Reply to comments of Reviewer #1:

Thank you for the time and efforts you have spent on reviewing our manuscript; this is truly appreciated. Based on your comments (copied below) we reply with a point-by-point discussion of your concerns (italic and in blue color). We also include a detailed description of how we have considered your suggestions in the revised manuscript version.

General remark: Because the calibration of radiation sensors in the laboratory and the required transfer of the calibration into the field by secondary standards cause additional uncertainties of the measured irradiances and the derived layer properties, we decided to use an in-flight calibration technique (instead of relying on the laboratory calibration and its uncertain transfer to the field) for the irradiance measurements. The in-flight calibration method was already successfully applied in previous field campaigns. It is based on radiative transfer simulations of the downward irradiance in clearly cloudless sky conditions at high altitudes. In this case the measurements are only slightly affected by the atmospheric layer above the sensor and the measurements can be adjusted directly to the simulations. This in-flight calibration approach is then transferred to all radiation sensors installed in the aircraft and AIRTOSS. We have applied this calibration and concentrate on a specific measurement of the flight of 30 August 2013, which is more appropriate than the example discussed in the previous manuscript version. This specific case is characterized by a relatively high optical thickness of the cirrus layer taken into account that the vertical separation between the aircraft and AIRTOSS is 200 meters only. Another criterion for selecting this measurement case was that there was no additional cirrus above or below the layer enclosed by the aircraft and AIRTOSS. So we have chosen a case most suitable to derive optical layer properties of cirrus.

The following figure shows the new measurement case from 30 August 2013, measured above the North Sea.

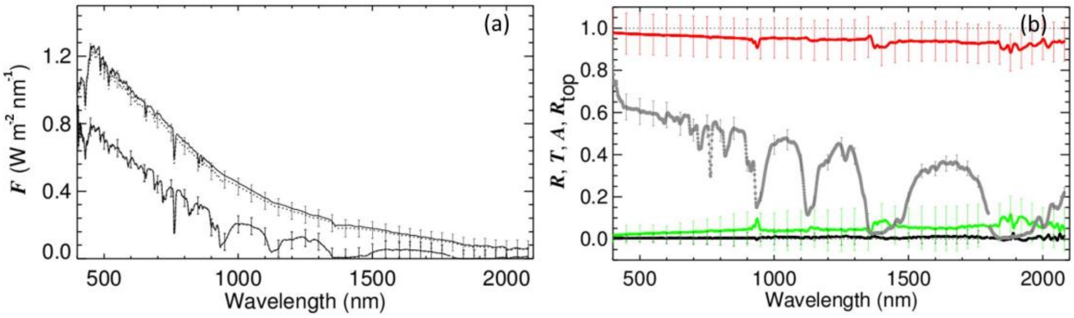

Fig.7: (a) shows measured spectral downward and upward irradiance F from the aircraft above the cloud layer (solid lines) and AIRTOSS below the cloud layer (dotted lines) at the time, indicated by the vertical dashed line in Fig 1. Ftop is simulated. (b) shows spectral reflectivity (black), transmissivity (red), absorptivity (green), and cloud top albedo (gray) according to irradiance in (a). The vertical bars indicate the systematic errors due to measurement uncertainties.

Reviewer #1: Abstract Line 18-21:
Mention the optical thickness of the low level cloud and say that the found differences in cirrus properties are only true for a low level cloud with these properties. Maybe add how an optically thicker/thinner and geometrically lower/higher low cloud changes the found impact.
Reply: *We have followed your advice and included a new Fig. 13, which shows the influence of the optical thickness of the underlying liquid water cloud and the cloud top height on the broadband radiative forcing of the cirrus, for different cirrus optical thickness values. This clearly quantifies the effect of low liquid water clouds on the cirrus radiative forcing.*

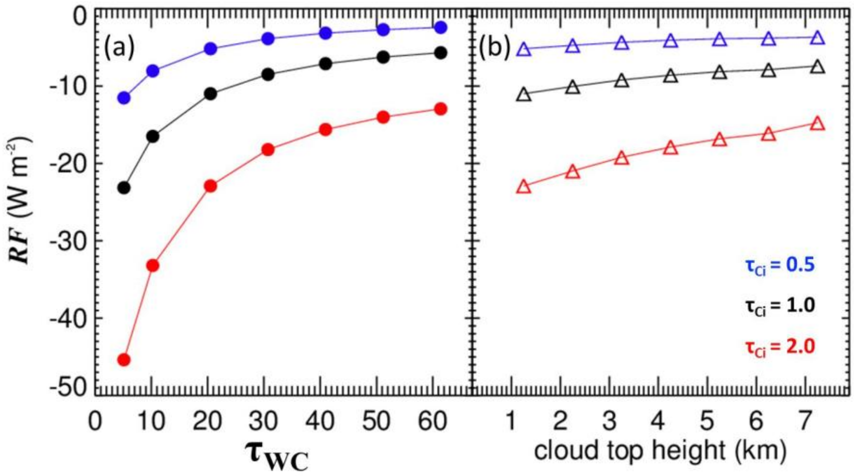

Fig. 13: Integrated values of cirrus radiative forcing when a low water cloud is present. The optical thickness (left panel), and the top height (right panel) of the water cloud are varied. The colors indicate a different cirrus optical thickness.

"The results obtained in this paper are valid for the respective cloud cases. To evaluate the low–level cloud effect on the cirrus the properties of the low water cloud, such as optical thickness and cloud top height, have to be investigated, too. Therefore, Fig. 13 (a) and (b) show values of integrated cirrus radiative forcings (wavelength range: 300–2300 nm) with varying water cloud optical thickness (a) and cloud top height (b). The cirrus is located between 6.7 km and 8.5 km altitude and consists of the mixture of shapes according to Baum et al. (2005). The color code represents the changing cirrus optical thickness.

In Fig.13 (a) the low–level cloud is located between 1 km and 1.25 km with an increasing optical thickness from 5 to 60. In general, the cooling of the cirrus decreases with increasing optical thickness of the low cloud resulting in an increasing influence of the low cloud on the upper lying cirrus. This is due to the reflected radiation by the low cloud being available to interact with the cirrus layer again. With higher water cloud optical thickness a saturating effect can be seen resulting in differences of 72% to 83%. Additionally, with increasing cirrus optical thickness the absolute difference of RF increases from 10Wm^{-2} to 32Wm^{-2}.

In Fig.13 (b) the low water cloud has a constant optical thickness of 20, and a vertical thickness of 250m with an increasing cloud top height from 1.25 to 7.25 km. Similar to Fig.13 (a) the cooling of the cirrus decreases with increasing cloud top height of the low–level cloud. Here, the amount of the reflected radiation by the low cloud, available in the cirrus level, depends on the vertical extension of the atmosphere in between and its interaction with the transmitted (from cirrus) and reflected (from water cloud) radiation. The trend of RF is similar to (a) with increasing cloud top height with a resulting in lower differences of 20% to 35% and absolute values of not more than 8Wm^{-2}. It is noticeable that the cloud optical thickness of the low cloud in comparison to the cloud top height has a significant effect on the radiative forcing of the above lying cirrus."

Reviewer #1: p.19047 Line 10ff:
Cirrus inhomogeneities are described in the motivation – where do you analyze their impact on layer properties? Regarding p.19047 Line 15ff: Here you describe impact of ice crystal size and shape on remote sensing retrievals – make extra paragraph to distinguish from impact of cirrus inhomogeneities.
Reply: *Spatial inhomogeneities of the microphysical cirrus properties, such as ice crystal shape, size and number concentration, result in spatially varying optical properties of the cirrus. The spatial variability of the microphysical properties is presented in Figure 5. The impact of these microphysical and optical cirrus parameters, that represent the cloud*

inhomogeneities, is investigated. As an example, Figure 11 illustrates the impact of different ice crystal shapes on both the optical cirrus layer properties and the cirrus radiative forcing. In Figure 10 the size distribution effect on the cirrus optical layer properties and its radiative forcing is quantified. What has not been done is to directly link the spatial variability of the microphysical/optical cirrus properties with optical layer properties and the radiative forcing. That would require to think about the need to consider three-dimensional radiative effects, which would go beyond the scope of this paper.

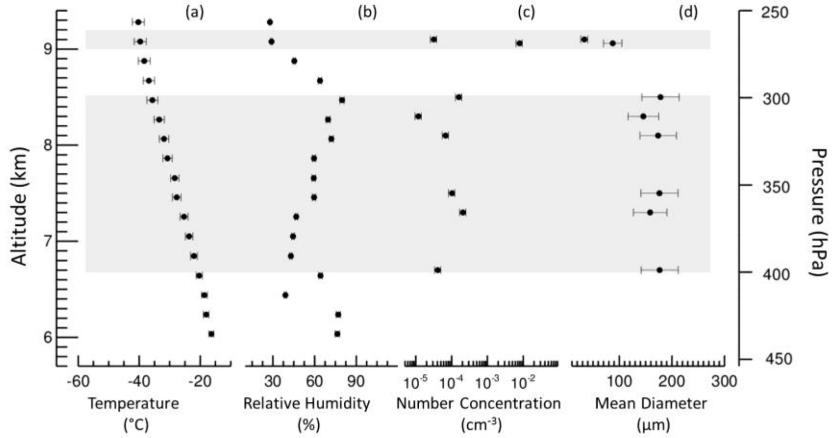

Fig. 5: Vertical profiles of (a) temperature, (b) relative humidity, measured on the Learjet 35A, (c) number concentration, and (d) mean diameter, derived by CIPg on AIRTOSS, from the flight of 30 August 2013. The bars show the corresponding measurement uncertainties. The gray area indicates the vertical extent of the cirrus layer.

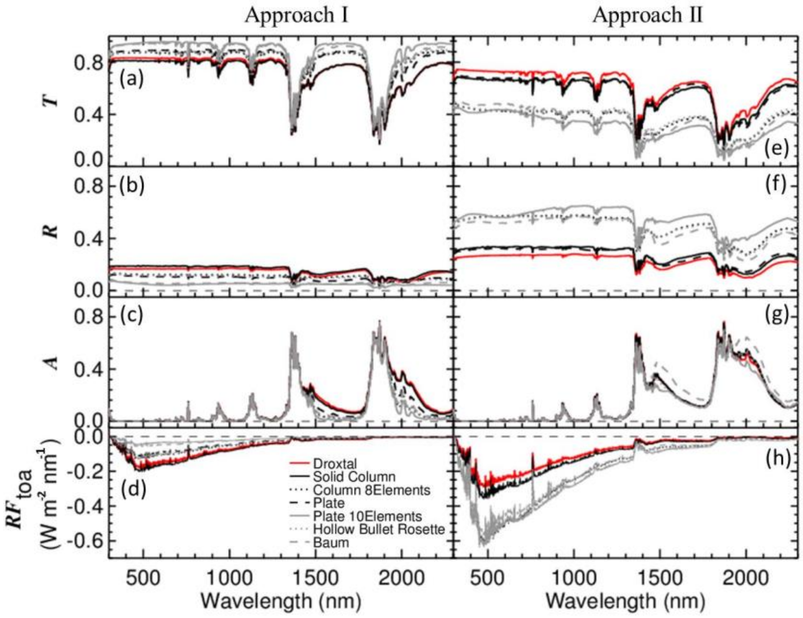

Fig. 11: Shown are spectral (a,e) transmissivity, (b,f) reflectivity, and (c,g) absorptivity of a cirrus layer between 6.7 and 8.5 km altitude. (e,h) are the radiative forcings at TOA, respectively. The simulations are based on a measured number size distribution assuming different ice particle shapes. The two panels indicate two conditions: constant number size distribution (Approach I) and constant ice water content (Approach II).

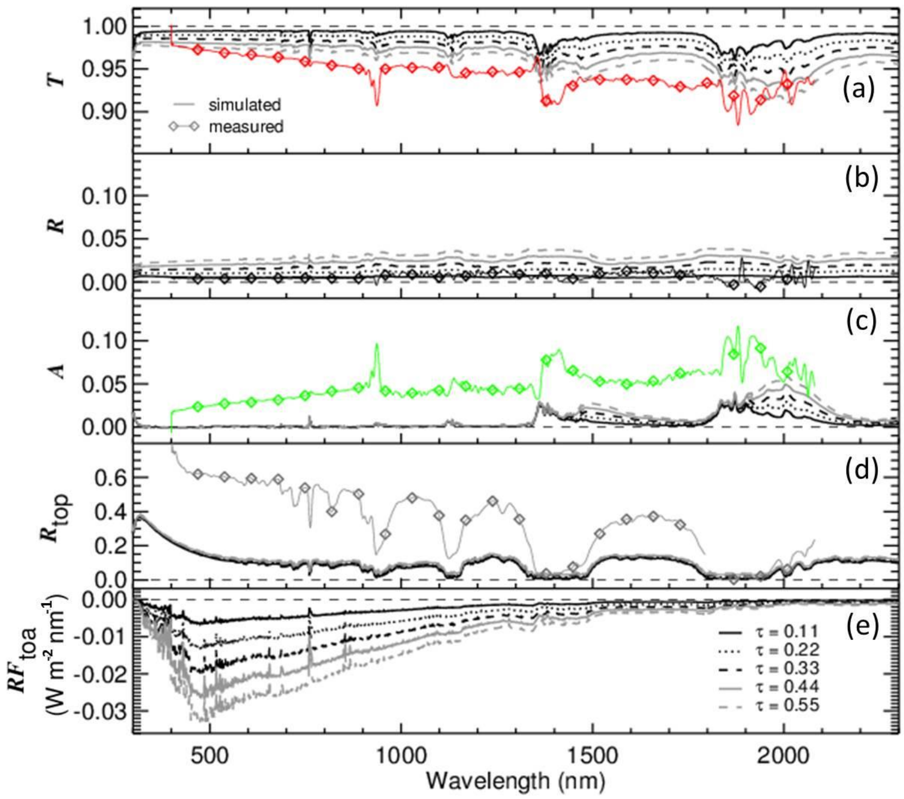

Figure 10. The lines show simulated, spectral (a) transmissivity, (b) reflectivity, and (c) absorptivity of a cirrus layer between 9 km and 9.2 km altitude. (e) are the radiative forcings at TOA, respectively. The simulations are based on a measured number size distribution assuming the mixture of shapes according Baum et al. (2005). Inserted is the measurement case (diamonds) from Fig.7.

Reviewer #1: p.19048 Line 10:
If I understand correctly, you are presenting the first collocated spectral radiation measurements above and below cirrus with a towing sonde to derive optical layer properties here? – Highlight here that this is the new contribution of this paper!
Reply: *Thank you for this advice! We have highlighted this crucial point of the paper in both the abstract and the conclusions of the paper.*

"Spectral solar optical layer properties of cirrus are derived from simultaneous and vertically collocated measurements of spectral upward and downward solar irradiances above and below the cirrus layer. From the irradiance data spectral transmissivity, absorptivity, reflectivity, and cloud top albedo of the observed cirrus layer are obtained. The radiation measurements are supplemented by in–situ microphysical measurements and radiative transfer simulations based on the microphysical data."

Reviewer #1: p.19049 Line 7ff:
Explain why you assure horizontal stabilization of the irradiance sensor mounted on top of the aircraft to measure downwelling irradiances but not of the sensor measuring upward irradiances mounted on the wingpod.
Reply: *The horizontal stabilization of the upward looking optical inlet is important to assure appropriate measurement data, especially due to the direct portion of the downward radiation. In contrast, the upward radiation consists of a larger amount of diffuse radiation being less influenced by the orientation of the sensor. An active horizontal levelling of all*

irradiance sensors would be desirable, however, from a technical point of view this is illusionary, and from a scientific perspective it is crucial only for the downward irradiance measurement, which has a major direct component, whereas the other sensor have mostly receive diffuse radiation, which is much less sensitive to horizontal sensor misalignments.

Reviewer #1: p.19053 Line 8ff:
Describe Fig.6 more in detail – strong variations of mean particle diameter are obvious, comment on them, they represent cloud inhomogeneities.
Reply: *Thank you for this hint. But for the new measurement example, showing very low number concentrations and a well–mixed cirrus cloud layer, we decided not to show this figure.*

Reviewer #1: p.19058 Line 1:
Explain why you choose this measured particle number size distribution and not a different one.
Reply: *The chosen number size distribution, measured by the microphysical sensors, installed in the AIRTOSS sensor platform, is considered to represent a cirrus cloud typical for the measurement case investigated in the paper. This has been shown by looking at time series of the size distribution measurements. If integrated, it eventually leads to an optical thickness of 1, typical for the investigated cirrus.*

Reviewer #1: p.19058 Line 26:
Radiative forcing of Solid Columns and Droxtals is strongest (not lowest!), they exhibit the strongest negative forcing. Be careful in describing your results properly.
Reply: *Thank you for reading that careful, we apologize for this misprint.*

Reviewer #1: p.19060 Line 2:
Choosing a water cloud with tau = 45 at 1.5-1.75km comes a bit out of the blue. Where do you take those values from? A 250m thick water cloud with tau = 45 seems unrealistic.
Reply: *This is a valid point. We have changed the properties of the low liquid water cloud to an optical thickness of 20 and an altitude range from 1 to 1.25 km. We base these assumptions on concurrent satellite data of MODIS. The corresponding text has been revised and a further investigation of the impact of the low-level cloud properties optical thickness and cloud top height is presented in Section 5.3 of the manuscript (see Fig. 13).*

Reviewer #1: p.19060 Line 21f:
Clarify that the "overestimation of the cooling effect of the cirrus" refers to the single-layer cirrus case. How often do we have conditions of cirrus with underlying clouds? – Quantify. Also comment on if previous studies in which cirrus radiative forcing was estimated paid attention to single-layer only cirrus or if they potentially overestimated the cooling effect by not excluding multi-layer conditions.
Reply: *Chang and Li (2005) have reported in their climatology of single-layered and overlapped clouds an annual and global occurrence of high clouds of 52 – 61 % (ocean – land) from which 27 % to 29 % represent cases with low clouds underneath the cirrus. Thus these low clouds beneath cirrus represent a significant portion. This quantitative information is now given in the text of the revised manuscript.*

„Chang and Li (2005) reported an annual and global occurrence of high clouds of 52 – 61% (ocean – land), from which 27% to 29% represent cases with low clouds underneath the cirrus. During the flights very often low clouds were observed, that is why the related effect of a low–level water cloud was investigated.“

Chang, F.–L., Li, Z.: A Near-Global Climatology of Single-Layer and Overlapped Clouds and Their Optical Properties Retrieved from Terra/MODIS Data Using a New Algorithm,
J. of Climate, 18, 4752–4771, 2005