# 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 #2 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.

## 2. Comments from Reviewer #2

### 2.1 General comments

**1) Referee comment:**

In the title, it should be mentioned that the Meteosat Second Generation retrievals have been evaluated and not the Meteosat only.

**Author's response:**

We have opted to update the title to help incorporate this.

**Author's changes in manuscript:**

We have retitled the manuscript to "Clouds over the summertime Sahara: An evaluation of Met Office retrievals from Meteosat Second Generation using airborne remote sensing"

The abstract (Page 1 Line 4) now refers to Meteosat Second Generation, rather than Meteosat. We have also changed "Meteosat" to "MSG" at Page 3 Line 6 and Page 3 Line 8 in the revised manuscript.

**2) Referee comment:**

It is never mentioned in the manuscript the problem of multi layered clouds for cloud retrieval (especially for cloud top height). I think authors should mention this at least in the minimum residual method weakness.

**Author's response:**

This is a very valid point, and does deserve mention. The minimum residual method assumes a single layer of cloud, however, some 20 – 40 % of cloud scenes globally have multiple layers of cloud, and this can result in retrieved cloud top heights in multi-layer scenes being intermediate between the two layers if the higher cloud is optically thin. On the other hand, we believe that for the present research, in most cases only one cloud layer is present for each of the scenes. We believe this to be reasonable because of the mechanisms for cloud formation discussed in Cuesta

et al. (2009), i.e. humidities being too low in the lower boundary layer for a low cloud layer, so that boundary layer clouds can only form near the capping inversion at about 6,000 m. The lidar curtains obtained on the aircraft also do not show evidence of distinct separate cloud layers at more than one level. Finally, cases with clouds above the aircraft (flying at ~ 8,000 m) have been screened out as described in section 2.3.

**Author's changes in manuscript:**

We add the following in Section 2.1 (Page 5 Line 26-32 in the revised manuscript): "Finally, we note that in general the cloud-top height product will sample multi-layered cloud for a significant portion (~20-40 %) of the SEVIRI full-disk. This can sometimes have the effect of cloud-top heights in multi-layer scenes appearing at an intermediate level for pixels retrieved with the minimum residual scheme, if the higher layer is optically thin. However, for the present dataset we are confident that the assumption of a single cloud layer is reasonable because: (1) the boundary layer is very dry as discussed in section 3.3 so that the formation of a lower cloud is very unlikely (Cuesta et al., 2009); (2) the inspection of the lidar curtains (not shown here) does not show any evidence of lower cloud layers, and (3) cases with clouds higher than the aircraft are filtered out, as discussed in section 2.3 below."

**3) Referee comment:**

As multi-layered cloud, nothing is provided about surface emissivity. What model did you used in the simulations? what are the error in the CTH retrieval? Surface temperature error is clearly an important source of error but surface emissivity is also important.

**Author's response:**

Regarding surface emissivity in RTTOV: For land surfaces the University of Wisconsin "UWiremis" IR emissivity atlas is used (Borbas and Ruston, 2010). This provides monthly climatological land surface emissivity values at wavelengths in the range 3.7 m – 14.3 m at a resolution of 0:1  0:1 degrees Lat/Lon, derived from MODIS observations. In the Met Office cloud products suite, the atlas emissivities are averaged over each model grid box for input to the RTTOV simulations. Errors in assumed emissivity will naturally propagate through to the CTH retrievals, and we acknowledge that this may contribute to the errors in an unknown way. We add an acknowledgment of this into Sect. 4.1.

Ref: Borbas, E. E. and B. C. Ruston, 2010. The RTTOV UWiremis IR land surface emissivity module. NWP SAF report. http://nwpsaf.eu/vs_reports/nwpsaf-mo-vs-042.pdf

**Author's changes in manuscript:**

We add the following at Page 4 Line 15-17 of the revised manuscript:  "Land-based surface emissivity values are incorporated into this model using the 'UWiremis' climatological IR emissivity atlas (Borbas and Ruston, 2010), averaged over each model grid box."

We add the the following at Page 15 Line 15-16 of the revised manuscript: "Any error in the assumed surface emissivity in RTTOV would also have a similar repercussion."

We have also added the above reference to the revised manuscript at Page 18 Line 16-17.

**4) Referee comment:**

The Figure 3 is very difficult to read. I suggest authors to find an other way to present the result.

**Author's response:**

We agree with this comment and we thank the reviewer for pointing this out. We attach to this response a revised version of Fig. 3.

**Author's changes in manuscript:**

The revised Fig. 3 is included as Fig. 1 of the attachment.

**5) Referee comment:**

The aircraft cloud retrieval is based on different thresholds (i.e., 3K for the radiometer, 7 W.m-2.s-1 for the BBR). What is the sensitivity of the retrievals to those thresholds? A discussion on that should be added.

**Author's response:**

We have evaluated this sensitivity by changing the 3 K threshold to either 2 K or 4 K for the Heimann test, and this affects the Heimann cloud flag for < 5% of the pixels in the Fennec dataset. A similar test was run for the BBR threshold, and we find that changing the threshold by 1 $Wm^{-2}s^{-1}$ results in a change of ~3% of points flagged as cloudy in the filter.

**Author's changes in manuscript:**

We add the following at Page 7 Line 14-15 of the revised manuscript: "Sensitivity testing on this threshold shows that a change of ±1 K affects the cloud flag for < 5 % of the pixels in the Fennec dataset."

We add the following at Page 8 Line 4-5 of the revised manuscript: "A sensitivity test reveals that a change of this threshold by ±1 $Wm^{-2}s^{-1}$ alters the assignment of cloudy datapoints by ~3 %."

**2.2 Specific comments**

**Referee comment:**

Page 3 Line 30: What is the RTTOV version?

**Author's response:**

The RTTOV version is v11.

**Author's changes in manuscript:**

We add the RTTOV version number to the revised manuscript at Page 4 Line 15.

**Referee comment:**

Page 3 Line 35: the reference to Eyre and Menzel is missing in the references list.

**Author's response:**

This missing reference has been added.

**Author's changes in manuscript:**

Reference added to Page 18 Line 35 in the revised manuscript

**Referee comment:**

Page 3 Line 41: It should be explain what "error-weighted" means?

**Author's response:**

"Error-weighted" is explained by the use of the variance, σ, in Eq. 1. Error-weighting means that each SEVIRI channel is given a different weight depending on the assumed accuracy of the observation. This is dealt with in the equation by dividing by the variance for each channel.

**Author's changes in manuscript:**

We add the following at Page 4 Line 21-23 in the revised manuscript: "The meaning of 'error-weighting' in this context is that each SEVIRI channel is given a different weight depending on the assumed accuracy of the observation, represented by dividing by $\sigma^2_j$ for each channel in Eq. 1."

**Referee comment:**

Page 3 Line 59: I am not an English native speaker but it sounds to me that there one “by” in excess.

**Author’s response:**

The extra “by” has been removed.

**Author’s changes in manuscript:**

Revised manuscript: Page 5 Line 7

**Referee comment:**

Page 4 Line 33: what is the spectral resolution and the absolute calibration error of the Heimann radiometer?

**Author’s response:**

The Heimann is actually broadband (8-14 m), and does not have a “spectral resolution”, but we can see why this was misunderstood. When we say that the dataset is “high-resolution” on Page 5 Line 29 of the original manuscript, we actually mean “high temporal resolution”, not “high spectral resolution”. We have attempted to clarify this in the edit shown below. As for the calibration, the Heimann is calibrated in the laboratory using known targets. The calibration is considered stable.

**Author’s changes in manuscript:**

Page 6 Line 19-20 of the revised manuscript now reads: “...the Heimann radiometer measures **broadband** upwelling radiation at a temporal frequency of 1 Hz, providing a high **temporal** resolution dataset...”

We add the following at Page 6 Line 21-22 in the revised manuscript: “This instrument is calibrated in the laboratory using known targets.”

**Referee comment:**

Page 4 Line 55: what is the accuracy of the CTH?

**Author’s response:**

By inspection of the lidar curtain plots, we estimate the uncertainty of the lidar CTH to be approximately ±150 m, although this has not been independently validated using an alternative measurement; on such a short vertical scale the exact definition of CTH is in any case ambiguous and we refer here to the region with a large scattering coefficient near the cloud top.

**Author’s changes in manuscript:**

Page 6 Line 30-31 in the revised manuscript now reads: “The cloud-top range $R_c$ is then converted to CTH, which we estimate to be accurate to within ±150 m.”

**Referee comment:**

Page 5 Line 45: It is not clear to me how did you use the MODIS albedo data? The part need more description.

**Author’s response:**

MODIS wasn’t directly used in this study; It is mentioned here as the source data from which the surface albedo map was created. This albedo map is compared to terrain and cloud distribution (using the SEVIRI cloud mask) in Fig. 8 (Fig. 9 in the revised manuscript). The albedo map is Fig. 8b (Fig. 9b of the revised manuscript), and is described in Sect. 3.4. We have re-worded the end of Sect. 2.4 in an attempt to be more clear.

**Author’s changes in manuscript**:

Page 8 Line 13-15 in the revised manuscript now reads: “Topography was provided using data from the GLOBE digital elevation model (Payne et al., 1999). A map of surface albedo, created by a compilation of MODIS satellite data (Gao et al., 2005), was also employed.”

**Referee comment:**

Page 5 Line 50: It has been shown by EUMETSAT that MSG Level 1.5 data has a constant geo-referencing offset towards the North and the West direction of 1.5 km. How did you take into account this? Some words about that should be included.

**Author's response:**

We are aware of a constant geo-referencing offset of 1.5 km to the North and West in the SEVIRI level 1.5 data which we have taken into account when evaluating the latitudes and longitudes of each SEVIRI pixel.

**Author's changes in manuscript:**

We add the following at Page 3 Line 12-14 in the revised manuscript: "A constant geo-referencing offset of 1.5 km to the North and West in SEVIRI level 1.5 data has been identified by EUMETSAT, and this has been corrected for in Lat/Lon grids used in this study."

**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."