Response to Interactive Reviewer 1's comments on "Microphysics of Summer Clouds in Central West Antarctica Simulated by Polar WRF and AMPS" by Hines et al.

Response to summary.

Perhaps it is important here to emphasize our motivation. The AMPS forecasts are widely used in Antarctica and support operations – including aircraft flights – in this difficult and extreme environment (Bromwich et al. 2005; Powers et al. 2009, 2012, Wille et al. 2017). The weakness in representing clouds has been known for some time. A former member of the Polar Meteorology Group at The Ohio State University did a Master's Thesis that looked at the representation of clouds in AMPS (Pon 2015). Also, we have plenty of experience running Polar WRF in both hemispheres (e.g., Bromwich et al. 2013, 2018) and this includes looking at the representations of clouds by Polar WRF in the Arctic (Hines and Bromwich 2017). We are highly motivated to study how well AMPS is doing in representing Antarctic clouds and how such forecasts might be improved. The recent AWARE project (2015-2017) was an obvious opportunity enabling working with AMPS cloud issues.

We took care to avoid overarching statements about how one of the newer microphysics schemes was generally better than the others, since extensive testing would be required make such general statements. The observations at WAIS Divide during December 2015-January 2016 are not detailed enough to show comprehensive ice and liquid cloud microphysics. In particular there is little direct measurement of cloud ice beyond generic "cloud". More extensive measurements are available at McMurdo. That site, however, is strongly influence by the detailed topography of Ross Island, while WAIS Divide has greater regional representativeness. We prefer to start with WAIS Divide for this reason. Additional work will be done with the more detailed measurements at McMurdo, but we believe we should be familiar with the characteristics of WAIS Divide first.

The existing combination of cloud and microphysics observations at WAIS Divide, nevertheless, enable many comparisons of model to observations. Model biases in cloud water, for example, can be expected to be revealed. Our results do show more liquid simulated with some schemes, especially those that include elements of two-moment microphysics. The expected impact of liquid water on radiation is demonstrated in the simulation results.

We believe the comparison of the WSM5C microphysics schemes to the other schemes – which we refer to as more advanced schemes – is well founded. The WSM5C microphysics scheme is well-known in WRF modeling community to have difficulty simulating supercooled liquid water. More generally, representing supercooled liquid water is known to be difficult in numerical modeling studies. We have added the reference of Morrison and Pinto (2006) in this regard. Hugh Morrison's microphysics scheme, which was developed with the Arctic in mind is relatively successful in representing Arctic cloud water (Hines and Bromwich 2017 and references therein). This is known in the polar climate modeling community. So we believe the comparison of the

WSM5C scheme – a one-moment microphysics scheme which is a relatively older generation algorithm – to newer generation schemes is a reasonable thing to do.

AMPS is considering changing microphysics schemes for better cloud representation. Other schemes, however, are more computationally expensive (Jordan Powers, personal communication, 2018), so the cpu cost must be weighed versus the gain in results. Our research is relevant to this decision.

We added some scatter plots for a different method of model vs. observation analysis than shown in the original submission of the manuscript. The new figure is shown here. In Fig. 4a, the negative temperature bias in AMPS is shown to be larger when the observed temperature is above about -10ºC. Thus, AMPS is unlikely to well represent melting events. The error in longwave radiation shown in Fig. 4c is larger when the observed longwave radiation larger than about 200 W m^{-2}. That is AMPS is less accurate at times when clouds are likely to be present. In contrast, Morrison, Thompson and P3 better treat cases when the observed longwave radiation is relatively large. The AMPS error tends to be smaller with the longwave radiation is relatively small. That is, the error tends to be smaller when cloudiness is small.

We have also added the lidar simulator from the CR-SIM Cloud Resolving Model (CRM) Radar Simulator version 3.2 for better comparison between modelled hydrometers and remote sensing of the clouds at WAIS Divide. This simulator has been used with WRF results.

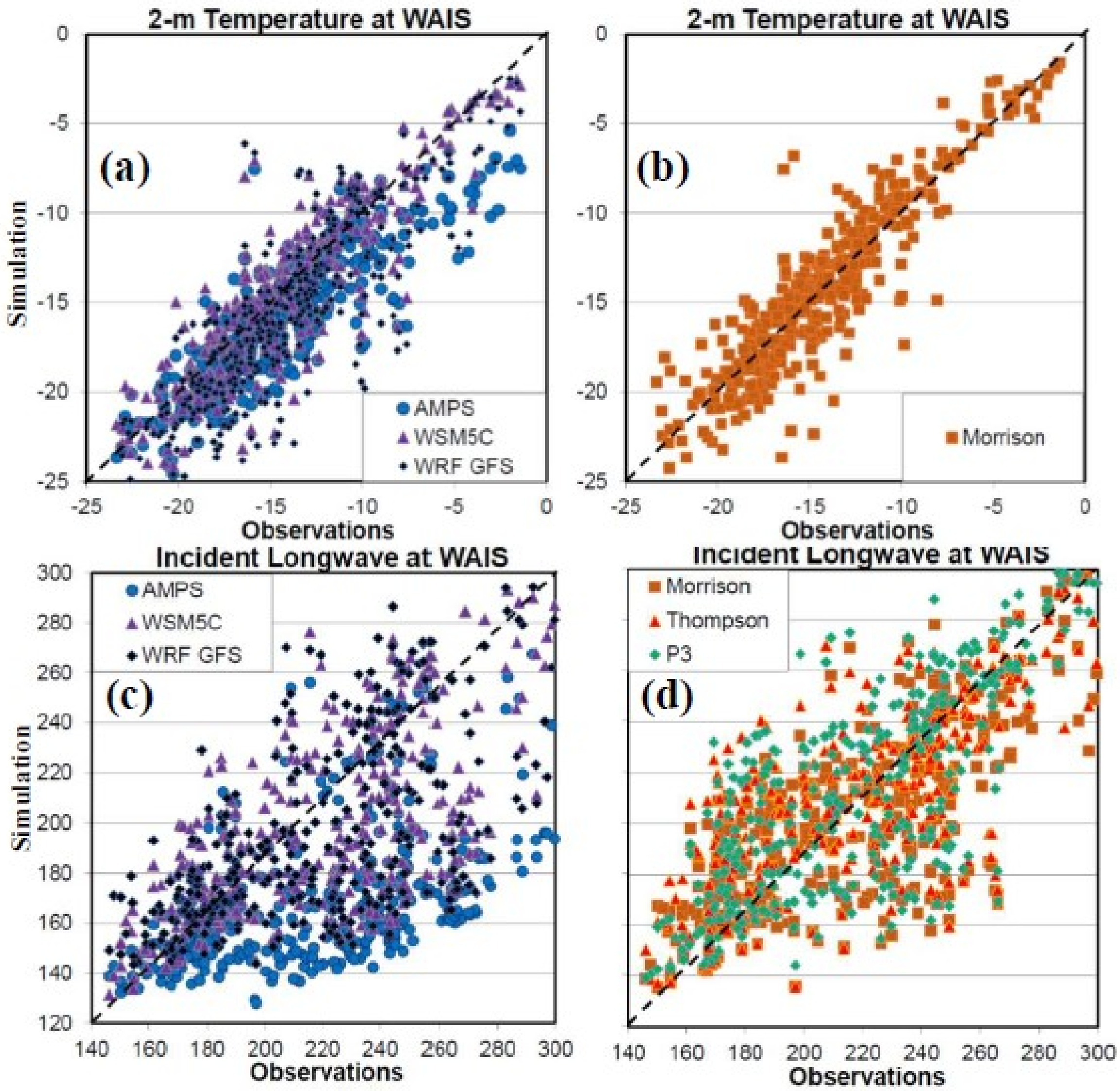

Figure 4: Scatter plots of observed values (horizontal axis) and simulated results (vertical axis) of 2 m temperature (°C) for (a) AMPS, WSM5C and WRF GFS and (b) Morrison, and downwelling longwave radiation (W m^{-2}) for (c) AMPS, WSM5C, and WRF GFS and (d) Morrison, Thompson and P3. The dashed line shows the 1 to 1 line.

Detailed Comments:

Page 2 line 19-28, P3 l5-6, P3 l10-11, P4 l3, P4 l11, P 5 l1, P5 l1-5, P 6 l4-5, P6 l22, P6 l25, P6 l28-29, P8 l26, P10 l11, P10 l13, P12 l14-15, P14 l19-20, P15 l1, P16 l11 and P17 129. The text has been modified to address these comments.

P3. l8. We have gone back and checked the Sibler et al. (2018) reference, and the modified text is consistent with the reference.

P4 l6-7. We were unable to connect this comment to any line in the first version of the manuscript.

P4 6-9. The text has been rearranged based upon this comment.

P4, l12-14. The AWARE site locations are added to Figure 1b and 2b.

P 4 l l29-31 and P14 l26. Thank you for proving the most recent community viewpoint on how the surface thermodynamic equation should be treated. First, we should provide some background on our use of the "surface energy balance" for Table 3 and Figure 7b. We had hoped to use the measurements of the conductive flux in the ice pack at WAIS Divide. Unfortunately, instrument errors resulted measurements of unacceptable quality. Previously, Nicolas et al. (2017) produced alternative estimates of the conductive flux by assuming a balance of terms, then solving for the "ground" term. This work was presented in the work published in refereed journal *Nature Communications*. The storage term could, of course, be large instantaneously, but should have a relatively small value when averaged over time compared to other terms in the thermodynamic equation. We think then this method provides a reasonable estimate of the conductive flux, given that quality direct measurements were unavailable. Again, these are previously published numbers.

P5 l9-12. To compensate for the attenuation of the lidar signal by hydrometers, we have added the lidar simulator from the CR-SIM Cloud Resolving Model (CRM) Radar Simulator version 3.2 to comparison between model-simulated hydrometers and remote sensing observations at WAIS Divide. This simulator is configured for WRF model output.

P5 l31. A reference is added for Tjernström et al. (2014).

P6 l1-2 and P6 l6-13. The text has been rearranged based upon these comments.

Page 6 l11. We added information on the levels. The lowest levels are at 10, 37, 73, and 119 m.

P6 l14. The smaller domains shown in Fig. 1a are nested domains. Thus, they are "forced" by the larger domains. We have modified the text slightly.

P6 l19. It was not possible to equalize all settings between AMPS and the Polar WRF 3.9.1 simulations. This was an important reason for the inclusion of the WSM5C simulation, since it would have the same microphysics scheme as AMPS, yet have the same settings, except for the microphysics scheme, as the Morrison, Thompson, and P3 simulations. Since we ultimately wished to compare our results to the observations at WAIS Divide, it was desirable to have a good framework for our comparison. We used the PBL scheme that we thought would give the best results. The addition of new simulation WRF GFS, discussed later, helps to bridge the gap between AMPS and WSM5C.

P6 l19-22. Large-scale data assimilation seeks to include many observations to set the analysis field. This may result in a smoothing of fields. Mesoscale data assimilation seeks to include mesoscale structures in the resulting field. So the goals of global data assimilation and mesoscale data assimilation are different. The risk/reward calculations are different. Mesoscale data assimilation tends to be more dependent on individual observations, as the goal is to represent fine features. An individual observation can influence both the global analysis field and the mesoscale data field derived in part from the global analysis field. In that sense the observation is "double dipping" but this is not an error. The key here is that data assimilation on different scales has different goals.

P6 l24-26. The AMPS source for sea ice fraction is now shown in the revised manuscript.

P8 l14. A reference is added for Cooper (1986).

P8 l18. Apparently, there is not a consensus as to the descriptions "Western Arctic" and "Eastern Arctic". We have changed the description of location of ASCOS in the revised manuscript.

P8 l30-31. The terminology "water friendly" and "ice friendly" is taken from the publication Thompson and Eidhammer (2014). We have had previous extensive discussions with Greg Thompson about this scheme. The wording has been changed in the revised manuscript.

P8 l8- P9 l6. We have added some words in section 3.2 on the differences between microphysics schemes.

P9 l14-21. The text has been rearranged based upon this comment.

P9 l21. We have checked and found no nudging is done in AMPS. There was some confusion in the preparation of the original manuscript because of a presentation by a former graduate student at Ohio State on the positive impact of "grid nudging" in WRF Antarctic forecasts that was inspired by AMPS forecasts. The manuscript has been changed to avoid confusion.

P9 l23-26. Please see the response to the summary explaining the importance of AMPS. We have added a simulation "WRF GFS" with the WSM5C microphysics and the GFS final analysis providing the initial and boundary conditions. We believe this helps to bridge the gap between the AMPS results, driven by the GFS forecast fields and the WSM5C simulation with Polar WRF 3.9.1 and driven by ERA-Interim.

P10 l5. It was not our intent to re-demonstrate in detail the West Antarctic warming discussed in the published paper Nicolas et al. (2017). The use of the word "demonstrated" in the original manuscript was unfortunate. The text has been changed.

We will take care in the submission of the final figures for quality and visibility. Unfortunately, the small size of figures in the first version limited visibility.

P10 l19-25. Yes, the difference between the simulations Morrison, Thompson and P3 is relatively small. No definitive claim can be made of superiority between these schemes. That could imply the fine detail differences between these more recent schemes has relatively small impact on the simulation results.

As to the WSM5C scheme, the addition of the new WRF GFS simulation helps. It has the same microphysics scheme as the WSM5C scheme, however it uses the GFS final analysis for initial and boundary conditions. This is not exactly the same as the GFS forecast used by AMPS (the final analysis is not available at forecast time, and AMPS is run prognostically). However, the GFS final analysis uses the same forecast system as the GFS forecasts. The simulations with the WSM5C scheme consistently produce too little cloud liquid, whether GFS or ERA-Interim is used for the initial and boundary conditions. Correspondingly, downwelling shortwave simulation is excessive and there is a deficit in downwelling longwave radiation. This is consistent with the experience of mesoscale modellers in the Arctic. The reference, Morrison and Pinto (2006), now used in the revised version, mentions that simulating supercooled liquid water is a known difficulty in the polar regions. Hugh Morrison's double-moment scheme has been known simulate supercooled water relatively well in multiple Arctic studies (several references are given in our earlier paper Hines and Bromwich 2017). In the present work, the three more recent microphysics schemes produce more liquid water, and have greater cloud forcing.

P11 1-6. The 2-m air temperature is close to the skin temperature, and the skin temperature is used for upwards longwave radiation at the surface and the calculation of conductive flux in the snowpack by the WRF Noah land surface model. So this temperature is important for the surface energy terms and the interaction therein. Therefore we choose to show the 2-m temperature in this paper. The 2-m temperature is also a widely-measured quantity, and at the height or near the height at which many other near-surface variables are measured.

Now, the surface boundary layer is of interest for the AWARE project, but our interest in this paper is the clouds and the related radiation. So we prefer not to divert attention away from the clouds and radiation by additional analysis of the boundary layer in this paper. We may look in greater detail at the boundary layer in our near-future AWARE work. This will probably involve the McMurdo observations that are more detailed than the WAIS divide observations.

The words have been changed about the description of biases in response to this comment. "Negative bias" and "positive bias" are now used in the text, and "cold bias" is less used in the revised manuscript.

P11 l19. The sentence is removed.

P11 l30-21. We change the explanation of how we determine the statistical significance.

P12 19-20 & l22-24. Perhaps it's understandable how discussion of the statistical significance of results for specific hours of the day versus that for all times could be confusing. We now mention in the text that Table 3 shows the biases for all times (rather than the bias for a specific time of day). It is easier to meet the criteria for statistical significance for all times, rather than for a specific time of day when the sample size is reduced.

P13 l29- P14 l14. We rearranged the discussion of the earlier satellite data studies in response to this comment.

P17 l3-4. We added the lidar simulator from the CR-SIM Cloud Resolving Model (CRM) Radar Simulator version 3.2 to comparison between model-simulated hydrometers and remote sensing observations at WAIS Divide. This simulator is configured for WRF model output.

P17 l21-22. We removed the sentence.

P17 l24-33. We removed some of the previous text. We added the sentence, "Similar to the profile displayed in Fig. 13a, the observations show a more shallow peak in the lower troposphere than in the simulations. (Fig. 14a)." The figure numbers in this reply are based upon the original submission of the manuscript.