CHAPTER 3

LONG TERM VARIABILITY OF RAINFALL OVER PENINSULAR INDIA
3.1 INTRODUCTION

Rainfall, a natural factor that determines the agricultural production, is changing at global (Dore 2005) and regional scale (Gemmer et al. 2004, Goswami et al. 2006, Kayano and Sans’golo 2008, Shamshudin shabid 2009). As the extreme events have the potential to indicate long-term seasonal climatic changes (Keim and Cruise 1998), a study on the variability of extreme events is essential. Moreover, such events are the result of small-scale convective instabilities in a moist atmosphere (Goswami et al. 2006). India being an agricultural country, the seasonal monsoon rainfall affects the socio-economic activities of the country. Even though the income from agriculture towards the national economy is less than 30%, any fluctuations in the seasonal rainfall can bring calamities in the agricultural sector (Rajeevan et al. 2007). Equally important is the case, when more rainfall is obtained in a short duration. Such events result in landslides, flash floods and crop damage that have significant impacts on society, economy, and the environment. So the extremes need to be warned earlier to reduce the vulnerability. Thus a study on the rainfall statistics provides an insight on the increasing extreme events over the country.

Observational studies suggested several reasons for the rise in extreme events. An increase in water vapour associated with the rise in tropical Indian Ocean SST (Goswami et al. 2006) and the active role-played by severe thunderstorms, synoptic disturbances like monsoon lows and depressions, in triggering extreme events are also notable (Francis and Gadgil 2006). A decrease in the strength of monsoon current (Joseph and Simon 2005), Tropical Easterly Jet (Sathiyamoorthy 2005 and Rao et al. 2004) and the number of depressions (Joseph and Xavier 1999) implies that a decrease in the rainfall amount received over the country may be influenced by these monsoon elements.

The present study analyses the trend of rainfall with different thresholds, seasonal total rainfall, and certain indices that measures extreme events during the period 1951-2003. The trend of some monsoon elements and its relation to the seasonal rainfall over the peninsular India region is also studied. The trend of seasonal rainfall at a subdivisional scale was carried out for the period 1951-2008. Preset values for defining moderate/extreme rainfall events is not suitable (Haylock and Nicholls, 2000) for regions of
high spatial and interannual variability. Also, the analysis at very small scales provides local information on the changing climate that is not usually extracted from the aggregated spatial mean (Bardossy and Hundecha, 2003). Such a study has been carried out for peninsular India (Ram Mohan et al. 2011). Therefore, the study is conducted at small spatial grids using the concept of percentiles.

3.2 RESULTS

3.2.1 Climatology of rainfall over peninsular India (1961-90)

The climatology of rainfall for the period 1961-90 is shown in Fig. 3.1a, which gives a spatial distribution of rainfall obtained during the June-September months. From the figure it is clear that the maximum rainfall is obtained in the west coastal region and rainfall decrease towards the southeastern parts of the peninsula. The total rainfall obtained from the threshold value of 50th percentile and more is shown in Fig. 3.1b. On comparing Fig. 3.1b with Fig. 3.1a it is clear that the rainfall over the southern peninsula is contributed mainly by the events with rainfall >=50th percentile. Therefore, rainfall events which fall under the category <50th percentile is not accounted in this study. Such events do not have any significant consequence on the societal activities, therefore the moderate and heavy rainfall events are studied using the thresholds greater than 50th percentiles. Such analysis of percentiles with different thresholds allows one to understand the spatial distribution of rainfall events. The Fig. 3.2a, b & c, 3.3a & b represent the Climatology values obtained for the 50th, 75th, 90th, 95th and 99th percentiles respectively. The Climatology is calculated with the rainfall for the 30 year period from1961-90.

The trend analysis is carried out for seasonal total rainfall, >50th, 50-75th, 75-90th, 90-95th, 95-99th and >99th percentile during the period 1951-2003. The frequency and rainfall totals of different percentiles are found on the basis of the climatology (1961-90) data.
Fig. 3.1. Climatology of Rainfall Total for June-September (a) season and (b) $\geq 50^{th}$ percentile during the period 1961-90.

Fig. 3.2. Rainfall climatology for June-September (a) $50^{th}$ percentile (b) $75^{th}$ percentile (c) $90^{th}$ percentile during the period 1961-90.

Fig. 3.3. Rainfall Climatology for June-September (a) $95^{th}$ percentile (b) $99^{th}$ percentile during the period 1961-90.
3.2.2 Trend Analysis for the period 1951-2003

3.2.2.1 Trend in seasonal total rainfall

The trend in the total rainfall for the period 1951-2003 is presented in Fig. 3.4a. The shaded grids show the results from Mann-Kendall trend test, whereas the contours represent the slope of the trend obtained by linear regression. The figure shows the trend obtained over the various grids over the peninsular Indian region. The region receives large amount of rainfall during the June-September season especially over the west coastal region. But southeastern parts of the peninsula receive much less amount of rainfall during this season. The trend in the rainfall is highly variable with a maximum decrease of 7 mm/yr period has been observed over the Kerala and Konkan coast and with 1-3 mm/yr over the southcentral peninsular region. The heavy rainfall over the west coast is due to the presence of the Western Ghats, which is oriented in the N-S direction along the west coast.

The trend of rainfall obtained for the threshold greater than 50th percentile is shown in Fig. 3.4b. Excepting over a few grids, the pattern of the trend resembles that obtained for the total rainfall. So it could be concluded that a large percentage of the rainfall trend is contributed by moderate and heavy rain (>50th percentile).

Fig. 3.4. Rainfall trend for June-September (a) season total (b) >=50th percentile total during the period 1951-2003.
3.2.2.2 Trend of rainfall events in different categories

\textit{i) 50}^{\text{th}} - 75^{\text{th}} \text{ percentile}

The 50-75\textsuperscript{th} percentile includes the rainfall above 10 mm and 20 mm over the southeastern and west coastal regions respectively (Fig. 3.5). The number of events obtained in this category is much more than the frequency of other events. As the amount contributed by such events are less, its influence on the seasonal total will be lesser than other categories. The trend over the region is dominated by negative values, but with positive values over the central peninsular region. Negative maximum is $-1.5$ mm/yr whereas the positive maximum is only 1 mm/yr.

\textit{ii) 75}^{\text{th}} - 90^{\text{th}} \text{ and } 90^{\text{th}} - 95^{\text{th}} \text{ percentiles}

The climatological values are as small as 20 mm over the southeastern parts of the peninsula and maximum values are observed over the west coast with values as high as 60 mm. As the frequency of such events are higher, the rainfall obtained during these moderate events contributes heavily to the seasonal totals obtained over the region. The 75\textsuperscript{th}-90\textsuperscript{th} percentile includes rainfall events in the range 20-70 mm, and for 90\textsuperscript{th}-95\textsuperscript{th} percentile the rainfall contributed by the events in the range 30-80 mm. These events are considered moderate compared to the extreme events with rainfall $>30$-80 mm (95\textsuperscript{th}-99\textsuperscript{th} percentile) and $>30$-100 mm (>99\textsuperscript{th} percentile). The trend shows that the moderate events (75\textsuperscript{th}-90\textsuperscript{th} percentile) decrease over the western, northern and eastern region of the peninsula (Fig. 3.6a). Parts of Tamil Nadu and south interior Karnataka show positive trend. The magnitude of the positive trend is 0.3-0.6 mm/yr, whereas the trend is
stronger for decreasing trend. Excepting a few grids over Karnataka, the trend pattern of 90\textsuperscript{th}-95\textsuperscript{th} percentile (Fig. 3.6b) almost follows as 75\textsuperscript{th}-90\textsuperscript{th} percentile.

\textit{iii) > 95\textsuperscript{th}-99\textsuperscript{th} percentiles}

The 95\textsuperscript{th}-99\textsuperscript{th} percentile denotes events that have the potential to produce flood over a region and an increase in such events can adversely affect the agriculture over the region. Similarly, these events contribute largely to the rainfall totals; therefore, a decrease can significantly affect the seasonal rainfall amounts and vice versa. As it is seen from Fig. 3.7a, there is an increase in these events over a major part of the peninsula.

The southernmost region experienced a decrease in these heavy rainfall events during the 1951-2003 period. The decrease in rainfall reported (Krishnakumar et al., 2009, Joshi and Rajeevan, 2006) over many of the subdivisions over the southernmost peninsula may be due to the decrease in heavy rainfall events.

\textit{iv) > 99\textsuperscript{th} percentiles}

From Fig. 3.7b it is clear that events with very heavy rainfall has an increasing trend over a large region of the peninsula. The rainfall obtained from these events is higher than from other rainfall events. Even though the rainfall amount is high (Fig. 3.3b) the number of such events is less. The amount of rainfall contributed to the seasonal totals is also high. The frequency of other events is higher than that for the 99\textsuperscript{th} percentile. The highest values for >99\textsuperscript{th} percentile are obtained over the Western Ghats, with rainfall amount of 70-100 mm/day. The surrounding region also shows high rainfall (30-70 mm/day). Thus over the entire study region 99\textsuperscript{th} percentile has very large values of rainfall.
Fig. 3.6. Rainfall trend for June-September (a) 75th-90th percentile (b) 90th-95th percentile during the period 1951-2003.

Fig. 3.7. Rainfall trend for June-September (a) 95th-99th percentile (b) >=99th percentile during the period 1951-2003.

The trend analysis of rainfall over the peninsular region with values greater than 99th percentile exhibits a decreasing trend over the Kerala subdivision. Excepting a few grids of negative trend, the region dominates with positive trend with a maximum strength of 3 mm/yr period. A decreasing trend with magnitude of −3 mm/yr is also observed over the west coastal region.

3.2.3 Trend in the frequency of extreme events

Even though the trend is insignificant and values are small, an increasing feature is dominant over the region. The frequency of events in the 95-99th percentile category decrease over the coastal grids, whereas it increases over the inland region (Fig. 3.8a). The pattern differs for the 99th percentile thresholds, with decreasing trend over the west coastal region and positive trend over rest of the peninsular region (Fig. 3.8b). The increase in these extreme events have influence over some parts of south interior Karnataka, south Andhra Pradesh, Rayalaseema and Tamil Nadu, but the
other subdivisions receive less rainfall in spite of the increase in extreme events. It could be understood that the moderate events decide the rainfall pattern over the peninsular region than the extreme events. Except Rayalaseema, where the trend is positive, all the other three subdivisions exhibit negative trends with very low values.

3.2.4 Trend over different subdivisions of peninsular India

A subdivisionalwise analysis helps to understand the present trend of the seasonal rainfall for which the subdivisional seasonal rainfall for the period 1951-2008 is subjected to trend analysis. The results for the different subdivisions are given below:

Subdivisions of Kerala, Tamil Nadu and Konkan and Goa

The strong decrease in the heavy rainfall events over the Kerala subdivision is reflected in the seasonal rainfall (Fig. 3.6b). The subdivisional rainfall obtained for a period 1951-2008 also shows a similar pattern with a decrease of 1.94 mm/yr during the period (Fig. 3.9). For a large region of Tamil Nadu subdivision, the increase in rainfall events from 99th percentile is compensated by the rainfall events of the other categories resulting in a decrease of seasonal rainfall. This is observed in subdivisional rainfall with a magnitude of decrease of 0.18 mm/yr (Fig. 3.9). The decrease for the Konkan and Goa is very high with values as large as 6.5 mm/yr. The decrease in rainfall is observed in all categories of rainfall events.

Coastal, North and South Interior Karnataka

For Coastal Karnataka, most of the regions shows a decrease in rainfall events while a few grids receive more rainfall in some categories (Fig. 3.6b). This is reflected in the subdivisional rainfall, which exhibits a negative trend of −1.18 mm/yr (Fig. 3.10). Except the 99th percentile, rainfall from all categories contributes negatively to the north interior Karnataka region, whereas for south interior Karnataka, the rainfall from all categories contributed positively to the rainfall, except the 99th percentile. This indicates a possibility for the decrease in rainfall over north interior Karnataka and an increase over
the south interior Karnataka. The trend analysis during the period shows that north interior Karnataka has a decrease of 1.74 mm/yr, at the same time south interior Karnataka also experienced a decrease in rainfall events. This may be due to the strong decrease in the rainfall amount contributed by 99th percentile. Thus it can be concluded that heavy rainfall events largely contribute to the seasonal total of the south interior Karnataka.

**Andhra Pradesh, Rayalaseema and Telangana**

For Andhra Pradesh, the rainfall from categories other than extremes bears a negative trend over south Andhra Pradesh but the seasonal rainfall shows a positive trend over the region. This positive trend is contributed only by the rainfall events in the 95-99th and >99th categories over the northern parts of the subdivision the trend is mainly contributed by 75-90th percentile. The subdvisional rainfall available to the recent years show that the negative trend is stronger than the positive trend over the subdivision resulting in an increase of −0.153 mm/yr (Fig. 3.11). Similarly, the positive trend obtained in the categories 95-99th and >99th percentile contributed positively to the trend in seasonal total of Rayalaseema. Thus the seasonal subdivision rainfall shows an increase of 1.2 mm/yr. Telangana shows a decrease in total rainfall during the June-September months. The values are as high as −2.71 mm/yr.

In spite of the increase in extreme events, the northcentral and northeastern regions of the peninsula experience a decrease in seasonal rainfall, which may be due to the decrease in rainfall in the 75-90th percentile category. The subdivisions of Kerala, Tamil Nadu and Karnataka show decrease with maximum decrease for Kerala. But the increase in seasonal totals over some parts of Tamil Nadu, Rayalaseema and south Andhra Pradesh is largely contributed by events with rainfall >99th percentile. Of all the subdivisions in south India, Konkan and Goa suffers from a maximum decrease at a rate of −6.5 mm/yr.
Chapter 3

Long term variability of rainfall

Fig. 3.9. The seasonal rainfall (June-September) of Kerala, Tamil Nadu and Konkan and Goa subdivisions for the period 1951-2008. The bold line denotes the trend line and the trend estimate are also displayed. The secondary axis is for Konkan and Goa.

Fig. 3.10. The seasonal rainfall (June-September) of the subdivisions of Karnataka for the period 1951-2008. The bold line denotes the trend line and the trend estimate are also displayed. The secondary axis is for south interior Karnataka.

Fig. 3.11. The seasonal rainfall (June-September) of the subdivisions of Konkan and Goa, Andhra Pradesh and Rayalaseema for the period 1951-2008. The bold line denotes the trend line and the trend estimate are also displayed. The secondary axis is for Andhra Pradesh.
3.2.5 Trend in Indices of rainfall extremes

3.2.5.1 DD and CDD

The count of dry days during the June-September season gives an indication of rainfall distribution. Over the peninsular India region, the count of dry days during the southwest monsoon season shows an increasing trend (Fig. 3.12a), which supports the decreasing trend obtained in the analysis of subdivisional rainfall. But regions over the central peninsula have decreasing trends and expected to get more rain. Certain regions of Tamil Nadu also have a decreasing trend. Many grids over the east coastal region have a significant increasing trend. The subdivision of south interior Karnataka experienced a decrease in the seasonal rainfall during 1951-2003 period, which is contradictory to the observed decrease in the number of dry days. From this it could be understood that the wet days (>1 mm rainfall) were more but the intensity of rainfall events were less, which resulted in the decrease of seasonal rain. The magnitude of the observed trend ranges from –0.3 mm/yr to 0.3 mm/yr. Most of the grids of south Andhra Pradesh have decreasing trends whereas the northern parts of the subdivision show a significant positive trend and the decrease in the rainfall amount is observed over the region.

The count of the consecutive dry days is a drought indicator. The increase in the CDD during the southwest monsoon season indicates a break in the monsoon rainfall and a large value of the CDD implies a long break in the wet days. Such events are found to increase significantly over the west and east coastal regions of peninsular India (Fig. 3.12b). The decrease in the trend is observed over the central regions of the peninsula and over south interior Karnataka, whereas Tamil Nadu is dominant with increasing trend. The regions of decreasing trends are expected to receive more rainfall and vice versa. Negative trend is stronger than the positive trend with magnitude of slope –0.16 mm/yr.

3.2.5.2 WD and CWD

The June-September season is the main rainy season of the peninsular region and expected to get rain throughout the season, especially over the west coastal region. But a
decrease in rainy days decreases the rainfall total and affects the annual rainfall obtained over the region. An increase in rainy days would result in increased rainfall as well. The results from the analysis show that the trend in the number of WD and CWD are opposite to that of DD and CDD. Almost all the coastal grids exhibit a negative trend while the central region shows a positive trend in the number of wet days. The trend is positive and significant over a few grids of Tamil Nadu and south interior Karnataka. At the same time, significant decrease is noticed over southern Kerala, eastern Tamil Nadu and northeastern Andhra Pradesh. Also, a region east of 75°E and north of 17°N exhibits a negative trend over which the trend of DD is positive (Fig. 3.13a). The magnitude of the positive trend has a maximum of 0.25 mm/yr whereas it is only –0.15 mm/yr for the decreasing trend.

Consecutive Wet Days indicate events with long rainfall spells. An increase in the CDD point out an increase in long rainfall spells which in turn results in large rainfall amounts. The peninsular region is dominated by a decreasing trend. Inland region of the peninsular India have a few grids with increasing trend (Fig. 3.13b) and most of the grids that exhibit a positive trend are insignificant. The maximum strength of the observed positive trend is 0.08 mm/yr. The significant decreasing trend of consecutive wet days is well distributed over the region and the maximum values are three times stronger (–0.24 mm/yr) than the positive trend.

3.2.5.3 PRCPTOT and SDII

This quantity is slightly different from the seasonal total as this considers only events with rainfall greater than 1 mm (wet days). The trend shows a decrease significant at 95% level over the west coast of peninsular India (Fig. 3.14a) whereas the interior regions exhibit an increasing trend, which indicate an increase in either frequency or intensity of rainfall. As we compare with the trends in the WD, a few of the grids that showed an increasing (decreasing) trend in WD are found to receive less (more) rainfall. This implies that there is a decrease (increase) in the intensity of rainfall. Excepting few grids, the pattern of increasing trend of WD and PRCPTOT are almost similar. The
positive trend has a maximum positive value of 3 mm/yr and a negative magnitude of more than -10 mm/yr.

SDII is a measure of the average rainfall received per wet day, a positive trend implies an increase in the mean intensity of rainfall events. An increase in the SDII can be due a increase in total rainfall from intense events. Only heavy/extreme can increase SDII, but regions with a decrease in both the WD and SDII indicate, a decrease in the mean rainfall received over the region. (Fig. 3.14b) shows several grids with increasing trend especially over the Southeastern region. The decreasing trend is concentrated in the western and interior regions of peninsular India. The maximum negative trend obtained has magnitude of -0.075 mm/yr whereas the value is only 0.05 mm/yr for the positive trend. The results indicate an increase in the intense rainfall events over the peninsular India region but over west coast, the intensity has reduced.

3.2.5.4 RX1 and RX5

The indices RX1 and RX5 give a measure of the short-period extreme rainfall activities during the June-September season. Such intense events are hazardous and affect the social activities adversely. These events over peninsular India exhibits

![Fig. 3.12. Spatial distribution of trend obtained for the (a) Dry Days (DD) (b) Consecutive Dry Days (CDD) for the period 1951-2008. Contours show the trend estimate from regression and the shaded grids display the results of Mann Kendall trend test.](image-url)
Chapter 3  
Long term variability of rainfall

Fig. 3.13. Spatial distribution of trend obtained for the (a) Wet Days (WD) (b) Consecutive Wet Days (CWD) for the period 1951-2008. Contours show the trend estimate from regression and the shaded grids displays the results of Mann Kendall trend test.

Fig. 3.14. Spatial distribution of trend obtained for the (a) rainfall from Wet Days (PRCPTOT) (b) Simple Daily Intensity Index (SDII) for the period 1951-2008. Contours show the trend estimate from regression and the shaded grids displays the results of Mann Kendall trend test.

Fig. 3.15. Spatial distribution of trend obtained for the (a) maximum one day precipitation (RX1) (b) Maximum five day precipitation (RX5) for the period 1951-2008. Contours show the trend estimate from regression and the shaded grids displays the results of Mann Kendall trend test.

increasing trend (Fig. 3.15a). The increasing trend is widespread over southeastern region including the subdivisions of Tamil Nadu, Rayalaseema and Andhra Pradesh. An increase in the highest one day rainfall is a good indication of the increase in intense rainfall events. Maximum magnitude of the positive trend is about 0.6 mm/yr. The west coast is dominated by negative trend and the strength of the trend is –0.6 mm/yr. It is evident
that the strength of the negative/positive trend is almost same implying that any increase in RX1 over a region is compensated by decrease in adjacent region of the peninsula.

RX5 at the same time is an indicator of extreme flood-producing events. A similar pattern as of RX1 is obtained for RX5. More spatial extent with the negative trend has been noticed, which implies a reduction in risk for human lives. The rainfall contributed to seasonal total will be so high that a decrease can significantly affect the rainfall total over the region. Decreasing trend is observed over the subdivisions of Kerala, parts of Tamil Nadu, south and north interior Karnataka that may be the one reason behind decreasing seasonal rainfall over these subdivisions. RX5 contributes about −2 mm/yr over the Kerala sub-divisional region and ±0.5 mm/yr over Andhra Pradesh, Rayalaseema, parts of Karnataka and Tamil Nadu (Fig. 3.15b).

3.2.6 Regional Trends

The above analyses are summarized over 5x5 boxes to form four regions over peninsular India (Fig. 3.16). The trend corresponding to each of these indices over these regions are presented in Table 1.

The trend over the Region 1 is not significant for any of these indices, even though all other regions secured a significant negative trend for consecutive wet days. Most of the indices have a negative trend over Region 1 and Region 2. Extreme events have a decreasing trend over regions 1 and 2 whereas it is found to be increasing over regions 3 and 4. Except Region 2 all other regions have a positive trend for highest one-day rainfall of the season. Both dry and the wet days are decreasing over region 3. Wet days and consecutive wet days are decreasing over all the four regions. Consecutive dry days are increasing whereas rainfall from wet days is decreasing over all regions.
Chapter 3  
Long term variability of rainfall

Fig. 3.16. The four 5x5 grid boxes considered over the peninsular Indian region

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<th>CWD</th>
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<th>RX5</th>
<th>SDH</th>
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<th>R95pTOT</th>
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</tbody>
</table>

Table 1. The trend obtained for each indices over the four regions of peninsular India for the period 1951-2003.

3.2.7 Possible reasons for the increasing/decreasing trend of monsoon rainfall

In order to understand the cause for the decrease in rainfall over many of the subdivisions of the peninsular India, the trends of some monsoon elements (already established) and their relation to the seasonal rainfall over the region is studied. Correlation analysis is used for the analysis and the spatial plots show the correlation patterns obtained between the various factors and peninsular India rainfall for the period 1951-2003. The temperature gradient, upper and lower level winds, Monsoon depressions and SST over adjacent ocean were considered.
3.2.7.1 Lower level wind

The study by Joseph and Simon (2005) have shown that the JJAS monsoon flow through India from surface to 1.5 Km altitude between latitudes 10-20°N had significant decreasing trend and that between 2.5-7.5°N a significant increasing trend during the period 1950 to 2003. The wind speed over the box (12.5-17.5°N, 70-85°E) with magnitude of 9m/s during the 1961-90 period has reduced to 8.48m/s in the last decade whereas over the box (2.5-7.5°N, 70-85°E), the values were 9.75 and 9.79m/s respectively. Even though the climatological value is higher than the value obtained in the recent decades, an increase in the trend was noticed over the box 2.5-7.5°N, 70-85°E. Indices made over these two boxes were correlated with the gridded rainfall. As seen from Fig. 3.17a the wind index over the peninsular region is significantly correlated with the rainfall over the Western Ghats region. An increase in the strength of the wind at this level over the peninsula enhances rainfall over the windward side of the Ghats. The decreasing trend in the wind has affected the rainfall drastically. All the subdivisions over the region suffered with a decrease in rainfall during the period with maximum decrease of –6.5 mm/yr for Konkan and Goa subdivision for the period 1951-2008. The decrease in the trend over the other box 2.5-7.5°N, 70-85°E has less effect on the peninsular India region as indicated by the correlation (Fig. 3.17b).

![Fig. 3.17. Spatial Correlation of peninsular India rainfall and 850 hPa wind over the a) 12.5-17.5°N, 70-85°E and b) 2.5-7.5°N, 70-85°E boxes.](image)
3.2.7.2 Upper level wind

*Rao et al* (2004) showed that the strength of the Tropical Easterly Jet (TEJ) is decreasing during the Asian Summer monsoon. Another study by *Sathiyamoorthy* (2005) found a large reduction in the size of the TEJ. TEJ has a maximum speed of 75m/s over the Indian peninsula (*Koteswaram*, 1958). As TEJ has the maximum strength over the Indian peninsula, the relation of the wind strength at 100hPa and 200 hPa over the core region (5-20°N, 40-100°E) is studied. The correlation with peninsular rainfall shows (Fig. 3.18) negative correlation over the west coast at 100 hPa and stronger correlation over the northeastern peninsular with the wind at 200hPa. Thus the wind at these levels has negative influence on rainfall and an increase in wind at this level would decrease the rainfall over the west coastal and northeastern peninsular region.

3.2.7.3 Monsoon Depressions

The monsoon depressions originating over the head Bay move along the monsoon trough bringing immense rain over the country (*Pant and Rupa Kumar*, 1997). A decrease in the number of such depressions decreases the rainfall over the country. Statistics shows that the average of 7 monsoon depressions formed in the early 1950s has decreased to 3 in the 1990s. Fig. 3.19a show the correlation between the number of monsoon depressions and rainfall over the peninsular India during the period 1951-2003.
The rainfall over the west coast region is positively related to the number of monsoon depressions. An increase in such events favours rainfall over the west coastal region.

### 3.2.7.4 SST index

The central equatorial Sea Surface Temperature ($7^\circ$S-$3^\circ$N, $60^\circ$-90$^\circ$E) shows a rapid increase during the 1950-2004 period. The relation of this SST to rainfall is as shown in Fig. 3.19b. The correlation is not significant to affect the rainfall over the region. So an increase in SST over the central equatorial Indian Ocean does not alter the rainfall over peninsular India. The recent warming of equatorial Indian ocean has also been shown in other studies (Charles et al., 1997 and Knutson et al., 2006).

### 3.2.7.5 Temperature gradient

The temperature gradient between the land and sea drives the monsoon current towards the Indian landmass. A strong gradient brings a strong monsoon current and a weak current is expected when the gradient is weak. The difference of temperature between the Indian landmass and Arabian Sea (TGIA) is correlated with Peninsular Indian rainfall and found to have positive values over the west coast (Fig. 3.20a), north of $14^\circ$N and rest of the region has insignificant correlation. The correlation between the temperature gradient between the Indian landmass and Bay of Bengal (TGIB) also shows positive correlation over the same region (Fig. 3.20b).
Chapter 3  

Long term variability of rainfall

Fig. 3.20. Spatial Correlation of peninsular India rainfall and temperature gradient at 850 hPa over Indian landmass (17.5-27.5°N, 72.5-82.5°E) and the box a) 10-20°N, 60-70°E at b) 10-20°N, 85-95°E.

3.3 SUMMARY

The trends of rainfall analysed over smaller spatial scales indicate that the rainfall is decreasing over the southwest coastal region of India. An exception to this was observed for the rainfall above the 99th percentile. At a subdivisional scale, except Rayalaseema, all the other eight subdivisions of peninsular India show a decrease in seasonal rainfall. Large region of the study area also exhibits an increasing trend in frequencies of heavy rainfall events.

However, a decreasing trend is observed over the west coast region for the number of wet days, the amount of rainfall from intense events and in the frequency of rainfall above the 95th percentile. A regionwise study indicates that the rainfall on wet days is decreasing and the number of consecutive dry days is increasing over all regions. A negative trend dominate over Region 1 and Region 2 whereas a positive trend exists in Region 3.

The possible reasons for the trends in rainfall were studied by analyzing the monsoon elements that showed significant trends. A significant positive correlation of 850 hPa zonal wind, number of depressions and a negative correlation of 100 hPa wind with west coast region is observed.