Reply to P. Pilewskie

We thank Peter Pilewskie for reading carefully our manuscript and for his valuable comments and suggestions. Please find below a discussion of the reviewer's comments (italic lines). Changes/additions made to the text are underlined.

1. In the abstract, p. 7730, l. 1, a combined active-passive remote sensing method is introduced. I found this to be misleading…

We changed the phrase "combined active-passive remote sensing" into "passive remote sensing"

<u>The sensitivity of passive remote sensing measurements to retrieve microphysical parameters of convective clouds, in particular their thermodynamic phase, is investigated by three-dimensional (3D) radiative transfer simulations.</u>

2. p. 7730, l. 7: "… spectral solar and radiance …" Presumably a typographical error.

Changed.

3. p. 7730, l. 8 (first occurrence): "Lidar" should not be capitalized; "lidar"

We changed it in the whole text.

4. p. 7730, l. 15: Saying "Clouds are relevant components of the Earth's climate" Is quite an understatement. Be more specific – for example, "strong modulator"

We changed it:

<u>Clouds are a dominant modulator of the Earth's climate.</u>

5. p. 7730, l. 22: change "relation" to "relationship"

Changed.

6. p. 7730, l. 24: "To investigate these complex interactions vertical profile measurements on microphysical…"; should be "To investigate these complex interactions, vertical profile measurements of microphysical…"

Changed.

7. p. 7731, l. 1: "Radar" to "radar"; "mostly based" to "based mostly"

Changed.

8. p. 7731, l. 20-23: misplaced modifier. Perhaps: "Since multiple scattering also increases the depolarization ratio of liquid water clouds with increasing penetration depth, how delta, which contains the information about the thermodynamic phase, changes with depth has to be examined"

We changed the sentence as follows:

Multiple scattering increases the depolarization ratio δ in with penetration depth in liquid water clouds. Therefore one must examine the changes of δ with penetration depth, and thereby can one get information about the thermodynamic phase of the cloud (Hu et al., 2001)

9. p. 7732, l. 1: There are new studies which derive vertical properties of cloud layers, at least for the upper portions. See Kokhanovsky, A. and Rozanov, V. V.: Droplet verti-cal sizing in warm clouds using passive optical measurements from a satellite, Atmos. Meas. Tech., 5, 517-528, doi:10.5194/amt-5-517-2012, 2012. There are other exam-ples as well, based on a study by Platnick et al. on wavelength dependent weighting functions for reflectance. .

We added the following citations:

The retrieval of vertical profiles from nadir or zenith radiance observations is inherently limited to determine either bulk properties integrated over the entire column (like the optical thickness) or to quantities representative of limited cloud portions depending on cloud thickness (like the thermodynamic phase or droplet size). Several publications have shown studies concerning the derivation of vertical properties of cloud layers from satellite observation. They based on spectral differences in penetration depths of NIR radiation using the concept of weighting functions (Platnick, 2000; Wang et al., 2009; Zhang et al., 2010). Chang and Li (2002) and Chang and Li (2003) proposed a method for retrieving the vertical profile of effective radius for stratiform clouds by combining the reflectances at three absorbing near-infrared wavelength bands (1.6, 2.1, 3.7 µm). Recently, Kokhanovsky and Rozanov (2012) presented an approach for shallow warm clouds which uses the optimal estimation method and direct radiative transfer simulations of respective weighting functions. However, vertical information of deep convective clouds cannot be derived from nadir observations applying these methods.

10. p. 7732, l. 2: "based mostly"

Changed.

11. p. 7732, l. 8-9: Be specific: what are the "certain assumptions?"

We specified the assumption:

Assuming non-precipitating clouds this vertical distribution corresponds to the vertical profile of the whole cloud (Rosenfeld and Lensky, 1998; Freud et al., 2008).

12. p. 7732, l. 19 (first occurrence): "exemplarily" is not common. Suggest changing to "for example"

Changed in the whole text.

13. p. 7733, l. 10: "It is shown, if there is a threshold which defines liquid, ice and mixed cloud phase." Something is missing.

We changed the sentence:

It is studied whether there is a specific threshold that distinguishes between liquid, ice and mixed cloud phase.

14. p. 7733, l. 21: There are simplifying procedures in Monte Carlo models to compute radiance that do not rely on tracing paths of individual photon events throughout the atmosphere – that would take too long. Suggest adding some qualifier to this sentence about additional procedures required to compute radiance.

We added:

To improve the computational effort for radiance simulations MCARATS uses several variance reduction techniques as a modified local estimation method or a truncation approximation for highly anisotropic phase functions (Iwabuchi, 2006).

15. p. 7733, l. 24: "enabled" change to "required"

Changed.

16. p. 7734, l. 8: "water" change to "liquid water"

Changed.

17. p. 7734, l. 11: ": : :extraterrestrial solar spectrum from: : :"; delete "as taken".

Changed.

18. p. 7734, l. 26: "entrance optic"

Changed.

19. p. 7735, l.1: "photodiodes"; presumably this is a linear photodiode array? Suggest writing that instead.

…which are detected by a linear photodiode array.

20. p. 7735, l.5: "ice index" is misleading since it may indicate liquid water! Suggest changing to "thermodynamic phase index" or simply "phase index".

We changed it to "phase index" in the whole text.

21. p. 7735, l.15: "The depolarization backscattering Lidar system (ALS300 from Leosphere, France) is primarily used for geometric information on the observed cloud." Change "on" to "of" but more importantly, I don't know what this means. Please be more specific about the "geometric information".

We changed the sentence:

The depolarization backscattering lidar system (ALS300 from Leosphere, France) is primarily used for geometric information as cloud height and cloud distance.

22. p. 7735, l. 23: "wavelength" not required.

Removed.

23. p. 7736: This section should be restructured. Since cloud droplet/ice crystal absorption will scale directly with the product of particle size and absorption coefficient, separating phase discrimination (due to differences in bulk absorption coefficient) from size dependence is very important. This appears to be a glaring weakness of the paper until the reader find at the bottom of the page that the authors did assess the sensitivity of the phase index to particle size. Please mention this much earlier. By the way, this ambiguity is one of the reasons why measurements beyond 2000 nm (discussed in Pilewskie, P., and S. Twomey, J. Atmos. Sci., 44, 3419, 1987) are very helpful for retrieving phase. Perhaps the authors can mention this in discussion section.

As suggested, we restructured Chapter 3.1 (Homogeneous Cloud) now starting with the effect of the effective radius followed by the discussion about the viewing geometry.

3D radiative transfer simulations of reflected radiances on cloud sides are performed for (i) different microphysical parameters (cloud particle size, water content) and (ii) sensor viewing geometries that is described by the solar azimuth and solar zenith angle (ϕ0, θ0) and the sensor azimuth and sensor zenith angle (ϕs , θs). From these calculations at 1.55 µm and 1.7 µm the phase index Ip was derived using Eq. 1. The model domain has 140 x 40 x 139 grid cells with a horizontal resolution grid cell of 250 m and a vertical resolution of 200 m below 22 km and variable resolution above. A homogeneous cloud (15 x 40 x 16 grid cells) either consisting of liquid water droplets or of ice crystals is placed into the center of the model domain between 3.8 and 7.0 km altitude. MCARATS simulates radiances for all 140 x 40 grid points at surface altitude.

First, the impact of the microphysical parameters reff and LWC/IWC is studied for a fixed viewing geometry (θs = 50◦, θ0 = 30◦, ϕs = ϕ0 = 0◦). For all cases shown in Fig. 5 the phase index of liquid water, regardless of particle size, is lower than zero, whereas ice clouds show a positive phase index. Due to the increase of absorption with increasing particle size, the largest phase index is derived for ice particles with reff = 50 µm. Less absorbing particles (as particles with decreasing size) lead to lower values of Ip. Additionally, Fig. 5 illustrates that for all particle sizes the phase index is most variable, more than 20 %, for water content values below 0.4 g m−3 . Above that threshold the variation of Ip is below 7 %. However, for the remote sensing of the thermodynamic phase the liquid or ice water content is not a critical parameter which needs to be known.

In a second step the phase index Ip is analyzed with respect to the effect of the sensor viewing geometry. Ip is determined for ϕ0 = 0◦, θ0 = 30◦ and variable sensor azimuth and zenith angles (ϕs , θs) between 0 and 80◦ in steps of 10◦. For the following example, the effective radius reff of the ice and the liquid water cloud is fixed to 15 µm, while the LWC/IWC is set to 0.7 g m−3. Fig. 3 shows the relative frequency of the phase indices of both clouds for all points in the model domain from which the reflected radiation of the cloud side are simulated. Overall, there is clear separation between liquid water clouds and ice clouds. Positive values of Ip correspond to ice clouds and negative values indicate a liquid water cloud element. The large range of phase index values indicates a significant impact of the sensor geometry which is also illustrated in Fig. 4a for different reff (between 15 and 50 µm). It presents the derived phase indices for clouds with uniform thermodynamic phase and uniform reff. Here, sensor and solar azimuth angle are fixed to 0◦ which means that the sun is in the back of the observer. For this configuration the sensor zenith angle θs was varied between 20◦ and 80◦ in 2◦ steps. As shown in Fig. 4 the viewing geometry in terms of the scattering angle affects Ip significantly. In this case, an increase of the sensor zenith angle and so the scattering angles (ranging here between 50 and 115◦) results in an increase of the phase index Ip for ice and liquid water clouds. Note, that for the largest sensor zenith angles and large liquid droplets the phase index can exceed values around zero. The geometry effect can be also observed for varying the sensor azimuth angle. In Fig. 4b Ip is shown for ice and liquid water clouds with reff = 15 µm and a fixed sensor zenith angle of θs= 70◦. Again, the sign of the phase index clearly separates the two thermodynamic phases in spite of the varying sensor viewing geometry. In summary, clouds with uniform microphysical parameters can yield a variety of phase indices, depending on the viewing geometry and the cloud particle size. Nevertheless, the thermodynamic phase can clearly be distinguished by the sign of Ip.

24. p. 7736, l. 25-26: "The ice index of liquid water, regardless of particle size, is almost always lower than zero, : : :"

Changed.

25. p. 7737, l. 1: "In summary, clouds : : :"

Changed.

26. p. 7737, l. 8: "mostly" change to "most"

Changed.

27. p. 7737, l. 8: the placement of (above 20%) may be confused with water content rather than the phase index. Suggest: ": : : is most variable, more than 20%, : : :"

Changed.

28. p. 7737, l. 13: "vertical direction" change to "the vertical"

Changed.

29. p. 7737, l. 14: delete "as"

Changed.

30. p. 7737, l. 19: delete "wavelength"

Changed.

31. p. 7737, l. 24: I think more needs to be said about how "the mixed layer can be identified." Please be quantitative

We added:

It illustrates a clear separation of ice and liquid phase. The differences of the phase index for the ice layer depend strongly on the effective radius. Large effective radii (as at the bottom of the layer) result in a strong absorption due the decrease of the single scattering albedo. Also the mixed-phase layer can be identified. The variation of the phase index with height for the region of liquid phase is low (-0.13 to -0.01) compared to the mixed-phase zone, where the phase index changes rapidly from negative to positive values (-0.01 to 0.31). When reaching the region with pure ice phase, the change of Ip with height is again reduced compared to the mixed-phase layer.

32. p. 7738, l. 1: "where the IWC is much lower than : : :" I found this a little confusing. How does the IWC vary in the simulation?

Fig. 6a gives the profile of the IWC/LWC.

33. p. 7738, l. 8: delete "part"

Changed.

34. p. 7738, l. 14: "high velocity"; how fast were they moving? I think the authors need to be specific about how rapidly the scene changed relative to sampling time of the measurement. That is what is relevant, not horizontal velocity of clouds which Is rarely classified as "high"

We gave information about sampling time and estimated the time of individual cloud events.

Some of the clouds were precipitating which is an indication for the existence of ice in the cloud. Satellite-based measurements with MODIS (Moderate-resolution Imaging Spectroradiometer) classified the cloud tops as ice and mixed-phase. The time resolution of the spectrometer measurements was below two seconds, while one lidar profile was sampled within 30 seconds. Due to the high velocity of the passing clouds (about 20 m/s) and their limited horizontal extent time series at constant observation angle of the reflected radiance were taken instead of vertical profiles. In many cases individual clouds did not last longer than two minutes.

35. p. 7738, l. 14: "low"change to "small"

Changed.

36. p. 7738, l. 15: "extension" change to "extent"

Changed.

37. p. 7738, l. 16: "included precipitation" change to "were precipitating"

Changed.

38. p. 7738, l. 17: delete "phase"

Changed.

39. p. 7738, l. 20: delete "wavelength"

Changed.

40. p. 7738, l. 21: "situation" change to "scene"

Changed.

41. p. 7738, l. 23-24: ": : :because the origin of the multi-scattered radiance is un-known." This is awkward. Suggest the authors be more specific about why the signal from shadowed cloud is contaminated.

We added here a discussion about the identification of the shadows for this specific measurement case:

The data interpretation is supported by photos which also help to sort out shadowed cloud portions which cannot be used for phase discrimination due to the contamination of the spectral slopes of the radiances which are used for the phase discrimination. For fully illuminated, non-shadowed cloud elements the spectral signature of the reflected signal depends mainly on the spectral signature of the downward solar radiation and its spectral extinction by the observed cloud element. In contrast, for shadowed cloud elements the incident radiation is mostly determined by diffuse radiation. This diffuse radiation is strongly affected by the spectral extinction of the shadowing cloud element but may also be affected by the spectral surface albedo. To identify the illuminated cloud portions all measured spectra were classified with respect to possible contaminations. Fig. 7a shows examples of measured spectra for different targets: fully illuminated cloud side, shadowed cloud parts, overcast situation, and no cloud. In particular the absolute value of the radiances in the visible spectral range and the slope of the spectrum between 500 and 880 nm reveals significant differences between the four spectra. In this spectral range the radiance reflected from the illuminated cloud part decreases with increasing wavelength whereas for spectra with contamination by other clouds the radiance shows an increase at about 730 nm. This feature is an effect of the interaction between clouds and a surface albedo which is affected by vegetation in this particular case. Spectra observed under cloudless conditions show the typical nonlinear decay of the radiance in the VIS caused by Rayleigh scattering. To quantify the spectral differences between reflected radiation from shadowed and illuminated cloud parts, all spectra were normalized to the radiance at 480 nm. Fig. 7b shows the ratio between the normalized spectra and a normalized spectrum of an illuminated cloud scene. As expected, the most significant difference is observed for the cloudless observation. The overcast situation is characterized by a strong decrease of the ratio in the NIR (ratio < 0.5 above 1100 nm). To distinguish the cloud scenes the radiance ratios at two wavelengths (857 nm and 1550 nm, vertical dashed lines in Fig. 7) were calculated. For ratios between 0.8 and 1.2 the cloud scene was defined as illuminated, whereas cloudless situations were identified for ratios lower than 0.5. All other spectra were classified as shadowed/overcast cloud scenes.

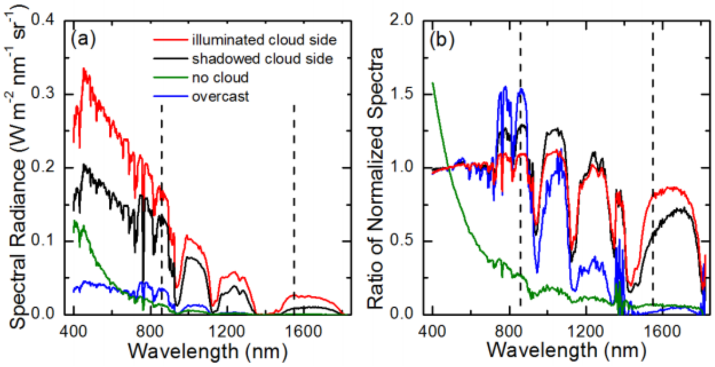

Fig. 7. (a) Spectra of different observing situations: illuminated cloud side, cloud shadow, overcast, and view out of cloud. (b) Normalized spectral ratios for the cloud scenes from (a) related to a spectrum of illuminated cloud side.

42. p. 7738, l. 24: delete "also"

Changed.

43. p. 7738, l. 25: comma after "7"

Changed.

44. p. 7739, l. 2: "index values" change to "indices"

Changed.

45. p. 7739, l. 2: ": : : after the mixed-phase cloud was observed."

Shortly after time step 1, even lower phase indices of about -0.6 were observed.

46. p. 7739, l. 11: comma after "3" and delete "also"

Changed.

47. p. 7739, l. 14: "steps"

Changed.

48. p. 7739, l. 17-18: an effective radius and phase index were not simulated; they were derived or retrieved.

Changed.

49. p. 7740, l. 5: "dealing with" change to "cloud were composed of"

Changed.

50. p. 7740, l. 12: I still think a more quantitative description of how mixed-phased was derived is required. This should be simple, based on the figures.

We added:

<u>From the profile of the phase index the three layers of liquid water, mixed-phase and ice particles could be identified, which gives confidence that detailed profile measurements of complex clouds can deliver cloud phase formation. The critical mixed-phase layer is indicated by the strong increase of the phase index with height from negative to positive values.</u>

51. p. 7740, l. 20: "with reff of" change to "to be"

Changed.

52. p. 7740, l. 21: "fast moving clouds" change to "fast changing cloud scenes"

Changed.