Chapter-2

Climatological Features

NE monsoon predominantly influences south peninsula, consisting of five meteorological sub-divisions (Coastal Andhra Pradesh, Rayalaseema, Tamil Nadu, South Interior Karnataka and Kerala) as shown in Fig. 2.1. In addition, NE monsoon contributes significant amount of rainfall over other south Asian countries like Sri Lanka and Maldives (Fig 2.2 a).

In Sri Lanka, the southwest monsoon season lasts during May to September. The period October to November is termed as second inter-monsoon season. The second Inter-monsoon period of October - November is the period with the most evenly balanced distribution of rainfall over Sri Lanka. Almost the entire island receives in excess of 400 mm of rain during this season, with the Southwestern slops receiving higher rainfall in the range 750mm to 1200 mm. NE monsoon is experienced during the period, December to February. During this period, the highest rainfall figures are recorded in the north, eastern slopes of the hill country and the eastern slopes of the Knuckles/Rangala range (http://www.meteo.gov.lk/index.php?option=com_content&view=article&id=94&Itemid=310&lang=en).

In India, the NE monsoon season (Oct-Dec) contributes about 11% of its annual rainfall over the country as a whole. South peninsula receives much more rainfall compared to northern parts of the country. Many districts over the south peninsula receive 30–60% of the annual rainfall during this season. This season is also termed the retreating monsoon season or the post-monsoon season in which the zone of maximum rainfall migrates to southern parts of India, Sri Lanka and the neighboring sea. With the withdrawal of the Southwest monsoon from the northern parts of India, the mean sea level pressure and upper tropospheric wind circulation patterns over India change rapidly from the summer monsoon type to winter type. By October, the Inter-tropical

Convergence Zone (ITCZ) or the monsoon convergence zone which is positioned over northern parts of India starts shifting southwards.

Fig.2.2 b shows the annual cycle of precipitation averaged over the longitudes 70^0-85^0, calculated using GPCP monthly rainfall data during the period 1979-2021. It clearly shows the northward movement of monsoon convergence and rainfall towards the northern parts starting from May and the retreat during October-December. NE monsoon season coincides with this retreating phase of the Inter Tropical Convergence Zone (ITCZ). There are also associated rapid changes in upper air circulation and sea level pressure patterns. During the October-December season, there is a clear evidence of rainfall maximum in the Southern Hemisphere (SH), coinciding with the presence of SH equatorial trough (SHET).

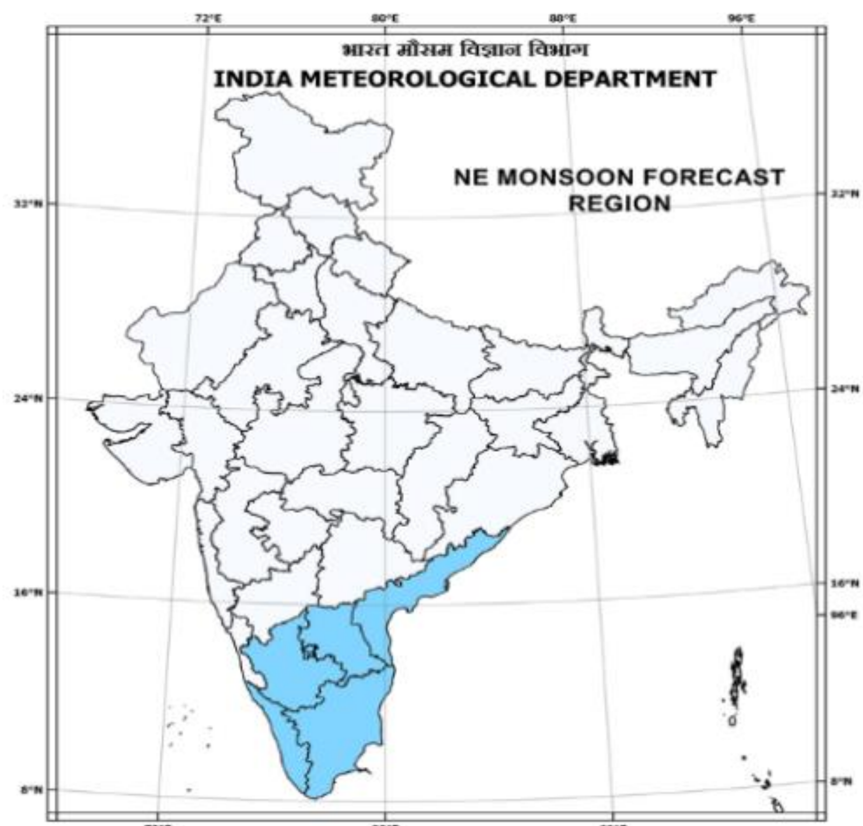

Fig. 2.1. Five Sub-divisions over South Peninsula under the NE monsoon region

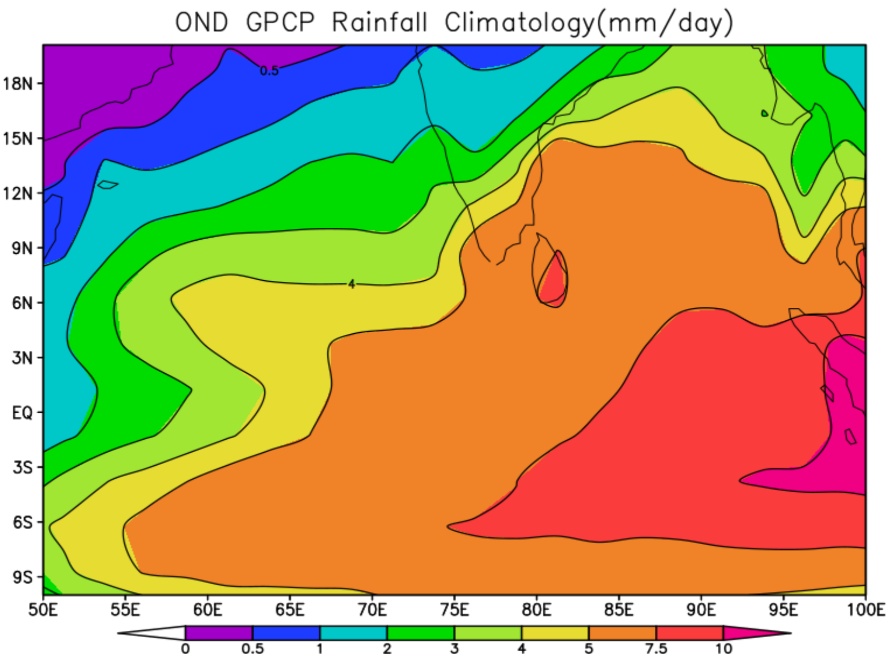

Fig. 2.2 a. NE monsoon rainfall (Oct-Dec) in mm/day over South Asia

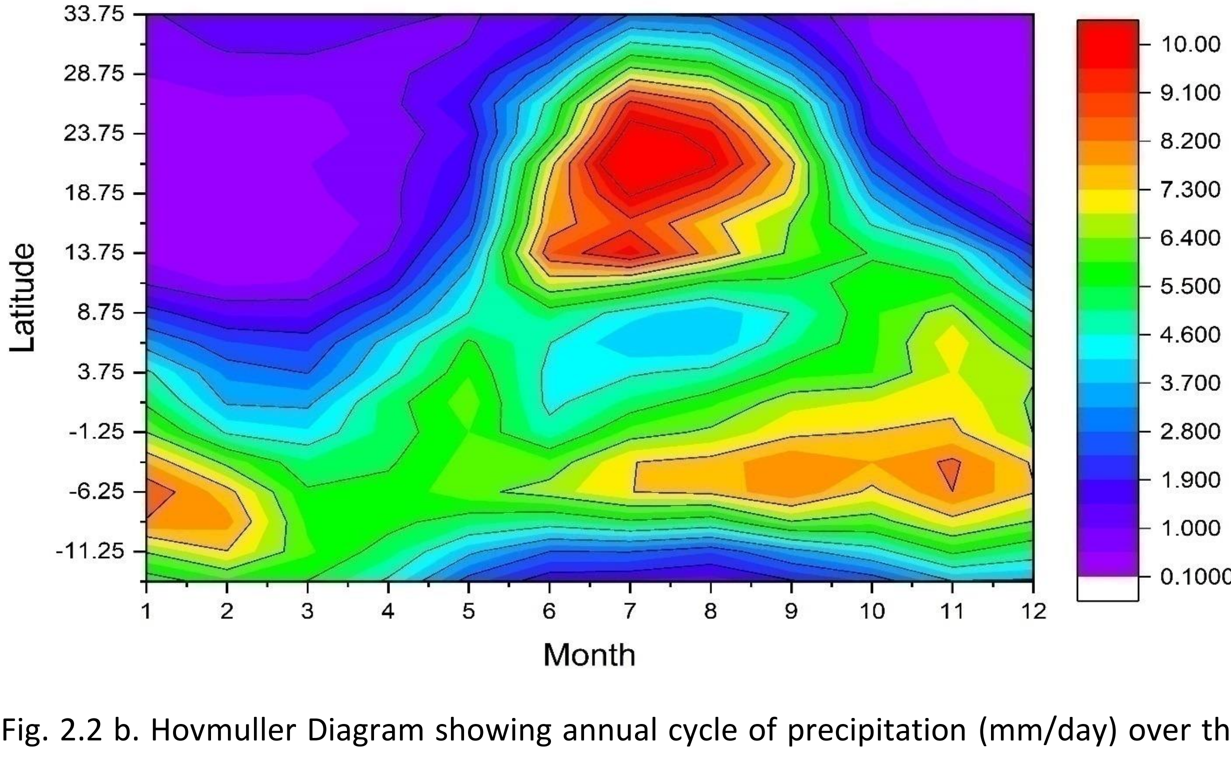

Fig. 2.2 b. Hovmuller Diagram showing annual cycle of precipitation (mm/day) over the Indian region, averaged over the longitudes between 70^0E- 90^0E. This plot is prepared using GPCP monthly rainfall data (1979-2021).

In the next sections, climatological aspects of sea level pressure and upper air circulation features are discussed.

2.1. **Sea Level Pressure**

The mean sea level pressure chart for the month of July is shown in Fig 2.3. The pattern shows a heat low over the northwestern parts of India and adjoining Pakistan with a south-north pressure gradient. The pressure gradient between the equator and 10^0N is about 12 hPa. However, by September, the pressure gradient generally weakens and by October the pressure gradient completely reverses with higher pressure over the northern parts of India.

The surface sea level pressure charts for Oct to Dec are given in Fig.2.4, 2.5 and 2.6 respectively. By October, a low pressure area gets established over the Central and South Bay of Bengal and adjoining east coast, which shifts to south Bay in November and further southwards, close to the equator in December. This low pressure area is more marked over the southwest Bay in October and November. In the Arabian Sea, the low pressure area is not well marked during these months. However, an east-west oriented trough of low pressure is observed in nearly the corresponding latitudes as in the Bay of Bengal, at least in October and November. In October, the pressure gradient is generally weak, which gets strengthened by November. While the low pressure area gets shifted southwards, the high pressure area associated with the Siberian High also gets strengthened over the northern parts of the country. The surface pressure gradient (high in the north and low in the south) over the Bay of Bengal also strengthens. During November and December, the isobars are nearly parallel to the equator, suggesting stronger surface easterlies/northeasterlies over the Bay of Bengal.

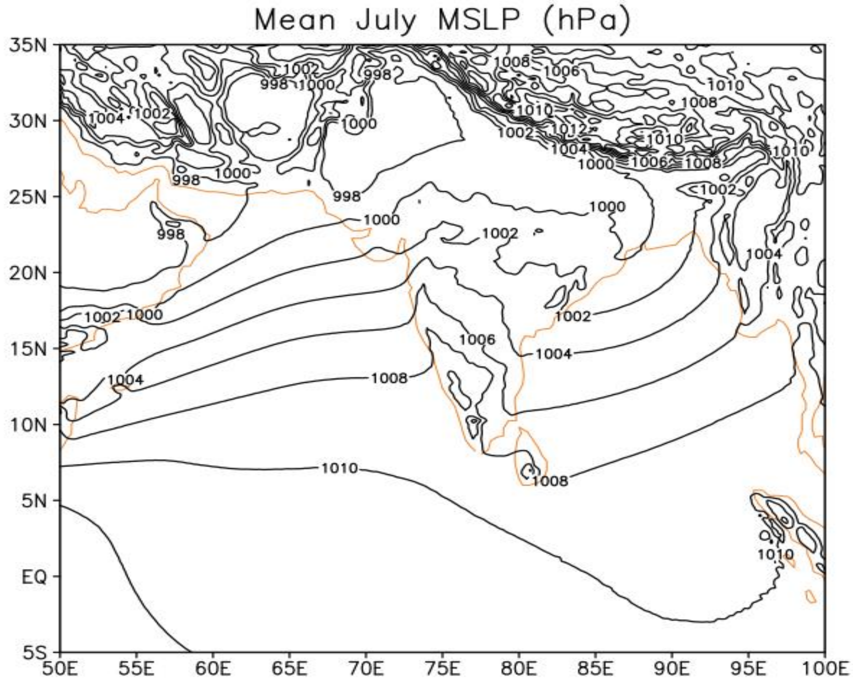

Fig. 2.3. Mean Sea Level Pattern (hPa) during July (period: 1979-2021). Source: ERA5 reanalysis.

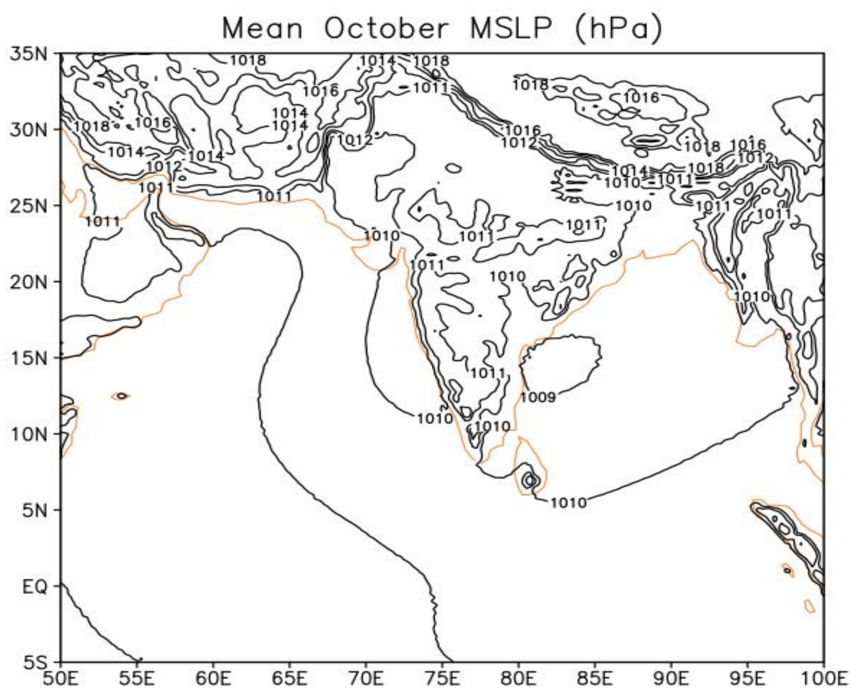

Fig. 2.4. Same as in Fig. 2.3 but for October.

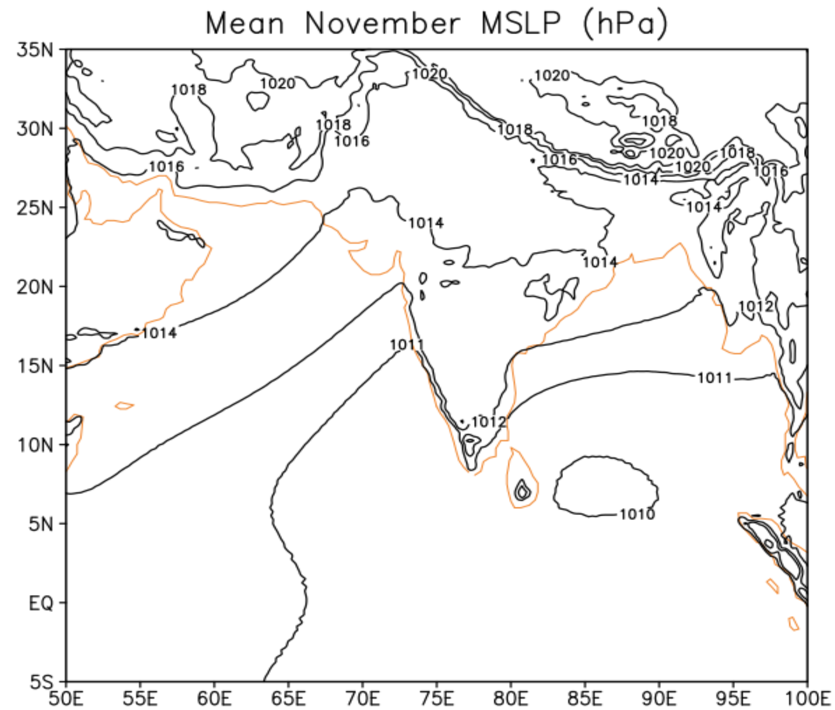

Fig. 2.5. Same as Fig 2.3 but for November.

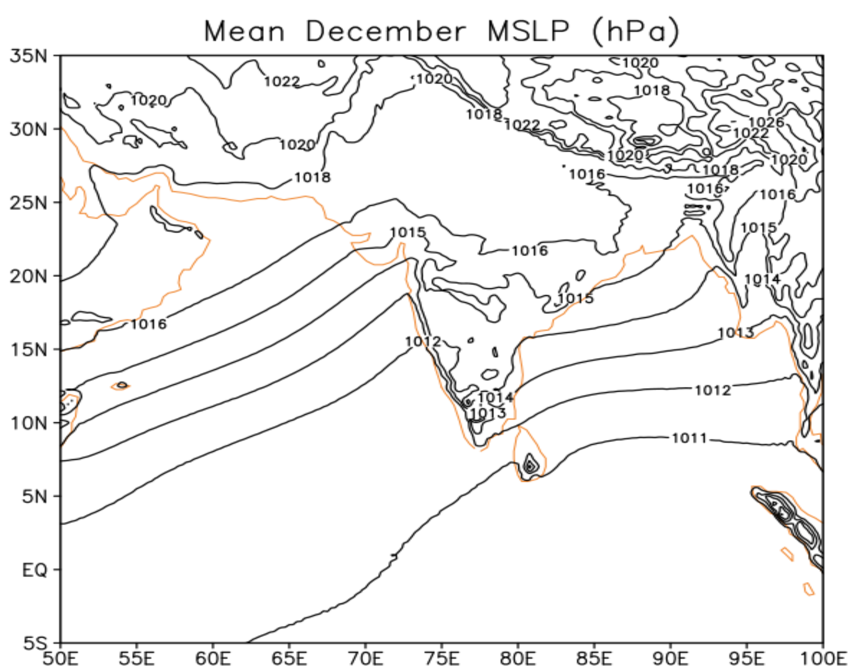

Fig. 2.6. Same as Fig 2.3 but for December.

2.2. **Upper Air Circulation Features**

The upper air circulation features from Oct to Dec are shown in Fig.2.7, 2.8 and 2,9 respectively. These maps show the mean wind pattern at 850, 700, 500 and 200 hPa levels. During October, an east-west trough is seen extending from the lower levels to 700 hPa from South Bay to the South Arabian Sea. This east-west trough is seen shifting southwards from October to December, consistent with the equatorward shifting of the ITCZ. By December, the east-west trough is seen close to 5^0 N. This east-west trough is the region with positive vorticity and convergence, thus causing abundant rainfall over this region. This shear zone in the lower troposphere contributes to the genesis of low-pressure systems over the Bay of Bengal and the Arabian Sea.

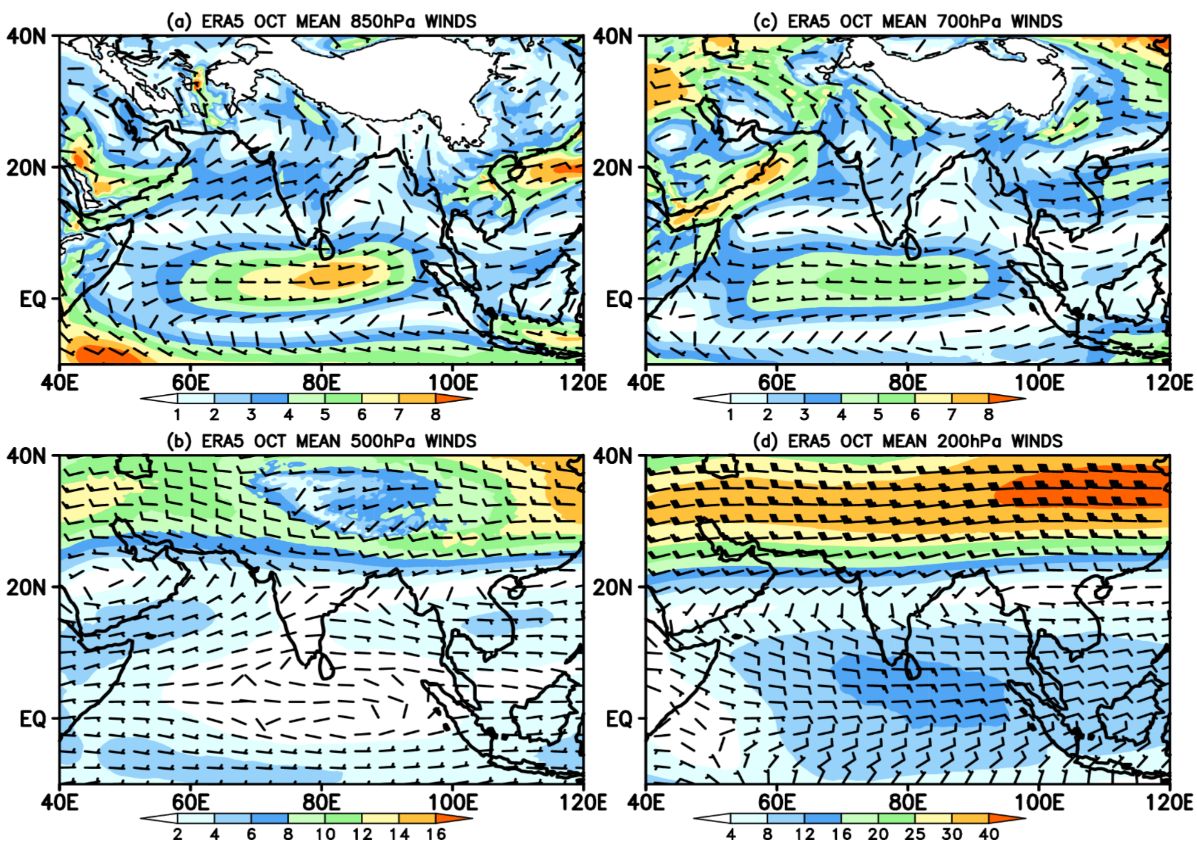

Fig. 2.7. Mean wind flow pattern during October at a) 850 hPa b) 700 hPa c) 500 hPa and d) 200 hPa levels. Source: ERA5 reanalysis. The colour shading represents wind speed in m/s. The data period: 1979-2021.

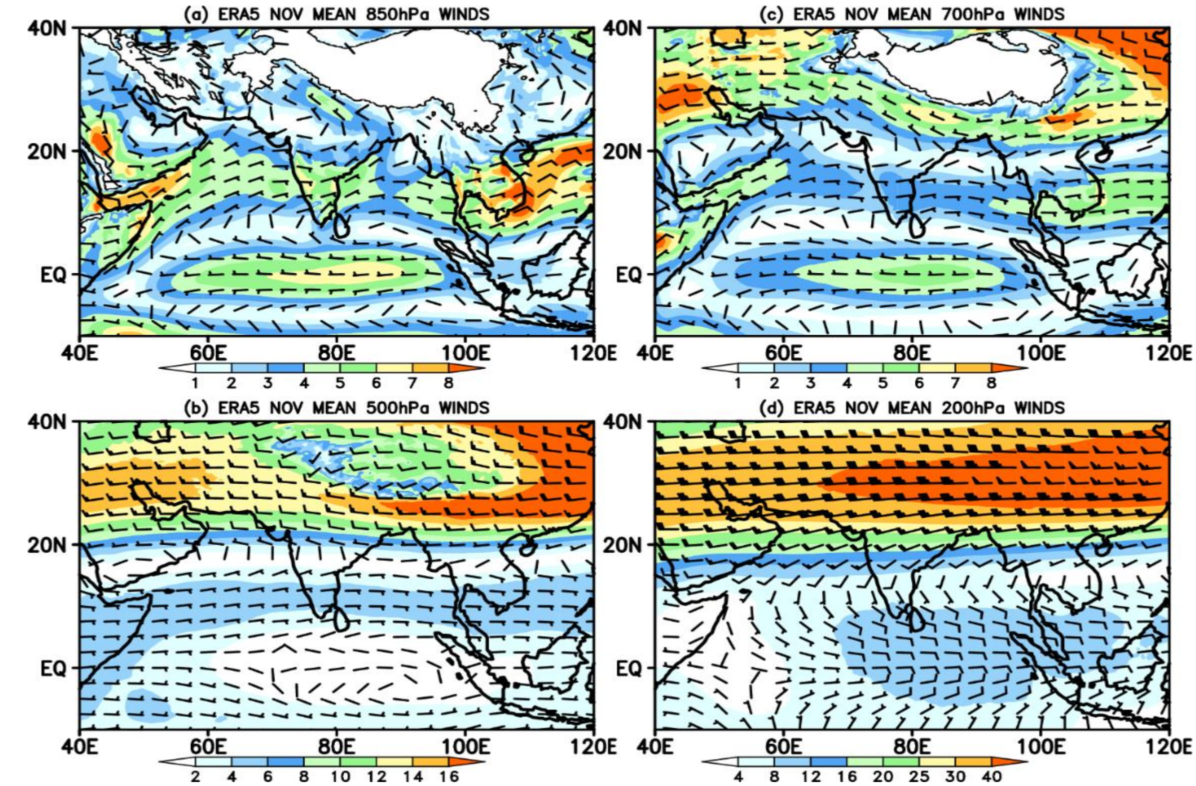

Fig. 2.8. Same as Fig 2.7 but for November.

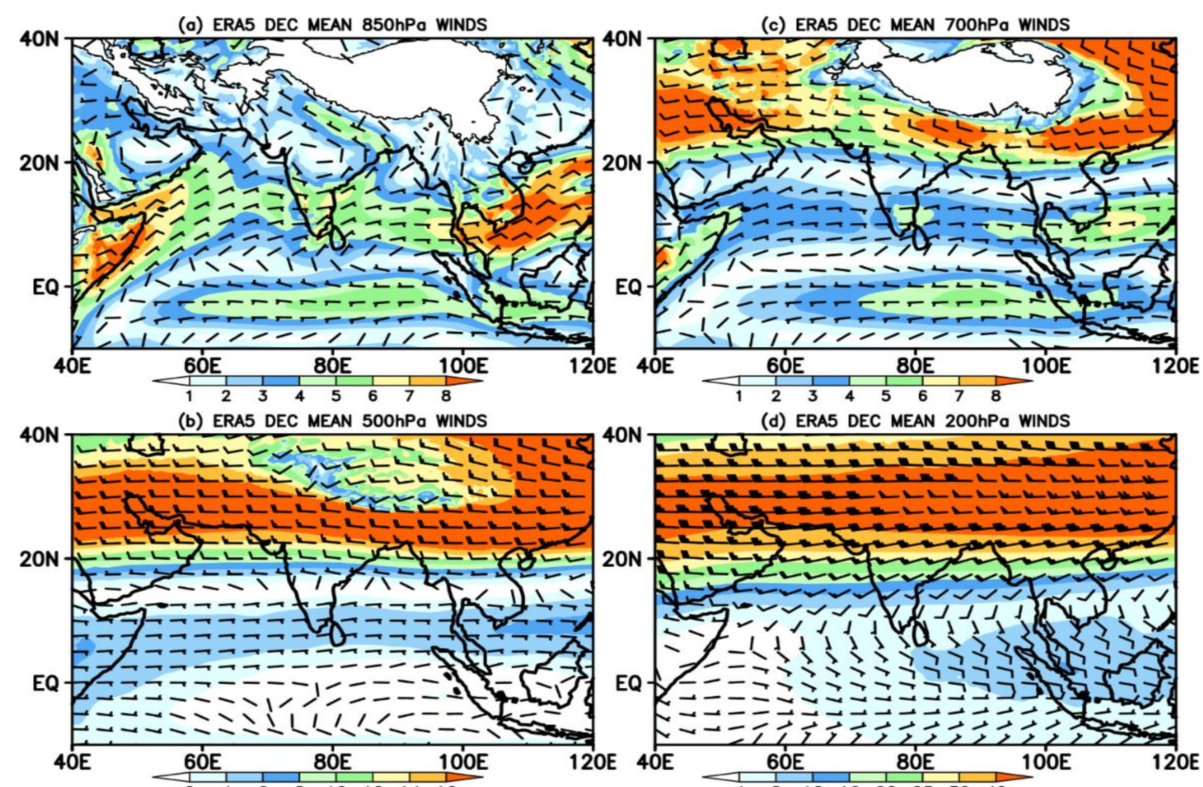

Fig. 2.9. Same as Fig 2.7, but for December.

In the middle and upper troposphere (500 hPa and 200 hPa), easterlies prevail over the south Peninsula and adjoining seas. The sub-tropical ridge at these levels also shifts southwards from October to December. The sub-tropical ridge in the upper levels is an area of divergence and contributes to the intensification of low pressure systems over the region. The Tropical Easterly Jet (TEJ), which is one of the semi-permanent systems during the southwest monsoon totally disintegrates once the southwest monsoon is withdrawn from the country. From October to December, the sub-tropical westerlies over the northern parts of the country also get strengthened and start moving to lower latitudes. An upper tropospheric ridge gets established over the southern parts of India by October and November at the 200 hPa level.

2.3. **Mean Precipitable Water Content (PWC)**

Spatial distribution of mean precipitable water content provides useful information on moisture sources and sinks over the region during the NE monsoon season. Mean precipitable water content is calculated as the weighted average of moisture from surface to upper troposphere (normally up to 300 hPa). It provides information of moisture content in the whole atmospheric layer. Higher values suggest moisture sources.

The PWC is a measure of available moisture for precipitation in the atmosphere. It measures the maximum possible precipitation of water, which may precipitate out from a given atmospheric column, if nothing else (e.g., surface evaporation, moisture advection) happens over a given time span. Of course, this is rather an oversimplified picture, because it is hard to imagine that all PWC would condensate within a given column under any conceivable process. Nevertheless, it would be good enough to interpret PWC as an upper bound for a possible precipitation at a given moment with a given atmospheric column.

Fig. 2.10 a, b and c show the spatial distribution of precipitable water content during October, November and December respectively. During October, the maximum

PWC is observed over the Southeast Bay of Bengal (east of Andamans) with values of 50 kg/m^2. The PWC reduces sharply westwards. Over the Bay of Bengal, PWAT values are more than 45 kg/m^2. Over south Peninsula, PWC varies between 40 to 45 kg/m^2. During November, the maximum zone of PWC slightly shifts southwards towards the equator. Over the south Peninsula, however, the PWC values are between 40 to 45 kg/m^2. During December, PWC maximum again shifts southwards and lies close to the equator. Over the south Peninsula, PWC values sharply reduce, ranging from 34 to 40 kg/m^2. During November and December, PWC decreases from south to north and isolines are almost parallel to the equator. Over the south Peninsula, PWC values are higher over the east coast as it reduces sharply towards interior parts.

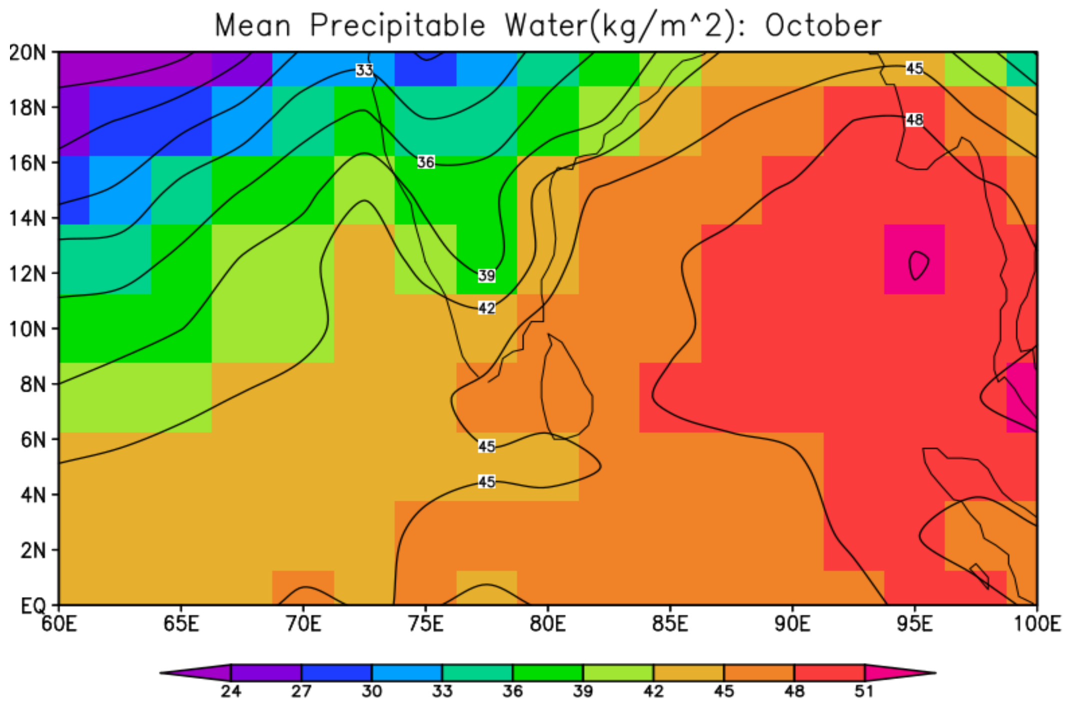

Fig. 2.10 a. Mean precipitable water content (mm) during October (1979-2021). Data source: NCEP/NCAR reanalysis.

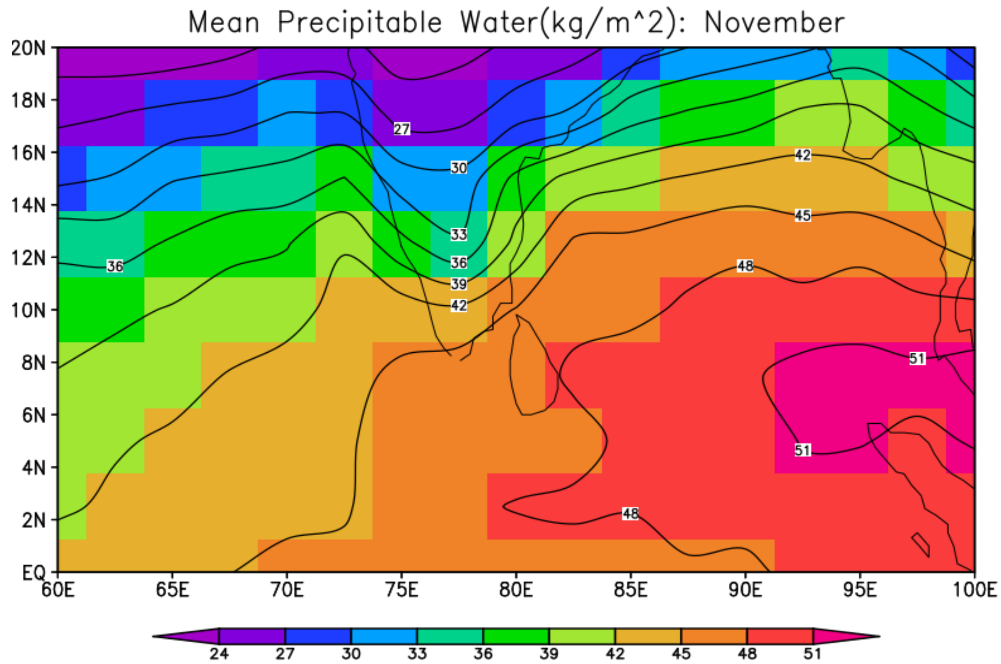

Fig. 2.10 b. Same as Fig 2.10 a but for November.

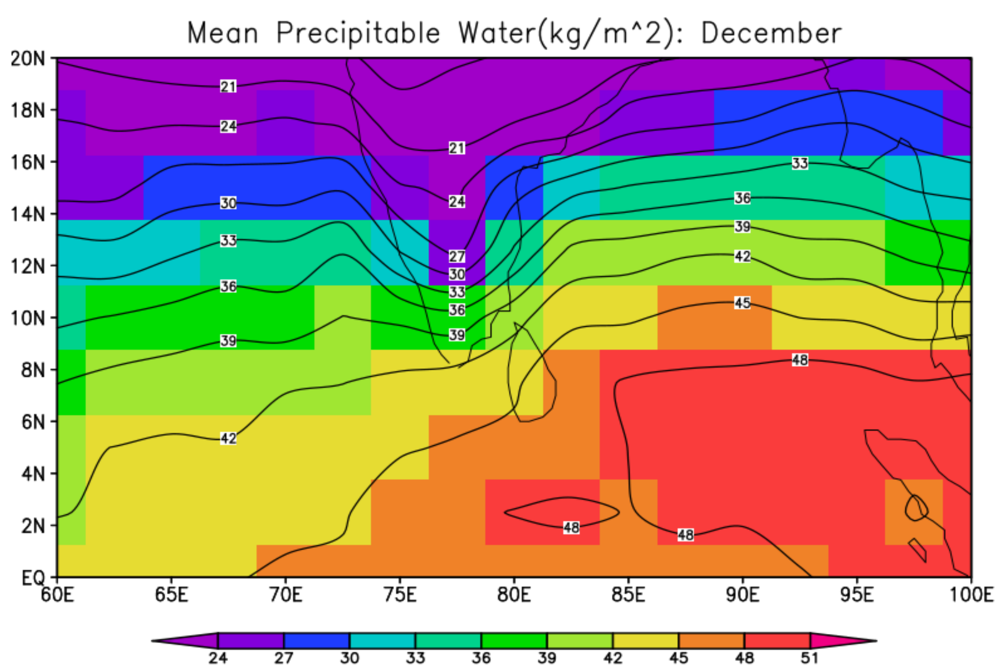

Fig. 2.10 c. Same as Fig 2.10 a but for December.

These are monthly mean patterns, calculated using long term climatological data. However, on a typical day, PWC values can either increase or decrease, depending upon the prevailing synoptic conditions. For example, low pressure weather systems transport more moisture and PWC values can increase sharply in a day or two. To see the variation of moisture content in the atmospheric column, it is better to monitor the PWC changes in addition to low-level humidity. PWC can be easily calculated using radiosonde profiles of moisture.

2.4. **Mean Air Temperatures**

Seasonal (October-December) mean minimum, maximum and mean temperatures over South Peninsula are shown in Fig. 2.11 a, b and c respectively. This analysis was made using the IMD's 1 × 1 degree gridded daily temperature data (Srivastava et al., 2009). Seasonal mean minimum temperatures are the highest along the coasts and they decrease towards the interior parts. Over the east coast, seasonal mean minimum temperatures are of the order of 22-23^{0}C. Over the eastern parts of the south peninsula, the isotherms run parallel to the coast. Over the interior parts, minimum temperatures are below 20^{0}C. Seasonal maximum temperature over the south peninsula varies between 28^0 – 31^{0}C, except over the interior parts of Karnataka where maximum temperatures are below 28^{o}C. Mean temperatures (Fig. 2.11 c) over the coastal Andhra Pradesh are more than 26^{o}C, while over the extreme south peninsula (Tamil Nadu and Kerala), the mean temperatures exceed 27^{0}C.

2.5. **Sea Surface Temperatures (SST)**

During the NE monsoon season, synoptic systems like tropical cyclones, lows and depressions and easterly waves, the presence of east-west trough contribute to rainfall over the South Peninsula. As these weather systems form over the Bay of Bengal and the Arabian Sea, oceanic conditions like Sea Surface Temperature (SST) play an important role. However, higher SSTs lead to more convection only if atmospheric conditions also are favourable. Therefore, it is important to monitor closely the oceanic conditions like SST and Ocean heat content regularly during the NE monsoon season.

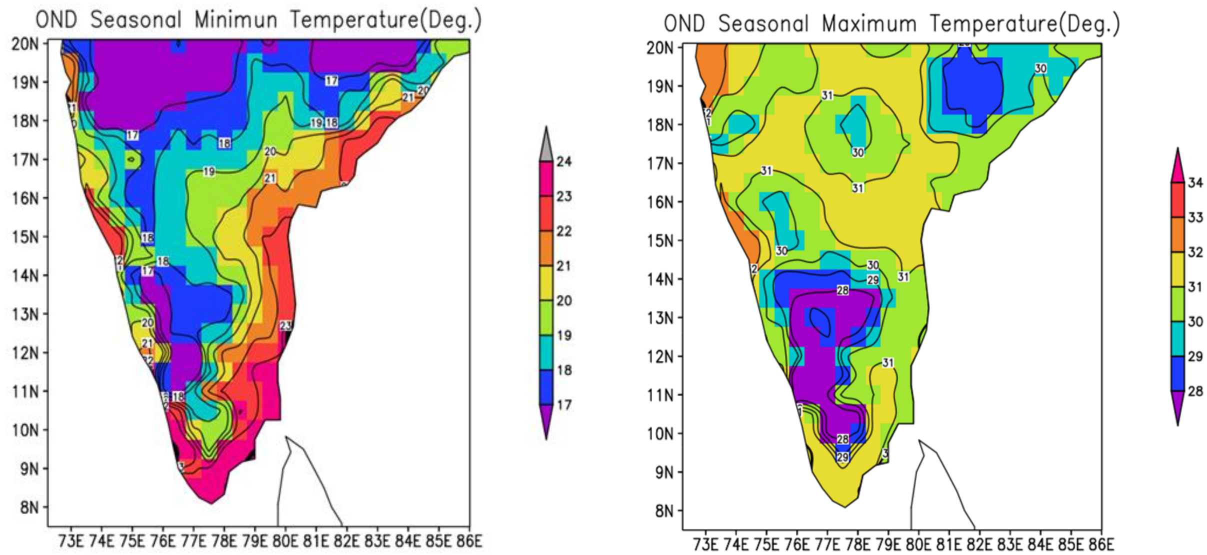

Fig. 2.11 a. Mean Minimum Temperatures (^{0}C) (b) Mean Maximum Temperatures during October to December (1972-2021) Source: IMD gridded temperature data.

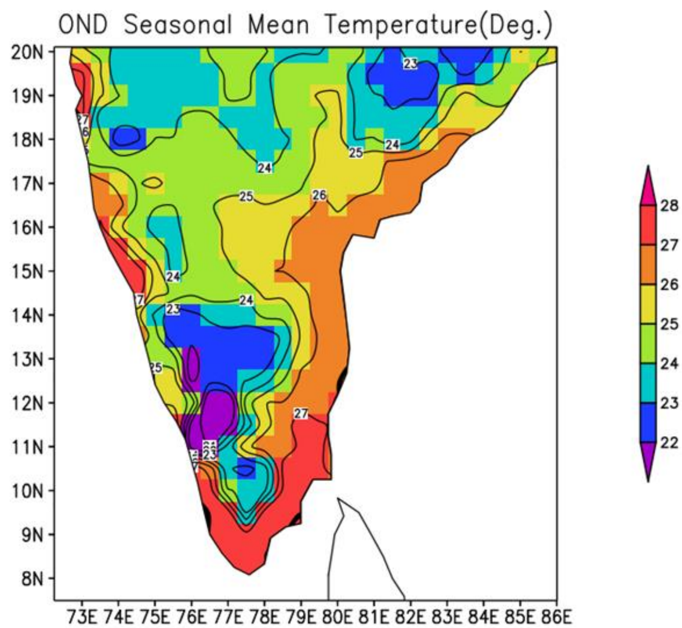

Fig. 2.11 c. Mean Temperatures during October to December (1972-2021) Source: IMD gridded data

Fig. 2.12 a, b and c show the spatial distribution of SSTs during October, November and December respectively. During October, SSTs are of the order of 28.5^{0}C over the central Bay of Bengal. Over the eastern parts of the Arabian Sea, SSTs are of the order of 28.5^{0}C. But it sharply reduces westwards and over the western Arabian Sea, SSTs are below 27.5^{0}C. During November, the SST maximum slightly shifts southwards and is located near the east central Bay of Bengal with values exceeding 28.5^{0}C. Another SST maximum is observed over the east central Arabian sea off the Kerala and Karnataka coasts. By December, both the Bay of Bengal and the Arabian Sea cools off quickly. The 28.5^{0}C isotherm is now seen near the equator. SSTs over the west central Bay of Bengal are below 28.0^{0}C and sharply decreases towards the north Bay of Bengal.

The next section discusses the relationship between SST and convection during the NE monsoon season.

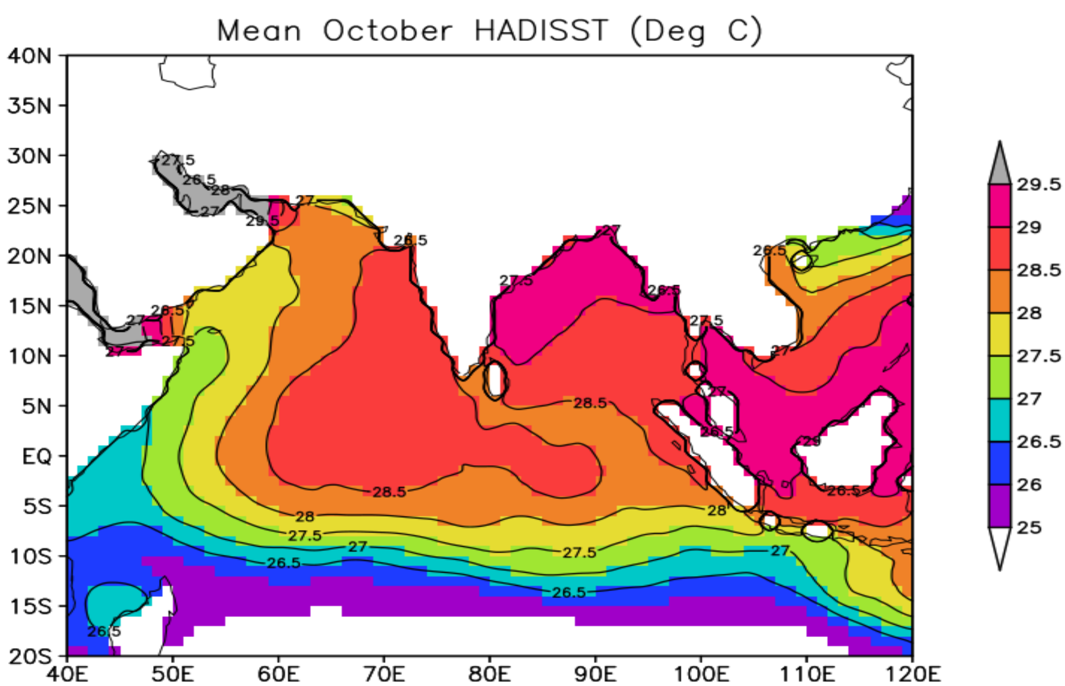

Fig. 2.12 a. Mean Sea Surface Temperature (SST) (degree C) during October, Period: 1972-2021. Source : HadISST, Met Office Hadley Centre.

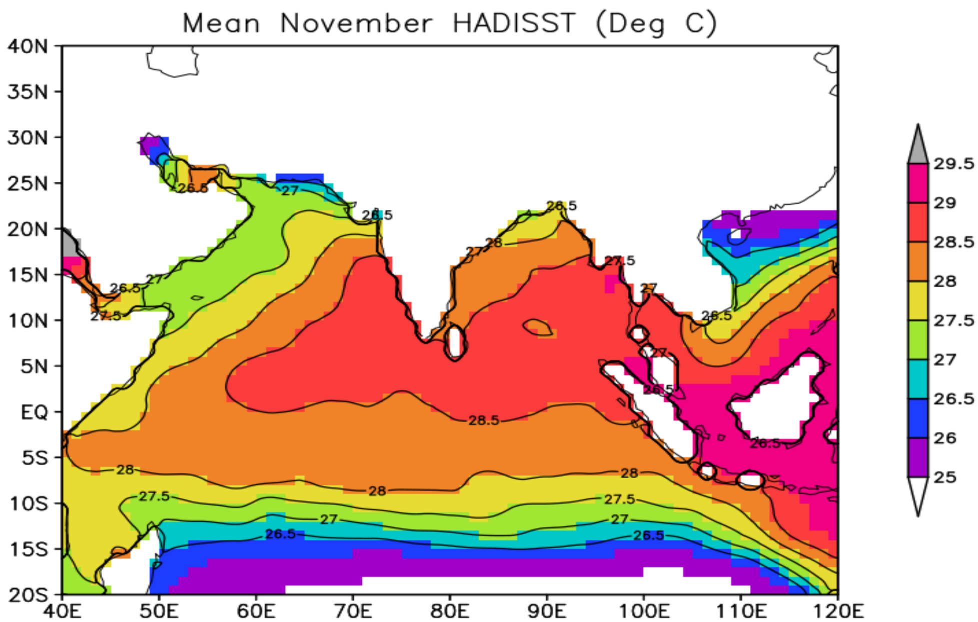

Fig. 2.12 b. Same as Fig 2.12 a but for November.

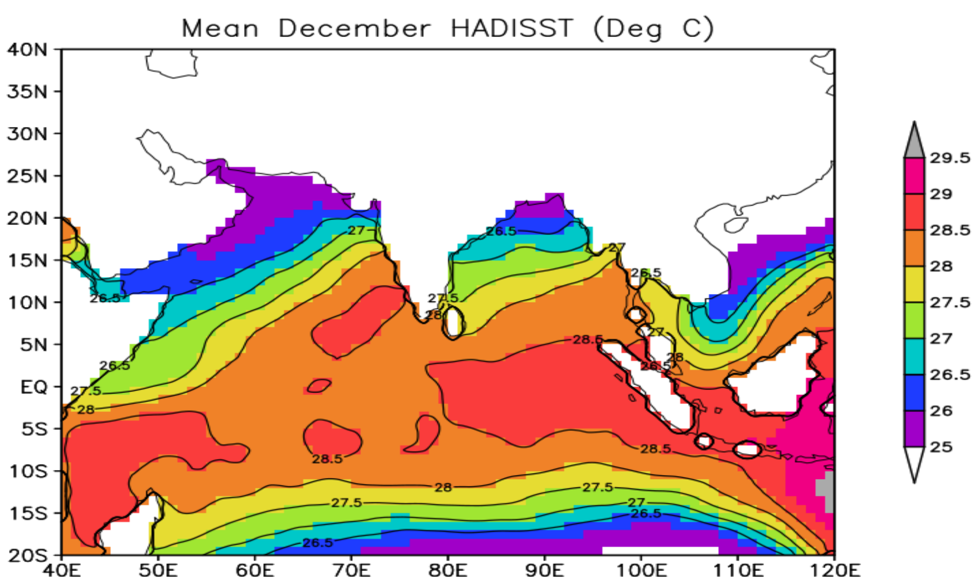

Fig. 2.12 c. Same as Fig 2.12 a, but for December.

2.6. **Relationship between SST and Convection during the NE monsoon**

There is a strong relationship between SST and atmospheric convection over the tropical ocean basins. Previous studies (Gadgil et al., 1984, Sabin et al., 2012) have shown that during the southwest monsoon season, convection over the Bay of Bengal is initiated when SSTs are between 27^0-28^0C. A similar analysis was made for the NE monsoon season (Oct-Dec) using long term data of SST and Outgoing Long Wave Radiation (OLR) data over the Indian Ocean. OLR is a proxy for atmospheric convection.

Fig. 2.12 d shows the scatter plot between SST and OLR over the a) the Arabian Sea (0-20^0 N, 60-75^0 E) and b) the Bay of Bengal (0-20^0 N, 80-100^0 E). The data during 1982-2021 have been used for these plots. Over the Bay of Bengal, convection starts abruptly and increases sharply once the SST threshold crosses 28.0^0 C. At 28.5^0C, the OLR in the Bay of Bengal is 20 Wm^{-2} lower than in the Arabian Sea due to much deeper clouds over the Bay of Bengal. The mode with the highest probability for SST above the threshold of 28^0C over the Bay of Bengal has low OLR (about 210 Wm^{-2}) corresponding to deep convection whereas that for the Arabian sea it is around 250 Wm^{-2}.

It is interesting to note that even above the SST threshold of 28^0C, there are points with OLR values more than 240 Wm^{-2} suggesting severe convection is not present at these locations. It may be worthwhile to note that only SST threshold will not decide whether convection will occur or not. Initiation of convection also depends on atmospheric circulation, which should be conducive for low level convergence and ascending motion (Lau et al., 1997). This aspect is not further examined here and should be taken up as a separate study.

2.7. **Spatial distribution of cloud properties**

A further analysis was made on the spatial structure of some vital cloud properties during November over the region using the International Satellite Cloud Climatology Product (ISCCP) data (Rossow et al., 1991) for the period 1998-2019. Fig. 2.13 a, b and c show the spatial pattern of Deep convective clouds (DCC) (%), Cloud

Optical Thickness and Cloud Water Path (cm) respectively. Cloud optical thickness is the vertical optical thickness between the top and bottom of a cloud. The optical thickness of a cloud is the degree to which the cloud prevents light from passing through it. It depends directly on the cloud thickness, the liquid or ice water content and the size distribution of the water droplets or ice crystals.

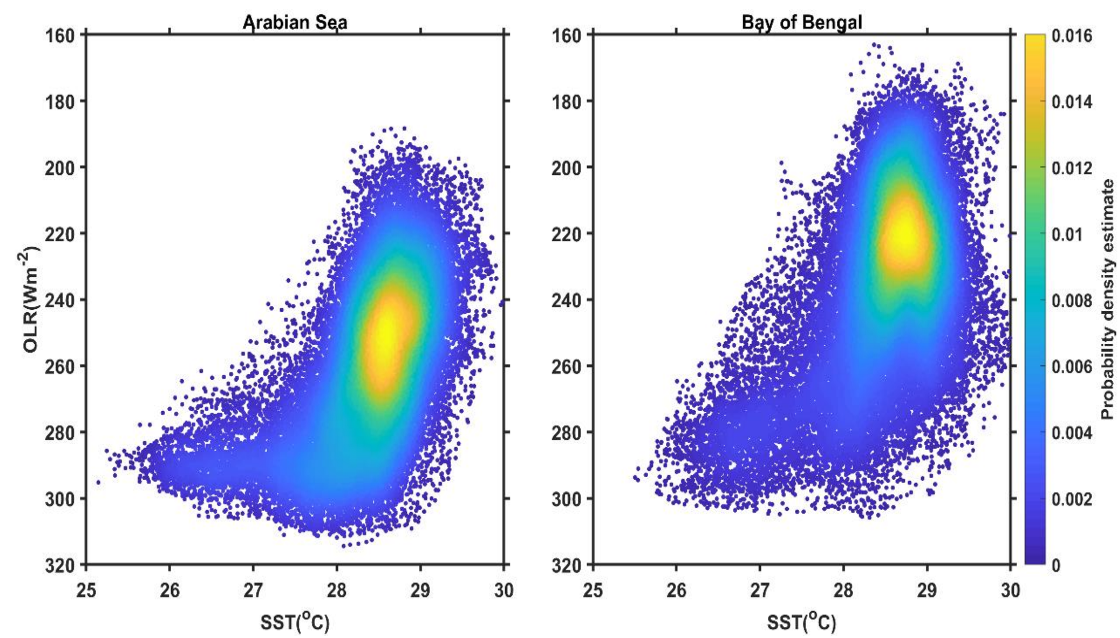

Fig. 2.12 d. The scatter plot between SST and OLR over a) Arabian Sea (0-20^0 N, 60-75^0 E) and b) Bay of Bengal (0-20^0 N, 80-100^0 E). The data during 1982-2021 have been used for these plots.

Deep convective clouds are clouds with cloud top crossing above 400 hPa. The spatial distribution of DCC suggests maximum percent DCC over the east equatorial Indian Ocean (12-14%) coinciding with warmer SSTs (Figs 2.13 a, b and c). Over the southwest Bay of Bengal and off the Tamil Nadu coast, DCC is around 8%. Comparatively, DCC distribution over the Arabian sea is much smaller, suggesting the Bay of Bengal has much deeper convective clouds.

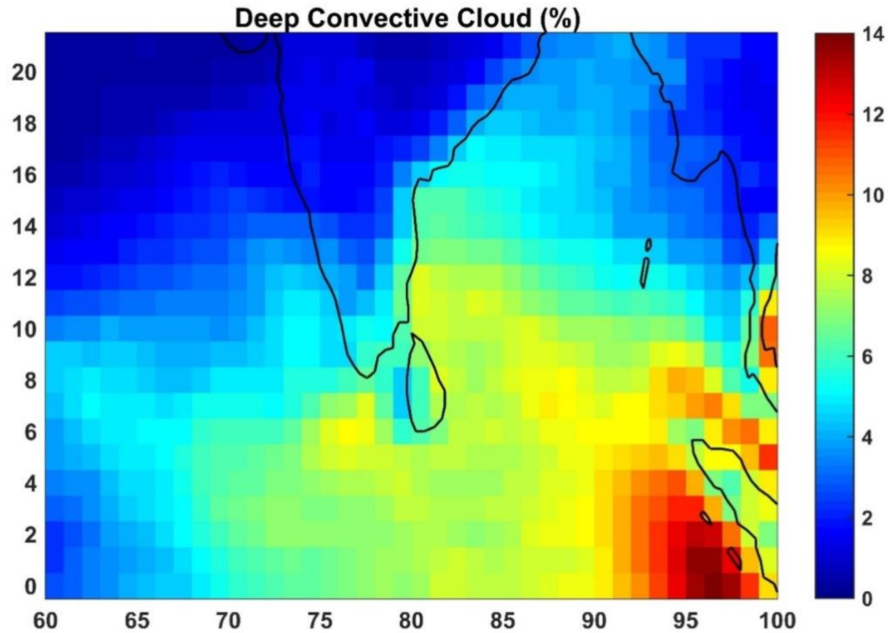

Fig. 2.13 a. Spatial distribution of Deep Convective Clouds during the NE monsoon season (October- December) based on the ISCCP data. Period: 1998-2019.

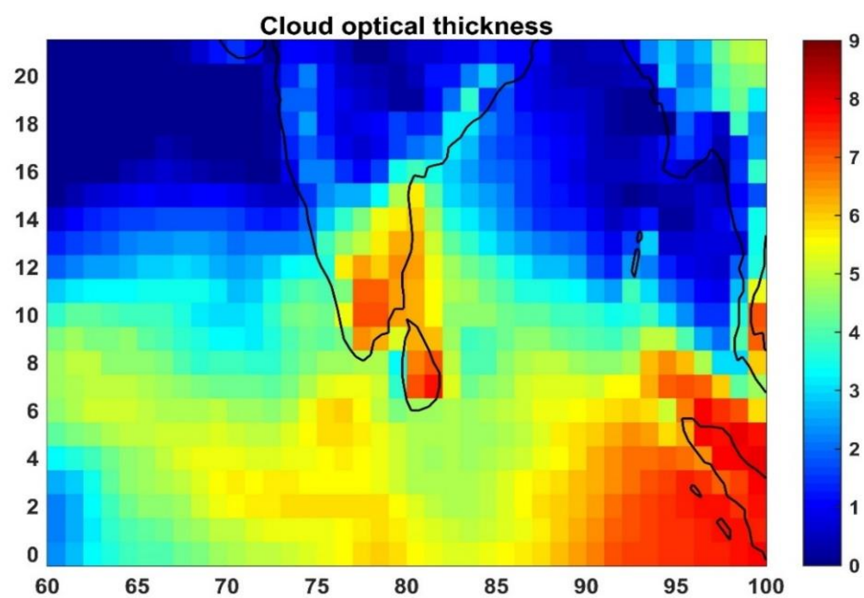

Fig. 2.13 b. Spatial distribution of Cloud Optical thickness during the NE monsoon season (October- December) based on the ISCCP data. Period: 1998-2019.

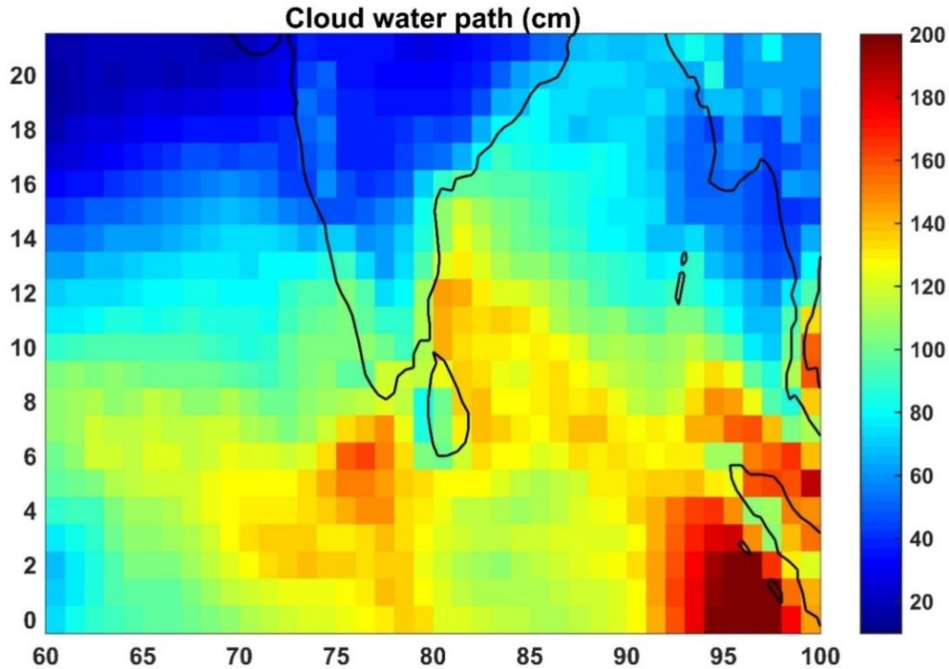

Fig. 2.13 c. Spatial distribution of Cloud water path (cm) during the NE monsoon season (October- December) based on the ISCCP data. Period: 1998-2019.

The spatial distribution of cloud optical thickness suggests maximum distribution over the east equatorial Indian Ocean coinciding with warmer SSTs and a large amount of deep convective clouds. Another maximum of cloud optical thickness is observed over the southeast Peninsula and adjoining Bay of Bengal. The spatial distribution of cloud liquid path (cm) shows that maximum is observed over the east equatorial Indian Ocean. Another maximum of cloud liquid path with values more than 120 cm is observed over the southwest Bay of Bengal off Tamil Nadu Coast. Therefore, the eastern parts of south peninsula and adjoining Bay of Bengal have deeper convective clouds with larger optical depth and cloud liquid water path. The spatial distribution shown here is based on long term climatology. On a day-to day basis, there could be significant variations in the distributions of cloud properties and they should be monitored using INSAT and similar satellite data products.

Characteristics of raindrop size distribution (DSD) are studied by Rao et al. (2009) during the southwest (SW) and northeast (NE) monsoon seasons using 4 1/2 years of Droplet Size Distribution (DSD) measurements made at Gadanki (13.5°N, 79.2°E) by an impact-type disdrometer. The observed DSD is found to be distinctly different in the NE monsoon from that of the SW monsoon. The stratified DSD (based on rain rate) shows more small drops and fewer bigger drops in the NE monsoon compared to the SW monsoon, particularly in the low rain rate regimes.

2.8. **Thunderstorms/ Lightning**

During the NE monsoon season, the south Peninsula experiences large scale thunderstorm activity. A good review of thunderstorm activity over India using station data is given in a recent paper by Omvir Singh and Bharadwaj (2017). A detailed study on lightning activity over the Indian region was published by Ranalkar and Chaudhari (2009) using the TRMM Lightning flash data. The average number of thunderstorm days during October, November and December are given in Fig. 2.14 a, b and c respectively. These plots are taken from the IMD Climate Hazards and Vulnerability Atlas of India (2022) (https://imdpune.gov.in/hazardatlas/index.html). The data from 1981-2010 have been used to prepare these spatial maps.

During October, some districts in coastal Andhra Pradesh, Tamil Nadu and Kerala experience more than 4 thunderstorm days. Over south interior Karnataka and Rayalaseema, average number of thunderstorm days is between 2 and 3. During November, thunderstorm activity is reduced in Coastal Andhra Pradesh. However, Tamil Nadu and Kerala still experience thunderstorms with average number varying between 3 and 7 days. Over the coastal Andhra Pradesh, south interior Karnataka and Rayalaseema, thunderstorm activity is slightly reduced. By December, thunderstorm activity is further reduced. During December, maximum thunderstorm days are observed over Kerala and southern parts of Tamil Nadu.

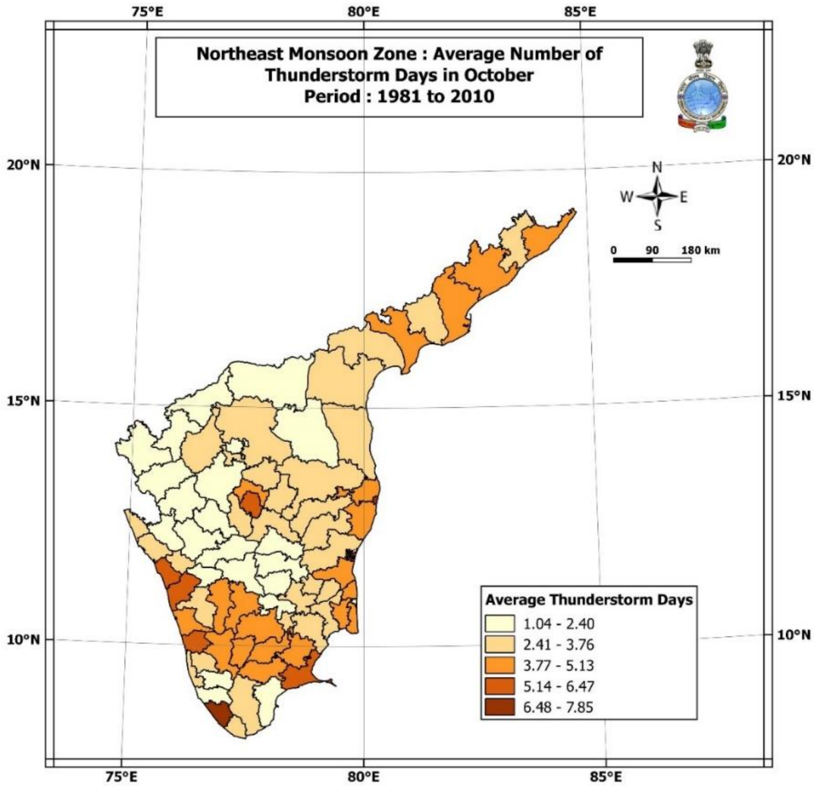

Fig. 2.14 a. Average number of Thunderstorm Days during October, 1981-2010. (Source: IMD Climate Hazards and Vulnerability Atlas of India, 2022).

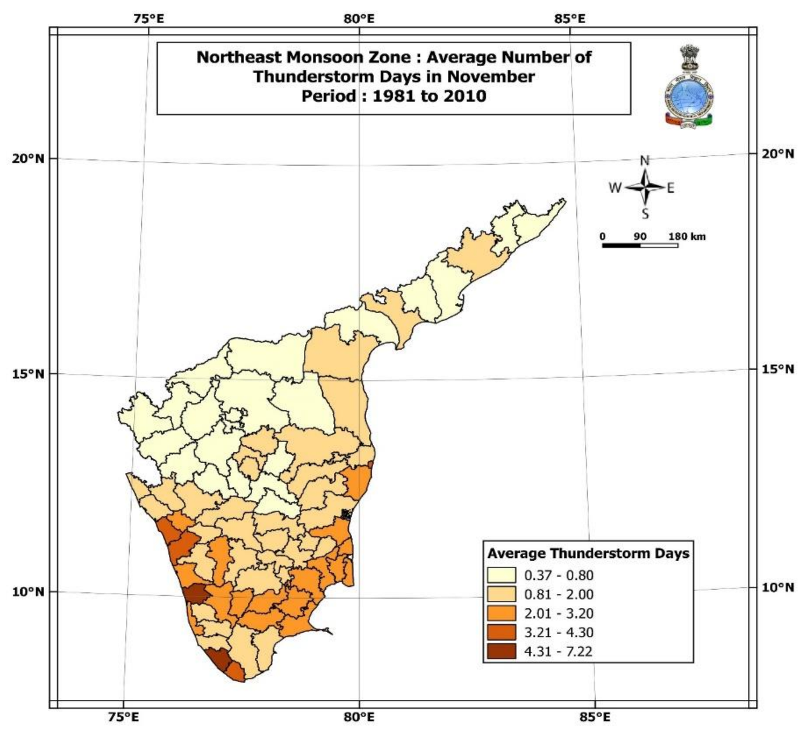

Fig. 2.14 b. Same as Fig 2.14 a, but for November.

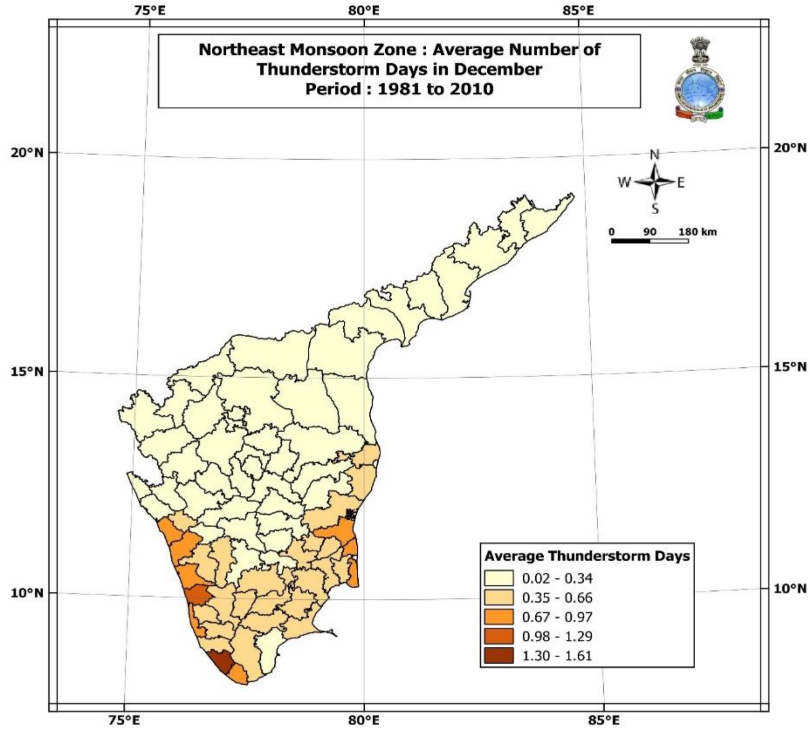

Fig. 2.14 c. Same as Fig 2.14 a, but for December.

Fig. 2.15 a, b and c show the spatial pattern of the average number of lightning flashes per sq km per day during October, November and December respectively. These plots are also taken from the IMD Climate Hazards and Vulnerability Atlas of India (2022). During October, maximum lightning activity is observed over the interior parts of Tamil Nadu and the northern parts of Kerala. During November, lightning flash activity is mostly confined to Kerala and adjoining south Tamil Nadu. During December, the lightning activity is mostly confined to Kerala. Thus, during the NE monsoon season, the state of Kerala witnesses maximum lightning activity. This could be related to proximity to the Arabian Sea, thus abundant moisture transport and orography along the west coast supporting deeper convective activity.

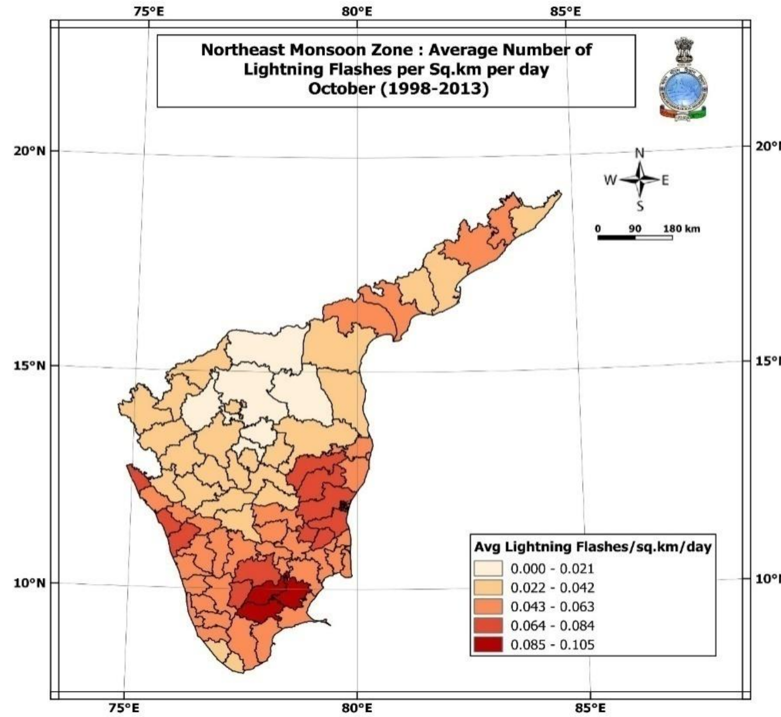

Fig. 2.15 a. Average number of Lightning flashes per sq km per day during October. (Source: IMD Climate Hazards and Vulnerability Atlas of India, 2022).

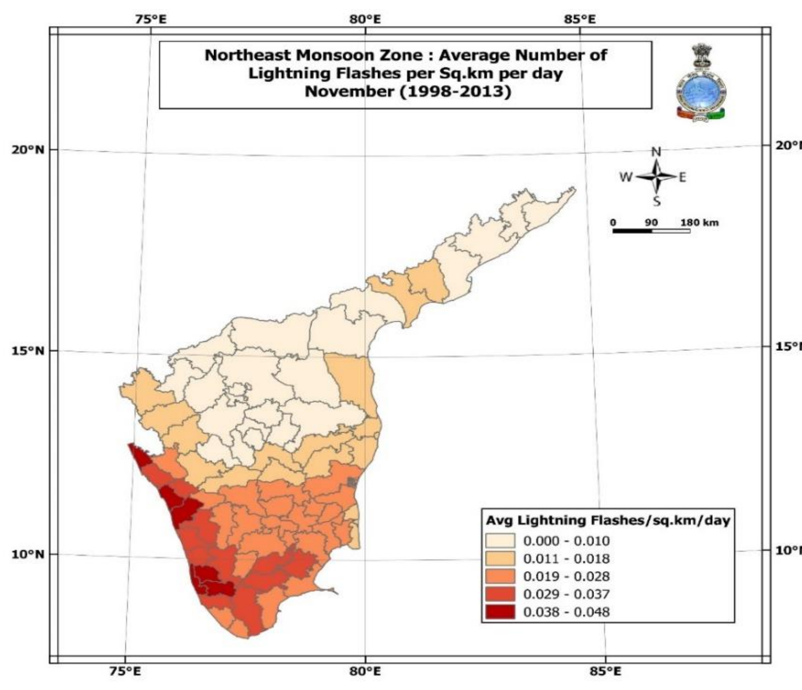

Fig. 2.15 b. Same as Fig. 2.15 a, but for November.

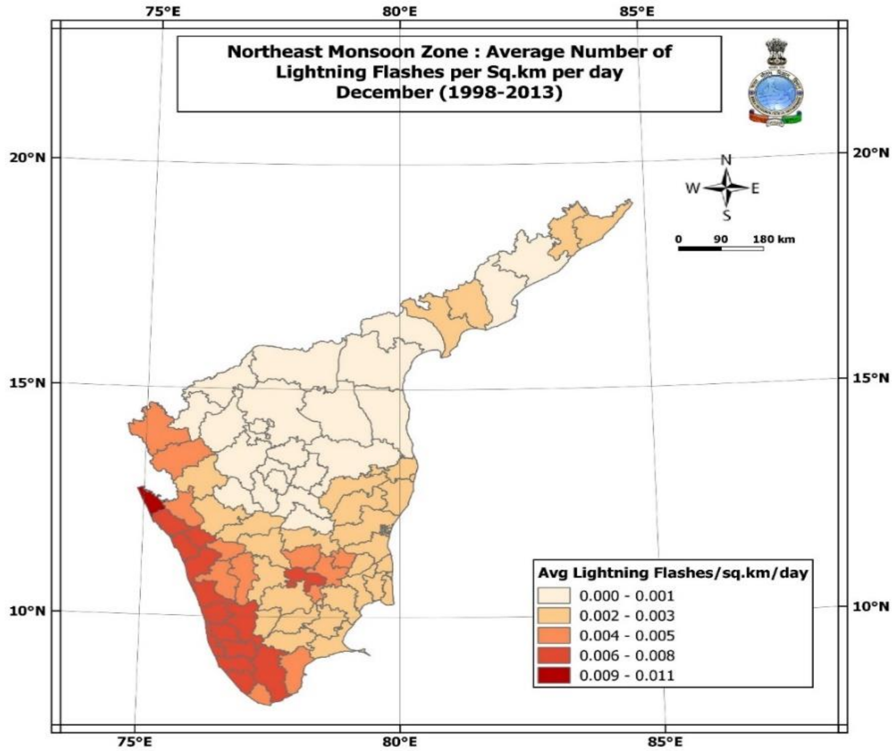

Fig. 2.15 c. Same as Fig 2.15 a, but for December.

2.9. **Extreme Wind Speed**

For providing wind speed forecasts for specific purposes to users, it is important to know the climatology of extreme wind speed during the NE Monsoon season. Fig. 2.16 a, b and c shows the spatial distribution of Extreme surface wind speed (in m/sec) in October, November and December respectively. The surface wind speed is normally measured at a height of 10.0 m. These maps are also derived from the IMD Climate Hazards and Vulnerability Atlas of India, 2022.

During October, extreme surface wind speeds exceeding 18 m/sec are observed over the north coastal Andhra Pradesh and interior parts of Tamil Nadu. Over other parts of the south Peninsula, extreme surface wind speed varies between 12 and 18 m/sec. During November, east coast of Tamil Nadu and coastal Andhra Pradesh has maximum risks due to extreme surface wind speeds. This region experiences tropical weather systems like depressions and cyclonic storms every year. Over this region, extreme surface wind speed varies between 22 and 57 m/sec. Thus, this region is very prone to extreme surface wind speed.

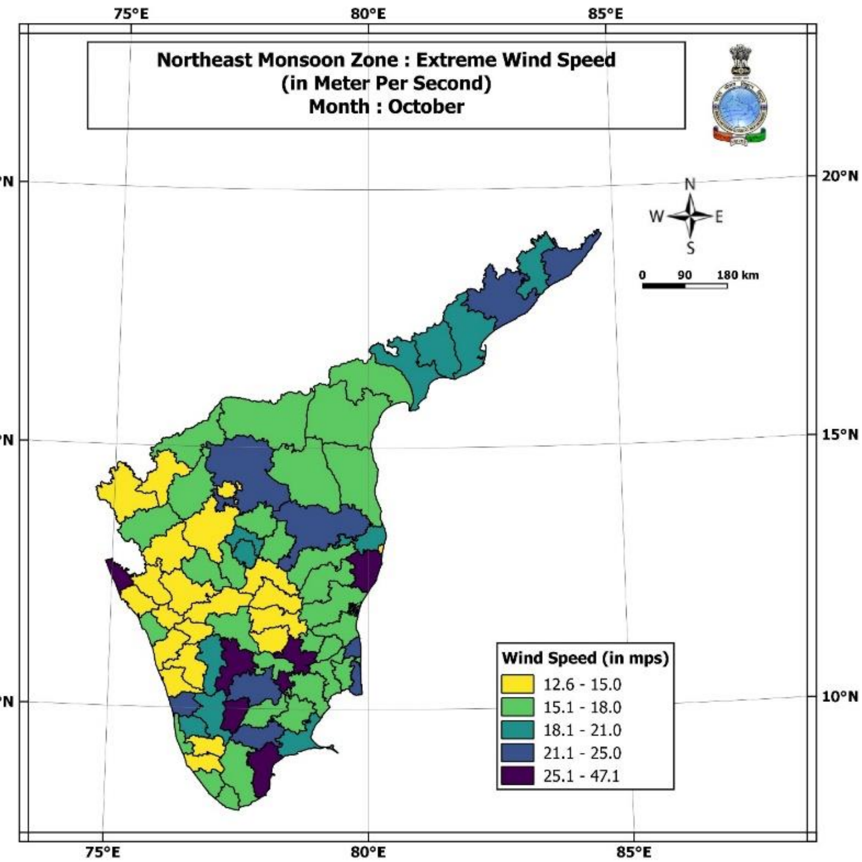

Fig. 2.16 a. Extreme Wind Speed (m/sec) during October (Source: IMD Climate Hazards and Vulnerability Atlas of India, 2022).

Extreme surface wind speed decreases sharply towards interior parts of south Peninsula. By December, northern parts of Tamil Nadu and adjoining parts of Rayalaseema experience the highest extreme wind speed. Over this region extreme surface wind speed varies between 41 and 59 m/sec. Over the southeast parts of Tamil Nadu, extreme surface wind speed varies between 31.0 and 41.0 m/sec. Over other parts of south Peninsula, extreme surface wind speed varies between 12.6 and 31.5 m/sec.

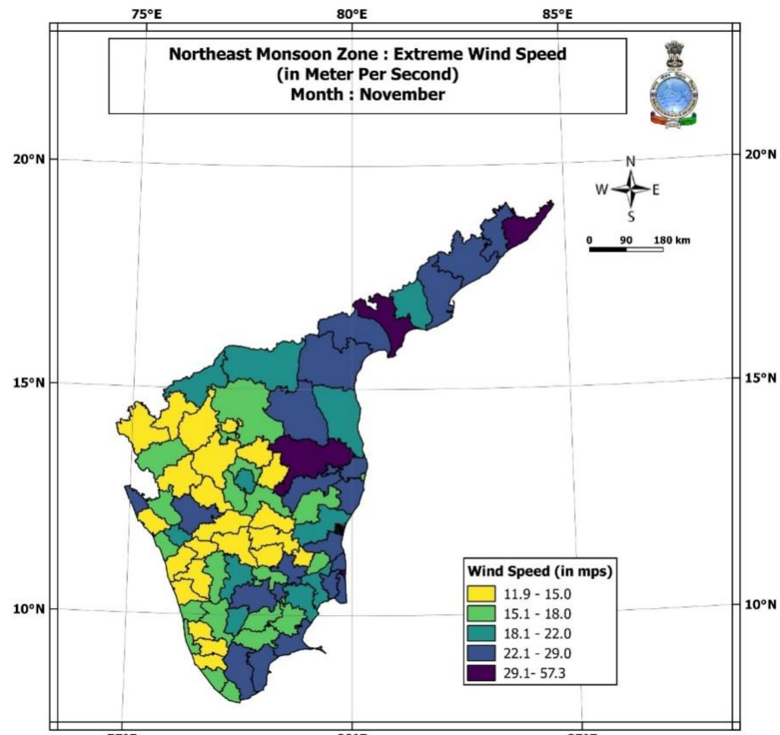

Fig. 2.16 b. Same as Fig 2.16 a, but for November.

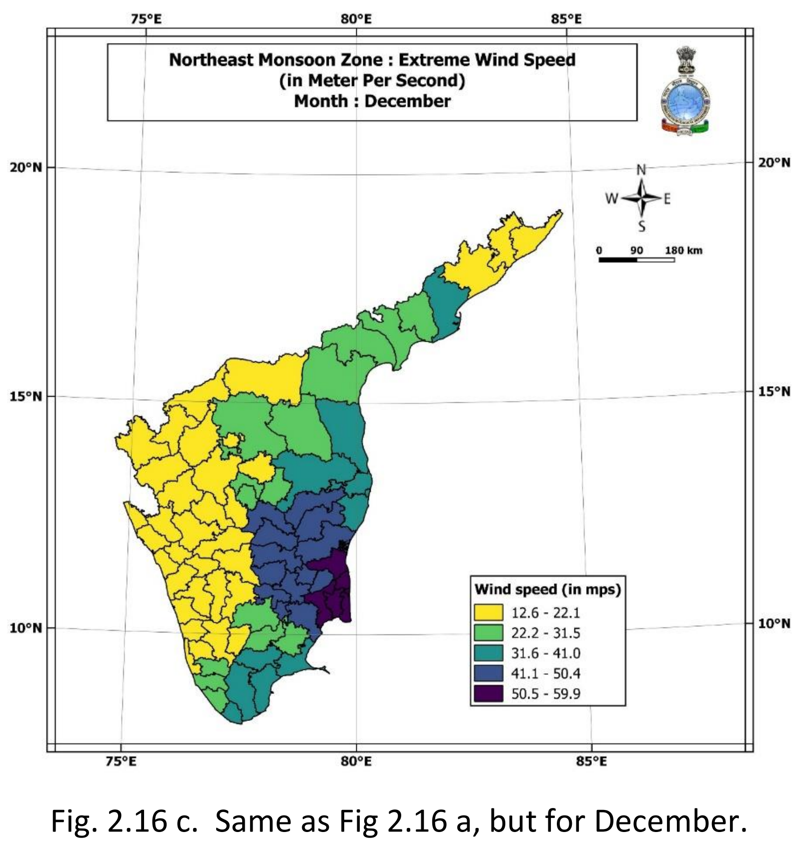

Fig. 2.16 c. Same as Fig 2.16 a, but for December.

Extreme surface wind speed observed over the eastern parts of south peninsula could be attributed to tropical cyclones making landfall over this region during the season. A detailed description of tropical cyclones including their tracks during the NE monsoon season is included in Chapter-4.