Other minor editorial changes (apart from the changes highlighted by yellow colour in the revised manuscript):

1) The abstract is revised, shortened and rewritten to improve clarity.
2) Line 119: Web-link to the data set documentation removed and the relevant reference (Henderson et al. 2011) is added instead.
3) Line 192: Citation to the GPCP precipitation data set moved in to the reference list.
4) Section 3.1: The first para from the old manuscript removed to improve continuity.
5) Section 3.5: Intraseasonal oscillations are referred consistently as active and break “periods” instead of using multiple words like “conditions” or “phases” as synonyms to improve coherency in the language.

Norrköping, 2015-07-28

Response to Referee #1

We would like to thank the referee for her/his comments that have helped improving the manuscript significantly. Please find below our point-by-point response to your comments.

1.This paper shows plots of geographic and seasonal variation of cloud radiative heating profiles over India, and speculates on the role that these heating rates may play in the monsoon, shows pdf's of cloud radiative heating in the TTL, and compiles some regional mean estimates of radiative energy balance terms. I don't have a substantive criticism with the analyses in the paper. However, the paper is mainly descriptive, and does not contribute a compelling contribution to any particular topic, in my opinion.

While we agree that the novelty of our work was not put forward justifiably in the previous version of the manuscript, we respectfully disagree that our work does not contribute at any particular topic. We had clearly defined and addressed four scientific questions related to intra-seasonal cloud variability during monsoon that can only be investigated using CloudSat+CALIPSO data. The main focus of our study is to quantify the vertical structure of cloud radiative heating and this aspect is not addressed by any previous study over the Indian subcontinent. The four scientific questions read:

1) How does the vertical distribution of CRH evolve over the Indian continent during pre-monsoon, monsoon and post-monsoon seasons?
2) What is the absolute contribution of different clouds types to the total CRH?
3) How do active and break periods of monsoon affect the distribution of CRH?
4) What are the net radiative effects of different cloud types at surface?

The first three questions are discussed with specific focus on the UTLS region. Addressing these questions would help accurately quantify the role of different cloud types in the total diabatic heat budget of the atmosphere and the impact of individual cloud types on the surface radiation budget, in order to eventually understand how clouds influence the monsoonal circulation.

2. For example, a substantive paper might have compared the estimates of cloud radiative heating, ice and liquid water path, and cloud fraction they were using with the globalCERES, or other, data sets.

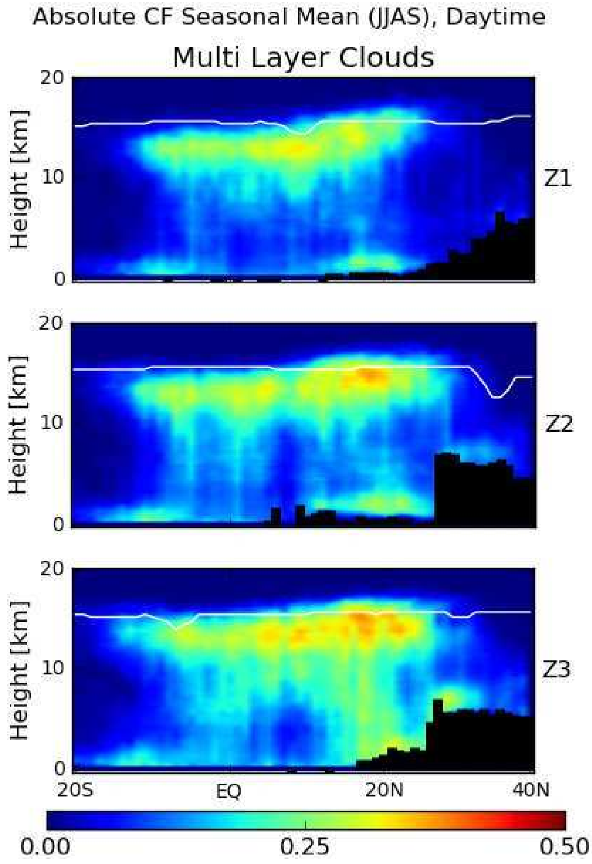
The point of the reviewer is well taken. However, it is to be noted that we have in fact used CERES data as shown in Fig. 7 of the manuscript.

The limitation of CERES (or other imager-based) data sets are that they cannot vertically resolve different cloud types that are of particular interest for detailed monsoon studies (convective towers, cumulonimbus, cirrus etc), nor do these data sets provide radiative heating profiles. So a direct comparison is in our case unfortunately not possible.

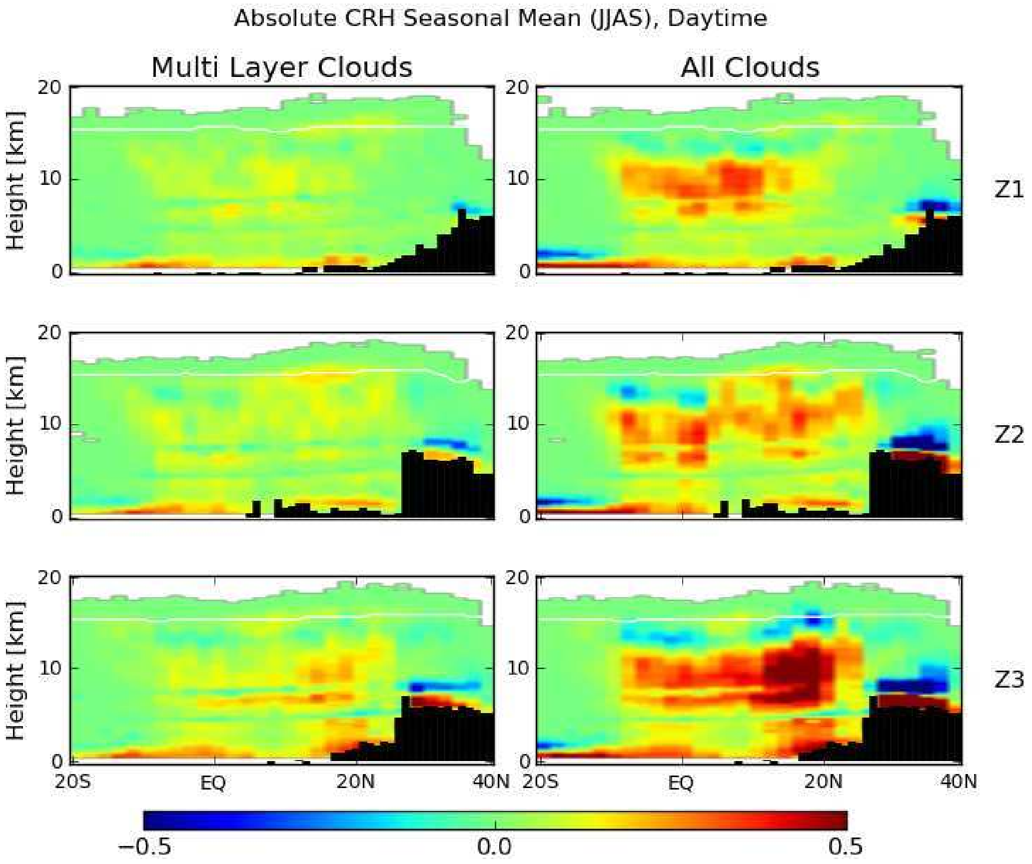
However, the CERES data are very useful to obtain a spatial overview of total net cloud radiative forcing and to set the stage for subsequent detail discussions using profiles from CloudSat+CALIPSO, as was done in the manuscript. Furthermore, we had clearly referred to CERES data wherever relevant (e.g. page 5439, line 19-23).

3. Maybe they could have looked at cloud vertical overlap statistics, an important consideration in cloud radiative modelling with larger grid cells. Perhaps these quantities could have been compared with model output.

The topic of multilayer clouds is indeed important, in particular for the modelling community. We have in fact analysed the cases with multilayer clouds, but chose not to show these results as the focus of the present study is on cloud radiative heating and the contributions from individual cloud types. The figure below shows a vertical cross-section of cloud fraction when two or more layers are detected by CloudSat+CALIPSO over the selected three zones and averaged over the JJAS months. We can clearly see increasing importance of cloud overlap towards the east of the study area (from the Arabian Sea to Bay of Bengal, and also on the continental parts) as well as a preponderance of high cirrus clouds and a zonal gradient in their occurrence.



The figure below shows corresponding radiative heating from these multilayer clouds. For comparison, the radiative heating from all clouds (i.e. single and multilayer clouds averaged together) is also shown. It is evident, based on these two figures below and Figs. 8-10 in the manuscript, that the heating produced by individual stratiform and convective clouds dominates the radiative heating budget in the middle and upper troposphere, and that the atmospheric cooling produced at the tops of these clouds would dampen the heating produced by high clouds under multilayer situations.



4. Perhaps the variation in cloud radiative heating rates could have been lacked at in relation to other geophysical variables such as rainfall.

As mentioned before, the focus of the present study is **purely on the radiative component of the heating** as this has been the key knowledge gap. In the future, as we additionally will investigate the role of **latent heating component** in governing the monsoonal circulation, the rainfall becomes an important variable to be considered.

5. I would therefore like to see a more strengthened and focused paper, and think the best option would be to reject and perhaps resubmit later.

We have carried out additional analysis of cloud radiative effects to strengthen the focus of the paper. For example, a new subsection has been added in the revised manuscript where the sensitivity of the CRE to the estimated ice water path is discussed.

The new subsection now reads:

…"High values of standard deviations in all cases indicate that a large variability exists in the net impact of clouds on the atmosphere and at the surface. One of the reasons behind such high standard deviation values could be variations in microphysical properties for a particular cloud type. This aspect is further investigated by examining the relationship between CREs and ice water path as ice phase clouds are predominant over the study area and the focus of the present study is on the upper troposphere and lower stratosphere region, where these clouds are prevalent. Fig. 13 shows the results for the entire study area for JJAS. Mean CREs and their standard deviations (in dotted lines) for daytime conditions are shown for the atmosphere and the surface. High clouds with low ice water path (< 0.1 kg.m^{-2}) produce CRE in the order of ±100 W m^{-2} at the surface, however, the cooling tendency becomes stronger as the total ice condensate increases with CREs reaching -500 W m^{-2} to -700 W m^{-2} at the surface when ice water path values reach 3.0 kg m^{-2}. The atmosphere is consistently warmed irrespective of the value of ice water path as ice crystals absorb radiation throughout the cloudy layers."

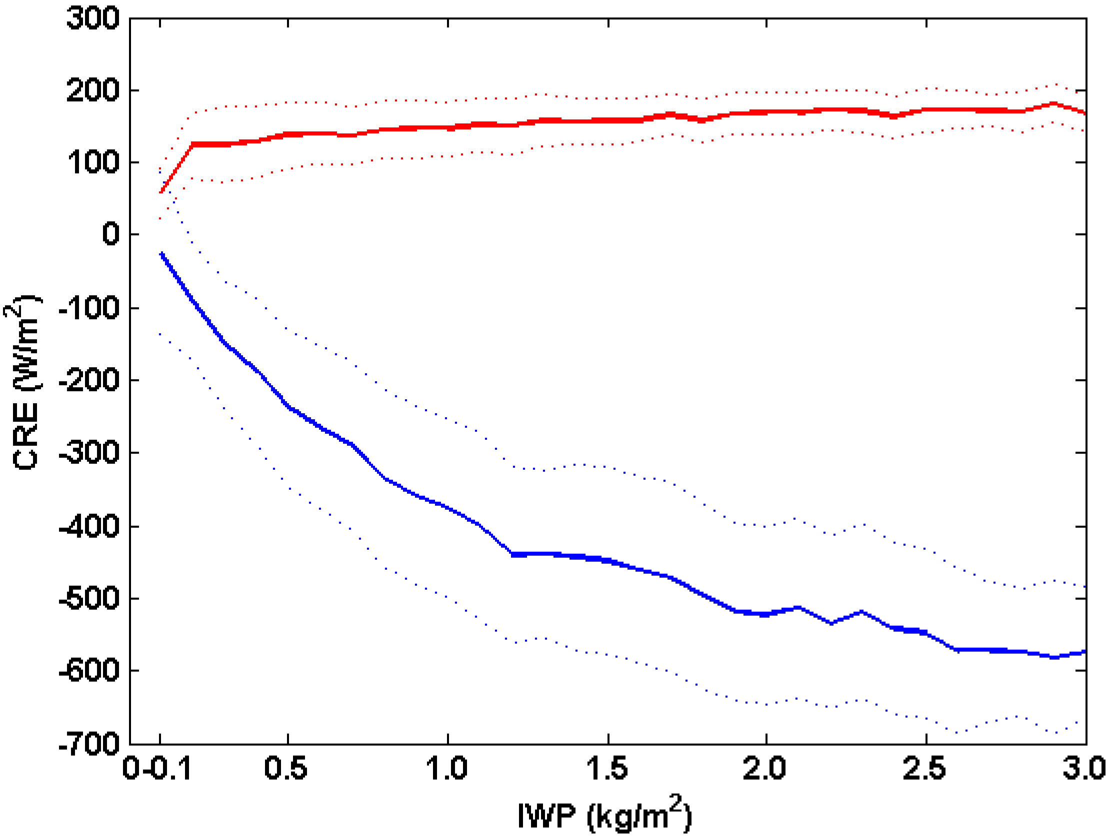


Fig. 13: CRE at surface (blue lines) and in the atmosphere (red lines) as a function of ice water path. The dotted lines show standard deviation in each case. The statistics is compiled for the JJAS months over the entire study area northward of the equator.

We hope that our clarifications would alleviate referee's concerns and that the revised version would meet her/his expectations. We kindly request the referee to read our response to Referee #2 as well.

Technical Issues

I didn’t find the cross-sections shown in Figure 4, 6, 8, 9, and 10, S1 - S5 very illuminating. What would have been more useful, and easier to interpret, would have been mean vertical profiles (and perhaps comparisons with other observational data sets).

As mentioned in the manuscript (page 5431, lines 3-14), the cross-sections are selected on the basis of distinct precipitation regimes that occur over these regions (Fig. 3, right panel) and also based on the spatio-temporal distribution of convective cloud regimes observed over these latitude bands investigated by previous studies (Devasthale and Grassl, 2009; Devasthale and Fueglistaler, 2010). We choose to retain height-latitude cross-sections as they provide important information on the zonal migration of cloud systems during monsoon months. Furthermore, these cross-sections illustrate the zonal gradient in radiative heating. Such information would be lost if we average data to mean vertical profiles as suggested by the referee. However we do understand the referee’s point that having mean vertical profiles would be easier to interpret. Hence we have now revised Figs. 4, 8, 9, 10 and S1-S3 and appended mean vertical profiles to them.

The paper at times contains odd language, e.g. "palpable", "potentcy", "tangible" in the Introduction

The introduction section is now revised and the usage of such words is avoided.

How are equations (5) and (6) related. Is "f" the same as "factor"?

Yes. This was already corrected in the manuscript version that appeared online.

It is unclear what "absolute fraction" after Eq (7) means.

As mentioned on Page 5430, lines 12-13, the absolute cloud fraction is the number of cloudy pixels within each altitude-latitude bin divided by the total number of observations (cloudy+clear) in that particular bin.

At various times, the paper has motherhood statements about the effects of cloud radiative heating on tropical dynamics. Of course this is true, but the paper does not really treat this topic, so the references to these interactions seems misleading. The paper also contains unneccessary references to e.g. the indirect aerosol effect.

The point of the reviewer is well taken. The revised version is more coherent and the reference to indirect aerosol effect is removed.

Norrköping, 2015-07-28

Response to Referee #2

We would like to thank the referee for her/his comments that have helped improving the manuscript significantly. Please find below point-by-point response to your comments.

General comments: The present study provides various cloud radiative parameters over the Indian summer monsoon region (eg., cloud radiative heating (CRH), contribution of different cloud types to total CRH, distribution of CRH during active and break monsoon conditions and radiative effects of different cloud types, etc) based on measurements from CloudSat and CALIPSO satellites which carry active radar and lidar sensors. Discussions on the role of CRH with regard to monsoon circulation are mostly descriptive. For example, the authors mention that the net radiative warming of clouds together with latent heating sustains the monsoon circulation. However, individual contributions of latent heating and net radiative warming of clouds on the monsoon circulation are unclear; and therefore deriving this information from satellites would be valuable for understanding monsoons. While some of the results are interesting, the present work needs to be substantially improved and greatly strengthened. This is essential to bring out important value additions about CRH over the Indian monsoon region. As such, this manuscript is not acceptable for publication in ACP in the present form.

Indeed, our ultimate aim is to fully understand the role of latent and radiative heatings in governing the monsoonal circulation. But before comparing and contrasting these two terms, both of them first need to be quantified. The latent heating component has already been investigated before over the South Asian monsoon regions (e.g. Zuluaga et al. 2010, and references therein) using TRMM data which has provided valuable information since 1997. **Comparatively, very little is known about the *radiative component* of the total heating. Thus, the focus of this study is precisely on this gap and to quantify the radiative heating using CloudSat+CALIPSO data.** For this reason, we exploit the ability of CloudSat and CALIPSO to provide a vertical structure of cloud cover and quantified the intra-seasonal variability in cloud radiative heating. Such detailed quantification, especially focusing on contributions from individual cloud types, has (according to your knowledge) never been done before.

In the revised draft, we have tried to clarify the additional value of our study. We have also added a section that investigates the sensitivity of the cloud radiative effects to derived ice water paths over the Indian subcontinent.

The revised paragraph from the Introduction section, that is relevant here, now reads:

…"While the role of latent heating has been previously investigated in a few studies (Zuluaga et al., 2010 and references therein), comparatively little is known about the radiative contribution to the total heating. This is the knowledge gap that the present study aims to address over the Indian subcontinent. This knowledge gap is evident from the significant differences in current CRH estimates amongst various reanalyses (Ling and Zhang, 2013; Wright and Fueglistaler, 2013), as well as disagreements between models and observations (McFarlane et al., 2007)."

Specific comments: (1) The authors suggest that deep convection produces strong cooling at the surface during active periods of monsoon; whereas stratiform clouds are important during break periods. These results are somewhat different from earlier studies. During active monsoon conditions and periods associated with monsoon synoptic systems like the Bay of Bengal depressions, measurements from the TRMM Precipitation Radar (PR) indicate preponderance of stratiform rain and the coverage of fewer deep convective elements (Ref: Stano et al. 2002, Houze et al., 2007, Krishnan et al., 2011, Romatschke and Houze, 2012). The dominance of nimbostratus clouds during monsoon depressions was noted by Stano et al. (2002). The latent heating due to stratiform precipitation during active monsoon conditions drives continental scale circulation in the mid-tropospheric levels extending vertically up to 300 hPa (Choudhury and Krishnan, 2011). According to these studies, stratiform clouds are very important for large scale organization of monsoon convective activity. This is something that the authors need to carefully address in the context of their analysis.

Firstly, we would like to thank the referee for the highly relevant references. We would like to point out that our results do not actually contradict the results from these earlier studies. We are not arguing that stratiform clouds are not important during active phases of monsoon in absolute terms, but, rather, we investigated **how their radiative effects comparatively vary** with deep convection during active and break phases. Stratiform cloud fraction is usually certainly higher than deep convective towers in both active and break periods. In fact, based on 25-year AVHRR climatology, we (Devasthale and Grassl, 2009; Devasthale and Fueglistaler, 2010) have previously shown that the presence of stratiform clouds (classified as optically thick ice clouds with top temperatures between 233K and 253K, denoted as Class III convection in that study) is critical to sustain active phases of monsoon over the Arabian Sea and western parts of the Indian subcontinent and over the Bay of Bengal as well. We are actually arguing that the stratiform clouds gain further importance under the break spells, as very deep convection is comparatively suppressed.

The results in Table 2 can be explained by the fact that CRE values are averaged over cloudy pixels only. But if we were to take into account the frequency of occurrence of stratiform and convective clouds (i.e. normalize CREs with cloud fraction), then the normalized magnitude of their CREs would be higher during active months compared to break periods and higher for stratiform clouds than convective clouds.

The two figures below (which are also added as supplementary figures S7 and S8 in the revised manuscript) show vertical cloud fraction during active and break periods for the two cloud types in question, i.e. deep convection and stratiform. It is evident that while deep convective towers are well established north of the equator during active phases (esp. in Z1 and Z2), they are suppressed during break phases and remain confined to the equatorial regions except in Z3 over the Bay of Bengal. Comparatively, stratiform clouds prevail not only under active phases, but also during break periods over the continent in Z3. Moreover, they are deeper over the continent in Z3 during break periods (in average). When stratiform clouds are formed after intense surface warming during pre-break periods, they are more vigorous and optically thicker, thus causing more cooling compared to active conditions (as reflected in Table 2).

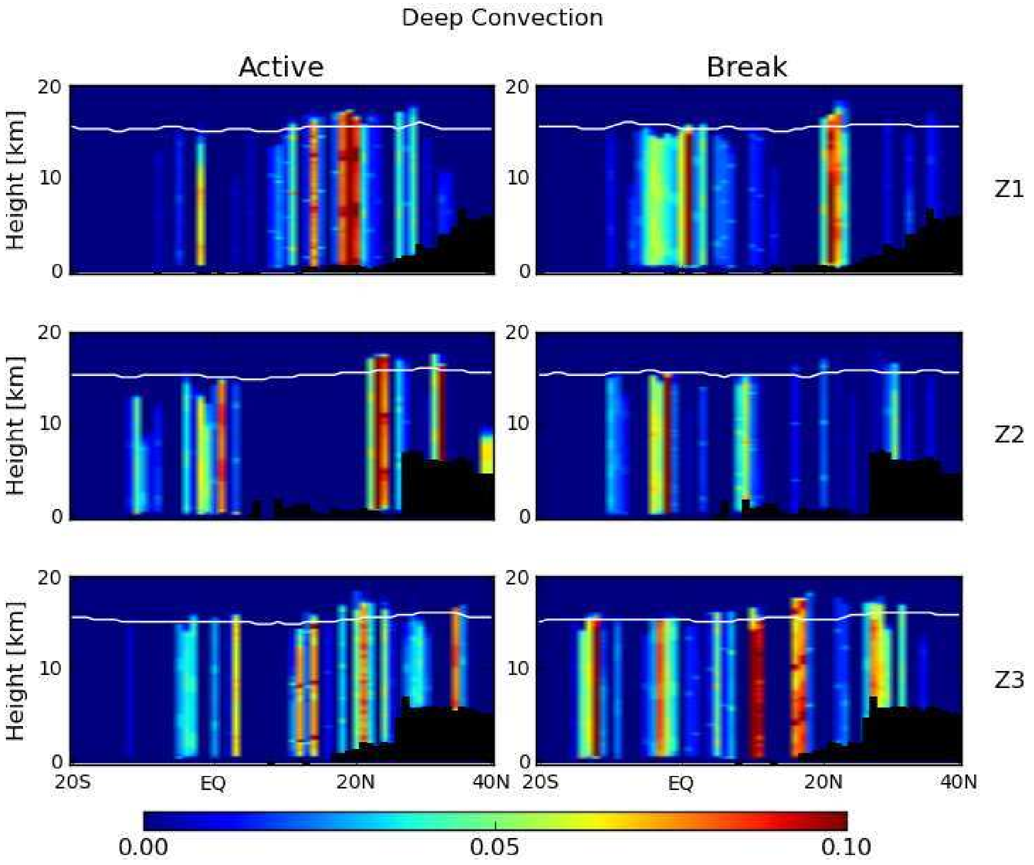


Fig. S7: Vertical cloud fraction of deep convective towers over the selected three zones during active and break periods of monsoon.

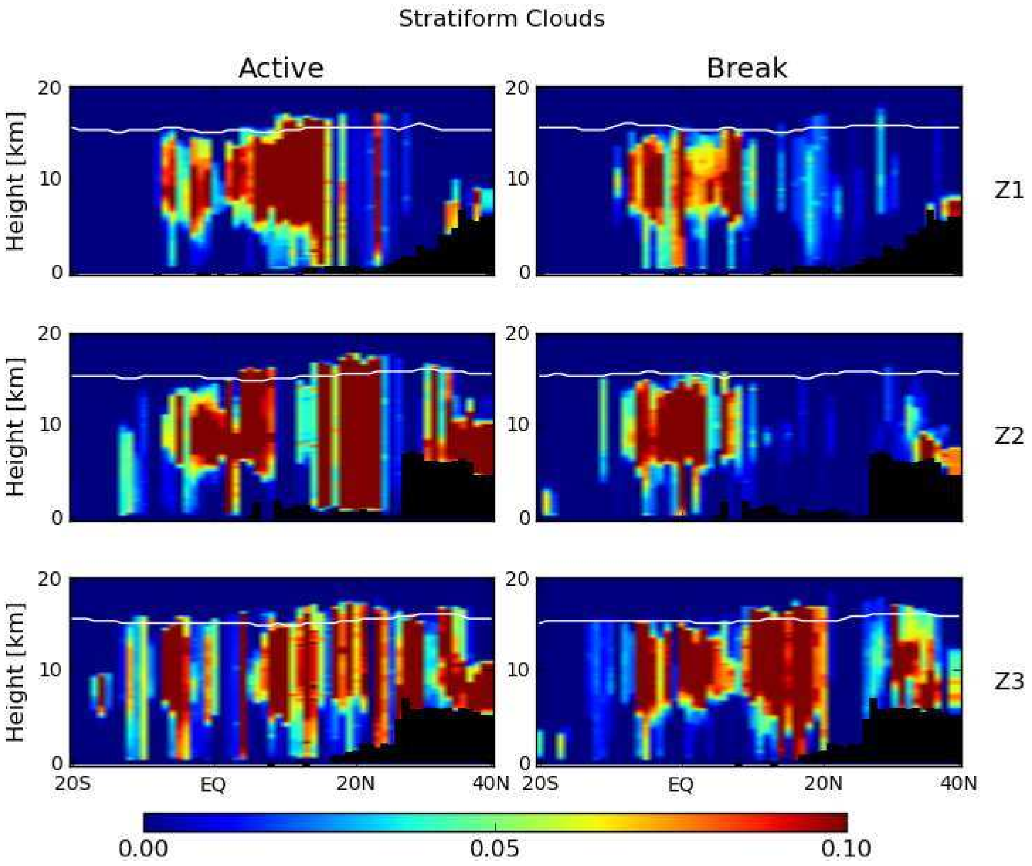


Fig. S8: Same as in Fig. S7, but for stratiform clouds.

This sub-section is revised and the text now reads:

Table 2 further shows the diurnally averaged CRE during active and break conditions of monsoon averaged over the all three zones northwards of the equator. Note that CRE values in both Tables 1 and 2 are averaged over only cloudy pixels and not normalized by the corresponding cloud type fractions. Thus, they represent the radiative impact of individual cloud types on the surface and in the atmosphere. The frequency of occurrence of both deep convective and stratiform clouds is higher during active periods, especially in Z1 and Z2 compared to break periods (Figs. S7 and S8). The stratiform clouds are more widespread than deep convective clouds during active phases. This is in agreement with previous studies that use passive imager and TRMM data sets (Stano et al. 2002, Basanta et al., 2007; Houze et al., 2007, Devasthale and Grassl, 2009; Devasthale and Fueglistaler, 2010; Choudhury and Krishnan, 2011; Krishnan et al., 2011; Romatschke and Houze, 2011). The average cooling effect of stratiform and deep convective clouds at the surface is in the order of -155 W m^{-2} and -508 W m^{-2}, respectively, during active periods. However, as the deep convection is generally suppressed during break periods, the importance of stratiform clouds further increases, especially in Z3 over the continental India. When stratiform clouds are formed after intense surface warming during pre-break periods, they are more vigorous, deeper and optically thicker, thus causing more cooling compared to active conditions (as reflected in Table 2).

(2) The issue of cloud radiative effects during monsoon breaks over the Tropical Indian Ocean has been examined using satellite data – CERES, SRB, ISCCP (Ref: Basanta Samala and Krishnan, 2007). It will be useful to highlight further value additions from the CloudSat and CALIPSO measurements, especially in the context of monsoon breaks.

The two value additions of combined observations from CloudSat and CALIPSO over other data sets are (a) their ability to provide cloud profiles and (b) delineation of individual cloud types/layers that are of particular interest for monsoon studies. In the context of intra-seasonal variability, these capabilities of CloudSat+CALIPSO data therefore allowed us to investigate cloud radiative effects during the active and break phases of monsoon. In the revised version of the Introduction section, the text now reads:

Due to their ability to resolve the detailed vertical structure of clouds in combination with possibility to precisely delineate different types of cloudy layers, the A-Train constellation of satellites is an extremely useful source of information in this context (L’Ecuyer and Jiang, 2010; Henderson et al. 2013). Especially the combination of data from CloudSat and CALIPSO satellites can address the inherent limitations of passive imagers, which can only provide a 2D image of clouds. Therefore we here exploit the state-of-the-art estimates of CRH for the years 2006-2011 derived from the application of broadband radiative transfer calculations to cloud and aerosol information obtained from space based lidar and radar observations (L’Ecuyer et al., 2008, Henderson et al., 2013)

(3) The tropical tropopause layer (TTL) cooling during the monsoon season is an interesting result. The authors further note that the TTL cooling is stronger during active monsoon conditions (-1.23 K day-1) as compared to break periods (-0.36 K day-1), since high clouds, associated with deep convection, emit at much colder temperature. The link between the vertical temperature gradients and strength of the monsoon circulation is an interesting problem for further investigations.

We thank the referee for encouraging comments. Indeed this is a research area where CloudSat+CALIPSO excel by providing information on thin and even sub-visual clouds in the TTL and their variability. The zonal-vertical radiative heating gradient produced by clouds just below and inside the TTL is not only important for the composition of the TTL, but also in sustaining monsoonal circulation by complementing the similar gradient produced by latent heating.

We further kindly request the referee to read our response to comments by Referee #1.

References:

Devasthale, A. and Fueglistaler, S., A climatological perspective of deep convection penetrating the TTL during the Indian summer monsoon from the AVHRR and MODIS instruments, Atmos. Chem. Phys., 10, 4573-4582, doi:10.5194/acp-10-4573-2010, 2010.

Devasthale A., and H. Grassl, A daytime climatological spatio-temporal distribution of high opaque ice cloud classes over the Indian summer monsoon region from 25-year AVHRR data, Atmos. Chem. Phys., 9, 4185-4196, 2009.

Zuluaga, M. D., C. D. Hoyos, and Peter J. Webster, 2010: Spatial and Temporal Distribution of Latent Heating in the South Asian Monsoon Region. *J. Climate*, **23**, 2010–2029. doi: http://dx.doi.org/10.1175/2009JCLI3026.1