Clouds over the summertime Sahara: An evaluation of Met Office retrievals from Meteosat Second Generation using airborne remote sensing

Author response to reviewer comments

February 24, 2017

We'd like to thank both reviewers for their words of appreciation for our work, and for their detailed review. In what follows, we address the reviewer #1 comments and provide a detailed response. We believe that the reviewer comments help us to improve the manuscript, and bring it to publication standard.

Please note that in our responses, page and line numbers now refer to the revised manuscript, which we will submit as soon as we are requested to do so by the journal.

1. Comments from Reviewer #1

1.1 General Comments

Referee comment:

1) The authors enter somewhat treacherous territory when attempting to evaluate a satellite derived cloud mask, for which the answer to "What is a cloud?" is often "I know a cloud when I see it." As they rightly point out, the design of a cloud mask, and the "accuracy" of cloud detection and derived cloud fractions, are determined in part by the science questions asked, e.g., detecting/removing clouds for a clear sky retrieval product vs detecting clouds for a cloud retrieval product. This in addition to the spectral channel information, sensor spatial resolution, etc. Many investigations lack an appropriate level of consideration for these distinctions, but the authors do a nice job here. My only quibble with the cloud mask analysis (and it is indeed only nit-picking) is the use at times of the term "validation," which implies a comparison of a given retrieved parameter with the direct-measured truth. I would suggest using the term "evaluation" as is done in the title and abstract, in particular because a satellite derived cloud mask is an ill-defined parameter and the fact that the "truth" used here, from the lidar and radiometer, are in fact retrievals themselves.

Author's response:

This is a nice point, and we absolutely agree. We have no problem with using the term "evaluation" in place of "validation".

Author's changes in manuscript:

We have replaced "validate" with "evaluate" at Page 2 Line 28 and Page 3 Line 6 of the revised manuscript.

Referee comment:

2) The authors are on more solid ground with the CTH evaluation, though I have a concern with the analysis as presented. The authors acknowledge that partly cloudy pixels that are treated as overcast will often yield biased CTH retrievals, and they include a nice discussion of the mechanisms for these biases. However, in Fig. 7 they use the SEVIRI derived effective cloud amount N to show the relationship between sub-pixel cloudiness and cloud top biases instead of

the aircraft derived cloud fractions. The authors themselves acknowledge that N is not explicitly calculated and should be used with caution. I suggest they either re-create this figure using the SEVIRI pixel-level aircraft cloud fractions instead of N, or add a figure/panel showing CTH biases as a function of the aircraft cloud fractions like what was done for the cloud mask analysis in Figs. 5 and 6. I believe this would be a much more defensible approach.

Author's response:

This is absolutely true. After some discussion, we have elected to follow the reviewer's suggestion and include this figure for completeness. We attach to this response a copy of this new figure (Fig. 1 in the attachment). However, we do wish to discuss the reason why we did not include this in the original manuscript.

Firstly, as you can see, the plot is very messy, and it is difficult to discern any quantifiable information from it. There do not appear to be any particular trends or biases that relate the absolute cloud-top height to the aircraft cloud fraction. This result simply tells us what we already know; the SEVIRI CTH does not match well with aircraft observations. This is already clear from Fig. 7a (Now Fig. 7 in the revised manuscript), and is also the reason why we chose an individual case study (Flight B608) to try to communicate the nature of the CTH error.

In our opinion, the plot of SEVIRI CTH vs N presents more useful information than the CTH vs aircraft cloud fraction plot. By using the SEVIRI N-value instead of the aircraft cloud fraction, some structure becomes apparent in the SEVIRI data, giving more insight as to the source of the error. This is certainly not ideal however, and we acknowledge this.

Finally, with respect to N not being explicitly calculated, do bear in mind that this is true only for the profile matching scheme; the N-value is explicitly calculated in the minimum residual and stable layer schemes. (See Page 12 Line 24-27 in the revised manuscript.)

Author's changes in manuscript:

We have now added a new figure of SEVIRI CTH vs aircraft cloud fraction, which is Fig. 8a of the revised manuscript. Fig. 7a in the original manuscript is now Fig. 7 in the revised manuscript. All subsequent figures are now incremented upwards, giving the manuscript a new total of 10 figures.

We add the following to Page 11 Line 19-29 in the revised manuscript (Fig. 8 now refers to the Fig. 7 of the original manuscript.) "To understand the CTH errors, we split the MSG retrievals into the component schemes from which they are calculated, plotted as a function of the aircraft cloud fraction (Fig. 8a) and effective cloud amount, N (Fig. 8b). Fig. 8a shows us that there is no dependence of retrieved CTH on actual cloud fraction, whereas Fig. 8b shows that there is a strong dependence of both the retrieval method and the retrieved effective cloud amount, and this highlights a retrieval problem under certain circumstances. By presenting the data as in Fig. 8b, it becomes apparent that a relationship exists between the highest/lowest retrieved SEVIRI CTH's and low values of N . This implies that the errors in CTH are intimately connected to the calculation of N . The scheme that shows the best agreement is the "stable layers", in which the CTH is retrieved independently from N and the latter is only computed successively. The "minimum residual" scheme, instead, derives N and the CTH simultaneously, with the results shown in Fig. 8b. Finally, in the profile matching scheme N is not used, and the value reported is the one derived from the "minimum residual"; the fact that there still remains a dependence tells us therefore that there are issues common to both schemes taking place at the same time."

We add the following to Page 16 Line 22-27 of the revised manuscript: "The results of the present research will be used to develop a newer version of the CTH product. The "stable layers" scheme, which mainly makes use of the model thermodynamic profile to identify CTH, is the one giving better results. This seems to be an indication that, for the conditions encountered in this research (i.e. deep and well-defined boundary layer in the daytime summertime Sahara) the model is actually a more reliable source of information for determining CTH than satellite radiances. On the other hand, only a few retrievals make use of this scheme; this seems to indicate that in a future revised version of the product this balance will probably have to be revisited."

1.2 Specific Comments

Referee comment:

p. 3, line 14: I assume the Hocking (2011) cloud mask is a widely-used product at the Met Office?

Author's response:

The cloud mask is used to initiate the cloud retrievals (CTH and effective cloud amount, cloud optical thickness, effective radius and aircraft icing potential). The cloud mask is also used as part of the cloud assimilation into the UKV configuration of the Unified Model. All of these products are available to operational meteorologists as well. So yes, it would be fair to say the mask is widely used at the Met Office, and we are happy to mention this.

Author's changes in manuscript:

We add the following at Page 3 Line 22-23 of the revised manuscript: "This mask is widely used at the Met Office for the derivation and assimilation of a series of products, and is derived by applying a variety of..."

Referee comment:

p. 4, Eqns. 1, 2: Should N be a function of cloud top pressure p?

Author's response:

Yes, N is fundamentally formulated as a function of cloud-top pressure p and we thank the reviewer for pointing out that this may have been unclear in the previous version. We have updated the manuscript to show explicit dependence on p in the equations.

Author's changes in manuscript:

Equations 1 and 2: explicit dependence on p now shown.

Referee comment:

p. 4, line 17: How is the channel variance defined?

Author's response:

We have added details about the channel variance into the manuscript as specified below.

Author's changes in manuscript:

We add the following at Page 4 Line 23-27 in the revised manuscript: "The variances are fixed, and equal to 1.23 K, 1.25 K, and 0.57 K for each of the channels used, which are centred at the 10.8 μm, 12.0 μm, and 13.4 μm channels respectively. These R-matrix (observation error) values are a combination of two sources: (a) the measurement "noise" (i.e. instrumental error, from EUMETSAT-published radiometric error data), and (b) the error in the simulated brightness temperatures, derived from off-line O-B monitoring statistics, which represent any errors in the background NWP profiles and the radiative transfer."

Referee comment:

p. 5, line 32: Can the authors comment on the size of the across-track field of view?

Author's response:

The lidar field of view is 4 milli-radians, meaning that the footprint at sea surface from 8,000 m altitude is ~32 m and at cloud-level (assuming a cloud ~2,000 m below aircraft) is ~8 m. The field of view for the Heimann is much larger, 22°, as specified in the revised manuscript at Page 6 Line 14. This implies a footprint at sea level of ~3 km when flying at ~8,000 m altitude. At cloud level (~2,000 m below aircraft) this is ~800 m.

Author's changes in manuscript:

We add the following at Page 6 Line 14-15 in the revised manuscript: "The lidar field of view is 4 mrad, meaning that the footprint at sea surface from 8,000 m altitude is ~32 m and at cloud-level (assuming a cloud ~2,000 m below aircraft) is ~8 m."

We add the following at Page 6 Line 20-21 in the revised manuscript: “This implies a footprint at sea level of ~3 km when flying at 8,000 m altitude, with a footprint of of ~800 m at cloud level (assuming a cloud level ~2,000 m below the aircraft).”

Referee comment:

p. 6, lines 9-12: How frequent are these missed detections?

Author’s response:

The average number of missed detections by lidar across all Fennec flights, expressed a percentage of all cloudy detections, is 15.4%. This pertains to flights for which the overall ratio of cloudy to non-cloudy points in the final cloud mask is greater than 10 % (as was done in the calculation of measurement uncertainty in Sect. 2.5). For reference, when we include flights with cloud amounts less than 10 % as well, this figure rises to 18.3 %. This shows that the Heimann radiometer data is a valuable tool in creating a robust cloud mask product.

Author’s changes in manuscript:

We add the following at Page 6 Line 33-34 in the revised manuscript: “We estimate that these missed detections represent ~15 % of all cloudy pixels for days exceeding 10 % cloud coverage.”

Referee comment:

Section 2.2: I assume a down-viewing imager that could be co-located with the lidar and radiometer was not flown? This would have been useful for evaluating the lidar and radiometer cloud masks.

Author’s response:

The BAe-146 is fitted with a downward-facing camera, but the images were unfortunately unusable because the high dust loading in the air caused a build up of dust on the lens. This was also the case for the forward and upward facing cameras. This is the reason that only the rearward facing camera was able to produce usable images (Fig. 4). We did spend a significant amount of time viewing this data, but even if the image quality was better, it would have been far too time consuming to give anything more than a qualitative picture of specific situations, as we have done in Fig. 4.

Author’s changes in manuscript:

None

Referee comment:

p. 7, line 10: Why are above-aircraft cloud detections not useful for the cloud mask comparison?

Author’s response:

Please bear in mind that both the lidar and the Heimann radiometer are both nadir (downward) facing. It is these instruments that are the source of the aircraft cloud mask, which is a well-tested and robust product. Therefore it is very possible for SEVIRI to observe a cloud which lies above the aircraft that these nadir facing instruments should not be able to see. The pyranometer, by contrast, is upward facing but the methods employed to create the pyranometer cloud filter are not the same as those used to create the aircraft cloud mask. The pyranometer cloud filter was designed to remove complete sections of the dataset, as opposed to identifying whether each individual datapoint is cloudy or not cloudy. This is visualised in Figure S2 of the supplement.

Author’s changes in manuscript:

None

Referee comment:

p. 7, lines 21-25: The across-track FOV of the aircraft is obviously not as wide as a SEVIRI pixel, so the aircraft derived cloud fractions do not sample the entire SEVIRI pixel. Can the authors comment on the impacts of this?

Author’s response:

This is an unfortunate limitation of the technique, and there is little that can be done to gain information about cloud which lies parallel to the aircraft flight track. On Page 9 Line 22-24 of the original manuscript we already commented on this. However, as this effect is random in its nature, it is assumed that overall, on a wide dataset such as the one discussed here, errors can be reasonably assumed to cancel out.

Author's changes in manuscript:

We add the following at Page 10 Line 18-19 in the revised manuscript: "As this effect is random in its nature, it is assumed that overall, on a wide dataset such as the one discussed here, errors can be reasonably assumed to cancel out."

Referee comment:

p. 7, lines 29-30: Can cloud movement cause an overestimation of the SEVIRI cloud mask uncertainty? As defined the uncertainty implies the assumption that changes in pixel-level cloud mask are due to cloud formation/dissipation.

Author's response:

What we have done here is to literally quantify the changes in the cloud mask field; i.e. which pixels change from cloudy to not-cloudy and vice versa between successive frames. This should take into account clouds forming, dissipating, or moving. Indeed, in some cases (see Fig. S4 and Page 8 Line 24 of the original manuscript) we find that the cloud boundaries tend to show the most change, and this may suggest that a significant part of the change will in fact be due to cloud movement.

Author's changes in manuscript:

For clarification, we add the following at Page 8 Line 22-23 in the revised manuscript: "Such changes may be the result of cloud formation, dissipation, or movement."

Referee comment:

p. 9, lines 19-25: Can the authors comment on the role of SEVIRI cloud mask "false positives" in regards to the positive cloud mask results having aircraft cloud fractions below 0.1?

Author's response:

We are not sure what the reviewer is referring to here. Our manuscript already comments on these "false positives". See e.g. on Page 9 Lines 19-25 of the original manuscript. In this paragraph we offer some explanations , including the measurement uncertainty induced by a changing cloud field, the limited cloud horizontal extent, and the possible mis-detection of cloud by the aircraft due to its smaller pixel size.

Author's changes in manuscript:

None

Referee comment:

Fig. 7a: The x-axis label states the units as (km), however the tick labels appear to have units (m).

Author's response:

This has been corrected.

Author's changes in manuscript:

Units in this figure are now all set to km. This is now Fig. 7 in the revised manuscript.

Referee comment:

Fig. 9b: What spectral channels are used to create this RGB?

Author's response:

The RGB is based on the following:

Red: BT12μm -BT10.8μm, Green: BT10.8μm –BT8.7μm, Blue: BT10.8μm, where BT denotes brightness temperature at the given wavelength. The thresholds are then applied to a colour scale.

Further details of this RGB can be found in Brindley et al. (2012), as cited at Page 13 Line 1 in the original manuscript. A catalogue of this product is also available on the EUMETSAT website at

http://oiswww.eumetsat.org/IPPS/html/MSG/RGB/DUST/WESTERNAFRICA/

Author's changes in manuscript:

None

Referee comment:

Section 4.1: Could cloud mask false positives also be due to solar reflectance tests?

Author's response:

Solar reflectance is one of the tests that goes in the cloud mask, therefore the answer to the question is "yes, this is a possibility". However, we have already thoroughly commented on the cloud mask in Section 2.1. Section 4.1 pertains to the uncertainty on the cloud top height product, which is a different thing. We are therefore unsure why the reviewer inserted this remark at this point in the manuscript.

Author's changes in manuscript:

None

Additional Author's changes to the manuscript

Further discussions between the co-authors initated by the helpful reviewer comments have also lead to the following minor changes to the manuscript.

We have added the following to the abstract at Page 1 Line 2 of the revised manuscript: "Novel methods of cloud detection are applied to **airborne remote sensing observations from** the unique Fennec aircraft dataset..."

We have added the following to the abstract at Page 1 Lines 9-12 of the revised manuscript: "The mean cloud field, derived from the satellite cloud mask acquired during the Fennec flights, shows that areas of high surface albedo and orography are preferred sites for Saharan cloud cover, consistent with published theories."

We have added to the following to the abstract at Page 1 Lines 13-14 of the revised manuscript: "The results of the CTH analysis presented here may also have wider implications for the techniques employed by other satellite applications facilities across the World."

We add the following reference at Page 3 Line 3 of the revised manuscript:

Ref: Trzeciak, T., Garcia Carreras, L., and Marsham, J. H.: Cross Saharan transport of water vapour via recycled cold-pool outflows from moist convection, Geophysical Research Letters, 2016.

We add the following to the acknowledgements, at Page 17 Line 2-3 of the revised manuscript: "John Marsham was funded by the NERC project SWAMMA (NE/L005352/1)."

We add the following at Page 16 Line 27-30 of the revised manuscript: "Since the the methods used by the Met Office in the determination of CTH are also applied in other forms by other satellite applications facilities globally, the relevance of the results presented here are not limited to Met Office products, but may also have implications for other cloud-retrieval algorithms which employ similar techniques."