AMT-2022-12: Response to reviewers

03 May 2022

The co-authors would like to thank all reviewers for their feedback and thoughtful suggestions. We have responded to each comment below. All line numbers refer to lines in the revised document unless otherwise stated.

In addition to edits made in response to reviewer comments, we have made the following additional minor corrections which have no further implications on the results:

1) We have corrected a typo on line 201, the number of verified clear sky hours between June and September 2019 is 179 not 236.
2) We have corrected an error in Fig. 4 panel (d): The original plot showed the temperature standard deviation ratio on the x-axis rather than the water vapor standard deviation ratio.

Original reviewer comments are included in *italics* below. Co-author responses are in simple text, and quotations from the revised manuscript are enclosed in square brackets ["..."].

Response to RC2:

General comments:

I found the paper interesting and well written, and I recommend it for publication. The figures are of good quality and the presentation is clear. If I may put forward a general comment for a minor modification, in my opinion the discussion part would benefit from a more balanced approach where, instead of trying to prove that the AERI is "better" than the MWR to detect radiation fog (which was not so clear to me at the end of the discussion), the advantages of using both instruments to improve fog forecast under a broad range of conditions are discussed.

This is a point made be multiple reviewers and we have tried to re-word the entire manuscript to address this. Notable additions include the following:

To the discussion (lines 449 to 469):

["This study focuses on cases of thin radiative fog (LWP < 40 g m-2), which is the most common type of fog at Summit, and draws attention to the benefits of the AERI, which is particularly sensitive to the small changes in LWP and strong shallow temperature inversions that are characteristic of these events. For other types of fog, onset might not be initiated by a small increase in LWP; for example in stratus lowering events, the reduction in cloud base height from the ceilometer might be a better indicator of fog onset. At other locations (in the mid-latitudes for example) thicker fogs with LWP > 50 g m-2 are more common and can be 100's of meters deep (Toledo et al., 2021). Although the AERI might still be a useful instrument for the early detection of such events, once the fog becomes optically thick in the infrared, the AERI can no longer provide information about the thermodynamic profile above the fog or the trend in LWP, both of which are useful parameters for understanding the development of deep well-mixed fog (Toledo et al.,2021). In such cases, thermodynamic profile and LWP retrievals from the MWR are valuable. The TROPoe algorithm can combine both AERI and MWR measurements in the same retrieval. Below cloud thermodynamic profiles from the combined MWR+AERI are essentially the same as retrievals based on AERI measurements alone (Turner and Lohnert, 2021) but the uncertainty in the LWP retrieval when both instruments are combined is $< 20\%$ across the entire range in LWP from 1 to over 500 g m-2 (Turner 2007b).

Although this study focuses on the passive remote sensing instruments that are essential for fog detection (since the active remote-sensing instruments have a blind spot immediately above the surface). Complementary information from active remote-sensing instruments are also necessary for accurate results. We demonstrate in section 3.1 that accurate cloud base height detection (from the ceilometer) is an important input for the AERIoe retrievals, and the radar is also required to filter out precipitation events than can invalidate retrievals from both the MWR and the AERI. Overall, this study highlights the importance of instrument synergy to provide optimal thermodynamic profile and LWP retrievals, supporting the findings of previous studies (Turner et al., 2007a; Löhnert et al., 2009; Turner and Lohnert, 2021; Smith et al., 2021; Djalalova et al.,2021), and expanding on this conclusion to include the specific conditions pertaining to the development of radiation fog."]

And to the conclusion (lines 517 to 521):

["This highlights the importance of a multi-instrument approach to improve fog forecasting under all sky conditions: ceilometer cloud base heights are necessary to generate accurate thermodynamic profile retrievals from the AERI, MWRs are needed to retrieve LWP and thermodynamic profiles above optically thick fog / clouds, and radar data is required to determine the presence of precipitation, which can invalidate retrievals from both passive instruments."]

To explain better this point, I'll mention here the 3 criteria used in the paper: Accurate temperature and humidity retrieval, characterization of shallow surface inversions, detection of small changes in LWP.

The temperature and humidity retrievals (section 3.2), at least in the dataset analyzed, appear reasonable from both instruments. I agree that the bias in the MWR channel is an issue that needs to be addressed, even in assimilation, but it can be addressed. The problem of detecting surface inversions (0-10 m) from the MWR (section 3.3) is easily overcome with the help of surface temperature measurements. Obviously, if using only brightness temperatures, the MWR won't be able to resolve the two heights because measurements at 0 and 10 m are highly correlated (that's why you get a constant difference in Fig. 6a). However, that is the reason why the instrument is equipped with surface sensors.

To emphasize the importance of including surface temperature measurements in the MWR retrievals and discuss the impact this has on the ability of the MWR retrieval to resolve surface temperature inversions, we have replaced Fig. 5 with Fig. B1 and integrated the discussion from the appendix to the main text.

See lines 225 to 233:

[“Due to the limited vertical resolution of the MWR, operational retrievals of thermodynamic profiles from MWRs are typically also constrained by an in-situ measurement of surface temperature, usually from a sensor that is integrated with the MWR (e.g. Cimini et al., 2015). For this study we run TROPoe in three physically consistent configurations; once using only the PAERI radiances as the observation vector (as in Turner et al., 2014, henceforth named AERIoe), once using only the microwave brightness temperature observations from the HATPRO MWR (as in Lohnert et al., 2009) to provide a direct comparison of the relative sensitivity of the two instruments (henceforth named MWRoe), and the final configuration is the same as the MWRoe but is additionally constrained by the in-situ surface temperature and water vapor observations from the HMP155 as it would be in an operational setting (henceforth named MWRoe-sfc).”]

It therefore appears that the only real advantage of the IR measurements is the higher sensitivity to small changes in LWP (section 3.4). Even here however, this advantage is true in very controlled conditions such as those carefully selected for this specific comparison, i.e. when the sky is clear, no ice, LWP < 40 g/m^2, and the cloud (fog) base is accurately known (as shown is section 3.1). It is not entirely obvious to me that a correct identification of all these conditions is easily achieved in NWP models and how the mischaracterization of any of these conditions could affect the results. When everything is put together therefore it almost seems that the advantages of using IR are not that clear. I understand that this paper is an initial step and that a more holistic assessment of fog detection with both instruments is out of its scope, but perhaps some ideas on how to use the synergy of both instruments to obviate shortcomings in each single one would be useful. For example, could having both estimates of fog (MW and IR) help identify cases when one of the two is not acceptable for any reason? Or to identify false positives or missed cases?

The TROPoe algorithm can combine both AERI and MWR measurements in the same retrieval. Below cloud thermodynamic profiles from the combined MWR+AERI are essentially the same as retrievals based on AERI measurements alone (Turner and Lohnert, 2021) but the uncertainty in the LWP retrieval when both instruments are combined is < 20% across the entire range in LWP from 1 to over 500 g m-2 (Turner 2007b).

We have expanded our discussion of instrument synergy in the additions to the discussion and conclusion section listed above (lines 449 to 469 and lines 517 to 521, quoted above).