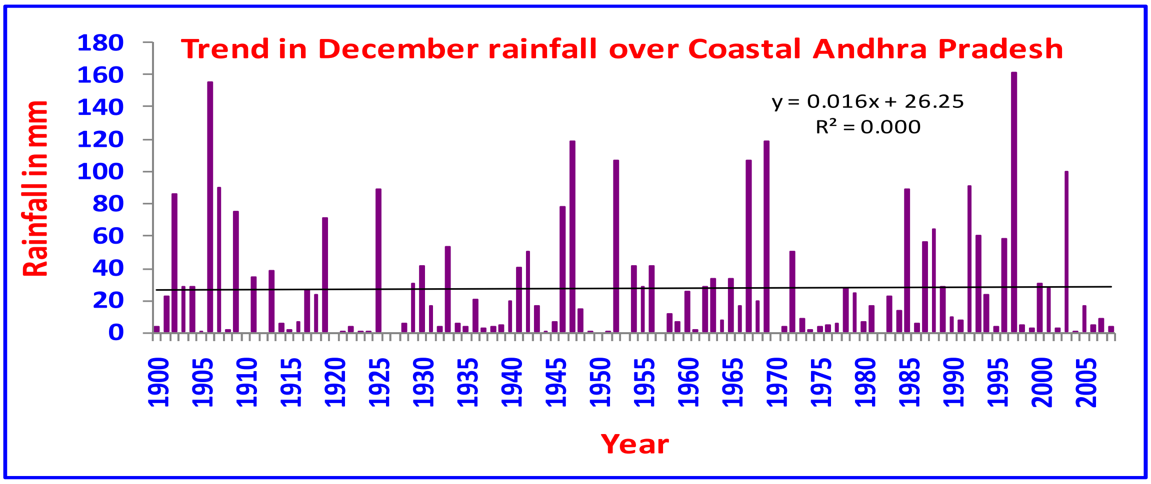
Fig. 18: Trend in the NEM seasonal (OND) rainfall of (a)CAP, (b)RYS, (c)TN, (d)KER and (e)SIK during the period 1900-2008



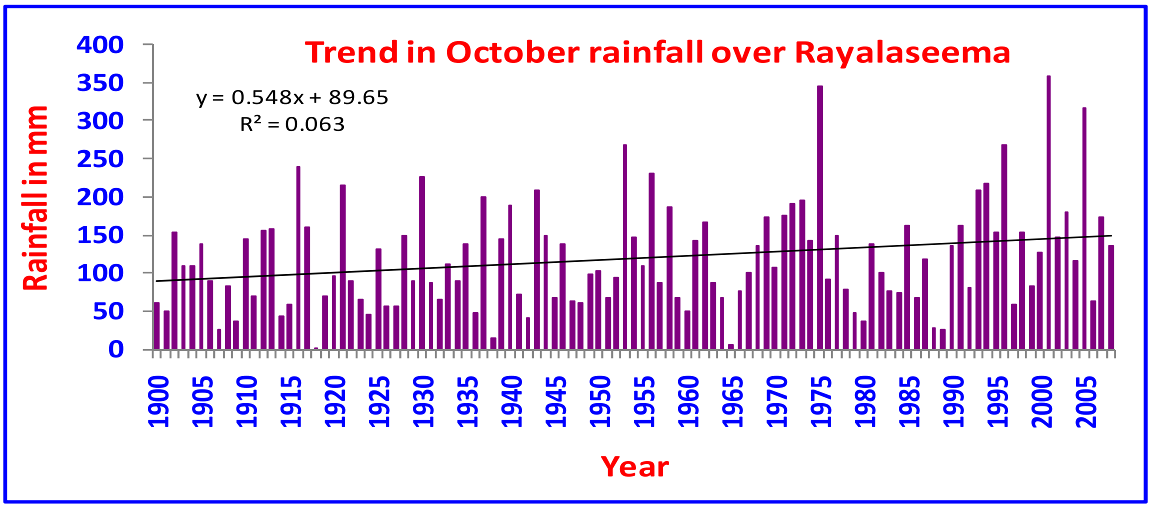
19(i a)



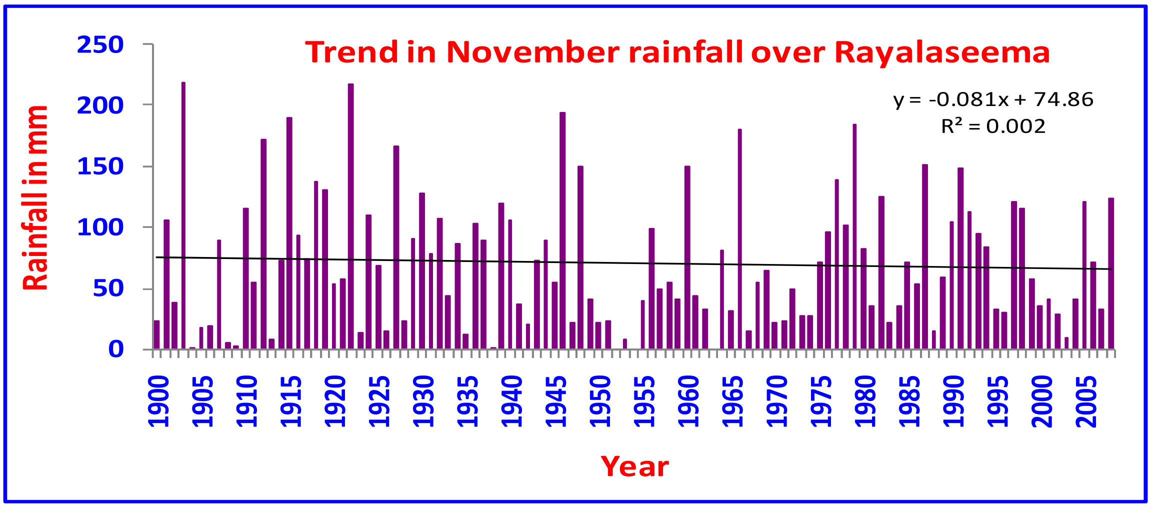
19(I b)



19(i c)



19 (ii a)



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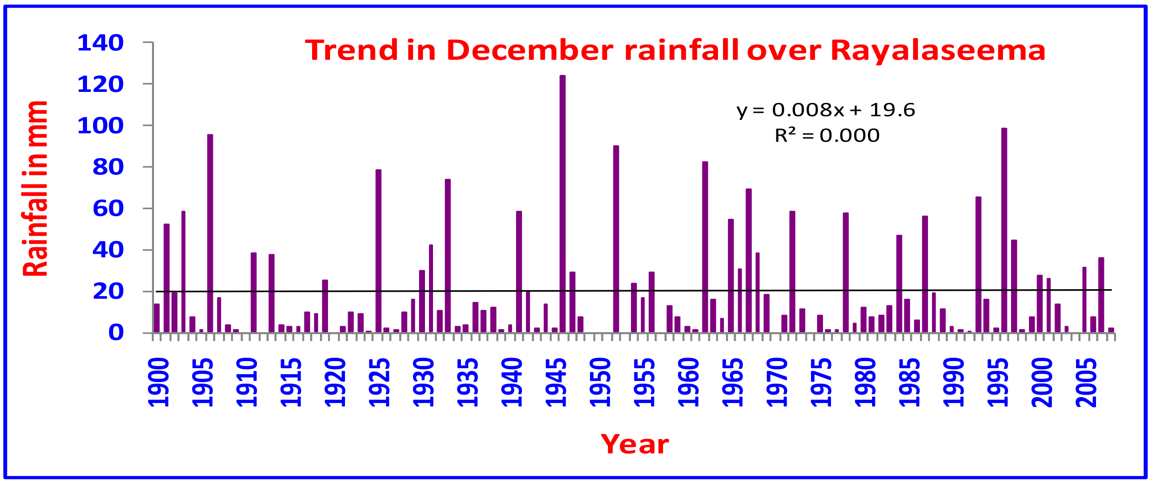

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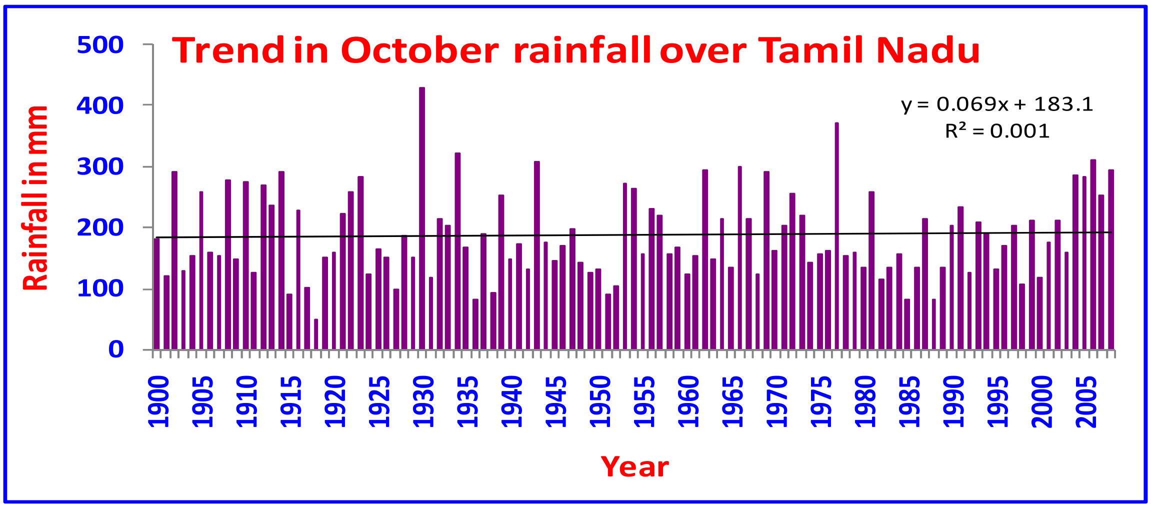

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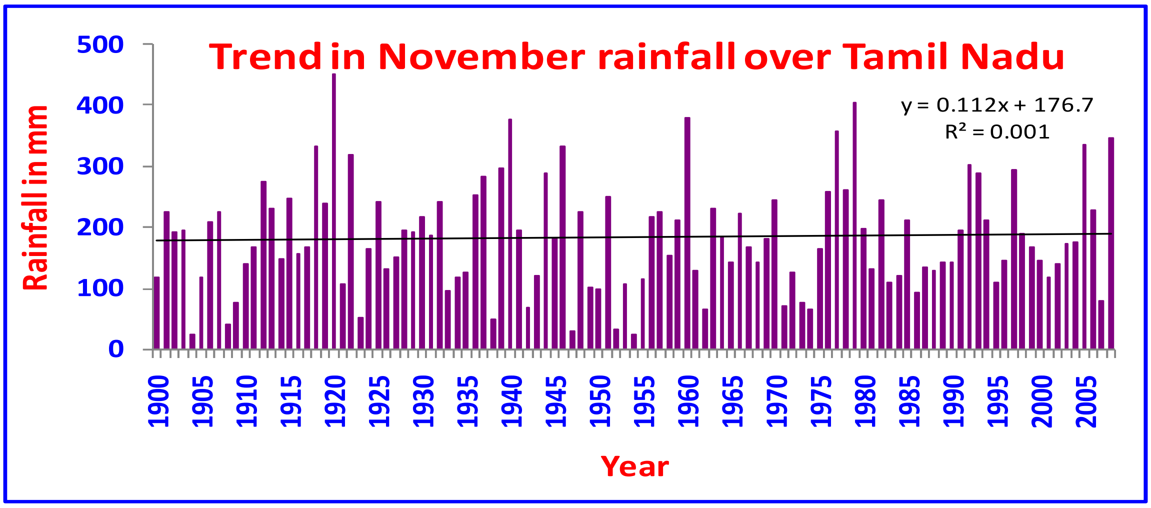

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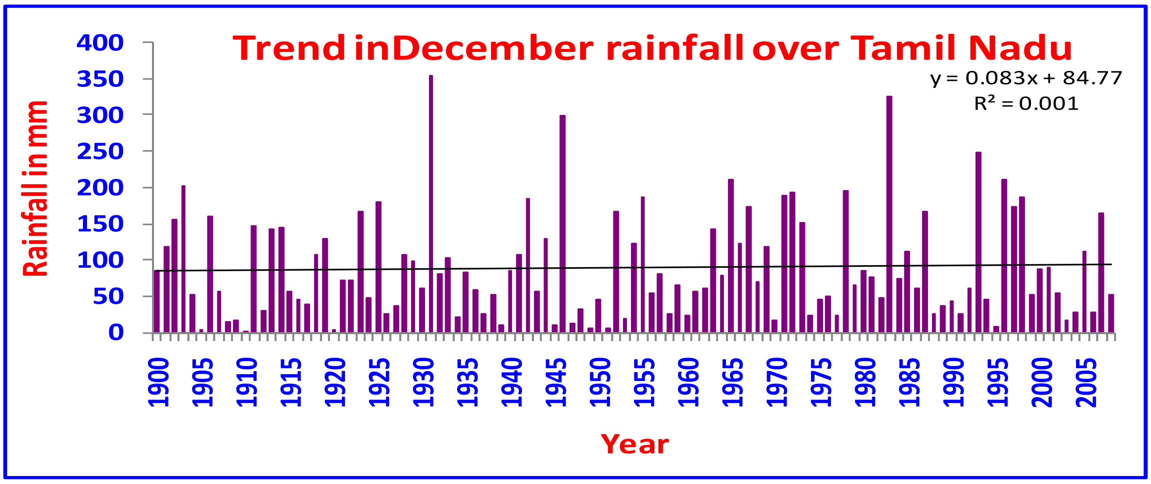
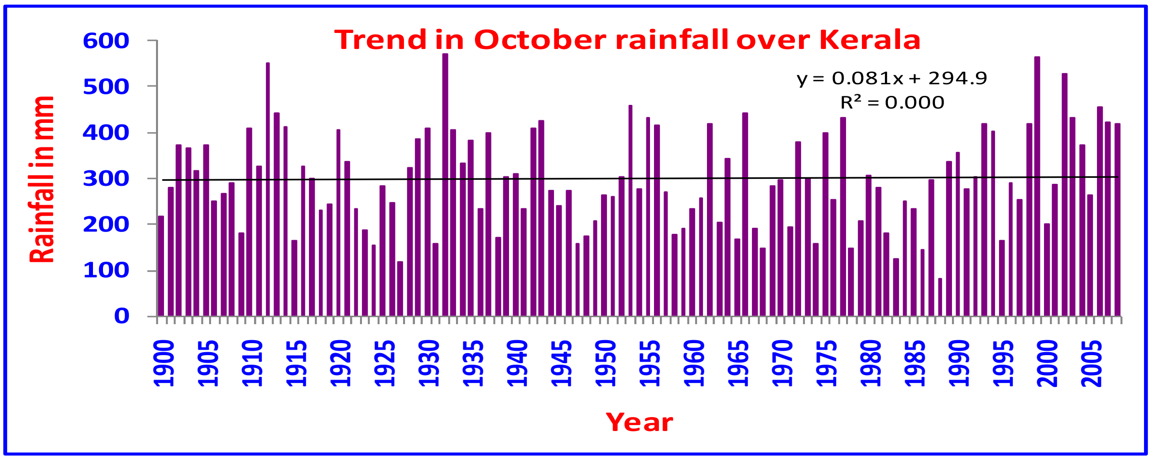
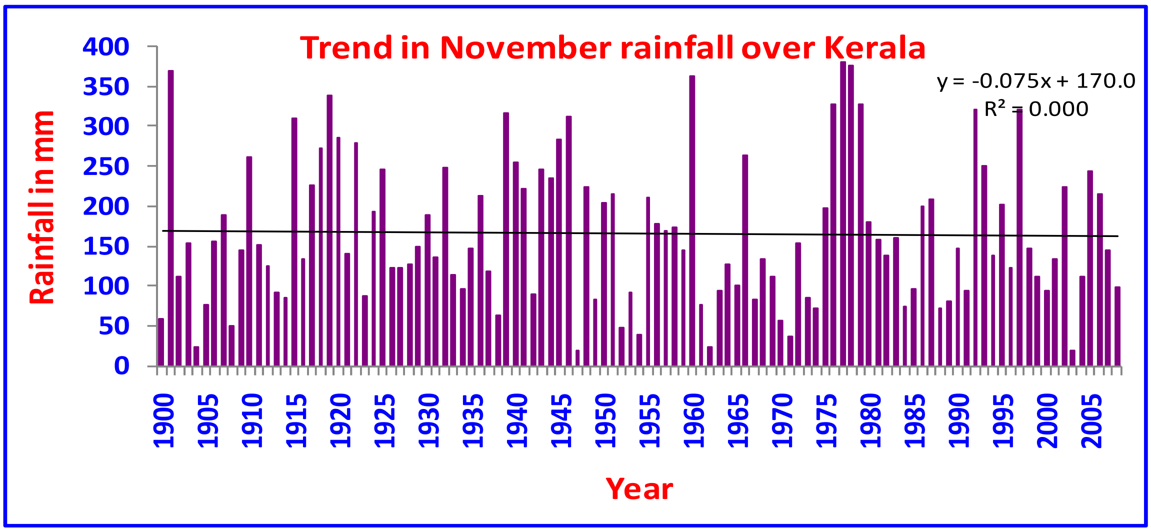


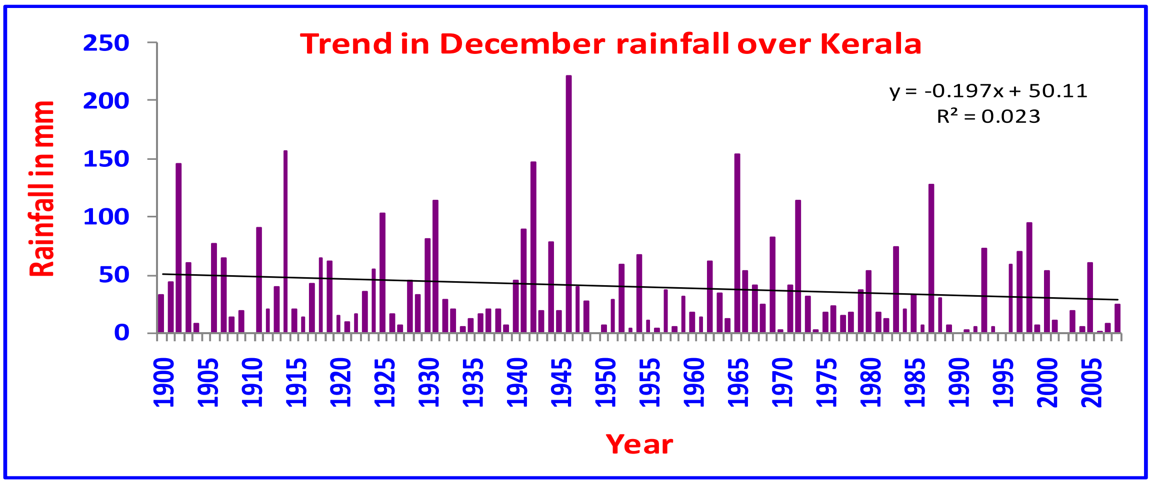
19 (iii c)



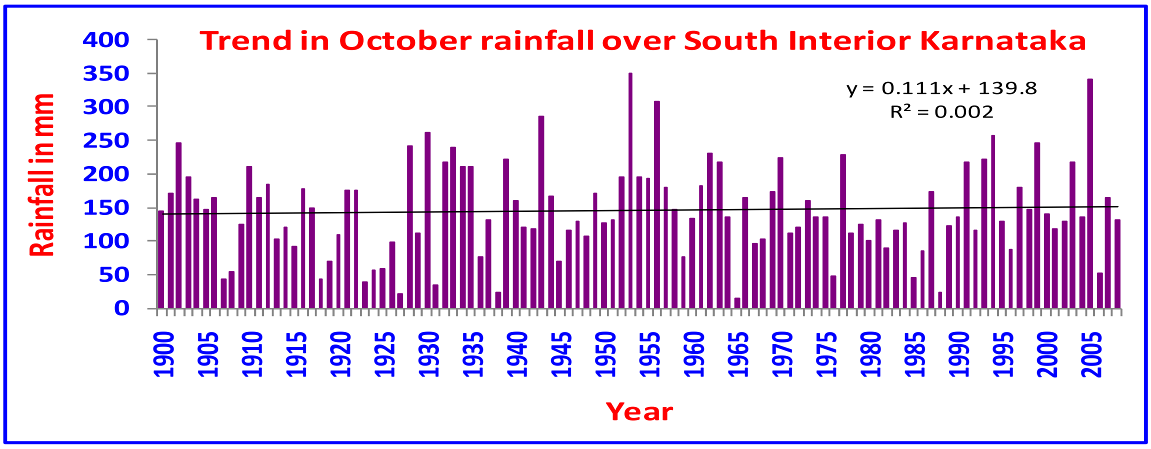
19 (iv a)



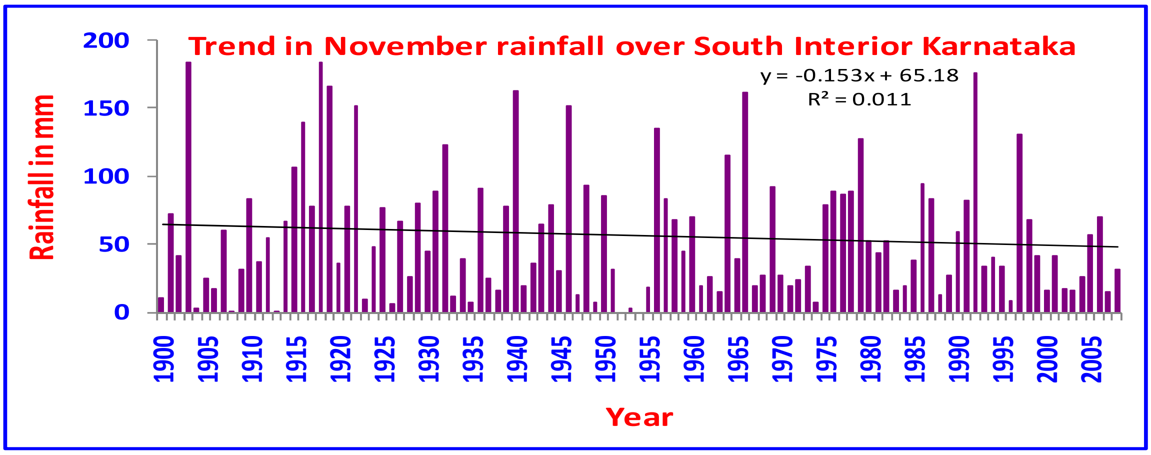
19 (iv b)



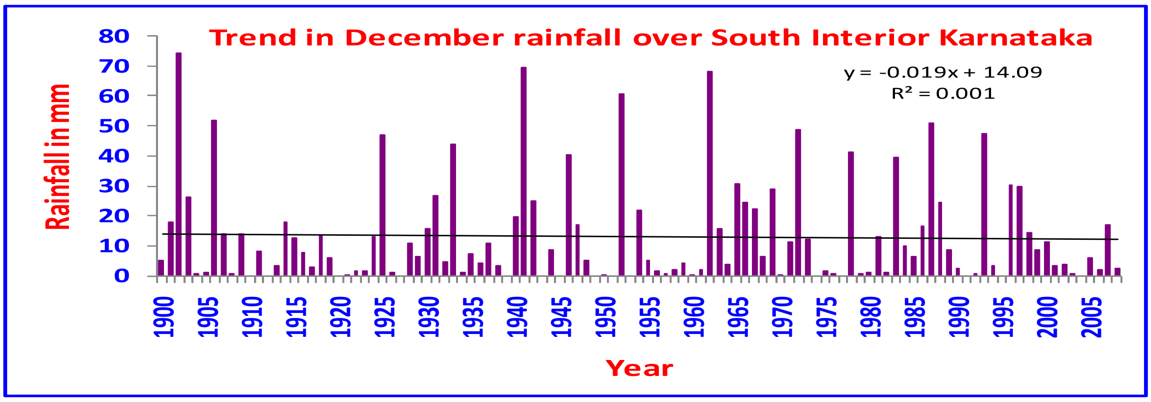
19 (iv c)



19 (v a)



19 (v b)



19 (v c)

Fig.19: Trends in the sub-divisional rainfall of CAP (19 i: a-c), RYS(19 ii: a-c), TN(19 iii: a-c), KER(19 iv:a-c) and SIK(19 v:a-c) during the NEM months of (a)October, (b) November and (c) December during the period 1900-2008

Chapter – V

FLOODS

Floods are caused by the inadequate capacity within the banks of the rivers to contain the high flows brought down from the upper catchment due to heavy rainfall. In coastal areas, they are caused by cyclones and typhoons. Other causes include backing up of waters in tributaries at their outfalls into the main river often with synchronization of floods in them; ice jams or landslides blocking stream courses resulting in the backwater overflowing river banks. Flash flood occurs in areas near foot hills. However the root cause of flood is excessive rainfall which occurs mainly in the monsoon months of July to September. Floods are also sometimes caused by Glacial Lake Outburst called Glacial Lake Outburst Floods (GLOFs) which can be catastrophic for people living immediately downstream and can cause serious damage to infrastructure and the economy.

Floods are recurrent phenomena since time immemorial. Almost every year some parts of the world or the other are affected by the floods of varying magnitude. Even in the same country of the region different parts have different climates and rainfall patterns and, as such, it is also experienced that while some parts are suffering under devastating floods, another part is suffering under drought. With the increase in population and developmental activity, there has been tendency to occupy the flood plains which has resulted in more serious nature of damages over the years. Because of the varying rainfall distribution, many a times, areas which are not traditionally prone to floods also experience severe inundation. Flood indeed is the single most frequent disaster faced not only in India but by various part of world including the South Asia region.

Losses due to floods

Floods inundate the banks, destroy crops, damage properties, perish live stock, disturb communication and power supply and endanger human life. Floods are followed by epidemics. Supply of drinking water and restore sanitation are post flood challenge. In past 50 years, India had lost assets of more than Rs 65000 crore and loss of more than 75000 human lives due to floods alone. However absolute immunity from floods is not technologically/ economically feasible. Damages (Rs. in crore) during the period 1953-2004 are shown in Fig. 20. The year wise frequency of floods such as Flash Floods, and total floods occurred are shown in the following bar diagram during the period 1980-2005. There is a sharp increase in flash floods and a slight decreasing pattern in total floods (Fig 21).

The flood problem in India is mostly confined to the states located in the Indo-Gangetic plains, northeast India and occasionally in the rivers of Central India. Heavy rainfall, inadequate capacity of rivers to carry the high flood discharge, inadequate drainage to carry away the rainwater quickly to Streams/ Rivers, storm surges, Man made factors such as failure of dams and other control works like reservoirs are the main causes of floods. Ice jams or landslides blocking streams, debris flow, back water, and cyclones also cause floods. Excessive rainfall combined with inadequate carrying capacity of streams resulting in over spilling of banks is the cause for flooding in majority of cases.

Rashtriya Barh Ayog (RBA) constituted by the Government of India in 1976 carried out an extensive analysis to estimate the flood-affected area in the country. RBA in its report (1980) has assessed the area liable to floods as 40 million hectares. It was determined by summing up the maximum area affected by floods in any one year in each state during the period from 1953 to 1978 for which data was analysed by the Ayog. This sum has been corrected for the area that was provided with protection at that time and for the protected area that got affected due to failure of protection works during the period under analysis to arrive at the total area liable to floods in the country as per break-up given in Table 8. The area affected by flood in the country from 1953 to 2007 is also depicted in Table 9. Decadal mean frequency of flood years is presented in Table 10

After the heavy floods in 1954, national policy on, “Floods in the country” was set up in 1954 by government of India which provides measures of flood control and its protection. The central flood board was set up in 1954. Flood prone areas of the country are depicted in Fig. 22. Flood forecasting has been recognized most important reliable and cost effective non-structural measure for flood mitigation. India meteorological department (IMD) and Central Water Commission (CWC) are working in close co-ordination for issue of flood forecasts. IMD has 10 flood meteorological offices (FMOs) and CWC has 20 flood forecasting divisions located in different flood prone river basins.

Table 8 **Area liable to Floods (million Ha.)**	
1. Andhra Pradesh	1.39
2. Assam	3.15
3. Bihar	4.26
4. Gujarat	1.39
5. Haryana	2.35
6. Himachal Pradesh	0.23
7. Jammu & Kashmir	0.08
8. Karnataka	0.02
9. Kerala	0.87
10. Madhya Pradesh	0.26
11. Maharashtra	0.23
12. Manipur	0.08
13. Meghalaya	0.02
14. Orissa	1.40
15. Punjab	3.70
16. Rajasthan	3.26
17. Tamil Nadu	0.45
18. Tripura	0.33
19. Uttar Pradesh	7.336
20. West Bengal	2.65
21. Delhi	0.05
22. Pondicherry	0.01
Total	**33.516**

Table 9
Flood Affected Area (Million Ha) during 1953-2007

Year	*Flood Affected Area*	*Year*	*Flood Affected Area*
1953	2.29	1981	6.12
1954	7.49	1982	8.87
1955	9.44	1983	9.02
1956	9.24	1984	10.71
1957	4.86	1985	8.38
1958	6.26	1986	8.81
1959	5.77	1987	8.89
1960	7.53	1988	16.29
1961	6.56	1989	8.06
1962	6.12	1990	9.303
1963	3.49	1991	6.357
1964	4.9	1992	2.645
1965	1.46	1993	11.439
1966	4.74	1994	4.805
1967	7.15	1995	5.245
1968	7.15	1996	8.049
1969	6.2	1997	4.569
1970	8.46	1998	9.133
1971	13.25	1999	3.978
1972	4.1	2000	5.166
1973	11.79	2001	3.008
1974	6.7	2002	7.09
1975	6.17	2003	6.503
1976	11.91	2004	8.031
1977	11.46	2005	3.376
1978	17.5	2006	0.437
1979	3.99	2007	3.549
1980	11.46	2008	---

Table 10

Decadal mean (% departure from normal), frequency of flood years

Decade	Decadal mean % departure from normal	Freq. of Excess year
1901-10	-2.2	0
1911-20	-2.5	3
1921-30	-0.4	0
1931-40	1.7	1
1941-50	3.3	1
1951-60	2.5	3
1961-70	-0.1	1
1971-80	-0.8	1
1981-90	-0.3	2
1991-2000	0.6	1
2001-2003	-5.9	0

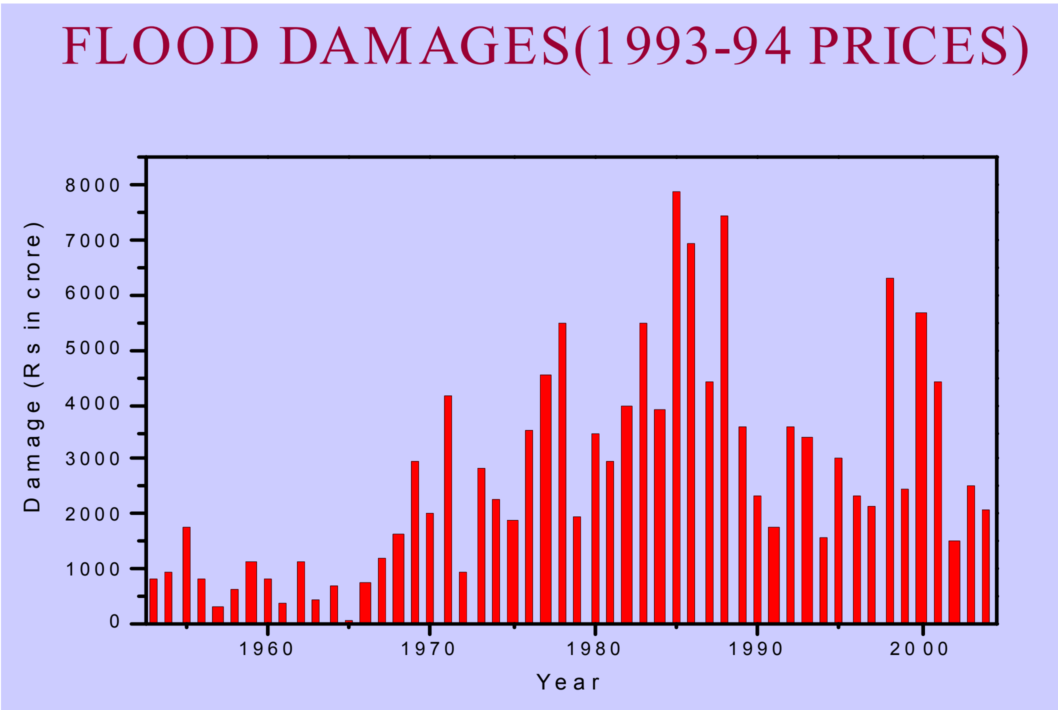


Fig. 20: Damages (Rs. in crore) during the period 1953-2004

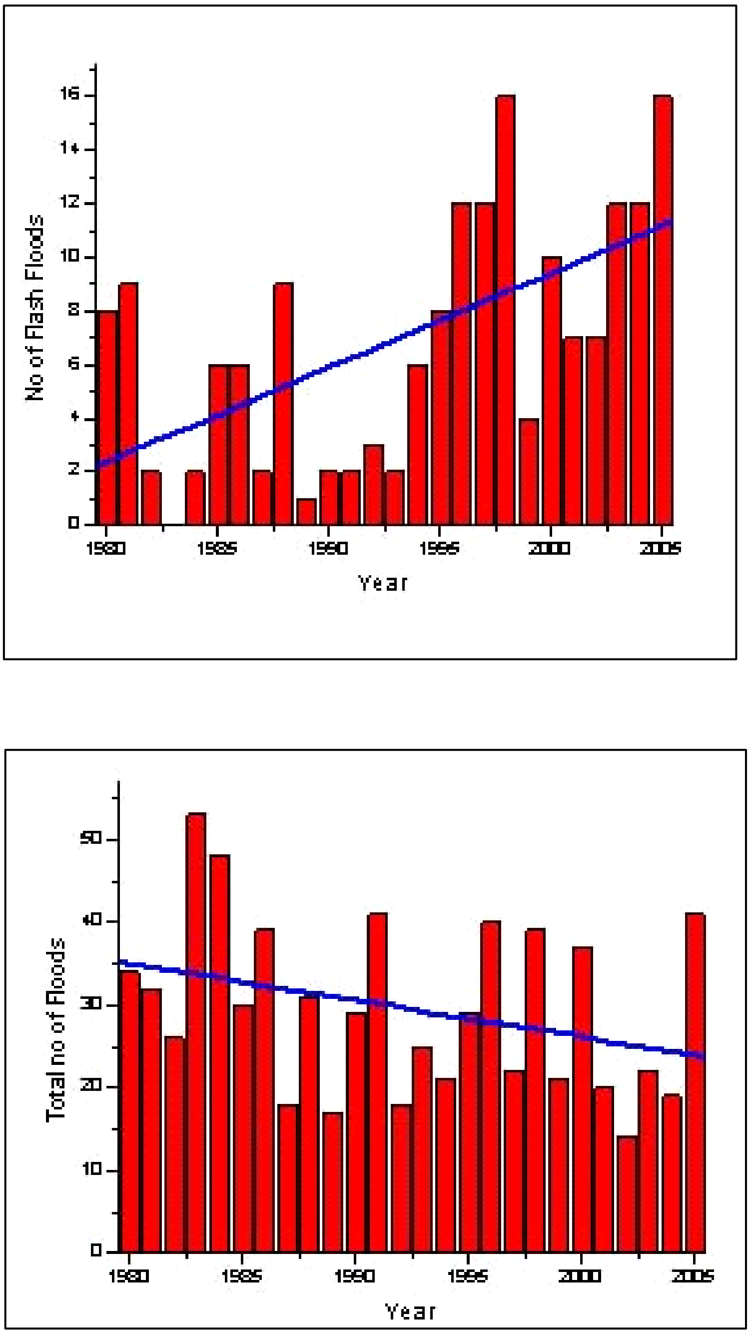


Fig. 21: Pattern of Flash and Total floods during 1980-2005

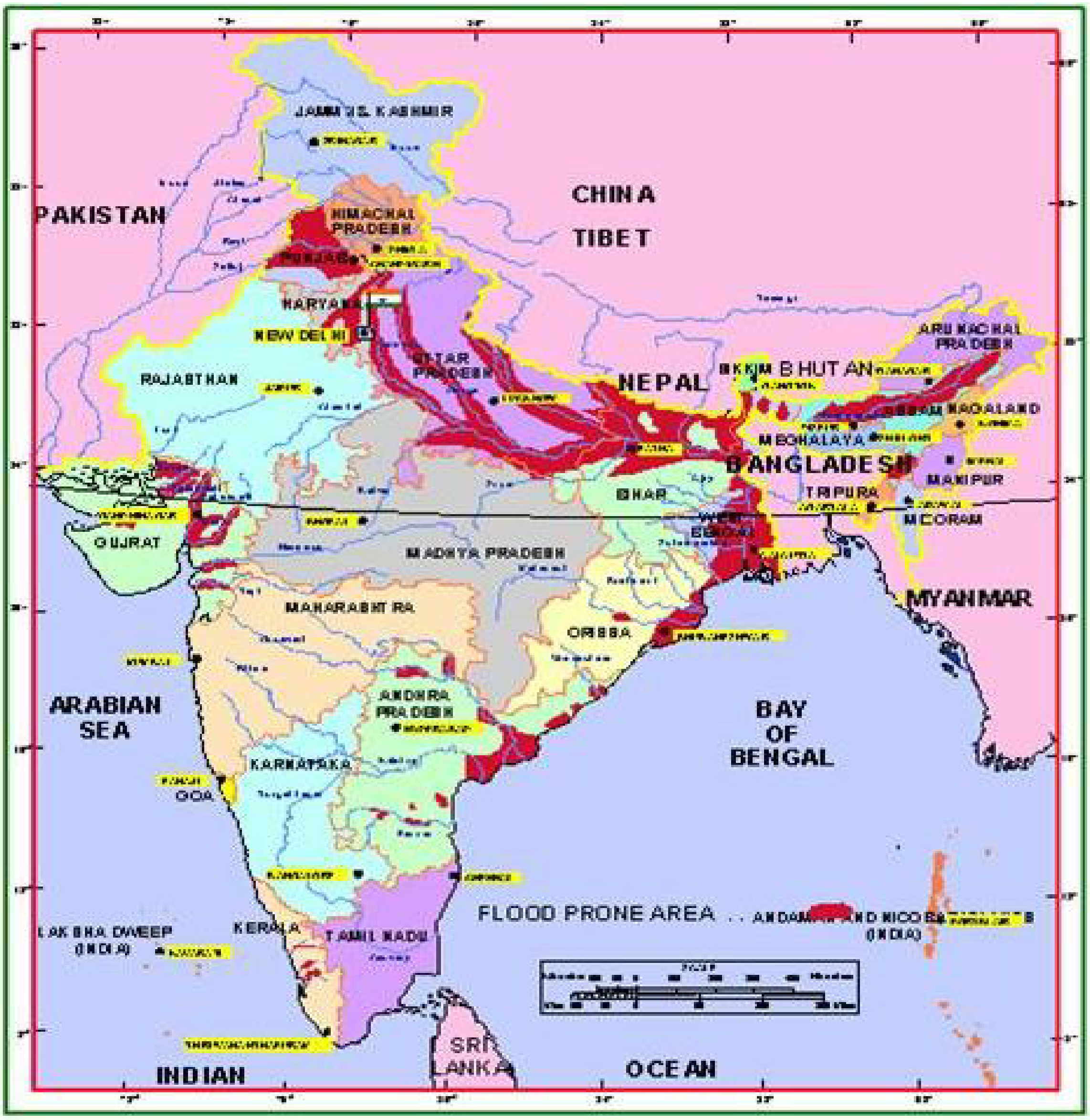


Fig. 22: Flood prone areas of India

Chapter – VI

TROPICAL CYCLONES

6.1 Introduction

Tropical cyclones (TC) are the most devastating phenomena among all natural disasters, having taken more than half a million lives all over the world in the last five decades. The havoc caused by tropical cyclones to shipping in the high seas and coastal habitats along the Indian coasts have been known since hundreds of years. They are large synoptic scale weather systems which originate over warm oceans, develop into massive vortices comprising of swirling winds, intense clouds and torrential rains by drawing energy from the ocean and move poleward. The formation and intensification are controlled by several atmospheric and oceanic parameters such as low level relative vorticity and humidity, vertical wind shear, low level convergence, upper level divergence, conditional instability and sea surface temperature (SST) (Gray,1968). A TC generally dissipates when it enters into land (which is generally referred as 'landfall') or into colder seas. The destructive potential of a TC is associated with strong and destructive *gale force winds* with speeds in the order of 200 kmph, *heavy rains* up to 40-50 cm per day and above all, *storm surge* which cause large scale damages over a vast area. The Bay of Bengal has experienced more than 75% of the total world-wide TCs causing human death of 5000 or more in last 300 years. India Meteorological Department (IMD) has maintained a meticulous record of tracks of cyclones and depressions that formed over the NIO since 1891 in the form of "*Storm track Atlas*". The same has recently been brought out electronically as '*Cyclone eAtlas – IMD*' CD (IMD, 2008). This software is extensively used in this work for generating most of the climatological and statistical information.

It is now a well known fact (IMD, 2008) that about 5 to 6 TCs occur in the North Indian Ocean (NIO) prominently during the pre-monsoon season (March-April-May) and the post-monsoon season (October-November-December). Nearly 7 percent of the global TCs form in the North Indian Ocean. Damage potential of cyclones and adaptation/ mitigate actions are summarized in Table 11.

Table 11 Damage potential of cyclonic disturbances		
System Intensity	Damage expected	Action Suggested
Deep Depression (28-33 Kts or 52-61Kmph)	Minor damage to loose and unsecured structures	Fishermen advised not to venture into the open seas.
Cyclonic Storm (34-47kts or 62-87 kmph)	Damage to thatched huts. Breaking of tree branches causing minor damage to power and communication lines	Total suspension of fishing operations
Severe Cyclonic Storm (48-63 kts or 88-117 kmph)	Extensive damage to thatched roofs and huts. Minor damage to power and communication lines due to uprooting of large avenue trees. Flooding of escape routes.	Total suspension of fishing operations. Coastal hutment dwellers to be moved to safer places. People in affected areas to remain indoors.
Very Severe Cyclonic Storm (64-90 kts or 118-167 kmph)	Extensive damage to kutcha houses. Partial disruption of power and communication line. Minor disruption of rail and road traffic. Potential threat from flying debris. Flooding of escape routes.	Total suspension of fishing operations. Mobilise evacuation from coastal areas. Judicious regulation of rail and road traffic. People in affected areas to remain indoors.
Very Severe Cyclonic Storm (91-119 kts or 168- 221 kmph)	Extensive damage to kutcha houses. Some damage to old buildings. Large-scale disruption of power and communication lines. Disruption of rail and road traffic due to extensive flooding. Potential threat from flying debris.	Total suspension of fishing operations. Extensive evacuation from coastal areas. Diversion or suspension of rail and road traffic. People in affected areas to remain indoors.
Super Cyclone (120kts or more or 222 kmph or more)	Extensive structural damage to residential and industrial buildings. Total disruption of communication and power supply. Extensive damage to bridges causing large-scale disruption of rail and road traffic. Large-scale flooding and inundation of sea water. Air full of flying debris.	Total suspension of fishing operations. Large-scale evacuation of coastal population. Total suspension of rail and road traffic in vulnerable areas. People in affected areas to remain indoors.

6.2 Climatology of cyclones

Every year, about 80-90 TCs form over the oceanic regions, out of which, about 45 TCs develop into severe cyclonic storms and cause damages over the landfalling areas of the various coastal regions (Landsea, 2007). Monthly frequency of cyclonic disturbances (Depression, Cyclonic Storm and Severe Cyclonic Storm: D, CS and SCS) that formed over the North Indian Ocean (NIO) during the 110 year period of 1900-2009 is presented in Table 12. It can be seen that 1387 cyclonic disturbances formed over the NIO out of which, 1081 (78%) formed over the Bay of Bengal (BOB), 191 (14%) over the Arabian Sea (AS) and 115 (8%) over the land. Of the 1387 disturbances that formed over the NIO, 568 intensified into CS and 268 further intensified into SCS. Of the 568 TCs that formed over the NIO, 449 were over the BOB and 106 over the AS. Only 13 out of 115 land depressions intensified into TCs. Thus, land depressions very rarely intensify into TCs. Of the 268 SCS that formed over the NIO, 202 were over the BOB, 63 over the AS and only three over the land.

From the monthly distribution of the frequencies, it can be seen that 714 depressions formed during the southwest monsoon season of June-September, 494 during the post-monsoon season of October-December, 156 during the pre-monsoon summer season of March-May and only 23 during the winter season of January–February. Of the 714 depressions that formed over the NIO during the southwest monsoon season, only 165 (23%) intensified into TC and 46 (6%) into SCS. On the contrary, during the post-monsoon season 284 out of 494 (57%) intensified into TC and 146 (30%) further intensified into SCS. Also, during the pre-monsoon season, 109 out of 156 (70%) intensified into TC and 76 (47%) further intensified into SCS. Thus the post-monsoon season of October to December is the principal cyclonic season over the NIO, followed by the pre-monsoon season of March to May.

Table12

Monthly frequency of cyclonic disturbances that formed over the various basins of NIO and reached various intensity levels during the period 1900-2009

Basin	Intensity level	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
BOB +AS +Land	D+CS+SCS	18	5	7	37	112	155	167	203	189	217	189	88	1387
	CS+SCS	8	2	5	27	77	56	38	28	43	103	130	51	568
	SCS	2	1	2	16	55	18	7	3	18	47	76	23	268
BOB	D+CS+SCS	17	5	7	29	81	100	133	168	142	170	152	77	1081
	CS+SCS	7	2	5	22	55	32	36	24	31	78	111	46	449
	SCS	2	1	2	13	38	3	7	3	13	36	63	21	202
AS	D+CS+SCS	1	0	0	7	30	46	8	2	11	42	35	9	191
	CS+SCS	1	0	0	5	22	22	1	1	8	24	17	5	106
	SCS	0	0	0	3	17	15	0	0	4	10	12	2	63
Land	D+CS+SCS	0	0	0	1	1	9	26	33	36	5	2	2	115
	CS+SCS	0	0	0	0	0	2	1	3	4	1	2	0	13
	SCS	0	0	0	0	0	0	0	0	1	1	1	0	3

6.3 Trends in frequency and intensity of cyclones over the North Indian Ocean

An extensive work on decadal variation in the ‘Variability and Trend in the Cyclonic Storms over the North Indian Ocean’ by analysing separately the long term data of 1891-2008 as well as during the recent 4-5 decades since 1961 have been undertaken by Niyas et al (2009). The results obtained are furnished below:

i. Taking the North Indian Ocean as a whole, on an average 5.2 cyclonic storms and 2.4 severe cyclonic storms form per year.

ii. For the North Indian Ocean as a whole, the number of cyclonic and severe cyclonic storms showed distinct decadal variability. The maximum number (67) occurred in the decade 1921-30 and minimum (38) during 1981-90.

iii. Long term linear trend (1891-2008) in frequency of tropical cyclones over the North Indian Ocean as a whole, the Bay of Bengal and the Arabian Sea for different seasons, generally, show a significant decreasing trend.

iv. However, an increasing trend in the frequency of tropical cyclones forming over the Bay of Bengal in the months of May and November, the principal cyclone months, was observed.

v. It may be observed that rate of decrease in frequency of tropical cyclone, is maximum for the monsoon season.

vi. Cyclone frequency data for the last four decades (1961 onwards), since when significant monitoring tools are available, show a significant decreasing trend for all the months and seasons; once again the maximum decrease was noticed in the monsoon season, however, their intensity appears to have increased.

Long term linear trend in the frequency of tropical cyclones over the north Indian Ocean, the Bay of Bengal and the Arabian Sea for different seasons and annual, generally, shows a significant decreasing trend (Srivastava et al.2000; Singh et al. 2000). Sharp decrease in the frequency of cyclones during the monsoon season was observed (Singh, 2001). However, an increasing trend in the frequency of tropical cyclones over the Bay of Bengal in the months of May and November is observed.

6.3.1. Trends in the annual and seasonal frequencies over NIO

(i) A decreasing trend in the annual frequency of cyclones (CS+SCS) that formed over NIO during 1900-2009 is discernible. However, there is a very slight increasing trend in the annual frequency of severe cyclones (SCS) that formed over the NIO during the said period (Fig.23 (i), a&b). An increasing trend in the intensification of CS to SCS is also seen (Fig.23 (i)c).

(ii) A decreasing trend in the formation of cyclones during the southwest monsoon season (Fig.23 (ii-iv),a&b) and an increasing trend in the formation of severe cyclones during the post-monsoon has been observed. The trends in the intensification of cyclones to severe cyclones is presented in Fig.23 (ii-iv)c

6.3.2 Trends in the annual frequencies of formation over BOB and AS

(i) Trends in the annual frequency of formation of cyclones (CS+SCS) and severe cyclones (SCS) over the BOB during the period 1900-2009 are presented in Fig.24(i),a&b. The trend in the frequency of SCS to total cyclones is presented in Fig.24(i)c. A slight decreasing trend in the annual frequency of cyclones that formed over BOB during 1900-2009 is seen. But, there is a slight increasing trend in the annual frequency of severe cyclones that formed over the BOB during the said period. Also, there is an increasing trend in the intensification of cyclones to severe cyclones.

(ii) Trends in the annual frequency of formation of cyclones (CS+SCS) and severe cyclones (SCS) over the AS during the period 1900-2009 are presented in Fig.24(ii),a&b. The trend in the frequency of SCS to total cyclones is presented in Fig.24(ii)c. No trend is noticeable in the frequencies of cyclones and severe cyclones that formed over the AS during the period 1900-2009.

(iii) Decreasing trend in frequency of cyclonic disturbances (depression and above) during 1891-2009 (Fig 25) and increase in low pressure areas during 1888-2009 (Fig 26) have been observed

6.3.3. Trends in the coastal crossings of the TCs over NIO

The trends in the frequency of TCs crossing various coastal regions of NIO during the period 1900-2009 have been studied. The frequency of TCs crossing various coasts of NIO as CS+SCS / SCS are presented in Table 13.

Table 13
Number of TCs crossing various coasts of NIO as CS+SCS / SCS during the period 1900-2009

Sl. No	Coast	CS+SCS	SCS
1	Tamil Nadu	50	26
2	Andhra Pradesh	68	27
3	Orissa	76	18
4	West Bengal	39	20
5	Bangladesh	65	32
6	Arakan	28	16
7	Kerala	2	1
8	Karnataka	-	-
9	Konkan & Goa	6	4
10	Gujarat	16	11
11	Pakistan	6	4
12	Sri Lanka	15	5
13	Iran, Arabia and Africa	13	5

The eastern coastal regions of India, viz., Tamil Nadu (TN), Andhra Pradesh (AP), Orissa and West Bengal (WB) are highly vulnerable to TC landfall whereas the western coastal regions of Kerala, Karnataka and Konkan & Goa are rarely affected by TC landfall. However, the state of Gujarat is affected by TC landfall. Further, Bangladesh, Arakan and Sri Lankan coasts are also greatly affected by landfalling TCs. It may be mentioned here that the TCs that crossed the TN and AP coasts were predominantly during the post-monsoon season and Orissa is mainly affected by TCs that form during the monsoon season. Fig. 27 (i-vii) a&b present the trends in the frequency of TC landfall over TN, AP, Orissa, WB, Bangladesh, Arakan and Gujarat coasts as CS+SCS / SCS. Here, those CS and SCS that retained their respective intensities at the time of coastal crossing are only considered for this analysis. Fig. 27(i-vii) c depicts the frequency of SCS to total cyclones that crossed these coasts.

The decreasing trend in the frequency of cyclones crossing Orissa and Arakan coasts and a slight increasing trend in the frequency of severe cyclones crossing Bangladesh and Gujarat coasts were observed. There is also an increasing trend in the frequency of CS intensifying into SCS and crossing TN, Orissa, Bangladesh, Arakan and Gujarat coasts.

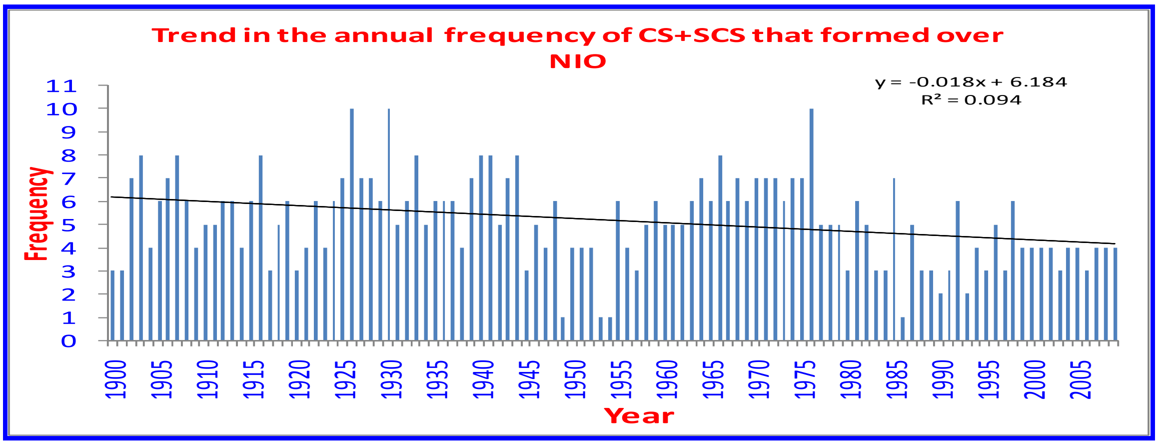
6.3.4 Trends in the frequency of TCs dissipating over sea without making landfall

No trends in the frequency of TCs (CS+SCS / SCS) forming over NIO dissipating over BOB and AS without making any landfall were observed during 1900-2009 (Fig 28 a-d).

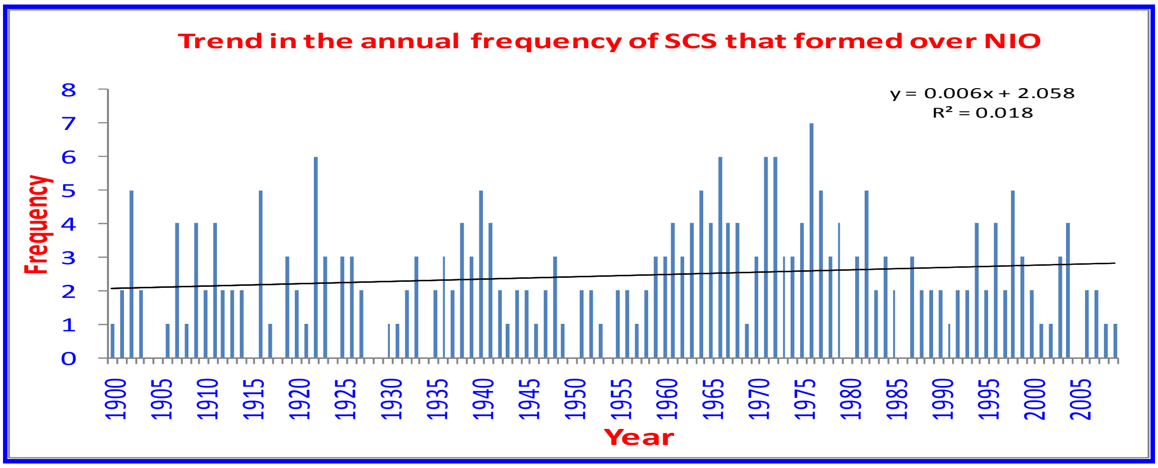
6.4 Storm Surge

Storm surge is the abnormal rise of sea level which occurs when the cyclone moves from ocean to continent. It is a disastrous and destructive feature of cyclone, which could cause massive destruction in the coastal region and misery to the coastal human population and livestock. Vulnerability in terms of the height of storm surge for the Bangladesh, East coast of India, West coast of India, Pakistan and Sri Lanka are available in Chapter 6 of SMRC(1998).

The crucial inputs for preparation of vulnerability atlases are the Probable Maximum Storm Surge (PMSS) over the various coastal areas. Infrastructure development over coastal regions has to take into consideration the respective PMSS values. The “Probable maximum storm surge heights for the maritime districts of India” by Kalsi et al, 2007 is an extensive work on computation of PMSS and the values obtained by them for the Indian coastal districts are given in Fig.29.



(a)



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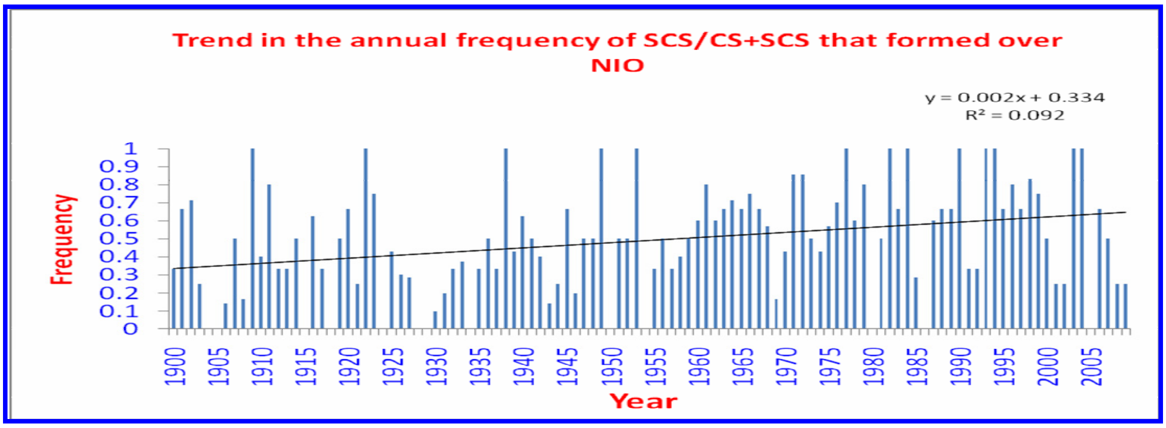
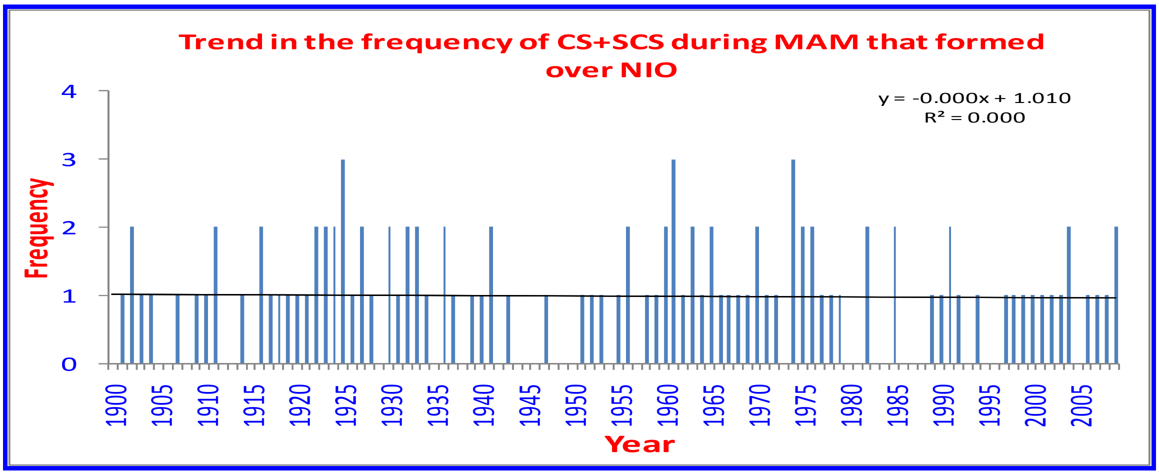


(c)

Fig.23 (i): Trends in the annual frequency of (a) cyclones (b) severe cyclones (c) severe cyclones to total cyclones that formed over the NIO during 1900-2009



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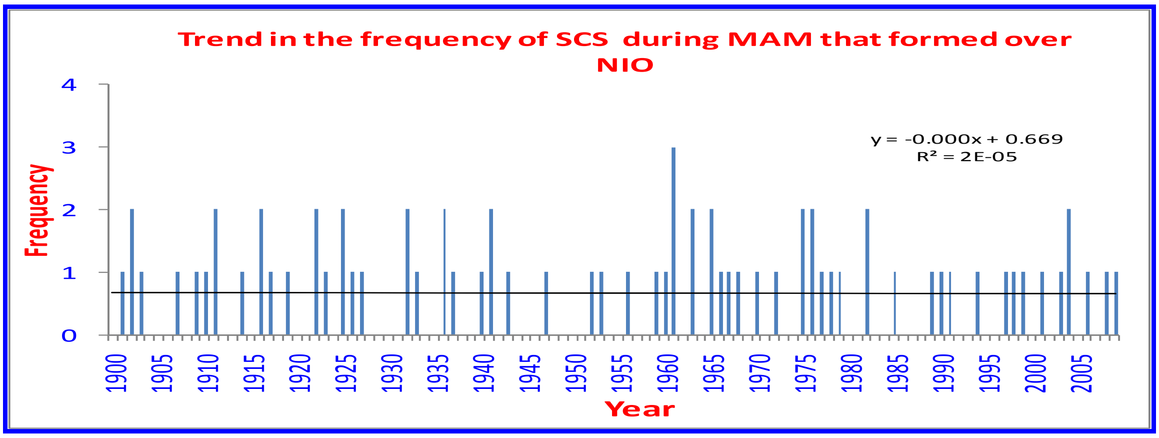

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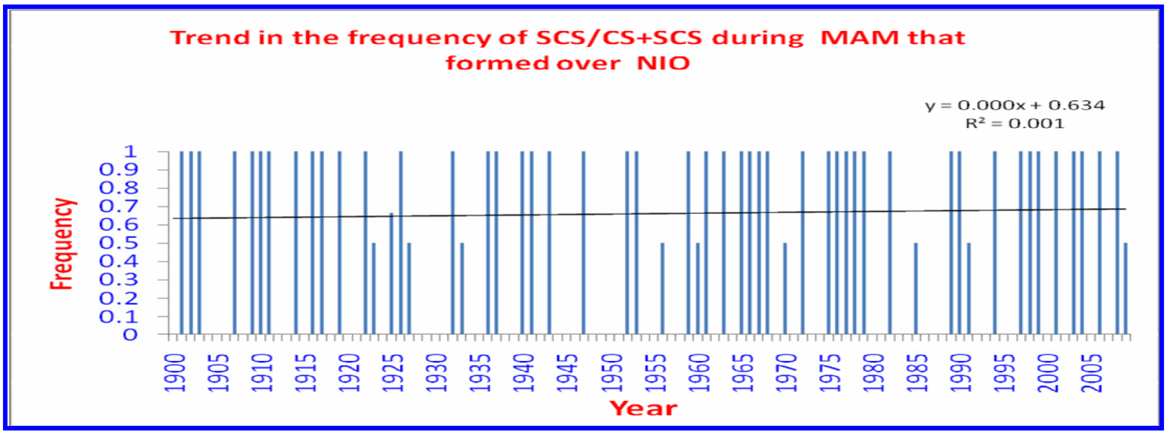
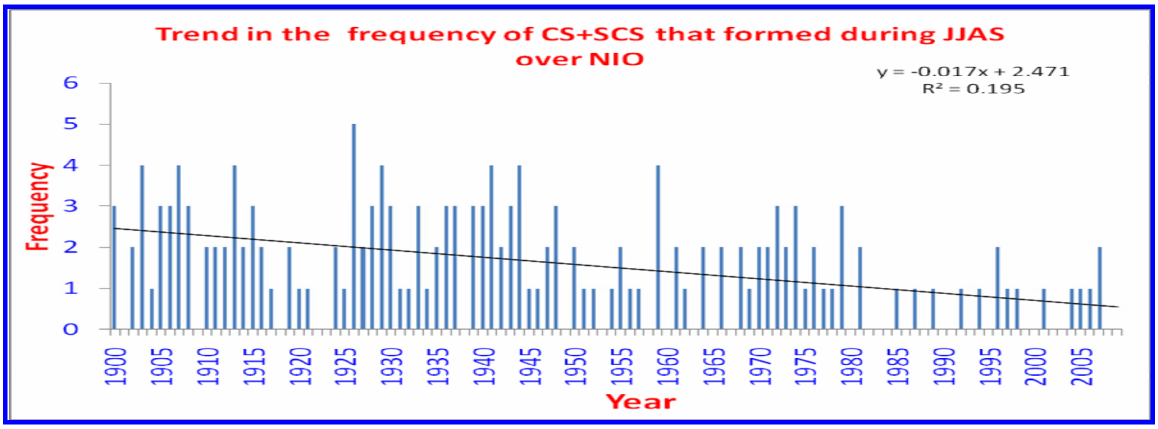
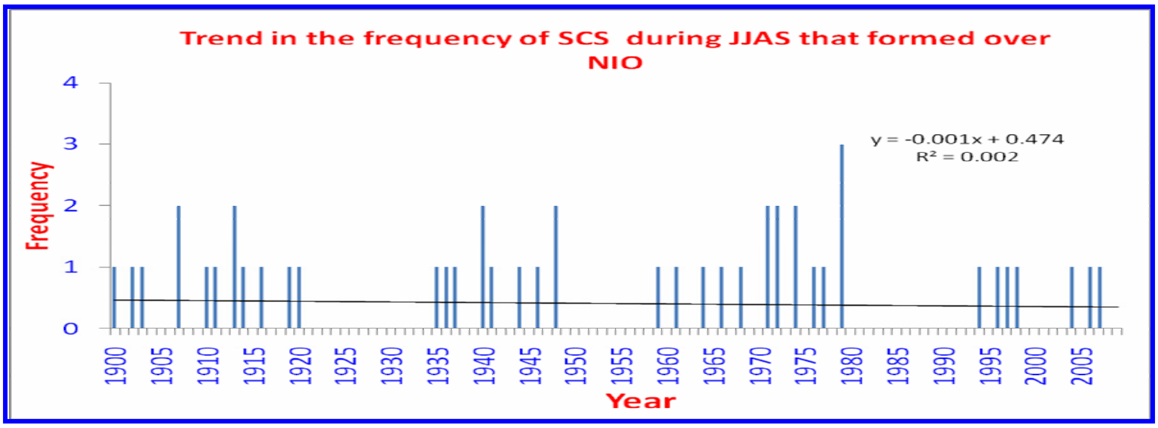


(c)

Fig.23 (ii): Trends in the seasonal frequency of (a) cyclones (b) severe cyclones (c) severe cyclones to total cyclones that formed in the pre-monsoon season (MAM) over the NIO during 1900-2009



(a)



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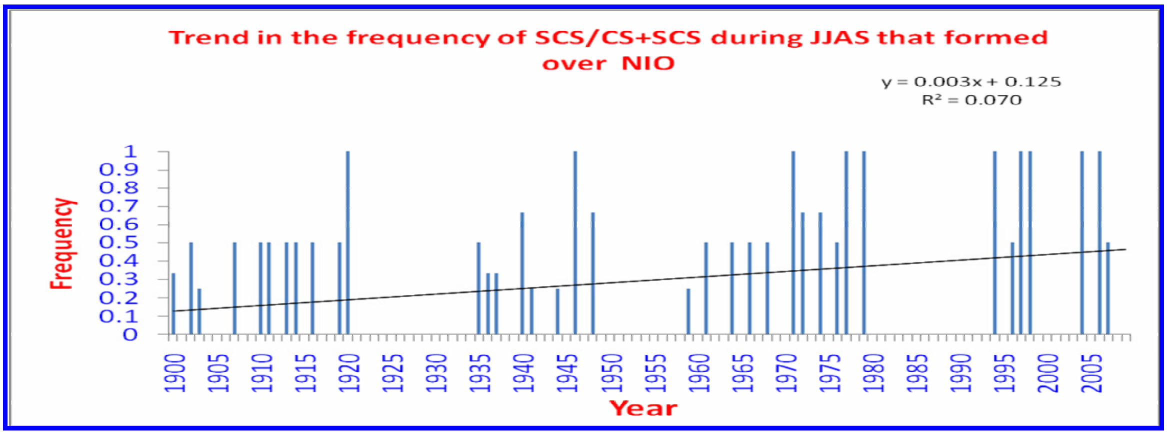
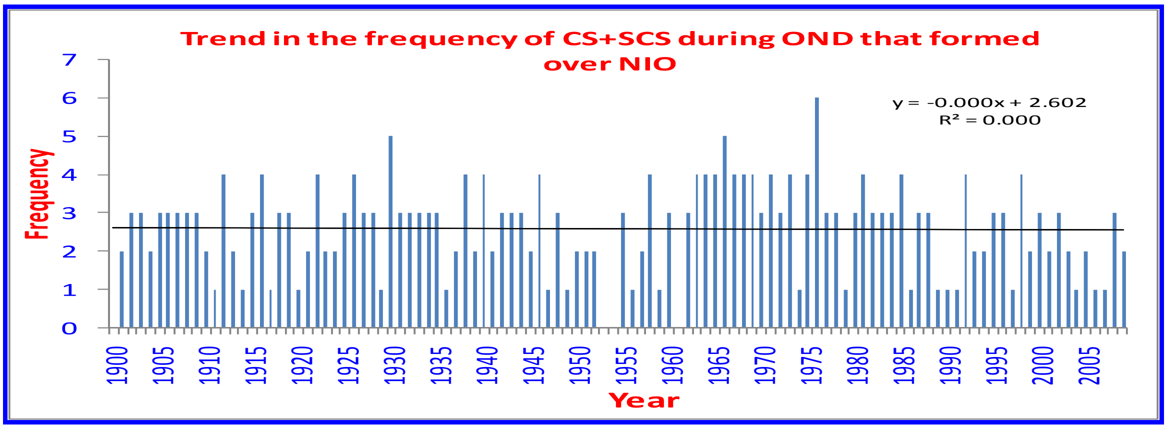


(c)

Fig.23 (iii): Trends in the seasonal frequency of (a) cyclones (b) severe cyclones (c) severe cyclones to total cyclones that formed in the monsoon season (JJAS) over the NIO during 1900-2009



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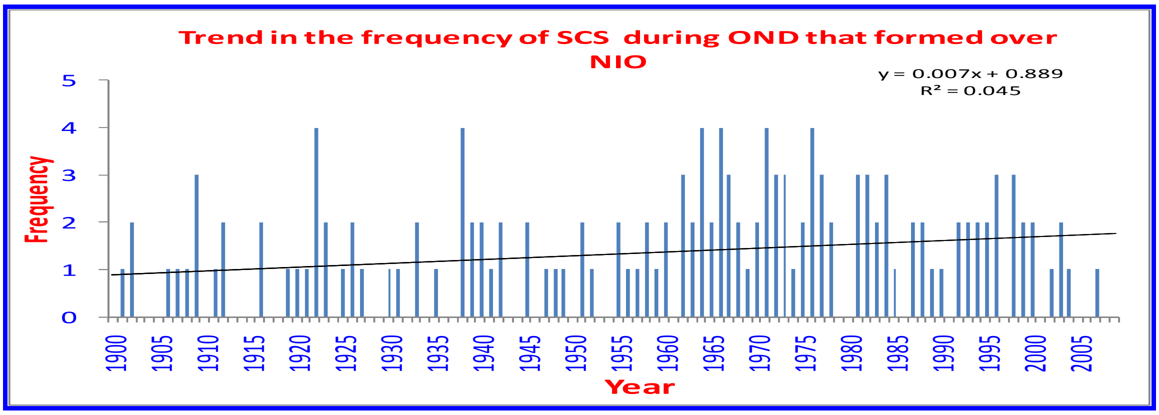

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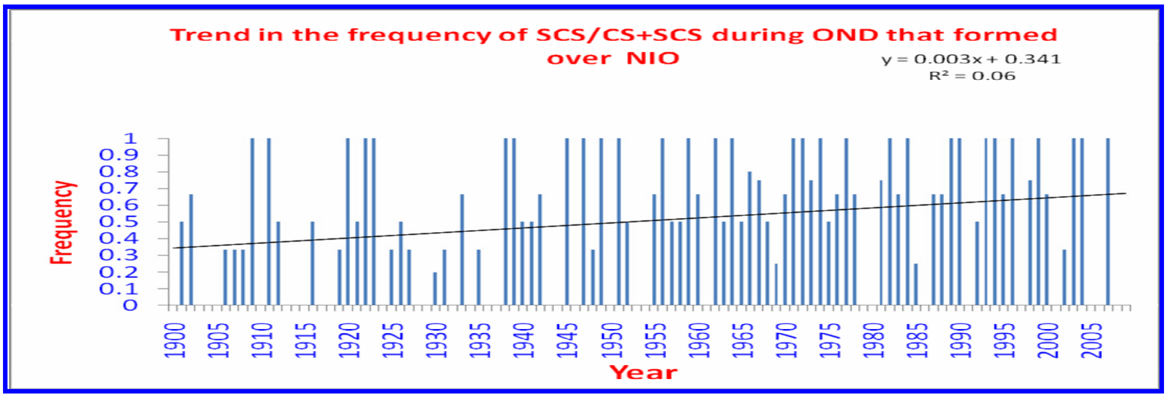
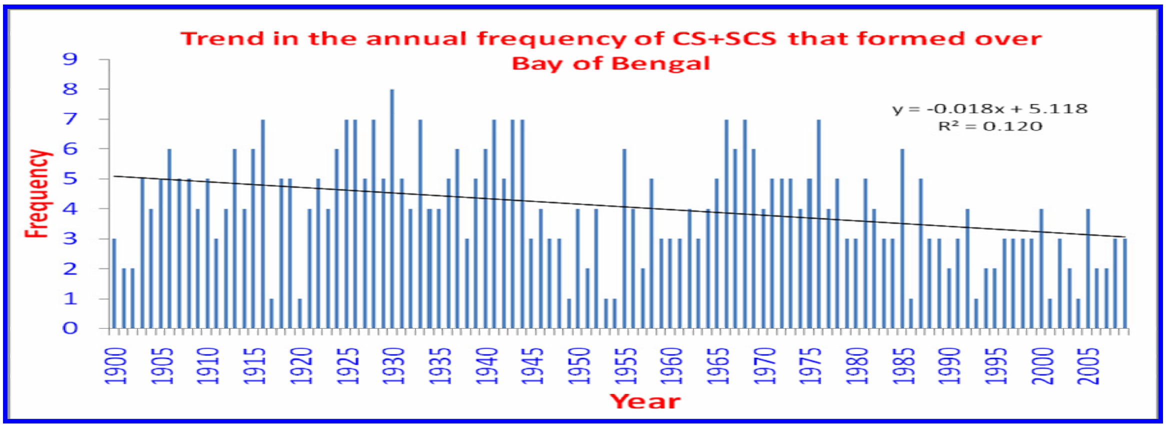


(c)

Fig.23 (iv): Trends in the frequency of (a) cyclones (b) severe cyclones (c) severe cyclones to total cyclones that formed in the post-monsoon season (OND) over the NIO during 1900-2009



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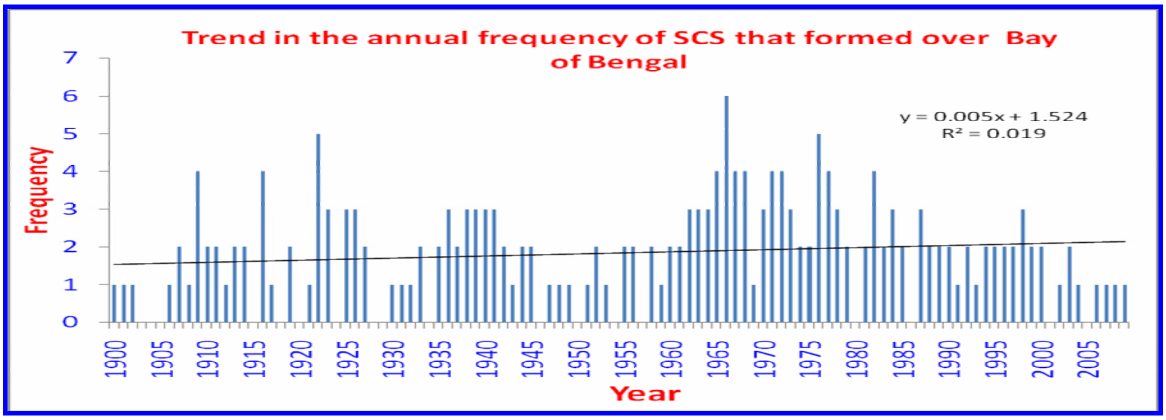

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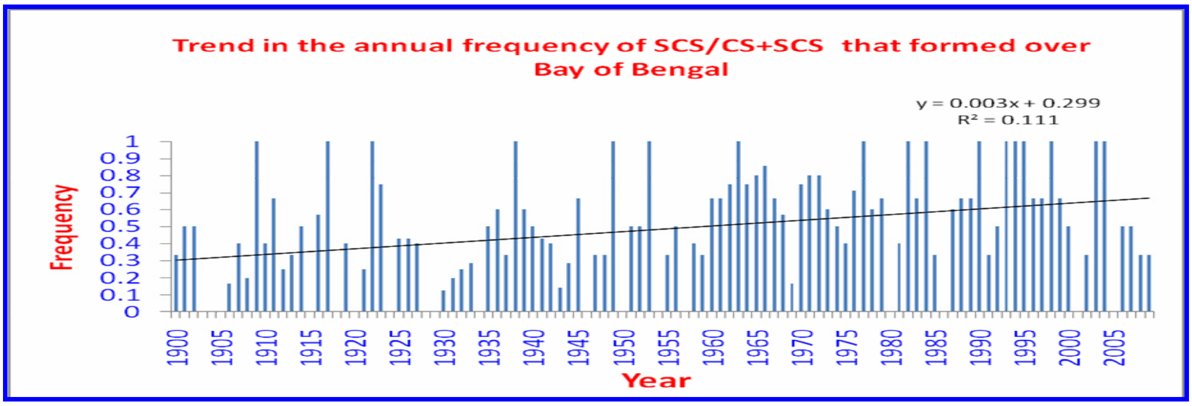
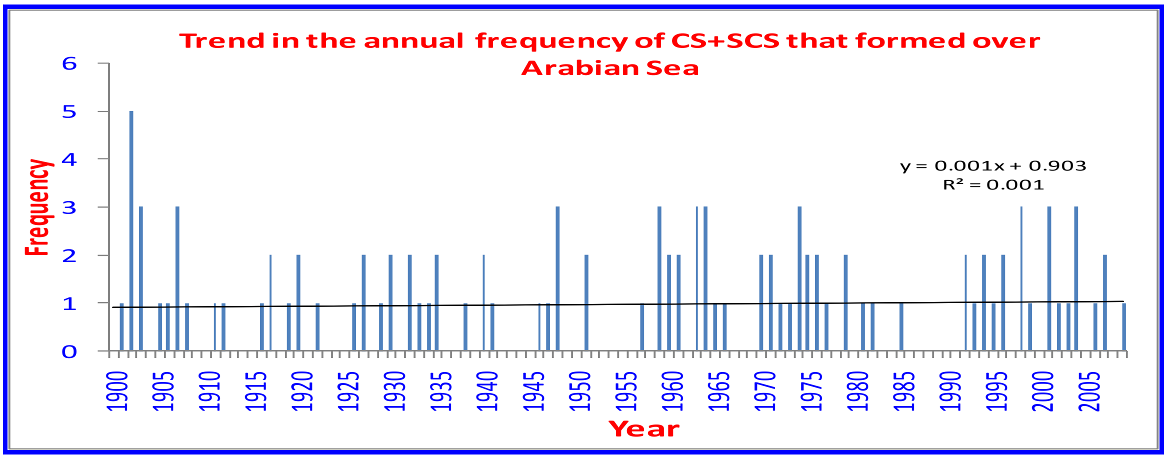


(c)

Fig. 24 (i): Trends in the annual frequency of (a) cyclones (b) severe cyclones (c) severe cyclones to total cyclones that formed over the Bay of Bengal during 1900-2009



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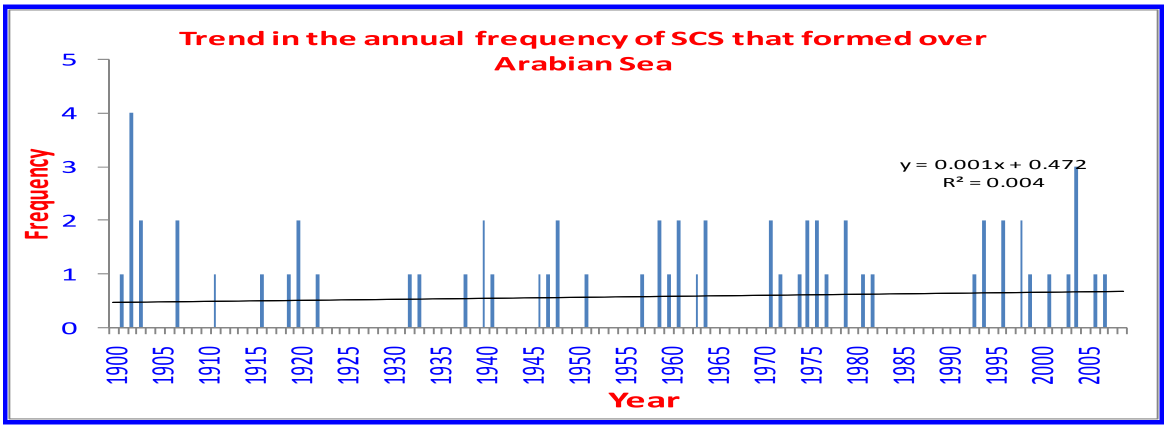

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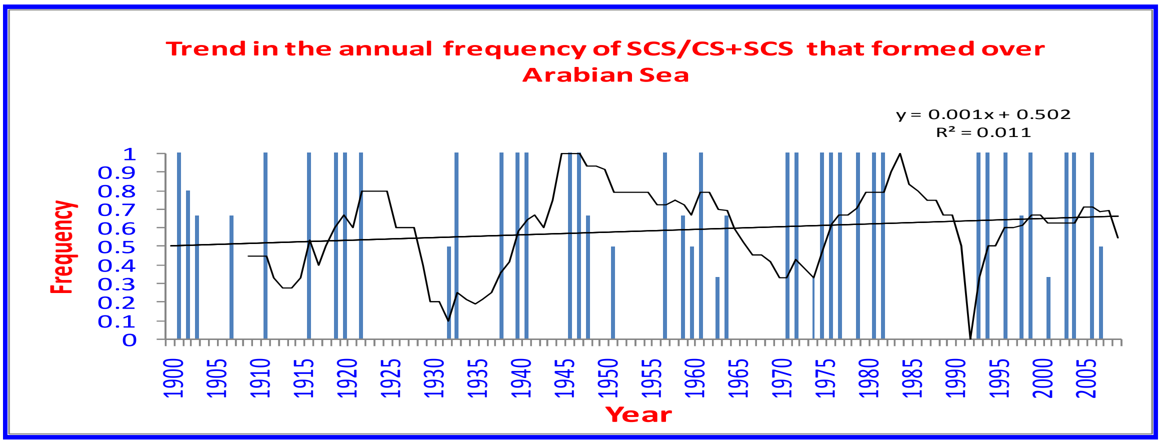


(c)

Fig.24(ii): Trends in the annual frequency of (a) cyclones (b) severe cyclones (c) severe cyclones to total cyclones that formed over the Arabian Sea during 1900-2009

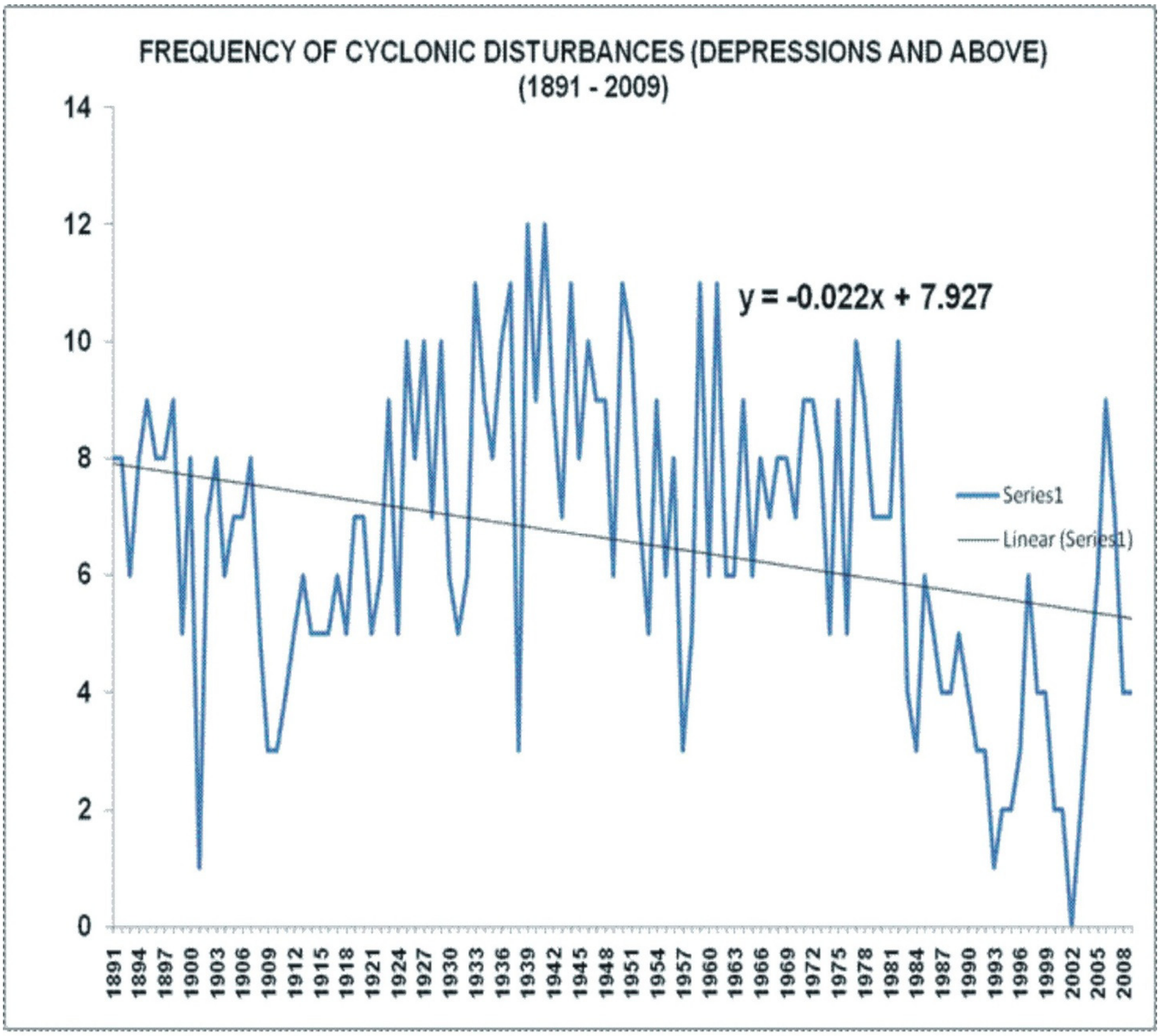


Fig. 25: Frequency of cyclones and depressions during 1891-2009

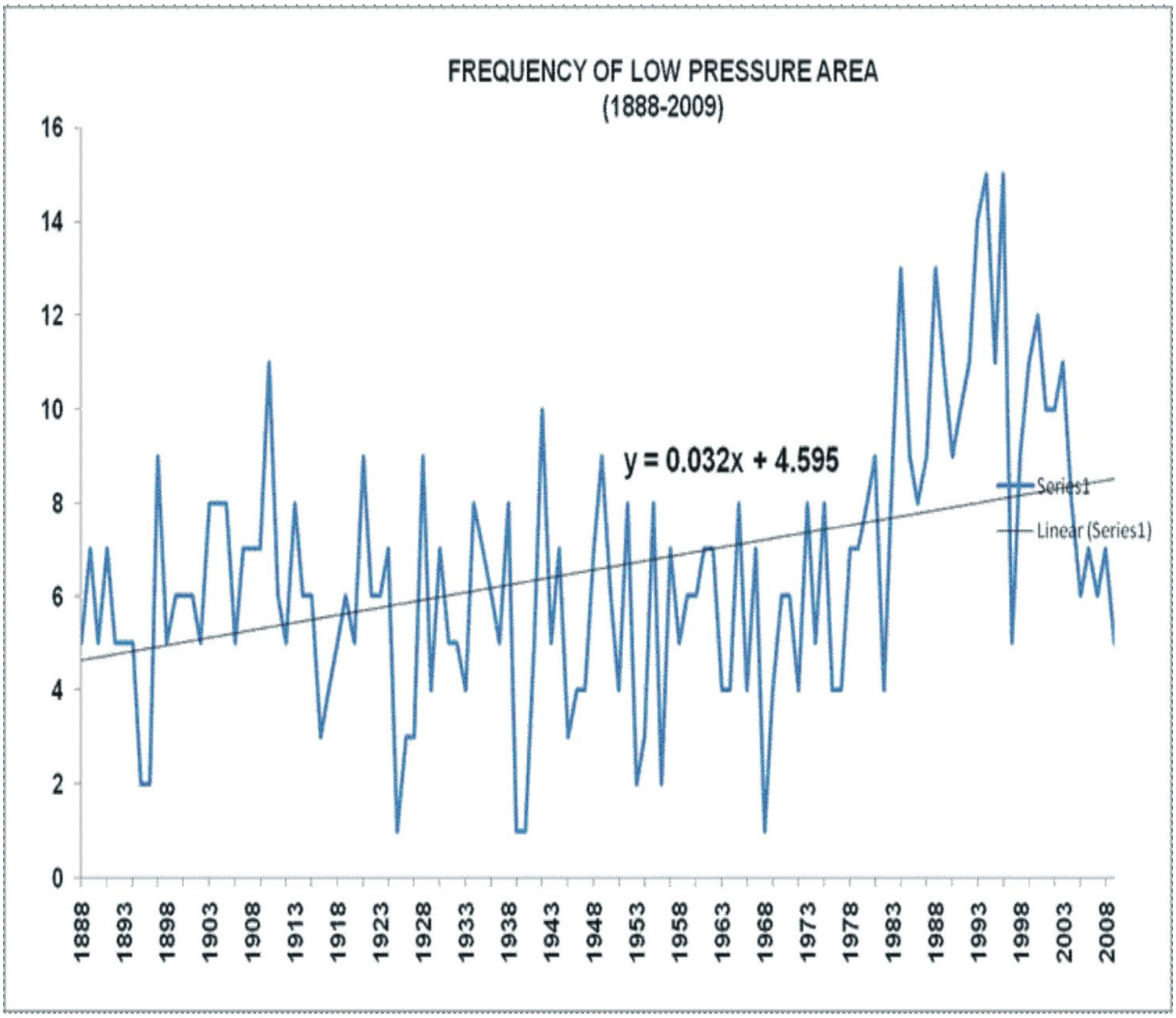
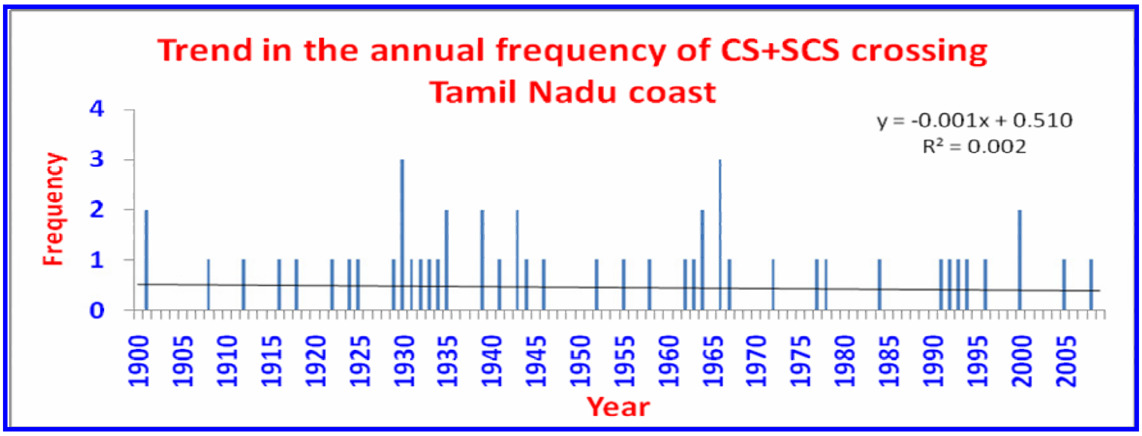


Fig 26: Trend in frequency of low pressure areas during 1888-2009



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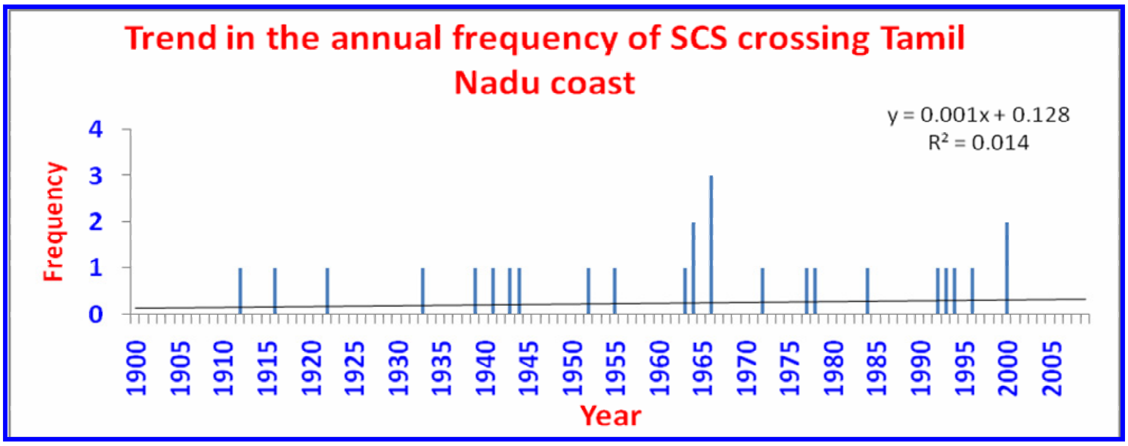

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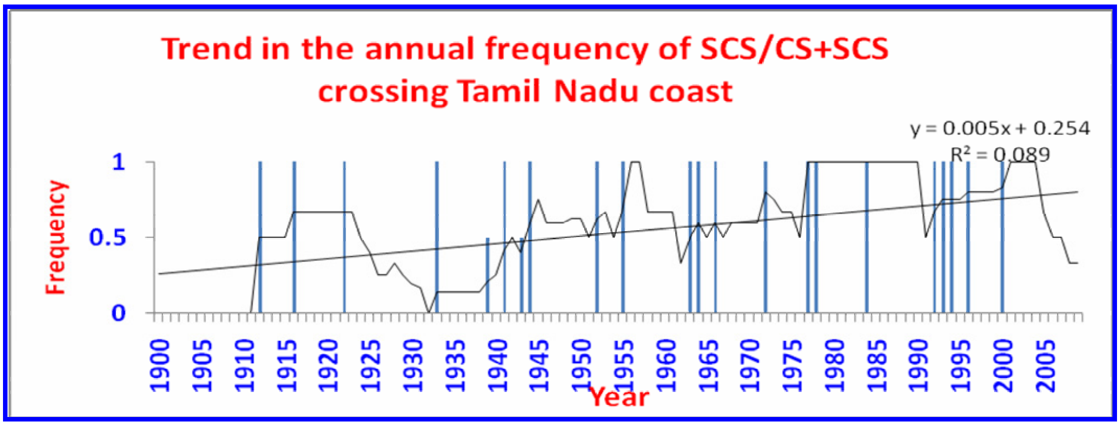
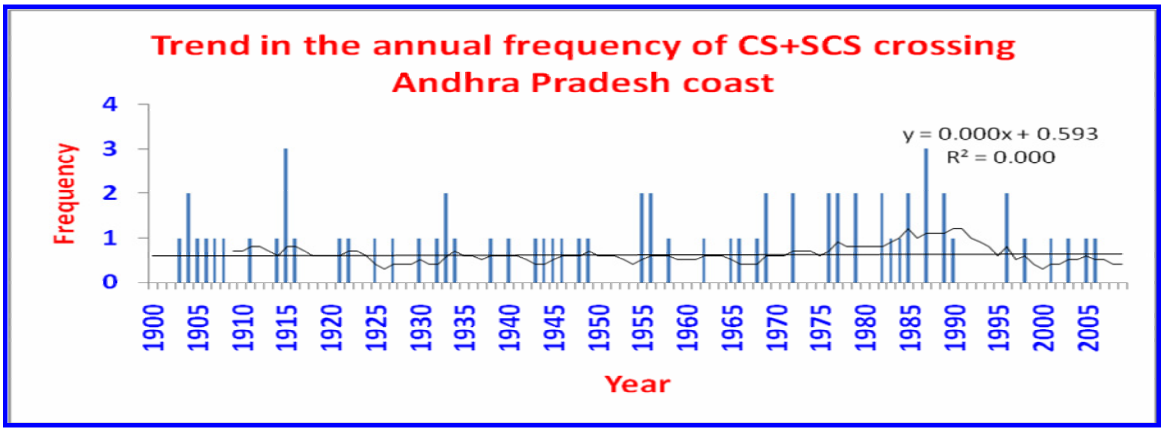


(c)

Fig.27 (i): Trends in the annual frequency of (a) cyclones and (b) severe cyclones (c) severe cyclones to total cyclones that crossed Tamil Nadu coast during 1900-2009



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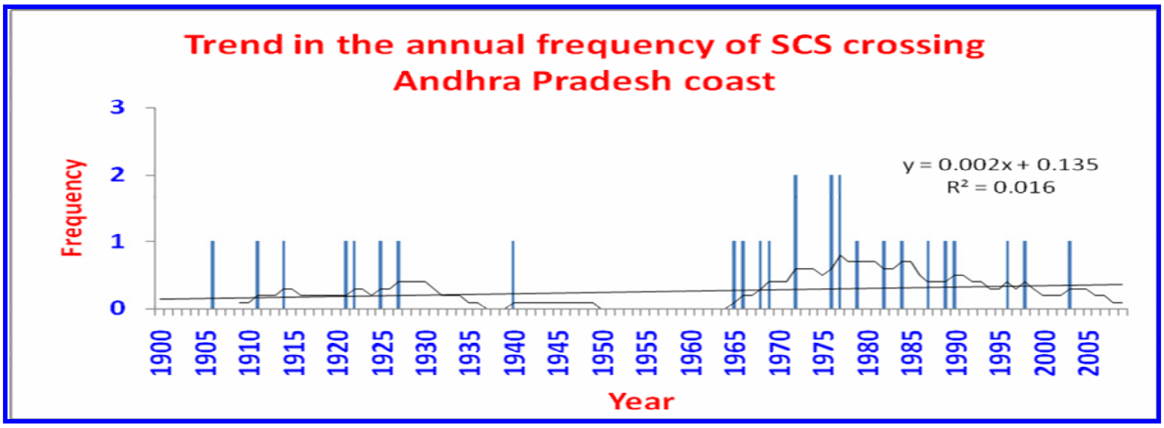

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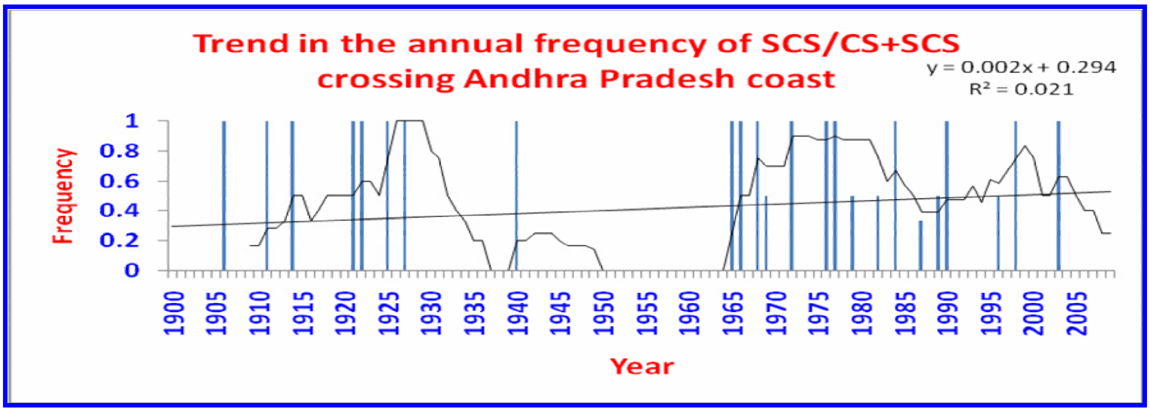
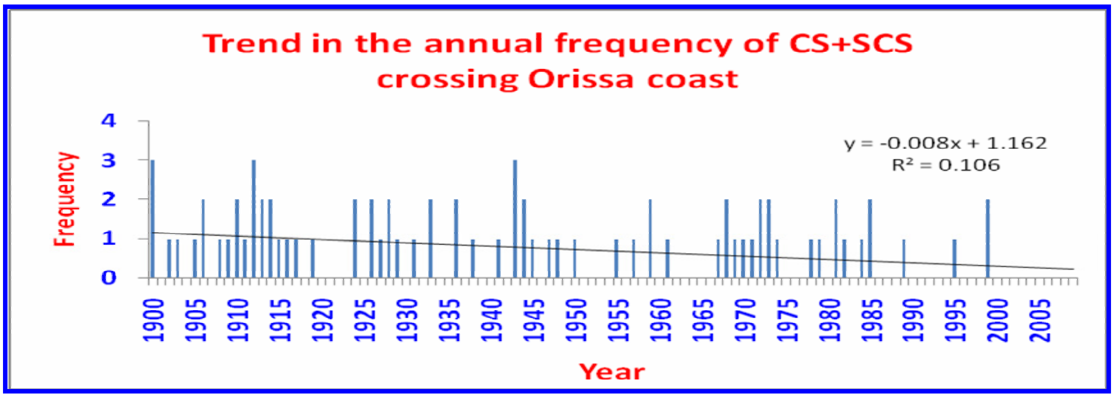


(c)

Fig.27 (ii): Trends in the annual frequency of (a) cyclones and (b) severe cyclones (c) severe cyclones to total cyclones that crossed Andhra Pradesh coast during 1900-2009



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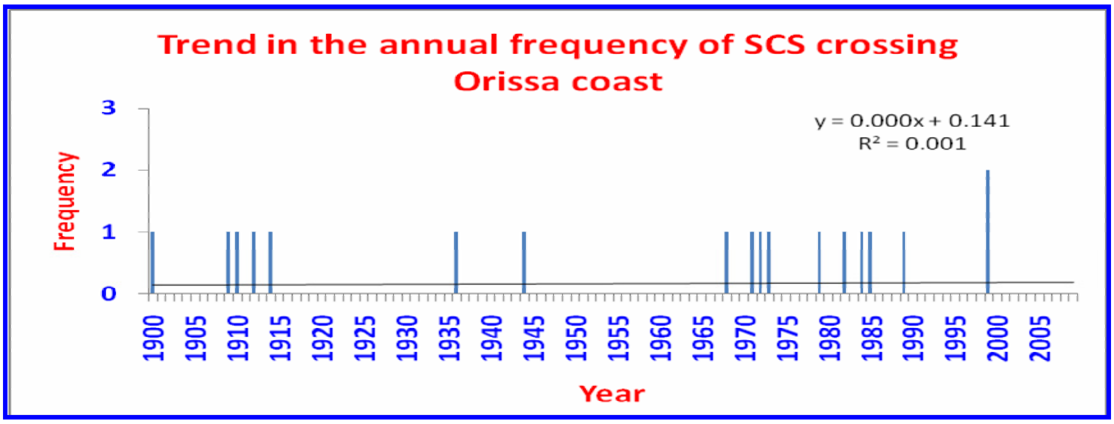

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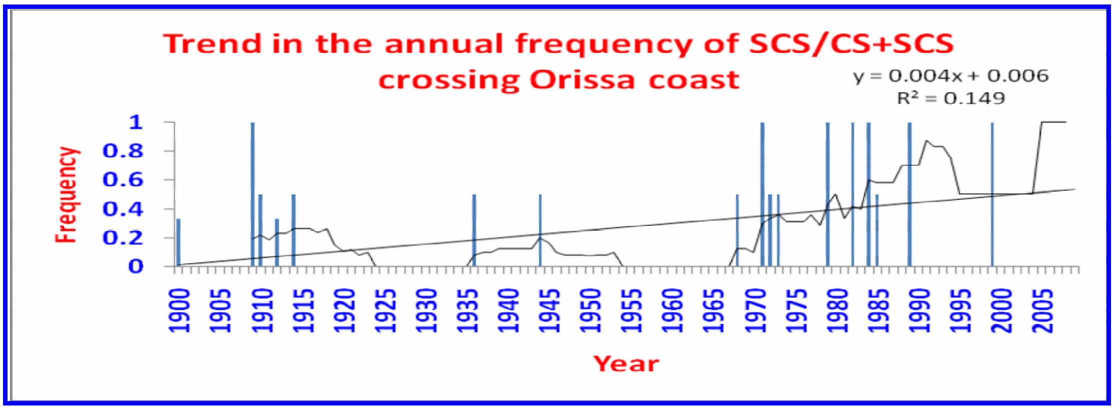
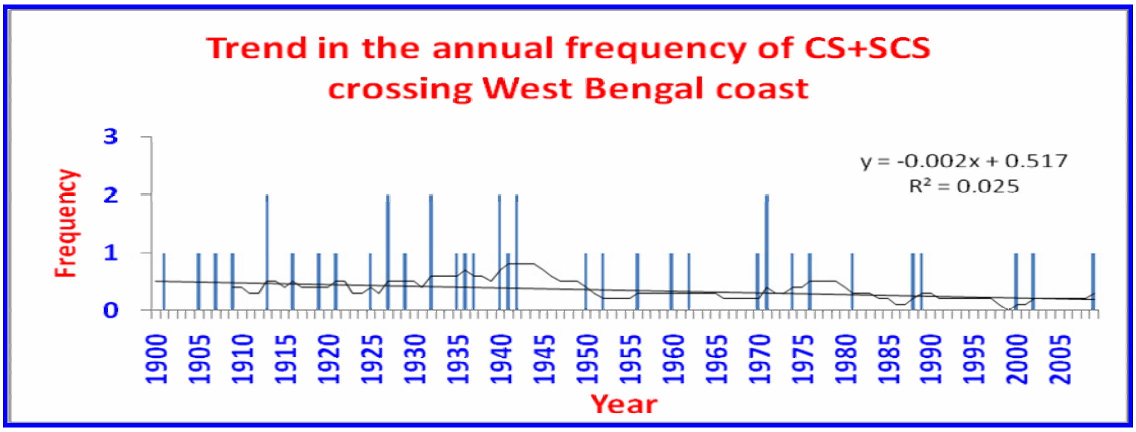


(c)

Fig.27 (iii): Trends in the annual frequency of (a) cyclones and (b) severe cyclones (c) severe cyclones to total cyclones that crossed Orissa coast during 1900-2009



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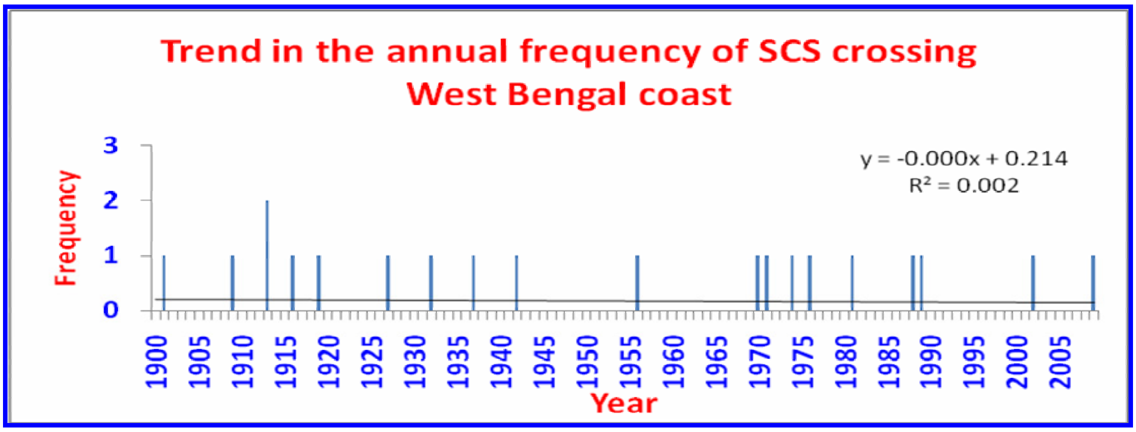

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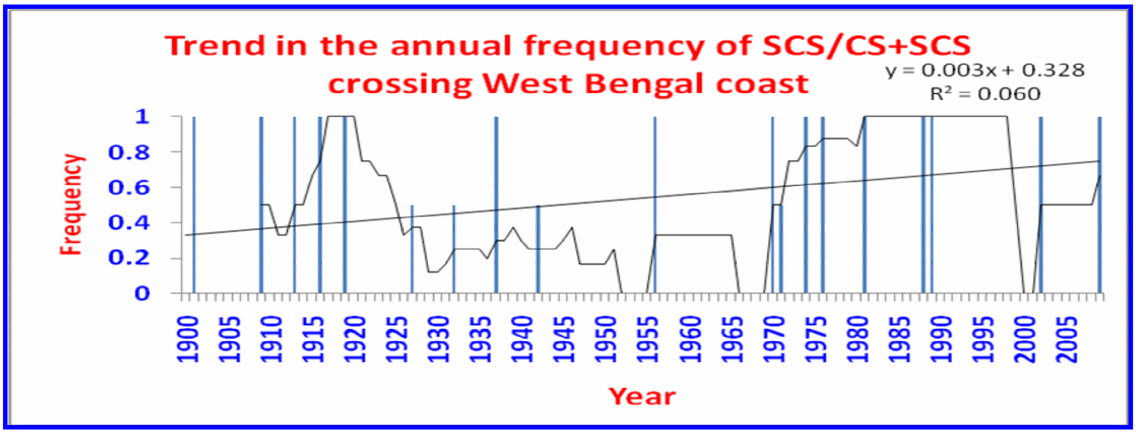
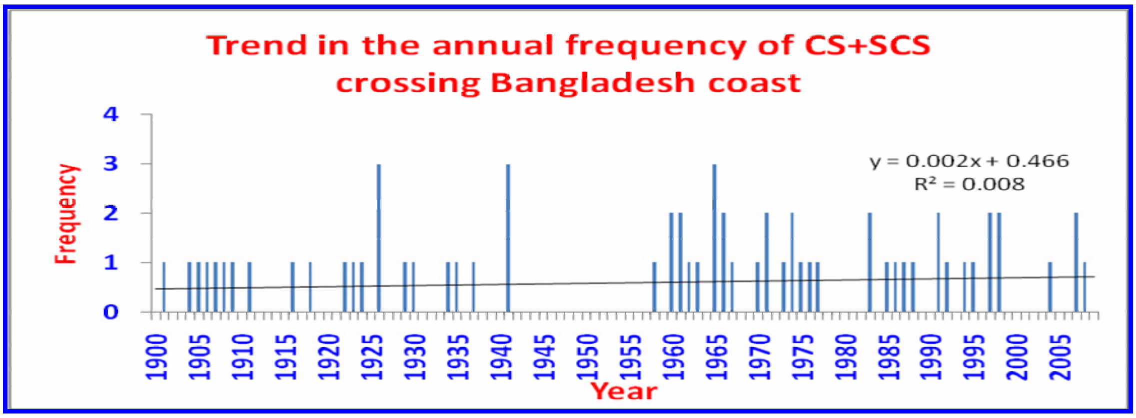


(c)

Fig.27 (iv): Trends in the annual frequency of (a) cyclones and (b) severe cyclones (c) severe cyclones to total cyclones that crossed West Bengal coast during 1900-2009



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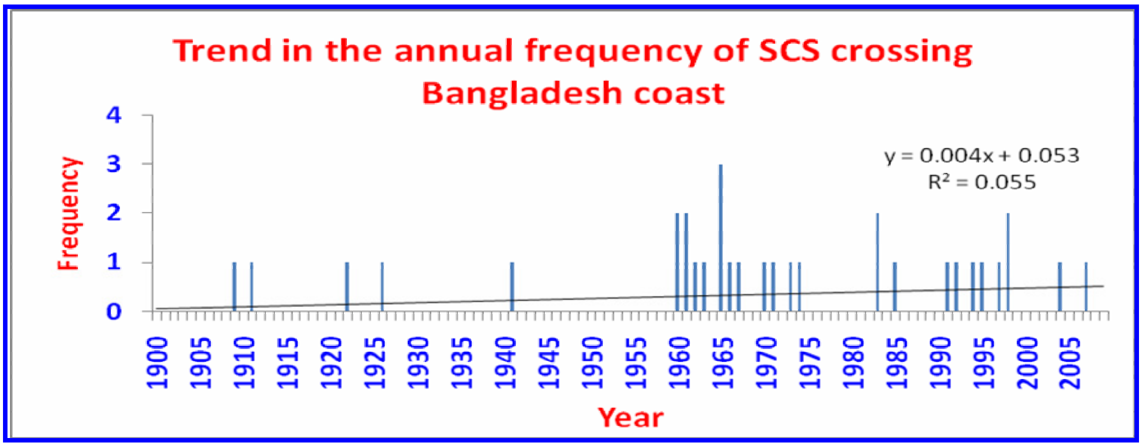

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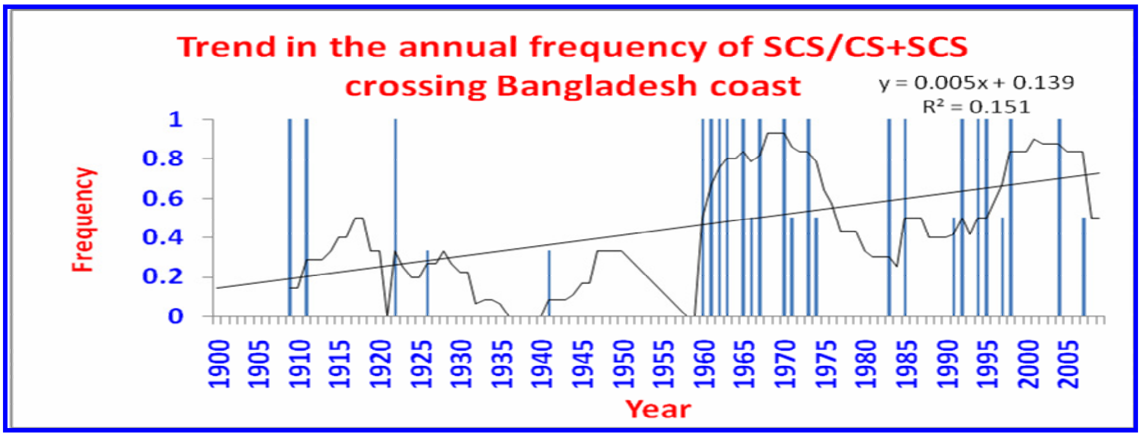
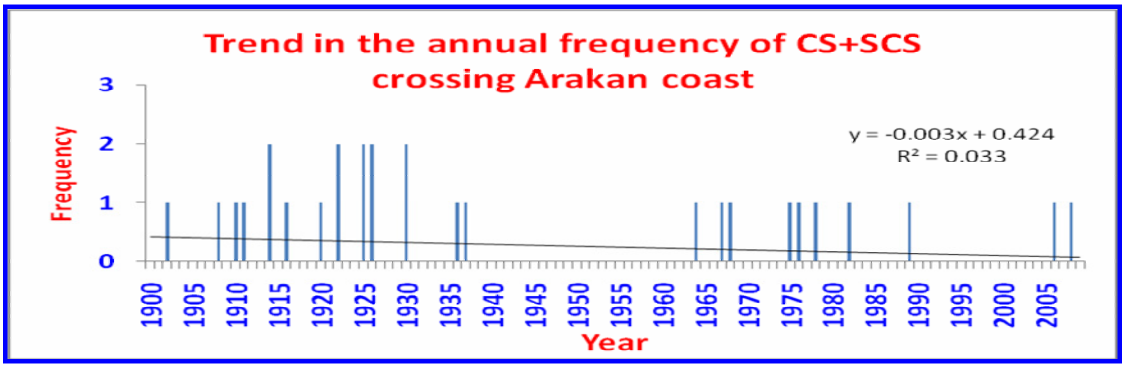


(c)

Fig.27 (v): Trends in the annual frequency of (a) cyclones and (b) severe cyclones (c) severe cyclones to total cyclones that crossed Bangladesh coast during 1900-2009



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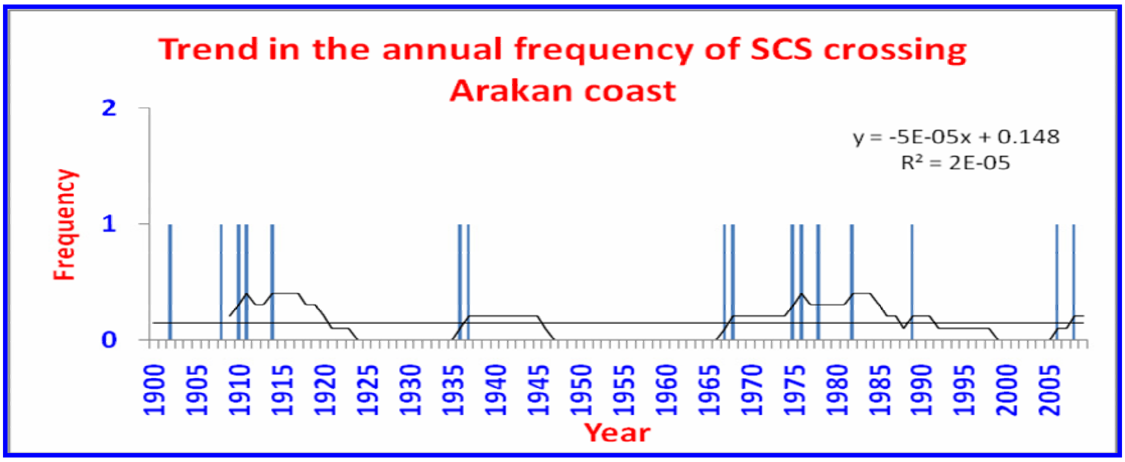

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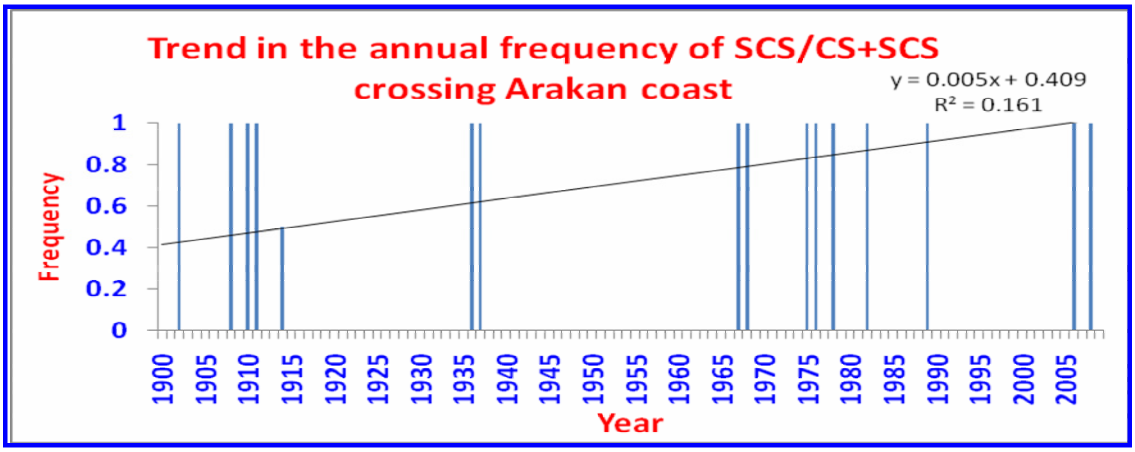
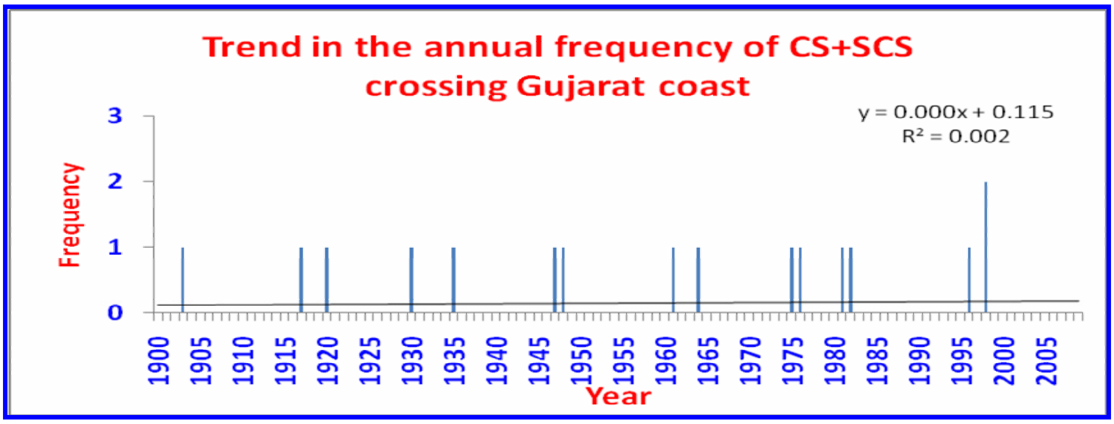


(c)

Fig. 27 (vi): Trends in the annual frequency of (a) cyclones and (b) severe cyclones (c) severe cyclones to total cyclones that crossed Arakan coast during 1900-2009



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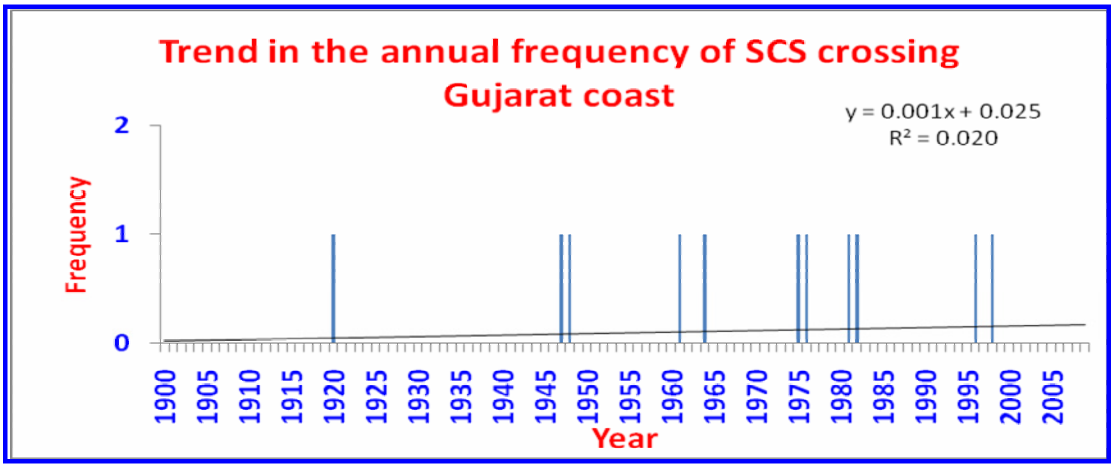

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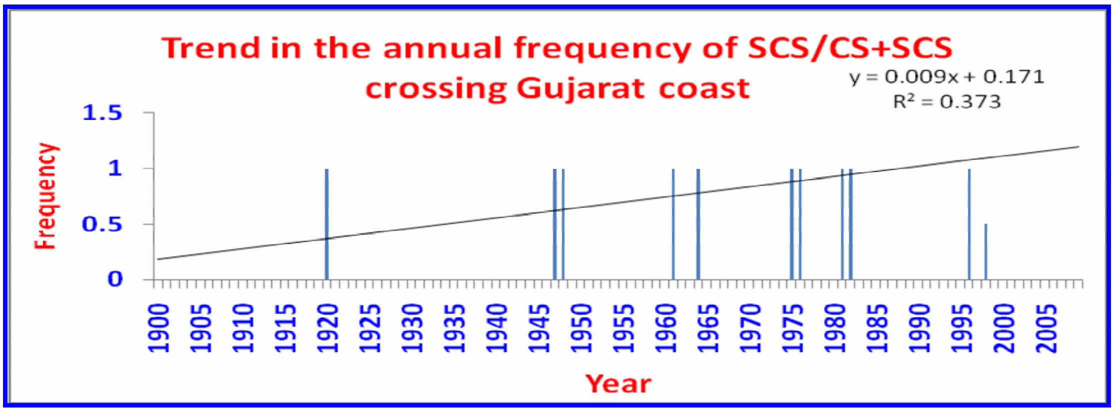
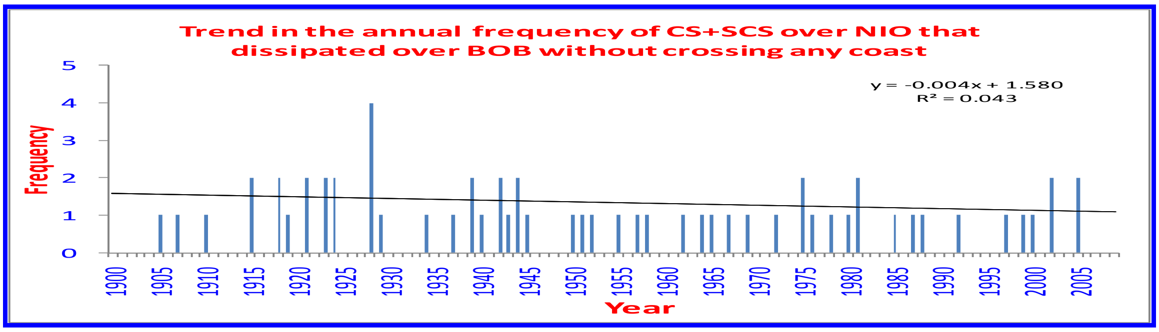


(c)

Fig. 27(vii): Trends in the annual frequency of (a) cyclones and (b) severe cyclones (c) severe cyclones to total cyclones that crossed Gujarat coast during 1900-2009



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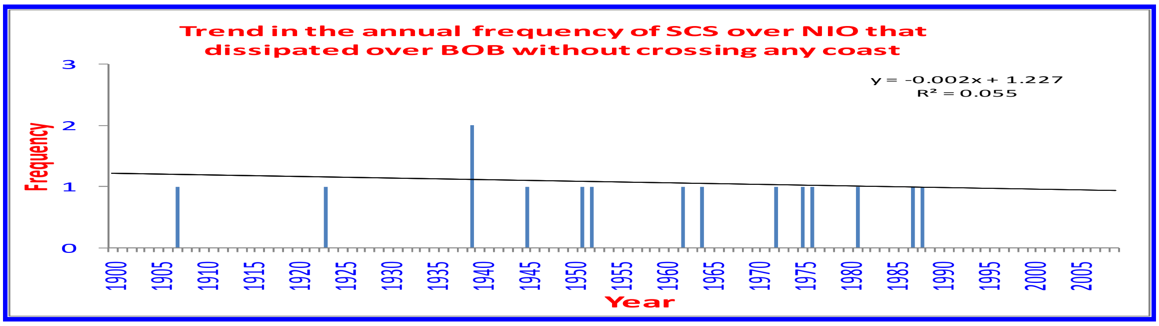

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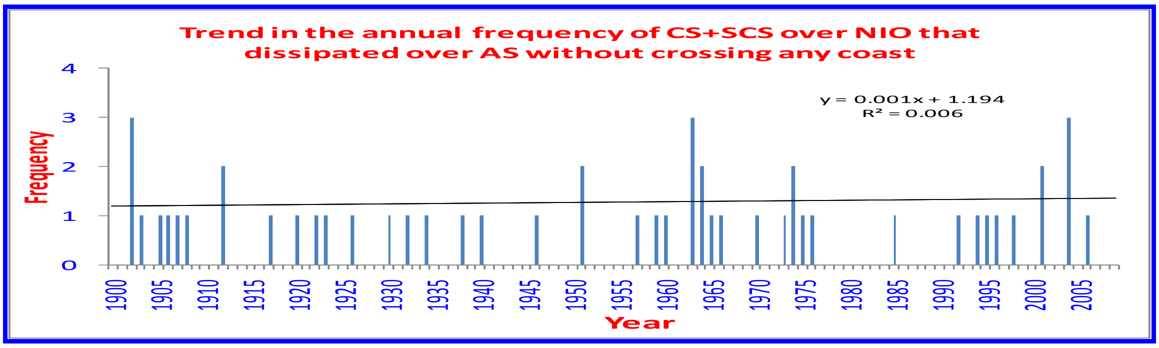

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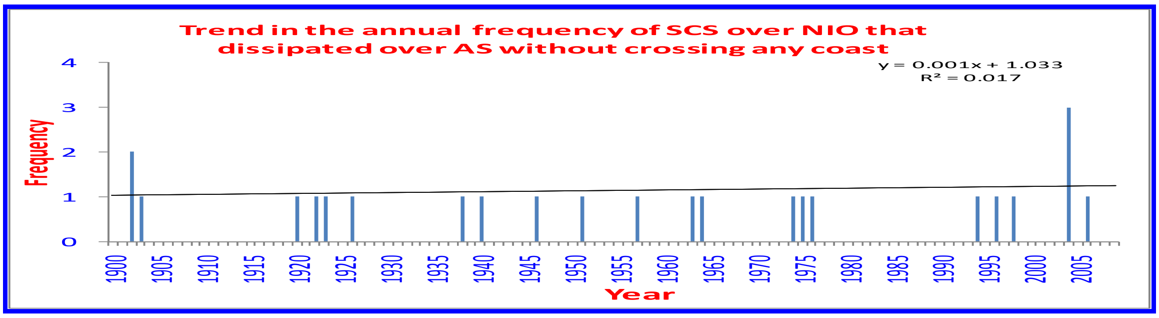


(d)

Fig 28 a-d: Trends in the annual frequency of cyclones / severe cyclones that formed over NIO and dissipated over the Bay of Bengal (BOB) / Arabian Sea (AS) without crossing any coast

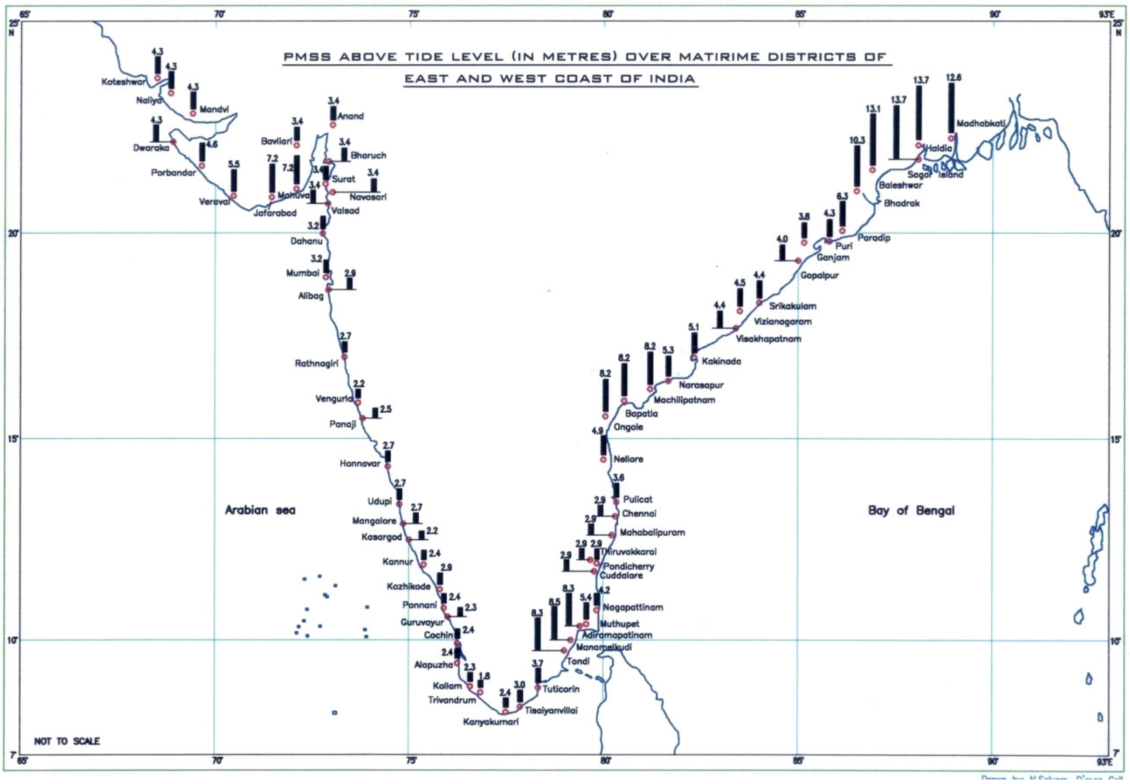


Fig. 29: PMSS above tide level (in metres) over maritime districts of east and west coast of India

6.5 Forecasting and Warning of cyclones

Cyclone warning is one of the most important functions of India Meteorological Department (IMD) and it was the first service undertaken by the Department as early as in 1865 and thus the service started before the establishment of the department in 1875. IMD at present is the nodal agency in the country to monitor and predict the cyclonic disturbances and issue the warning and advisory bulletins. IMD, New Delhi also acts as a Regional Specialised Meteorological Centre (RSMC) for providing tropical cyclone advisories to the World Meteorological Organisation (WMO)/ Economic and social cooperation for Asia and the Pacific (ESCAP) Panel member countries, viz., Bangladesh, Myanmar, Thailand, Srilanka, Maldives, Pakistan and Oman. IMD, New Delhi also works as a Tropical Cyclone Advisory Centre (TCAC) for international civil aviation as per the requirement of International Civil Aviation Organisation (ICAO).

Cyclones are monitored using various technique like Synoptic technique, Satellite technique, *Radar Techniques etc. Different models like* Quasi-Lagrangian Model (QLM, Non-hydrostatic Meso-scale Model MM-5 (Version 3.6), WRF Model, Multi-model ensemble (MME) technique are run at IMD for forecasting of cyclones. Apart from the models run in IMD, the model product from other centers like ECMWF, UKMO, JMA, NCMRWF (T254) IIT, Delhi, Indian Air Force (MM5) and INCOIS (wave forecast models) are considered. Various stations models like CLIPPER, Chaos/Senaric algorithim model developed by Space Application Centres, Indian Space Research Organisation, Ahmedabad run operationally in IMD for track prediction.

The cyclone warnings are issued to state government officials in four stages:

- First Stage warning known as "PRE CYCLONE WATCH" issued 72 hours in advance
- Second Stage "CYCLONE ALERT"issued at least 48 hrs in advance of the expected commencement of adverse weather over the coastal areas
- Third Stage warning known as "CYCLONE WARNING" issued at least 24 hours in advance of the expected commencement of adverse weather over the coastal areas.
- Fourth Stage of warning known as "POST LANDFALL OUTLOOK" issued at least 12 hours in advance of expected time of landfall

IMD has prepared Road map for cyclogenesis and further intensification , monitoring and prediction which are presented are under:

Step I

- SST exceeding 26°C and a deep thermocline (50 m)
- Analysis of SST in models available
- http://www.aoml.noaa.gov/phod/cyclone/data/ni.html
- IMD (Satellite)
- Depth of the 26°C isotherm. SST field provided on a daily basis from TMI measurements (Tropical Rainfall Measuring Mission's Microwave Imager).

Step II

- Conditional instability through a deep atmospheric layer
- Area of deep convection on satellite imagery
- Favorable synoptic scale conditions for development of deep convection (Madden Julian Oscillation/Outgoing Longwave Radiation) : http://www.bom.gov.au/bmrc/clfor/cfstaff/matw/maproom/OLR_modes/
- Maps of the MJO real-time filtered OLR anomalies, each averaged for a period of 7 days.

Step III

- Large values of relative humidity in the lower and middle troposphere.
- Location of deep convection areas on geostationary satellite imagery
- Presence of a pre-existing disturbance in the lower atmosphere : analysis of pre-existing lows in the ITCZ (their location, organization, intensity)
- Satellite imagery
- Animated visible and IR geostationary imagery on Synergie : estimation of the areas of organizing deep convection, their evolution during the last 24 hours; first estimation of associated LLCCs (low level circulation centers); analysis of exposed LLCCs (when out of deep convection).
- Micro-Wave imagery over suspected convective areas (Monterey website, or Synergie Cyclone), to see the low or mid-level improving cyclonic organization, under Cirrus clouds. (http://www.nrlmry.navy.mil/tc_pages/tc_home.html)

Step IV

- Ocean surface winds derived from satellite :
- Quikscat : http://manati.orbit.nesdis.noaa.gov/quikscat/ Ocean Surface Winds derived from the SeaWinds Scatterometer aboard the QuikSCAT satellite
- Ascat : http://manati.orbit.nesdis.noaa.gov/ascat/ Ocean Surface Vector Winds derived from the Advanced Scatterometer (ASCAT - 50km) aboard the EUMETSAT METOP satellite
- Windsat : http://manati.orbit.nesdis.noaa.gov/windsat/ Ocean Surface Winds derived from WindSat/Coriolis Measurements

Step V

- Significant value of planetary vorticity (Coriolis force) ~5 deg. from Equator.
- Tropical storm can been observed ~ 2.5° sometimes also
- Weak vertical shear of the horizontal winds
  - Upper level winds at 200/300 hPa
  - http://cimss.ssec.wisc.edu/tropic2/
  - Good upper level outflow: Models analysis
- Good low level inflow
  - Models analysis
  - Low level winds data (Quikscat, …)
- Wind Shear based on satellite observation is defined as follows:
- Wind Shear =(150-300) mb layer mean minus (700-925)mb layer mean
- Wind shear is classified as follows:

  5-10 kt : weak (favorable for development)

  10-20 kt : moderate (unfavorable for weak system, or neutral for mature cyclone) more than 20kt: strong (unfavorable)

CHAPTER – VII

DROUGHT

7.1 Introduction

Drought is universally acknowledged a phenomenon associated with scarcity of water. It is a normal, recurrent feature of climate and is observed in all the climatic zones. It is still largely unpredictable and varies with regard to the time of occurrence, duration intensity, and extent of the area affected from year to year. It is a temporary condition caused by significantly less (deficient) rainfall for an extended period of time, usually during a season when substantial rainfall is normally expected over the area. The deficiency in the rainfall is measured relative to the long-period average (LPA) of rainfall over the area. The severity of the drought can also be aggravated by other climatic factors such as high temperature, high wind and low humidity. Though the number of deaths directly attributable to drought during 1963-1992 is quite less (3%) compared to that caused by floods (26%) and tropical cyclones (19%), yet the number of persons affected by drought (33%) is the highest amongst all the natural disasters (number of persons affected by floods and tropical cyclones being 32% and 20% respectively) and the significant damage caused by drought is 22% which is comparable to the corresponding values of floods (32%) and tropical cyclones (30%) (WMO, 1994).

7.2 Monitoring of Meteorological Drought

India Meteorological Department (IMD) monitors meteorological and agricultural drought based on 'percentage of rainfall departure' and 'aridity anomaly index' respectively.

Meteorological drought over an area is defined as a situation when the monsoon seasonal (June-September) rainfall over the area is less than 75% of its long-term average value. It is further classified as 'moderate drought. if the rainfall deficit is 26-50% and 'severe drought' when the deficit exceeds 50% of the normal. Further, a year is considered as a 'drought year' when the area affected by moderate and severe drought either individually or together is 20-40% of the total area of the country and seasonal rainfall deficiency during southwest monsoon season for the country as a whole is at least 10% or more. When the spatial coverage of drought is more than 40% then it is called as all India severe drought year. Based on the index of percentage departure of rainfall from normal, IMD has delineated sub-divisionwise drought since 1875 and frequency of moderate and severe drought and occurrences of probabilities of drought years during 1875-2009 have been presented in Table 14. It is observed that arid west viz. West Rajasthan (34 cases) and Saurashtra and Kutch (31 cases), have the highest occurrences of drought. The adjoining Gujarat Region which mostly belongs to semi-arid climate also experiences high incidences of drought (28). Other areas recording large incidences of drought are Haryana, Delhi & Chandigarh, Punjab, Himachal Pradesh and East Rajasthan in northwest India and Rayalaseema in southern peninsula. The per-humid and humid areas of the east and north-east India (viz. Arunachal Pradesh, Assam& Meghalaya, Orissa, Gangetic West Bengal and Jharkhand), for obvious reasons, have the lowest occurrences of drought.

Percent area of the country affected by drought during 1901-2003 and details of moderate and severe droughts during 1875-2003 are depicted in Fig 30, and Fig 31 respectively. Based on the probabilities of occurrence of drought (percentage), the entire country has been divided (Fig. 32) into chronically drought prone area (probability of occurrence of drought more than 20%), frequently drought prone area (probability of occurrence of drought 10-20%) and least drought prone area (probability of occurrence of drought less than 10%). West Rajasthan and the entire Gujarat State fall in the category of chronically drought prone area. Therefore, these areas deserve special attention for drought proofing like evolving crop varieties resistant to moisture stress, better water management, effective land management etc. East Uttar Pradesh, Uttarakhand, Haryana, Punjab, Himachal Pradesh, East Rajasthan, West Madhya Pradesh, Marathwada, Vidarbha, Telangana, Coastal Andhra Pradesh and Rayalaseema fell in the category of frequently drought prone areas which can expect drought once in 6-10 years. These areas generally belong to sub-humid climate zone (IMD Met. Monograph No. 21/2005).

7.2.1 Drought Index based on Standardized Precipitation Index (SPI)

Although rainfall deviation from the long-term mean continues to be a widely adopted indicator for drought intensity assessment because of its simplicity, yet its application is strongly limited by its inherent nature of dependence on mean. Rainfall deviations cannot be applied uniformly to different areas having different amounts of mean rainfall since a high and a low rainfall area can have the same rainfall deviation for two different amounts of actual rainfall. Therefore, rainfall deviations across space and time need to be interpreted with utmost care. SPI expresses the actual rainfall as standardized departure from rainfall probability distribution function. Computation of SPI involved fitting a gamma probability density function to a given frequency distribution of precipitation totals. The alpha and beta, shape and scale parameters respectively, of the gamma distribution were estimated for a suitable timescale of for each year. Alpha and beta parameters were then used to find the cumulative probability of an observed precipitation amount, which was then transformed into the standardized normal distribution. This index has gained importance in recent years as a potential drought indicator permitting comparisons across space and time (Naresh Kumar et al, 2009). SPI as a drought index is very versatile as it can be calculated on any timescale. This versatility is also critical for monitoring the temporal dynamics of a drought, including its development and decline. These aspects of a drought have always been difficult to track with other indices; further, as SPI values are normally distributed, the frequencies of extreme and severe drought events for any location and timescale are consistent. The classification of the drought intensities based on the SPI value is as follows; It is called moderately dry/ moderate drought for SPI value from -1.0 to -1.49, severely dry/ severe drought for SPI value from -1.5 to -1.99 and extremely dry/ extreme drought for SPI value of - 2 and less

The analysis of long series data during 1875 – 2009 (Table 15) , indicates that five years – 1877, 1899, 1918, 1972 and 2009 were All India extreme drought years when SPI value exceeded -2.0. Mooley (1994) defined Phenomenal All India drought as a phenomenon when % departure of monsoon season's rainfall was ≤ -2 SD i.e. -20% and the percentage area under deficient monsoon rainfall was equal to or more than mean+2SD i.e. 47.7%. Therefore, phenomenal drought years identified by Mooley (1994) has been effectively diagnosed as extreme drought years by the SPI. Further, SPI was also able to diagnose properly the other All India moderate/severe drought years that affected our country.

However, it may be mentioned that despite the current optimism about the SPI, it cannot solve all moisture monitoring concerns. Rather, it can be considered as a tool that can be used in coordination with other tools, such as aridity anomaly index or remote sensing data, to detect the development of droughts and monitor their intensity and duration. This will further improve the timely identification of emerging drought conditions that can trigger appropriate responses by the policy makers.

7.2.2 Drought Climatology of the District Rainfall

District wise Drought Climatology of the Southwest Monsoon Season over India based on Standardized Precipitation Index (SPI) during 1901-2003 has been brought out by Pai et al (2010). The Percent of Normal (PN) was calculated by dividing actual rainfall by its long period average. While for SPI, long time series of rainfall is fitted to a probability distribution, which is then transformed into a standardized normal distribution so that the mean SPI for the location and desired period is zero. Positive SPI values indicate greater than median rainfall and negative values indicate less than median rainfall. Important results are summarised as under:

- Based on PN, majority of the districts in the northwest part of the country consisting of Rajasthan, Gujarat, Jammu & Kashmir, Punjab, Haryana have drought probabilities of ≥20%. The probabilities decrease as moving eastwards from northwest India to northeast India. Over northeast India, most of the districts have probabilities of less than 10%. Over the peninsula, many of the interior districts have probability of ≥20%. Districts along the west coast show less than 10% probability. The probability for severe drought are also highest in the districts from northwest India. Some isolated districts over various other parts of the country shows probability for severe drought of more than 5% (Fig. 33 a&b).

- The highest probabilities of drought of various intensities are not distributed only over the arid or semi-arid regions based on SPI. It can be seen that for all the districts, the probability for the moderate drought is more than 10% and over majority of the districts the probability of the severe drought is more than 5% (Fig. 34 a ,b & c).The districts with probabilities more than 15%, though spread in almost all parts of the country, are somewhat concentrated in northwestern part of the country (consisting of Gujarat, Rajasthan, Punjab, Haryana, Chandigarh, Delhi and Jammu & Kashmir) and eastern part of the Peninsula (Gangetic West Bengal, Orissa, Vidarbha, Marathwada, Andhra Pradesh, Interior Karnataka and Tamil Nadu).
- The trend analysis of district-wise SPI series showed significant decreasing trends over many districts in Uttanranchal, Kerala and in the subdivisions from east central India and such as east Madhya Pradesh, Vidarbha, Chhattisgarh, Jharkhand, Bihar etc., and significant increasing trend was observed over several districts from Konkan region, Karnataka, west Madhya Pradesh, Andhra Pradesh, Punjab and West Uttar Pradesh. Some districts from Kerala and Chhattisgarh showed decreasing trends in SPI series and relatively high probability for drought occurrences of moderate and above intensity (Fig 35).

7.2.3 Drought mapping over different regions

Drought is one of the short term extreme events. There is no operational practice to forecast the drought. As such, mapping of drought prone areas is required for developmental planning (Fig 36). The results of mapping study (Gore et al 2010) are summarised as under:

1) In the Northwest region of India, the probability of moderate drought varies from 12 to 30% and that for severe drought varies from 1 to 20% in most of the parts and about 20-30% in the extreme north-western parts.
2) In West Central India, the probability of moderate drought varies from 5 to 26% and that for severe drought varies from 1 to 8%.

3) In the Peninsular region, the probability of moderate drought varies from 3 to 27%, and that for severe drought varies from 1 to 9% in major parts.
4) In the Central Northeast region, the probability of moderate drought varies from 6 to 37% and that for severe drought varies from 1 to 10%.
5) In the Northeast region, the probability of moderate drought varies from 1 to 26% and that for severe drought varies from 1 to 3%.
6) In the hilly region, the probability of moderate drought varies from 9 to 31% and that for severe drought varies from 1 to 12% except in Leh and Lahul & Spiti.

In general it can be concluded that in most parts of India, probabilities of moderate drought are in the range 11 to 20%. Major parts of India show probabilities of severe drought in the range 1 to 5%. In some West Central, Central Northeast and Northeast region of India, no severe drought is experienced.

7.3 Monitoring of Agricultural Drought

IMD identifies meteorological drought for subdivisions every year based on rainfall analysis since its establishment in 1875. An aridity anomaly index (AI) is developed to monitor the incidence, spread, intensification, and recession of agricultural drought . AI is given as

$$AI = \frac{PE - AE}{PE} \times 100$$

where PE is potential evapotranspiration and AE actual evapotranspiration. The aridity anomaly is calculated by using the normal Aridity Index for 210 well-distributed stations over the country. These anomalies are be used for crop planning and in the early warning system during drought/desertification.

Criterion for Aridity Anomaly Areas

0 or negative	Non-arid
1 – 25	Mild arid
26-50	Moderate arid
> 50	Severe arid

It should be remembered that aridity is different from drought. It is a permanent climatic situation of a region, while drought may occur at any place and on any time scale. As such, anomaly reports do not indicate arid regions; on the contrary, they give an indication of the moisture stress in any region on the time scale of one or two weeks, and they are useful early warning indicators of agricultural drought. Based on this aridity index, weekly/fortnightly Aridity Anomaly Maps/ Reports are prepared for the country as a whole during the southwest monsoon season and over 5 subdivisions (Coastal Andhra Pradesh, Rayalaseema, South Interior Karnataka, Tamil Nadu, and Pondicherry and Kerala) during the northeast monsoon season. A Weekly Aridity Report during September 2010 is depicted in Fig 37.

Table - 14
Sub-divisionwise frequencies of Moderate and Severe drought during 1875-2009 and probabilities of drought years

S.N.	Name of Sub-division	Moderate	Severe	Total	Drought probabilities (Total) %
1.	Andaman & Nicobar Islands	17	0	17	13
2.	Arunachal Pradsh	7	1	8	6
3.	Assam & Meghalaya	5	0	5	4
4.	Nagaland, Manipur, Mizoram & Tripura	12	0	12	9
5.	Sub-Himalayan West Bengal	7	0	7	5
6.	Gangetic West Bengal	2	0	2	1
7.	Orissa	5	0	5	4
8.	Bihar	12	0	12	9
9.	Jharkhand	6	0	6	4
10.	East Uttar Pradesh	13	1	14	10
11.	West Uttar Pradesh	13	1	14	10
12.	Uttarakhand	16	2	18	13
13.	Haryana, Delhi & Chandigarh	21	4	25	19
14.	Punjab	20	4	24	18
15.	Himachal Pradesh	20	3	23	17
16.	Jammu & Kashmir	21	6	27	20
17.	West Rajasthan	22	12	34	25
18.	East Rajasthan	18	5	23	17
19.	West Madhya Pradesh	14	0	14	10
20	East Madhya Pradesh (including Chhattisgarh)	12	0	12	9
21.	Gujarat Region	17	11	28	21
22.	Saurashtra & Kutch	16	15	31	23
23.	Konkan & Goa	9	0	9	7
24.	Madhya Maharashtra	7	2	9	7
25.	Marathwada	17	1	18	13
26.	Vidarbha	16	1	17	13
27.	Coastal Andhra Pradesh	13	0	13	10
28.	Telangana	18	0	18	13
29.	Rayalaseema	20	2	22	16
30.	Tamil Nadu & Pondicherry	12	0	12	9
31.	Coastal Karnataka	5	0	5	4
32.	North Interior Karnataka	10	0	10	7
33.	South Interior Karnataka	9	0	9	7
34.	Kerala	10	0	10	7
35.	Lakshadweep	10	3	13	10

Table – 15
Drought Intensity over India based on Standardized Precipitation Index (SPI)

Drought Year	Seasonal (June –Sept.) Rainfall (cm)	SPI value	Drought intensity as per SPI value
1877	58.7	-3.47	ED
1899	62.1	-3.01	ED
1901	76.5	-1.21	MD
1904	77.6	-1.08	MD
1905	72.7	-1.66	SD
1911	75.1	-1.38	MD
1918	66.1	-2.48	ED
1920	73.3	-1.59	SD
1941	76.3	-1.23	MD
1951	71.5	-1.81	SD
1965	72.0	-1.75	SD
1966	76.4	-1.22	MD
1972	67.0	-2.37	ED
1974	77.4	-1.11	MD
1979	71.4	-1.82	SD
1982	75.2	-1.36	MD
1986	76.8	1.18	MD
1987	70.9	-1.88	SD
2002	71.3	-1.83	SD
2004	76.6	-1.20	MD
2009	69.8	-2.02	ED

ED = Extreme Drought (SPI: More than -2.0)

SD = Severe Drought (SPI: -1.50 to -1.99)

MD = Moderate Drought (SPI: -1.0 to -1.49)

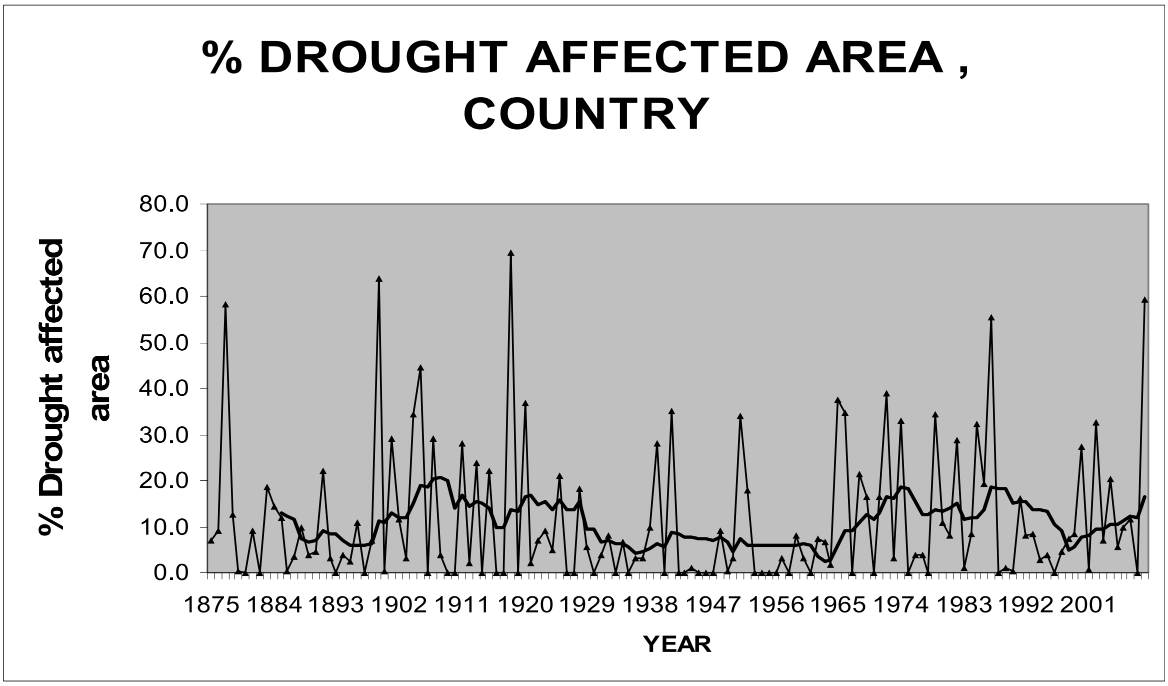


Fig 30: Percentage drought affected area over India during 1875-2003

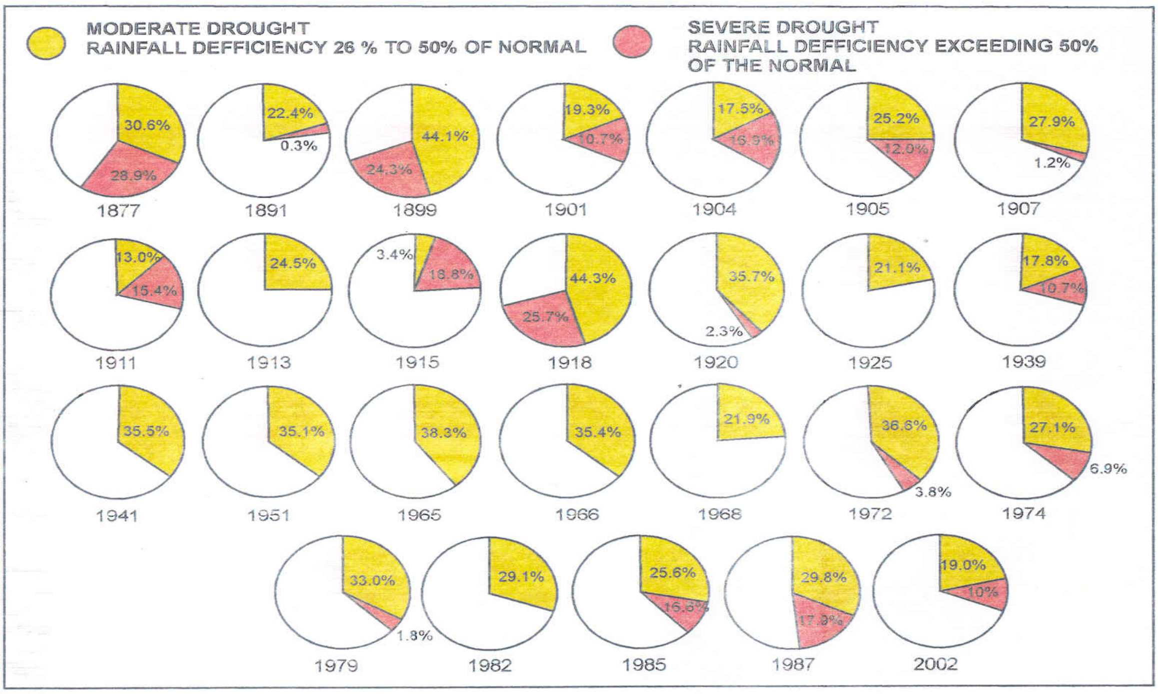


Fig 31: Details of individual drought years since 1875

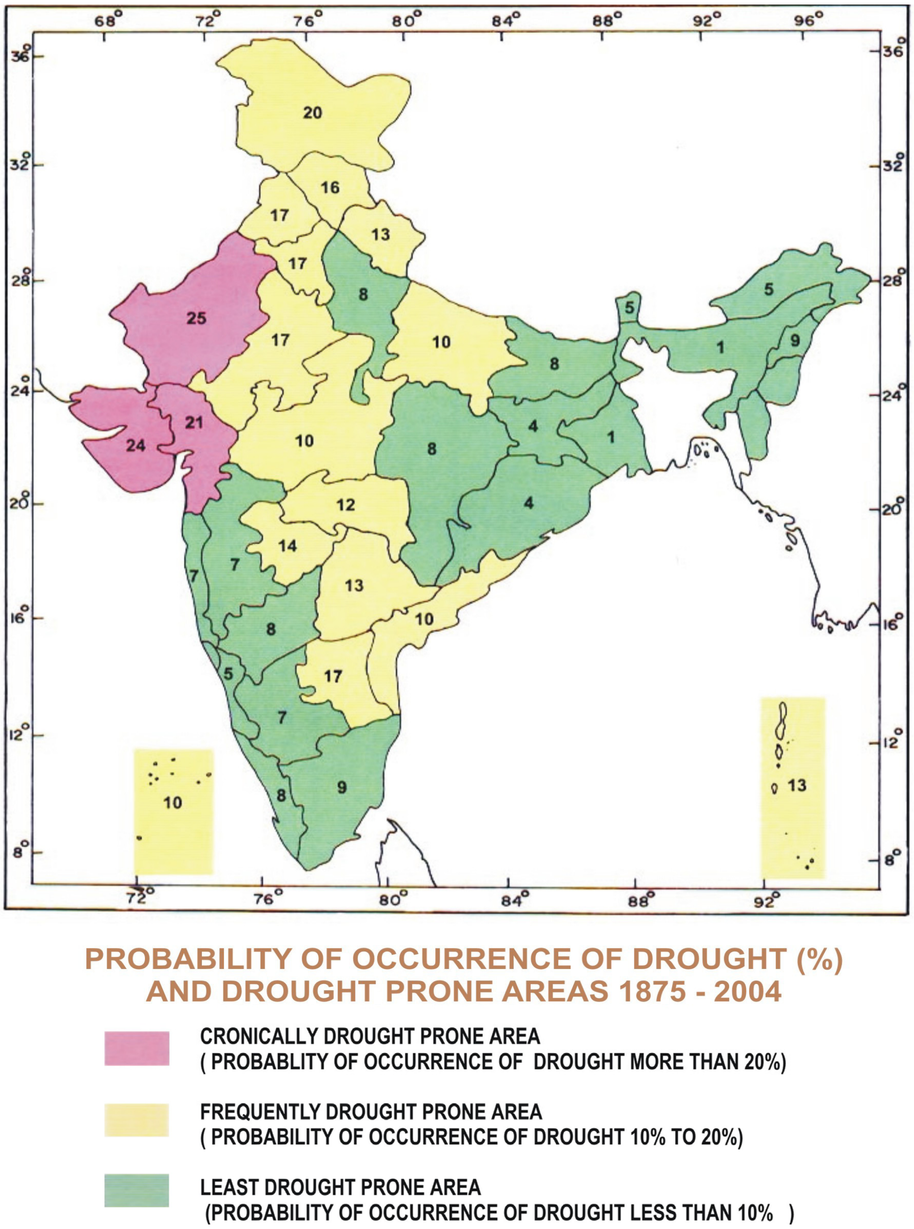


Fig. 32: Probability of Occurrence of Drought and Drought Prone areas during 1875-2004

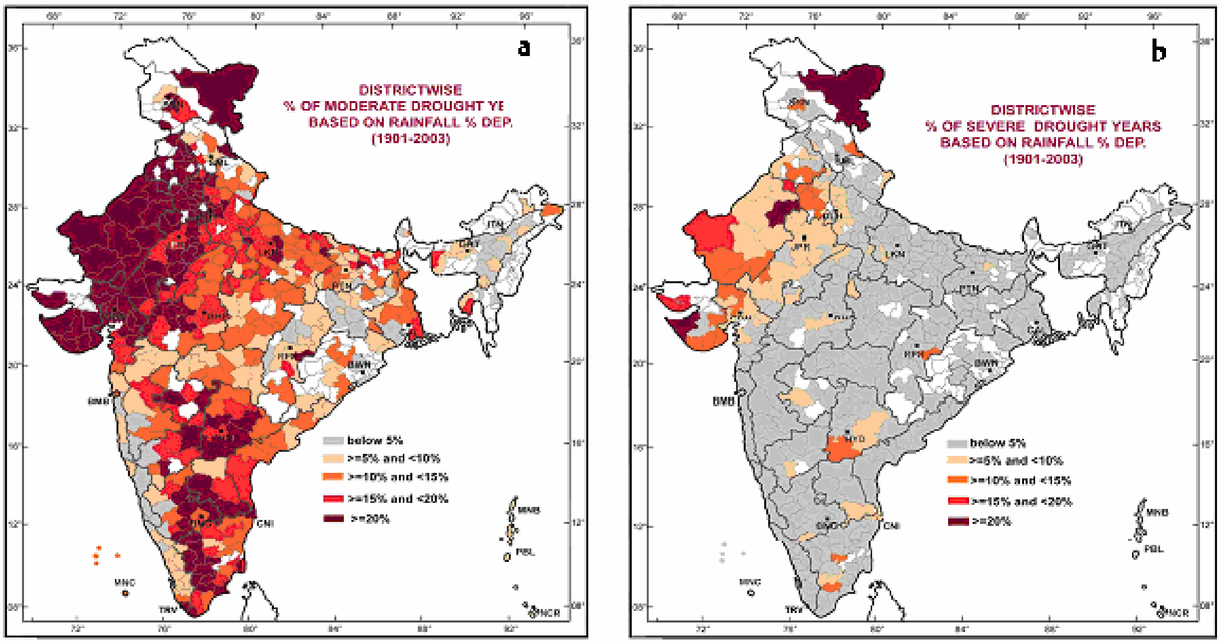


Fig 33: District-wise percentage of incidences (probability) of drought of (a) moderate intensity and (b) severe intensity during the southwest monsoon season for the period 1901-2003

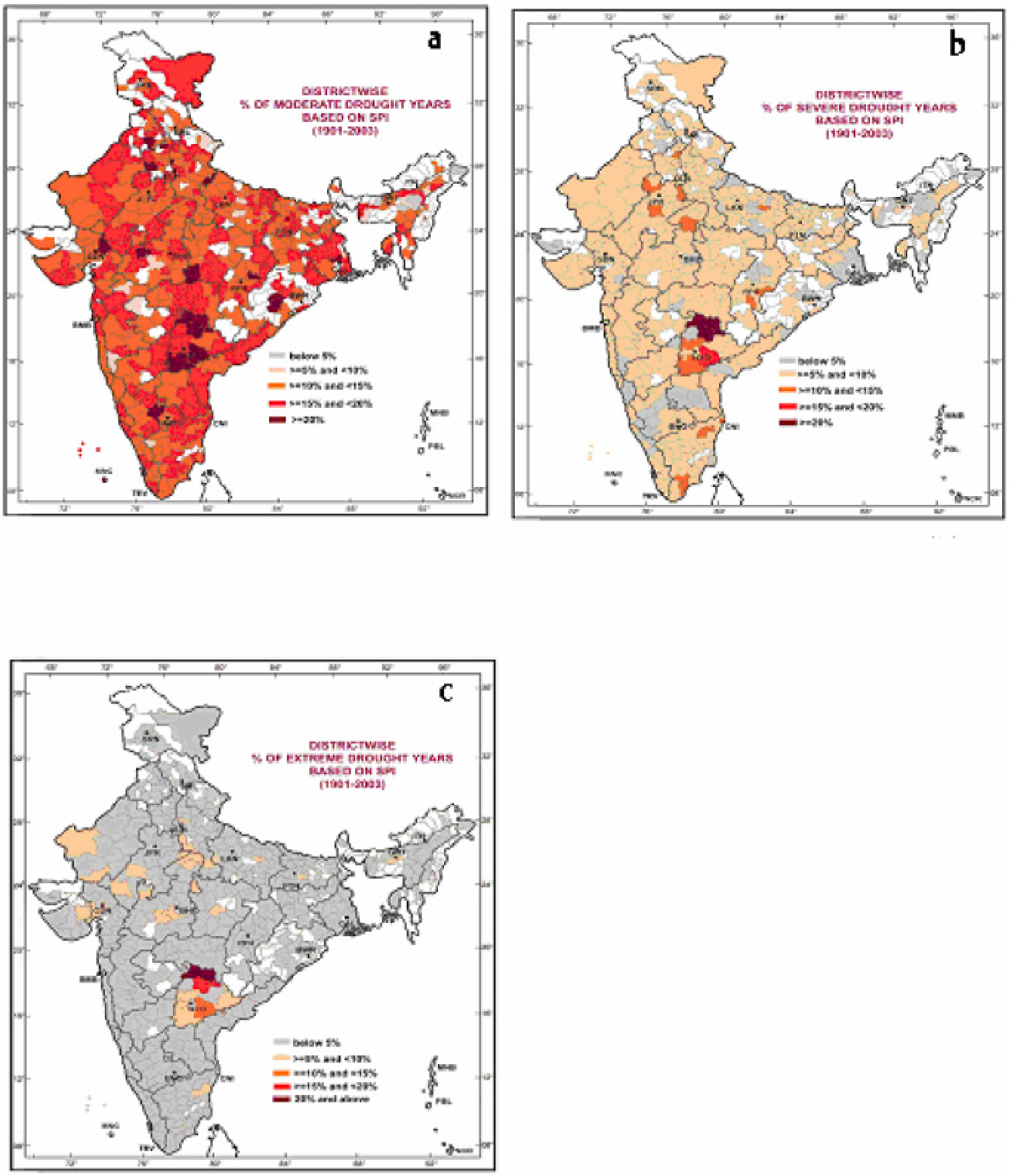


Fig 34: District-wise percentage of incidences (probability) of drought of (a) moderate and above intensity, (b) severe and above intensity, and (c) extreme intensity during the southwest monsoon season based on SPI during the period 1901-2003

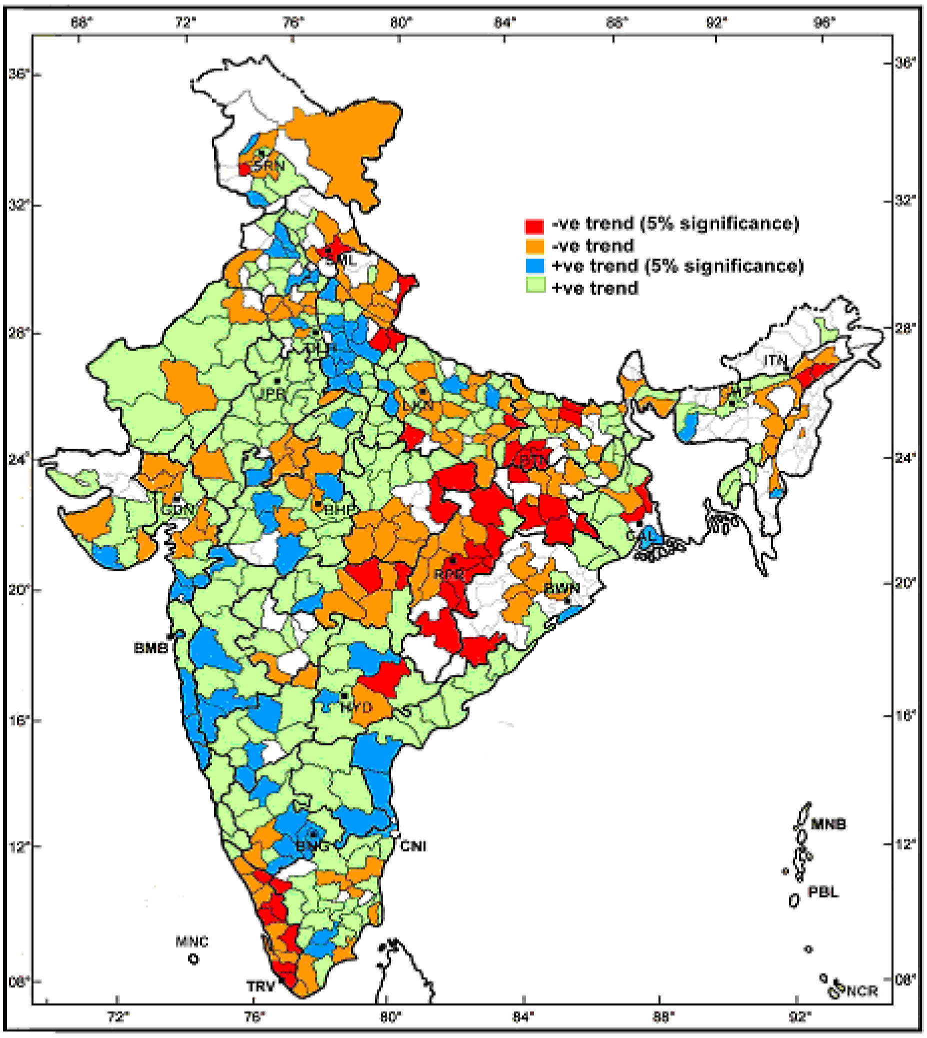


Fig 35: Long-term linear trends in the district-wise SPI during the period 1901-2003

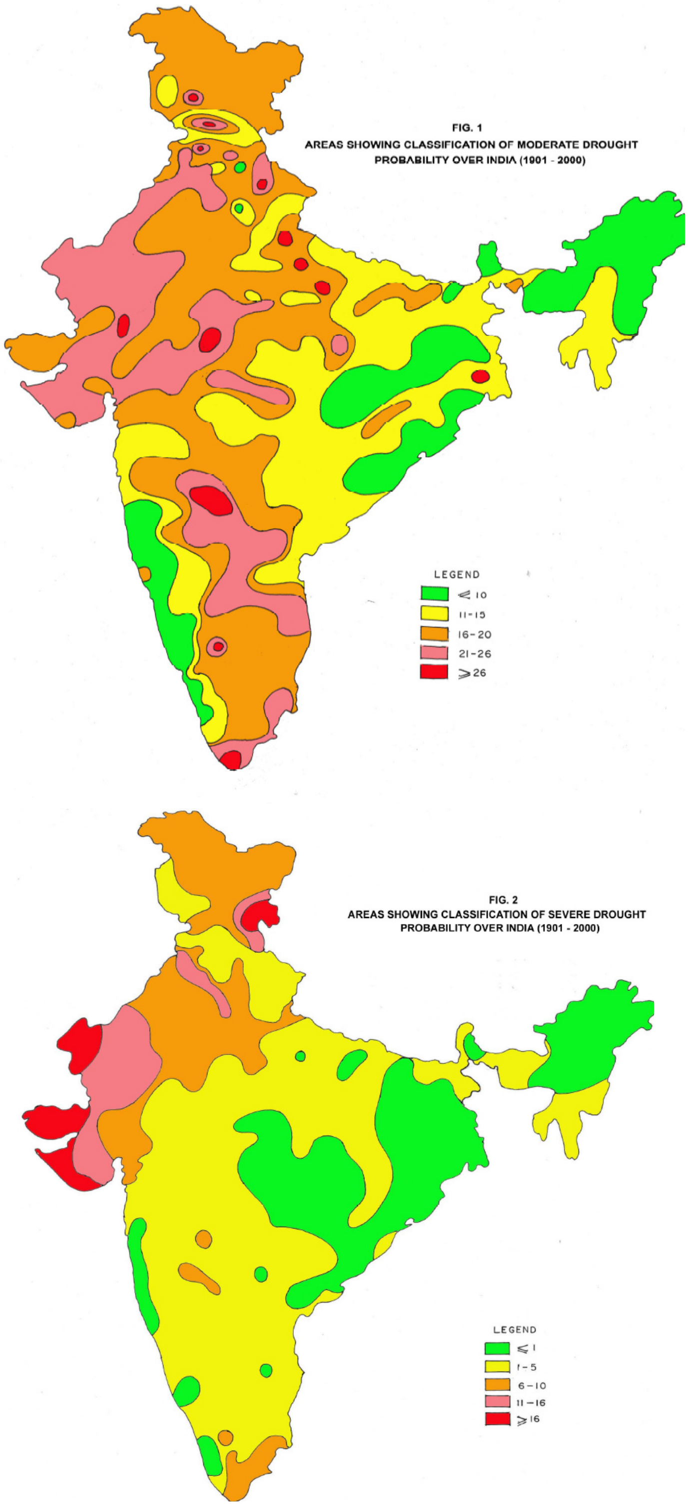


Fig 36: Mapping of (a) Moderate drought (b) severe drought during 1901-2000

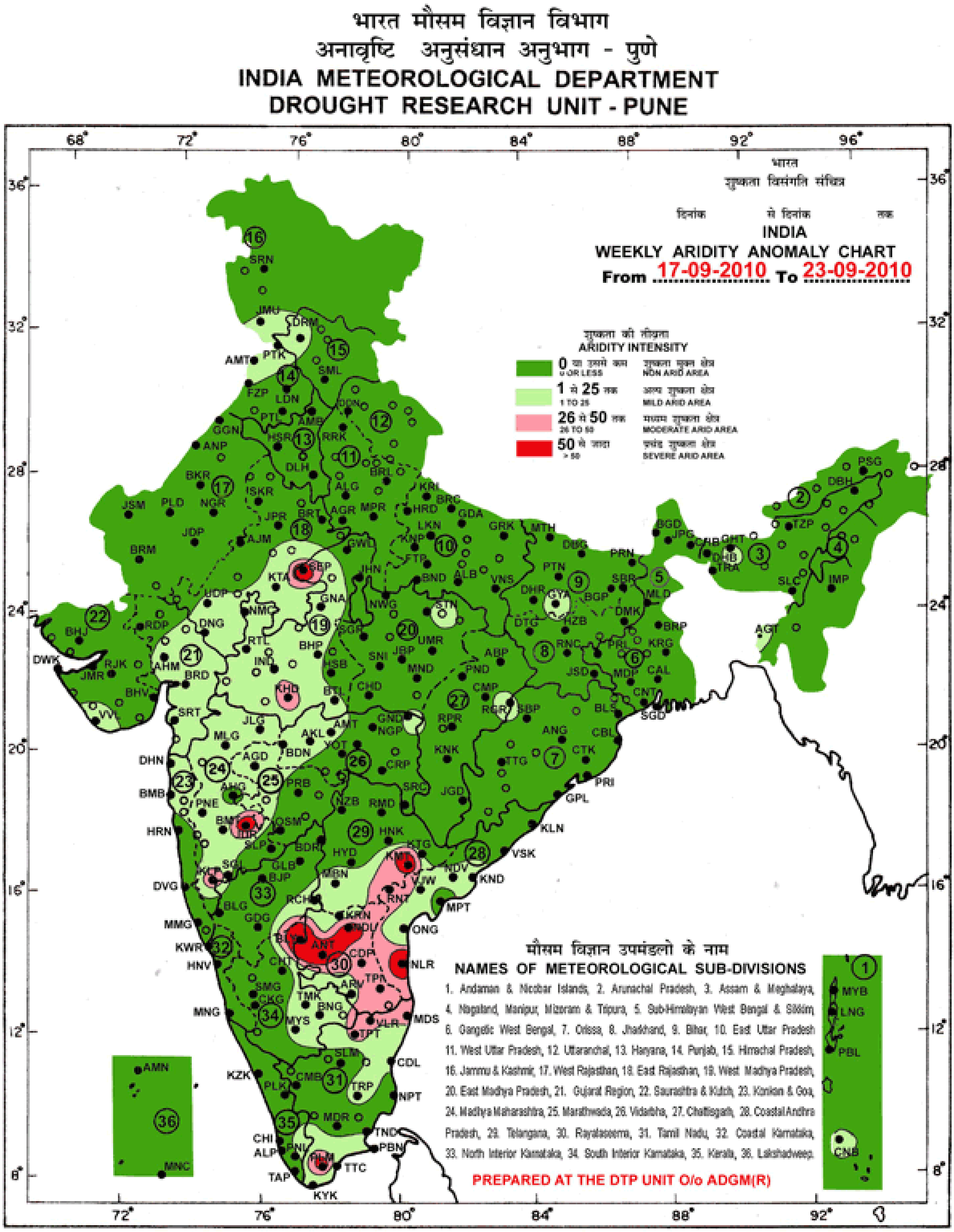


Fig 37: Weekly Aridity Anomaly Report during 2010

CHAPTER – VIII

ENVIRONMENTAL STATUS IN INDIA

India Meteorological Department's (IMD) tradition of monitoring weather and climate spans more than 135 years giving it a sound and useful dataset to fall back upon for environmental assessment. Ozone network was started as a globally pioneering effort as early as in 1954 realizing that this trace gas plays a very important role in atmospheric chemical mechanisms. It also started radiation measurements about 50 years back and currently maintaining 45 stations in the country for providing exclusive countrywide dataset for assessment of solar energy resources. Atlas on "Hourly Mixing Height and Assimilative Capacity of Atmosphere in India" has been brought out by Attri et al (2008)

A network of 10 Global Atmosphere Watch stations (GAW, formerly Background Air Pollution Monitoring Network or BAPMoN) consisting of Allahabad, Jodhpur, Kodaikanal, Minicoy, Mohanbari, Port Blair, Pune, Nagpur, Srinagar and Vishakhapatnam, is maintained by IMD as per WMO protocols and standards since 1974 to generate data/ information on the exchange of trace materials between the atmosphere and the earth's surface, making atmospheric turbidity and air quality measurements to quantify trends and acid rain threats. The ultimate fate of most biogenic or anthropogenic gaseous emissions is their highest state of oxidation which are acidic and render them water soluble too. In recent years it has been noted that when certain areas are subjected to high load of acidic deposition the natural alkaline buffer action of soil derived crust gives way to acid rain, which is potentially harmful.

8.1 Precipitation Chemistry (Acid rain threats)

The trends of pH monitored in rain water samples during last two decades at GAW stations are presented in Fig 38 and the salient finding of various studies (Krishna Nand and Maske, 1983; Krishn Nand, 1984, 1986; Mukherjee et al, 1985, 1986; Mukhopadhyay et al, 1992, 1993; Sarkar et al, 2004; Soni and Sarkar, 2006; Soni et al., 2006, Srivastava et al., 1992, Varma, 1989) are summarized as under:

- All the GAW stations except Jodhpur indicate a lowering trend of pH of rainwater (increasing acidity). This can be attributed not only to increasing sulfate concentration but even more by increasing nitrate concentration. The data showed that rather than large-scale geographical influences, local effects seem to be more important for chemical wet deposition, e.g. the vicinity of a large urban and industrial area, major combustion sources, sea, arable fields or forest, etc. It is observed that upto 1980, pH values from Indian GAW stations were around 7.0 or even higher. Around the year 2000, large number of pH values ranged between 5.0 and 6.0.
- The concentration of H^+ ions showed a major geographical gradient from west to east. At north-western station (Jodhpur), the range of annual average pH values was 6.6 to 7.8, whereas at Allahabad it was 5.2 to 7.6 and low values of the order of 4.5 to 6.8 were found in north-east (Mohanbari).
- Kodaikanal shows the least mineralized samples among other stations. Except for the H^+ values, the concentrations of all compounds either represent the minimum among all stations or else close to it. Strong influence of NO_3^- was observed over Kodaikanal, which could be the product of biogenic process from abundant vegetation around the station. Organic acids (formic and acetic mainly) can also play a significant role in lowering the rainwater pH values at densely vegetated areas like Mohanbari in north-east India and Kodaikanal in Tamil Nadu. Low content of alkaline radicals in the precipitation is also one of the cause of low pH values at these stations.
- Analysis of the decadal mean data of sulfate and nitrate indicate that concentration of both the anions have gone up significantly in last two decades. Significant increasing trend in concentration of nitrate at Pune, Minicoy Portblair and Jodhpur and that of sulphate at all the stations except at Kodaikanal have been observed in later decade.
- A somewhat positive feature emerging from the comparison of pH and other wet deposition data is that India is much better off compared to many other countries as far as acid rain situation is concerned.

- TSPM values at Jodhpur exhibited significant positive correlation with pH indicating its alkaline behavior. The soil derived aerosols have pronounced effect on the precipitation acidity at a place.
- Principal Component analysis of rain water constituents indicate that marine and coastal aerosols predominantly govern the acidity of rainwater.

8.2 Atmospheric turbidity

Significant increase in atmospheric turbidity during the last few decades has been reported by several authors (Mani et al., 1973; Krishnand and Maske, 1983; Singh et al, 1997; Singh et al, 2004; Srivastava et al., 1992, Soni and Kannan, 2003). The observed atmospheric turbidity values at all the Indian GAW stations showed systematic seasonal as well as long-term variation apart from random fluctuations (Fig 39). However, the nature of variation is station dependent. Annual mean values of the turbidity coefficients showed a general increase of turbidity at all stations except Kodaikanal. The increasing trend of the turbidity at short wavelength (500 nm) indicates that it is caused more by fine size range aerosol, which are the product of primary and secondary production processes associated with anthropogenic activities. On an annual basis, the lowest turbidity was observed at Kodaikanal and Srinagar and highest in the north and central India.

Diurnal and seasonal variations of radiative properties of aerosols have been monitored during 2006-2007 in New Delhi using Sky-radiometer (POM-I) operating at wavelengths 315, 340, 400, 500, 670, 1020 nm. The results indicate that Aerosol Optical Depth (AOD) remains lowest at all wavelengths during Monsoon season while high values of Single Scattering Albedo (SSA) and Alpha (α) represent the presence of small aerosols and washout effect of large aerosols by rains. In Pre-monsoon season, AOD was found as second minimum with SSA and AOD lower than Monsoon season. However, AOD was lower in winter season as compared to Post-monsoon season because of movement of westerly systems (Singh et al, 2008). Measurements have also shown that AOD values were higher at shorter wavelengths in comparison to the values at longer wavelengths for all four seasons of the year (Fig 40). Comprehensive studies in the country are planned.

Volcanic eruptions across the globe in tropical latitudes have shown increased turbidity over the Indian region. Sony (2006) and Mukhopadhyay (1992) have reported a seasonal scale anomaly to the extent of 10-15% increase from mean values.

8.3 Radiation

Solar radiation data from 12 stations of IMD network having continuous long-term measurement from 1971-2009 were evaluated and the results are presented in Table 16. Long-term trend of global solar radiation during last four decades at four stations in different geographic regions are depicted in Fig 41. Analysis of the data indicates that the Global Solar Radiation (Direct + Diffuse) and Bright Sunshine duration are showing decreasing trend while Diffuse Solar Radiation is showing increasing trend at most of the stations. The change in solar radiation can be attributed to change in aerosol load in the atmosphere and cloud cover. Aerosol loading in the atmosphere may be attributed to the biomass burning and smoke released by the industries. The decline in global solar radiation (solar dimming) continues over India while recent evidence suggests that the decreasing trend did not persist beyond 1990 at several locations (North America, western Europe, China).

8.3.1 Global Radiation

All the four major cities with population more than ten million, show significant decline in global irradiance of 3.4% (7.8 Wm^{-2}) per decade at Delhi, 4.1% (8.4 Wm^{-2}) per decade at Kolkata, 1.7% (4.1 Wm^{-2}) per decade at Chennai and 2.4% (5.5 Wm^{-2}) per decade at Mumbai. The decline was stronger from 1990 onwards at all the four stations. Delhi is one of the highly polluted major cities of Asia and is also subjected to heavy injection of dust load brought by winds blown dust from the desert in the west. Total suspended particulate matter concentration during the pre-monsoon season goes enormously high and local radiative forcing is significantly affected (Singh et al. 2004). The long-term average of global irradiance at Delhi is 216.2Wm^{-2} with a standard deviation in the annual mean of 10.2 Wm^{-2}. Kolkata is heavily populated with large industrial installations; it is situated in the Gangetic delta and nearer to the east coasts. The long-term average of global irradiance at Kolkata is 191.4 Wm^{-2} with a standard deviation in the annual mean of 10.5 Wm^{-2}. Another major city is Chennai (earlier Madras), located along the east coast of India. The long-term average global irradiance at Chennai is 224.8 Wm^{-2} with a standard deviation in the annual mean of 7.7 Wm^{-2}. Mumbai is also a major city situated along the west coast of India. The long-term average global irradiance at Mumbai is 215.4 Wm^{-2} with a standard deviation in the annual mean of 8.4 Wm^{-2}.

Ahmedabad is located south of desert region and is an industrialized place since long. Ahmedabad received an average 226.2 Wm^{-2} of global irradiance. The statistically significant decrease in global irradiance was found to be 7.8 Wm^{-2} (3.3%) at Ahmedabad. Over the coastal stations Panjim, Trivandrum and Visakhapatnam global radiation decreased at the rate of 2.0% (4.8 Wm^{-2}), 3.4% (8.0 Wm^{-2}) and 3.9% (9.0 Wm^{-2}) per decade, respectively.

8.3.2 Diffuse Radiation

Spatial and temporal pattern of observed trends in diffuse irradiance is complex and inhomogeneous. Jodhpur has the lowest long-term average diffuse irradiance of 85.2 Wm^{-2} and also the smallest inter-annual variability with a standard deviation of 5.2 Wm^{-2} in the annual mean. Ten of the twelve stations evaluated in this study for diffuse irradiance showed increasing trend ranging from 0.4% (0.3 Wm^{-2}) per decade at Ahmedabad to 2.2% (1.9 Wm^{-2}) per decade at Nagpur, although the trend is statistically significant only at four stations: Chennai, Mumbai, Nagpur and Panjim. Chennai showed statistically significant increasing trend of 2.0 Wm^{-2} per decade. Given the geographic distribution of these stations, there does not appear to be any spatial pattern to this decline/increase in diffuse irradiance. The relative portion of the diffuse radiation in the global solar radiation varies from 37% to 50% in annual mean. The diffuse component accounts for 50% of the global irradiance at Kolkata which is highest among all the stations. The diffuse component formed 37% at Hyderabad and 39% at Jodhpur of global solar radiation in annual mean.

8.4 Sunshine Duration

The sunshine duration, defined as the amount of time when solar direct irradiance exceeds a specified threshold is often used as a substitute of radiation measurement. Bright sunshine duration has large uncertainty in measurement. All the stations showed decreasing trend in sunshine duration except Jodhpur. The duration of sunshine shows a maximum over central and northwest India. In the arid and semi-arid zones of central and northwest India, average bright sunshine duration of more than 8 hours a day is observed during all-sky conditions. The lowest values are found in NE India due to clouding associated with and the decrease in the length of the day with increasing latitude. The significant decreasing trend in bright sunshine duration at Delhi, Kolkata, Chennai, Nagpur, Pune, Panjim, Shilong, Trivandrum and Visakhapatnam was observed which ranged from 2,4 to 6.3% per decade. The decrease in sunshine duration was concomitant with the decrease in global solar irradiance.

8.5 Evaporation

A reduction in surface solar radiation can lead to a reduction in surface evaporation because _50–85% of the radiative heating at the surface is balanced by evaporation (Kiehl and Trenberth, 1997). The decline in global radiation is consistent with decreased pan evaporation from Indian region. Significant decreasing trend over all parts of India except northeast have been observed. For the country as a whole the evaporation declined by 19% during the period 1971-2000. The annual evaporation trends vary from as high as -42.5 mm per year at Delhi to -5.5 mm per year at Trivandrum. They also observed that the decline in evaporation was comparatively more during the decade 1991-2000.

8.6 Ozone

Ozone has a strong relationship with biomass burning, traditionally seen over eastern parts of the subcontinent extending into that East Asia. This area is also a thickly vegetated region releasing organic compounds that participate in atmospheric photochemistry in whish ozone has a significant role to play. Thus the anthropogenic emission define the residence times of various GHGs of biogenic origin via the ozone link in this region.

Total ozone and Umkehr observation by Dobson Ozone spectrophotometer are taken daily basis from 4 stations viz. Delhi, Varanasi, Pune and Srinagar. At Delhi, Kodaikanal and Maitri (Antarctica) ozone is monitored with Brewer Spectrophotometer, which has an additional facility to measure NO_2, SO_2 and UV-B radiation also. Vertical distribution of ozone is measured by balloon-borne ozonesonde (IMD-made) fortnightly frequency at Delhi, Pune, Thiruvananthapuram and Maitri (Antarctica). Surface ozone measurement is taken at 6 stations viz. New Delhi, Nagpur, Pune, Kodaikanal, Thiruvananthpuram, and Maitri (Antarctica). Monitoring is being augmented by establishing stations in NE India and A&N Islands. Important results from the Ozone Programme spanning over more than 50 years are as follow:

- Ozone data of Maitri (Antarctica) has also confirmed occurrence of ozone hole during spring months over Antarctica (Peshin, 2006).
- Analysis of the data available so far does not establish any clear ozone trends in the total ozone over India. However, increasing trend in tropospheric and decreasing trend in stratospheric ozone have been observed.
- From the equator to about 20ºN, the tropospheric ozone concentration remains practically the same throughout the year.
- The maximum ozone concentration of the order of 150µmb occurs at a height of 26-27 Km over Thiruvananthapuram, 25-26 Km over Pune and 23-25 Km over New Delhi. Double maxima appears over New Delhi during winter and spring.

Table 16

Long-term mean values and trend analyses of global irradiance (G), diffuse irradiance (D) and daily bright sunshine duration (S) in India under all sky conditions for 1971-2009. Trend values in bold are statistically significant.

Station Name	Long-term Mean (Standard Deviation)			Trend (% per decade)		
	G (Wm^{-2})	D (Wm^{-2})	S (Hours)	G	D	S
Ahmedabad	226.2 (11.7)	87.6 (4.6)	8.2 (0.3)	**-3.3**	0.4	-1.3
Jodhpur	228.4 (12.1)	85.2 (5.2)	8.5 (0.4)	**-3.6**	0.8	0.0
Delhi	216.2 (10.2)	93.4 (3.8)	7.5 (0.7)	**-3.4**	0.4	**-6.3**
Kolkata	191.4 (10.5)	95.5 (5.0)	6.1 (0.6)	**-4.1**	-0.4	**-3.5**
Chennai	224.8 (7.7)	98.4 (6.8)	7.4 (0.4)	**-1.7**	**2.1**	**-3.6**
Mumbai	215.4 (8.5)	92.7 (4.9)	7.3 (0.4)	**-2.4**	**1.6**	-0.4
Nagpur	214.6 (7.1)	88.1 (4.8)	7.5 (0.5)	**-2.0**	**2.2**	**-2.4**
Pune	228.7 (8.6)	88.6 (3.5)	7.8 (0.4)	**-1.5**	-1.4	**-2.5**
Panjim	228.3 (12.2)	95.7 (5.1)	7.6 (0.4)	**-2.0**	**1.7**	**-2.8**
Shillong	191.0 (8.6)	90.6 (3.7)	5.7 (0.3)	-0.1	0.5	**-2.4**
Trivandrum	226.1 (11.4)	101.1 (3.6)	6.3 (0.4)	**-3.4**	0.8	**-3.0**
Visakhapatnam	218.5 (10.8)	94.3 (5.3)	7.2 (0.6)	**-3.9**	1.0	**-5.7**

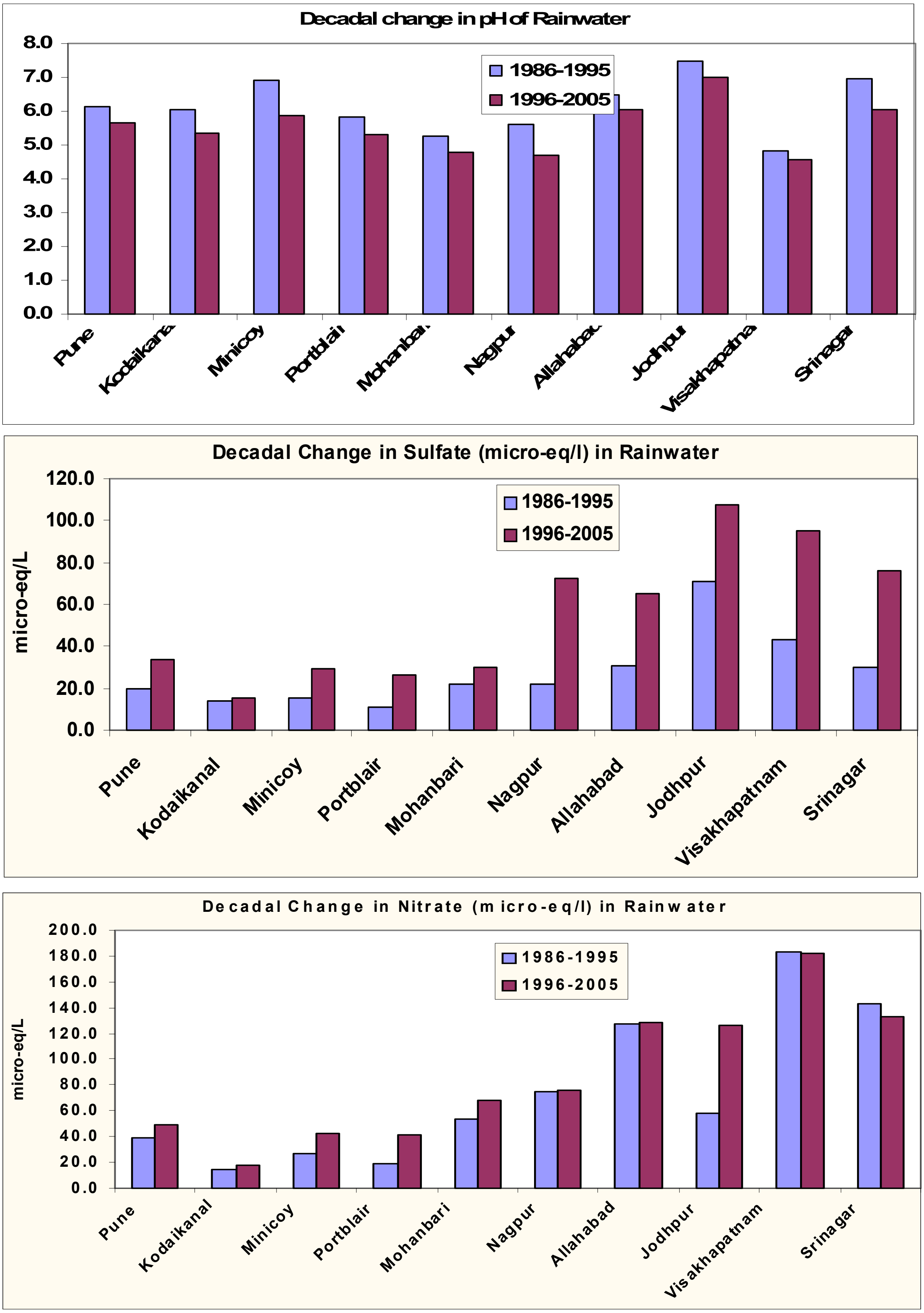
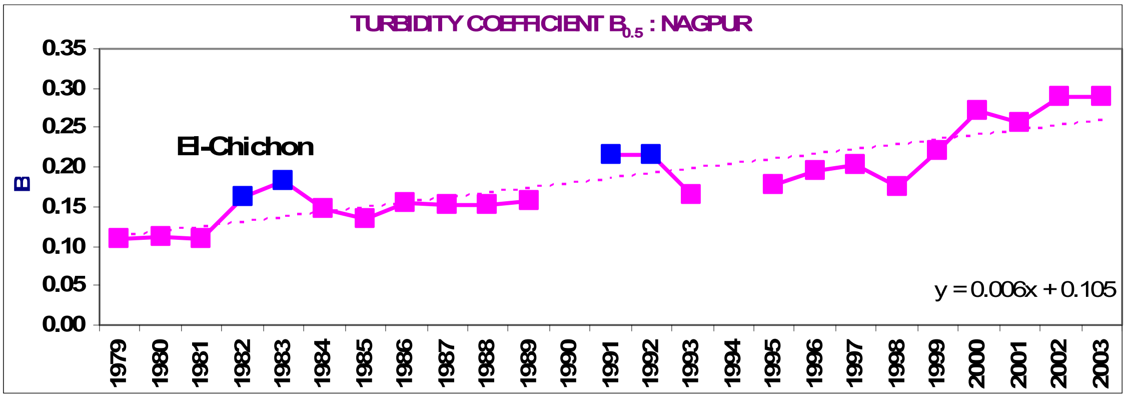
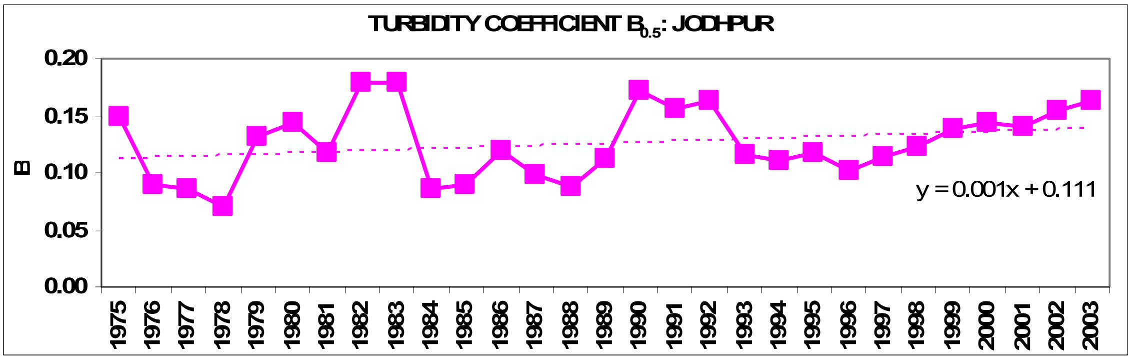
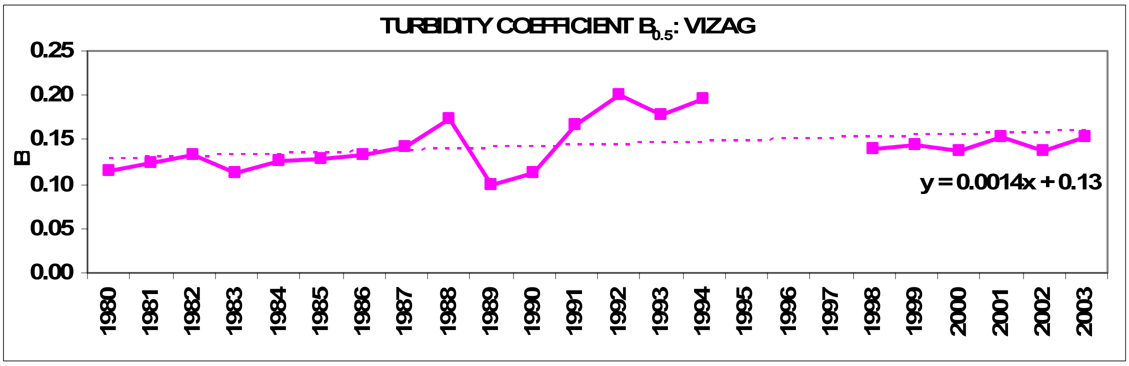


Fig 36: Trends of pH, SO_4 and NO_3 at GAW stations in India







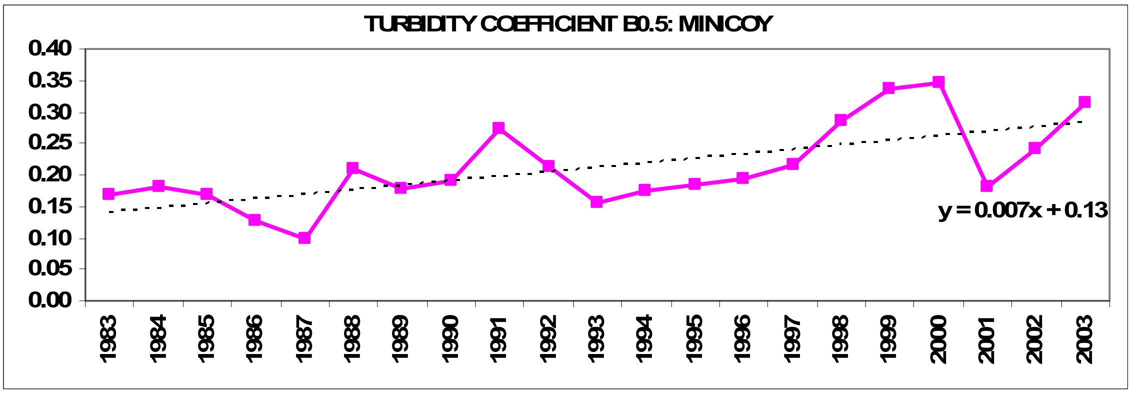


Fig 37: Aerosol loading at GAW stations in India

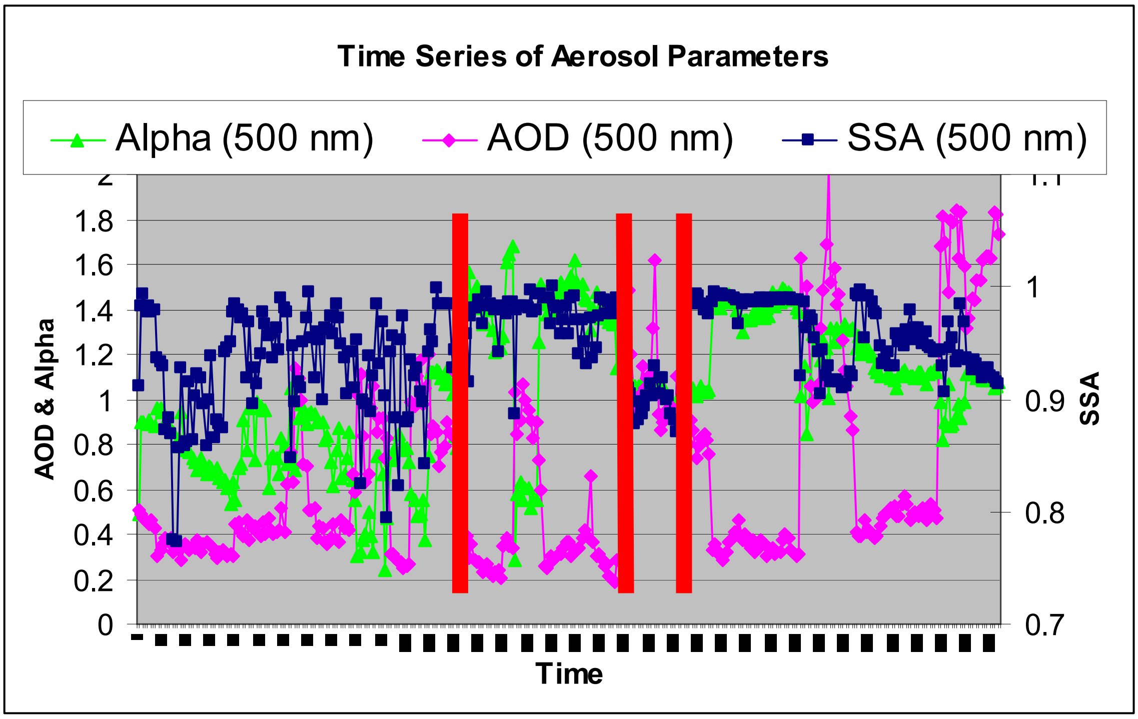


Fig 38: Aerosol radiative properties in Delhi

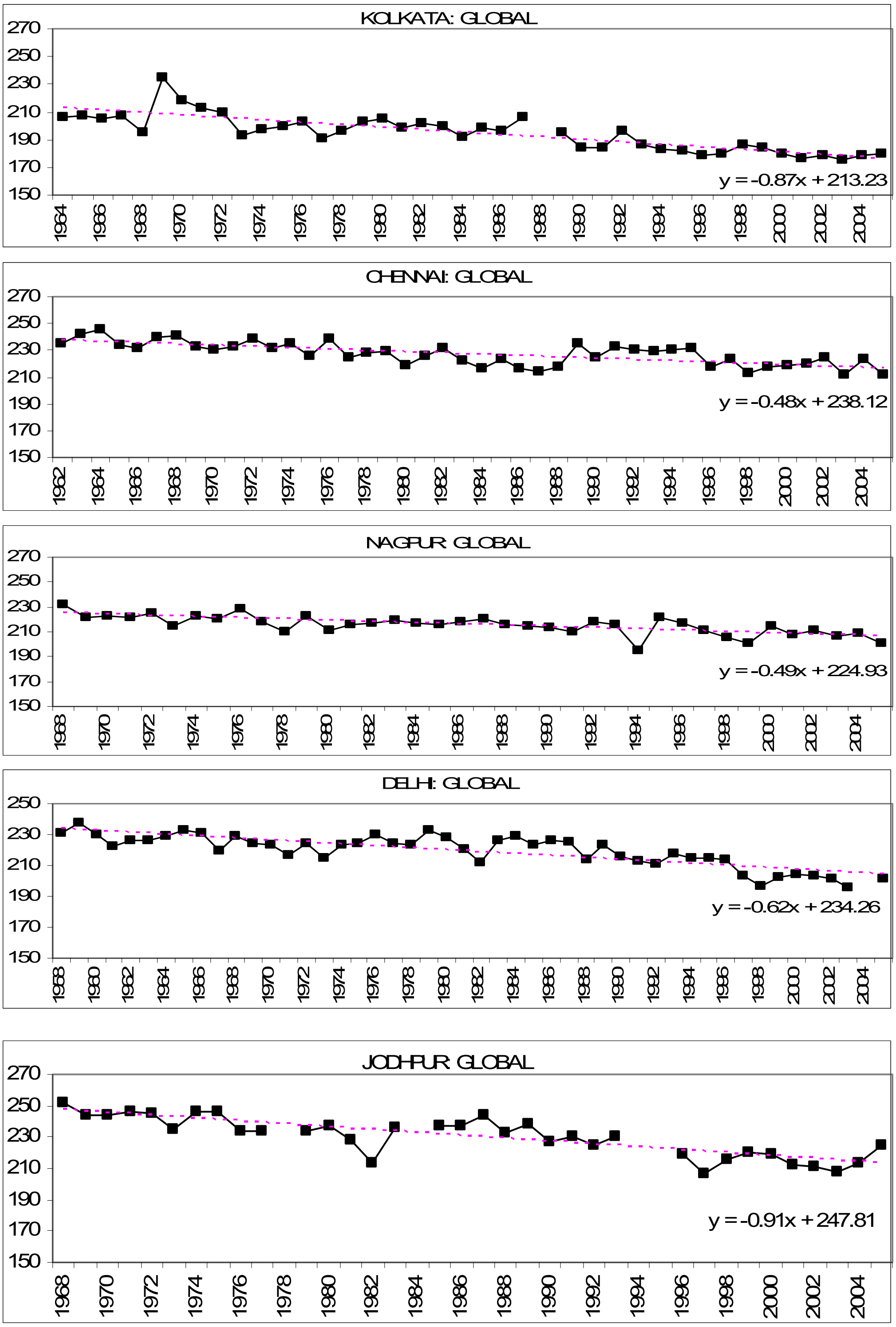


Fig 39: Long Term Trends of Global Solar Radiation (W/m^2) over GAW stations

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