Response to reviews

We want to thank the referees for appreciating our work and for the thoughtful comments and suggestions. Most of them have been taken into account to improve the manuscript. We apologize for the difficulties associated with the length of the manuscript and excessively long sentences. We have re-worked the manuscript and addressed each comment. In the text below, the reviewer's comments are marked in italics blue and our answers are given in normal font.

As the referee has correctly pointed out, the method itself is not new (the first author developed it in the 1990s for TOVS), and there exist several publications, which are referenced in the article. Indeed it was a difficult task to select what should be presented and what left out, which is reflected in differing opinions of the 2 referees.

Since both referees suggested to shorten the manuscript, we have done our best to do it without losing the message we wanted to deliver to the community. Here is the list of actions performed

1) shortening section 2 Data and methods and moving a shortened version of section 3.1 Collocated AIRS-CALIPSO-CloudSat data to this section
2) simplifying Table 2, taking out 5 figures / 22 figure panels (3 figures moved to supplement)
3) taking out the ENSO discussion in section 5 (together with Fig. 16) and
4) revising the remaining applications in section 5

We do not agree with the suggestion of a complete removal of section 5 Applications as the presented method is not new and one of the goals of this article was to present scientific applications (as indicated in the title).

Since the results similar to those presented in new Fig. 12 have recently been published for other data sets, it would be difficult to use the presented material in a separate publication. We compare our results to one of them and point out an interesting extension. We plan to work on a more complex analysis to pursue this subject further, but we think it is important to present already these results in the current publication.

Response to Referee#1

Title: the authors should consider a better title that is punchier and emphasizes the great aspects of using sounders for cloud properties (and not have weaknesses in the title)

the title was changed to: Cloud climatologies from the InfraRed Sounders AIRS and IASI: Strengths and Applications

Abstract: it is pretty long and not very specific. For instance, lines 24-28 has a single long sentence making multiple points about the apparent cloud top/base. Is the correction for co2 really that original and worth advertising in the abstract? On lines 23-24, the global cloud amount is detected clouds, not effective emissivity?

We have substantially re-worked the abstract, to be more specific.

Rewritten to: The global cloud amount is estimated to 0.67 i 0.70, for clouds with IR optical depth larger than about 0.1. The spread of 0.03 is associated with ancillary data.
It is really the amount of detected clouds; it is interesting to mention that global effective cloud emissivity of detected clouds is very similar: 0.65-0.66;

This leaves global effective cloud amount (detected clouds weighted by cloud emissivity) to about 0.46-0.48.

*p. 5, lines 20-21: did the authors try (or consider) using a SST data set independent of the IR sounders, say, RTG-SST or the optimal approach using microwave made available at www.remss.com?*

There are two philosophies in creating cloud climatologies: 1) ancillary data are also taken from observations, and 2) ancillary data are taken from model forecast or meteorological reanalyses. The advantage of the first is that these climatologies are independent of model input, however the problem is that the ancillary data might have biases due to faults in clear sky detection and due to interpolation when no good quality data are available.

In this article we compare these approaches; for the first one, we preferred to stay with data which include the same instrument (the ancillary data come from a combined IR sounder – microwave retrieval). For IASI, at the time of the development, the available ancillary data did not have the quality needed. Therefore we switched to the second approach.

A separate SST data set would not help, as we also need surface temperature over land, and both are needed at the satellite observation times. In addition they also should be coherent with the retrieved atmospheric profiles.

*p. 5, lines 23-24: ‘quite different’ is not quantitative and not useful in the context of this discussion. How different were they?*

Rewritten to: The comparison with collocated temperature profiles of the Analyzed RadioSoundings Archive (ARSA, available at the French data centre AERIS) has shown that, while AIRS-NASA and ERA-Interim (section 2.3) temperature profiles do agree in general with the ARSA profiles within 1 K, differences between IASI-NOAA and ARSA profiles were often larger than 1 K in the lower troposphere (not shown).

In the following plots we present differences in T profiles between NASA AIRS V6 and ARSA, ERA Interim and ARSA and NOAA IASI and ARSA, separately for different latitude bands over land (above) and ocean (below). Whereas AIRS and ERA agree in general within 1 K, NOAA IASI differs from ARSA often more than 1 K in the lower troposphere.
the IASI and AIRS sounders will not resolve the diurnal cycle but will capture aspects of it.
We agree that the diurnal cycle is difficult to resolve with data given in temporal intervals with 4h–8h, but as one can see in the cited conference proceeding (publication is under preparation), by using appropriate analysis techniques, both the amplitude and phase of the diurnal cycle of upper tropospheric clouds can be obtained, especially due to the fact that IR sounders provide unbiased day-night results.

Rewritten to:

This brought us to the conclusion, that ancillary data from the same source are necessary to make use of the AIRS–IASI synergy for exploring cloud diurnal variability in a coherent way.

Lines 26-27: if it is of any help, there is a paper that describes cloud type comparisons between AIRS and ECMWF T/q:

Yue, Q. et al. (2013), Cloud-state dependent sampling in AIRS observations based on CloudSat cloud classification, J. Climate, 26, 8357–8377.

Unfortunately this very interesting article refers to NASA AIRS L2 data of Version 5; We have used in our revised cloud climatology NASA AIRS L2 data of Version 6

p. 6, lines 9-12: the variables should be listed here (e.g., T, q, emissivity, sfc T, etc.)

the whole paragraph was taken out, as this issue was already partly discussed in 2.2.

p. 7, lines 11-12: here is a good example of over explaining. Why should for which temperature first increases with height before decreasing be included? This is technically only true if ascending in the atmosphere. Line 12: moved to the inversion layer is not clear. Is the cloud placed at the base of the inversion? Hopefully not the top because that would be impossible in reality. Line 14: about 7 to 15% of the time.

Text improvements taken into account.

In the case of an inversion, the cloud height is set to the level at which the temperature starts to decrease with height.

p. 8, lines 20-23: this statement is unclear. How can clear sky be not too cloudy?

text in parentheses taken out; the synergy of IR sounder and microwave also leads to retrievals for party cloudy scenes. In that case, a cloud clearing is performed before the retrieval.

p. 9, line 7: there is a specific QC approach that filters based on a PBest or PGood pressure level. Was this done on a per profile basis? Or were the Level 3 gridded AIRS Team products used?

We used the quality criteria on a per profile basis, as we work with L2 data; reference added

p. 9, lines 8-9: there is a paper that describes AIRS surface temperature biases with respect to ship observations:

Again, the problem is that this paper refers to AIRS V5; we had problems to find published results for the AIRS V6 version, apart from the V6 L2 Performance and Test Report.

p. 9, line 11: with respect to what is the land more complex?

We meant that there was not a clear bias found as over ocean; clarified in the text to:

Since differences over land might be positive or negative (Fig. 2), we left the AIRS-NASA surface temperature ($T_{surf}$) values as they are.

p. 10, line 23: is the artifact in cloud amount causing more clouds? Less clouds? Higher clouds? Lower clouds?

Global cloud amount is increasing, when the CO2 increase is not taken into account in the computation of atmospheric spectral transmissivities (new Fig. 10); When splitting into low-level and high-level cloud amounts, the artefact led to increasing CAL and slightly decreasing CAH.

p. 11, line 3: base of the inversion?

In the case of atmospheric temperature inversions, the cloud height is moved to the level at which the temperature starts to decrease with height, and $e_{cld}$ is scaled accordingly.

p. 11, line 25: is 'not cloudy' the same as 'clear' or something else?

As the IR sounder footprint size is large, it is difficult to distinguish between completely clear sky and cloudy. Even the evaluation with CALIPSO-CloudSat stays approximate as the sampling is only about 1.5 km x 2.5 km, which corresponds to a sampling of about 2%.

p. 12, line 10: 'explainable' should be 'explained'. The paper could use a good thorough editing for clarity of English.

Unfortunately, all authors are non-native English speakers; we tried however to improve the readability of the present version to the best of our abilities.

p. 12, lines 14-16: are there three different sigmas for the three different emissivity_i values? It appears that some of the clear will be selected as cloudy, and vice-versa. Is this correct?

The thresholds were chosen separately for 1) ocean, 2) land and 3) snow/ice, as the distributions in new Fig S1 (original Fig. 2 moved to the supplement) showed slightly different distributions. Indeed, all methods using thresholds include misidentifications. These are difficult to estimate because of the sampling (2% of CALIPSO-CloudSat per AIRS footprint). The cloud detection includes 80 (over ice) to 92% (over ocean) cases for which CloudSat-lidar GEOPROF and CALIPSO at 5 km resolution (excluding subvisible cirrus) have identified at least one cloud layer, and 30% cases for which the samples did not include a cloud layer. The latter might look at first as a large misidentification of clear
sky as cloudy, but the very small coverage of the CloudSat-CALIPSO samples (2%) certainly includes partly cloudy fields.

Results in section 3 show that by using these thresholds the overall agreement with CloudSat-CALIPSO is 70% (over ice) to 85% (over ocean), given as hit rates.

p. 12, lines 20-21: the emis < 0.1 threshold is very conservative. The IR sounders will capture a lot of optically thinner clouds than that. Are the authors arguing the point that below that threshold some clear values could leak in? The paper by Kahn et al. (2008) seems to argue that the emis threshold could be lower than that:


Indeed, the AIRS-LMD climatology (Stubenrauch et al. 2010) went down to an $\varepsilon_{\text{cl}}$ of 0.05.

Considering the large footprint and a comparison of $\varepsilon_{\text{cl}}$ distributions for cloudy and clear sky CloudSat-CALIPSO scenes (see below), we decided to exclude scenes with $\varepsilon_{\text{cl}} < 0.1$.

We made the sentence more explicit: To reduce misidentification of clear sky as high-level clouds, only clouds with $\varepsilon_{\text{cl}} \geq 0.10$ are considered.

Indeed, this came out of a study with CALIPSO-CloudSat:

The above figures present normalized $\varepsilon_{\text{cl}}$ distributions of high-level clouds, after multi-spectral cloud detection, but leaving clouds with 0.05 < $\varepsilon_{\text{cl}}$ < 0.10 as clouds, separately for cloudy scenes defined by GEOPROF and CALIPSO (full line) and for all scenes (dotted line). The first bin includes scenes with 0.05 < $\varepsilon_{\text{cl}}$ < 0.10; in the tropics this bin has more clear sky than high-level clouds. Therefore we have moved the threshold to 0.1. As the contribution of the first bin is small compared to the integral, this seemed a reasonable choice.

p. 12, section 3.1: this is where the paper starts to be a real grind. Wasn’t the methodology of the AIRS and C/C comparison described in a previous paper(s) by the lead author? There must be a way to tighten this up and make it more concise, but I am lacking any good suggestions for that.

Indeed, part of the description of the collocated dataset was already published before, though not the computation of the cloud height corresponding to a specific optical depth. Referee #2 finds that this section is not detailed enough.

We have rewritten this section and moved it to section 2.4, hoping that in this way the paper gains clarity. It also allows the reader who is only interested in the results, directly to go to sections 3-5.
p. 14, start of Section 3.2: it is really nice to see that the level of agreement is very similar to the AIRS Team cloud retrievals in Kahn et al. (2008) with a finer breakdown of surface type and ancillary data.

We don’t completely agree with the statement about the level of agreement with the AIRS cloud data from NASA V5: one important difference is that while the AIRS NASA V5 cloud data agree well for high-level clouds, they have a very large height bias for low-level clouds. This is stated by the Kahn paper: a bias which reaches about 5 km! Actually, this was the reason for adapting the $\chi^2$ retrieval method to AIRS. Our comparison with the NASA V5 AIRS cloud height was published (Fig. 12) in 2008. Our goal was to build a cloud climatology which is reliable for all clouds. If this is not the case, there will be many cloud type misidentifications. Though the retrieved properties of low-level clouds might be noisier, it was important that their height is not biased, so that they are not confounded with higher level clouds.

Kahn et al. have published a new version of the NASA AIRS cloud climatology, but as unfortunately the team does not yet participate in the GEWEX cloud assessment (though invited), a direct comparison is difficult.

Is the fact that the percentage is slightly higher over ice/snow indicative of a loss of skill at sounding T/q over these surfaces, and Era-Interim is superior? What is different about these profiles over ice/snow?

Better detection of inversions and isothermal layers in ERA-Interim?

The frequency of retrievals with good quality decreases over ice/snow, probably also because clouds over these surfaces are more difficult to detect. In addition, polar regions might oft be covered by clouds (especially in SH ocean). We show a map of relative frequency of good quality retrievals of $T_{surf}$ for December 2007, at 1:30AM LT (criteria described in 2.5.1). When only 10% of the time during a month, data are available and the meteorological situation is very variable during the month, the interpolation gets to its limits, whereas ERA-Interim data are always available. ERA-Interim also detects twice more inversions than AIRS (though we do not know which of the dataset is closer to the reality).

Rel. frequency of good quality $T_{surf}$, Dec 2007, 1:30AM

p. 14-16: this section is extremely long and detailed. A lot of it seems consistent with previous paper by the first author. Around lines 31-32 on p. 15 there is one quite interesting point about opaque clouds and a reduced geometrical thickness. Could this be because the IWC is larger in these clouds and thus leads to a smaller difference between the sounders and CALIOP?

This reminds me of a paper by Sherwood et al. discussing these types of discrepancies:


We have substantially shortened this section, also by taking out Fig. 6 and taking out 3 panels of Fig 4 and moving 3 panels of Fig 5 to the supplement. We also tried to be more concise. Compared to Stubenrauch et al. 2010, the estimation of the height at which the cloud reaches a COD of 0.5 is new, though one has to keep in mind that it depends on several assumptions (section 2.4). Concerning the
slight drop in difference between $z_{\text{cld}}$ and $z_{\text{top}}$ for $e_{\text{cld}}$ close to 1, it probably means that for these clouds
opacity is reached within a smaller vertical extent, as for those clouds $z_{\text{cld}}$ also corresponds to the mean
between top and height at which clouds gets opaque. We cited the Sherwood paper in Stubenrauch et al.
2010, where we had already shown that $z_{\text{top}} - z_{\text{cld}}$ increases with $z_{\text{top}} - z_{\text{app(base)}}$, reaching up to 3 km.

p. 17-21, Section 4: another really long section with figures 8-14 that have a combined total of over 80
sub-panels. A lot of these figures are known from previous papers or are common knowledge. Some of
these panels appear to show some redundant information. I would suggest trying to trim this down as
much as possible and try and keep the information to the most interesting and novel bits.

We took out 16 panels of Fig. 10-13 and 6 panels of Fig. 14, which we also moved to the supplement.
This leaves 5 Figs, and we shortened the discussion. On the other hand, we want to show the quality of
the new climatologies, so we have to show some comparisons, even if they might not be novel.

p. 19, lines 25-27: I don’t see why which might have important consequences on radiative feedbacks should be there. Since the SW and LW budgets are not shown with respect to the different cloud types
described in the paper, this is speculative. I would further emphasize that there are many other
interesting things about these particular clouds, including the hydrological cycle, not just radiation and
its feedbacks.

We agree with this suggestion so we took this part out and shortened the sentences to:

The independent use of $p_{\text{cld}}$ and $e_{\text{cld}}$ made it possible to build a climatology of upper tropospheric cloud
systems, using $e_{\text{cld}}$ to distinguish convective core, cirrus anvil and thin cirrus of these systems. These data
have revealed for the first time that the $e_{\text{cld}}$ structure of tropical anvils is related to the convective depth
(Protopapadaki et al., 2017).

p. 20, lines 27-28: Are the authors suggesting that the global cloud amount should be related to the
global surface temperature? Is there a previous reference that argues for this? Most studies show a
relationship of the patterns of global cloud distributions, height, types, etc. can change with respect to
global averaged surface temperature, but I’ve never seen an argument for an average global cloud
amount. Also, another point here regarding surface temperature that it did not increase much. If the
authors are referring to the alleged hiatus I think that is basically proven that there was no hiatus (a
recent paper by T. Karl at NOAA).

http://science.sciencemag.org/content/348/6242/1469

Thank you for the interesting article. We just wanted to make the point that global cloud amount stays
stable during this period; we have removed the sentence about surface temperature.

p. 21, lines 28-29: what is the justification to relate infrared derived cloud amount to SW reflected
radiation? Are there any previous papers that have shown a correlation? The infrared derived cloud
amount saturates around an optical depth of 5 or so, but the SW does not. How can the infrared derived
cloud products be used to infer consistency with SW results?

We talk here about total CA, which we have shown in section 4 to be consistent with all other
climatologies. Also CAH, CAM and CAL are reliably identified, as all discussions in section 4 have
shown ! Indeed the effective cloud emissivity saturates at 1 (corresponding to visible COD of about 10),
while VIS COD continues to increase. However, the paper of Stephens et al. 2015 is relating the
planetary albedo to cloud amount.
p. 22, lines 1-3: how can the CAH be used as a proxy for precipitation rate? Because the ITCZ is narrower in the CIRS data, one can infer a more intense precipitation rate? I'm not sure I understand the logic used here.

We understand the InterTropical Convergence Zone as the zone with strong convection which then produces large cirrus anvils. The latter stay longer in the atmosphere than the convective towers themselves. It is also seen in all maps that the ITCZ has a strong occurrence of high-level clouds (which are mostly cirrus anvils, see for example (Protopapadaki et al. 2017)). Hence, we assume that the ITCZ can be determined by the latitude with a peak in CAH (new Fig. 8). We have partly rewritten this section and hope that the motivation and analysis are easier to follow.

p. 22, first paragraph of Section 5.2: there is no reason to have a basic tutorial on ENSO in the paper. The authors should just get to the results and describe what is novel and delete that part.

we have taken out the introduction and Figure 16 and its discussion.

Figure 3: numbers are too small and blurry for reading
fixed in new Figure 2

Figure 4: why bother with the right column? Were these differences previously described by the lead author?
Right column taken out

Figure 6: three figures in a row describing apparent cloud top and biases with CALIOP. Need to emphasize the novel results and parts of figures that support them. The numbers are overlapping on the x-axis at the edges of the subpanels too.
Figure taken out and added quartiles to Fig 4, so that the width of the distributions are shown together with the medians; this makes the discussion more concise

Figure 13: can’t tell the difference between open and closed red circle, red square, and red dashed line
fixed in new Figure 10

Figure 14: the seasonal variability in latitude bands is well understood. What is new in this figure? Are there new insights between different instruments and inferences of the seasonal cycle?
Panels with CAM taken out and Figure moved to supplement (new Figure S4); there is nothing new, it is just to show the quality of the new cloud climatologies, compared to other datasets.

Response to Referee #2
5 particular issues that need further explanation:

- the role of CALIPSO-CALIOP data for tuning the method

The cloud property retrieval was originally developed for TOVS data (Stubenrauch et al. 1996, 1999, 2006); at that time the cloud detection, which indeed was applied before the cloud retrieval, was essentially based on interchannel regression tests using a combination of IR sounder and microwave (MSU) brightness temperatures.

When we adapted the cloud retrieval to AIRS, channel 7 of AMSU did not work, so we could not adapt the cloud detection. However the retrieval itself provides cloud pressure and emissivity for each measurement (only about 5% of the data do not give a solution, these are declared immediately as clear sky). We then considered it more interesting to develop a cloud detection which could be applied after the retrieval. The idea was to test the reliability of the results to decide if a footprint is cloudy. By comparing clear sky and cloudy scenes determined within time synchronous samples from CALIPSO L2 5km cloud data, provided by NASA, we found that the relative spectral spread of cloud emissivities determined at atmospheric window wavelengths is small if the footprint contains a cloud for which the cloud height and emissivity are well determined (both are used in the computation of the spectral emissivities), while most clear sky scenes lead to very large values. These distributions have been published in Stubenrauch et al. 2010, and for the retrievals with new ancillary data in Fig. S1. These distributions show a nice distinction between clear and cloudy, but the thresholds themselves have been determined by examining many different aspects, like maps and comparison with other datasets, distributions separately over tropics, midlatitudes and polar regions. One important aspect was also to test that AIRS, using two different ancillary data sets, together with IASI gave coherent answers, day and night.

So, the CALIPSO-CloudSat data have been essential to guide us in the cloud detection, but they were not used to tune it.

- the exact description of the used CALIPSO dataset for tuning and for evaluation of cloud properties

Again we want to stress that we did not use CALIPSO for tuning.

We have moved the section of the collocated AIRS-CALIPSO-CloudSat data forward, so that the description is placed before the description of the cloud detection. It was well written that we used version 3 of the NASA CALIPSO L2 cloud data averaged over 5 km (Winker et al. 2009); and we explained the procedures how we used the data (for example excluding subvisible cirrus). By the way, we published comparisons with lidar already in 2005, when we compared TOVS Path B cloud properties with LITE (Stubenrauch et al. 2005) where we also investigated subvisible cirrus. In this paper we just wanted to show that the CIRS cloud data are of slightly better quality than the AIRS-LMD cloud climatology, and the effect of ancillary data, which in our opinion has not been stressed with other cloud climatologies.

- the consequence of using some unphysical assumptions in the retrieval

We accept cloud emissivities up to a value of 1.5, due to noise. This is explained in the reference Stubenrauch et al. 1999, which is cited:

As in Eq 2 the denominator includes two terms (Icld and Iclr) which get very close to each other in the case of low-level clouds, the cloud emissivity can get larger than 1 when taking into account uncertainties. In Stubenrauch et al. (1999), it was shown that the original method, which excluded values larger than 1, underestimated the amount of low-level clouds considerably.
The limit larger than 1 has been chosen to compensate for radiation noise and ancillary data uncertainties and this leads to a better identification of low-level clouds.

- the balance between finding spectral coherence in the solutions and still maintain physically reasonable emissivity differences

The multi-spectral cloud detection is indeed based on wavelengths in an interval which is sensitive to thermodynamical phase and ice crystal sizes. As can be seen in Fig. 3 of Guignard et al. (2012), the relative cloud emissivity difference between 9 µm and 12 µm can go up to 0.3 for small IWP and ice crystal size. However, instead of using a spectral difference, we use a standard deviation between 6 wavelengths, divided by retrieved cloud emissivity. This should be always smaller than 0.15, even in the case of small IWP and ice crystal sizes which produce the largest slope (we have studied that in detail when developing the method in 2010). In this empirical method, the error one makes, if the used cloud pressure does not correspond to the real pressure, is larger, and Fig. S1 (of the supplement) illustrates nicely, that this relative standard deviation is larger than 0.3 for clear sky scenes, while for cloudy scenes the distributions are really narrow, using CALIPSO-GEOPROF to separate cloudy and clear sky scenes.

- justification of the statement of achieving successful cloud detection down to IR cloud optical thicknesses of 0.1

optical thickness can be deduced from cloud emissivity as COD = - ln(1 - ε_{cl})

As we present clouds with ε_{cl} > 0.1, this corresponds to clouds with IR COD > 0.1 (or with VIS COD > 0.2 as VIS COD = -2ln(1 - ε_{cl})).

To reduce misidentification of clear sky as high-level clouds, only clouds with ε_{cl} ≥ 0.10 are considered. Indeed, this came out of a study with CALIPSO-CloudSat:

The above figures present normalized ε_{cl} distributions of high-level clouds, after multi-spectral cloud detection, but leaving clouds with 0.05 < ε_{cl} < 0.10 as clouds, separately for cloudy scenes defined by GEOPROF and CALIPSO (full line) and for all scenes (dotted line). The first bin includes scenes with 0.05 < ε_{cl} < 0.10; in the tropics this bin has more clear sky than high-level clouds. Therefore we have moved the threshold to 0.1. As the contribution of the first bin is small compared to the integral, this seemed a reasonable choice.

Specific comments

1. Page 1, Abstract, line 19, “to evaluate”:
The term "to evaluate" should be changed to "to design and evaluate." You used A-train data to find your 'a posteriori' cloud masking thresholds, right? Then you should be clear in your description that A-train data is not completely independent from your data/method. This is important for the reader to know.

We do not quite agree with this comment; the cloud retrieval was originally developed for TOVS data (Stubenrauch et al. 1996, 1999, 2006); at that time the cloud detection, which indeed was applied before the cloud retrieval, was essentially based on interchannel regression tests using a combination of IR sounder and microwave (MSU) brightness temperatures.

When we adapted the cloud retrieval to AIRS, channel 7 of AMSU did not work, so we could not adapt the cloud detection. However the retrieval itself provides cloud pressure and emissivity for each measurement (only about 5% of the data do not give a solution, these are declared immediately as clear sky). We then considered it more interesting to develop a cloud detection which could be applied after the retrieval. The idea was to test the reliability of the results to decide if a footprint is cloudy. By comparing clear sky and cloudy scenes determined within time synchronous samples from CALIPSO L2 5km cloud data, provided by NASA, we found that the relative spectral spread of cloud emissivities determined at atmospheric window wavelengths is small if the footprint contains a cloud for which the cloud height and emissivity are well determined (as both are used in the computation), while most clear sky scenes lead to very large values. These distributions have been published inStubenrauch et al. 2010, and for the retrievals with new ancillary data in Fig. S1. These distributions show a nice distinction between clear and cloudy, but the thresholds themselves have been determined by examining many different aspects, like maps and comparison with other datasets, distributions separately over tropics, midlatitudes and polar regions. One important aspect was also to test that AIRS, using two different ancillary data sets, together with IASI gave coherent answers, day and night.

So, the CALIPSO-CloudSat data have been essential to guide us in the cloud detection, but they were not used to tune it.

2. Page 1, Abstract, line 23, "coincides":

To use the term "coincides" here is a too strong conclusion from your results. Figure 6 (lower right panel) clearly shows a rather broad distribution of results where frequencies at the two extremes (0 and 1) are still about 20-25 % of the frequency for the value 0.5 (representing the middle of the defined layer). Therefore you can possibly only state that the cloud height can be "approximated" by the middle of the defined layer. Also "middle" could possibly be replaced by "the mean layer height" to make the description scientifically stricter.

3. Page 1, Abstract, line 27, "apparent vertical cloud extent":

The explanation here is confusing, indicating that upper level clouds generally have higher cloud emissivities than lower level clouds. This cannot be true. I guess the authors mean something else. Please clarify!

Rewritten as:

CIRS cloud height can be approximated by the mean layer height (for optically thin clouds) or the mean between cloud top and the height at which the cloud reaches opacity. For high-level clouds, especially in the tropics, this height lies on average 1 km to 3 km below cloud top.

4. Page 2, Abstract, lines 5-8, "response to climate change" + Page 3, Section 1, lines 23-25 and the entire section 5: The last sentence in the abstract, the sentence about Section 5 in Section 1 and the entire section 5 could possibly be removed for shortening the paper (see also comment 25!).
We have considerably shortened section 5, but have left two main studies, which have been described in a more concise manner. The latter study is also compared to recent results using other data.

Changed last part of abstract to:

The 5% annual mean excess in high-level cloud amount in the Northern compared to the Southern hemisphere has a pronounced seasonal cycle with a maximum of 25% in boreal summer, in accordance with the moving of the ITCZ peak latitude, with annual mean of 4°N, to a maximum of 12°N. This suggests that this excess is mainly determined by the position of the ITCZ. Considering interannual variability, tropical cirrus are more frequent relative to all clouds when the global (or tropical) mean surface gets warmer. Changes in relative amount of tropical high opaque and thin cirrus with respect to mean surface temperature show different geographical patterns, suggesting that their response to climate change might differ.

5. Page 2, Section 1, line 11, "70 % cloud cover":

Although this is a widely used and accepted figure for global cloudiness, I would like to point out that a value of global cloud cover cannot be stated without first defining what you mean by a cloud. The figure 70% is kind of representing clouds which have a significant impact on radiation budgets and it could possibly be relevant if you define that clouds should have at least a cloud optical thickness of approximately 0.2. But if including also the thinnest clouds (often called sub-visible clouds and so far only observed by high sensitive instruments like CALIPSO-CALIOP) the figure may increase to values well above 80%. I think it would be appropriate to at least make a short statement on what clouds are considered when stating that global cloudiness is about 70%.

Indeed, in the GEWEX Cloud Assessment we found out that global cloud amount is about 0.68±0.03 when considering clouds with VIS optical depth of larger than 0.2, and additional 0.06 arise from subvisible clouds detected by CALIPSO (Stubenrauch et al. 2013), which brings it to 0.74. This is written in Section 4.

It seems for us appropriate to leave the about 70%, as this sentence is the first in the introduction and is just meant to bring up the importance of clouds because of their large coverage. 7 lines further the reader finds more detail on the threshold (IR optical depth > 0.1).

6. Page 3, Section 1, line 3: "optical depth less than 3":

My impression is that the capability is better than that, i.e., the capability of having reasonable cloud optical depth estimations from CALIOP data covers the interval 0-5. Please check that the value of 3 is really justified.

The optical depth at which clouds are opaque is difficult to determine. In an earlier publication (Lamquin et al. 2008), we wrote that the upper limit lies between 3 and 5. One should not forget that the uncertainty is easily 20% due to uncertainty in multiple scattering contributions (Lamquin et al. 2008).

We have rewritten this in accordance:

Whereas the lidar can detect sub-visible cirrus, its beam can only penetrate the cloud down to optical depth of about 3 to 5 (in visible range). For optically thicker clouds, the radar provides the cloud base.

7. Page 7, Section 2.4, line 4, "emissivities larger than 1":

I must say that it is quite disturbing to be forced to use unphysical values in the retrieval. I understand that uncertainties can lead to this but I am not sure that this is then the best way of handling these
uncertainties. Why not restrict emissivities to 1 in the optimization/minimization process when knowing that this is physically correct? I can’t see why your present method gives better uncertainty descriptions of the retrieved cloud pressures than when using a restricted emissivity value. Don’t inconsistencies give rise to new inconsistencies? Please explain and motivate.

The reason is explained in the reference Stubenrauch et al. 1999 which is cited:

As in Eq 2 the denominator includes two terms (Icld and Iclr) which get very close to each other in the case of low-level clouds, the cloud emissivity can easily get unphysical when taking into account uncertainties. In Stubenrauch et al. (1999), it was shown that the original method, which excluded values larger than 1, underestimated the amount of low-level clouds considerably.

The limit larger than 1 has been chosen to compensate for radiation noise and ancillary data uncertainties and this leads then to a better identification of low-level clouds.

8. Page 7, Section 2.4, lines 22-28, “a posteriori cloud detection”:

The “a posteriori cloud detection” has already been briefly introduced (page 4, lines 7-11). Why repeating this information here? Delete these lines or move part of this to the relevant section 2.5.

deleted

9. Page 9, Section 2.4.1, lines 18-20, “ocean cloud amounts larger during night”:

To find larger ocean cloud amounts at night than during day is found in many regions (e.g. over marine stratocumulus areas). What made you think this was a problem specifically for ERA-Interim? Please explain.

The problem is not that the cloud amount is larger during night than during day, but that results are different when using two different sets of ancillary data; we had to find out which dataset had a problem, and after some time we found that the amplitude of the ERA-Interim SST diurnal cycle is not in agreement with observations. It is reassuring that after applying a correction, this had a positive effect on the cloud amounts, as now the diurnal variation of cloud amount is more similar.

Rewritten to: Without this correction, the cloud amount (CA) at night/early afternoon was 78%/71%, compared to 71%/71% when using AIRS ancillary data. The correction led to 76%/73%, closer to the results using AIRS ancillary data.

10. Page 10, Section 2.4.2:

The CO2 correction appears to be a very relevant change (also visualized nicely in Figure 13. This appears to be one of the most important improvements of the methodology. Should become mandatory in all sounding-based retrievals for climate datasets, in my opinion.

Thank you for the compliment 😊 In our case this was necessary, as the spectral transmissivities came from look-up tables computed for a fixed CO2 concentration.

Actually, Menzel et al. (2016) also use a varying CO2 concentration adjustment, for a 35-year HIRS cloud climatology.

11. Page 11, Section 2.5, general comment on the “a posteriori cloud detection”:

The methodology appears a bit awkward compared to many other cloud retrieval methods in that cloud properties are first derived and then a determination whether a FOV is cloudy is carried out as a second
step. Most common otherwise is that a cloud screening is done first and then followed by a cloud property retrieval. So, could you confirm that after having performed the cloud property retrieval, all FOVs are still assumed to be cloudy? Does it mean that you will always find a solution to Equation 2? You have already mentioned some problems in finding a distinct minimum for lowlevel clouds (page 7, lines 2-3) but what happens in obviously cloud-free situations?

Actually, we see this method as an advantage, because the method tests if the retrieved values are coherent, whereas most cloud detection methods use many different threshold tests, mostly based on brightness temperatures. We would have liked to adapt the cloud detection which was based on the comparison of temperatures (after correction for water vapour effects) obtained from HIRS to those of the microwave sounding unit MSU (developed for TOVS) to AIRS. Unfortunately, the AMSU channel which sounded closest to the surface did not work from the beginning. Therefore we have developed this method. Indeed, the $\chi^2$ method provides in most cases (95%) a solution. The cloud detection is based on the coherence of spectral emissivities which are calculated using the retrieved cloud pressure. If the retrieved cloud pressure does not correspond to reality (as for clear sky or partly cloudy situations), the spectral variability gets large, as illustrated in Fig. S1.

We have now moved section 2.5 to section 2.4.3 and have rewritten part of the text.

12. Page 11, Section 2.5, line 16 + lines 20-21, meaning of spectral coherence:

I am a bit concerned about the concept indicating that, for a cloud to be identified, the differences between emissivities in the six infrared channels should be small. In this wavelength region we know that the refractive indices of water and ice, respectively, varies considerably. For example, this is one of the fundamental properties that allows separating water clouds from ice clouds in passive imagery (e.g. as introduced by Pavolonis et al., 2005, J. Appl. Meteorol.). This fact would also certainly introduce considerable differences in cloud emissivities depending on if it is a water or ice cloud in addition to variations in optical thickness or partial coverage within each FOV. So, isn't there a risk that the demand on spectral coherence is in conflict with reality? Or are you able to find a balanced and optimized method based on reference observations from CALIPSO-CALIOP data and still retain reasonable resulting emissivity differences? I guess that the access to CALIPSO-CALIOP data here is essential since it would be difficult otherwise (e.g. through detailed cloud model simulations) to find an optimal way here. Please comment.

The multi-spectral cloud detection is indeed based on wavelengths in an interval which is sensitiv to thermodynamical phase and ice crystal sizes. As can be seen in Fig. 3 of Guignard et al. (2012), the relative cloud emissivity difference between 9 μm and 12 μm can go up to 0.3 for small IWP and ice crystal size. However, instead of using a spectral difference, we use a standard deviation between 6 wavelengths, divided by retrieved cloud emissivity. This should be always smaller than 0.15, even in the case of small IWP and ice crystal sizes which produce the largest slope (we have studied that in detail when developing the method in 2010). In this empirical method, the error one makes, if the used cloud pressure does not correspond to the real pressure, is larger, and Fig. S1 (of the supplement) illustrates nicely, that this relative standard deviation is larger than 0.3 for clear sky scenes, while for cloudy scenes distributions the distributions are really narrow, using CALIPSO-GEOPROF to separate cloudy and clear sky scenes.

13. Page 11, Section 2.5, line 25, standard deviation:

How do you calculate the standard deviation here? Do you use all values in the AIRS golf ball (i.e., 9 values) for the calculation for each wavelength? The current description is not clear enough on this.

It is a standard deviation over all 6 emissivities per AIRS footprint.
14. Page 11, Section 2.5, line 27, "CALIPSO samples":

Unfortunately, here you introduce the use of CALIPSO data without having described what data you actually used (this description comes later in Section 3.1). More clearly, it is not obvious to the reader that you will get three CALIPSO samples in the AIRS golf ball. For this, you need to know that you use 5 km CALIPSO data. Because of the importance of A-train data for your method and study, I am of the opinion that you should have introduced them already in Section 2 on "Data and Methods". Can you consider changing this?

Section 3.1 now moved to section 2.4

15. Page 12, Section 2.5, lines 18-19, "minimum optical depth":

In the introduction section you mention that with IR vertical sounding data "reliable detection of cirrus with IR optical depths as low as 0.1" is possible indicating that this is much better than what can be achieved from other sensors (except from active sensors). I wonder what this restriction in order "to reduce noise" means in this context? Have you estimated further the minimum cloud optical depths being detected after introducing this restriction? CALIPSO-CALIOP offers the possibility to do such in-depth studies.

We made this sentence more explicit: To reduce misidentification of clear sky as high-level clouds, only clouds with $\varepsilon_{\text{cd}} \geq 0.10$ are considered.

Indeed, this came out of a study with CALIPSO-CloudSat:

The above figures present normalized $\varepsilon_{\text{cd}}$ distributions of high-level clouds, after multi-spectral cloud detection, but leaving clouds with $0.05 < \varepsilon_{\text{cd}} < 0.10$ as clouds, separately for cloudy scenes defined by GEOPROF and CALIPSO (full line) and for all scenes (dotted line). The first bin includes scenes with $0.05 < \varepsilon_{\text{cd}} < 0.10$; in the tropics this bin has more clear sky than high-level clouds. Therefore we have moved the threshold to 0.1. As the contribution of the first bin is small compared to the integral, this seemed a reasonable choice.

16. Page 13, Section 3.1, lines 16-19, "CALIPSO and CloudSat data":

This requirement should mean (?) that you require that both CloudSat and CALIPSO say it is cloudy. But what about the fact that CALIPSO sees much more of the very thin cirrus clouds being available? Does it mean that these cirrus cases are not included in your evaluation study despite the fact that you several times have emphasized the capability of your method to detect very thin cirrus? Or is it different for studies of cloud amount (as indicated by description in lines 7-15) and cloud top height? Please comment!
We use CloudSat-lidar GEOPROF data, which detect a cloud layer when either CALIPSO or CloudSat detect a cloud layer (footprint 2.5 km x 1.5 km), and to add a different sampling (and because we needed a few other variables like COD) we use the CALIPSO 5km cloud data. In the latter we exclude subvisible cirrus (admitting only clouds detected with horizontal averaging \(< =5 \text{ km}) for the evaluation, as we know that IR sounders are not sensitive to those. This corresponds to clouds with COD > 0.05 to 0.1, according to Winker et al. (2008).

Then, we require that both samplings detect a cloud, just to be sure that the sampling is coherent. These data are then used for all studies in this paper. We have tried to explain it better in the new section 2.4:

é. The CALIPSO cloud data also indicate at which horizontal averaging along the track the cloud was detected (1 km, 5 km or 20 km), which is a measure of the COD. As in Stubenrauch et al. (2010), for a direct comparison with AIRS cloud data, we use clouds detected at horizontal averaging over 5 km or less. This corresponds to clouds with visible COD larger than about 0.05 to 0.1 (Winker et al., 2008). The scene type of an AIRS footprint is estimated as cloudy when the CALIPSO sample as well as the GEOPROF sample include at least one cloud layer. Clear sky is defined by cloud-free CALIPSO and GEOPROF samples within the AIRS footprint.

17. Page 13, Section 3.1, line 23, "underestimated COD":

Just for your information: The latest version of the CALIPSO-CALIOP dataset (version 4.1) gives indeed higher CODs. This change can possibly be connected to what you write here (currently I do not know the details behind this change).

Thanks for this information!

18. Page 14, Section 3.2, lines 2-3, "agreement":

I have to ask you to specify better what you mean by "agreement". There are so many skill scores around so you better be strict in describing exactly the measure you use. I guess you refer to what is normally called "Hit Rate" which is the number of correct cloudy AND clear cases divided by the total number of cases.

Indeed, it is the hit rate which we have calculated. We have changed this in the text:

The hit rates between the "a posteriori" cloud detection and the CALIPSO-CloudSat cloud detection are 85% (84%) over ocean, 82% (79%) over land and 70% (73%) over ice / snow.

19. Page 14, Section 3.3, generally on results in Figure 4 (Page 40):

First, please revise the wording of the caption of this figure. The first sentence here is too complicated and the description should possibly be made more clear (the same is actually true for Figure 5). Also make clear (in all figures) what you mean by "1:30 LT" (AM or PM??). The question raised in the previous comment 16 remains: Are thin cirrus detected by CALIPSO but not by CloudSat part of this study or not?

If not, what can be said about the quality of these retrieved cloud heights (as compared to CALIPSO data alone)?

1:30 is 1:30AM, as defined in section 2.1 (1:30 and 13:30); however, as this leads to confusion with American readers, we will change this in the whole paper to 1:30AM and 1:30PM etc.

As explained before, for this comparison CALIPSO cloud data with COD > 0.05 to 0.1 are used.
The other referee suggested to take out the right panels of Figure 4 (which look very similar to the results published in Subenrauch et al. 2010). We have worked on all figure captions.

Compared to the publication of Kahn et al. 2008 about the NASA AIRS Science team results of cloud height from Version 5, we show that in both cases, high-level clouds as well as mid- and low-level clouds the height is determined without bias, if one considers the cloud height given by AIRS as the height of maximum lidar backscatter (Stubenrauch et al., 2010), by the mean layer height (for optically thin clouds) or the mean between cloud top and the height at which the cloud reaches opacity, as shown in Figure S2 (considering mid-$\rho_{lid}$), or by $z_{COD0.5}$ (Figure 3).

21. Page 16, Section 3.3, lines 5-24, Figure 7:

Very interesting and impressive results shown here! Results for medium and high clouds are probably quite superior to those being presented from passive imagery in other CDRs. Only for low-level clouds we still see quite some discrepancies which is understandable for several reasons. This indicates that the best representation of the true vertical distribution of cloudiness in a climate sense could be a combination of sounding and passive imagery data. Do you agree? Maybe you should mention this. Interesting is that problems for low clouds for sounding applications is not showing up very clearly later in Figure 9, except possibly during night for the land-ocean difference. Maybe you should explain why?

Indeed, a combination of IR sounder and passive imagery would increase the quality during day. During night, sounding provides better results, though the large footprints are a handicap for the identification of low-level cloud fields (as shown in the analysis of new Fig. 5). The concept of the CIRS retrieval was guided by the goal to create a cloud climatology with small biases, also for low-level clouds. Indeed, the noise is much larger for low-level clouds than for high-level clouds, but the biases are small compared to other IR sounder cloud climatologies. The comparison with CALIPSO-CloudSat comes to its limit in the analysis of new Fig 5, as the size of the footprints is very different.

20. Page 15, Section 3.3, line 9, ŒcoincidesÓ:

See previous comment 2.

22. Page 16, Section 3.3, line 32, ŒcoincidesÓ:

See previous comment 2.

26. Page 26, Section 6, line 1, ŒcoincidesÓ:

See previous comment 2.

Replaced by Œcan be approximatedÓ

23. Page 18, Section 4, lines 15-16, Œsensitivity of lidarsÓ:

You write that Œactive lidar is the most sensitiveÓ. Quite true but you havenÔ explained whether CALIPSO results in Figure 9 are already ŒfilteredÓ (so that the thinnest clouds as given by the original CALIOP CLAY product are removed) or not. Has there been any filtering of Œsub-visible cloudsÓ (I assume there has)? This is a relevant question to ask also for the statement in the Conclusions section on page 25, line 25. We need to know exactly what is the used CALIPSO dataset used as reference!

In section 4, the CALIPSO L3 data of the GEWEX Cloud Assessment data base are used; two teams have provided their data, with the main difference by vertical (CALIPSO-GOCCP) or horizontal averaging (CALIPSO-ST), as mentioned in the text. The details of the GEWEX Cloud Assessment data base are found in (Stubenrauch et al. 2013) and especially in the WCRP report (Stubenrauch et al. 2012),
where each team gave details how they created the L3 data. As I remember, CALIPSO-ST includes subvisible cirrus, which explains the larger CA, compared to all other datasets.

In section 3, L2 products have been used, as described in the new section 2.4.

24. Page 21, Section 4, line 4, Figure 14, "Seasonal cycle of cloud temperatures":

How come there is a rather large consensus between different methods when studying cloud temperatures for the polar areas (leftmost and rightmost columns) when the spread is very large when it comes to cloud amount (top row of the same columns)? I suspect it is an indication of that cloud temperatures and surface temperatures are very similar here. This implies (in my opinion) that the separation of cloudy and cloud-free areas is indeed not very accurate. So, where is really the truth as regards polar cloudiness? Apart from this reflection, I consider Figure 14 as a very nice compilation of global cloudiness and its variation.

This actually shows that cloud amount, depending on thesholds, might be different by 10%, while the averages of retrieved cloud properties, which only can be given when a cloud is detected, are more similar. (Missing 10% does not mean that the average properties of the clouds are completely different).

In addition the polar regions are to be considered with care, as written in the discussions: the CALIPSO data does not conform with the other data sets in the GEWEX Cloud Assessment data base, because they exclude measurements from 1:30PM during polar night (polar winter) and from 1:30AM during polar day (polar summer).

As a similar figure was already published in Stubenrauch et al. (2013) (though not CT), we moved this Fig. to the supplement, in order to shorten the paper, and as suggested by referee#1.

25. Pages 21-24, Section 5, "beyond scope??

In my opinion, Section 5 feels like out of scope of this study. Although introducing highly interesting topics (especially section 5.2), this work would benefit from being presented as a separate (or companion) publication. This manuscript is very, very long and it will put the readers (as it truly has for reviewers!) to a real test when digesting it. I would say that especially section 5.2 on the ENSO effects and its coupling to cloud/radiation feedbacks also requires a different category of expertize for reviewing it with more focus on modelling and studies of climate change and climate feedback effects. Consequently, I have not provided specific comments on this section and I suggest that it is removed for the shortening of this paper.

We do not agree with the suggestion of a complete removal of section 5 "Applications" as the presented method is not new and one of the goals of this article was to present scientific applications (as indicated in the title).

However, we have considerably shortened the section by removing the introduction on ENSO and the discussion about Fig. 16 as well as Fig. 16 itself.

Since the results similar to those presented in new Fig. 12 have recently been published using other data sets, it would be difficult to use the presented material in a separate publication. We plan to work on a more complex analysis to pursue this subject further, but we think it is important to present these results in the current publication.

27. Page 24-27, Section 6, general comment:

A very comprehensive and good summary of the content of the paper. However, it could be shortened (page 26, lines 14-32) as a consequence of comment 25 above.
Thank you! We have revised the part considering section 5.

Technical corrections

1. Page 1, Abstract, line 11-14:

The current introductory sentences assumes that the reader already knows about the LMD cloud retrieval scheme. I suggest a slight reformulation to make it less unclear, e.g. like the following

The Laboratoire de Météorologie Dynamique (LMD) cloud retrieval scheme CIRS (Clouds from IR Sounders) has been adapted to cope with any Infrared (IR) sounding instrument. This has been accomplished by applying improved radiative transfer calculations as well as by introducing an original method accounting for atmospheric spectral transmissivity changes associated with varying CO2 concentrations.

This is not fully correct, as the cloud retrieval developed in the 1990s did not have the name CIRS; this name corresponds to the adapted version.

We have rewritten the beginning as:

Global cloud climatologies have been built from 13 years of Atmospheric IR Sounder (AIRS) and 8 years of IR Atmospheric Interferometer (IASI) observations, using an updated Clouds from IR Sounders (CIRS) retrieval. The CIRS software can handle any Infrared (IR) sounder data. Compared to the original retrieval, it uses improved radiative transfer modelling, accounts for atmospheric spectral transmissivity changes associated with CO2 concentration and incorporates the latest ancillary data (atmospheric profiles, surface temperature and emissivities).

2. Page 2, Abstract, line 3, “5 % asymmetry”:

Please clarify better what you mean with asymmetry. Does it mean that there is generally 5 % more high clouds in the Northern Hemisphere? I assume this is what you mean (supported also by Figure 10) but you should make it crystal clear for the reader in the Abstract!

Rewritten as:

The 5% annual mean excess in upper tropospheric cloud amount in the Northern compared to the Southern hemisphere has a pronounced seasonal cycle with a maximum of 25% in boreal summer, in accordance with the moving of the ITCZ peak latitude to a maximum of 10°N.

3. Page 2, Section 1, line 17, “properties”:

Do you really mean properties? I would rather say cloud detection.

Yes: we meant here that in addition to identification (which means detection), also their properties (height and emissivity) are well determined (even better than those for low-level clouds)

4. Page 2, Section 1, line 32, “determine”:

Like the previous comment, I am not sure about the correct wording here. The word determine is very strong and almost indicates that the CALIPSO and CloudSat satellites together are creating/defining the clouds. Rather, you should express that they are capable of observing the cloud vertical structure.

Changed according to suggestion
5. Page 3, Section 1, line 5, "the cloud retrieval method":
Be a bit more specific, e.g. write "the evolution of the original cloud retrieval method".
changed

6. Page 3, Section 1, line 9, "radiative transfer":
I think you should write "radiative transfer calculations" or "radiative transfer modelling". To only write "radiative transfer" is too general and (I guess) just a shortening of more correct terms.
changed

7. Page 3, Section 1, line 11, "initial": See 5 above (consider using same notation).
Changed to original

8. Page 3, Section 1, line 11, "radiative transfer": See 6 above (consider using same notation).
changed

9. Page 4, Section 2.1, line 11, "The NASA Science team":
I would recommend to start a new paragraph here to increase the readability.
done

I see inconsequent reference formulations on several places in the manuscript. When you make a direct reference to other publications directly in the text (like here) you should (according to my experience) preferably write: "The methodology is essentially unchanged from that described in Susskind et al. (2003)." You have done this correctly in other places (e.g., Page 5, line 27). I think you should be consistent here. Use the formulation above when specifically discussing a publication and use reference in parenthesis when not making a direct statement of the referred publication (a "softer" reference). Check also the following references for the same reason:
- Page 4, line 27
- Page 6, line 5

11. Page 4, Section 2.1, line 20, "shortwave window channels":
Please write "shortwave infrared window channels" since "shortwave" most often is reserved to define visible channels.
changed

12. Page 4, Section 2.1, line 22, "partial cloud cover":
A better formulation is probably "under partially cloudy conditions".
changed

13. Page 4, Section 2.1, line 24, "snow or ice":

Maybe a better formulation is "snow or ice covered surfaces also provided by NASA L2 data".

changed

14. Page 4, Section 2.1, line 26, "ideology":

I would suggest using the term "concept" rather than "ideology".

changed

15. Page 4, Section 2.1, line 27, "and allow":

I suggest replacing this with "which allows".

Rewritten to: The CIRS cloud retrieval allows cloud levels up to 30 hPa above the tropopause.

16. Page 5, Section 2.2, line 1, "12 km":

Is the 12 km valid for each individual footprint or the 2x2 array?

For each individual footprint, clarified in text

17. Page 5, Section 2.2, line 9, "the cloud retrieval":

You should write "the CIRS cloud retrieval".

changed

18. Page 5, Section 2.2, lines 9-10, "retrieved atmospheric profiles":

Be more specific. You should write "IASI-retrieved atmospheric profiles".

changed

19. Page 5, Section 2.2, line 15, "Therefore":

You should not start a new paragraph here if you refer directly to what was written in the previous sentences. Make it also very clear that you never (well, not in time for your development) got access to EUMETSAT Version 6 data otherwise this statement appears rather strange.

We could have gotten access after the development and evaluation of the cloud climatologies were nearly at the end. Since it would have taken another year to build the ancillary data from this data set and evaluate again the IASI cloud climatology (also in combination with AIRS), we opted for ERA-Interim ancillary data to build the combined AIRS-ASI cloud climatologies.

As the sentence about V6 EUMETSAT retrievals seems to cut the flow, we took it out.

20. Page 5, Section 2.2, line 21, "same source":

22
I guess you rather mean a "less instrument-dependent source"?

We think it is more "retrieval quality-dependent source" but this would be difficult to write, as the different Science Teams are doing the best with the fundings they have available. (In the case of NOAA for example, the team had to move working on CrIS).

21. Page 6, Section 2.3, line 1, "proxy":
I don't like the word "proxy" in this context. It indicates that it is a kind of simulation or approximation of the real vertical velocity. The vertical pressure velocity \( \nu \) is just another formulation of the vertical velocity which arises when you use pressure as your vertical coordinate instead of the standard geometrical height in meters. So, to my knowledge, it's the "real thing" and not a "proxy".

But I guess you refer to the fact that the direct calculation of \( \nu \) is difficult without making approximations. The most common here is the geostrophic assumption leading to the so-called \( \nu \)-equation. In this sense, I guess you may be correct in interpreting it as an approximation. But still, present day NWP models are capable of calculating \( \nu \) so I just wonder what value you are using here?

On the other hand, the approximated value at the 500 hPa level is probably quite accurate anyway (conditions here are largely quasi-geostrophic on the large scale) so perhaps this discussion is less important. Anyway, give it a thought.

We needed the vertical velocity for the interpretation in the ENSO analysis. Since Fig. 16 and its interpretation is taken out according to the referees suggestion, this sentence is also taken out.

22. Page 7, Section 2.4, line 12, "arise":
Maybe reformulate to "these cases occur in about 7 to 15 % of all cases."?

Changed to: these cases occur in about 7 to 15 % of all cloudy cases.

23. Page 8, Section 2.4.1, line 14, "less than ..?..":
Strange formulation. You'd better write "0.99 for wavelengths less than 10 \( \mu \)m and 0.98 for wavelengths larger than 10 \( \mu \)m."

Changed to: the surface emissivity is set to 0.99 for \( \lambda_1 < 10 \mu \)m and 0.98 for \( \lambda_1 \geq 10 \mu \)m.

24. Page 13, Section 3.1, line 6, "spatial resolution CALIPSO":
Shouldn't it be 5 km x 0.3 km? I thought the basic FOV of CALIOP was 300 meter.

I have understood that the diameter of the spots is 90m, and the sampling along track is 333 m.

For example: https://calipso.cnes.fr/en/CALIPSO/lidar.htm or Winker et al. (2009), p. 2312

25. Page 15, Section 3.3, Figure 5 (Page 41):
I suggest that you try to include some additional explanatory features or legends in the figure (e.g., legend with the three coloured dots explained). To look for all explanations in the caption is not very reader-friendly. Try to speed up the correct interpretation of figures with the use of more graphical legends or marks. This remark is probably valid for many other figures in the manuscript.

We have taken into account the referee's suggestion and revised all figures accordingly.
I suggest starting a new paragraph here in order to avoid too long chunks of text (unnecessary tiring for the reader).

This whole paragraph has been rewritten (as Fig. 6 has been taken out, and Fig. 5 has been rebuilt with medians and interquartiles to show the width of the distributions within the same figure). We hope that it is now much easier to read.

27. Page 15, Section 3.3, line 28; Figure 6 (Page 42):
In the caption you describe one of the curves as “broken line”. I am not sure whether this is the most common way of describing such a curve. More often the term “dashed line” is used. Consider changing to “dashed”. This suggestion is valid for many other figures in the manuscript.

Thanks; changed everywhere; though dashed lines seems also to exist, at least according to google ;)

28. Page 16, Section 3.3, lines 28-29, “height of COD”:
Semantically, it sounds strange (or even incorrect) to express COD as representing a height. Of course, I understand what you mean but it can actually be misinterpreted. Since you have already defined zCOD0.5 why not use this terminology here, e.g. “The retrieved cloud height exceeds zCOD0.5 for optically thin clouds while it is lower than zCOD0.5 for optically thick clouds.”

This is obvious from the figure, but we want to stress the following:
In that case, zcld of thin cirrus should be approximated to a height at which COD reaches a value < 0.5 and zcld of opaque high clouds to a height at which COD reaches a value > 0.5.

29. Page 20, Section 4, line 17, “three CIRS datasets”?
It is not obvious what three datasets you mean (not explained in text)! Please clarify.

three CIRS climatologies (AIRS, using AIRS-NASA and ERA-Interim ancillary data, as well as IASI, using ERA-Interim ancillary data)

References


Cloud climatologies from the InfraRed Sounders AIRS and IASI: Strengths, Weaknesses and Applications

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Abstract

Global cloud climatologies have been built from 13 years of Atmospheric IR Sounder (AIRS) and 8 years of IR Atmospheric Interferometer (IASI) observations, using an updated Clouds from IR Sounders (CIRS) retrieval. The CIRS software scheme developed at the Laboratoire de Météorologie Dynamique (LMD) can now be easily adapted to handle any Infrared (IR) sounder data. The CIRS (Clouds from IR Sounders) retrieval compared to the original retrieval, it uses improved radiative transfer modelling, accounts for atmospheric spectral transmissivity changes associated with CO₂ concentration and incorporates the latest ancillary data (atmospheric profiles, surface temperature and emissivities), applies improved radiative transfer, as well as an original method accounting for atmospheric spectral transmissivity changes associated with CO₂ concentration. The latter is essential when considering long-term time series of cloud properties. For the 13-year and 8-year global cloud climatologies of cloud properties from observations of the Atmospheric IR Sounder (AIRS) and of the IR Atmospheric Interferometer (IASI), respectively, we used the global cloud amount is estimated to 0.67 ± 0.70, for clouds with IR optical depth larger than about 0.1. The spread of 0.03 is associated with ancillary data. Cloud amount is partitioned into about 40% high-level clouds, 40% low-level clouds and 20% mid-level clouds. The latter two categories only are only detectable only when not hidden by the absence of upper clouds, latest ancillary data (atmospheric profiles, surface emissivities and atmospheric spectral transmissivities). The A-Train active instruments, lidar and radar of the CALIPSO and CloudSat missions, provide a unique opportunity to evaluate the retrieved AIRS cloud properties such as cloud amount and height as well as to explore the vertical structure of different cloud types.
CIRS cloud-detection agreement with CALIPSO CloudSat is byis about 85% over ocean, 80% over land and 70% over ice/snow. Global cloud amount has been estimated to 67%—70%. CIRS cloud height coincides can be approximated either by the mean layer height (for optically thin clouds) or by the mean middle between the cloud top and the apparent cloud base (real base for optically thin clouds or height at which the cloud reaches opacity) independent of cloud emissivity. This is valid for high-level as well as for low-level clouds identified by CIRS. For high-level clouds, especially in the tropics, this height is lies on average about 1 km and 1.5 km to 2.5 km below cloud top for low-level clouds and about 1.5 km to 2.5 km below cloud top for high-level clouds, respectively. For the latter the slight increase relates positively slightly increase with cloud emissivity. This height is larger for large cloud emissivity. IR sounders are particularly advantageous for the retrieval of upper tropospheric cloud properties, with a reliable cirrus identification down to an IR optical depth of about 0.1, day and night. Total cloud amount consists of about 40% high-level clouds and about 40% low-level clouds and 20% mid-level clouds, the latter two only detected when not hidden by upper clouds. Upper tropospheric clouds are most abundant in the tropics, where high opaque clouds make up 7.5%, thick cirrus 27.5% and thin cirrus about 21.5% of all clouds. The asymmetry—5% annual mean excess in upper tropospheric high-level cloud amount between in the Northern and compared to the Southern hemisphere with annual mean of 5% has a pronounced seasonal cycle with a maximum of 25% in boreal summer, in accordance with the moving of the a maximum ITCZ peak latitude, with annual mean of 4°N, to a maximum of shift to 12°N, which can be linked to the shift of the ITCZ peak latitude. This suggests that this excess is mainly determined by the position of the ITCZ. Comparing interannual variability, tropical geographical change patterns, tropical of high opaque clouds with that of thin cirrus and thin cirrus are more frequent among relative to all clouds when the global (or tropical) mean surface temperature gets warmer. Changes in relative amount of tropical high opaque and thin cirrus with respect to mean surface temperature show different geographical patterns, suggesting a function of changing tropical mean surface temperature indicate that their response to climate change might be quite different, with potential consequences on the atmospheric circulation.

1 Introduction

Clouds cover about 70% of the Earth’s surface and play a key role in the energy and water cycle of our planet. The Global Energy and Water Exchange (GEWEX) Cloud Assessment (Stubenrauch et al., 2013) has highlighted the value of cloud properties derived from space observations for climate studies
and model evaluation and has identified reasons for discrepancies in the retrieval of specific scenes, especially in particular thin cirrus, alone or with underlying low-level clouds). Compared to other passive remote sensing instruments, the high spectral resolution of IR vertical sounders leads to especially reliable properties of cirrus, with IR optical depth as low as 0.1, day and night. CO₂-sensitive channels varying in CO₂ absorption of IR vertical sounders allow are used to determine height and emissivity of a single cloud layer, which corresponds to the uppermost cloud layer in the case of multiple cloud layers. While measured radiances near the center of the CO₂ absorption band are only sensitive to the upper atmosphere, radiances from the wing of the band are emitted from successively lower levels in the atmosphere.

Spaceborne IR sounders have been observing our planet since the 1980s: the High Resolution Infrared Radiation Sounders (HIRS) aboard the National Oceanic and Atmospheric Administration (NOAA) polar satellites provide data since 1979, the Atmospheric InfraRed Sounder (AIRS) aboard the National Aeronautics and Space Administration (NASA) Earth Observation Satellite Aqua since 2002, the IR Atmospheric Sounding Interferometers (IASI) aboard the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Meteorological Operation (MetOp) since 2006 and the Cross-track Infrared Sounder (CrIS) aboard the Suomi National Polar-orbiting Partnership (NPP) satellite since 2011, while a next generation of IR sounders (IASI-NG) is foreseen as part of the EUMETSAT Polar System Second Generation (EPS-SG) program for 2021 (Crevoisier et al., 2014).

Active sensors are part of the A-Train satellite formation (Stephens et al., 2002), synchronous with Aqua, since 2006: The CALIPSO lidar and CloudSat radar, together, are capable of observing the cloud vertical structure (Stephens et al., 2008; e.g., Henderson et al., 2013; Mace and Zhang, 2014). Whereas the lidar is highly sensitive and can detect sub-visible cirrus, its beam can only penetrate the cloud down to optical depth of about 3 to 5 (in visible range) only reaches the cloud base of clouds which are not opaque with an optical depth less than 2 to 5. For larger optical depth (COD) larger than about optically thicker clouds, the radar is providing the cloud base location.

Our goal to establish a coherent long-term cloud climatology from different IR sounders has led to the evolution of the original LMD cloud retrieval method developed at the Laboratoire de Dynamique (Stubenrauch et al., 1999, 2006, 2008, 2010) towards an operational and modular cloud retrieval algorithm suite (CIRS, Feofilov and Stubenrauch, 2017). The CIRS retrieval which has so far been applied to AIRS and IASI data as well as to HIRS data (Hanschmann et al., 2017). The cloud property retrieval employs radiative transfer modelling and atmospheric and surface ancillary data (atmospheric temperature and water vapour profiles, surface temperature and surface emissivity,
identification of snow and ice). Compared to the \textit{initial-original method retrieval}, the CIRS retrieval applies \textit{an-improved radiative transfer calculations and an original-novel calibration method, accounting for latitudinal, seasonal and interannual atmospheric CO$_2$ variations, which to adjusts the atmospheric spectral transmissivity look-up table/sies from look-up tables, computed once for a fixed-atmospheric gaseous composition, according to latitudinal, seasonal and interannual atmospheric CO$_2$-variations.}

Compared to the 6-year AIRS-LMD cloud climatology (Stubenrauch \textit{et al.}, 2010), which participated in the GEWEX Cloud Assessment. \textit{In this article, we present, the results of i) an updated and extended 13-year AIRS cloud climatology (2003 ÷ 2015), using two different sets of the latest ancillary data (originating from retrievals and from meteorological reanalyses), and ii) a new 8-year IASI cloud climatology (2008 ÷ 2015) are presented in this article. After the description of data and methods in section 2, section 3 is dedicated to the evaluation of cloud detection and cloud height using the unique A-Train synergy of synchronous passive and active measurements. Section 4 presents average cloud properties and their regional, seasonal, inter-annual and long-term variability, in comparison with other datasets, as well as uncertainty estimates with respect to the used ancillary data. Section 5 concentrates on the variability of the upper tropospheric clouds with respect to changes in atmospheric conditions in order to illustrate how these data may be used for climate studies. Conclusions and an outlook are given in section 6.}

\section{Data and methods}

\subsection{AIRS Data}

The AIRS instrument (Chahine \textit{et al.}, 2006) provides very high spectral resolution measurements of Earth emitted radiation in 2378 spectral bands in the thermal infrared (3.74-15.40 \textmu m). The spatial resolution of these measurements varies from 13.5 km x 13.5 km at nadir to 41 km x 21 km at the scan extremes. The polar orbiting Aqua satellite provides observations at 1:30 AM and 13:30 PM local time (LT). Nine AIRS measurements (3 x 3) correspond to one footprint of the Advanced Microwave Sounder Unit (AMSU), and are grouped as a \textquoteleft golf ball\textquoteright.

The CIRS cloud retrieval uses measured radiances \textit{around-along the the-wing of the} 15 \textmu m CO$_2$ absorption band. We have chosen AIRS channels closely corresponding to the five channels used in the TIROS-N Operational Vertical Sounder (TOVS) Path-B cloud retrieval, at wavelengths of 14.19, 14.00, 13.93, 13.28 and 10.90 \textmu m, and three additional channels at 14.30, 14.09 and 13.24 \textmu m (with peaks in the weighting function at 235, 255, 375, 565, 415, 755, 885 hPa and surface, respectively). \textit{The cloud property retrieval (section 2.5.4) is applied to all data. In a second step, after which an \textquoteleft a posteriori\textquoteright The multi-spectral cloud detection, based on the spectral coherence of retrieved cloud emissivities, obtained
by using the retrieved cloud pressure, decides whether the AIRS footprint is cloudy (section 2.5.3)-
or mostly clear (section 2.5). For the latter, radiances in the atmospheric window between 9 and 12
μm are used, at six wavelengths of 11.85, 10.90, 10.69, 10.40, 10.16, 9.12 μm.

Ancillary data necessary for the cloud retrieval, which include atmospheric temperature and water
vapour profiles as well as surface skin temperature, are provided by the NASA Science Team provides
L2 standard products (Version 6 (V6); Olsen et al., 2017). which include atmospheric temperature and
water-vapour profiles as well as surface skin temperature. These are necessary ancillary data for the
CIRS cloud retrieval. They were retrieved from cloud-cleared AIRS radiances within each AMSU
footprint. The methodology is essentially unchanged from that described in (Susskind et al., 2003). Compared to Version 5 (V5), the most significant changes are: i) V6 uses an
IR–microwave neural network solution (Blackwell et al., 2014) as a first guess for the retrieval of
atmospheric temperature and water vapour profiles as well as for surface skin temperature, instead of the
previously used regression approach (Susskind et al., 2014). This leads to physical solutions for many
more cases than in Version 5 (V5). ii) The retrieval of surface skin temperature only uses shortwave IR
window channels (Susskind et al., 2014). These modifications have resulted in significant improvement
of accurate temperature profiles and surface skin temperatures under partially cloudy cover conditions
(Van T. Dang et al., 2012). Compared to V5, the surface skin temperature is larger over land in the
afternoon (especially over desert) and over maritime stratocumulus regions.

In addition, we also use the microwave identification of snow or ice covered surfaces, also provided
from by the NASA L2 data.

Since the retrieved cloud pressure should be within the troposphere to lower stratosphere, we have
determined the tropopause pressure from the atmospheric profiles, using the ideology concept described
in Reichler et al., (2003) and in Feofilov and Stubenrauch, (2017), and. The CIRS cloud retrieval
allows cloud levels to be up to 30 hPa above the tropopause.

2.2 IASI data

IASI, developed by CNES in collaboration with EUMETSAT, is a Fourier Transform Spectrometer
based on a Michelson interferometer, which covers the IR spectral domain from 3.62 to 15.5 ㎛. As
a cross-track scanner, the swath corresponds to 30 ground fields per scan, each of these measures a 2 × 2
array of footprints. The latter have a (12-km diameter at nadir). IASI raw measurements are
interferograms that are processed to radiometrically calibrated spectra on board the satellite. Two
instruments were launched so far onboard the European Platforms Metop-A and Metop-B (in October
2006 and September 2012, respectively), with measurements of at 9:30 AM / 7:30 PM LT and
IASI has been providing water vapour and temperature sounding profiles for operational meteorology (accuracy requirements respectively of 1 K and 10% in the troposphere), while observing simultaneously as well as whole suite of trace gas concentrations, surface and atmospheric properties, including those of aerosols and clouds (Hilton et al., 2012). For the cloud retrieval, we use radiances at the wavelengths 14.30, 14.20, 14.06, 14.00, 13.93, 13.40, 13.24 and 10.90 µm, and for the multi-spectral cloud detection the radiances at 11.85, 10.90, 10.70, 10.41, 10.16, and 9.13 µm.

At the time we started incorporating IASI data to the CIRS cloud retrieval, two data sets of IASI retrieved atmospheric profiles and surface temperature were available: one provided by EUMETSAT (Version 5) and one by NOAA. EUMETSAT L2 temperature and water vapour Version 5 products were only available for clear and partly cloudy scenes, leaving atmospheric and surface retrievals in only 9% of all cases, while the recent Version 6 has extended the retrieval of thermodynamical parameters (such as temperature and water vapor) to cloudy scenes.

Therefore we first used IASI L2 ancillary data provided by NOAA. The comparison with collocated temperature profiles of the Analyzed RadioSoundings Archive (ARSA, available at the French data centre AERIS) has shown that, while AIRS–NASA and ERA–Interim (section 2.3) temperature profiles do agree in general with the ARSA profiles within 1 K, differences between IASI–NOAA and ARSA profiles were often larger than 1 K in the lower troposphere (not shown). In addition, however, a study of the influence of the different ancillary data on the CIRS a–cloud amount has demonstrated that the comparison with cloud amounts of low-level clouds over ocean was underestimated, when using those deduced from IASI–NOAA (Feofilov et al., 2015a). This might be most probably explained from AIRS via CIRS has demonstrated that the amount of low-level clouds over ocean was underestimated (Feofilov et al., 2015a), probably due to by an underestimation of the sea surface temperature (SST) linked to cloud contamination. In addition, the comparison with collocated temperature profiles of the Analyzed RadioSoundings Archive (ARSA, available at the French data centre AERIS) has revealed that the AIRS–NASA and IASI–NOAA L2 atmospheric profiles were quite different. This brought us to the conclusion: From this we concluded, that the AIRS–IASI synergy to explore cloud diurnal variability in a coherent way needs one needs ancillary data from similar retrievals or from the same source, necessary: if one wants to use of the AIRS–IASI synergy to for exploring the cloud diurnal cycle variability in a coherent way. Therefore, Thus we also implemented ancillary data from the European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological reanalyses into the CIRS cloud retrieval.

2.3 ERA-Interim meteorological reanalyses
ECMWF provides the meteorological reanalyses ERA-Interim, covering the period from 1989 until now. Dee et al. (2011) give a detailed description of the model approach and the assimilation of data. The data assimilation scheme is sequential: at each time step, it assimilates available observations to constrain the model, which then provides a short-range–built with forecast information obtained in the previous step. The analyses are then made to make a short-range model forecast for the next assimilation time step. Gridded data products (at a spatial resolution of 0.75° latitude x 0.75° longitude) include 6-hourly surface temperature, atmospheric temperature and water vapour profiles, as well as dynamical parameters such as horizontal and vertical large-scale winds. These data are given at universal time of 0:00, 6:00, 12:00 and 18:00. A common proxy for the intensity of the vertical motions in the atmosphere is the vertical pressure velocity at 500 hPa level, w500 (e.g. Bony and Dufresne, 2005; Martins et al., 2011). To match these data, given at universal time of 0:00, 6:00, 12:00 and 18:00, with the AIRS and IASI observations, we interpolate the m to the corresponding local time, using a cubic spline function, as in Aires et al. (2004).

2.4 Collocated AIRS–CALIPSO–CloudSat data

All satellites of the A-Train follow each other within a few minutes. We use the same collocation procedure as in Feofilov et al. (2015b): First, each AIRS footprint is collocated with NASA CALIPSO L2 cloud data averaged over 5 km (version 3, Winker et al., 2009) in such a way that for each AIRS golf ball, three CALIPSO samples are matched to the centres of three AIRS footprints. These data are then collocated with the NASA L2 CloudSat-lidar geometrical profiling (GEOPROF) data (version R04, Mace and Zhang, 2014). Each of these AIRS footprints thus includes cloud top and cloud base for each of the cloud layers, detected by lidar or radar, at the spatial resolution of the radar footprints (1.4 km x 2.3 km); from the GEOPROF data, and Cloud optical depth (COD), cloud top, ztop, and apparent cloud base (corresponding to the real cloud base or to the height at which the cloud reaches opacity), zapp_base, are given at the spatial resolution of the CALIPSO cloud data (5 km x 0.09 km). A cloud feature flag indicates whether the cloud is opaque. The CALIPSO L2-cloud data also indicate at which horizontal averaging along the track the cloud was detected (1 km, 5 km or 20 km), which is a measure of the optical thickness of the cloud COD. As in Stubenrauch et al. (2010), for a direct comparison with AIRS cloud data, we use clouds detected at horizontal averaging over 5 km or less. This corresponds to clouds with VIS visible optical depth COD larger than about 0.05 to 0.1 (Winker et al., 2008).

The scene type over of an AIRS footprint is estimated as cloudy when the CALIPSO sample as well as the GEOPROF sample include at least one cloud layer. Clear sky is defined by a cloud-free by using the cloud detection of all three CALIPSO and GEOPROF samples perwithin the AIRS footprint golf ball as: clear sky (all three samples clear sky), overcast (all three samples cloudy) and partly cloudy.
For the evaluation of cloud height, we identify the GEOPROF cloud layer which is closest to \( z_{\text{COD}} \) from AIRS and estimate the height at which the cloud reaches a COD of 0.5, \( z_{\text{COD0.5}} \), from CALIPSO. \( z_{\text{COD0.5}} \) is required to be located within the corresponding GEOPROF cloud layer.

\( z_{\text{COD0.5}} \) is deduced from the CALIPSO L2 COD, assuming a constant increase of COD from cloud top towards cloud base, except for high-level clouds, for which the shape of the ice water content profile as a function of cloud emissivity is taken into account (Feofilov et al., 2015b). As the COD of CALIPSO might be slightly underestimated (Lamquin et al., 2008), especially for larger COD, we reduce the ratio \( 0.5/\text{COD} \) to \( 0.4/\text{COD} \), used in the estimation of \( z_{\text{COD0.5}} \).

To avoid uncertainties in atmospheric and surface ancillary data in the analysis of the diurnal cycle of upper tropospheric clouds from AIRS and IASI retrievals, we use ERA-Interim as ancillary data (Feofilov et al., 2015a). By using different sets of ancillary data in the cloud retrieval we are also able to estimate uncertainties in cloud amounts (sections 3 and 4).

### 2.54 CIRS cloud property retrieval

The cloud property retrieval is based on a weighted \( \chi^2 \) method using channels around the wing of the 15 \( \mu \text{m} \) CO\(_2\) absorption band (Stubenrauch et al., 1999). Cloud pressure and effective emissivity are determined by minimizing \( \chi^2(p_k) \), computed at different atmospheric pressure levels by summation over \( N \) wavelengths \( \lambda_i \) within the CO\(_2\) absorption band and atmospheric window:

\[
\chi^2(p_k) = \sum_{i=1}^{N} [(I_{\text{.rad}}(p_k, \lambda_i) - I_{\text{chl}}(\lambda_i)) \cdot \varepsilon_{\text{chl}}(p_k) - (I_{\text{m}}(\lambda_i) - I_{\text{chl}}(\lambda_i))]^2 W^2(p_k, \lambda_i)
\]

where \( I_{\text{rad}} \) corresponds to the measured radiance, \( I_{\text{chl}} \) is the simulated radiance, the IR Sounder would measure in the case of clear sky, and \( I_{\text{chl}}(p_k) \) is the radiance emitted by a homogeneous opaque single cloud layer at pressure level \( p_k \), calculated for 42 \( p_k \) levels \( p_k \)-above surface (from 984 hPa to 86 hPa), and for the corresponding viewing zenith angle of the observation. A sensitivity study has shown that in general, five (for HIRS) to eight channels (AIRS and IASI) around the 15\( \mu \text{m} \) CO\(_2\) band (regularly spaced) are sufficient, as a sensitivity study has shown. Doubling the number of channels in the retrieval did not change the results.

By introducing empirical weights \( W(p_k, \lambda_i) \), the method takes into account i) the vertical weighting contribution of the different channels, ii) the growing uncertainty in the computation of \( \varepsilon_{\text{chl}} \) with increasing \( p_k \) and iii) uncertainties in atmospheric profiles. These weights are determined for each of five typical air mass classes (tropical, midlatitude summer...
and winter, polar summer and winter) as in (Stubenrauch et al., 1999) and in Feofilov and
Stubenrauch (2017), using the spread of clear sky radiances within these air mass classes. The clear sky radiances have been simulated for each
of the atmospheric profiles of these five air mass classes, using the 4A radiative transfer
model (Scott and Chédin, 1981), and stored in within these air mass classes obtained from the
Thermodynamic Initial Guess Retrieval (TIGR) data base (Chédin et al., 1985; Chevallier et
al., 1998; Chédin et al., 2003). Minimizing \( \chi^2 \) in Eq. 1 is equivalent to \( d\chi^2/d\varepsilon_{cld} = 0 \), from
which one can extract \( \varepsilon_{cld} \) as:

\[
\varepsilon_{cld}(p_k) = \frac{\sum_{i=1}^{N} [I_m(\lambda_i) - I_{cl}(\lambda_i), I_{cl}(p_k, \lambda_i) - I_{cl}(\lambda_i)] \cdot W^2(p_k, \lambda_i)}{\sum_{i=1}^{N} [I_{cl}(p_k, \lambda_i) - I_{cl}(\lambda_i)] \cdot W^2(p_k, \lambda_i)}
\]

(2)

In general, the \( \chi^2(p) \) profiles have a more pronounced minimum for high-level clouds than for low-level clouds. We stress here that for the identification of low-level clouds it is important to allow values larger
than 1 for \( \varepsilon_{cld} \), because at larger pressure \( I_{cl} \) and \( I_{cl} \) become very similar and their uncertainties may lead
to values larger than 1 (Stubenrauch et al., 1996-1999). Therefore, only pressure levels leading to
\( \varepsilon_{cld} > 1.5 \) are excluded from the solution. Typical \( p_{cl} \) uncertainties have been estimated from a statistical
analysis of the \( \chi^2(p) \) profiles: they range from 30 hPa for high-level clouds to 120 hPa for low-level
clouds, corresponding to about 1.2 km in altitude, \( z_{cl} \).

In the case of atmospheric temperature inversions in the lower troposphere, for which temperature first
increases with height before decreasing, with \( T(z_{inv}) - T_{surf} \) the cloud height is moved to the inversion
layer level, \( z_{inv} \), defined as the highest level with \( T(z_{inv}) > T_{surf} \). To detect these cases, the inversion
strength, defined by \( T(z_{inv}) - T_{surf} \), has to be larger than 2 K. Depending on the ancillary data, these cases
arise in about 7 to 15 % of all the time cloudy cases. \( \varepsilon_{cl} \) as defined in Eq. (2) does not have a
physical meaning in the case of an inversion, since \( I_{cl}(p_{cl}) \) will be greater than \( I_{cl} \). Therefore, we scale
\( \varepsilon_{cl} \) and the spectral emissivities in accordance with the ratio \( p_{inv} / p_{cl} \).

Cloud temperature, \( T_{cl} \), is determined from \( p_{cl} \), using the ancillary temperature profile similar to the
observed situation (see section 2.5.4.1). Cloud types are distinguished according to \( p_{cl} \) and \( \varepsilon_{cl} \). High-
level clouds are defined by \( p_{cl} < 440 \) hPa, midlevel clouds by \( 440 \) hPa < \( p_{cl} < 680 \) hPa and low-level
clouds by \( p_{cl} > 680 \) hPa. High-level clouds may be further distinguished into opaque (\( \varepsilon_{cl} > 0.95 \)), cirrus
(0.95 > \( \varepsilon_{cl} > 0.50 \)) and thin cirrus (\( \varepsilon_{cl} < 0.50 \)). \( p_{cl} \) is transformed to cloud altitude, \( z_{cl} \), using a standard
hydrostatic conversion, with the virtual temperature profile accounting for humidity, again from ancillary data similar to the observed situation.

The retrieval is applied to all footprints. In a second step, an *a posteriori* cloud detection is applied (section 2.5). When sufficient channels are available in the atmospheric window, as for the high spectral resolution IR sounders like AIRS, CrIS and IASI, a test based on the spectral coherence of retrieved cloud emissivities decides whether the footprint is cloudy (overcast or mostly cloudy) or clear (or not cloudy enough to determine reliable cloud properties). Thresholds have been established using the A-Train synergy (section 3). In the case of HIRS, other methods have been developed to decide if the scene is cloudy (e.g. Stubenrauch et al., 2006; Hanschmann et al., 2017).

For the computation of $I_{clr}$ and $I_{cld}$ in Eq. (1), we need i) surface type (ocean, land, ice / snow), skin surface temperature and spectral surface emissivities, ii) as well as atmospheric temperature and water vapour profiles as well as and spectral transmissivity profiles for the atmospheric situation of the measurements. The atmospheric spectral transmissivity profiles were have been calculated using the 4A radiative transfer model (Scott and Chédin, 1981), separately for each satellite viewing zenith angle (up to 50°) and for about 2300 representative clear sky atmospheric temperature and humidity profiles of the TIGR data base.

In the cloud retrieval, the TIGR data base is searched for the atmospheric profile corresponding best to the observational conditions by applying a proximity recognition which compares the atmospheric temperature and water vapour profiles from the ancillary data with those from TIGR as in (Stubenrauch et al., 2008). The preparation and evaluation of these ancillary data is presented in 2.5.4.1.

### 2.5.4.1 Preparation and comparison of atmospheric / surface ancillary data

*Spectral surface emissivities:* Over land, we use monthly mean spectral surface emissivity climatological values at a spatial resolution of 0.25° x 0.25°, retrieved from IASI measurements (Paul et al., 2012). For AIRS, these spectral surface emissivities have been—spectrally interpolated to the AIRS channels wavelengths. Over ocean, the surface emissivity is set to 0.99 for $\lambda < 10 \, \mu m$ and 0.98 for $\lambda \geq 10 \, \mu m$ wavelengths larger than 10 μm (Wu and Smith, 1997). Over snow and ice, the spectral surface emissivities are taken from (Hori et al., 2006), and since they depend on the viewing zenith angle, they are had to be corrected as like in (Smith et al., 1996).

*Atmospheric profiles and surface temperature:* Since—AsSince IR sounders, in combination with microwave sounders, were originally designed for the retrieval of atmospheric temperature and humidity profiles, the atmospheric clear sky situation can then be directly described by simultaneous L2 atmospheric profiles of good quality (when the situation is not too cloudy). When these are In the case...
that ancillary data of good quality data are not available for a given measurement, we use these atmospheric profiles, surface skin temperature and tropopause those of good quality are averaged within, averaged over 1° latitude x 1° longitude averages of good quality data, and if there are still no data are available, we interpolate these averages in time (inversely proportional to distance within maximal ±15 days) and then in space (inversely proportional to distance within maximal 3° longitude, considering the same surface type).

To define atmospheric temperature and humidity profiles as well as surface temperature of good quality, one has to find a compromise between an acceptable quality and enough statistics.

This led to the following quality criteria in the case of ancillary data from AIRS-NASA (V6):

- Surface temperature is of good quality, if the provided retrieval error is smaller than 3 K / 6 K / 7 K for ocean / land / ice or snow, respectively. It should also be larger than 180 K and smaller than 400 K.

- Atmospheric temperature profiles are of bad quality, when three consecutive layers have large retrieval errors larger than 2 K / 2K / 2K over ocean, 2.5 K / 2.5 K / 3 K over land and 2.5 K / 2.5 K / 5 K over ice or snow, with thresholds in the upper part (between 70 hPa to-and-500 hPa) / lower-part of the troposphere (between 500 hPa to-and-surface) / near surface of 2 K / 2K / 2K over ocean, 2.5 K / 2.5 K / 3 K over land and 2.5 K / 2.5 K / 5 K over ice or snow, respectively.

- For atmospheric water vapour profiles the NASA L2 quality criteria of NASA were kept (Olsen et al., 2013).

Nevertheless, the when-comparing SSTs of good quality from AIRS-NASA with were still slightly colder than those from of ERA-Interim, AIRS values were slightly colder. Since As this effect is most probably due to a slight underestimation of the AIRS-SST linked to AIRS-NASA residual cloud contamination, we applied a small added to the AIRS-NASA SSTs the minimum between the retrieval error and 0.5 K correction to SST by adding the minimum between 0.5 K and the retrieval error. Since differences the behaviour over land is might be positive or negative (Figure 2) more complex, we left the AIRS-NASA surface temperature (Tsurf) values as they are unchanged.

For ERA-Interim, the When we use time-interpolated ERA-Interim atmospheric profiles and surface temperatures are always available as ancillary data in the cloud retrieval, these data are always available. However, however, since the analysis revealed, we observed that the time-time-interpolated ERA-Interim SSTs did not show a diurnal cycle, with most of the amplitudes are less than 0.2 K, which as this is not consistent with observations (e.g., Webster et al., 1996), we applied a simple parameterized correction, which linking the SST diurnal cycle to peak insolation (based on Fig. 11 of Webster et al., 1996). This parameterization links the SST diurnal cycle to peak insolation. The
coefficient between the SST diurnal amplitude and the maximal solar flux at given latitude, longitude, solar zenith angle and local time and the SST diurnal amplitude was adjusted to 0.005 K/Wm². to-so that the SST diurnal amplitude is make the latter consistent with that of recent observations (e.g. Seo et al., 2014). Without this correction, the cloud amount (CA) difference between at over ocean was larger during night (78%) than in the and early afternoon was 78% - (71%), while compared to 71% - (71% when using AIRS ancillary data. The correction led to now cloud amount is more similar (76% - (73%), in better agreement with the results using AIRS ancillary data (71% - 71%). The behaviour over land is more complex, so we left the without changes in $T_{surf}$ values as they are, leading to CA of during at night / dayearly afternoon is 62% / 56%, with ERA-Interim, and 56% / 58%, with AIRS-NASA, at 1:30AM/1:30PM respectively.

Figure 1 presents comparisons of between $T_{surf}$, as used in the cloud retrieval, deduced from NASA AIRS-NASA retrievals and from ERA-Interim, with and collocated surface air temperature, $T_{surf}^{air}$, from the ARSA data base. One would expect that over land $T_{surf}$ is colder than $T_{surf}^{air}$ during night and warmer than $T_{surf}^{air}$ in the afternoon; this effect should be stronger for temperate and warmer temperatures, especially if the climate is dry. SST should be similar to $T_{surf}^{air}$ in the tropics, slightly warmer in midlatitudes and colder in polar regions. Considering Figure 1, The distributions in Figure 1 reflect the expectations, with similar peak positions for AIRS-NASA and ERA-Interim corresponding to similar differences with ARSA. When looking more in detail, Though the land distributions over land are slightly larger broader for AIRS-NASA than for ERA-Interim, and they are also shifted towards colder values for colder $T_{surf}$ and at night for warmer $T_{surf}$. In the afternoon, for warmer $T_{surf}$ in the afternoon, $T_{surf}$ of AIRS-NASA $T_{surf}$ is slightly larger than $T_{surf}$ of ERA-Interim $T_{surf}$ for situations with warm $T_{surf}$. Colder AIRS-NASA values might still indicate some cloud contamination, whereas the colder values of ERA-Interim over warm land in the afternoon might indicate an underestimation, especially over desert, as has already been pointed out by Trigo et al. (2015). The effect of $T_{surf}$ on cloud amount will be further investigated in section 3.12.

2.54.2 Calibration-Accounting for changes in atmospheric CO₂ concentration

The TIGR data base of atmospheric spectral transmissivities was created for an atmosphere with a fixed CO₂ volume mixing ratio of 372 ppmv. However, the atmospheric CO₂ concentration varies latitudinally, seasonally and with time. While both the increase during the last ten years and the seasonal variability in the Northern hemisphere (NH) are of the order of ~20 ppmv, the latitudinal gradient in the NH varies from 0.1 ppmv/°C to +0.1 ppmv/°C. Seasonal variability in the NH is related to the vegetation and fossil fuel burning seasonality. The difference between an averaged value and actual CO₂ volume mixing ratio can easily reach 10%, which This is a noticeable change.
the concentration enters the power of the exponent in the calculation of the transmissivity, \( \tau \). To avoid errors associated with CO\(_2\) changes in the radiative transfer computations associated with CO\(_2\) changes, we rescale the transmissivity according to the following rules:

\[
\tau = \exp(-\alpha \cdot CO_2^\text{current})
\]

(3)

\[
\tau = \exp(\beta \cdot CO_2^\text{current})
\]

\( \alpha = -k \cdot \log(CO_2^\text{ref}) \) and \( \beta = \alpha \cdot CO_2^\text{ref} \cdot \log(1-k)/k \), where \( k \) is the relative CO\(_2\) contribution to the opacity of the channel. Details are described in Feofilov and Stubenrauch (2017). The CO\(_2\) concentrations are taken from (GLOBALVIEW-CO2, 2013).

This correction also removes long-term biases due to increasing CO\(_2\) in the atmosphere from anthropogenic CO\(_2\) emissions, which introduced an artificial increase in the cloud amount time series. Applying the correction of equation (3) has eliminated this bias (see section 4).

2.5.3 Multi-spectral \( \chi \) posteriori\( \chi \) cloud detection

Once the cloud properties are retrieved, to constrain cloud definition, we use the spectral standard deviation \( \sigma(\chi_{\lambda_i}) \) of retrieved cloud emissivities between 9 and 12 \( \mu \)m, wavelengths in the IR atmospheric window, as described in Stubenrauch et al. (2010). For each footprint, cloud emissivities \( \varepsilon_{\text{cld}} \) are determined at six wavelengths, \( \lambda_i \) (section 2.1), as:

\[
\varepsilon_{\text{cld}}(\lambda_i) = \frac{I_{\text{m}}(\lambda_i) - I_{\text{clr}}(\lambda_i)}{I_{\text{clr}}(P_{\text{cld}}, \lambda_i) - I_{\text{clr}}(\lambda_i)}
\]

(4)

\( I_{\text{clr}} \) is now determined for \( p_{\text{cld}} \) retrieved by the \( \chi^2 \) method (see above).

The relative standard deviation of these cloud emissivities, \( \sigma(\chi_{\lambda_i})/\varepsilon_{\text{cld}} \), is much larger when the footprint is partly cloudy or clear and hence \( p_{\text{cld}} \) is biased, than for cloudy cases, when \( p_{\text{cld}} \) and \( \varepsilon_{\text{cld}} \) are well determined. This behaviour is illustrated in Figure 2 of Stubenrauch et al. (2010) and in Figure S1 of the supplement, contrasting distributions of the relative standard deviation of these cloud emissivities, \( \sigma(\chi_{\lambda_i})/\varepsilon_{\text{cld}} \), of cloudy and clear sky scenes from CALIPSO samples. Guided by these figures and experimenting with thresholds to obtain a good agreement in cloud amount compared to CALIPSO-CloudSat (section 3) and to other datasets (section 4), we define the AIRS footprint is identified as cloudy if the following conditions are fulfilled: \( \sigma(\chi_{\lambda_i})/\varepsilon_{\text{cld}} < 0.17 \) for ocean (both ancillary data), \( \sigma(\chi_{\lambda_i})/\varepsilon_{\text{cld}} < 0.20 \) for land (both ancillary data) and \( \sigma(\chi_{\lambda_i})/\varepsilon_{\text{cld}} < 0.30 / 0.20 \) for ice and snow (AIRS-NASA / ERA-Interim ancillary data).
For IASI we do not have the possibility to distinguish $\tilde{\sigma}(\lambda_i)/\sigma_{\text{clcd}}$ distributions according to CALIPSO-CloudSat cloudy and clear sky scenes. However, the overall distributions of $\tilde{\sigma}(\lambda_i)/\sigma_{\text{clcd}}$ are similar for AIRS and IASI, comparing retrievals based on ERA-Interim ancillary data. Therefore we use the same thresholds for the IASI cloud detection.

To reduce misidentification of clear sky as high-level clouds, only clouds with $\sigma_{\text{clcd}} \geq 0.10$ are considered.

2.54.43 Summary of changes compared to the previous version of the AIRS-LMD cloud climatology retrieval

Compared to the retrieval used to produce the six-year AIRS-LMD cloud climatology (Stubenrauch et al., 2010), the following changes have been implemented into the CIRS algorithm:

- **Extension of minimum cloud pressure**: has been extended from 106 hPa to 86 hPa.
- **Update of ancillary atmospheric and surface data**: have been updated from NASA V5 to NASA V6.
- **Improved interpolation**: of atmospheric and surface ancillary data of good quality, the interpolation method has slightly changed.
- **Moving**: In the case of atmospheric temperature inversions, the cloud is moved to the inversion layer and scaling $\sigma_{\text{clcd}}$ is scaled accordingly in the case of atmospheric temperature inversions.
- **Improved radiative transfer computations**: to determine the TIGR atmospheric spectral transmissivities.
- **Have been improved**.
- **The adjusting the TIGR atmospheric near-surface spectral transmissivity** for the lowermost layer of the TIGR data base near the surface were adjusted in accordance with the observed pressure of the observed situation.
- **Decreased cloud detection thresholds**: in the cloud detection are decreased, thanks to the improved radiative transfer computations of clear sky radiances led to a decreased thresholds on the variability of the cloud spectral emissivities between 9 and 12 µm, used in the cloud detection, (see section 2.5.35).
- **Only reducing the number of one cloud detection tests to one, which is based on the coherence of cloud spectral emissivity, is applied**.
- **Considering Only clouds with $\sigma_{\text{clcd}} \geq 0.10$, are considered (instead of $\sigma_{\text{clcd}} \geq 0.05$)**.
Taking into account variable CO₂ concentration in Simulated clear sky atmospheric spectral transmissivities have been corrected for variability in atmospheric CO₂ concentration.

As we will see in section 4, the impact of these changes, however, is in general small, but taking into account variable CO₂ concentration is important for addressing the long-term variability of clouds, as can be seen in the latitudinal averages of total, high, midlevel and low-level cloud amounts presented in section 4.

**A posteriori cloud detection**

Once the cloud properties are retrieved, we use the same cloud detection strategy as in (Stubenrauch et al., 2010), based on the spectral coherence of retrieved cloud emissivities between 9 and 12 μm, wavelengths in the IR atmospheric window. For each footprint, cloud emissivities $e_{cld}$ are determined at six wavelengths, $\lambda_i$, as:

$$e_{cld}(\lambda_i) = \frac{I_m(\lambda_i) - I_{clr}(\lambda_i)}{I_{cld}(p_{cld}, \lambda_i) - I_{clr}(\lambda_i)}$$

where $I_{clr}$ is now determined for $p_{clr}$ which has been retrieved by the $\chi^2$-method (see above). When $p_{clr}$ is well determined, these spectral cloud emissivities should only slightly differ. The variability should be larger, when the footprint is partly cloudy or clear and hence $p_{clr}$ is not well determined. In that case, the footprint is declared as not cloudy.

To determine thresholds, we make use of the A-Train synergy: by comparing distributions of the standard deviation $\sigma(e_{\lambda})$ over these wavelengths divided by the retrieved $e_{cld}$ separately for cloudy scenes and for clear sky scenes as determined by CALIPSO (see section 3.1). Overcast / clear sky scenes are situations for which all three CALIPSO samples within the AIRS golf ball are cloudy / clear, respectively, and partly cloudy scenes include a mix of cloudy and clear sky within the three samples. Figure 2 presents these distributions, separately over ocean, land and ice / snow, when AIRS ancillary data and when ERA-Interim ancillary data are used in the AIRS cloud retrieval. First of all, we observe that the distributions are in general narrower for cloudy scenes than for clear sky, as expected. The large tails of the clear sky distributions are presented as a large peak at $\sigma(e_{\lambda})/e_{cld} = 0.59$, the maximum value to which $\sigma(e_{\lambda})/e_{cld}$ was set. The separation between cloudy and clear is best over ocean, followed by land and then ice / snow. Distributions are similar over ocean and land between both ancillary data, whereas the distinction between cloudy and clear sky over ice / snow is slightly better when ERA-Interim is used.

This might be explainable by the fact that the retrieval of atmospheric profiles with good quality is challenging over ice / snow. According to these figures and by experimenting with thresholds to obtain a
good agreement in the identification of cloudy and clear-sky scenes with CALIPSO-CloudSat (see section 3.2), we perform the following tests for the AIRS-CIRS cloud detection.

The footprint is identified as cloudy if the following conditions are fulfilled:

\[ \frac{e_{\lambda}}{e_{cld}} < 0.17 / 0.20 / 0.30 \]  
for ocean / land / snow or ice and AIRS ancillary data

\[ \frac{e_{\lambda}}{e_{cld}} < 0.17 / 0.20 / 0.20 \]  
for ocean / land / snow or ice and ERA-Interim ancillary data

For IASI we do not have the possibility to test these distributions with CALIPSO-CloudSat. However, the overall distributions of \( \frac{e_{\lambda}}{e_{cld}} \) are similar for AIRS and IASI, comparing retrievals both based on ERA-Interim ancillary data. Therefore we use the same thresholds for the IASI cloud detection.

To reduce noise, we declare footprints with a cloud of \( e_{cld} < 0.10 \), corresponding to a visible (VIS) optical depth of about 0.2, as not cloudy.

3 Evaluation of cloud properties using the A-Train synergy

The A-Train active instruments, lidar and radar of the CALIPSO and CloudSat missions, provide a unique opportunity to evaluate the retrieved AIRS cloud properties such as cloud amount and cloud height, as well as to explore the vertical structure of the AIRS cloud types (Stubenrauch et al., 2010). These results can then be transposed to cloud types determined by the CIRS retrieval method using other IR sounders.

In the following, we analyse three years (2007-2009) of collocated AIRS-CALIPSO-CloudSat data, separately for three latitude bands: tropical/subtropical latitudes (30°N-30°S), midlatitudes (30°N-60°N and 30°S-60°S) and polar latitudes (60°N-90°N and 60°S-90°S).

3.1 Collocated AIRS–CALIPSO–CloudSat data

We use the same colocation procedure as in (Feofilov et al., 2015b): all satellites of the A-Train follow each other within a few minutes. First, each AIRS footprint is collocated with NASA CALIPSO L2 cloud data averaged over 5 km (version 3, Winker et al., 2009) in such a way that for each AIRS golf ball, three CALIPSO samples closest to the centres of each AIRS footprint are kept. These data are then collocated with the vertical profiling of the NASA L2 Lidar–CloudSat–geometrical profiling (GEOPROF) data (version P1_R04; Mace and Zhang, 2014). Each AIRS footprint includes thus information on the vertical structure (cloud top and cloud base for each of the cloud layers) at the spatial resolution of the radar footprints (1.4 km x 2.3 km) and in addition to cloud detection, cloud optical depth, cloud top and apparent cloud base (corresponding to the real cloud base or to the height at which the cloud reaches opacity) at the spatial resolution of the CALIPSO cloud data (5 km x 0.09 km). A cloud feature flag indicates whether the cloud is opaque. The CALIPSO L2 cloud data also indicate at
which horizontal averaging the cloud was detected (1 km, 5 km or 20 km), which is a measure of the optical thickness of the cloud. For a direct comparison with AIRS cloud data, we use clouds detected at horizontal averaging over 5 km or less, corresponding to minimum particle backscatter coefficient of about 0.0008 km$^{-1}$sr$^{-1}$ at night and about 0.0015 km$^{-1}$sr$^{-1}$ during day, for a cirrus with an altitude of about 12 km (Fig. 4 of Winker et al., 2009). This corresponds to clouds with VIS optical depth larger than about 0.05 to 0.1 (Winker et al., 2008). The scene over each AIRS footprint is estimated by using the cloud detection of all three CALIPSO samples per AIRS golf ball as: clear sky, partly cloudy and overcast.

For the evaluation of cloud height we determine the lidar CloudSat GEOPROF cloud layer which is closest to $z_{cld}$ from AIRS. From the 5 km averaged CALIPSO data we also determine the height at which the cloud reaches a certain optical depth, in particular $z_{COD0.5}$. We then require that this height is located within the corresponding cloud layer of the lidar CloudSat GEOPROF data.

Cloud optical depth (COD) determined from lidar backscatter depends on a correction for multiple scattering which itself depends on COD and microphysics (e.g., Comstock and Sassen, 2001; Chen et al., 2002; Lamquin et al., 2008). As CALIPSO assumes a constant multiple scattering coefficient of 0.6 in the retrieval (Winker, 2003), COD might be slightly underestimated, especially for larger COD. We therefore estimate from Figure 3 in (Lamquin et al., 2008) a correction factor and deduce that a COD of 0.50 should correspond to a COD given by CALIPSO of about 0.37. To determine the height within the cloud at which COD reaches 0.5 we also use an assumption on the shape of the ice water content vertical profile between cloud top and cloud base (Feofilov et al., 2015b).

In the following, we analyze three years (2007-2009) of collocated AIRS-CALIPSO-CloudSat data, separately for three latitude bands: tropical/subtropical latitudes (30°N-30°S), midlatitudes (30°N-60°N and 30°S-60°S) and polar latitudes (60°N-90°N and 60°S-90°S).

### 3.12 Cloud detection

The hit rates (fraction of agreeing cloudy and clear cases) between the a posteriori AIRS-CIRS cloud detection leads to an agreement with the lidar-radar CALIPSO-CloudSat cloud detection (section 2.4) from GEOPROF and CALIPSO in about 85% (84%) over ocean, 82% (79%) over land and 70% (73%) over ice/snow. Values in parantheses correspond to using atmospheric and surface ancillary data, deduced from AIRS-NASA (ERA-Interim) ancillary data. Table 1 presents separate agreements/comparisons separately for the three latitude bands. CALIPSO-CloudSat cloud detection is defined by at least one cloud layer from GEOPROF and from CALIPSO and clear sky is defined by three CALIPSO clear sky samples within one golf ball (section 2.4). In general, these agreements hit
rates are quite high, considering that CALIPSO and GEOPROF data only sample a small area of the AIRS footprints. They are slightly higher over ocean than over land. Compared to the AIRS-LMD cloud retrieval presented in (Stubenrauch et al., 2010), the agreement with CALIPSO-CloudSat has improved both over ocean and land, but slightly decreased over sea ice. The latter can be explained by applying now only one test over all surface types. In the earlier version we used an additional brightness temperature difference test related to temperature inversions. A detailed analysis (not shown) indicated that it also introduced noise.

To further illustrate cloud amount (CA) uncertainties due linked to ancillary data, we investigate, in Figure 2, presents geographical maps of differences in CA differences and $T_{surf}$ between using AIRS-CIRS based on ancillary data from AIRS-NASA and from ERA-Interim, together with $T_{surf}$ differences, are shown in Figure 3. When using With AIRS-NASA ancillary data, CA over land is mostly often smaller during night and larger in the afternoon, with one might observe a positive correlation with differences in $T_{surf}$. $T_{surf}$ of the ancillary data deduced from AIRS-NASA is slightly also smaller during night and larger in the afternoon during daytime over large parts of the continents. From considering the $T_{surf}$ comparison with ARSA in (section 2.5), 4 leads to the conclusion this means we deduce that over land AIRS-CIRS-CA is slightly underestimated during night when using with AIRS-NASA ancillary data, while slightly underestimated in the afternoon when using with ERA-Interim ancillary data. Patterns of differences in atmospheric water vapour are less reflected in those of CA (not shown), but slightly more atmospheric water vapour in the ancillary data (as in the tropics for AIRS-NASA compared to ARSA and ERA-Interim) might lead to a slight underestimation of CA.

### 3.23 Cloud height

For the evaluation of cloud height we determine the lidar CloudSat GEOPROF cloud layer which is closest to $z_{cld}$ from AIRS. From the 5 km averaged CALIPSO data we also determine the height at which the cloud reaches a certain optical depth, in particular 0.5, $z_{COD0.5}$. We then require that this height is located within the corresponding cloud layer of the lidar CloudSat GEOPROF data.

Cloud optical depth (COD) determined from lidar backscatter depends on a correction for multiple scattering which itself depends on COD and microphysics (e.g. Comstock and Sassen, 2001; Chen et al., 2002; Lamquin et al., 2008). As CALIPSO assumes a constant multiple scattering coefficient of 0.6 in the retrieval (Winker, 2003), COD might be slightly underestimated, especially for larger COD. We therefore estimate from Figure 3 in (Lamquin et al., 2008) a correction factor and deduce that a COD of 0.50 should correspond to a COD given by CALIPSO of about 0.37. To determine the height within the cloud at which COD reaches 0.5 we also use an assumption on the shape of the ice water content vertical profile between cloud top and cloud base (Feofilov et al., 2015b).
Figure 34 presents normalized distributions of the difference between the height at which COD reaches a value of about 0.5, \( z_{COD0.5} \), from CALIPSO (section 2.4) determined from CALIPSO, and the retrieved cloud height from AIRS, \( z_{clt} \), from AIRS for the three latitude bands as well as normalized distributions of the difference between the cloud top height from CALIPSO, \( z_{cld} \), and \( z_{clt} \). We compare results for \( p_{cld} < 440 \) hPa and \( p_{cld} \geq 440 \) hPa, of the CIRS cloud retrieval, using ancillary data from AIRS-NASA and ERA-Interim, separately for AIRS-NASA and ERA-Interim ancillary data for high-level clouds (\( p_{cld} < 440 \) hPa) and lower-level clouds (\( p_{cld} \geq 440 \) hPa). The AIRS cloud height is compared to the CALIPSO-CloudSat cloud layer, which is the closest to \( z_{clt} \). This is justified, because CALIPSO and CloudSat sample only sparsely the AIRS footprint, and AIRS could observe a mixture of several clouds. In general, all distributions of differences between \( z_{COD0.5} \) and \( z_{clt} \) peak around 0 km and are slightly narrower for lower-level clouds than for high-level clouds. Results are similar for both ancillary data, with a slight cloud height overestimation for lower level clouds in the over tropics over ocean (not shown), when using for ERA-Interim (not shown), and a height overestimation of some clouds in over polar regions over ocean (not shown), when using for AIRS-NASA ancillary data (not shown). The latter might can be explained by the fact that in some of these regions surface temperature \( T_{surf} \) and atmospheric profiles of good quality are only available in 10% of the situations time. When comparing distributions of \( z_{exp} - z_{clt} \), the peaks for lower clouds are still around 0 km, whereas for high-level clouds \( z_{clt} \) lies on average 1.5 km below the cloud top (not shown), as very similar to results in Stubenrauch et al. (2010).

This, meaning that \( T_{clt} \) is about 10 K warmer than the cloud top (Figure S2 of the supplement4). The broader distributions for high-level clouds compared to low-level clouds may be explained by the fact that high-level clouds often have diffuse cloud tops (e.g., Liao et al., 1995), especially in the tropics (\( z_{exp} - z_{clt} \) is slightly larger for the same \( z_{clt} \), as shown in Figure 5). To summarize, \( z_{clt} \). The CIRS retrieved cloud height coincides can be approximated with by i) the height of maximum lidar backscatter (Stubenrauch et al., 2010), with by ii) \( z_{COD0.5} \) (Figure 3), or iii) mid-height the mean between of cloud top and apparent cloud base layer height (real cloud base for optically thin clouds) or the mean between cloud top and cloud the height at which the cloud reaches opacity, as shown in Figure S2 (considering mid-p\( _{cld} \)) or with by \( z_{COD0.5} \), as shown in Figure S34.

To For a more detailed investigation of the different height approximations more in detail how the CIRS retrieved cloud height, relates to the height of COD of about 0.5 and to cloud top (\( z_{exp} \)), we analyze in Figure 45 compares median values of \( z_{clt} - z_{COD0.5} \), \( z_{cld} - z_{clt} \) and (\( z_{exp} - z_{clt} \))/\( z_{exp} - z_{exp} \) of their average difference as a function of AIRS CloudSat separately for high-level clouds and lower-level clouds. For this analysis we have selected cases for which \( z_{exp} \) AIRS cloud height lies within the cloud borders between top and base from of the closest CALIPSO-CloudSat GEOPROF cloud layer.
This leaves about 82% / 73% / 57% and about 55% / 59% / 58%-of the statistics of high-level and lower-level clouds over the in tropics / midlatitudes / polar regions, respectively. In general, for low-level clouds, the AIRS cloud height lies about 250 m to 500 m below the height at which the cloud reaches an optical depth of about 0.5, independently of \( \z_{\text{COD}} \), while \( \z_{\text{COD}} \) lies about 1 km below the cloud top. For high-level clouds, \( \z_{\text{COD}} \) varies from 1 km above for \( \z_{\text{COD}} = 0.1 \) to 1 km below \( \z_{\text{COD}} \) the height corresponding to COD of 0.5–for \( \z_{\text{COD}} = 1 \), assuming that \( \z_{\text{COD}} \) is accurately determined estimated for all \( \z_{\text{COD}} \) (section 2.4). In that case, This means that for thin cirrus \( \z_{\text{COD}} \) from AIRS of thin cirrus should be approximated corresponding to by a height at which with COD reaches a value < 0.5, while for and \( \z_{\text{COD}} \) of opaque high clouds to by a height at which with of COD reaches a value > 0.5. On the other hand, \( \z_{\text{COD}} \) lies about 1.5 km to 2.5 km below \( \z_{\text{COD}} \) the cloud top, the difference to cloud top increasing with \( \z_{\text{COD}} \) (except for \( \z_{\text{COD}} \) close to 1). Since \( \z_{\text{COD}} \), the apparent vertical extent also increases with \( \z_{\text{COD}} \), (not shown), the \( \z_{\text{COD}} \) difference between \( \z_{\text{COD}} \) and \( \z_{\text{COD}} \) scaled by apparent vertical extent does not depend on \( \z_{\text{COD}} \), and it is about 0.5–for high-level and for low-level clouds. Considering the normalized frequency distributions of \( \z_{\text{COD}} \), \( \z_{\text{COD}} \) and \( \z_{\text{COD}} \), as well as these differences scaled by apparent cloud vertical extent, presented in Figure 6, We deduce that it probably needs less geometrical thickness vertical extent for opaque clouds than for semi-transparent clouds cirrus to reach a COD of 0.5, while the \( \chi^2 \) method determines a height within the cloud, which corresponds well to the middle-mean between cloud top and apparent cloud base or the height at which the cloud reaches opacity, in dependent of \( \z_{\text{COD}} \). This is important to take into account for the determination of radiative fluxes and heating rates of upper tropospheric clouds, when using the CIRS cloud heights retrieved from IR sounder measurements. We want to stress that also for low-level clouds (\( \z_{\text{COD}} \) - \( \z_{\text{COD}} \))/\( \z_{\text{COD}} \) difference between \( \z_{\text{COD}} \) and \( \z_{\text{COD}} \) is about 0.5 (0.4 to 0.6), while The broader distributions for high-level clouds compared to low-level clouds in Figures 4 and 6 may be explained by the fact that high-level clouds often have diffuse cloud tops (e. g. Liao et al., 1995), especially in the tropics (\( \z_{\text{COD}} \) is slightly larger for the same \( \z_{\text{COD}} \)). \( \z_{\text{COD}} \) of low-level clouds lies only about 0.1400 km to 1.4000 km below \( \z_{\text{COD}} \), while \( \z_{\text{COD}} \) lies about 0.5 km below \( \z_{\text{COD}} \) and (\( \z_{\text{COD}} \) - \( \z_{\text{COD}} \))/\( \z_{\text{COD}} \) varies between 0.4 and 0.6. Finally, in order to see how well the distribution of clouds is represented within the atmosphere, we compare in Figure 5 presents7 the normalized frequency distributions of \( \z_{\text{COD}} \) from AIRS, using both sets of ancillary data, and of \( \z_{\text{COD}} \) from CALIPSO, whenever clouds are detected (excluding subvisible cirrus, see section 3.4.2.4). The CALIPSO \( \z_{\text{COD}} \) distributions have a slightly larger part of high-level clouds, especially in the tropics, and the AIRS \( \z_{\text{COD}} \) distributions show a slightly larger part of low-level clouds over land, separately over land and over ocean in the three latitude bands. AIRS \( \z_{\text{COD}} \) distributions are very similar, with slightly more low-level clouds over land using ERA Interim and slightly more
higher clouds over polar ocean (which are mostly misidentifications as pointed out earlier). The $z_{COD0.5}$ distributions from CALIPSO have a slightly larger part of high-level clouds in the tropics and AIRS $z_{46}$ distributions show a slightly larger part of low-level clouds in the tropics. The latter disappear if one considers only cases with all three CALIPSO samples cloudy within an AIRS golf ball. Thus these low-level clouds are part of partly cloudy fields for which it is difficult to compare results from samples of very different spatial resolution. Thus the distributions look more similar when only mostly covered cloud fields are considered (three CALIPSO samples cloudy within an AIRS golf ball).

In the tropics, the peak of the AIRS $z_{46}$ distributions for high-level clouds is still slightly broader towards lower heights than for CALIPSO (not shown). Additional filtering, excluding multi-layer clouds, ultimately leads to very similar distributions, also presented in Figure 57. A plausible interpretation is, that in cases of multiple cloud layers and if the upper cloud layer does not fully covering the large
AIRS footprint, instrument the 15-km footprints received of AIRS often mix radiation is mixed from different cloud layers, when the upper cloud layer does not fully cover the footprint, and thus determines a cloud height $z_{46}$ which might be slightly lower than the one of the uppermost cloud layer. The distributions in the midlatitudes still peak at slightly lower heights, due to the fact that high-level clouds in these latitudes are on average optically thicker (storm tracks) than in the tropics. In these cases $z_{46}$ lies below $z_{COD0.5}$ and as we have seen in Figure 45, in these cases $z_{46}$ lies below $z_{COD0.5}$. The choice of ancillary data influences only mildly the $z_{46}$ distributions, with a slightly larger contribution of low-level clouds over land for ERA-Interim. This difference disappears when considering if we consider only mostly covered cloud fields, as the contribution of low-level clouds in all data sets, strongly decreases over land and over ocean, the effect is much smaller. This indicates that low-level clouds over ocean appear more often as stratus decks whereas those over land appear more frequently as cumulus, as expected.

To summarize, the evaluation of cloud height has shown that IR sounders capture quite well the vertical distribution of uppermost clouds in the atmosphere. The retrieval provides a cloud height of about 1 km below cloud top in the case of low-level clouds and of about 1.5 km to 2.5 km below cloud top height in the case of high-level clouds. In the latter case, the retrieved cloud height corresponds to a height of COD $< 0.5$ for optically thin clouds and to a height of COD $> 0.5$ for optically thick clouds. On the other hand, multiple scattering within optically thicker clouds is in general larger so that the correction we have applied above, which was meant for clouds with a total COD of 0.5, was probably not enough. As already shown by Stubenrauch et al. (2010), the CIRS retrieved cloud height coincides with the middle between cloud top and apparent cloud base, and this for all cloud heights. Even though the spatial
resolution of 1.5 km may mix clear sky and cumulus clouds, or thin cirrus with optical thicker high clouds, the cloud height is in general well determined within 1.5 km.

4 Average Cloud Cloud properties and variability

In this section we give a short overview of cloud properties obtained from the AIRS-CIRS and IASI-CIRS cloud climatologies. Monthly L3 data, gridded at a spatial resolution of 1° latitude x 1° longitude, have been produced in the same manner as for the GEWEX Cloud Assessment data base (Stubenrauch et al., 2013): in a first step, averages were determined cloud properties and their uncertainties, deduced from the $\chi^2$ method, were averaged per observation time over 1° latitude x 1° longitude, and in a second step, these cloud properties were averaged per month. In addition to the monthly averages, the data base also includes time variability and histograms of the cloud properties. In addition, we have also added provide $p_{cl}$ and $e_{cl}$ uncertainties on $p_{cl}$ and $e_{cl}$ deduced from the $\chi^2$ method.

Figure 68 compares normalized frequency distributions of $p_{cl}$ (CP) over 30° wide latitude bands during boreal winter and boreal summer, separately over land and over ocean. As one can see, the AIRS and IASI CP distributions are very similar. Their relative contribution of high-level clouds is slightly larger over land than over ocean, especially in the tropics, and while the contribution of low-level clouds is larger over ocean. Considering seasonality, the strongest signature is the shift of the Intertropical Convergence Zone (ITCZ) towards the summer hemisphere, linked to a large amount of high-level clouds (from cirrus anvils), especially over land.

Figure 79 presents global averages of total cloud amount (CA) and relative contributions of high-level, mid-level and low-level clouds, determined by dividing these cloud amounts (CAH, CAM, CAL) by CA. The sum of the relative contributions, CAHR, CAMR and CALR is equal to 1. Pressure limits for high-level/mid-level and mid-level/low-level cloud classification are 440 hPa and 680 hPa, corresponding to altitudes of about 6 km and 3 km, respectively. Relative cloud amount values give an indication of how the detected clouds are vertically distributed in the atmosphere, when observed from above. Compared to the absolute values, they are less influenced by differences in cloud detection sensitivity and should be more useful for comparison with climate models (Stubenrauch et al., 2013).

Global averages of AIRS-CIRS and IASI-CIRS are compared with those from selected cloud climatologies of the GEWEX Cloud Assessment data base: the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer, 1999), two cloud climatologies derived from observations of the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua satellite, by the MODIS Science Team (MODIS-ST; Frey et al., 2008) and by the MODIS CERES Science Team (MODIS-CE; Minnis et al., 2011), and two cloud climatologies derived from CALIPSO
observations, the one by-of the CALIPSO Science Team (CALIPSO-ST; Winker et al., 2009) and the GCM-Oriented CALIPSO Cloud Products (CALIPSO-GOCCP; Chepfer et al., 2010). The latter two use vertical averaging (CALIPSO-GOCCP) and horizontal averaging (CALIPSO-ST) to reduce the noise of the relatively small samples. The latter is more sensitive to thin layers of subvisible cirrus. ISCCP is essentially using two atmospheric window channels (IR and VIS, the latter only during daytime). Considering passive remote sensing, For the GEWEX Cloud Assessment data base the eight-times-daily ISCCP results have been averaged to four specific local observation times: 3:00 AM, 9:00 AM, 3:00 PM and 9:00 PM, and a day-night adjustment on CA, which is included in the original data, has not been included to better illustrate the differences between VIS-IR and IR only results. We separately examine daytime and nighttime observations mostly during day, corresponding to 1:30 PM (3:00 PM for ISCCP, 9:30 AM for IASI), and mostly during night, corresponding to 1:30 AM (3:00 AM for ISCCP and 9:30 PM for IASI) LT, respectively. (Total cloud amount from the GEWEX Cloud Assessment data base is about 0.68±0.03 (Stubenrauch et al., 2013), while CALIPSO-ST provides a cloud amount of 0.73, because it includes subvisible cirrus.

We separately examine daytime and nighttime observations. While all data sets agree quite well on the total cloud amount CA, with ISCCP and MODIS-CE providing smaller CA during night (both including VIS information for cloud detection during daytime), CAHR exhibits a large spread, essentially due to different sensitivity to thin cirrus: active lidar is the most sensitive, followed by IR sounders, as confirmed in Figure 9. The CIRS results are very similar to the results from the AIRS-LMD cloud climatology (Stubenrauch et al., 2010). The choice of ancillary data only slightly affects CA at night. AIRS-CIRS results based on different ancillary data are also very similar as well as IASI-CIRS and AIRS-CIRS results are also very similar, day and night. They present global averages of CA around 0.67 ± 0.70, formed by 40% high-level clouds, 20% midlevel clouds and 40% low-level uppermost clouds as seen from above. This is in excellent agreement with the results from CALIPSO. The slightly higher smaller value in CALIPSO CAMR (2014% instead of 4420%) can be explained is due to the fact that the different distinction between high-level and mid-level clouds of CALIPSO is according-touses cloud top height, whereas AIRS and IASI provide-use a cloud height which is about 1.5 km lower than the top (see-section 3.2.3). When combining VIS and IR information, thin cirrus above low-level clouds tend to be misidentified as mid-level clouds (ISCCP) or as low-level clouds (MODIS), leading to a not negligible underestimation of CAHR (30% instead of 40%). During At nighttime, for which when only one the IR channel is available, ISCCP underestimates the height of all semi-transparent high-level clouds, so that CAHR drops to 15%. When IR spectral information is available, as for IR sounders and MODIS, results are similar to those during daytime.
Differences between ocean and land, also presented in Figure 97, correspond to about 45% for 0.15 in total CA, with about 20% more low-level clouds over ocean and about 10% more high-level and mid-level clouds over land. The CIRS retrievals provide similar values during day and night. It is interesting to note that during daytime the difference in CA shows a larger spread between the datasets, while during nighttime at night the spread is larger for CALR. During nighttime at night, low-level clouds are more difficult to detect, especially over land.

Table 2 summarizes averages of these cloud amounts over the whole globe, over ocean and over land, also contrasting NH and Southern hemisphere (SH) midlatitudes (30°-60°) and tropics (15°N-15°S). The largest fraction of high-level clouds is situated in the tropics, and while the largest fraction of single layer low-level clouds in the SH midlatitudes. Only about 10% of all clouds in the tropics are single layer midlevel clouds, compared to about 22% in the midlatitudes. As already discussed in sections 2.54 and 3.12, the uncertainty due to ancillary data in CA, as well as in CALR, due to ancillary data is largest over land (about 5% and 10%, respectively), because linked to underestimation of low-level clouds are underestimated during nighttime with AIRS-NASA. during night and in the afternoon with ERA-Interim in the afternoon. Uncertainties due to ancillary data are much smaller for high-level clouds. When separating them into three distinct high-level cloud classes, of opaque, thick cirrus and thin cirrus according to $cld_{nh}$ (see section 2.54), uncertainties due to ancillary data are less than 5% at low latitudes. In the midlatitudes, increasing uncertainties for opaque clouds increase to 10% at midlatitudes for opaque clouds, while those for cirrus do not exceed 5%. This can be explained by the fact that might be due to interpolation of ancillary data in the case of opaque clouds the ancillary data often have to be interpolated in time, with and atmospheric profiles and $T_{surf}$ have having a larger variability in the midlatitudes than in the tropics. While high-level opaque clouds only make up about 5.2% of all clouds, while relative cloud amounts of thick cirrus and thin cirrus are about 21.5% and 13%. Maximum values are observed in the tropics, respectively, with maximum appearance in the tropics, of 7.5%, 27.5% and 21.5%, respectively (Table 3). Their relative amounts are summarized in Table 3. The AnThe independent use of $p_{nh}$ and $\varepsilon_{nh}$ made it possible enabled us to construct build a climatology of upper tropospheric cloud systems, by i) applying a spatial composite technique on adjacent $p_{nh}$ and ii) using $\varepsilon_{nh}$ to distinguish convective core, cirrus anvil and thin cirrus of these systems. These data have revealed for the first time that the $\varepsilon_{nh}$ structure within of tropical anvils is related to the convective depth (Protopapadaki et al., 2017), which might have important consequences on radiative feedbacks.

Figure 40-8 presents zonal averages of CA, CAH and CAL as well as effective cloud amount for total (CAE) high-level (CAEH) and low-level (CAEL) clouds. The annual zonal averages are presented.
from the three CIRS climatologies (AIRS, using AIRS-NASA and ERA-Interim ancillary data, as well as IASI, using ERA-Interim ancillary data) and the prior AIRS-LMD cloud climatology. In addition, boreal winter and boreal summer zonal averages are shown for AIRS-CIRS alone, but separately for each of the thirteen years to illustrate the inter-annual spread. Effective cloud amount corresponds to the cloud amount weighted by cloud emissivity, and it therefore includes the IR radiative effect of the detected clouds. In general, CAE is about 0.2 smaller than CA. Maximum CAH and CAEH appear in the ITCZ, while maximum CAL and CAEL is found in the SH midlatitudes.

All the results of all CIRS climatologies are very similar. Interannual variability is largest in CA and CAL (CAE and CAEL) in the NH polar region. One also observes that the midlatitude interannual variability of CAH is larger in winter than in summer, most probably linked to storm track variability. When comparing the different CIRS retrievals, all agree in general very well, with AIRS-CIRS and IASI-CIRS with ERA-Interim being very close, while with AIRS-CIRS with using AIRS-NASA ancillary data представляя slightly more high-level clouds and less low-level clouds around 60S and slightly less CA and CAL in the NH polar region.

Figures 11 and 12 present geographical maps of annual CAH and CAL, respectively. We as well as seasonal differences. Compared are AIRS-CIRS, ISCCP and CALIPSO-GOCCP, the latter two from the GEWEX Cloud Assessment data base. In all datasets the most prominent feature in CAH is the ITCZ and its shift towards the summer hemisphere. However, due to the better sensitivity to cirrus, the absolute values and seasonal variations are more pronounced for AIRS-CIRS (IASI-CIRS, not shown) and CALIPSO-GOCCP than for ISCCP. Due to the narrow nadir track of CALIPSO and the reduced statistics of CALIPSO-GOCCP in the present GEWEX Cloud Assessment data base, these data look noisier than AIRS-CIRS and ISCCP. In addition, jet streams and midlatitude storm tracks in winter, as well as continental cirrus in summer can be distinguished. Considering CAL, AIRS-CIRS well captures well the stratocumulus regions off the West coasts of the continents and stratus decks in the subtropical subsidence regions in winter, even if this type of cloud is easier to detect by using instruments including VIS channels (during daytime, ISCCP) or active instruments (CALIPSO-GOCCP).

Time series of deseasonalized anomalies in global monthly mean CA, CAEH and CAEL of the three CIRS data sets are shown in Figure 13 over the time period of 2004–2016 for AIRS and 2008–2016 for IASI. To illustrate the effect of the calibration accounting for changes in atmospheric CO₂ concentration (section 2.5.4.2), a-the time series of the AIRS-CIRS deseasonalized CA anomalies, without having applied this correction, is added. Whereas the uncorrected CA anomalies increase by about 0.040 within a decade, the magnitude of the calibrated CA and CAEL variations lie within 0.010
and of CAEH within 0.005, being mostly stable within the uncertainty range. Indeed, the global surface temperature did not increase much over this period (not shown).

The latitudinal seasonal cycles of different cloud properties CA, CAH, CAL and $T_{\text{cl}}$ (CT) from the different data sets agree in general quite well (as presented in Figure 4S4 of the supplement); they agree in general quite well for six 30° wide latitude bands ranging from SH polar to NH polar, comparing results from CIRS data and those from the GEWEX Cloud Assessment data base. As already acknowledged during the GEWEX Cloud Assessment (Stubenrauch et al., 2013), the seasonal cycles agree quite well between the different data sets, with exception of the polar regions where passive remote sensing does not perform well and the CALIPSO data are not conform with the other data sets in the GEWEX Cloud Assessment data base, because they exclude measurements from 1:30PM during polar night (polar winter) and from 1:30AM during polar day (polar summer). The most prominent features of the latitudinal seasonal cycles are i) the shift of the ITCZ towards the summer hemisphere, seen as an amplitudinal signal of 0.1 in CA, 0.3 in CAH and 16 K in CT in the SH and NH tropical bands (mostly over land, not shown) and ii) less clouds in late summer in the midlatitudes (mostly over ocean and stronger in NH, not shown). The seasonal cycle of cloud temperature CT is largest in the polar regions (coherent for all data sets), followed by SH sub-tropical band, NH midlatitudes, NH sub-tropical band and smallest in SH midlatitudes, with amplitudes ranging from 20 K to 10 K. However, while the CT amplitude is linked to change in cloud height in the low latitudes, it is more related to change in atmospheric temperature (and corresponding cloud temperature CT) at higher latitudes.

5 Applications

After the comparisons to other datasets having demonstrated the reliability of the CIRS cloud climatologies in sections 3 and 4, which have proven the reliability of the CIRS upper-tropospheric clouds, we present in the following two analyses on upper tropospheric (UT) cloud variability with respect to changes in atmospheric conditions. These illustrate the usefulness-added value of the CIRS cloud data for climate studies.

5.1 Studying hemispheric differences in UT clouds

While the NH and the SH reflect the same amount of sunlight within 0.2 Wm$^{-2}$ (Stephens et al., 2015), there is a small energy imbalance between both hemispheres of our planet, with slightly more energy absorbed by the SH (0.9 Wm$^{-2}$). This yields more frequent precipitation in the SH and while more intense precipitation in the NH (Stephens et al., 2016). The latter might be linked to the characteristics of the ITCZ, a zone of strong convection, which itself produces large cirrus anvils. As the size of these anvils is on average positively related to convective strength (e.g., Protopapadaki et al., 2017), we
explore the annual mean and seasonal hemispheric difference of high cloud amount and try to relate it
to the characteristics of the ITCZ, such as its peak strength, the latitudinal position of the peak and its
width.

The more intense precipitation in the NH is probably linked to the fact that on annual average the ITCZ
peak latitude is about 5°N, shown in Figure 115. On average, total CA is about 10% (0.06) smaller in the
NH than in the SH (excluding the polar regions), without a pronounced seasonal cycle (not shown). This
is linked to more clouds over ocean than over land, producing the increased reflection in the SH
midlatitudes as discussed in (Stephens et al., 2015).—From Figure 45–11 we deduce that the annual NH–
SH difference in CAH between NH and SH is 0.05, with a pronounced seasonal cycle of about 0.3 in
amplitude. Results from the three CIRS cloud climatologies (AIRS with two ancillary data sets and
IASI), AIRS-LMD, CALIPSO-GOCCP, ISCCP and MODIS-CE are very similar. This seasonal cycle
permits an indication of the strength of the ITCZ. It is also interesting to note that the width of the ITCZ is smaller in July / August (10.5° f 12.5°) than in
January (17°) and the CAH peak is about 10% larger in August than in January, which might suggest a more even precipitation when it is located in the NH in boreal summer than when it is located in the SH.

All datasets agree well on the ITCZ peak latitude. The smaller maximum CAH values of MODIS-CE
and ISCCP are due to smaller sensitivity to thin cirrus, and the reduced seasonal cycle of maximum
CAH and of ITCZ width for CALIPSO-GOCCP is due to the inclusion of ubiquitous thinner cirrus,
leading to less well pronounced CAH minima in the subtropics. The CIRS climatologies reveal the
seasonal behaviour of the ITCZ characteristics clearly. For this analysis, the properties of the ITCZ have
been determined by fitting the tropical peak of the latitudinal CAH distributions per month and year (as
in Figure 10). While all datasets agree on the ITCZ peak latitude and mostly on the ITCZ width (with the
Gaussian fit on the ITCZ maximum producing falsely a smaller width for CALIPSO-GOCCP, because
due to ubiquitous thin cirrus, the minima in the subtropics are not as well pronounced as in the other data
sets), MODIS-CE and ISCCP produce smaller absolute values of maximum CAH because of smaller
sensitivity to thin cirrus. The seasonal cycle of maximum CAH is reduced for CALIPSO-GOCCP and
AIRS-LMD due to the inclusion of thinner cirrus (for AIRS-LMD clouds down to e<sub>-cl</sub> > 0.05, compared
to a threshold for CIRS clouds of 0.10). Figure 15 confirms and extends the interpretation of the results
of (Stephens et al., 2016), by displaying a linking relation between the hemispheric difference in hemispheric CAH and the shifting characteristics of the ITCZ, which seems to be more intense when its peak is situated in the NH and its stronger intensity in the NH during boreal summer (smaller width and larger maximum).

5.2 Studying El Niño-Southern Oscillation (ENSO) effects

Relating surface temperature anomalies to changes in UT clouds

ENSO is the most dominant mode of interannual variability in the Earth’s climate system (e.g., Bjerknes, 1969). The trade winds, blowing from east to west, warm the water as they push it, which leaves warm water in the West Pacific Maritime Continent (WPMC) and cool water in the tropical East Pacific. While warm air is rising, building up convection and upper tropospheric clouds, air dries over the cooler water in the east, thus this SST gradient is responsible for the Walker circulation. ENSO events, El Niño (warm phase) and La Niña (cold phase), are characterized by large-scale SST anomalies in the tropical Pacific, compared to the normal situation described above. El Niño events are initiated by a positive SST anomaly in the equatorial eastern and central Pacific which reduces the east-west SST gradient and hence the strength of the Walker circulation (Gill, 1980), resulting in weaker trade winds. The weaker trade winds in turn drive the ocean circulation changes that further reinforce the SST anomaly. The positive ocean-atmosphere feedback leads to the warm phase of ENSO, which is characterized by strong rising motion in the central Pacific and a descending branch over the initially strong convective area over the WPMC. After an El Niño reaches its mature phase, negative feedbacks are required to terminate growth. According to Lloyd et al. (2012), the major source of this negative feedback stems from the reduction in solar energy at the ocean surface by increased cloud cover over the warm water. Depending on the location of maximum SST anomalies and associated atmospheric heating, El Niño events may be distinguished as eastern and central Pacific warming events. A review is given by Wang et al. (2016).

The cold phase of ENSO (La Niña) starts with a cold SST anomaly in the tropical Pacific, increasing the SST gradient and amplifying the Walker circulation, leading to stronger convection and more upper tropospheric clouds over the WPMC.

To illustrate maximum climate variability patterns in the tropics, we contrast the strongest El Niño and La Niña events during the AIRS observation period, with multivariate ENSO index of 2.1 in Dec. 2015 and −1.6 in Dec. 2010, respectively. Figure 16 presents geographical difference patterns between these two ENSO modes in surface temperature and resulting atmospheric parameters, using AIRS CIRS cloud data, collocated ERA-Interim data and outgoing longwave radiation (OLR) from NASA AIRS (Susskind et al., 2012). As described in the literature, and summarized in the paragraph above, Figure 16 confirms that during an El Niño event East and central Pacific strongly warm, while temperatures are
slightly cooler over the WPMC. The latter is warmer during La Niña. Higher SSTs lead to more water vapour in the atmosphere, while the WPMC with its lower SSTs is drier. The vertical updraft (negative difference in vertical wind) intensifies in a narrow band just north of the equator over the Pacific west of the WPMC and a short branch to the South-East, in a typical pattern. The pattern differences in fraction of opaque high clouds represents the ones of convection, very similar to the updraft pattern, while high-level clouds increase over a wider part as outflowing anvils, in coherence with increasing water vapour, while they decrease over the drier WPMC. Thin cirrus increase as parts of anvils in the two branches, but also in the drier WPMC and North-west of the convective band. The OLR pattern is very similar to the one of CAH, increasing over WPMC and decreasing where CAH increases over the Pacific. The pattern of changes in high-level cloud temperature (CTH) shows some differences from the patterns of the other variables. In general, CTH warms where there are also less high-level clouds and it is lower where the updraft increases.

So far, the observational period of AIRS and IASI is too short to directly study long-term cloud feedback variability related to climate warming. An alternative approach is to assess cloud feedback variability in response to interannual climate variability like ENSO. Dessler (2010) demonstrated that as the surface warms, cloud changes lead to trapping additional energy, i.e. the longwave cloud feedback is positive. Zelinka and Hartmann (2011) investigated the response of tropical mean cloud parameters to the ENSO cycle and their effect on top of atmosphere radiative fluxes. They found during El Niño periods a decrease of high-level cloud amount as well as an increase in their height which would have opposite effects on the OLR, with a dominating effect coming from the first. Susskind et al. (2012) have shown that global mean and tropical mean OLR anomaly time series are strongly correlated with ENSO variability, with OLR change resulting primarily from changes in mid-tropospheric water vapour and cloud amount over the WPMC and the East Pacific. Observed variability in cloud, atmospheric and surface patterns due to ENSO variability can be used to constrain climate modelling and to understand the processes behind these changes (e.g. Stephens et al., 2017). Though interannual global tropical mean the ENSO-related SST surface temperature anomalies might not directly relate to patterns of anthropogenic climate warming, Zhou et al. (2015) have shown that interannual cloud feedback may be used to directly constrain the long-term cloud feedback. Changes in the geographical pattern and amount of tropical high-level UT tropical clouds leads to variations in cloud radiative atmospheric heating and cooling which then may influence the large-scale circulation as has already been shown by (e.g. Slingo and Slingo (1991), Tian and Ramanathan, 2003).

Since the radiative effects of high opaque clouds and thin cirrus are quite different, we investigate the geographical patterns of UT cloud amount changes anomalies (p≤330 hPa) with respect to tropical
and tropical–global mean surface temperature changes in tropical–global mean surface temperature changes, separately by separating them into for high–opaque, thick cirrus and thin cirrus (p<sub>330hPa</sub> < 330 hPa, e<sub>sl</sub> > 0.95, e<sub>sl</sub> between 0.45 and 0.95 and e<sub>sl</sub> < 0.45, corresponding to visible COD > 6, 1 - 6 and < 1, respectively). By making use of the whole period between 2003 and 2015 (covering 156 months), we determine a change in upper tropospheric UT cloud amount as a function of change in tropical–mean surface temperature by a linear regression of their deseasonalized monthly time–anomalies, at a spatial resolution of 1° latitude x 1° longitude. Similar techniques were already utilised in other studies related to El Niño and Southern Oscillation (ENSO) and cloud feedback (e.g. Lloyd et al., 2012; Zhou et al., 2013, Zhou et al., 2014, Yue et al., 2017, Liu et al., 2017). Figure 47–12 presents the change in amount of high opaque cloud (mostly of convective origin), in thick cirrus (which might be formed as anvil or via in situ freezing) per K°C of global surface warming in the tropics (20°N – 20°S), obtained as the linear slopes of these deseasonalized monthly time–anomaly relationships. The cloud amounts are from AIRS–CIRS, while the surface temperatures are from the ERA–Interim ancillary data. Results are very similar when using Tsurf anomalies surface temperatures from AIRS–NASA (not shown Figure S5 of the supplement). Zhou et al. (2013) have shown that ERA–Interim Tsurf anomalies give similar results in their short–term cloud feedback analysis, compared to other Tsurf data sets. In our study, we concentrate on the change of UT clouds of different height (p<sub>330hPa</sub> < 440 hPa and p<sub>330hPa</sub> < 330 hPa), and we compare changes in absolute UT cloud amounts and in UT cloud amounts relative to total cloud amount. Figure 12 also presents the geographical patterns of the relative slope uncertainty are shown in Figure S5 in the supplement. In general, large changes in cloud amount per °C of warming have smaller uncertainty than small ones, indicating robust patterns.

During this period, global mean Tsurf anomalies and tropical mean Tsurf anomalies are strongly correlated (not shown), and the spatial patterns in Figure 12 are compatible with ENSO–like patterns. The left panels of Figure 12 agree quite well with Figure 98 of Liu et al. (2017), based on MODIS cloud amount and HadCRUT4 Tsurf anomalies, even though our cloud types categories differ slightly. In particular, we have separated thin cirrus. Therefore the analyses suggest that the change patterns address ENSO variability rather than long–term trends. When considering relative cloud type changes (middle panels in Figure 12), the signals are stronger. An interesting feature appears when considering changes in the relative amounts of higher clouds (p<sub>330hPa</sub> < 330 hPa, left panels of Figure 12): Even though the change in tropical mean temperature is mostly linked to ENSO variability over the studied period and it is still uncertain how to relate these to long–term patterns due to anthropogenic climate warming, it is very interesting to note that high opaque clouds and thin cirrus show very different change patterns. While the high opaque clouds, linked to strong precipitation (Protopapadaki et al., 2017), relative to all clouds,
increase in a narrow band in the tropics, there is a large increase in relative thin cirrus amount around these regions, the latter might hypothetically directly affect the atmospheric circulation through their radiative heating (e.g. Sohn, 1999; Lebsock et al., 2010).

As in Liu et al. (2017), we have also examined linear regression slopes from anomaly averages over the tropics and other latitudinal bands, as in Liu et al. (2017). Although in general the relationships are very noisy, on the interannual scale tropical cirrus amount slightly decreases with warming (−0.76 ± 0.21 %/K), while thin cirrus amount seems not affected (−0.09 ± 0.20 %/K), in agreement with Liu et al. (2017). However, when considering changes in tropical cirrus and thin cirrus amount relative to total cloud amount, at higher altitude (p<sub>p</sub> < 330 hPa), both increase with warming (1.87 ± 0.52 %/K and 1.70 ± 0.54 %/K), which means that these clouds are more frequent among all clouds when T<sub>surf</sub> gets warmer.

Even though the changes in mean T<sub>surf</sub> are mostly linked to interannual variability over the studied period and it is still uncertain how to relate these to long-term patterns due to anthropogenic climate warming, it is very interesting to note that changes in amounts of high opaque clouds and thin cirrus, relative to all clouds, show very different geographical patterns. To get a better understanding on these underlying feedback processes one has to consider the heating rates of these upper tropospheric UT cloud systems and link them to the dynamics, which is foreseen in future work.

6 Conclusions

We have presented two global climatologies of cloud properties, obtained built from AIRS and IASI observations by the CIRS cloud retrieval. This retrieval software package, developed at LMD, can be easily adapted to any IR sounder. The retrieval method itself, based on a weighted χ² method on radiances around-along the wing of the 15 µm CO₂ absorption band, and the “a posteriori” multi-spectral cloud detection, based on the spectral coherence of retrieved cloud emissivities, have already been evaluated in previous publications. In this study, we have further demonstrated the reliability of these updated cloud climatologies in this study. IR sounders are especially advantageous for retrieval of upper tropospheric cloud properties. Their good spectral resolution allows a reliably determines cirrus identification properties down to an IR optical depth of 0.1, day and night. The CIRS retrieval uses an improved radiative transfer modelling, employs the latest ancillary data (surface temperature, atmospheric profiles), and an original calibration method to account for atmospheric spectral transmissivity changes according to latitudinal, seasonal and interannual atmospheric CO₂ concentration variations. This taking into account CO₂ calibration method has removed variability. The latter eliminates an artificial CA trend of about 4% over the observation period 2004 to 2016, which was directly related to not having taken into
account the anthropogenic CO₂ increase in the spectral transmissivities simulated for a specific atmospheric CO₂ concentration. The magnitude of calibrated cloud amount and effective low-level cloud amount deseasonalized variations lie within 1% and of effective high-level cloud amount within 0.5% over this period.

Common ancillary data (surface temperature, atmospheric profiles) come from the meteorological reanalyses ERA-Interim, which have been interpolated to the observation times of AIRS and IASI. Additional ancillary data, established application from NASA AIRS retrievals, retrieved AIRS-NASA ancillary data allowed to iteratively make adjustments to both sets of ancillary data for optimal results in cloud properties and also to estimate uncertainties in cloud amounts. Since the cloud detection depends on the coherence of spectral cloud emissivity, the surface temperature influences only slightly the cloud amount (in particular the one of low-level clouds). AIRS total cloud amount is 67.0% / (70.67%), high-level cloud amount 27% / (27%) and low-level cloud amount 29.9% / (27%), using ERA-Interim (AIRS-NASA) / ERA-Interim ancillary data. This giving an uncertainty estimate of ~5% and 10% uncertainty on global averages for of CA and CAL, respectively. Uncertainties are larger over land and ice or snow than over ocean, in particular because Tₐₚₖ of ERA-Interim is underestimated in the afternoon and Tₚₖ of AIRS-NASA is underestimated during night due to cloud contamination. In the future, the CIRS cloud retrieval might use ancillary data from ECMWF meteorological analyses or from the new ECMWF meteorological reanalysis ERA5, both also having with a better temporal and spatial resolution.

Cloud / clear sky detection hit rates between AIRS-CIRS and detection agree with the one of CALIPSO. CloudSat are 84.4% / (84.85%) over ocean, 79.82% / (83.79%) over land and 73.79% / (79.73%) over ice and snow, for ERA-Interim (AIRS-NASA) / ERA-Interim ancillary data, respectively. Typical uncertainties in cloud pressure range from 30 hPa for high-level clouds to 120 hPa for low-level clouds, coinciding with which corresponds to about 1.2 km in altitude. A comparison with CALIPSO-CloudSat has shown, that on average the CIRS retrieved cloud height lies only about 1 km below is close to cloud top in the case of low-level clouds and lies about 1–5 km to 2.5 km below cloud top in the case of high-level clouds. The latter leads to retrieved cloud temperatures which are about 10 K warmer than the cloud top. This has to be considered when determining radiative effects or when evaluating climate models. The CIRS retrieved cloud height coincides can be approximated with the middle-mean layer height (for optically thin clouds) or the mean between cloud top and apparent cloud base (real cloud base for optically thin clouds or the cloud height at which the cloud reaches opacity, for both high-level and low-level clouds), independently of cld. When comparing to the height at which the cloud reaches a VIS optical depth of about 0.5, the CIRS retrieved cloud height, in the case of high-level
clouds, lies about 1 km above for optically thin clouds and about 1 km below for optically thick clouds. While for low-level clouds the apparent cloud vertical extent distance is about 1.0 km, for high-level clouds it slightly increases with $\lambda_{ab}$ from 3.0 km to 1.54 km, with slightly higher-larger values in the tropics than in the midlatitudes, linked to diffusive cloud tops.

Total cloud amount consists of is partitioned into about 40% high-level clouds, and about 40% low-level clouds and 20% mid-level clouds. The latter two categories only are only detected when not hidden byin the absence of upper clouds. Upper tropospheric clouds are most abundant in the tropics, where high opaque clouds make out 7.5%, thick cirrus 27.5% and thin cirrus 21.5% of all clouds. IASI values are very similar. The most prominent features of latitudinal seasonal cycles are is the shift of the ITCZ towards the summer hemisphere, with seen as an, an-amplitude signal of 0.1 in CA, 0.3 in CAH and 16 K in CT in the SH and NH tropical bands, (and even stronger over land).

The 5% annual mean excess in upper tropospheric cloud amount in the Northern compared to the Southern hemisphere has a pronounced seasonal cycle with a maximum of 25% in boreal summer have been related to the characteristics of the ITCZ. The annual mean ITCZ peak latitude lies about 5°N with a maximum of 10°N in boreal summer. At that time the ITCZ width is also narrower and the peak slightly larger. This suggests that the NH-SH excess in CAH is mostly determined by the position and moving-of the ITCZ.

The asymmetry in CAH between Northern and Southern hemisphere with annual mean of 5% has a pronounced seasonal cycle with a maximum of 25% in boreal summer, which can be linked to the shift of the ITCZ peak latitude. The latter has an annual mean of 5°N, moving to 12°N with a slightly more intense ITCZ (smaller width and larger maximum) in boreal summer.

To illustrate further the usefulness added value of the CIRS cloud data for climate studies, we have finally presented ENSO effects and tropical geographical change patterns in changes of amount of high opaque, cirrus and clouds and thin cirrus with respect to tropical-global mean $T_{surf}$ surface temperature changes. These are in agreement with earlier studies, while an examination of changes in tropical high cirrus and thin cirrus amounts relative to total cloud amount revealed that these are more frequent among all clouds when $T_{surf}$ gets warmer. Even though the change in tropical-mean $T_{surf}$ temperature is mostly linked to ENSO variability over the studied period and it is still uncertain how to relate these to long-term patterns due to anthropogenic climate warming, the large difference in geographical changes of amounts of high opaque clouds and thin cirrus, relative to total cloud amount, indicates that their response to climate change may be different. which This might then have consequences on the atmospheric circulation. To get a better understanding on the underlying...
feedback processes, one has to consider the heating rates of these upper tropospheric cloud systems and link them to the dynamics. Therefore the AIRS-CIRS and IASI-CIRS cloud data have been further used to build upper tropospheric cloud systems (based on $p_{sl}$) and then to distinguish convective cores, cirrus anvil and thin cirrus according to $e_{ul}$ (Protopapadaki et al., 2017). These data are being further exploited, together with other data and modelling at different scales, within the framework of the GEWEX PROcess Evaluation Study on Upper Tropospheric Clouds and Convection (UTCC PROES, Stubenrauch and Stephens, 2017) to advance our understanding on upper–tropospheric UT cloud feedbacks.

The AIRS-CIRS and IASI-CIRS cloud climatologies will be made available at the French data centre AERIS, which also will continue their production.

7 Data availability


Acknowledgements

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Table 1. Agreement in cloudy and clear sky scenes Hit rates between CALIPSO and the AIRS-CIRS and CALIPSO-CloudSat a posteriori cloud detection. Statistics include three years (2007-2009) collocated observations at 1:30 AM LT.

<table>
<thead>
<tr>
<th>surface \ latitude</th>
<th>tropics</th>
<th>mid- latitudes</th>
<th>polar</th>
</tr>
</thead>
<tbody>
<tr>
<td>ancillary data</td>
<td>AIRS</td>
<td>ERA</td>
<td>AIRS</td>
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<tr>
<td>ocean</td>
<td>86.5%</td>
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<td>90.2%</td>
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<td>83.2%</td>
<td>80.7%</td>
</tr>
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<td>sea ice</td>
<td></td>
<td></td>
<td>71.5%</td>
</tr>
<tr>
<td>snow</td>
<td>73.5%</td>
<td>71.9%</td>
<td>74.9%</td>
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</table>


<table>
<thead>
<tr>
<th>latitude band</th>
<th>AIRS-LMD V4 CA (%)</th>
<th>AIRS-CIRS CAHR (%)</th>
<th>IASI-CIRS CAMR (%)</th>
<th>CALR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>globe</td>
<td>67 / 67 / 67 / 67</td>
<td>41 / 41 / 40 / 406²</td>
<td>67 / 18 / 19 / 19 / 20</td>
<td>41 / 40 / 41 / 40</td>
</tr>
<tr>
<td>ocean</td>
<td>72 / 74 / 72 / 74</td>
<td>38 / 38 / 37 / 37 / 74</td>
<td>16 / 16 / 17 / 17 / 18 / 72</td>
<td>47 / 45 / 46 / 44</td>
</tr>
<tr>
<td>60°N to 30°N</td>
<td>69 / 72 / 69 / 69</td>
<td>40 / 40 / 40 / 40 / 40 / 69</td>
<td>69 / 22 / 23 / 22 / 22</td>
<td>38 / 37 / 38 / 38</td>
</tr>
<tr>
<td>15°S to 15°N</td>
<td>67 / 66 / 66 / 66</td>
<td>59 / 58 / 57 / 58 / 63 / 66</td>
<td>62 / 11 / 10 / 10 / 11 / 11</td>
<td>30 / 32 / 33 / 31</td>
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<tr>
<td>30°S to 60°S</td>
<td>80 / 85 / 85 / 85</td>
<td>28 / 30 / 30 / 29 / 44 / 85</td>
<td>85 / 21 / 23 / 22 / 23</td>
<td>51 / 47 / 48 / 48</td>
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Table 3. Averages of relative amount (in %) of opaque ($\varepsilon_{\text{clid}} > 0.95$), cirrus ($0.95 > \varepsilon_{\text{clid}} > 0.5$) and thin cirrus ($0.5 > \varepsilon_{\text{clid}} \leq 0.15$) from AIRS-CIRS (2003-2015, using AIRS-NASA / ERA-Interim ancillary data) / IASI-CIRS (2008-2015, using ERA-Interim ancillary data).

<table>
<thead>
<tr>
<th>Latitude band</th>
<th>Opaque / tot CA</th>
<th>Cirrus / tot CA</th>
<th>Thin Cirrus / tot CA</th>
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<td>13.4 / 13.0 / 12.9</td>
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<tr>
<td>Ocean</td>
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<td>20.0 / 19.9 / 19.2</td>
<td>12.5 / 12.0 / 12.1</td>
</tr>
<tr>
<td>Land</td>
<td>6.1 / 5.9 / 6.6</td>
<td>25.8 / 25.3 / 24.9</td>
<td>15.6 / 15.2 / 14.7</td>
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<tr>
<td>60°N−30°N</td>
<td>5.4 / 4.8 / 5.4</td>
<td>22.9 / 23.5 / 22.8</td>
<td>11.1 / 11.0 / 10.9</td>
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<td>15°N−15°S</td>
<td>7.3 / 7.0 / 7.7</td>
<td>28.2 / 27.5 / 26.8</td>
<td>21.6 / 21.3 / 22.1</td>
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<tr>
<td>30°S−60°S</td>
<td>4.8 / 4.2 / 4.4</td>
<td>17.5 / 18.9 / 18.1</td>
<td>6.9 / 6.6 / 5.9</td>
</tr>
</tbody>
</table>


Figure 1. Normalized distributions of the difference between surface skin temperature, as used in the cloud retrieval, deduced from AIRS-NASA of good quality and from ERA-Interim, and collocated surface air temperature of the ARSA data base. Statistics includes January and July from 2003 to 2015, separately over land for colder temperatures ($T_{\text{surf}} < 290$ K), over land for warmer temperatures ($T_{\text{surf}} > 290$ K) and over ocean.
Figure 32. Geographical maps of difference in total CA (above) between the two AIRS-CIRS data sets, based on ancillary data from AIRS-NASA and from ERA-Interim, and in $T_{surf}$ (below) between AIRS-NASA and ERA-Interim as used in the retrieval, separately at 1:30AM (left) and at 1:30PM (right).
Figure 34. Normalized frequency distributions of the difference between the cloud height at which the optical depth reaches a value of 0.5 from CALIPSO and $z_{cld}$ from AIRS (left) and between the cloud top height from CALIPSO and $z_{cld}$ from AIRS (right). $z_{cld}$ from AIRS is compared to the cloud cloud layer of CALIPSO, coherent with which also corresponds to the one of CALIPSO-CloudSat-lidar GEOPROF, and which is the closest to $z_{cld}$. Analysis over tropics (30°N-30°S), midlatitudes (30°-60°) and polar latitudes (60°-85°), separately for high-level clouds and for clouds with $p_{cld} > 440$ hPa. Statistics includes three years (2007-2009) of observations at 1:30 LT. AIRS-CIRS cloud retrievals. The effect of using different ancillary data is also presented from AIRS-NASA in red and from ERA-Interim in black, separately for high-level clouds (full line) and for clouds with $p_{cld} > 440$ hPa (broken line). Analysis over three latitude bands: 30°N-30°S (upper panel), 30°-60° (middle panel) and 60°-85° (lower panel). Statistics includes three years (2007-2009) of observations at 1:30AM LT.
Figure 45. Average difference between a) \( z_{cld} - z_{COD0.5} \) from AIRS-CIRS and CALIPSO height at which the COD reaches about 0.5 (top), between b) \( z_{app} \) from CALIPSO and \( z_{cld} \) (middle) and between c) \( (z_{top} - z_{cld}) / (z_{top} - z_{app base}) \) scaled by 'apparent' cloud vertical extent, (bottom) as function of AIRS–CIRS–CALIPSO cloud emissivity for high-level clouds in the tropics (red), midlatitudes (green) and polar latitudes (blue), separately for high-level clouds (left) and for low-level (right) clouds. Presented are median values and the interquartile ranges. Three years of statistics, for cases where \( z_{cld} \) from AIRS and \( z_{COD0.5} \) from CALIPSO height lie within vertical cloud borders determined from CloudSat–CALIPSO lidar–GEOPROF. Observations at 1:30 AM LT.
Statistical errors are negligible and the broken lines indicate a range between single-layer clouds and multi-layer clouds.

Figure 6. Normalized frequency distributions of differences between CALIPSO cloud top and height at which the COD reaches about 0.5 (left) and between CALIPSO cloud top and $z_{\text{cl}}$ from AIRS (right) for high-level clouds, in absolute values (top) and scaled by apparent vertical cloud extent (bottom). Distributions are compared for clouds with $c_{\text{cl}} > 0.8$ (full line), $0.8 > c_{\text{cl}} > 0.4$ (broken line) and $0.4 > c_{\text{cl}} > 0.1$ (dotted line). Three years of statistics for cases where $z_{\text{cl}}$ from AIRS and CALIPSO height lie within vertical cloud borders determined from CloudSat-CALIPSO GEOPROF. Observations at 1:30 LT.
Figure 57. Normalized frequency distributions of $z_{CD0.5}$ from CALIPSO (black) and of $z_{cd}$ from AIRS, using ancillary data from AIRS-NASA (red) and from ERA-Interim (green) and $z_{CD0.5}$ from CALIPSO (black), separately over land (top) and over ocean (bottom), in the tropics (left), midlatitudes (middle) and polar latitudes (right). For each data set, two distributions are shown: compared for statistics of all detected clouds, except subvisible cirrus, (broken-dashed line) and for only of single layer clouds with a mostly cloudy field of coverage filling the AIRS golf ball single layer clouds (full line).
Figure 68. Normalized frequency distributions of $p_{cld}$ separately over land and over ocean in six latitude bands of 30° from SH polar (left) to NH polar latitudes (right), in boreal winter (December, January, February; blue) and in boreal summer (June, July, August; red). Compared are results from AIRS-CIRS using two sets of ancillary data from AIRS-CIRS, using ancillary data from AIRS-NASA (dashed line) and from ERA-Interim (dotted line), as well as from IASI-CIRS (full line), separately over land (top) and over ocean (bottom) in six latitude bands of 30° from Southern hemisphere polar (left) to Northern hemisphere polar latitudes (right), in boreal winter (December, January, February; blue) and in boreal summer (June, July, August; red). Statistics from 2008.
Figure 7.9. Top: Global averages of total cloud amount (CA), as well as of high-level, mid-level and low-level cloud amount, relative to total cloud amount, (CAH + CAMR + CALR = 1). Comparisons of IR sounder cloud data (AIRS, IASI) with L3 data from the GEWEX Cloud Assessment database, separately for observations mostly during day (left), corresponding to 1:30PM (3:00PM for ISCCP and 9:30AM for IASI), and mostly during night (right), corresponding to 1:30AM (3:00AM for ISCCP and 9:30PM for IASI). Compared to the original ISCCP data, the day-night adjustment on CA has not been included to better illustrate the differences between VIS-IR and IR-only results. Bottom: Averages of ocean-land differences for the same parameters and data sets.
Figure 10. Annual mean zonal distributions of CA, CAH and CAL (left) and CAE, CAEH and CAEL (right), separately as annual mean (top), in boreal winter (December, January, February; middle) and in boreal summer (June, July, August; bottom). Results for the annual mean, cloud amounts are compared between AIRS-CIRS, using ancillary data from AIRS-NASA (full line) and from ERA-Interim (broken dashed line), IASI-CIRS (dotted line) and AIRS-LMD (dash-dotted line).
For boreal winter and boreal summer, AIRS-CIRS (using AIRS-NASA ancillary data) is shown separately for each year between 2003 to 2015, illustrating inter-annual variability.

Figure 9-11. Top: Geographical maps of annual CAH (left) and CAL (right), from of AIRS-CIRS (2003-2015, top), compared to ISCCP (2003-2007, middle) and CALIPSO-GOCCP (2007-2008, bottom). The latter two from the GEWEX Cloud Assessment data base, as well as seasonal anomalies of DJF (middle) and of JJA (right).
Figure 12. Geographical maps of annual CAL (left) of AIRS-CIRS (2003-2015, top) compared to ISCCP (1984-2007, middle) and CALIPSO-GOCCP (2007-2008, bottom) from the GEWEX Cloud Assessment data base, as well as seasonal anomalies of DJF (middle) and of JJA (right).
Figure 1. Time anomalies of deseasonalized CA, CAEH and CAEL over the globe. In the case of CA, additional values are shown without calibration of spectral atmospheric transmissivities for changes in atmospheric CO₂ concentration.
Figure 1. Seasonal cycle / annual average of (1) CAH differences between NH hemisphere (0°-60N) and SH hemisphere (60S-0°-60N); seasonal cycle / annual average of (2) ITCZ peak latitude, (3) maximum CAH within ITCZ and (4) width of ITCZ width.
Figure 16. Differences between December 2015 and 2010, corresponding to El Niño and La Niña, respectively, in $T_{surf}$ (1. Panel, left), total atmospheric water vapour (1. Panel, right) and vertical wind at 500 hPa (2. Panel, left) from ERA-Interim, in CAH (2. Panel, right), fraction of Cb (3. Panel, left), cloud temperature of high-level clouds (3. Panel, right) and fraction of thin cirrus (4. Panel, left) from AIRS-CIRS, and OLR (4. Panel, right) from AIRS–NASA.
Figure 1. Geographical maps of linear regression slopes of between change-monthly mean anomalies in amount of Cb ($e_{cld} > 0.95$, top row), cirrus-Ci ($0.95 > e_{cld} > 0.4$, middle row) and thin cirrus Ci ($0.4 > e_{cld} > 0.1$, bottom row) amount from AIRS-CIRS in % per °C of tropical and global mean surface temperature anomalies warming (20°N–20°S) from ERA-Interim; left: $p_{cld} < 440$ hPa, middle: relative cloud amount; right: $p_{cld} < 330$ hPa and relative cloud amount. Results using slope uncertainty for Cb (top), cirrus (middle) and thin cirrus (bottom) amount change per °C of tropical warming. Results using upper tropospheric ($p_{cld} < 330$ hPa) cloud type anomalies from AIRS-CIRS and surface temperature anomalies from ERA-Interim of 156 months during the period 2003-2015.