Norrköping, 2019-06-12

**Response to Reviewer #1**

We thank the reviewer for providing constructive remarks. We have tried to incorporate your suggestions in the revised manuscript. Please find below a point by point response to them.

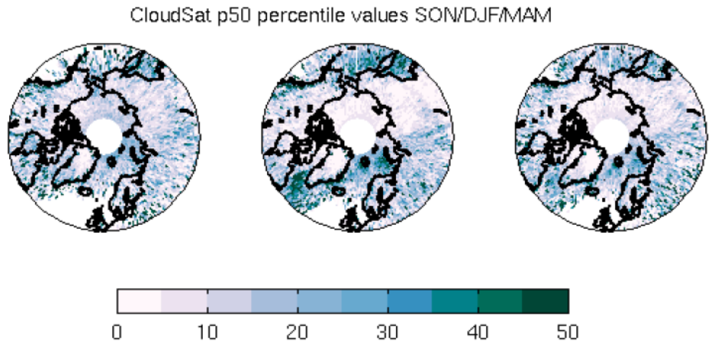
1(a). Inadequate methodological description. I found that the methods used were not adequately described. For instance, how was the regridding of CloudSat measurements to 1 x 3 degrees performed? Were all instantaneous profiles within a grid box simply averaged together, or something else? On P3 L25 it states that model data were regridded to 1x1 degree, so how were comparisons made between model and CloudSat if the grids are different? Further, P4 L18 states that 1x3-degrees provides "sufficient" sample size, but how was "sufficient" determined, and what constitutes "robust"? Was the comparison of mm snow water equivalent (SWE), or snow depth? If the former, then the conversion method and treatment of snow density should be included.

We did in fact started the evaluations on the 1x1 deg grid for CloudSat before settling for the 1x3 deg grid. The latter was chosen in order to avoid having patchiness in the data that arises due to poor sampling along the latitudes as the spacing between the longitudes in the Arctic is very low. A figure below shows CloudSat p50 values over 1x1 deg and 1x3 deg grids respectively. As can be seen the spatial consistency in the snowfall estimates is better in the 1x3 deg grid.

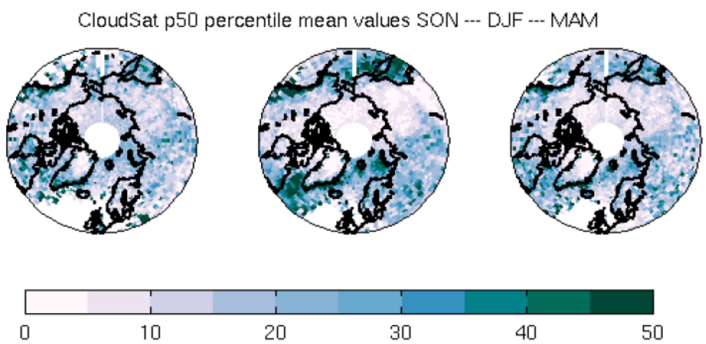
Level-3 gridded snowfall accumulation (mm/month) estimates from CloudSat are used in this study. However, the models provide the snowfall flux (kg/m2/s). This is converted to snowfall accumulation so as to carry out a fair comparison with observed data. These points are now clarified in the revised manuscript.

With regard to the sample size, we kindly refer the reviewer to our response given to Reviewer #2 on the similar topic.

**(a) Original**




**(b) Regridding the data to 1 deg latitude x 3 deg longitude**




(b) Another concern is the treatment of missing data: on P12 L5 the 2011 battery failure is discussed; however, we are aware of two other battery failures [September 2009 - December 2009] and [January 2011], but these periods are seemingly unaffected in Fig.6. Was any gap-filling/interpolation required during these times?

We agree that there were two other brief anomalies due to battery failures in December 2009 and January 2011, but neither lasted the whole month so we still have data for those months to compute the averages. This is now clarified in the revised manuscript.

2. Set of models used for comparison. When the authors mentioned an evaluation of low, versus high, resolution models, I expected to see at least a couple of "typical" CMIP5-class GCMs/ESMs included, to provide a reference for how/if these high resolution simulations represent an improvement for the simulation of snow. The low/high res sample evaluated here is somewhat artificial, since even the "low res" models are among the highest resolution simulations one would find in CMIP5. I would strongly recommend that the authors include one, or more, CMIP5-era simulations, to provide some more context for the HighResMIP results.

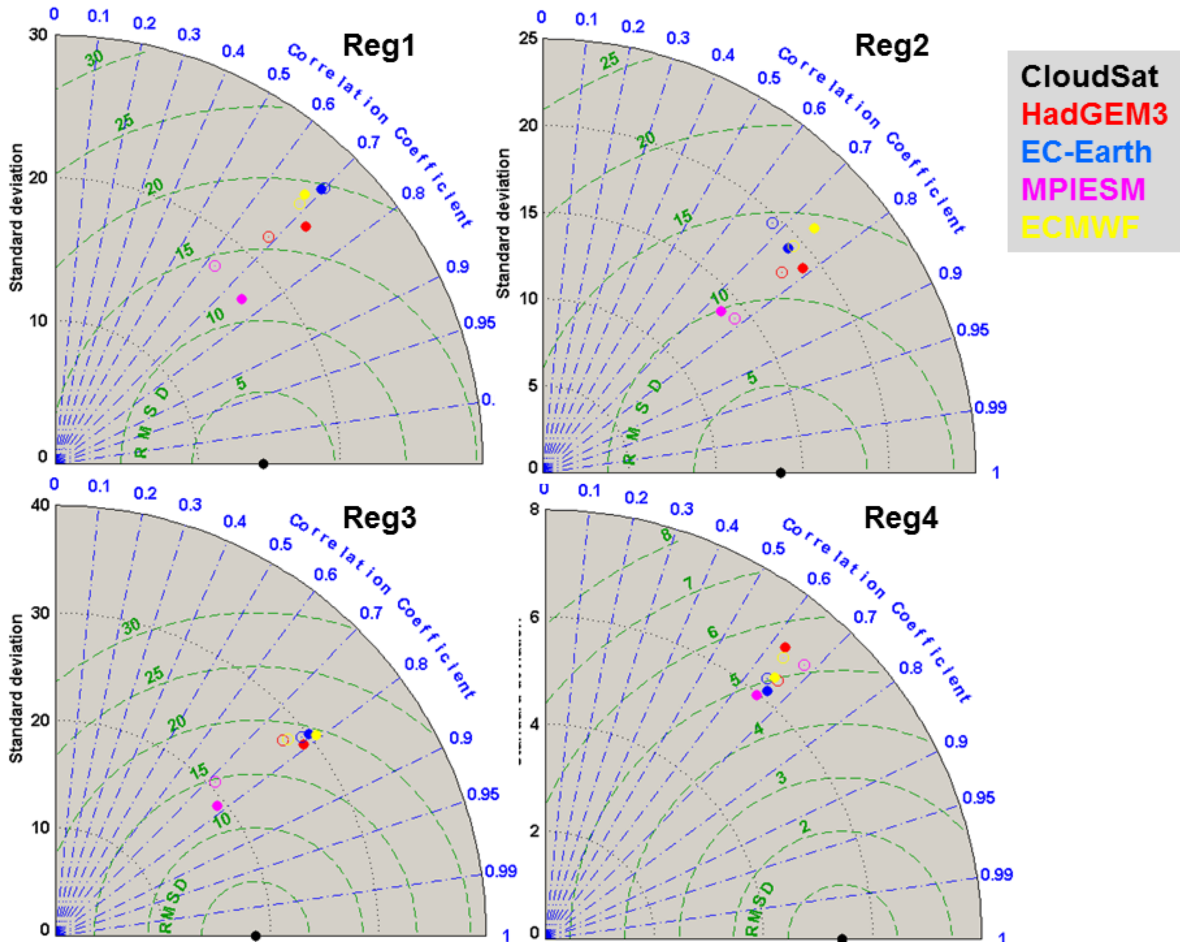
We understand that the ‘low’ resolution models here can be classified as ‘high’ resolution simulations in the CMIP5 context. The main aim of this project was to understand the effect of resolution, keeping the model and nudging the same, in simulating the snowfall estimates. A direct and fair comparison cannot be made with the CMIP5 model simulations in this context for the following reasons:

1. The models used in the present study have been improved in terms of physics and parameterization schemes compared to their counterpart versions used in CMIP5 simulations. Hence, it would be difficult to say if an improvement, if seen is indeed due to a change in resolution or change(s) in other processes.
2. Also, the time period of the simulation used here is different than in the CMIP5 simulations.

However, if the reviewer still sees a value in including the results from a typical CMIP5 simulation, we would be happy to include those in the further revision.

3. Figure quality. I found the maps very difficult to read, because of the small size and choice of colour scale. In general, it is very challenging to ask readers to evaluate by eye how well a set of model simulations compares to a reference map. I strongly recommend condensing these maps into standard model v obs diagnostics, for instance using Taylor Diagrams. This would provide a much more rigorous evaluation of each model than can be provided by eye, and would make it easier for the authors to add more models to the comparison (see point 2 above). In addition, the CloudSat map panels have a data-wrapping issue at the date line.

Following the reviewer suggestion, we have now added and described Taylor diagrams in the revised version, as shown below. The standard deviations, root mean squared differences and Pearson's correlation coefficients are plotted using the entire time series for the three regions shown in Fig. 5 in the manuscript and as well as for the Arctic region (70N-83N, 180W-180E, denoted as Reg4). The colour-filled circles show results for the high resolution versions and the empty circles their standard resolution counterparts. The correlations typically range between 0.6-0.8, Over all the regions and in the models, the snowfall variability is higher compared to the CloudSat observations. The regional differences among models are strong. For example, over Reg1, the standard deviations have large spread among models, while over Reg3 the models tend to cluster together (except MPIESM versions which are closest to the observations) and have similar variability. The comparison of standard resolution model versions with their high resolution counterparts against CloudSat observations does not show a clear improvement in the high resolution versions or a particular tendency that holds across all models.




The CloudSat maps are revised to remove the data wrapping at the date line. Thanks for pointing out this plotting artifact. Also the other maps are replotted to improve image quality.

4. Uncertainties. The devil is in the details with this type of comparison, and I would have appreciated a much more thorough discussion of the various sources of uncertainty that are present in these results. A much-needed addition to Fig.6 could be a credible interval for each estimate, considering sampling, instrumental and model uncertainty. Due to sampling, I would expect to see much larger uncertainties on the CloudSat snow estimates coming from more southerly latitudes (e.g. Reg#3).

We have revised and added the following information on the various uncertainties in the CloudSat retrievals and analysis.

Uncertainties in the CloudSat snowfall estimates derive from numerous sources including the need to assume an exponential particle size distribution with temperature-dependent number concentration, the lack of explicit information about particle density, potential influences of attenuation from supercooled liquid water, and the blind zone induced by ground clutter contamination in the four lowest CPR range bins that extend to 1 km above the surface (Hiley et al, 2009; Kulie and Bennartz, 2009). The impacts of these uncertainties have been assessed through numerous prior studies that compare CloudSat snowfall estimates to ground-based radar, in situ accumulation measurements, and seasonal and continental-scale accumulation estimates from reanalyses. While each source of snowfall information used in these studies has its own strengths and weaknesses precluding absolute error estimates from being derived, these studies generally suggest that the CloudSat snowfall product performs well over mid- and high-latitude regions. Comparisons against ground-based radar networks in the United States and Sweden, for example, suggest that CloudSat reproduces snowfall frequency and accumulation with to within 25% of ground-based radar over the range of scenes where the latter provide (Smalley et al., 2014; Norin et al., 2015, 2017). Palerme et al. (2014, 2017) further demonstrate that on continental scales, CloudSat reproduces seasonal snowfall accumulations in the ECMWF Interim reanalyses with high fidelity. While ERA-interim regional snowfall accumulations suffer from model uncertainties, the integrated accumulation over Antarctica ultimately represents the net water vapor convergence over the ice sheet. Since the reanalyses routinely assimilate water vapor from satellite observations, this integrated accumulation is well-constrained by independent satellite observations and provides a strong constraint on the net snowfall over the ice sheet. This result is further supported by Boening et al. (2012) who show remarkable consistency between estimates of recent Antarctic snowfall variability derived from reanalyses and CloudSat and completely independent ice sheet mass estimates from the Gravity Recovery and Climate Explorer (GRACE) satellite.

Never-the-less, a number of recent studies have pointed out the inherent limitations in the CloudSat observations that must be acknowledged when considering the results that follow. For example, due to contamination from ground clutter, CloudSat snowfall estimates must be extrapolated from 1 km above the surface (Smalley et al., 2014). This has implications for the snowfall estimates in those regions in the Arctic where low level supercooled liquid clouds or diamond dust that precipitate very light snow are observed (Lemonnier et al, 2019). The snowfall from these systems could be either underestimated or missed entirely by CloudSat (Bennartz et al, 2019) although a recent study by Maahn et al. (2014) showed that a fraction of this under-estimate may be offset by snow virga that CloudSat also fails to represent below 1 km. It is beyond the scope of the current study to add to the existing body of literature concerning the evaluation of CloudSat snowfall estimates but additional discussion of the strengths and limitations of the dataset can be found in Panegrossi et al. (2017) and Milani et al. (2018).

Another important limitation associated with the CloudSat snowfall observations is the limited spatial sampling provided by the nadir sampling CPR. This is somewhat mitigated at high latitudes where sampling is greatly increased over lower latitudes, in particular if data are regridded to coarser resolution. Here, CloudSat data are accumulated over a 3 degrees longitude and 1 degree latitude grid and averaged over ten seasons to provide a sufficient number of samples to compute robust statistics.

References:


1. Boening, C., Lebsock, M., Landerer, F., and Stephens, G.: Snowfall driven mass change on the East Antarctic Ice Sheet, Geophys. Res. Lett., 39, L21501, https://doi.org/10.1029/2012GL053316, 2012.
2. Florentin Lemonnier, Jean-Baptiste Madeleine, Chantal Claud, Christophe Genthon, Claudio Durán-Alarcón,Cyril Palerme, Alexis Berne, Niels Souverijns, Nicole van Lipzig, Irina V. Gorodetskaya, Tristan L'Ecuyer, and Norman Wood, The Cryosphere, 13, 943–954, 2019 https://doi.org/10.5194/tc-13-943-2019
3. Maahn, M., Burgard, C., Crewell, S., Gorodetskaya, I. V., Kneifel, S., Lhermitte, S., Van Tricht, K., and van Lipzig, N. P.: How does the spaceborne radar blind zone affect derived surface snowfall statistics in polar regions?, J. Geophys. Res.-Atmos., 119, 13– 604, 2014.
4. Palerme, C., Kay, J. E., Genthon, C., L'Ecuyer, T.,Wood, N. B., and Claud, C.: How much snow falls on the Antarctic ice sheet?, The Cryosphere, 8, 1577–1587, https://doi.org/10.5194/tc-8-1577-2014, 2014.
5. Kulie, M. S. and Bennartz, R.: Utilizing spaceborne radars to retrieve dry snowfall, J. Appl. Meteorol. Clim., 48, 2564–2580, 2009.
6. Hiley, M. J., Kulie, M. S., and Bennartz, R.: Uncertainty Analysis for CloudSat Snowfall Retrievals, J. Appl. Meteor. Climatol., 50, 399–418, 2010.
7. Palerme, C., Claud, C., Dufour, A., Genthon, C., Wood, N.B., L'Ecuyer, T.S., 2017. Evaluation of Antarctic snowfall in global meteorological reanalyses. Atmos. Res. 190, 104–112. http://dx.doi.org/10.1016/j.atmosres.2017.02.015.
8. Panegrossi, G., Rysman, J.-F., Casella, D., Marra, A.C., Sanò, P., Kulie, M.S., 2017. CloudSat-based assessment of GPM microwave imager snowfall observation capabilities. Remote Sens. 9, 1263. http://dx.doi.org/10.3390/rs9121263.
9. Milani, L., Mark S. Kulie, Daniele Casella, Stefano Dietrich, Tristan S. L'Ecuyer, Giulia Panegrossia, Federico Porcù, Paolo Sanò, Norman B. Wood, 2018. CloudSat snowfall estimates over Antarctica and the Southern Ocean: An assessment of independent retrieval methodologies and multi-year snowfall analysis, Atmospheric Research 213, 121-135.
10. Bennartz, R., Fell, F., Pettersen, C., Shupe, M. D., and Schuettemeyer, D.: Spatial and temporal variability of snowfall over Greenland from CloudSat observations, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-1045, in review, 2019.