CLOUD RADIATIVE HEATING (CRH) OVER THE INDIAN SUBCONTINENT DURING SUMMER MONSOON

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Abstract

The total cloud fraction is close to 100% during June to September over large areas of the Indian summer monsoon, ISM, region. In the lower troposphere (< 8 km) the clouds are mainly convective and in the upper troposphere (10-15 km) cirrus clouds caused by convection are about as frequent as in-situ formed cirrus clouds. Recent satellite data (from CloudSat) with unprecedented vertical detail has been used to study the cloud radiative heating, CRH, over the Indian subcontinent during the ISM. We found an upper tropospheric meridional gradient in the CRH between the equator and roughly 30°N present over the whole monsoon region. The sign of this gradient reverses over the course of the transition from pre-to-post monsoon. A comparison of the CRH between the active phase and the break phase of the ISM revealed that very deep convection penetrating the bottom of the tropical tropopause layer, TTL, is more frequent during active phase than during break phase. The heating of the upper troposphere is at the same time found to be larger during active than break phase and the meridional gradient is steepest during the active phase. The heating in the lower troposphere is confined to a narrow layer at about 7-8 km altitude which is the level most convection reaches and detrains. In this layer, thick anvil clouds are responsible for most of the CRH.
1 Introduction

The English word *monsoon* originates from the Portuguese word *monção* which, in turn, comes from the Arabic *mawsim* meaning season (Schwartz et al., 1990). It refers to the periodic pattern of wet and dry periods that occur over Asia, Australia, West Africa, North and South America. During the wet season, winds blow inland from the tropical oceans bringing warm, moist air and large amounts of rain. During the dry periods the winds are reversed and cold, dry air from the inland of the winter continents are transported with the winds (Webster et al., 1998). More than 50% of the earth’s population live in areas with climates dominated by monsoons. Most of the countries in these areas are developing countries where the agriculture is the main means of livelihood and the monsoon rains are of vital importance. Variability in onset and withdrawal and the intraseasonal fluctuations heavily affect the agriculture and the countries are vulnerable to the whimsicalities of the monsoons (World Climate Research Programme\(^1\)).

The Indian monsoon is the strongest and most prominent of the world’s monsoons. It dictates the climate for India and its surrounding countries. A significant part of India’s Gross Domestic Product is provided from the agricultural sector and agriculture is the means of livelihood for millions of people\(^2\).

1.1 Overall context of the work

Considering its high enviro-socio-economical importance, it is essential to understand the energy and hydrological cycle over the Indian subcontinent and its variability. However, this is a complex task with many variables and processes interacting with each other at different spatio-temporal scales.

One of the distinct features of the monsoons is the dominance of convective clouds that pour enormous amounts of rain during the wet seasons. In the specific case of the Indian Summer Monsoon, *ISM*, convective clouds, associated anvils and thin cirrus clouds cover much of the subcontinent during monsoon months (Devasthale and Grassl, 2009; Devasthale and Fueglistaler, 2010). These cloud types are a source of radiative and latent heating in the atmosphere that helps drive and maintain the monsoonal circulation pattern (Webster et al., 1998; Zuluaga et al., 2010).

In spite of its crucial role in the total heat budget, the precise contribution of Cloud Radiative Heating, *CRH*, over the Indian subcontinent is still far from being quantified accurately. In fact, there are only a handful studies that specifically investigate the vertical structure of *CRH* and the majority of them are focused on the upper troposphere and lower stratosphere (e.g., Bergman et al., 2012).

Until recently, radiative heating data could only be attained from ground stations and reanalysis data\(^3\). Now, however, that data from advanced sensors and lidar


\(^{2}\)http://www.india.gov.in/topics/agriculture, Dec 22, 2012

\(^{3}\)Reanalysis is a way of assimilating historical meteorological observations to a forecast model
instruments onboard satellites make it possible to derive a 3D view of clouds, we can study the vertical structure in more detail. This capability of newer satellite instruments is exploited in the present study. More specifically, we use data from CloudSat, one of NASA’s A-Train constellation satellites (L’Ecuyer and Jiang, 2010; L’Ecuyer et al., 2007), over India during the summer months over the years 2007-2010 to characterize the influence of CRH during the ISM. To our knowledge it is the first time the vertical structure of CRH is quantified over the monsoon region with such unprecedented detail and accuracy.

1.2 Scientific questions
The aim of this study is to better understand the ISM, through the analysis of CRH. To specify this we have formulated three scientific questions which we will seek the answers to.

The ISM is characterized by the progression of moisture and convective systems over the Indian subcontinent starting from May/June. During July and August the all-India rainfall peaks (Webster et al., 1998) and in September the monsoonal convective systems start receding back towards equatorial regions. This transitioning from pre-to-post monsoon season would, as expected, lead to variations in the CRH. The CRH in the upper troposphere and lower stratosphere, as the monsoon peaks, also has a profound impact on the composition of the Tropical Tropopause Layer, TTL. In order to gain insights into these aspects, the first question posed here is: **How does the cloud radiative heating change from pre-monsoon to post-monsoon season?**

One of the intrinsic characteristics of the ISM is the observed intraseasonal oscillations in the all-India rainfall (Goswami and Ajaya Mohan, 2001; Gadgil and Joseph, 2003). In reality, it leads to a period of active monsoon followed by a break and so on. Although the mechanisms leading to such intraseasonal oscillations and their predictability are currently being researched, there is hardly any doubt about their important role in observed natural variability of rainfall. Devasthale and Grassl (2009) documented the variability of convective clouds during these periods of opposite nature, and Devasthale and Fueglistaler (2010) further reported on the importance of these periods with regard to convection reaching and penetrating the TTL. These intraseasonal oscillations lead to differences in the radiative heating owing to corresponding variability in the convective systems. Therefore, the second question to be addressed here is: **How do intraseasonal oscillations in monsoonal rainfall influence the vertical structure of cloud radiative heating?**

with the aim of describing the state of the atmosphere as accurately as possible for a certain historic time period. Both the European Center for Medium-Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) have their own reanalysis data sets (Dee et al., 2011; Kistler et al., 2001).
It is still under debate whether the primary driver of monsoonal circulation is the land-sea temperature contrast between the Indian subcontinent and the Indian Ocean or seasonal fluctuations in the Inter-Tropical Convergence Zone, ITCZ. Irrespective of the underlying mechanism, purely from the meteorological point of view, zonal and meridional heating gradients produced by clouds contribute in sustaining the circulation pattern. Having this in mind, the third question proposed here is to understand:

*How do the zonal and meridional vertical heating gradients change during monsoon months?*

### 1.3 Outline of the thesis

In Chapter 2, a more detailed overview of the ISM is carried out. Here the roles of different meteorological variables, the role of the Tibetan Plateau and the intraseasonal oscillations (the active and break periods) are described. A presentation of the TTL is given to illustrate its complexity, a couple of relevant tropical atmospheric circulations are also briefly described to give a more fundamental background to the origin of the ISM. Chapter 3 describes the data sets used in the present study. The method of approaching this work is presented in Chapter 4 and the results are presented and discussed in Chapter 5. A short summary and outlook is presented in the final chapter.

### 2 The Indian Summer Monsoon

It was in 1877, after a great drought and sequent famine in India, that the Indian Government Famine Commission gave the head of the Indian Meteorological Service, Mr H.R. Blandford, the mission of "so far as it may become possible, with the advance of knowledge, to form a forecast in the future, such aids should be made use of, though with due caution" (Webster et al., 1998). The first attempts to address this matter was through looking at local forcings of the radiative balance, for example the snow cover in the Himalayas in the previous winter (Blandford, 1884). Gradually the area of examination was expanded and many large tropical atmospheric circulations were scrutinized during this work. (Webster et al., 1998)

The ISM is often described as a very large sea breeze. The lower heat capacity of soil than water makes the land mass of Asia warm faster than the Indian Ocean during the boreal summer, creating a heat low over the Asian continent. This differential heating gives rise to a temperature gradient directed roughly northwards, and the corresponding pressure gradient generates southerly, or rather southeasterly, winds. These winds bring lots of warm, moist air in over the Indian subcontinent where convection occurs and heavy rain falls (Holton, 2004).

Extending the picture somewhat we note that the ISM and the Australian Winter Monsoon act together in creating the southwesterlies. The winds originate from the southern hemisphere as easterlies emerging from the Australian Winter Mon-
soon, then creating a large arc, cross the equator and sweep in over the Indian subcontinent as part of the ISM (Wallace and Hobbs, 2006).

The ISM sets in over the southernmost part of India around the beginning of June and spreads to the whole of India by around the very beginning of July. At withdrawal, it starts in the northwest and pulls away in a southeasterly direction. In appendix A, figures from the India Meteorological Department are included showing the normal onset and withdrawal of the ISM.

2.1 General characteristics of monsoon meteorology

2.1.1 Winds

Included in the definition of a monsoon is the seasonal reversal of the winds and in the case of the Indian monsoon the winds are mainly southwesterly during the summer and northeasterly during the winter. Figure 1 shows the mean surface wind patterns during the year, the picture is taken from the Indian National Institute of Oceanography. We can follow the wind pattern as it switches from northerly winds during March to southwesterly around the end of April/beginning of May. The winds are then persistently southwesterly during the summer months to reverse again towards the end of September/beginning of November. We can discern two branches of the summer monsoon approaching the Indian subcontinent, one western branch over the Arabian sea approaching the west coast of India and one eastern branch over the Bay of Bengal approaching the central, eastern and northeastern India.

2.1.2 Clouds

Most of the clouds in the monsoon region are of convective origin and deep convection is frequent. Even very deep convection that penetrates the bottom of the TTL occur in certain regions. Devasthale and Grassl (2009) studied deep convection in the Indian monsoon area during May to September 1982-2006. They identified three cloud classes in terms of their brightness temperature, $BT$; Class I: very deep convection ($BT < 220$ K), Class II: deep convection ($220$ K $<=$ $BT < 233$ K) and Class III: background convection ($233$ K $<=$ $BT < 253$ K). They derived a climatological spatial distribution of cloud amount for the three classes which are presented in figure 2. From the figure we can see that clouds are most frequent over eastern India and the Bay of Bengal and that the very deep convection is mostly occurring over the Bay of Bengal. We also note that Class II and Class III clouds have similar patterns except that Class III clouds are more frequent over the Tibetan Plateau.

Devasthale and Grassl (2009) also studied the cloud distribution for the individual monsoon months (May to September) over the years 1982-2006. Monthly distributions of the three cloud types are included in appendix B. From their figures it is clear that the eastern branch of the monsoon flow is the most convective one. We can follow the progression of the monsoon as it approaches from the east in May-June, covers most of central India and the Bay of Bengal in July-August and then withdraws towards the southeast again in September.

Other types of clouds that occur in the monsoon region are different types of cirrus clouds. Anvil clouds that remain after deep convective cores has died out, detrainment cirrus that is a product of the decay of the anvil clouds and in-situ formed cirrus clouds all appear in the tropical upper troposphere. In-situ formed cirrus clouds are produced by dynamical processes such as small-scale turbulent motions, gravity waves, large-scale waves or periods of large-scale uplift and are about as frequent as cirrus clouds caused by convection (Luo and Rossow, 2004).

2.1.3 Moisture

The air is moistened during the transport over the sea. As the western branch of the monsoon strikes the Western Ghats and the eastern branch strike the Eastern Ghats and the Himalayas, orographic precipitation is generated.

Convection is associated with low level convergence and so moisture is accumulated where convection occurs. Wong et al. (2011) studied water vapour and heat sources in the Indian monsoon area and found that when the convection is strongest over the tropical Indian Ocean the positive anomalies in the specific humidity tendency are located north of the convective area and found a link between this feature and the intraseasonal oscillations of the ISM (the intraseasonal oscillations are described in section 2.3). They also found that precipitation maxima over the India-Bengal region lags the strongest convection with about 10 days.

Ordóñez et al. (2012) identified four major moisture sources for Western and Southern India, WSI, two of them active during the wet season. The most important
moisture source during the wet season is the Somali Low Level Jet, *SLLJ*. This low level jet is a part of the prevailing southwestely winds during the summer months, located at around 850 hPa and strongest off the Somali coast. They also found that air parcels aimed for *WSI* often pass the area just to the northwest of *WSI* where they are moistened and this is the second most important moisture source. Towards the end of the monsoon season the recycling of moisture from the *WSI* itself becomes increasingly important but the other two sources acts during the whole monsoon period.

### 2.1.4 Precipitation

During the *ISM* heavy precipitation falls over India and in appendix C a figure from the India Meteorological Department is included showing the average spatial rainfall distribution over land areas during June to September and figure 3 A from Mishraa et al. (2012) showing the same over land and ocean. It is obvious that most rain over land areas falls along the Western Ghats and over eastern India and Bangladesh. Over the ocean most rain falls over Bay of Bengal and eastern Indian Ocean. Most of the rain that falls during the *ISM* is convective but the areas with the most rainfall is located where the topography causes additional orographic precipitation. The rain that falls over the west coast of India is mostly orographic as the western branch
of the monsoon winds strikes the Western Ghats. The area around eastern India and Bangladesh is highly convective but it is also at the foothills of the Himalayas so the precipitation here is a mixture of orographic and convective. The wettest place on Earth can be found in the mountains in Meghalaya in northeastern India (Devasthale and Grassl, 2009).

2.2 The role of the Tibetan Plateau

One of the features of the Asian continent that likely contributes to making the ISM the most distinguished of the monsoons, is the Tibetan Plateau. The mean elevation of the Tibetan Plateau is about 4500 m and it slopes steeply at its edges. It is argued that during the summer when the sun warms the soil of the continental Asia, the fact that the Tibetan Plateau is elevated intensifies the Asian heat low by providing conditions of elevated heating. (Kuo and Qian, 1981)

Others argue that it is the mechanical effect on the atmospheric flow that is the most significant of the Tibetan Plateau on the ISM. When the southerly monsoon winds hits the steep slopes on the southern side of the Tibetan Plateau it is forced to rise. As it does so it condensates, releasing latent heat and with this added energy enhances the rising motion. This way the Asian heat low and the ISM is enhanced. (Hahn and Manabe, 1975)

Yet another aspect of the Tibetan Plateau is that it mainly acts as a mechanical barrier between the warm moist air south of the Himalayas and the cold dry air further north. This barrier prevents the monsoon from propagating further inland, condensing and enhancing the monsoon. Boos and Kuang (2010) carried out model simulations with the Tibetan Plateau removed, but the Himalayas and adjacent mountain ranges preserved, and found that the monsoon was largely unaffected.

2.3 Active and break periods

The ISM experiences both interannual and intraseasonal fluctuations. The major feature of the intraseasonal fluctuations are the active spells, periods of abundant rainfall and strong winds, and weak or break spells, periods of deficit rainfall and weak winds. Active and break periods can be defined in terms of rainfall distribution or low level pressure and wind patterns. For the major part of the Indian population, the rainfall is the main point of interest of the monsoon and Kumar and Dessai (2004), for example, have defined a criteria for identifying active and break spells using rainfall anomalies. Gadgil and Joseph (2003) instead identify active and break spells through the synoptic weather situation, i.e. the surface pressure distribution and circulation associated with the rainfall anomaly. The India Meteorological Department apply this strategy of using the synoptic situation rather than the rainfall anomaly to identify active and break spells.

The cloud distribution during active and break conditions was also analysed by Devasthale and Grassl (2009). Figures 3 and 4 show the cloud amount distribution of the three cloud classes stated above during active and break periods respectively.
Figure 3: Cloud amount distribution, in %, of the different cloud classes (Class I represents very deep convection, Class II deep convection and Class III background convection) during active conditions averaged over the years 1982-2006. (Figure 6 from Devasthale and Grassl (2009).)

Figure 4: Same as figure 3 but during break conditions. (Figure 7 from Devasthale and Grassl (2009).)
averaged over the years 1982-2006. The most apparent difference in cloud cover between active and break periods is over the Arabian sea. During both active and break periods there are convective clouds over the Bay of Bengal and northeastern India but during break conditions there is almost no convective clouds at all over western India and the Arabian sea.

2.4 Relevance of large-scale atmospheric circulations

Being such a large atmospheric circulation pattern, the monsoon circulation cannot be neither unaffected by nor avoid affecting other atmospheric circulations in the area such as the *Walker circulation* and the *Hadley circulation*.

The Hadley circulation

The Hadley circulation, or the *Hadley cell*, is a thermally direct meridional circulation confined to the tropics and closely related to the trade winds. The heated air at the surface near the equator rises and is transported poleward in the upper troposphere. In the subtropics the air subsides and is then transported equatorward near the surface. At the same time the Coriolis force acts to deflect the meridional flow to the east at height creating easterlies here, and to the west near the surface creating the trade winds (Holton, 2004).

The *ITCZ* can often be identified as a zonal band near the equator with mighty convection and convergence in low levels. During the march of the year, as the solar zenith angle shifts northward or southward, the *ITCZ* shifts locations accordingly. Zonal bands with deep convection and convergence in low levels are also observed where the converging flow does not cross the equator. These zones are referred to as just Tropical Convergence Zones, *TCZ*. The *TCZ* in the region of the Indian monsoon can be viewed as the rising branch of the Hadley cell (Goswami and Ajaya Mohan, 2001). Sikka and Gadgil (1980) found that the *TCZ* over the Indian monsoon has two preferred locations, one to the north over the Indian continent and one to the south over the ocean. The location of the *TCZ* is associated with an active or break period. During an active period the northern position of the *TCZ* is typically favoured over the southern position and the other way around during a break period, when the southern position is preferred (Goswami and Ajaya Mohan, 2001).

The Walker circulation

The Walker circulation is a thermally direct zonal circulation over the equatorial Pacific Ocean. It has its rising branch over the warm waters in the western equatorial Pacific Ocean and the Maritime Continent. At higher altitude the air is transported eastwards to subside over the relatively cold waters in the eastern equatorial Pacific Ocean. The trade winds then close the circulation by transporting air westwards, back again over the Pacific Ocean (Holton, 2004).
Walker (1924) discovered a see-saw pattern in pressure fluctuations between western and eastern equatorial Pacific Ocean and named it the Southern Oscillation. Coupled with the oceanic phenomena of El Niño/La Niña the El Niño Southern Oscillation, ENSO, is a major oscillating phenomenon in the equatorial Pacific Ocean. The El Niño/La Niña include irregular annual warm water anomalies in the eastern equatorial Pacific Ocean. When the eastern equatorial Pacific Ocean becomes warmer, the trade winds are weakened and thereby, so is the Walker circulation. This is an El Niño event and its opposite condition is called La Niña. During an El Niño event when the trade winds are weakened, the large convective region over the Maritime continent can shift further east and the convection over the eastern Indian Ocean is hence weakened. In the case of a La Niña event, on the other hand, the pressure gradient over the Pacific Ocean is enhanced and the convection over the Maritime Continent is concentrated over the western equatorial Pacific Ocean/eastern Indian Ocean. This is a state that might have an amplifying impact on the ISM (Kumar et al., 1999). According to the National Oceanic and Atmospheric Administration, NOAA\(^5\), in July 2007 and 2008 ENSO-neutral conditions persisted, during July 2009 weak El Niño conditions were developing but during July 2010 the El Niño were suppressed and La Niña conditions started to develop.

### 2.5 The tropical tropopause layer

The standard view of the tropical tropopause as a sharp boundary between the troposphere and stratosphere is somewhat simplified. It is better described as a layer referred to as the Tropical Tropopause Layer, TTL, in which several processes occur that define the tropopause. The different parameters would each give slightly different levels of the TTL, but put together they give a consistent picture. Figure 5 is taken from Fueglistaler et al. (2009) and describes the complexity of defining the TTL. Fueglistaler et al. (2009) describe all the processes presented in the figure in detail but we will here settle for brief descriptions in the caption.

In this study we will use the Level of Zero clear-sky Radiative Heating, \(LZRH\), to define the bottom of the TTL (Fueglistaler et al., 2009). This is the most relevant parameter in our case as it can be derived directly from our data set of the radiative heating.

### 3 Data

We have analysed data of radiative heating and cloud fraction over India and surrounding areas for the summer months (April-September) 2007-2010. The data set used is the Level 2 Fluxes and Heating Rates Product, 2B-FLXHR, from CloudSat, a satellite developed by NASA and which is a part of NASA’s Earth System Science

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Figure 5: Processes involved in the definition of the TTL. $\Gamma$ is the temperature lapse rate, $T_{\text{min}}$ is the temperature minimum of the profile, $|T^*|$ is the amplitude of quasi-stationary zonal temperature anomaly, $|T'|$ is the amplitude of tropical mean temperature seasonal cycle, QBO is the mean stratospheric quasi-biennial oscillation and LZRH is the Level of Zero Radiative Heating. (Picture, figure 14 from Fueglistaler et al. (2009).)

Pathfinder Mission\(^6\). It carries an instrument called the Cloud Profiling Radar, CPR, which is a 94 GHz nadir-looking radar, measuring the power backscattered by clouds as a function of height. The CPR was developed by NASA Jet Propulsion Laboratory and the Canadian Space Agency jointly (CloudSat’s webpage\(^7\)).

CloudSat was launched in April 2006 and is part of a formation of 5 satellites with the same orbital tracks, separated by only 7 minutes from the first to the last. This means that the sensors on the different satellites observe virtually the same atmosphere, giving the scientists the opportunity to make use of a multisensor tool that no platform would have been able to accommodate by itself (L’Ecuyer and Jiang, 2010). This formation of satellites crosses the equator at around 1.30 PM local

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\(^6\)http://science.nasa.gov/about-us/smd-programs/earth-system-science-pathfinder/

\(^7\)http://cloudsat.atmos.colostate.edu/instrument
time, northbound, and is called the *A-Train*, short for the Afternoon Constellation (NASA’s A-Train constellation webpage\(^8\)). The A-Train satellites are near polar orbiting and carry both active and passive instruments. Collectively the sensors aboard the satellites in the A-Train view the Earth in a four-orders-of-magnitude wavelength range, from UV to microwave (L’Ecuyer and Jiang, 2010).

### 3.1 The 2B-FLXHR product

The algorithm in the 2B-FLXHR product uses atmospheric state variables and cloud ice/liquid water inputs retrieved from the *CPR* and post processed in other CloudSat 2B products\(^9\), listed below, to produce estimates of broadband radiative fluxes and corresponding heating rates at discrete levels for each radar profile. Each 2B-FLXHR output file consists of several vertical profiles making up one satellite orbit. In the algorithm aerosols are presently excluded (i.e. aerosol concentration is set to zero) and uniform mixing ratios of \(\text{CO}_2\), \(\text{CH}_4\) and \(\text{N}_2\text{O}\) are assumed of 360.0, 1.6 and 0.28 ppmv respectively. (L’Ecuyer et al., 2007)

2B CloudSat products required as inputs to the 2B-FLXHR product algorithm:

**2B-GEOPROF** The CloudSat geometric profile product which gives the starting time for the specific profile, time elapsed since that starting time, latitude and longitude, the height of each range bin and the surface bin number for each CloudSat pixel.

**2B-CWC** The CloudSat cloud water content product which gives vertical profiles of cloud liquid and ice water content, liquid and ice cloud effective radius, ice phase fraction and a status flag for each pixel.

There are also ancillary data that are used as input to the 2B-FLXHR algorithm. Atmospheric state variables, such as water vapour, temperature and ozone, is obtained from the European Center for Medium-Range Weather Forecast (ECMWF), visible and near-infrared surface albedo estimates is obtained from the CloudSat ancillary albedo product, AN-ALBEDO, and solar zenith angle is obtained from *MODIS* (Moderate Resolution Imaging Spectroradiometer, on board Aqua). (L’Ecuyer et al., 2007)

### 3.2 OLR from AIRS

In order to identify the active and break periods we used Outgoing Longwave Radiation, *OLR*, data derived from the Atmospheric Infrared Sounder, *AIRS*, instrument onboard NASA’s Aqua satellite, one of the other satellites in the A-Train. The time difference between Aqua and CloudSat is less than a minute which allows using *OLR* from *AIRS* without introducing any artifacts related to different spatio-temporal

\(^8\)http://atrain.nasa.gov

\(^9\)2B products implies a certain amount of post processing of the raw data from the satellite to retrieve geophysical variables
4 Method

The general approach of this study was:

- Relevant time periods and areas were selected and data were retrieved from the CloudSat Data Processing Center.
- For each cross section day-time data was selected, sorted into clear-sky and all-sky data points and CRH and LZRH was calculated.
- The data were binned to give a resolution of 250 m vertically and 5 degrees (roughly 550 km) horizontally to smooth out noise.
- A quality control of the data was applied by selecting only those fluxes and heating rate estimates where the input of temperature and cloud properties were also retrieved with high confidence based on the status flags provided in the data. The accuracy of the data is 1 K/day for instantaneous retrievals but when averaged over years and over 5 degree spatial bins, thousands of pixels are taken into account, thus improving the robustness of the analysis.
- The CRH was presented in vertical cross sections, three zonal and four meridional collectively covering the Indian subcontinent and surrounding seas, the latitudes and longitudes of which are listed in table 1. Section z1 roughly covers the Arabian Sea, section z2 the Indian peninsula, section z3 the Bay of Bengal, section m1 equatorial Indian Ocean, m2 southern India and parts of Arabian sea and Bay of Bengal, section m3 Central India and northern Arabian sea and northern Bay of Bengal and section m4 covers mainly the Himalayas and the Tibetan Plateau.
- The CRH was defined as:

\[
CRH = (SWHR_{allsky} - SWHR_{clear}) + (LWHR_{allsky} - LWHR_{clear})
\]

Where \( SWHR_{allsky} \) is the all-sky shortwave heating rate, \( SWHR_{clear} \) is the clear-sky shortwave heating rate, \( LWHR_{allsky} \) is the all-sky longwave heating rate and \( LWHR_{clear} \) is the clear-sky longwave heating rate.
- We defined the bottom of the TTL in terms of the clear-sky LZRH. The locations of this level was retrieved from the daytime clear sky conditions net radiative heating and applied to the corresponding plots of the CRH.
Active and break periods were selected as follows; First, a time series of daily \textit{OLR} values for Central India was prepared for the July and August months of 2007-2010. June and September data were excluded as the variability of the onset and withdrawal of the monsoon may give too much influence; a late onset or an early withdrawal could give false signals of break days. The same geographic region as considered in the study by Rajeevan et al. (2010) (roughly 18-28°N and 68-90°E) is used for our \textit{OLR} analysis. The whole \textit{OLR} time series, for the study period of interest, is then standardized by subtracting the calculated climatological mean from each daily value (averaged over Central India) and dividing it by the standard deviation. An active period is then defined as a period when standardized \textit{OLR} values are less than -1.0 and remain so for at least three consecutive days. A break period is conversely defined as a period when the standardized \textit{OLR} values are greater than 1.0 and remain so for at least three consecutive days. \textit{CRH} is then calculated for the two composites of active and break periods.

Matlab was used to process the data and to plot the figures and everything was run on the National Supercomputer Center’s, NSC’s, supercomputer Vagn.

\begin{table}[h]
\centering
\caption{Areas for the different vertical cross sections, three zonal and four meridional.}
\begin{tabular}{|c|c|c|}
\hline
\textbf{Zonal cross sections, 20°S - 40°N} & \textbf{Meridional cross sections, 50°E - 110°E} \\
\hline
one \_z1 & 65 - 75°E & one \_m1 & 1 - 12°N \\
two \_z2 & 75 - 85°E & two \_m2 & 12 - 20°N \\
three \_z3 & 85 - 95°E & three \_m3 & 20 - 28°N \\
\hline
four \_m4 & 28 - 35°N & & \\
\hline
\end{tabular}
\end{table}

5 Results and Discussion

The total cloud fraction over India averaged over the monsoon months June-September is presented yearly from 2007 to 2010 in figure 6. It is clear that the cloud fraction is in general very high, close to 100\% over convectively active regions and that there is little variability between the years. This provides further support as to why clouds are so important to the monsoon system and why we should study radiative heating of clouds.

The results will be presented here in the following order: First we present the total \textit{CRH} averaged over all summer months June-September over the years 2007-2010, then monthly \textit{CRH} from pre monsoon (April) to post monsoon (September), with a comparison with the vertical cloud fraction, and finally \textit{CRH} in the cases of active and break periods.
5 RESULTS AND DISCUSSION

Figure 6: Total cloud fraction averaged over the monsoon months June-September for each of the examined years 2007-2010.

5.1 Zonal and meridional distribution of CRH

The zonal distribution of CRH averaged over all summer months, June-September, over the years 2007-2010 is presented in figure 7 along with corresponding LZRH representing the bottom of the TTL, for sections z1, z2 and z3. Figure 8 shows the same for sections m1, m2, m3 and m4.

5.1.1 Zonal distribution

The most noticeable feature in figure 7 is that the average CRH is stratified in two layers, most likely as a result of compositing different cloud types together. As an example, three cloud scenarios from different days during our study period is included in appendix D. The cloud scenarios show the cloud types of the present cloud cover along the path of CloudSat and further explain the observed stratification in the CRH.

As mentioned in section 2.1, a number of cloud types occur over the Indian monsoon region. Both convectively and in-situ formed cirrus clouds are frequently present above 7-8 km, i.e. close to the tropopause (Luo and Rossow, 2004). Most of the convection and the decaying remnants of convective anvils are on the other hand typically observed up to 8 km altitude (e.g. Zuluaga et al., 2010). Compositing these cloud types may have lead to the stratified pattern observed in figure 7.
5 RESULTS AND DISCUSSION

Figure 7: Zonal cross sections of the total CRH [K/day] averaged over the whole monsoon period, June to September for the years 2007-2010. The uppermost subfigure shows z1, the middle one shows z2 and the lowermost shows z3. White lines in all figures are the LZRH, representing the bottom of the TTL, for each cross section.

In general, there is a clear meridional heating gradient in the upper troposphere (around 10-12 km), flanked on either side of 5-10°N latitude band. This gradient is relatively steeper across the northern latitudes. This could mainly be because the convection over land areas is stronger and deeper than over ocean. Enhanced deep convection support an increase in the formation of convectively formed cirrus clouds in the upper troposphere leading to a higher heating rate. Especially, along the foothills of the Himalayas (20-25°N), heating rates close to or exceeding 2 K/day are observed. It is well known that the strong solar heating of the surface together with the blockage of advected moisture by the Himalayas and the Tibetan Plateau provide favourable conditions for the formation of penetrative convection over this latitude band. The mechanical lifting of the moist air also promotes the convection in which latent heat is released which process further enhances the convection. The height difference in maximum heating between the equator and 30°N is about 2 km which is significant. This meridional heating gradient is an important strengthening factor of the atmospheric monsoon circulation.

The CRH in the lower troposphere is confined to a narrow layer at about 7-8
km altitude. This is the level most convection reaches and detrains. The absolute amount of the CRH in the lower troposphere is as large as in the upper troposphere (approximately 1.5 K/day) but condensed in this narrow layer, where thick anvil clouds are responsible for most of the CRH.

5.1.2 Meridional distribution

The meridional distributions, figure 8, show a similar vertical two-layer stratification of CRH as seen in the zonal cross sections in all sections except m4. Over the Tibetan Plateau, the Himalayas and adjacent mountain ranges i.e in section m4, clouds mainly occur in the lower troposphere and cirrus are rare. This gives us the opportunity to see the effect the absence of an additional cloud layer has on the cloud tops in the lower troposphere. In section m4, heating rates are high (up to 5 K/day) in the lower troposphere whereas there is a layer of cooling located directly above the heating layer. The cooling layer is caused by the presence of clouds underneath that block the long wave radiation from the surface to this level. This type of cooling always occurs at the top of a cloud layer but in sections m1-m3 it is masked by the presence of cirrus clouds which emit longwave radiation downwards. If we scrutinize the zonal cross sections (figure 7) we can distinguish the same type of cooling layer as in m4 in the middle troposphere in the northernmost part of all sections.

In sections m1 and m2 the maximum CRH is found in the lower troposphere over the Bay of Bengal (90°E). This is consistent with the intense mesoscale convective systems frequently occurring over this region. The largest bulk of heating though occurs in the upper troposphere where the cirrus clouds absorb radiation. In section m3, heating in the upper troposphere is strongest in the region just to the south of the Himalayas (80-90°E) where the mountains enhance the convection and deep convection is most frequent (most heating in the lower troposphere occurs near 60°E but that is in Iran).

5.2 Pre-to-post monsoon transitioning of CRH

In this section we will focus only on the zonal cross sections as these provide sufficient information on the progress of the monsoon. The meridional cross sections are for completeness included in appendix E.

Figure 9 presents the vertical cloud fraction monthly over the zonal cross sections to put the CRH in relation to the general cloud distribution. Figure 9 clearly shows the progression and recession of the monsoonal cloud systems over the Indian subcontinent. In April, high convective cloud systems are mainly confined to near-equatorial regions, while low and medium level clouds are present over the northermost parts of the study area. In May, convection starts intensifying over the southern parts of the Arabian Sea (z1) and Bay of Bengal (z3) and progress towards the subcontinent. In June, July and August, the entire subcontinent is covered by clouds, and convection is the most intense and deepest. In September, the overall cloud fraction is reduced over the subcontinent as the monsoon withdrawal begins.
RESULTS AND DISCUSSION

Figure 8: Same as figure 7 but meridional cross sections. Upper left subfigure shows section m1, upper right m2, lower left m3 and lower right m4.

Figure 9: Vertical cloud fraction for all three zonal cross sections, monthly from April to September averaged over the years 2007-2010. White lines in all figures are the LZRH, representing the bottom of the TTL for each cross section and month.
It is interesting to note that the cloud fraction displays signs of a similar type of vertical stratification as noted in the CRH rates. When the monsoon is at its peak, highest cloud fraction is observed at 10-13 km altitude.

The footprints of this pre-to-post monsoon transitioning of convective systems over the Indian subcontinent can also be distinguished in the CRH patterns shown in figures 10-12 for the sections z1-z3 respectively. The meridional heating gradient mentioned in section 5.1 reverses during the course of the transition from pre-to-post monsoon. In April, the maximum heating rate is at 10°N located around 12 km altitude. Further south and further north, the heating maximum is located at lower altitudes. In May, the heating maximum is located at approximately the same altitude at all latitudes. During the monsoon season, the vertical location of the maximum heating increases significantly south and north of 10°N and the meridional heating gradient in the upper troposphere is thus reversed compared to the pre-monsoon season.

The meridional heating gradient is in general the steepest in z1\textsuperscript{10}. In z2 and z3, the entire upper troposphere between 10 and 30°N remains warm throughout June to September, reducing the meridional gradient. The highest heating over z1 occurs in August at around 14 km, over z2 in July at around 13 km and over z3, in June at around 12 km, with an absolute amount of about 2 K/day in all sections.

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\textbf{Figure 10:} Monthly CRH [K/day] from April to September in section z1 averaged over the years 2007-2010. White lines are the LZRH, representing the bottom of the TTL.

\textsuperscript{10}There is a discontinuity in the upper troposphere in section z1 during May and June. This is presumably due to the data sampling because we cannot find any physical explanation.
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Figure 11: Same as figure 10 but for section z2.

Figure 12: Same as figure 10 but for section z3.
5.3 CRH during active and break periods

Figure 13 shows the CRH during active and break periods, and the difference between them, for the three zonal cross sections. We still have the same two-layer vertical structure, both during break and active periods. It is also clear that clouds reach, and thus likely penetrate, the TTL more often during active periods compared to breaks (this is especially visible at around 20°N in the lower row of subfigures). This was expected since the convection during active periods is deeper than during breaks and hence associated anvil and cirrus clouds are more frequent. The heating of the upper troposphere is for the same reason found to be larger during active than break periods. In combination with the increased frequency of penetration of the bottom of the TTL the active phase of the ISM may have impact on the composition of the TTL.

Comparing active and break periods, there is a positive difference in heating (about 1 K/day) that is especially pronounced through the vertical column around 20°N in section z2 suggesting strong differences in deep convective activity during active and break periods over this region. In section z3 the area with positive difference in heating around 20°N is stretched both horizontally and vertically but it is not very strong in terms of absolute amount (about 0.5 K/day), suggesting relatively smaller differences in convective activity. The difference in heating in section z1 is on the other hand relatively unchanged and rather slightly negative than positive around 20°N. It is surprising that the difference in CRH over the Arabian sea is less than over the Central India and the Bay of Bengal when according to figures 3 and 4 the largest difference in cloud cover between active and break periods occur over the Arabian sea. This discrepancy is most likely due to the fact that Devasthale and Fueglistaler (2010) (from which paper we have taken figures 3 and 4) used a definition of the active and break days based on the all-India rainfall and ours is based on the OLR over Central India. We chose this definition because we study clouds and are most interested in the Indian subcontinent. The discrepancies between the two definitions is mainly that the definition used by Devasthale and Fueglistaler (2010) takes a larger area into account (the whole India) while our definition only consider Central India. This way days where active or break conditions prevail in Central India are included during which active or break conditions are not met over the Arabian sea. The results in sections z2 and z3 are still reliable and the maximum difference in CRH between active and break periods, 1.5 K/day, occur at around 20°N in section z2, at the foothills of the Himalayas. The meridional cross sections are included in appendix F.

6 Conclusions and Outlook

Clouds are an important component of the global water and energy cycle. Their role for the Indian climate is crucial considering the dependence of India’s socio-economic structure on seasonal monsoonal rainfall which, in turn, is mainly derived from the
Figure 13: \( CRH \) [K/day] during active and break periods and the difference between them for zonal cross sections z1, to the left, z2, in the middle, and z3, to the right, respectively. White lines are the \( LZRH \), representing the bottom of the \( TTL \).

convective systems. Examining the radiative heating/cooling produced by clouds (\( CRH \)) is essential to fully understand cloud-radiation-climate links. \( CRH \) has been studied here using state-of-the-art satellite data. To the authors knowledge, this is the first time that the vertical structure of \( CRH \) has been quantified with such a high detail and accuracy. The total cloud fraction is close to 90-100% over large parts of the ISM region. This alone justifies the study of the \( CRH \).

Some intriguing results have been found in this study. Key points include:

- In the upper troposphere (above 10 km) a well-defined meridional gradient in \( CRH \) extending from the equator to 30°N was found during the monsoon months. This gradient is mainly a result of high cirrus cloud fraction originating from convection, which is strongest towards the north of the monsoon region, as well as formed in-situ.

- An analysis of the monthly evolution of \( CRH \) shows that the sign of the meridional heating gradient in the upper troposphere reverses as pre-to-post monsoon transition occurs.

- The meridional heating gradient in the upper troposphere is steepest when the monsoon is in an active phase. An additional heating of about 1-2 K/day was observed over the latitude band at 20-25°N during the active phase compared to the break phase.
The heating along the bottom of the TTL is higher during active periods compared to break periods, indicating a high impact of the active periods on the composition of the TTL.

An interesting extension to this thesis would be to study the total diabatic heating in the monsoon area by taking into account latent heating, $LH$, as well. Zuluaga et al. (2010) studied the $LH$ in the ISM region (see appendix G where figure 4 from their paper is included). It is interesting to note that although the $LH$ rates are in general clearly larger than the $CRH$ rates, the two heating rates are still of the same order of magnitude. Further investigations to assess how the differences in $CRH$ and $LH$ during active and break periods would influence the atmospheric circulation and the composition of the TTL may also yield some interesting results.

Another interesting aspect of this work, which we have excluded due to time limitations, would be to look into the contribution to the $CRH$ from different cloud types. The CloudSat algorithm does sort the clouds into different cloud types and so it is seamlessly compatible with our data.

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References


REFERENCES


A Normal onset and withdrawal of the ISM

Figure 14: Normal onset of the ISM. (Picture from the India Meteorological Department; http://www.imd.gov.in/section/nhac/dynamic/Monsoon_frame.htm, Nov 29, 2012.)

Figure 15: Normal withdrawal of the ISM. (Picture from the India Meteorological Department; http://www.imd.gov.in/section/nhac/dynamic/Monsoon_frame.htm, Nov 29, 2012.)
B Cloud distribution

Figure 16: Cloud amount, in %, Class I clouds, very deep convection, for each month, May-September, averaged over the years 1982-2006. (Figure 3 from Devasthale and Grassl (2009).)

Figure 17: Cloud amount, in %, Class II clouds, deep convection, for each month, May-September, averaged over the years 1982-2006. (Figure 3 from Devasthale and Grassl (2009).)
Figure 18: Cloud amount, in %, Class III clouds, background convection, for each month, May-September, averaged over the years 1982-2006. (Figure 4 from Devasthale and Grassl (2009).)
C Normal rainfall during June-September

**Figure 19:** Normal rainfall distribution during the summer months June-September. (Picture from the India Meteorological Department; http://www.imd.gov.in/section/nhac/dynamic/Monsoon_frame.htm, Jan 29, 2013)

**Figure 20:** Climatological rainfall distribution for June-September averaged over the 30 year period 1979-2008. Figure 3 A from Mishraa et al. (2012).
Cloud scenarios

Cloud scenarios from the CloudSat 2B-CLDCLASS product.

Figure 21: Cloud scenario June 26 2007, identifying the cloud types in the cloud cover observed by CloudSat.

Figure 22: Cloud scenario July 8 2008.
Figure 23: Cloud scenario July 18 2008.
E Monthly meridional cross sections

Figure 24: Monthly $CRH$ [K/day] from April to September in section m1 averaged over the years 2007-2010. White lines are the $LZRH$, representing the bottom of the $TTL$.

Figure 25: Monthly $CRH$ [K/day] from April to September in section m2 averaged over the years 2007-2010. White lines are the $LZRH$, representing the bottom of the $TTL$. 
Figure 26: Monthly $CRH$ [K/day] from April to September in section m3 averaged over the years 2007-2010. White lines are the $LZRH$, representing the bottom of the $TTL$.

Figure 27: Monthly $CRH$ [K/day] from April to September in section m4 averaged over the years 2007-2010. White lines are the $LZRH$, representing the bottom of the $TTL$. 
Meridional cross sections during active and break conditions

Figure 28: CRH [K/day] during active and break periods 2007-2010 and the difference between them for meridional cross sections m1, m2, m3 and m4. White lines are the LZRH, representing the bottom of the TTL.
G Latent heat distributions

Figure 29: Longitude-height distributions (i) and average vertical profiles of LH (ii) for each year from 1998 to 2006 and the mean over all years for (a) Bay of Bengal, (b) Equatorial Indian Ocean, (c) Western Ghats and (d) Central India. (Figure 4 from Zuluaga et al. (2010).)