Chapter 3

General Characteristics of the Spatial and Vertical Distribution of Clouds, their Seasonal Variations and Association with General Circulation of the Atmosphere

3.1 Introduction

Clouds and their genesis play a key role in the redistribution of energy and water vapour in the earth-atmosphere system [Kiehl and Trenberth, 1997; Ringer and Shine, 1997; Moore et al., 2001; Trenberth et al., 2009]. Temperature of the Earth’s surface and the thermal structure of the atmosphere are considerably modulated by clouds through interaction with radiation and latent heat released [Ramanathan et al., 1989; Harrison et al., 1990; Rossow and Lacis, 1990; Gupta et al., 1993; McFarlane and Grabowski, 2007]. Magnitude of these effects depends on several factors, such as the horizontal and altitude distributions, geometrical thickness, optical depth, liquid/ice water content, droplet size distribution and emissivity of clouds: the first and foremost among them being the spatial and vertical distribution of clouds. Horizontal and vertical distributions of clouds as well as the cloud properties are strongly coupled to general circulation of the atmosphere, moisture convergence, and efficiency of air-surface (land/sea) interactions. Conversely, clouds play a dominant role in modulating the energy and moisture budget of the earth-atmosphere system, meteorological parameters and atmospheric general circulation through feedback processes. Genesis of clouds and the cloud feedback take place through a sequence of complex and highly
non-linear processes [e.g., Hartmann and Short, 1980; Liebmann and Hartmann, 1982; Gadgil et al., 1984; Graham and Barnett, 1987; Slingo and Slingo, 1988; Hartmann et al., 1992; Pai and Rajeevan, 1998; Wang and Rossow, 1998]. One key difficulty in modeling the radiative and climate effects of clouds is in the treatment of the complex space-time variabilities in cloudiness [Stephens, 1988; Rossow, 1989]. Further, an adequate understanding of the air-sea interaction processes requires a detailed analysis of the cloud distribution under different conditions of Sea Surface Temperature (SST) and atmospheric thermo-dynamics. Knowledge of the cloud distribution is also essential for the estimation of the actual impact of aerosols on climate.

Parameterization of the cloud generation and feedback processes are major challenges in numerical models for weather prediction and climate simulation [e.g., Bony et al., 2000]. Improvement in understanding the cloud processes essentially requires detailed studies on the spatial and vertical distribution of clouds, their properties, and variations under variety of meteorological conditions. The spatio-temporal variations in cloud distribution can also act as tracers of some of the important aspects of atmospheric dynamics and air-sea interaction [Meenu et al., 2007] that are not understood hitherto. Studies focusing on the spatial distribution of clouds, their temporal variations and impact on the atmospheric energetics over the Indian subcontinent and the surrounding oceanic areas are rather limited [e.g., Saha, 1971; Grossman and Garcia, 1990; Gambheer and Bhat, 2000; Rajeevan and Srinivasan, 2000; Roca and Ramanathan, 2000; Roca et al., 2002; Zuidema, 2003; Sathiymoorthy et al., 2004; Meenu et al., 2007, 2010, 2011; Nair et al., 2011, 2012; Rajeevan et al., 2012] compared to those over the other regions [e.g., Hanson et al., 1991; Fu et al., 1990; Klein and Hartmann, 1993; Zhang, 1993; Mapes and Houze, 1993; Norris, 1998a, b; Hall and Vonder Haar, 1999; Gettelman and Forster, 2002; Rossow and Pearl, 2007; Hong et al., 2008]. Long-term regional distribution of clouds over the Indian region has been carried out using the spaceborne imager data [Meenu et al., 2007, 2010, 2011]. Vertical distribution of the upper tropospheric semitransparent cirrus clouds and their spatial variations were also investigated earlier based on ground-based and spaceborne lidars [Sunilkumar and Parameswaran, 2005; Sunilkumar et al., 2010; Meenu et al., 2011].

While the passive radiometer imager data can provide information on the horizontal distribution of clouds and cloud top temperature (and hence an idea about the cloud top altitude), they cannot ‘see’ the clouds that are present underneath the top layer and hence cannot provide the vertical distribution of clouds. The spaceborne Lidar onboard CALIPSO can provide the vertical distribution of clouds (mainly optically thin semitransparent cirrus clouds), but cannot penetrate through thick clouds, including thick cirrus. The CloudSat can provide the vertical distribution of all optically thick clouds (except the semitransparent ones), and is the first and only such satellite to
monitor the altitude profiles of clouds around the globe as of now. Barring a few [Nair et al., 2011; Rajeevan et al., 2012], studies on the vertical distribution of clouds occurring over the entire troposphere and their spatial variations over the Indian region and the surrounding oceans are extremely sparse. Main driving force for the present study is to fill this gap. This is essential for improving the understanding on clouds, their genesis and potential impact on the atmospheric thermo-dynamics over the Indian region and the surrounding oceans which have several unique dynamical features.

Importance of the tropical clouds and their distribution over the Indian region, in particular, are discussed in Chapter 1. Main aspects of this uniqueness are:

1. The deepest convection over the entire globe occurs over the north Bay of Bengal during the Asian summer monsoon season.

2. Associated with the largest annual migration of the Inter Tropical Convergence Zone (ITCZ) and the resulting monsoons, cloudiness over the Indian region undergoes large variations in space and time.

3. Considerable spatio-temporal variations of SST and atmospheric dynamics over this region make it a natural laboratory to test some of the important hypotheses on air-sea interactions such as the SST-convection-cloudiness relationship [e.g., Gadgil et al., 1984; Graham and Barnett, 1987; Meenu et al., 2012].

General characteristics of the altitude distribution of distribution of clouds and its spatial variations over the Indian subcontinent and the surrounding oceanic regions over the geographical region from 30°S to 30°N and 30°E to 110°E derived from CloudSat data during July 2006 to February 2011 are presented in this chapter. A picture on the long-term monthly mean regional distribution of total cloudiness (all cloud types) derived using the daily data of NOAA-AVHRR during 1996 to 2010 is also presented for comparison. Association between the horizontal and vertical distribution of clouds and atmospheric general circulation is investigated using the circulation data obtained from MERRA.

The main objectives of this chapter are:

1. To provide a quantitative estimate of multi-year monthly and seasonal mean vertical distribution of clouds and its spatial variations over the Indian subcontinent and the surrounding oceans.

2. To understand the influence of atmospheric general circulation - especially the ITCZ, Hadley and Walker circulation cells - on the vertical distribution of clouds and its spatial variations.
This chapter also provides the background information on the horizontal-vertical distributions of clouds and the prevailing atmospheric circulation, which are essential for the topics investigated in the subsequent chapters.

3.2 Data and method of analysis

3.2.1 Altitude variations of the frequency of occurrence of clouds using CloudSat data

Vertical distribution of clouds and its spatial variations are obtained from the polar orbiting sun-synchronous satellite, CloudSat, having a Cloud Profiling Radar (CPR) operating at 94 GHz, which provides the altitude profiles of backscattered radar signal from hydrometeors with a vertical resolution of 240 m along the sub-satellite track [Haynes and Stephens, 2007]. Details of the CloudSat data are provided in Chapter 2. This study utilizes the cloud geometrical profile product, 2B-GEOPROF (Version-4) provided by NASA, which gives the cloud mask containing the information on cloud layers and their top and base altitudes for the individual profiles along the satellite orbit [Mace et al., 2007]. The vertical resolution of the cloud mask is 240 m and the horizontal resolution (along track) is 1.7 km. This provides the vertical distribution of clouds only along the sub-satellite track. Note that the repetivity of CloudSat orbits is 16 days and the individual orbits are separated longitudinally by $\sim 1.6^\circ$ at the equator (Chapter 2). This is one of the major limitations of CloudSat compared to the conventional imager data (e.g., NOAA-AVHRR) wherein the across-the-track scan with a large swath ($\sim 2600$ km) ensures that each geographical location is observed everyday. In the case of CloudSat, the same region (located along the well-defined orbital tracks) will be observed twice during the 16-day period: one during daytime and the other during night. Due to this limitation in the frequency of observation, the data are analyzed here to study the latitude and longitude variations of the vertical distribution of clouds at different longitude and latitude bands of sufficiently large width (typically $10^\circ$).

Operating wavelength of the Cloud Profiling Radar (CPR) onboard the CloudSat is 3.19 mm. As the typical size range of cloud droplets (8 to 100 µm) is substantially smaller than the CPR wavelength, the signal detected by CPR from clouds arises mainly from Rayleigh scattering. It is found that the CPR mainly detects optically thick clouds, which produce sufficiently strong Rayleigh lidar signals. The signal from optically thin clouds (mainly the semitransparent cirrus clouds) will be considerably weak and are not detectable using CloudSat. Though the lower boundary (in terms of cloud optical depth) of CloudSat detection is not well-defined, an inter-comparison
between CloudSat and CALIPSO observations indicate that the clouds having optical
depth less than 1.0 are mostly not detected by CloudSat. The reliability of cloud
detection by CloudSat increases with cloud optical depth (COD). For optically thick
clouds (COD > 1.0), the accuracy of cloud detection using CloudSat is more than 90%
in addition to the COD, physically thin clouds especially those with thickness < 240 m
also contributes to the uncertainty of ∼10% [Mace, 2007]. Hence, the present study
using CloudSat data mainly shows the vertical distribution of optically thick clouds
and not the semitransparent cirrus clouds. However, as demonstrated by the results
presented in the following sections, the CloudSat can detect thick cirrus clouds, most
of which originate from deep convective anvils.

The CloudSat data are used to estimate the monthly and seasonal mean altitude
profiles of the frequency of occurrence of clouds and their zonal and meridional dis-
tributions during the June to September period of 2006 to 2010. For each individual
satellite track, the 2B-GEOPROF data provide the base and top altitudes of the cloud
layer for up to 5 cloud layers as a function of profile number. This data also provides
the latitude and longitude of the footprint corresponding to each profile. The individ-
ual profiles are separated by 1.7 km. The monthly mean latitude-altitude cross section
of the frequency of occurrence of clouds for a given longitude band (of 10° width) is
determined as described below:

1. For each individual profile, all the altitude bins (of 240 m vertical resolution) that
occur between the base and top of the cloud layer (as given by 2B-GEOPROF
data) are filled with a value of 1 to identify the presence of cloud; all other altitude
bins are filled with zeros. This provides a two-dimensional matrix (as a function
of profile number and altitude) of cloud occurrence for the given track.

2. The above matrix of cloud occurrence for all satellite orbits, that occur within
this given longitude band of 10° width (say, between 60 to 70°E) during a month
(say, January 2007), are averaged and gridded into a uniform latitude-altitude
matrix having cell sizes of 0.1° (latitude) and 240 m (altitude). This is obtained
by summing all the observations occurring within each latitude grid (of 0.1° size)
and altitude bin (240 m size) and dividing by the total number of observations
within each latitude grid (the number of observations at all altitude bins within
a latitude grid is the same). This provides the monthly mean latitude-altitude
cross section of the frequency of clouds within the given longitude band. As the
polar orbiting CloudSat provides data at very fine spatial intervals long its track
(somewhat aligned along the longitude circle), the latitude grid size of 0.1° is
used in this study. However, it is important to note that, though the estimates
are carried out at fine latitude grid size of 0.1°, this analysis can provide only the
longitudinally averaged gross features of cloud distribution during each month.
Very small scale features (spanning for, say, less than few degrees) cannot be discerned using this analysis. However, reducing the longitudinal band width is also not advisable as the number of satellite orbits for small longitude bands are highly limited.

3. The multi-year (2006 to 2011) monthly and seasonal mean latitude-altitude cross sections of the frequency of occurrence of clouds are determined by averaging the corresponding frequency of occurrence of clouds observed during individual years.

The longitude-altitude cross sections of the frequency of occurrence of clouds within a given latitude band of 10° width (say, between 10° to 20°N) are estimated following the same method as explained above, but for a longitude grid size of 2°. The coarser longitude grid size of 2° is used here as the individual tracks of the Polar orbiting CloudSat satellite within the 16-day orbit cycle are distinctly separated in longitude.

3.2.2 Spatial distribution of the frequency of occurrence of total cloudiness using NOAA-AVHRR data

As explained earlier, the frequency of observation of a given location using CloudSat are limited. Observations using NOAA-AVHRR can provide the information on cloud occurrence at high spatial resolution (4 km at nadir) on a daily basis and has been extensively used to study the regional distribution of clouds over the Indian region [Meenu et al., 2007, 2010, 2012; Meenu, 2010]. The main advantage of this data is its high spatial resolution and availability over a long duration. However, it cannot provide the vertical distribution of clouds as the IR and visible radiation detected by the passive sensors onboard AVHRR mainly originate from top of the cloud or surface layer. Further, the cloud discrimination using NOAA-AVHRR data on brightness temperature might underestimate the low-altitude clouds (especially when the cloud top temperature is comparable to the surface temperature). In the present study, the features observed using multi-year observations of the vertical and spatial distribution of clouds derived from CloudSat data are compared with those observed using the long-term (1996 to 2010) monthly and seasonal mean frequency of occurrence of total clouds derived using NOAA-14/16/18-AVHRR. While the former provides the vertical distribution clouds and their zonal and meridional variations, the latter provides the spatial distribution of total cloudiness with high spatial resolution which is not vertically resolved.

Daily data obtained from the polar orbiting NOAA-14/16/18-AVHRR (equatorial crossing time: approx. 01:30 PM/AM) during the period of 1996 to 2009 over the Indian region and surrounding oceans (30°S to 30°N and 40°E to 105°E) are used in
this analysis. The Global Area Coverage (GAC) data used here has a pixel resolution of 4 km at nadir. The occurrence of clouds in a pixel is identified using the methods explained in Chapter 2 and is same as that followed in Meenu et al. [2010, 2012] and Meenu [2010]. The pixel-wise cloud amount derived from each satellite pass is composited for each day and transformed into a uniform geographical grid of size $0.2^\circ \times 0.2^\circ$ to derive the frequency of occurrence of clouds. The monthly mean frequency of occurrence of clouds in each grid is obtained by averaging the observed daily mean fractional cloud amount in that grid in the respective month.

Role of atmospheric circulation on the vertical and horizontal distribution of clouds is investigated using the atmospheric circulation data obtained from MERRA. This is one among the most extensively used datasets for understanding the atmospheric circulation features. The MERRA data provides the atmospheric wind and temperature with a horizontal resolution of $1^\circ$ at 42 vertical levels. Monthly mean spatial distributions of SST are examined using the TRMM Microwave Imager (TMI). The TMI-SST is based on observations of TMI at 10.7 GHz which are nearly transparent to clouds. This data is advantageous over the infrared SST observations that require a cloud-free field of view. The TMI-SST provides daily observations covering the global region extending from $40^\circ S$ to $40^\circ N$ at a pixel resolution of $0.25^\circ$. Comparison of the TMI-SST with in situ observations using buoys shows that, on average, the former is accurate to better than $0.5^\circ C$ [Reynolds et al., 2010].

### 3.3 Monthly mean features of atmospheric circulation and SST

Gross features of the monthly mean atmospheric circulation and SST, which are closely linked to the cloud distribution, are briefly presented in this section.

#### 3.3.1 Atmospheric circulation

Figure 3.1 shows the monthly mean horizontal winds at the isobaric level of 950 hPa prevailing over the study region (2006 to 2011). During January, the Hadley circulation is manifested by the convergence of lower-tropospheric airmass from the northern hemisphere and southern hemisphere at the south of the equator: typically between $10^\circ S$ to $5^\circ S$ over the west and central equatorial region and near the equator over the equatorial Indian Ocean. This is the Inter-Tropical Convergence Zone (ITCZ: the rising limb of Hadley cell), which has a small north-south tilt over the Indian Ocean region during this month. The high-pressure area, manifested by the anticyclonic circulation centered on the central Indian region and Arabia represents the descending limb of Hadley cell in the northern hemisphere. The lower tropospheric winds during
this month are predominantly northerly (northeasterly/northwesterly) from the continental regions into the Arabian Sea, the Bay of Bengal and the tropical Indian Ocean. A similar anticyclonic system prevails around 30°S in the southern hemispheric Indian Ocean, which represents the descending limb of Hadley cell in the southern hemisphere during January. Largest wind speeds are observed at the south Indian Ocean (between 15°S to 25°S) and western parts of the equatorial Indian Ocean and the Arabian Sea. Convergence of air is largest over the east equatorial Indian Ocean and least over the west. This east-west asymmetry is due to the Walker circulation cell. The general circulation features during the other months of winter (December to February) are more or less similar.

General circulation of the atmosphere during the pre-monsoon season (March to May) is characterized by the transition from the winter pattern to the summer monsoon pattern. Overall characteristics of the Hadley and Walker cells, including the locations of their ascending (ITCZ) and descending limbs during March are more or less similar to that during February. In April, the ITCZ over the west and central Indian Ocean migrates towards the north and the region of lower tropospheric convergence over the equatorial Indian Ocean is rather broad. The descending limb of Hadley cell in the northern hemisphere during April is located over the north Arabian Sea and central India. The lower tropospheric winds are strongly diverging near the western equatorial Indian Ocean (indicating strengthening of the descending limb of the Walker cell over this region), while the convergence associated with the Walker circulation prevails over the east equatorial Indian Ocean. By May, the anticyclonic vortex over the Indian subcontinent is replaced by a low pressure area, resulting in the trough regions observed in the central and north-western parts of the Indian subcontinent. The prevailing lower tropospheric winds in the northern hemisphere change from northerlies to southerlies/westerlies/southwesterlies over the Arabian Sea, the equatorial Indian Ocean, and the Bay of Bengal. Though the high-pressure area over the southern hemispheric Indian Ocean prevails during March to May, its location is slightly shifted towards the north during May.

Most important features of the atmospheric circulation during the Asian summer monsoon season (June to September) are the occurrence of a persistent low-pressure system (Heat Low; mean sea level pressure <999 hPa) over the north-western parts of the Indian subcontinent, the monsoon trough generally extending from the Heat Low to the north Bay of Bengal, the high-pressure zone over the Tibetan plateau (Tibetan High, at ~600 hPa level), the low-level jet (LLJ) extending from the west Arabian Sea to the Peninsular India, the equatorial trough over the equatorial Indian Ocean, the subtropical high-pressure area over the southern hemispheric Indian Ocean (Mascarenes High: mean sea level pressure >1023 hPa), and the tropical easterly jet stream (TEJ)
Figure 3.1: Monthly mean horizontal winds at 950 hPa level obtained from MERRA data during 2006 to 2011.

in the upper troposphere [e.g., Das, 1968; Rao, 1976]. On average, latitude gradient of the mean sea level pressure is >4.8 hPa/10° between the Mascarenes High and Heat Low, which is the primary driving force for the massive monsoon circulation from the southern hemispheric Indian Ocean to the Indian subcontinent. The convergence zones at the monsoon trough and the equatorial trough regions and the anticyclonic circulation at the Mascarenes High are well discernible in Figure 3.1. The anticyclonic
circulation over the Mascarenes High is the seat of the strong descending limb of the Hadley cell and closes the circulation loop by the strong ascending of airmass at the Monsoon Trough and the equatorial trough regions and upper tropospheric flow towards the south. The availability of lower tropospheric vorticity available at the north Bay of Bengal (associated with the extension of the Monsoon trough up to this region) is conducive for the generation of monsoon depressions over this area. On average, wind speeds are largest over the western Arabian Sea and the Bay of Bengal. Orographic lifting of this high velocity air current (which appear as bursts, producing breaks and active precipitation over the region) over the western parts of the Indian subcontinent by the Western Ghats and over the northern and eastern boundaries of the Bay of Bengal are evident in Figure 3.1 as a rather abrupt reduction in horizontal wind in the upwind direction. This causes convection over the east Arabian Sea and the north and northeast Bay of Bengal. Horizontal winds over the western Arabian Sea (Figure 3.1) as well as the Arabian region have significant divergence at the lower tropospheric level. In general, the lower-tropospheric circulation is similar during June to September. However, strength of the summer monsoon circulation gets diminished during September, especially in the northern parts of the Indian subcontinent.

By October, anticyclonic circulation prevails over the central and northern parts of the Indian subcontinent and Arabia, which manifests the descending limb of the Hadley cell. Under its influence, the lower-tropospheric circulation over the northern and central parts of the Indian subcontinent and the Arabian Sea turns to northerly. A strong cyclonic vorticity appears at the south peninsular India. The ITCZ, as seen from the extended cyclonic circulation patterns in Figure 3.1, is very broad and straddles on either side of the equator between \(\sim 10^\circ S\) to \(\sim 15^\circ N\). The descending branch of the Hadley cell over the southern hemispheric Indian Ocean is located at south of \(\sim 15^\circ S\) where the lower tropospheric wind is anticyclonic. Associated with the Walker cell, an anticyclonic circulation (descending limb) appears over western parts of the equatorial Indian Ocean while the eastern equatorial Indian Ocean is manifested by the strong ascending limb with cyclonic vortex. By November, the anticyclonic circulation over the northern hemispheric continents strengthens (including over most parts of the Peninsular India), resulting in the equatorward movement of the ITCZ in the northern hemisphere. The cyclonic circulation at just south of the equator (part of ITCZ) and the location of the descending limb of Hadley cell at the southern hemispheric Indian Ocean observed during October continue to prevail during November as well. Interestingly, the ITCZ during this month has a tendency to appear as two independent bands on either side of the equator, producing a double-ITCZ feature [Saha, 1972; Meenu et al., 2007; RameshKumar et al., 2012].
3.3.2 Spatial variations of SST

The spatial distribution of clouds are also strongly influenced by the SST [Gadgil et al., 1984; Graham and Barnett, 1987; Waliser and Graham, 1993; Fu et al., 1990, 1994; Joseph and Sabin, 2008; Meenu et al., 2012]. Further, the absolute magnitude and spatial gradient of SST significantly influence the atmospheric circulation and convection. Figure 3.2 shows the monthly mean spatial distribution of SST over the Arabian Sea, the Bay of Bengal and the tropical Indian Ocean. Throughout the year, the warmest SSTs are observed over the equatorial region. The SST over this region increases from January to April-May. The largest SST (∼30.5°C) over the study region is observed over the central Arabian Sea and the equatorial Indian Ocean (called the ‘Warm Pool’) around 53 to 70°E and 0 to 10°N during April-May; such warm pockets with SST>30°C are also observed at the south Bay of Bengal and the east equatorial Indian Ocean during these months. A reduction of SST (by ∼1°C) occurs over most regions during the summer monsoon season, especially from July to September; the warmest SSTs (SST>29°C) during this season are observed near the equator. However, most of the areas of the east Arabian Sea, the equatorial Indian Ocean and the Bay of Bengal have SST>28.5°C during this season. The SST further reduces during October to January, when most of the regions have SST<29°C). In general, the SSTs are the least at the south Indian Ocean, especially at south of ∼15°S to 20°S during all seasons. The SSTs are typically <26°C over this region. Low SSTs (SST<27°C) are also observed at the north Arabian Sea during winter and early part of pre-monsoon seasons.

3.4 Spatial distribution of clouds derived from NOAA-AVHRR

Figure 3.3 shows the monthly mean spatial distribution of the frequency of occurrence of clouds (F_C) derived from NOAA-AVHRR data over the study region, averaged during 1996 to 2010. This figure is mainly shown here to discern the gross features of the spatial distribution of clouds over the study region based on long-term data (1996 to 2010). Together with the features of atmospheric circulation described in the earlier section, the cloud distribution presented in Figure 3.3 shows the following major features.

During January to February, the ITCZ is manifested in Figure 3.3 as an east-west oriented band of large cloudiness with F_C>70% at the centre of the band, which decreases to <50% within 10° on either side of the ITCZ. The slight north-south tilt of the ITCZ observed in the atmospheric convergence is clearly manifested in the cloud distribution as well. The total width of this band of large cloudiness is about 20°. The
cloudiness undergoes remarkable latitude variations across the northern and southern boundaries of this cloud band, with substantially less cloud occurrence (<20%) at the regions where the descending limbs of the Hadley cell are located in the northern (centered over Central India and the Arabian Sea) and southern hemispheres (south Indian Ocean at south of 20°S). The ascending branch of the Walker cell at the east
equatorial Indian Ocean is manifested by larger cloudiness (F_C ∼80%) while the western equatorial Indian Ocean (descending branch of the Walker Cell) has substantially smaller cloudiness. A zone of large cloudiness (F_C ∼80%) is observed at the southwestern Indian Ocean near Madagascar in January and February. This region has warm SST (>29°C) and has a large cyclonic vortex (associated with the ITCZ), leading to convection and large-scale cloudiness.

Overall, the spatial distribution of cloudiness during March is similar to that during January-February, especially with respect to the locations of the enhanced cloudiness associated with the ITCZ and the descending limbs of the Hadley and Walker cells. However, the cloud amount shows an overall reduction in March, especially over the western Indian Ocean. Compared to March, the latitudinal width of the band of enhanced cloudiness associated with the ITCZ broadens further in the central and eastern equatorial Indian Ocean during April. Despite the warm SSTs (SST>30°C) over the western equatorial Indian Ocean, the cloudiness in this region is substantially reduced to <40% in April. This is associated with the strengthening of the descending limb of the Walker cell over this region. The cloudiness over the north-eastern parts of the Indian subcontinent increases from March to April. Cloudiness over the Bay of Bengal as well as the northern parts of the Indian subcontinent increases to 40 to 80% in May, and is associated with the corresponding increase in lower tropospheric convergence (Figure 3.3). Further, the eastern branch of the summer monsoon current (originating from the Australian region) appears in the Bay of Bengal during May [e.g., Singh and Salvekar, 2004]. An increase in cloudiness (F_C ∼60%) is also observed at the southeast Arabian Sea in May and is caused by an enhancement in the westerly wind from the warm Arabian Sea region. The descending limb of Hadley cell in the southern hemisphere Indian Ocean as well as in the northern parts of the Indian subcontinent and Arabia have cloudiness <20% during all months of the pre-monsoon season.

In general, the horizontal distributions of cloudiness over the study region during June to September are similar, with substantially large cloudiness over the east Arabian Sea, Indian subcontinent, the Bay of Bengal and the equatorial Indian Ocean. Largest cloudiness during this season is observed over the north and east Bay of Bengal (F_C of 80 to 100%), with most intense cloudiness during July to August. This is among the most intense deep convective regions in the world [e.g., Newell and Gould-Stewart, 1981; Meenu et al., 2010; Meenu, 2010]. The large spatial gradient of F_C across the coastal regions at the north and east Bay of Bengal are particularly notable and are significantly contributed by the orographic lifting, in addition to the favourable conditions prevailing over the Bay of Bengal for convection and moisture convergence during this season. Cloudiness over the east Arabian Sea also enhances (F_C >70%) during the summer monsoon season. The high wind speed associated with the LLJ and the
orographic lifting of this moist airmass over the Arabian Sea at west of the Western Ghats (Figure 3.1) contribute to this enhanced cloudiness. The large cloudiness along an east-west oriented band between the equator and $\sim 7^\circ$S is caused by the equatorial trough [Meenu, 2010; Meenu et al., 2010]. Minimum cloudiness over the entire region occurs at the Mascarenes High over the south Indian Ocean, the west equatorial Indian Ocean, the west Arabian Sea, and Arabia where the values of $F_C$ are usually less than 20%. All these regions are manifested by strong subsidence associated with the prevailing tropical circulation cells. Reduction in cloudiness between the southern boundary of the equatorial trough and the Mascarenes High is remarkably sharp. One important feature of the cloud distribution during the summer monsoon season is the appearance of a region of distinctly small cloudiness over the southwest Bay of Bengal near Sri Lanka, which is surrounded by large scale cloudiness on all sides. The characteristics and genesis of this ‘pool of inhibited cloudiness’ are presented in detail in Chapter 4.

Associated with placement of the descending limb of Hadley cell over the northern parts of the Indian subcontinent in October, the frequency of occurrence of clouds over this region decreases considerably ($F_C < 30\%$). The broad ITCZ and the cyclonic
vortex over the Peninsular India results in considerable cloudiness \((F_C > 50\%)\) over the south Peninsular India and the central and eastern equatorial Indian Ocean. The most remarkable feature observed in October is the strengthening of the Walker cell, with large cloudiness \((\sim 80\%)\) over the eastern equatorial Indian Ocean and substantially reduced cloudiness \((< 20\%)\) over the western part. Cloudiness at the southern hemispheric descending limb of Hadley cell is also \(< 20\%\). Overall, the spatial distribution of cloudiness during October is similar to that in April. One of the most remarkable features observed in November is the double-ITCZ structure around the equator. This feature is more prominent in the 50°E to 85°E longitude region \([Meenu et al., 2007]\). The northern band is centered at \(\sim 5^\circ\)N, while the southern band is centered at \(\sim 7^\circ\)S. The double band structure of the ITCZ during November is clearly discernible in the atmospheric circulation also (Figure 3.1). In December, cloudiness increases considerably over the western part of the south Indian Ocean and Madagascar, due to the influence of the prevailing cyclonic circulation over the west of Madagascar. The double-band structure of ITCZ is discernible during December as well.

### 3.5 Vertical and horizontal distributions of clouds derived from CloudSat and their association with atmospheric circulation

Altitude distribution of clouds and their spatial variations observed using CloudSat data are presented in this section. Vertical cross sections of the frequency of occurrence of clouds \((F_{ALT})\) averaged along different longitude and latitude bands are presented to obtain a 3-dimensional distribution of the monthly and seasonal mean cloud distribution. Notwithstanding the uniqueness of the CloudSat data in terms of the high-resolution observations of the vertical distribution of clouds at very small fine spatial scales along the satellite track, these observations are limited to the sub-satellite track for a 16-day orbit cycle, as explained in Section 3.2. Due to this limitation, the latitude-altitude cross sections of \(F_{ALT}\) are averaged for different longitude bands of 10° width. Similarly, the longitude-altitude cross sections are presented for latitude bands of 10° width. As seen in Figure 3.3, all major features of cloud distributions have sufficiently large spatial scales to be detected in the present analysis. Structures having very fine spatial scales (of the order of a couple of degrees) may not be detectable in this analysis and are not examined in detail.
3.5.1 Winter season

3.5.1.1 Altitude-latitude cross sections of cloud distribution and atmospheric circulation

The latitude-altitude cross sections of the multi-year (2006 to 2011) seasonal mean $F_{ALT}$ during the winter season (December to February) for different longitude bands (30 to 40°E, 40 to 50°E, ..., 100 to 110°E) are depicted in Figure 3.4. The corresponding monthly mean pictures are shown in Figure 3.5. Overall, the features observed in the vertical distribution of $F_{ALT}$ during the individual months are similar to the seasonal mean pattern. The vertical distribution of clouds and its spatial variations are well in agreement with the mean spatial distribution of total cloudiness observed using AVHRR data (Figure 3.3). As seen from the lower tropospheric circulation (Figure 3.1) and AVHRR-observations of cloud occurrence (Figure 3.3), the ITCZ is located around the equator and south of it during this season. CloudSat observations show that the vertical distribution of clouds over the ITCZ is marked by large values of $F_{ALT}$ at all altitudes in the troposphere below ~14 km. The small northward tilting of the ITCZ from the west Indian Ocean to the east is clearly discernible in the vertical distribution of clouds shown in Figures 3.4 and 3.5. Compared to December, this feature is more prominent during January-February. The amount of cloudiness as well as the strength of the ITCZ (as inferred from the values of $F_{ALT}$ and its vertical distribution) varies considerably at different longitudes. Strength of the ITCZ is largest over the eastern equatorial Indian Ocean (especially at the east of 90°E) and consistently decreases towards the west upto 50 to 60°E. This feature is more prominent during December. The east-west asymmetry in the strength of the ITCZ is caused by the Walker circulation, with the ascending limb over the east equatorial Indian Ocean and the descending limb over the west.

The cloudiness in the middle and upper troposphere in the deep convective regions generally increases with altitude to attain the peak occurrence around 9 to 13 km. This is because of the occurrence of thick cirrus clouds, whose probability of occurrence increases with altitude at least up to 12 km. Most of these clouds might have been formed from the outflow of deep convective clouds as anvils or might be the remnants of deep convective clouds after precipitation. The cirrus clouds are non-precipitating and have large atmospheric residence time (of several hours to 2 days) compared to the low- and middle-level clouds (few minutes to few hours). The enhanced cloudiness observed in the upper troposphere (typically between 9 to 13 km altitude) which spread to either side of the ITCZ is the result of the strong outflow from the deep convective clouds at the ITCZ. Figures 3.4 and 3.5 clearly shows that the meridional winds associated with the Hadley cell carries the outflow to considerably large distances (~10 to 20° latitude).
from the ITCZ. This aspect is further examined using the meridional cross sections of the Hadley cell inferred using MERRA data.

Figure 3.6 shows the meridional circulation averaged in the longitude bands of 50 to 60°E, 70 to 80°E and 90 to 100°E, indicated by the vector plots of the meridional and vertical winds as a function of altitude and latitude. As the magnitudes of vertical winds are very small compared to the horizontal winds, the former are multiplied by 50 while plotting, for clearly representing the circulation pattern. Figure 3.6 reveals that the ITCZ (marked by horizontal wind convergence and large updraft) is indeed strongest over the east equatorial Indian Ocean where strong convection extends up to ~150 hPa level (~14 km) in the latitude band confined between ~10°S and ~8°N. In the longitude band of 90 to 100°E, the largest vertical winds are observed between 600 hPa and 250 hPa levels, above which the meridional outflow becomes prominent. Strength of the sinking branch of the Hadley cell as well as the meridional outflow from the ITCZ in the upper troposphere in this longitude sector is more prominent in the northern hemisphere compared to the southern hemisphere. Though the downdraft associated with the Hadley cell is observed at the north and south of the ITCZ, the core of the sinking branches are located at south of 25°S in the southern hemisphere and 20 to 30°N in the northern hemisphere. Meridional cross section of the vertical distribution of clouds is in agreement with this meridional circulation. Largest vertical development of clouds occurs between 10°S and 5°N, where the cloudiness is quite large up to ~14 km altitude. The upper tropospheric cloudiness associated with the outflow from the ITCZ is larger in the northern hemisphere where the cloudiness associated with the outflow is significant at least up to 8° away from the northern boundary of the convective core. A careful examination of the meridional cross-section of cloudiness suggests that the clouds originating from deep convective outflow from the ITCZ extend up to the core of the descending limb of Hadley cell, though the overall cloudiness is quite small. The cloudiness is considerably weak at the descending branches, with the least values observed in the middle and upper troposphere in the sinking core region indicated by the meridional circulation. It is important to note that the latitudinal width of the ITCZ inferred from the meridional circulation as well as the vertical distribution of clouds (~15°) are in agreement, while the width of the large-scale cloudiness in the ITCZ region observed using AVHRRR data (Figure 3.3) are significantly larger (>20°). This is primarily because of the optically thick cirrus clouds caused by the outflows from the ITCZ which could not be discriminated in the observations using passive radiometer (AVHRR) data.

As seen in Figure 3.6, strength of the Hadley cell (including the convection at the ITCZ and the meridional circulation) weakens towards the west. Except for this, the gross features of the Hadley cell over the central Indian Ocean region (70 to 80°E
Figure 3.4: Multi-year (2006 to 2011) seasonal mean latitude-altitude cross sections of the frequency of occurrence of clouds averaged for different longitude bands of 10° width (30 to 40°E, 40 to 50°E, ..., 100 to 110°E) over the Indian subcontinent and the surrounding oceanic regions during winter (DJF).
Figure 3.5: Multi-year (2006 to 2011) monthly mean latitude-altitude cross sections of the frequency of occurrence of clouds averaged for different longitude bands of 10° width (30 to 40°E, 50 to 50°E, ..., 100 to 110°E) over the Indian subcontinent and the surrounding oceanic regions during December, January and February.
longitudinal band) are somewhat similar to those over the east equatorial Indian Ocean (90 to 100°E). The convection associated with the ITCZ in the longitude band of 70 to 80°E mainly occurs in the latitude band of 13°S to 5°N, with the maximum convection centered about 10°S to 5°S (Figure 3.6). This convection is limited to <200 hPa level and the outflow is quite significant above 300 hPa level. Core of the descending branches of the Hadley cell are located at 15 to 25°N in the northern hemisphere and 20 to 25°S in the southern hemisphere, with downdraft occurring at poleward of the northern
and southern boundaries of the ITCZ. Meridional cross section of cloudiness in this longitude band (Figures 3.4 and 3.5) is in agreement with the meridional circulation discussed above. The largest vertical development of clouds occurs between 12°S and 5°S, which extends up to ~13 km. The overall cloudiness in this region is significantly lesser than that over the east equatorial Indian Ocean. As the separation between the ITCZ and core of the sinking cell is larger in the northern hemisphere compared to the southern hemisphere, the outflow also extends to larger distance (at least 10° from the northern boundary of the ITCZ) in the former region. Though quite small, the cloudiness associated with this outflow extends up to core of the descending limb of the Hadley cell. Cloudiness caused by the outflow from the ITCZ is weaker in the southern hemisphere. Cloudiness at the descending branches of the Hadley cell is considerably smaller, with the least values observed in the middle and upper troposphere in the core region.

Figure 3.6 shows that the Hadley circulation cell is quite weak over the east Arabian Sea. In the longitude band of 50 to 60°E, convection associated with the ITCZ is substantially weak both in terms of spatial extent of the convection and magnitude of the updraft in this region. Updraft is observed between 15°S to 5°S with the largest vertical winds between 7°S to 5°S. The updraft is prominent below ~250 hPa level and ceases above 200 hPa level. The downdraft associated with descending branch is significant only in the northern hemisphere (with core between 15°N to 25°N) while it is feeble in the southern hemisphere where significant descending is not seen up to 30°S. Vertical distributions of F_{ALT} (Figures 3.4 and 3.5) are in agreement with the above dynamical features. Associated with the descending limb of Walker cell, substantially reduced cloudiness is observed in this longitude band. Relatively larger cloudiness is observed between 15°S to 5°S, which is the mean location of the ITCZ. As the ITCZ is very weak, cloudiness in the mid-troposphere is distinctly small in this region compared to the ITCZ in the central and east equatorial Indian Ocean. Cloudiness is negligible at the descending branch of the Hadley cell in the northern hemisphere. On the contrary, the reduction in cloudiness towards the south of the ITCZ is rather insignificant as the downdraft in the southern hemisphere in this longitude sector is very weak.

### 3.5.1.2 Persistent occurrence of low altitude clouds over the South Indian Ocean

One of the most remarkable features observed in Figures 3.4 and 3.5 is the persistent occurrence of low altitude clouds below 3 km at the descending limb of the Hadley circulation over the southern hemispheric Indian Ocean. They are present throughout the southern hemisphere Indian Ocean, right up to the ITCZ. In contrast, a similar feature is almost completely absent in the northern hemisphere, except at 100 to 110°E. These
clouds are very shallow and occur mostly in the altitude band of 1 to 3 km, with a peak around 1.5 km. Their frequency of occurrence is about 30 to 40% at the peak altitude of occurrence. However, the frequency of occurrence of these clouds is significantly underestimated in the AVHRR data (Figure 3.3), which is primarily based on the observed brightness temperature. This underestimation arises mainly because of the small difference between the temperatures at the surface and cloud top altitude, which makes the discrimination of these clouds by AVHRR more ambiguous. As explained earlier, the AVHRR observations of clouds using the methodology followed here employing the brightness temperature would underestimate the low-altitude clouds, especially those occurring below ~1 to 2 km altitude over regions of cold SST.

It may be noted that the cold ocean surface over this region, where the SST is in the range of 25 to 27°C, cannot provide large amount of moisture flux to the atmosphere for generating clouds (This is clearly shown in Chapter 5 which deals with the relationship between cloudiness and SST). It is likely that the lower tropospheric moisture required for the observed cloud development might have been mainly produced by the sea agitation arising from strong surface winds in this region. The moisture thus produced (through evaporation of water droplets from sea spray) gets mixed in the atmospheric boundary layer by the turbulence generated by large wind shears. The moisture is trapped in the lower troposphere by the strong downdraft at the descending branch of the Hadley cell which effectively prevents their upward transport from the lower troposphere. This leads to accumulation of moisture and subsequent development of shallow clouds in this region. In contrast, compared to the southern hemispheric Indian Ocean, the surface wind speeds, sea agitation and wind shears are rather weak in the northern hemisphere. Further, spatial extent of the north Arabian Sea region (where the downdraft occurs during winter) is rather small and the prevailing dry winds from the continents in this region would further decrease the water vapour mixing ratio generated by the evaporation from ocean surface. In contrast, the south Indian Ocean is considerably vast and the influence of dry winds from the continents is negligible over most of the regions. A combination of the above mechanisms might prevent significant development of lower tropospheric clouds over the Arabian Sea region while the south Indian Ocean might have larger moisture accumulation in the lower troposphere and occurrence of low altitude clouds, as seen in the CloudSat observations. However, this needs to be ascertained based on observations of moisture and atmospheric thermodynamics in this region.
3.5.1.3 Altitude-longitude cross sections of cloud distribution and atmospheric circulation

Figure 3.7 shows the multi-year (2006 to 2011) seasonal mean longitude-altitude cross sections of $F_{ALT}$ averaged for different latitude bands of 10° width (30°S to 20°S, 20°S to 10°S, ..., 20 to 30°N) over the Indian subcontinent and the surrounding oceanic regions during winter. As shown earlier, the ITCZ during this season generally persists around the equator and south of it in the equatorial Indian Ocean, with a small shift towards the north at the east equatorial Indian Ocean. The longitude-altitude cross section of cloudiness (Figure 3.7) at 0 to 10°S represents the zonal cross section of the cloud distribution along the ITCZ, which clearly shows the effect of the Walker circulation in the vertical development of clouds. The $F_{ALT}$ is largest over the east equatorial Indian Ocean between 90 to 110°E at all altitudes, while the cloud vertical development is almost fully suppressed between 40 to 55°E. The zonal cross section of cloudiness at 0 to 10°S shows largest deep convective clouds at 100 to 110°E and the near-absence of clouds between 40 to 55°E. This aspect of the Walker circulation is further examined using Figure 3.8, which depicts the seasonal mean zonal circulation during winter averaged in the latitude bands of 0 to 10°S and 0 to 10°N during winter. The updraft is largest at east of 90°E where the convection crosses 150 hPa level (Figure 3.8). It systematically decreases towards the west and turn to downdraft in the longitude between 40 to 55°E. In the 0 to 10°N latitude band, this downdraft exists at eastward of 70°E. Vertical distribution of clouds is in agreement with this circulation.

It may be noted that the increase in the vertical development of clouds seen at west of 40°E is the result of the convergence and convection at the ITCZ region over the south African region, which is more prominently seen in the latitude band of 10 to 20°S. This is seen in Figure 3.7, which shows large updraft extending upto ∼200 hPa level at west of 40°E. Associated with the descending limb of the Hadley cell, cloudiness in the longitude band of 10 to 30°N is <20% at all altitudes at west of 100°E. Similar feature is also observed in the middle and upper troposphere at south of 20°S in the southern hemisphere. The south Indian Ocean is manifested by the large occurrence of lower tropospheric clouds at <3 km altitude in all the longitudes.

3.5.2 Pre-monsoon season

3.5.2.1 Altitude-latitude cross sections of cloud distribution and atmospheric circulation

Figure 3.9 shows the multi-year mean meridional cross sections of $F_{ALT}$ averaged for 10° longitude bands during the pre-monsoon season. Figure 3.10 shows the corre-
Figure 3.7: Multi-year (2006 to 2011) seasonal mean longitude-altitude cross sections of the frequency of occurrence of clouds averaged for different latitude bands of 10° width (20 to 30°N, 10 to 20°N, ..., 30°S to 20°S) over the Indian subcontinent and the surrounding oceanic regions during winter.

The corresponding plots for the individual months: March, April and May. Overall, the spatial distribution of clouds observed in Figure 3.9 and 3.10 are similar to that observed using NOAA-AVHRR (Figure 3.3). Similar to winter, spatial variations of the vertical distribution of cloudiness during this season are strongly coupled to the Walker and Hadley cells. This season represents the transition period: the vertical distribution of clouds observed during March has several similarities to those during January-February months. This is especially the case with the location of ITCZ, its north-south tilt and the east-west asymmetry. The ITCZ over the central and west equatorial Indian Ocean moves equatorward during April and May and the north-south tilt of ITCZ almost completely disappears by May. However, the east-west asymmetry in the vertical distribution of clouds (intense deep convection over the east equatorial Indian Ocean and
rather weak convection over the western parts) associated with the Walker circulation prevails during all months of this season.

The vertical development of clouds during this season is largest in the longitude band of 90 to 110°E, with strong outflows to either side of the ITCZ. The vertical cross sections of the meridional circulation during this season, depicted in Figure 3.11 for the longitude bands of 40 to 50°E, 70 to 80°E and 90 to 100°E, show a wide region of large-scale convection over the east equatorial Indian Ocean between ~12°S and 25°N (larger width of this convective region in Figure 3.11 is partly contributed by the seasonal averaging, as the summer monsoon current advances to the Bay of Bengal sector during the second half of May). Figure 3.11 shows that, in the longitude band of 90 to 100°E, the convection is largest between 8°S and 15°N and extends up to ~150 hPa level. However, the magnitude of convection reduces substantially above ~200 hPa level, giving rise to large scale divergence which is manifested in the vertical distribution of clouds as outflow from the ITCZ band. Over this longitude region,
descending limb of the Hadley cell is stronger over the southern hemisphere compared to the north. This results in the substantially reduced amount of cloudiness in the south Indian Ocean with the minimum cloudiness observed around 20°S, which almost coincides with the core of the sinking branch. In contrast, the vertical development of clouds is quite significant at most of the northern latitudes, except around 20°N. The region at north of 20°N witnesses significant cloudiness ($F_{ALT} 40\%$) below ~6 to 8 km altitude, with rapid reduction in cloudiness above. Though less prominent, a similar feature is observed in the longitude band of 80 to 90°E as well. This feature is also seen in the total cloudiness observed using NOAA-AVHRR (Figure 3.3). Note that this feature appears at the orographically dominated Sub-Himalayan region at the northeastern parts of the Indian subcontinent (the presence of mountains and their average altitude are also seen from the white band appearing at the bottom of Figures 3.9 and 3.10 at north of 26°N in the longitude band of 70 to 90°E). Figure 3.11 shows a region of strong updraft below ~600 to 500 hPa level, capped by an equally strong downdraft above. However, the vertical distribution of cloudiness shows peak values at ~6 to 7 km, which is ~1 to 2 km above the base altitude of the region of strong subsidence. This difference between the regions of maximum cloudiness and downdraft might be because of the uncertainties in the MERRA data arising from the orographic influence.

Meridional circulation shows that, in the Indian longitude band of 70 to 80°E, the descending limbs of the Hadley cell are strong (with comparable strengths) in both the hemispheres. Correspondingly, the cloudiness is quite small at these descending limbs of Hadley cell centered around 20°S and 20°N. In the western longitude band of 40 to 50°E, the ITCZ is very weak as this region is occupied by the descending limb of the Walker cell. Except for a weak convection at 6°S to equator, all latitudes in this region experiences strong subsidence in the middle and upper troposphere. Cloud occurrence is the least in this region and the occurrence of vertically developing clouds is almost negligible. Clouds in the middle and upper troposphere that occur in this longitude band at south of 25°S are primarily the result of convection at the southeast African region/Madagascar observed in March–April period.

As seen in the winter season, cloudiness in the upper troposphere increases with altitude, especially between 8 and 12 km. Most of these clouds are thick cirrus clouds having larger atmospheric residence time compared to the other cloud types, which lead to increase in their frequency of occurrence. As revealed by the meridional cross section of $F_{ALT}$, clouds in the upper troposphere generated by the outflow from the ITCZ prevail at all longitudes. Maximum cloudiness due to the outflow occurs in the altitude band of 9 to 13 km, with the base of this cloud band increasing (and its thickness reducing) away from the ITCZ. They extend meridionally to as large as 8...
Figure 3.9: Multi-year (2006 to 2011) seasonal mean latitude-altitude cross sections of the frequency of occurrence of clouds averaged for different longitude bands of $10^\circ$ width (30 to 40$^\circ$E, 40 to 50$^\circ$E, ..., 100 to 110$^\circ$E) over the Indian subcontinent and the surrounding oceanic regions during the pre-monsoon season (MAM).
to $10^\circ$ from the boundary of the ITCZ. Considering that the typical meridional wind speed at 9 to 13 km altitude is $<10$ m/s, it takes $>24$ hours for these clouds to spread meridionally as observed. This provides an indirect evidence for the relatively long residence time of cirrus clouds. Weaker meridional winds in the southern hemisphere results in the smaller distance to which the outflow of cirrus clouds occur at south of the ITCZ.

High frequency of occurrence of lower tropospheric clouds persists over the south Indian Ocean during all months of the pre-monsoon season. These clouds occur in the downdraft zones associated with the Hadley cell, which effectively prevents the penetration of moisture into the middle and upper troposphere. Largest frequency of occurrence of these clouds is observed at $\sim 1.5$ km altitude and they seldom penetrate $\sim 3$ km altitude. Such clouds are almost absent in the descending branch of the Hadley cell in the northern hemisphere. All features of their occurrence as well as their absence in the northern hemisphere are similar to those observed in winter. The generation mechanisms for their occurrence in the southern hemisphere and their absence in the northern hemisphere proposed for the winter Section 3.5.1.2 hold good during the pre-monsoon season as well.

3.5.2.2 Altitude-longitude cross sections of cloud distribution and atmospheric circulation

Figure 3.12 shows the multi-year mean meridional cross sections of $F_{ALT}$ averaged at $10^\circ$ latitude bands during the pre-monsoon season. The longitudinal variations around the equator represents the zonal cross section of cloudiness within the ITCZ, which clearly reveals the systematic decrease in deep convection from the east equatorial Indian Ocean to the west. The most intense (in terms of cloudiness) and deepest convection occurs in the latitude band of 0 to $10^\circ$S over the east equatorial Indian Ocean between 95 to 100$^\circ$E longitude. The convection and vertical development of clouds are considerably weaker at west of 80$^\circ$E. It is likely that a significant fraction of the clouds appearing in the upper troposphere at west of 80$^\circ$E might be the clouds transported westward by the prevailing easterlies in the tropics. The frequency of occurrence of clouds is insignificant between 40 and 55$^\circ$E in the latitude band of 0 to $10^\circ$S. The longitude of least cloudiness is wider (40 to 65$^\circ$E) in the latitude belt of 0 to $10^\circ$N compared to that at 0 to $10^\circ$S. These features are in agreement with the altitude-zonal cross section of the zonal winds averaged in the 0 to $10^\circ$S latitude band (Figure 3.13) which shows persistent easterlies in the upper troposphere over the equatorial Indian Ocean.

The zonal cross section of the vertical distribution of clouds shows deep convective clouds at 10 to 30$^\circ$N in the longitudes at east of 90$^\circ$E (the northeast Bay of Bengal
Figure 3.10: Multi-year (2007 to 2010) monthly mean latitude-altitude cross sections of the frequency of occurrence of clouds averaged for different longitude bands of 10° width (30 to 40°E, 40 to 50°E, ..., 100 to 110°E) over the Indian subcontinent and the surrounding oceanic regions during March, April and May.
Chapter 3: Spatial and vertical distribution of Clouds

Figure 3.11: Longitudinally averaged seasonal mean meridional circulation during the pre-monsoon season, shown by vector plots of the average meridional and vertical winds in the longitude bands of 40 to 50°E, 70 to 80°E and 90 to 100°E as a function of altitude and latitude. The vertical winds are multiplied by 50 for clearly representing the circulation pattern. Blue shade indicates downdraft and red shade indicates updraft.

One of the most interesting features observed in the cloud distribution over the equatorial Indian Ocean is the rather weak convection that prevails over the warm and northern parts of the Indian subcontinent. In the latitude belt of 20 to 30°N, this enhancement is mainly caused by the convective clouds in the Sub-Himalayan region. At 10 to 20°N, the deep convection primarily occurs over the warm (SST>29°C) east Bay of Bengal during May, leading to large-scale vertical development of clouds in this region. In contrast, the convection is almost fully suppressed in the latitude band of 10°S to 30°S, where the occurrence of clouds are primarily limited to <3 km altitude (especially at 20 to 30°S).

One of the most interesting features observed in the cloud distribution over the equatorial Indian Ocean is the rather weak convection that prevails over the warm
Figure 3.12: Multi-year (2006 to 2011) seasonal mean longitude-altitude cross sections of the frequency of occurrence of clouds averaged for different latitude bands of 10° width (20 to 30°N, 10 to 20°N, ..., 30 to 20°S) over the Indian subcontinent and the surrounding oceanic regions during the pre-monsoon season.

pool region in the west equatorial Indian Ocean and southern parts of the Arabian Sea, where the SST exceeds 30°C over a vast region, especially between 60 to 70°E and 0 to 10°N during May (Figure 3.2). This is clearly seen in Figure 3.10, which shows the occurrence of convection over the equatorial Indian Ocean in the longitude band of 60 to 70°E and latitude region of 0 to 10°N during May. (The absence of large-scale cloudiness in this region in Figure 3.12 is because of the averaging of data during March to May; the warm pool does not exist in March). Notwithstanding this, the convection and vertical development of clouds over the Indian Ocean Warm Pool is considerably less than the convection and cloudiness over several other regions which are relatively cooler than the warm pool (e.g., in March, the deep convective clouds over the east equatorial Indian Ocean between 90 to 100°E at 0 to 10°S with SST of
Chapter 3: Spatial and vertical distribution of Clouds

3.5.3 Asian Summer Monsoon (ASM) Season

3.5.3.1 Altitude-latitude cross sections of cloud distribution and atmospheric circulation

Multi-year (2006 to 2011) seasonal mean latitude-altitude cross sections of the frequency of occurrence of clouds averaged for different longitude bands of 10° width over the Indian subcontinent and the surrounding oceanic regions during the Asian summer monsoon season (JJAS) are shown in Figure 3.14. A better graphical representation of the longitude variations of $F_{ALT}$ depicted in Figure 3.14 is shown in Figure 3.15 ex-
cept for partial masking of the $F_{ALT}$ values in the lower altitudes. The corresponding monthly mean variations of $F_{ALT}$ during the individual months (June, July, August and September) are shown in Figure 3.16. One of the most remarkable features of the cloud distribution during the ASM is the deepest convection over the entire study domain and among the deepest global convective regions [Newell and Gould-Stewart, 1981] occurring over the north and northeast Bay of Bengal in the longitude bands of 80 to 90°E and 90 to 100°E. Though these features prevail throughout the season, they are more intense during July to August compared to June and September. The zone of intense convection is centered around 16 to 22°N over the north Bay of Bengal (80 to 90°E, which cover the north Bay of Bengal adjoining the east coast of Peninsular India) and around 12 to 20°N over the northeast Bay of Bengal (90 to 100°E). Figures 3.14 and 3.16 shows that the altitude of largest cloud occurrence over both these deep convective zones tends to shift southward. Frequency of occurrence of clouds over the northeast Bay of Bengal is larger than that over the north Bay of Bengal. These features are in agreement with the total frequency of occurrence of clouds depicted in Figure 3.3, which shows that the total cloudiness exceeds 90% over most of these regions.

Over most parts of the north and northeast Bay of Bengal, $F_{ALT}$ exceeds 40% at all altitudes during July to August. A significant fraction of the deep convective clouds reach up to ~15 km altitude in this region, above which the values of $F_{ALT}$ rapidly decreases. In contrast, the occurrence of deep convective clouds almost ceases at the altitude of ~13 to 14 km over all other regions (including the east and central equatorial Indian Ocean, the Arabian Sea sector, and the Indian landmass) during the ASM; similar is the case with the vertical distribution of clouds during the other seasons as well. This clearly shows that the top altitudes of deep convective clouds over the north/northeast Bay of Bengal extends at least 1 to 2 km above that over the other deep convective regions. These results on the largest deep convection over the north Bay of Bengal are in agreement with the inferences made by Meenu et al. [2010] based on the brightness temperature data, which showed that the deep convective cloud tops over the north and northeast Bay of Bengal is about 10 to 15 K cooler than that over the other regions. It is also important to note that only optically thick clouds are detected by CloudSat. Based on CALIPSO observations, Meenu et al. [2011] showed that the frequency of occurrence of semitransparent cirrus clouds (which are not detectable using CloudSat) extends up to 16.5 km altitude over the north and northeast Bay of Bengal, while the corresponding altitude over the other deep convective regions is 14 to 15 km. A small fraction (<5%) of these semitransparent cirrus clouds were found to cross the cold point tropopause over the north and northeast Bay of Bengal [Meenu et al., 2011].
Throughout the summer monsoon season, the frequency of occurrence of clouds consistently decreases northward and southward of the deep convective regions observed at 80 to 100°E. One of the most remarkable features observed in Figures 3.14 and 3.16 is the persistence of a large region of negligible cloudiness occurring below ~7 km altitude in the region encompassed between ~5 to 12°N latitude and 80 to 90°E longitude. This appears like a dome structure with cloudiness <10% at all altitudes below ~7 km. Though this structure appears throughout the season, it is most prominent during July to August. The cloudiness systematically increases away from this region (in all directions), though the signature of relatively less cloudiness is seen in the longitude bands of 70 to 80°E and 90 to 100°E, especially during July to August. This is one of the least explored aspects of the Asian summer monsoon [Nair et al., 2011] and is investigated in detail in Chapter 4.

Deep convection is also prominent between the latitudes of ~10 to 22°N in the 70 to 80°E longitude band, which covers most of the India landmass. This deep convection, mainly caused by the monsoon trough, is most prominent towards the northern latitudes, and extends up to ~14 km altitude. However, the overall cloudiness in this convective region is lesser (typically, $F_{ALT} < 35\%$) than that over the north and northeast Bay of Bengal. Cloudiness in this region is most prominent during June-July and starts weakening from August onwards. Intensity of this convection reduces substantially towards the west, and is rather feeble in the longitude band of 60 to 70°E. On average, cloudiness over the northern hemisphere is the least in the longitude band of 40 to 60°E.

In addition to the above regions in the northern hemisphere, a zone of large-scale convection is observed around the equator and south of it, which is associated with the equatorial trough. This region of enhanced cloudiness is also observed in total cloudiness shown in Figure 3.3. This feature is prominent at the central and east equatorial Indian Ocean at east of ~60°E. Deep convection associated with the equatorial trough extends between the equator and ~5°S latitude. The upper altitude limit of this deep convection is ~13 km, above which the cloudiness rapidly decreases; this upper altitude limit of deep convection is at least 2 km below that over the north and northeast Bay of Bengal. Thick cirrus outflows in the upper troposphere from the equatorial trough extends up to 5° southward of the southern boundary of the trough region.

South of the equatorial trough is marked by the persistent occurrence of low altitude clouds in the south Indian Ocean. These clouds have maximum occurrence at ~1.5 km and are confined to less than 3 km altitude. These features are similar to that observed during the other seasons as well and are associated with the descending limb of the Hadley cell. However, the frequency of occurrence of these clouds is largest (>50% at the peak altitude of occurrence) during the summer monsoon season.
Figure 3.14: Multi-year (2006 to 2011) seasonal mean latitude-altitude cross sections of the frequency of occurrence of clouds averaged for different longitude bands of 10° width (30 to 40°E, 40 to 50°E, ..... 100 to 110°E) over the Indian subcontinent and the surrounding oceanic regions during the Asian summer monsoon season (JJAS).
Association between the latitude variations of the vertical distribution of clouds and atmospheric circulation is examined using the meridional circulation shown in Figure 3.17, which depicts the vector plots of the longitudinally averaged meridional and vertical winds obtained from MERRA as a function of latitude and altitude. The predominant deep convection in the 90 - 100°E longitude band over the Bay of Bengal which extend above ~150 hPa level is clearly discernible in Figure 3.17. This convection is strongest between the latitudes of 10°N to 22°N. The altitude of largest updraft increases towards the south (which appear as the southward lilt in the convective core in Figure 3.17). Correspondingly, the altitude of largest cloudiness also shows a southward tilt in this longitude band (Figure 3.14). The updraft at south of the equator (0 to 5°S) is considerably weaker than that in the northern hemisphere, resulting in the weaker vertical development of clouds at 0 to 5°S. The meridional outflow from the northern hemisphere and the equatorial trough is limited to a few degrees at south of the equatorial trough (Figure 3.17), which results in the relatively small spatial extent of the outflow clouds observed in the upper troposphere over the southern hemispheric Indian Ocean (Figures 3.14 and 3.16). Strong downdraft associated with the Hadley circulation prevails in the middle and upper troposphere at south of ~5°S. However, the core of this downdraft is located at south of ~25°S. In general, the convection in this region is highly inhibited and the cloudiness at the south Indian Ocean are mainly
Figure 3.16: Multi-year (2006 to 2010) monthly mean latitude-altitude cross sections of the frequency of occurrence of clouds averaged for different longitude bands of 10° width (30 to 40°E, 40 to 50°E, ..., 100 to 110°E) over the Indian subcontinent and the surrounding oceanic regions during June, July, August and September.
Figure 3.17: Longitudinally averaged seasonal mean meridional circulation during the summer monsoon season, shown by vector plots of the average meridional and vertical winds in the longitude bands of 40 to 50°E, 70 to 80°E and 90 to 100°E as a function of altitude and latitude. The vertical winds are multiplied by 50 for clearly representing the circulation pattern. Blue shade indicates downdraft and red shade indicates updraft.

Figure 3.17 shows that strong updraft, right from the lower troposphere to $\sim$150 hPa level, prevails in the latitude band of 10 to 25°N over the Indian region (70 to 80°E). This convection is strongest towards the northern latitudes, especially at north of 15°N. Mid- and upper tropospheric convection prevails above 550 hPa level at south of this deep convective region. Convection at the Equatorial Trough is seen at the north of 5°S, but is weaker than the northern hemispheric convection over the Indian region. Strong downdraft prevails at south of the Equatorial Trough, especially at south of 10°S. The vertical distribution of clouds in this longitude band is in agreement with

confined to $<3$ km altitude.
this pattern of the meridional circulation.

Except for a weak convection prevailing over the relatively dry land areas in east Africa and Arabia in the northern hemisphere, downdraft prevails over the eastern longitude band of 40 to 50°E. Strong downdraft is present over all latitudes in the southern hemisphere in this longitude band, where the cloudiness is extremely weak. The shallow clouds below ~3 km altitude, which usually prevail in the southern hemisphere, extends up to ~3°N. A mid-tropospheric band of cloudiness prevails between 5 to 7 km altitude in this longitude band, which is an extension of a similar feature in the longitude band of 30 to 40°E.

3.5.3.2 Altitude-longitude cross sections of cloud distribution and atmospheric circulation

Figure 3.18 shows the multi-year (2006 to 2011) seasonal mean longitude-altitude cross sections of $F_{ALT}$ averaged for different latitude bands during the Asian summer monsoon season. East-west cross section of the zonal circulation, averaged at 10° latitude bands are shown in Figure 3.19 for investigating the effect of zonal circulation on cloudiness. Strong vertical development of clouds over the north and northeast Bay of Bengal is clearly seen in the 10 to 20°N latitude band, with maximum cloudiness at 95 to 100°E. Another region of strong vertical cloud development, though less prominent, is observed at 72 to 76°E, which is the region at west of the Western Ghats. This is in agreement with the zonal circulation which shows largest updraft at east of 90°E and a relatively weaker updraft at west of 76°E. Most importantly, strong easterly winds of average magnitude $>10$ ms$^{-1}$ prevails in the upper troposphere in this latitude band, which causes a pronounced westward transport of clouds and moisture from the deep convective region of the Bay of Bengal. This westward outflow of convective anvils is seen in Figure 3.18. Almost similar features are observed at the 0 to 10°N latitude band as well, though the updrafts at 90 to 100°E and 70 to 76°E are considerably less than those at the 10 to 20°N latitude band. However, the westward spreading of the deep convective outflow is more prominent in this latitude as the average tropical easterly wind speed is larger here than at 10 to 20°N. Notably, this outflow extends upto ~55°E, which is ~15° away from the convection at east Arabian Sea and 35° away from the deep convective region in the east Bay of Bengal. It is very likely that the outflow from deep convective regions of the east Bay of Bengal gets added with the outflow from convection at the east Arabian Sea, which eventually spreads up to ~55°E. Notwithstanding this, the westward transport of $>15°$ from the deep convective region is quite large and is primarily aided by the strong easterly winds associated with the tropical easterly jet stream (TEJ) prevailing in this region. This is in agreement with the conclusions drawn by Sathiyamoorthy et al. [2004] based on
the spatial distribution of total cloudiness. A better graphical representation of this is shown in Figure 3.15, which clearly depicts the westward spreading of clouds from the deep convective areas of the Bay of Bengal and east Arabian Sea. As seen in the zonal circulation (Figure 3.19, strong downdraft prevails at 45 to 60°E longitude band in all the latitudes (both in the northern and southern hemisphere), which inhibits further westward propagation of the outflows as well as any in situ generation of convection.
Figure 3.19: Latitudinally averaged seasonal mean zonal circulation during the summer monsoon season, shown by vector plots of the average zonal and vertical winds in the latitude bands of 10 to 20°N, 0 to 10°N, 0 to 10°S and 10°S to 20°S as a function of altitude and longitude. The vertical winds are multiplied by 50 for clearly representing the circulation pattern. Blue shade indicates downdraft and red shade indicates updraft.

3.5.4 Post-monsoon Season

3.5.4.1 Altitude-latitude cross sections of cloud distribution and atmospheric circulation

Seasonal mean (2006 to 2010) latitude-altitude cross sections of $F_{ALT}$ averaged for different longitude bands over the study region during the post-monsoon season are
shown in Figure 3.20 and the corresponding monthly mean variations of $F_{ALT}$ during October and November are shown in Figure 3.21. Most intense cloudiness over the east equatorial Indian Ocean occurs during this season. Significant vertical development of clouds (with $F_{ALT} > 20\%$ at all altitudes) occurs right from the lower troposphere to the upper troposphere within the latitudes of $10^\circ$S and $10^\circ$N in the 90 to 100°E longitude band, which is the ITCZ. The values of $F_{ALT}$ maximizes in this longitude band within about 5° on either side of the equator where the upper tropospheric cloudiness is >40% in the altitude band of 10 to 13 km. Drastic reduction of $F_{ALT}$ occurs above ~13.5 km. Despite the intense vertical development of clouds in this region, the upper altitude of large cloudiness as well as the frequency of occurrence of clouds is lesser than the corresponding values observed over the northeast Bay of Bengal during the Asian summer monsoon season. Cirrus outflows from the convective cells extend up to ~5 to 8° from the northern and southern boundaries of the ITCZ. The mean latitudinal positions of the ITCZ at all longitude bands during this season are centered around the equator, though their strength decreases westward of 90°E.

Associated with the descending limb of the Hadley cell, the cloudiness rapidly decreases towards south and north of the ITCZ. This reduction in cloudiness at south of the ITCZ is considerably larger than that at the north in the longitude band of 80 to 110°E. The cloudiness shows an increase at north of ~20 to 25°N in the sub-Himalayan region. Similar to the other seasons, large amount of lower tropospheric clouds prevail below ~3 km altitude in the south Indian Ocean where the descending limb of the Hadley cell appears. These clouds have the maximum frequency of occurrence in the altitude range of 1 to 1.5 km. Their amount is largest between 70 to 90°E where the values of $F_{ALT}$ is >30% at the peak altitude of occurrence. Their occurrence is rather insignificant at 40 to 50°E, especially at north of ~25°S. As in the other seasons, such a cloud band does not appear in the northern hemisphere.

The east-west asymmetry in cloudiness associated with the ITCZ over the equatorial region is highly prominent during this season. Vertical development of clouds as well as their frequency of occurrence in the equatorial region decreases systematically towards the west. The lowest values of $F_{ALT}$ at all altitudes occur in the longitude band of 40 to 50°E where their values are mostly <10%. These results are in agreement with the spatial distribution of total cloudiness derived from the NOAA-AVHRR data (Figure 3.3) and indicate that the Walker cell is very strong during this season.

Effect of the atmospheric circulation on the vertical distribution of clouds is examined using Figure 3.22 which shows the seasonal mean meridional circulation in the longitude bands of 40 to 50°E, 70 to 80°E and 90 to 100°E during the post-monsoon season. Strong updraft in the ITCZ which is almost symmetric around the equator at the central and east equatorial Indian Ocean is clearly manifested in this figure.
Figure 3.20: Multi-year (2006 to 2010) seasonal mean latitude-altitude cross sections of the frequency of occurrence of clouds averaged for different longitude bands of 10° width (30 to 40°E, 40 to 50°E, ..., 100 to 110°E) over the Indian subcontinent and the surrounding oceanic regions during the post-monsoon season (ON).
Figure 3.21: Multi-year (2006 to 2010) monthly mean latitude-altitude cross sections of the frequency of occurrence of clouds averaged for different longitude bands of 10° width (30 to 40°E, 40 to 50°E,..., 100 to 110°E) over the Indian subcontinent and the surrounding oceanic regions during October and November.
Figure 3.22: Longitudinally averaged seasonal mean meridional circulation during the post-monsoon season, shown by vector plots of the average meridional and vertical winds in the longitude bands of 40 to 50°E, 70 to 80°E and 90 to 100°E as a function of altitude and latitude. The vertical winds are multiplied by 50 for clearly representing the circulation pattern. Blue shade indicates downdraft and red shade indicates updraft.

Updraft in the ITCZ at the east equatorial Indian Ocean (90 to 100°E) prevails in the latitude band of 8°S to 10°N, with largest convection around the equator. Though the updrafts prevail up to ~150 hPa level in this longitude band, their magnitude decreases above ~250 hPa level, leading to the divergence of winds above this level. Associated with the Hadley cell, strong downdrafts prevail at south of 10°S and north of ~20°N latitudes over the east equatorial Indian Ocean; subsidence at the southern branch is stronger than that at the north. The vertical distribution of clouds over this region is in agreement with the MERRA-derived meridional circulation. The updraft in the sub-Himalayan region extending up to ~600 to 500 hPa level, which is capped
by downdraft above, is clearly manifested in the meridional circulation in the longitude band of 90 to 100°E. Though this feature is observed in the vertical development of clouds as well, they show cloudiness extending up to \(\sim 6\) to 7 km, which is well above the region of updraft in the sub-Himalayan region. These features on the cloudiness at the sub-Himalayan region and their genesis though the orographic influence are manifested in all seasons, though with varying degree. Difference between the observed vertical extent of clouds and updraft in the reanalysis data might have been caused by the deficiency of MERRA in the orographically dominated regions.

Strength of the updraft in the ITCZ at the Indian longitude sector of 70 to 80°E is weaker than that over the east Indian Ocean region. This results in rather weaker cloudiness over the ITCZ in this longitude band (Figures 3.20 and 3.21). However, strength of the subsidence at descending limbs of the Hadley cell in this longitude band is comparable in both hemispheres. This results in the nearly symmetrical vertical distribution of clouds with respect to the equator in this longitude band (Figures 3.20 and 3.21). Subsidence prevails at almost all latitudes in the 40 to 50°E longitude band. The near-absence of updraft associated with the ITCZ in this longitude band is caused by the strong subsidence associated with the Walker cell. This leads to the negligible vertical development of clouds as observed in (Figures 3.20 and 3.21). However, strength of the subsidence at the south Indian Ocean and northern hemisphere is substantially weaker than that at the descending limbs of the Hadley cell observed at other longitude bands. Such weak subsidence cannot effectively trap the moisture to the lower atmosphere. This might have been one of the main reasons for the large reduction in the occurrence of low-altitude clouds in this longitude band over the south Indian Ocean.

### 3.5.4.2 Altitude-longitude cross sections of cloud distribution and atmospheric circulation

Figure 3.23 shows the multi-year (2006 to 2010) seasonal mean longitude-altitude cross sections of \(F_{ALT}\) averaged for different latitude bands (30°S to 20°S, 20°S to 10°S, ... 20 to 30°N) over the study region during the post-monsoon season. The corresponding latitudinally averaged zonal circulations around the equator are depicted in Figure 3.24. The longitude-altitude cross sections of cloudiness and the zonal circulation in the latitude bands of 0 to 10°N and 0 to 10°S represent their zonal cross sections at the ITCZ region. These figures clearly show the Walker circulation cell with large deep convection and cloudiness at the east equatorial Indian Ocean and the subsidence at east of 55°E longitude. Cloudiness generated by the deep convection over the east equatorial Indian Ocean extends from the lower troposphere to \(\sim 13.5\) km altitude, while the corresponding top altitude is \(\sim 0.5\) to 1 km smaller at \(\sim 60\) to 70°E.
Figure 3.23: Multi-year (2006 to 2011) seasonal mean longitude-altitude cross sections of the frequency of occurrence of clouds averaged for different latitude bands of 10° width (20 to 30° N, 10 to 20° N, ..., 30° S to 20° S) over the Indian subcontinent and the surrounding oceanic regions during the post-monsoon season.

These are in agreement with the zonal cross section of the circulation obtained from MERRA data. On average, over the central and east equatorial Indian Ocean, the updraft attains maximum strength between the isobaric levels of ~600 and ~250 hPa. The winds are diverging above ~250 hPa level, though updrafts still prevail up to ~150 hPa, especially over the east equatorial Indian Ocean. This limits the convection mostly to <13.5 km altitude, as seen in the vertical structure of cloud distribution. The upper tropospheric zonal winds over the equatorial Indian Ocean during this season is substantially weaker than that during the summer monsoon season. This has resulted in the weak zonal convective outflow of cirrus anvils from the deep convective regions at the east and central equatorial Indian Ocean to the western parts.

The updraft at west of ~40° E in the equatorial region manifested in the MERRA
data is collocated with the convective clouds observed using CloudSat data. Both the updraft and cloudiness are weaker in this region compared to that over the east equatorial Indian Ocean. In the sub-Himalayan region (20 to 30°N), vertical development of clouds shows an enhancement in the upper altitude from 105°E to 90°E; this cloud structure is absent at west of 85°E. Frequency of occurrence of the low-altitude clouds observed at the south Indian Ocean is larger in the 10°S to 20°S (F_{ALT} >40% at the peak altitude) compared to that at 20°S to 30°S latitude band (F_{ALT} <30%). Further, these clouds are prominent only in the longitude band of 50 to 105°E.

### 3.6 Interannual variations of the vertical distribution of clouds

The relatively short period of observation (June 2006 to February 2011) as well as the smaller frequency of observation (due to the profiling limited to the sub-satellite track in the 16-day orbit cycle) do not permit an exhaustive investigation on the interannual variations in the vertical distribution of clouds. Hence, this section is mainly limited to the examination of the reproducibility of the seasonal mean latitude-altitude
cross sections of $F_{ALT}$ during different years. Figure 3.25(a-d) shows the seasonal mean latitude-altitude cross sections of $F_{ALT}$ in the longitude band of 80 to 90°E (the Bay of Bengal sector) during the winter, pre-monsoon, summer monsoon and post-monsoon seasons of the individual years.

3.6.1 Winter season

CloudSat data during 07 December 2009 to 16 January 2010 and 01 January to 06 February 2011 were not released by CloudSat data processing centre due to technical reasons and hence could not be included in the present analysis. Excluding the winter period of 2010 and 2011 due to the above reason, the cloud distribution during all years during the winter period are consistent. The following are the major differences during the individual years.

1. The amount of cirrus clouds over the south Indian Ocean during 2007 is larger than that during the other years.

2. Location of the deep convective clouds associated with the ITCZ during 2008 extends up to $\sim 12^\circ$S, which is at least 3° southward compared to the other seasons.

3. Cloudiness at the descending limb of the Hadley cell in the northern hemisphere during 2008 is $\sim 10\%$ while the corresponding values are $\sim 5\%$ or less during the other years.

3.6.2 Pre-monsoon season

Overall, cloud distribution during the pre-monsoon season of the individual years are similar, except for the following differences.

1. The mid- and upper tropospheric cloudiness over the south Indian Ocean (descending limb of the Hadley cell) during 2007 is distinctly larger than that during the other years when this region is almost cloud-free.

2. The amount of clouds at the ITCZ region and the cirrus clouds at the outflow region are distinctly larger during 2008 compared to the other years.

3. The amount of lower-tropospheric clouds (at $< 3$ km altitude) at the south Indian Ocean (at the descending limb of Hadley cell) is relatively smaller during 2008 compared to the other years.

Figure 3.25: (a–d) Seasonal mean latitude-altitude cross sections of $F_{ALT}$ in the longitude band of 80 to 90°E (the Bay of Bengal sector) during the winter, pre-monsoon, summer monsoon and post-monsoon seasons of the individual years.
3.6.3 Summer monsoon season

On average, the vertical distribution of clouds and its spatial variations have similar structures during all years. However, the intensity of cloudiness as well as the characteristics of certain features had significant year-to-year variations. The most prominent among them are the following.

1. Magnitude of cloudiness and the location of maximum cloudiness at the deep convective region of the Bay of Bengal: The values of $F_{ALT}$ in this region are largest during 2007 and 2008 and least during 2009 and 2010.

2. Cloudiness at the equatorial trough shows maximum convection and cloudiness during 2009 and 2010; however, during these years, its location has been shifted by $\sim 3$ to $5^\circ$ towards the south of its position during the other years.

3. Spatial extent of ‘the pool of inhibited cloudiness’ over the southwest Bay of Bengal is largest and the values of $F_{ALT}$ below $\sim 7$ km altitude in this region are the least during 2009. In contrast, spatial extent of the pool is the least and cloudiness at the pool is largest during 2007, 2008 and 2010.

Variations in the vertical development of clouds can have an important role in governing rainfall over the Indian region.

3.6.3.1 Vertical distribution of clouds during the drought year – 2009

It may be noted that the all-India rainfall was 698 mm during the summer monsoon season of 2009 as against the long-term seasonal average of 892.2 mm, resulting in a seasonal rainfall deficit of 21.8%. The largest deficit occurred in June (-47.2%), followed by August (-26.5%), September (-20.2%) and July (-4.3%) [Source: Summary of Rainfall characteristics by the India Meteorological Department]. In contrast, the All-India rainfall during ASM of other years during the 2006 to 2010 period were normal and within -1.7% to +5.7% of the long-term average. The seasonal mean vertical distribution of clouds during 2009 clearly shows weakening of convection and vertical development of clouds over the Bay of Bengal longitude sector in the latitude band of 18 to 22°N where intense convection usually takes place during the ASM. While the values of $F_{ALT}$ in this region is larger than 35% during the ASM of normal years (e.g., 2007, 2008), its values were generally $\sim 30\%$ or less during 2009. The weaker convection over the north Bay of Bengal led to a vast region over the Bay of Bengal to be devoid of large-scale cloudiness during 2009: as a result, the spatial extent of ‘the pool of inhibited cloudiness’ over the southwest Bay of Bengal has increased.
Figure 3.26: Latitude-altitude cross sections of $F_{ALT}$ at different longitude bands during June, July, August and September of 2009.
significantly. Further a large area in the ‘pool of inhibited cloudiness’ during 2009 had $F_{ALT} < 5\%$ at altitudes below $\sim 7$ km.

As 2009 had large deficit in summer monsoon rainfall, the vertical distribution of cloudiness during this year is examined in detail. The latitude-altitude cross sections of $F_{ALT}$ at different longitude bands during June, July, August and September of 2009 are shown in Figure 3.26. Comparison of this figure with the multi-year monthly mean cloud distribution depicted in Figure 3.16 shows the following features.

1. During June 2009, the vertical development of clouds over the Indian region and the west Bay of Bengal (70 to 90°E) is considerably weaker compared to the multi-year mean. As a result, amount of cirrus clouds at the east Arabian Sea sector (60 to 70°E) also is weak. In contrast, the vertical development of clouds over the northeast Bay of Bengal (90 to 100°E) and the equatorial trough region have enhanced substantially. A distinct increase in the top altitude of convective clouds over the northeast Bay of Bengal (90 to 100°E, 10 to 20°N) is also observed. Spatial extent of the ‘pool of inhibited cloudiness’ over the southwest Bay of Bengal during June 2009 is considerably larger.

2. Vertical distribution of clouds and its spatial variations during July 2009 are comparable to those in the corresponding multi-year monthly mean variations during July. Large-scale convection over the north Bay of Bengal and the Indian landmass is seen during July 2009. Anomalous convection at the equatorial trough observed in the longitude band of 80 to 100°E is weakened.

3. Vertical development of clouds over the whole region is somewhat weaker during August 2009 compared to the corresponding multi-year mean. This deficit is most pronounced in the Indian region (70 to 80°E; 10 to 25°N) followed by the north Bay of Bengal (80 to 90°E). On the contrary, convection at the equatorial trough region in the longitude band of 70 to 100°E strengthens during August 2009.

4. The vertical development of clouds over the Indian and the west Bay of Bengal sectors continues to be weaker during September 2009. The equatorial trough also continues to be stronger with positive anomaly in the vertical development of clouds, especially in the longitude band of 80 to 100°E.

Monthly variations of the vertical distribution of clouds observed using CloudSat are in agreement with the corresponding variations in rainfall distribution described above. Most importantly, the anomalous weakening of convection and vertical development of clouds over the Indian region and the west Bay of Bengal occurs together.
Chapter 3: Spatial and vertical distribution of Clouds

with an anomalous strengthening of the equatorial trough region, especially at the east equatorial Indian Ocean. In general, intensification of convection and cloudiness over the northeast Bay of Bengal is also observed during the anomalous weakening of convection over the Indian region.

3.6.4 Post-monsoon season

Though broad features of the vertical distribution of clouds are similar during the individual years, the absolute magnitude of the vertical development of clouds undergoes considerable year to year variations, as listed below:

1. The values of $F_{\text{ALT}}$ at the ITCZ are the least during 2006 when their values are generally $<25\%$ in most of the regions. In contrast, the corresponding values are $>35\%$ during 2007, 2008 and 2010 – the largest values observed being in 2008 ($F_{\text{ALT}} \sim 40\%$).

2. The outflow of cirrus clouds from the deep convective regions of the ITCZ (especially at the southern hemisphere) is the least during 2006.

3. Cloudiness between 5 to $12^\circ$S is the least during 2006. This is especially the case with the lower-tropospheric clouds below the altitude of 3 km, which are present in this region during all other years.

3.7 Summary and conclusions

Vertical distribution of the monthly and seasonal mean frequency of clouds and their spatial variations over the Indian subcontinent and the surrounding oceanic regions in the geographical region between $30^\circ$S and $30^\circ$N and 30 to 110$^\circ$E derived from multi-year (2006 to 2011) observations using spaceborne Cloud Profiling Radar onboard the polar orbiting CloudSat are presented in this chapter. Characteristics of the spatial distribution of clouds are compared with their long-term horizontal distribution derived from imager (NOAA-AVHRR) data. CloudSat can provide the vertical distribution of all optically thick clouds (except the semitransparent clouds), and is the only such satellite to monitor the altitude profiles of clouds around the globe as of now. Notwithstanding the uniqueness of CloudSat data in terms of the high-resolution vertical profiling of clouds, these observations are limited to the sub-satellite track for a 16-day orbit cycle. Due to this limitation, the monthly and seasonal mean latitude-altitude cross sections of $F_{\text{ALT}}$ are averaged for different longitude bands of $10^\circ$ width. Similarly, the longitude-altitude cross sections are estimated for latitude bands of $10^\circ$ width. These zonal and meridional cross sections provide a 3-dimensional distribution of the seasonal and monthly mean cloudiness. However, structures having spatial
scales of the order of a few degrees may not be detectable in this analysis. The observations using passive radiometer imagers (such as NOAA-AVHRR) can provide only the horizontal distribution of total cloudiness and are biased to the high altitude clouds. Role of the atmospheric circulation and SST in governing the horizontal and vertical distribution of clouds are investigated using the SST derived from TRMM Microwave Imager and atmospheric circulation obtained from MERRA. Main accomplishments of this study are: (a) it provides a quantitative estimate of multi-year monthly and seasonal mean vertical distribution of clouds and its spatial variations over the Indian subcontinent and the surrounding oceans, and (b) assessment of the influence of atmospheric circulation on the horizontal and vertical distribution of clouds. Features of the cloud distribution and atmospheric circulation presented in this chapter also provide the necessary background information for the following chapters. Some of the important features observed in this study are further investigated and are presented in the subsequent chapters.

Structure of the Hadley and Walker circulation cells are well discernible in the horizontal and vertical distribution of clouds. Meridional and zonal structure of the vertical distribution of clouds at the ITCZ (the ascending limb of the Hadley cell), the descending limb of the Hadley cell and the east-west asymmetry in the zonal distribution of clouds at the equatorial region caused by the Walker circulation are compared with the corresponding dynamical structures inferred from the MERRA data; the former can be used to indirectly verify the latter.

During all seasons, CloudSat observations show that the vertical distribution of clouds over the ITCZ is marked by large values of $F_{ALT}$ at all altitudes in the troposphere below $\sim$13 to 15 km. Cloudiness in the upper troposphere in the deep convective regions increases with altitude to attain peak occurrence in the altitude band of $\sim$9 to $\sim$13 km. This is primarily because of the occurrence of thick cirrus clouds, most which are formed from the outflow of deep convective clouds as anvils or might be the remnants of deep convective clouds after precipitation. The relatively long atmospheric residence time of cirrus clouds (several hours to 2 days) compared to the low- and middle-level clouds (few minutes to few hours) also lead to increased amount of cirrus clouds in the upper troposphere. As a result of the strong outflow from the deep convective clouds, meridional cross section of the vertical distribution of clouds shows well-developed anvils on either side of the ITCZ. Depending on the strength of the Hadley circulation cell and the resulting upper tropospheric wind divergence (which vary with longitude and season), these cirrus outflows are found prominently up to $\sim$4 to $\sim$10° (approx. 440 to 1100 km) meridionally from the northern and southern boundaries of the ITCZ core. Though these cirrus outflows in the meridional direction get weakened further poleward, their presence could be traced well up to the sinking
zones of the Hadley cell on both hemispheres (up to ∼10 to 20° meridionally from the boundaries of the ITCZ). Thickness of these anvil structures is ∼4 to 5 km near the ITCZ boundaries and decreases monotonically with increase in distance. This is mainly because of the increase in base altitude while the top altitude remains almost the same. This increase in the base altitude of the cirrus anvils might have been mainly contributed by: (i) increase in meridional wind with altitude and (ii) radiative heating of the cirrus cloud base due to absorption of IR radiation from the cloud-free or low-level cloud regions below and subsequent evaporation of the cirrus from the base. In contrast, the IR radiative cooling from the cirrus top would help its sustenance for a longer period, till the cloud becomes very thin. These cirrus clouds would be prominent in modulating the radiation budget of the earth-atmosphere system and thermal structure of the upper troposphere, which need to be further investigated.

One of the most important features of the vertical distribution of clouds during the Asian summer monsoon season (ASM) is the occurrence of deepest convection over the entire study domain and among the deepest global convective regions at the north and northeast Bay of Bengal. Though these features prevail throughout the ASM, they are more intense during July-August. The zone of intense convection is centered around 16 to 22°N and 80 to 90°E (the north Bay of Bengal adjoining the east coast of Peninsular India) and around 12 to 20°N and 90 to 100°E (the northeast Bay of Bengal) the latter is stronger than the former. The altitude of largest cloud occurrence over both these deep convective zones tends to shift southward. A large fraction of the deep convective clouds reach up to ∼15 km altitude in these regions. In contrast, the occurrence of deep convective clouds almost ceases at the altitude of ∼13 to 14 km over all other regions during the ASM as well as the other seasons. This clearly shows that the top altitudes of deep convective clouds over the north/northeast Bay of Bengal extends at least 1 to 2 km above that over the other deep convective regions. Though less intense compared to the north/northeast Bay of Bengal, deep convective clouds are also prominent over the monsoon trough, the equatorial trough and the southeast Arabian Sea. The tropical easterly jetstream (TEJ) causes westward transport of large amount of cirrus outflows from the deep convective regions in the Bay of Bengal up to the central Arabian Sea. Eastward extent of this cirrus spreading is ∼30 to 40° from the deep convective regions in the Bay of Bengal and is further aided by the outflow from the southeast Arabian Sea. Another major feature observed during the ASM is the persistence of a ‘pool of inhibited cloudiness’ with negligible cloudiness below ∼7 km altitude in the region encompassed between ∼5 to 12°N and ∼80 to 90°E. This is one of the least explored aspects of the Asian summer monsoon and is further investigated in detail in Chapter 4.

During all seasons, the meridional cross section of the vertical distribution of clouds
shows minimum cloudiness at the descending limbs of the Hadley cell in both hemispheres. Strength of the ITCZ as inferred from the vertical development of clouds is largest at the east equatorial Indian Ocean and minimum at the west (mainly $\sim$40 to 50$^\circ$E). This east-west asymmetry prevails during all seasons and is caused by the Walker circulation which has its ascending limb at the east equatorial Indian Ocean (and the western Pacific) and descending limb at the west equatorial Indian Ocean. In general, this east-west asymmetry in the vertical development of clouds in the equatorial region is most prominent during October-November and April-May periods. As seen from the meridional cross sections of the frequency of occurrence of clouds in the lower to upper troposphere and their spatial gradients, the latitudinal width of the ITCZ is found to be largest ($\sim$10 to 16$^\circ$) at the east equatorial Indian Ocean and least ($\leq$10$^\circ$) at the western Indian Ocean where the ITCZ is rather weak and less organized. Structure of the ITCZ and the Hadley and the Walker cells observed using the zonal and meridional cross sections of the vertical distribution of clouds are well in agreement with those inferred from the atmospheric circulation obtained from the reanalysis data.

CloudSat observations show persistent occurrence of low-level clouds throughout the south Indian Ocean (at south of the ITCZ) at the descending limb of the Hadley cell during all seasons. These clouds are very shallow and occur mostly in the altitude band of 1 to 3 km, with the largest frequency of occurrence of $\sim$30 to 40% at $\sim$1.5 km. The cold SST at the south Indian Ocean (SST in the range of 25 to 27$^\circ$C) cannot provide sufficient moisture flux to the atmosphere for generating the observed persistent cloudiness. It is likely that the lower tropospheric moisture required for the observed cloud development might have been produced mainly by the sea surfing caused by the strong surface winds in this region. The moisture produced through evaporation of sea spray gets mixed in the atmospheric boundary layer by the turbulence generated by the wind shears. The moisture is trapped in the lower troposphere by the strong downdraft at the descending limb of the Hadley cell which effectively prevents their upward transport from the lower troposphere. This leads to accumulation of moisture in the lower troposphere and subsequent development of shallow clouds in this region. In contrast, a similar feature is almost completely absent in the northern hemisphere. Compared to the southern hemispheric Indian Ocean, the surface wind speeds, sea agitation and wind shears are rather weak in the northern hemisphere. Further, the prevailing dry winds from the continents would further decrease the water vapour mixing ratio generated by the evaporation from ocean surface at this region. In contrast, the south Indian Ocean is considerably vast and the influence of dry winds from the continents is negligible over most of the regions. A combination of the above mechanisms might prevent significant development of lower tropospheric clouds over the Arabian Sea region while the south Indian Ocean can have larger moisture accumulation and cloudiness in the lower troposphere. However, this hypothesis needs to be further ascertained using
Chapter 3: Spatial and vertical distribution of Clouds

observations of moisture and atmospheric thermo-dynamics in this region.

Overall, the seasonal mean vertical distribution of clouds and their spatial variations are more or less similar during the individual years. However, remarkable differences were observed in these features during the summer monsoon season of 2009, which was a drought year with a seasonal mean all-India rainfall deficit of 21.8%. The seasonal mean vertical distribution of clouds during 2009 clearly shows weakening the vertical development of clouds over the Indian landmass and the north Bay of Bengal where intense convection usually take place during the ASM. While the values of $F_{ALT}$ in this region is larger than 35% during the ASM of normal years (e.g., 2007, 2008), its values are $\sim 30\%$ or less during 2009. The weaker convection over the north Bay of Bengal led to a vast region over the Bay of Bengal to be devoid of large-scale cloudiness during 2009: as a result, the spatial extent of ‘the pool of inhibited cloudiness’ over the southwest Bay of Bengal has increased significantly. During June 2009, the vertical development of clouds over the Indian region and the west Bay of Bengal (70 to 90°E longitude) is considerably weaker compared to the corresponding multi-year mean. In contrast, the vertical development of clouds over the northeast Bay of Bengal (90 to 100°E) and the equatorial trough region have enhanced substantially. However, the vertical distribution of clouds and its spatial variations during July 2009 are comparable to those in the corresponding multi-year monthly mean. Vertical development of clouds over the Indian and Bay of Bengal regions are somewhat weaker during August and September 2009 compared to the corresponding multi-year mean. This deficit is most pronounced in the Indian region (70 to 80°E; 10 to 25°N) followed by the north Bay of Bengal (80 to 90°E). Monthly variations of the vertical distribution of clouds observed using CloudSat are in agreement with the corresponding variations in rainfall distribution. Most importantly, the anomalous weakening of convection and vertical development of clouds over the Indian region and the north Bay of Bengal occurs together with an anomalous strengthening of convection at the equatorial trough region and the east Bay of Bengal.