Norrköping, 2015-07-10

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.

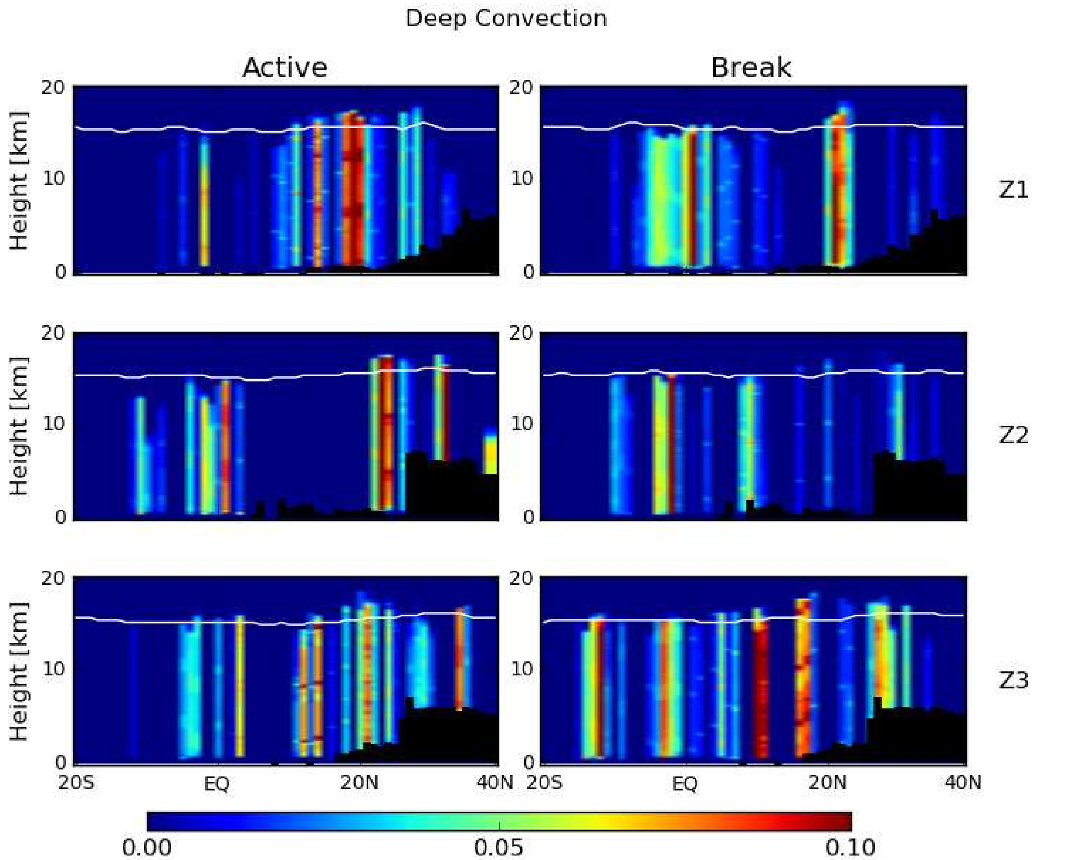
Specific comments: (1) The authors suggest that deep convection produces strong cooling at the surface during active periods of monsoon; whereas stratiform clouds are important during break periods. These results are somewhat different from earlier studies. During active monsoon conditions and periods 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.

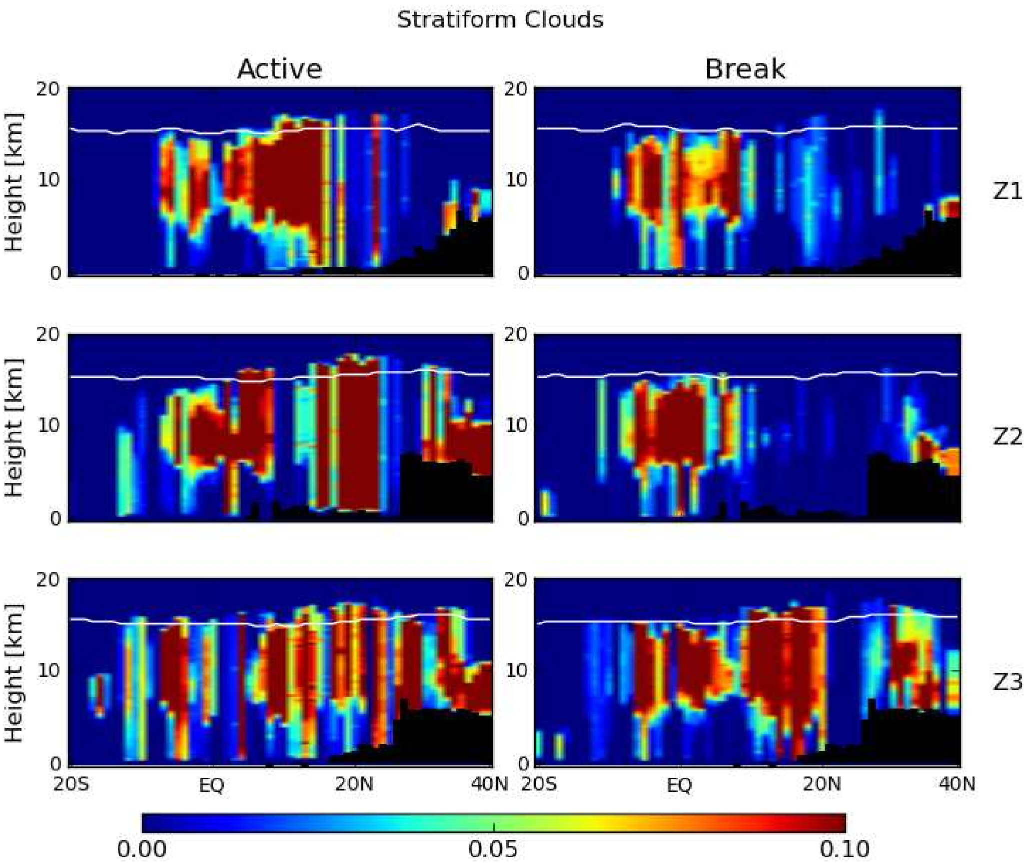
Firstly, we would like to thank the referee for the highly relevant references. We would like to point out that our results do not actually contradict the results from these earlier studies. We are not arguing that stratiform clouds are not important during active phases of monsoon in absolute terms, 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 information 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).

This sub-section is revised and the discussion is added comparing results to the earlier studies mentioned by the referee.





(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. The revised version of the manuscript highlights these value additions.

(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