Answer to reviewers for article:

“How much snow falls in the world’s mountains? A first look at mountain snowfall estimates in A-train observations and reanalyses”

For the reviewers and the editor: Line and page numbers are indicated for each comment based on the version of the manuscript with markups.

Reviewer #1:

This paper discusses several assessments of snowfall accumulation in mountainous areas over the globe. Apart from one observational dataset (CloudSat), also several reanalyses datasets are considered. The paper is short and limited to giving an estimate of mountainous snowfall within the different datasets. Some short explanations for specific behavior are given. The methodology in the paper is rigor, but the results / conclusions are not very exciting or novel. I also question the relevance of the main conclusions of the paper.

General comments:

- Mountainous precipitation or snowfall is very difficult to capture in models or reanalysis. The precipitation scheme, orography, horizontal and vertical resolution and largescale forcing all highly influence how precipitation develops and where precipitation is falling. The range of snowfall in the reanalyses is also extremely high (from 489 till 1891 mm (table 1)) which makes it almost impossible to state anything about ‘how much snowfall is falling in the world’s mountains’ based on these datasets.
- The second research question the author’s want to answer is ‘what percentage of continental snow falls on mountainous regions?’. While reading the paper, I was wondering why this number matters? In the conclusions, the authors state that it is important for researchers who use snowfall estimates from reanalyses or observations, but I don’t see how the 4-5% can help these researchers: : : The only conclusion I can draw from this analysis is that this percentage is similar in reanalysis and CloudSat, which states that the large-scale precipitation events are well captured in reanalyses, which is expected since these processes are assimilated herein. Is there another extra value of this result?
- Generally, I think the authors maybe have to rethink the scope of the paper. In my opinion, there are two options which are both already a bit discussed in the outlook of this paper. Option 1 would be to focus on CloudSat only, making advantage of the high-resolution product it offers and discuss in more detail mountainous or orographical snowfall by zooming in on specific features or large-scale processes and see how well these are captured by CloudSat. Option 2 would be to include other models (e.g. CMIP5?) and focus on the differences between these models in mountainous regions. This would also have a much higher impact and relevance for the scientific community.

Although I agree with some parts of your critics (more discussion about the differences between the datasets, cf. new Figure 3), I also strongly disagree with some of them and would like to explain why. Based on my experience presenting these results, I think the scope of the paper should not change but could certainly be better explained.

We think this paper is useful for number of communities: for example, for people developing the different datasets and for researchers using them. Some of the users are part of the climate community and might be aware of the differences and biases in these datasets but some of them are not (e.g. impact modelers) and they are most of the time very surprised by and interested in these differences. In an impact model, these differences can make a huge difference. Even in the climate community, researchers who know these datasets are usually very surprised by our results (e.g. MERRA2 South America). I have presented this work in a couple of conferences and it clearly appeared to us that these results were useful to a lot of people working with snow datasets from the climate community or other communities. So, I agree with you, we know all these datasets, but we need more papers giving a simple comparison of them to be aware of their limitations and abilities in different regions. A better knowledge on how these measurements compare is also very important because mountain snow is critical for water runoff, which is used for example as fresh water or for agriculture but is also susceptible to create flooding.

About the novelty, I think this paper is novel in several different ways: 1) because all these reanalyses and CloudSat data had not been compared before in terms of snowfall on all these regions at the same time, 2) because they had not been compared before in terms of mountainous and non-mountainous snowfall, 3) there have never been an observational estimate of the amount of snow that falls in the major mountain ranges and its distribution throughout them. Thus, this study provides a critical benchmark of the current climate and the accuracy to which we know it against which future trends can be monitored and predictions can be assessed.

So in general, I think we could clarify the aim of the paper in the abstract and the introduction as well as improving the section discussing the results, including some of the limitations you mentioned for example (height acquisition Maahn et al. 2014), however, I really think we should keep the scope of the paper as it is one because it is very useful for a number of researchers.

Smaller comments:

- L76: This section deals about previous snowfall research using reanalyses. This section is very short compared to CloudSat. Has there been no more research on snowfall / precipitation in mountainous areas using reanalyses which could be added here?

Yes we agree, this is certainly something lacking in the article. More results from recent publications have been added to the Introduction (p. 4-5, l.90-105):

1) Wang, C., Graham, R. M., Wang, K., Gerland, S., and Granskog, M. A.: Comparison of ERA5 and ERA-Interim near-surface air temperature, snowfall and precipitation over Arctic sea ice: effects on sea ice thermodynamics and evolution, The Cryosphere, 13, 1661–1679, https://doi.org/10.5194/tc-13-1661-2019, 2019.
2) Orsolini, Y., Wegmann, M., Dutra, E., Liu, B., Balsamo, G., Yang, K., de Rosnay, P., Zhu, C., Wang, W., Senan, R., and Arduini, G.: Evaluation of snow depth and snow cover over the Tibetan Plateau in global reanalyses using in situ and satellite remote sensing observations, The Cryosphere, 13, 2221–2239, https://doi.org/10.5194/tc-13-2221-2019, 2019.
3) Cohen L. and S. Dean, 2013: Snow on the Ross Ice Shelf: comparison of reanalyses and observations from automatic weather stations. The Cryosphere, 7, 1399-1410. Doi:10.5194/tc-7-1399-2013.

4) Liu Y. and S.A. Magulis, 2019: Deriving bias and uncertainty in MERRA-2 snowfall precipitation over High Mountain Asia. Front. Earth. Sci., https://doi.org/10.3389/feart.2019.00280

- L166: The study of Maahn et al. (2014) is used to state that the height acquisition level of CloudSat has no huge influence on the ground precipitation estimate. However, this study focusses on polar regions. I think conditions might be very different for other mountainous regions. It is difficult to prove this of course for other regions without ground-based observations. Maybe add a line which refers to Grazioli et al. (2017) which gives a vertical profile of ERA-Interim precipitation compared to observations and clearly shows differences between both.
Yes thank you, the results from Grazioli et al. (2017) has been added to the text to temper the results from Maahn et al. (2014), (p.9, l.201-204).

- Are any of the CloudSat observations assimilated in any of the reanalyses used? If this is the case, it should be noted and the results should be discussed with this in mind
Yes, I agree with you, this is a very important point. CloudSat is not assimilated into any of the four reanalyses and this is now clearly mentioned in the text, (p.11, l. 245-246).

- The discussion in section 4 is in my opinion a bit too short. Some results are discussed, but only a few times the behavior is explained and put in relation with the results of previous studies. For example, on line 275, it is stated that JRA-55 underestimates the intensity of snowfall. But what is the cause of this? Is JRA-55 not holding enough moisture? Is only snowfall underestimated? Are the number of events similar, but is there just too little precipitation? These are interesting features that are currently missing in the discussion, which might be retrieved from literature or small extra analyses. The same is true for line 285
Yes, thank you, the discussion has now been slightly extended to include more references to previous work comparing the reanalysis datasets and showing some of their differences. For example, our previous work on the representation of clouds in the in different reanalyses showed some large differences between them and major biases for JRA-55 and MERRA-2, (p.18, l.396-407).

- Figure 2/3: why is mm/month shown? Would mm/year not be more appropriate?
In this type of study it seems that researchers are using different units, mm/month is one of them. We have also seen mm/day and mm/year. However, as our datasets are aggregated by month, mm/month seemed like a better choice for this study.
- Figure 4: the frequency of occurrence could maybe be replaced by events/year? This is more easy to understand by readers
Frequency of occurrence is a standard metric used in the remote sensing community, so we think we should keep this metric intact.

Reviewer #2:

This paper quantifies the fraction of total snowfall that falls in the world mountains as well as the absolute amount of snowfall in the mountains, based on the CloudSat radar and different reanalyses. It analyzes the different datasets and gives possible explanations for the differences seen in the datasets, especially as it comes to the absolute amount of snowfall. A significant effort was made to compare the different datasets on the same grid, rigorously. The paper is well written and informative, and I think it deserves to be published.

However, some points need to be analyzed in greater depth. I have one major comment and many smaller changes I would like to see in the final version of the paper. This won't require new work on the data though (I believe).

Thank you very much for the constructive and very helpful comments in your review. Most of them have been included in the text and have participated to increase the quality of the article.

Major comments:

My major comment is the following: the maps (Figure 2) are great, but not analyzed at all, and it is a shame, because they DO contain a lot of information. The authors say "the geographical distribution of mountain snowfall is similar between CloudSat and all the reanalyses", but I disagree. There are many interesting differences. I think the authors must work more on the maps, by considering for example maps of the differences between the different datasets, or by computing mean RMS errors between each reanalysis and CloudSat (even though I understand CloudSat has its own uncertainties).
For example, in the case of MERRA-2 (which clearly stands out), there is a lot of snowfall over the mountains of eastern Russia and Kamtchatka, more than for MERRA-1.
Why ? JRA55 seems to miss a lot of the patterns too. Please elaborate more on these interesting maps !

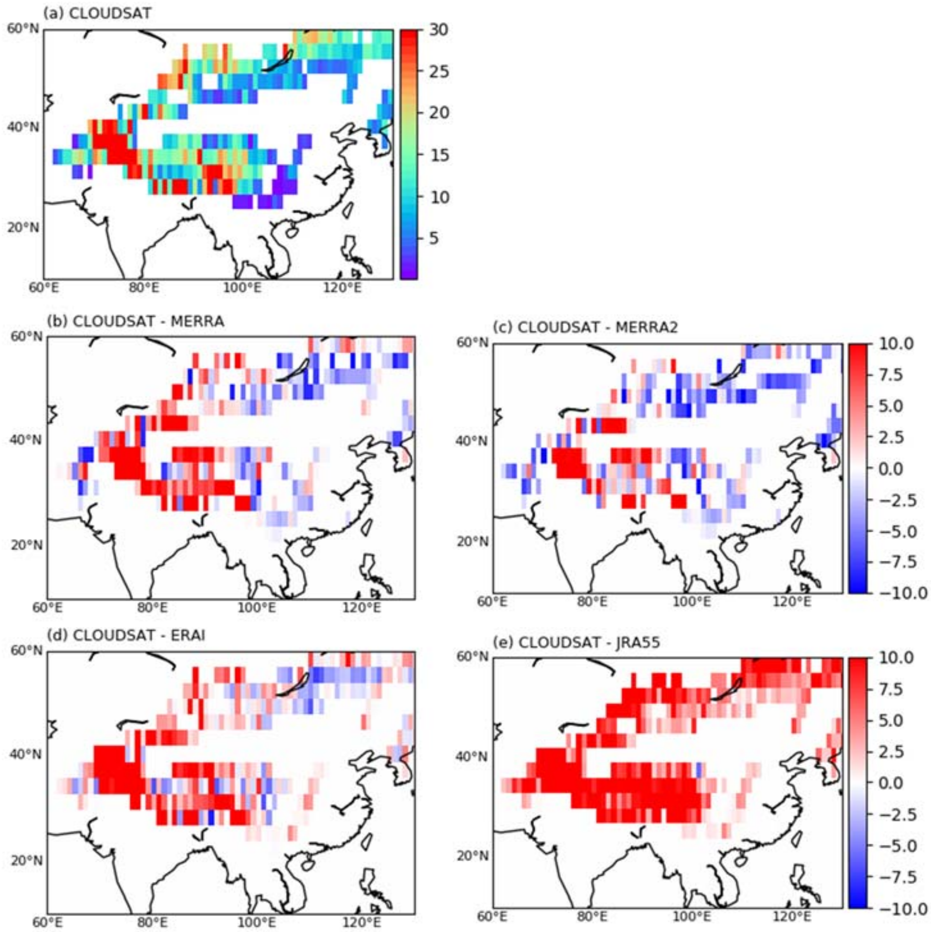

Figure 3: *Spatial maps of the global cumulative mountain snowfall (mm/month/gridbox) over the High-mountains Asia for a) CloudSat, b) CloudSat minus MERRA, c) CloudSat minus MERRA-2, d) CloudSat minus ERA-Interim and d) CloudSat minus JRA-55, over the time period 2007-2016*

Yes, this is a very good point. In general, section 3.1 has been reorganized and is longer now. Figure 2 is now analyzed in more details and a new figure (Figure 3) has been added to this section to complement the analysis. Figure 3 shows the differences between CloudSat and the other datasets over the High-mountain Asia. To have a more interesting analysis of the differences between the datasets, we decided to focus on one region, (p.13-14, l.297-313).

Minor comments:

l.34 : "the fraction of mountain snowfall" is ambiguous; the authors might want to change it to something like "the proportion of snow that falls in the mountains compared to the continent as a whole".
Yes, thank you. This has been corrected in the text where it is mentioned, (p.2, l.34-35)
l.37 : I agree with the authors point regarding the large-scale forcings, and it is an interesting conclusion of the paper; all the models predict precipitation when air masses are converging. but I disagree on the point that the differences in the snowfall amounts result from differences "at smaller scales". As said line 327 in the conclusion, it is more likely due to differences in the physical parameterizations of the models, as well as subgrid-scale parameterizations of orographical effects.
We agree with you on the point but apparently, we did not explain it correctly. This hypothesis has been reformulated in the article and is hopefully clearer and in phase with your explanation, (p.2, l.39-41; p.20, l.441-442).

l.84 : what do the authors mean by "is more realistic" ? and what does it have to do with the previous sentence ?
This sentence has been reformulated, so it follows more logically the previous one, (p.4, l.90-93).

l.93 l.97 l.117 l.120 : you might be interested in the papers of my colleague, F. Lemon-nier, on that subject :
CloudSat-inferred vertical structure of snowfall over the Antarctic continent:
F. Lemonnier, J.-B. Madeleine, C. Claud, C. Palerme, C. Genthon, T. L'Ecuyer, N. Wood JGR Atmospheres, doi:10.1029/2019JD031399, December 2019
Evaluation of CloudSat snowfall rate profiles by a comparison with in-situ micro rain radars observations in East Antarctica
F. Lemonnier, J.-B. Madeleine, C. Claud, C. Genthon, C. Durán-Alarcón, C. Palerme, A. Berne, N. Souverijns, N. van Lipzig, I. V. Gorodetskaya, T. L'Ecuyer, N. Wood The Cryosphere Discuss., doi: 10.5194/tc-2018-236, March 2019
Thank you, these references have been added to the text in the related section (p.5, l. 114).

l.154 : I believe the Snow Retrieval Status (SRS) in release 5 was improved, and this might help select the profiles the authors use, especially in mountainous regions where the ground clutter might affect the retrievals. I am not saying that the authors should use release 5 and redo everything from scratch (please don't !), but that they might want to check if release 5 gives different results or not, just in case !

You might be referring to the ground clutter contamination affecting the snowfall retrieval. One part of the snow retrieval status variable can help diagnose when ground clutter could cause the snowfall retrieval results to be in error. The snow retrieval status variable is evaluated in the same way in both R04 and R05. One of the differences between R04 and R05, however, is that the digital terrain elevation map used in R05 is improved compared to the map in R04. As a result, the retrieval does a better job of identifying the position of the lowest clutter-free bin and there are fewer retrievals contaminated with ground clutter. Globally, the long-term annual snowfall amount changes from 76.0 mm/y in R04 to 75.7 mm/y in R05, but there are locations that are more strongly impacted. The areas that are most strongly affected are Greenland, the edges of the Tibetan plateau, and some mountainous points in Antarctica. From the mountain mask figure in the paper, Greenland and Antarctica have no locations that are classified as mountainous. The Tibetan plateau is part of a much larger area of Asia that is classified as mountainous. Because of this, we believe the impacts of R05 on the results of the paper would be negligible. This has been clarified in the text, (p.9, l.189-193).

l.167 : "somewhat compensated by the competing effects of evaporation and undetected shallow snowfall"; I have not read Maahn et al. (2014), but this sounds quite speculative to me. A lot can happen between the 1200m level and the surface, especially in mountains (slope winds, complex boundary layer). I think the authors should remain cautious about this point, and not say there is some kind of compensation of errors.
This sentence has been reformulated to be more conditional (p.10, l.209).

l.168 : this should be said earlier, when describing the CloudSat dataset.
Yes, it is now said at the beginning of this section, (p.8, l.174).

l.174 : "less than about 15% at the surface"; what is "the surface" here ? the 1200m level ?
The surface is considered as 1.2 km and this is now clarified in the text, (p.10, l.218). Instantaneous CloudSat quantitative precip retrievals (units of mm/h) are derived from the first usable bin above the surface. However, ECMWF temperature profiles are used to determine the probable *surface* phase (rain versus mixed versus snow) to account for possible melting in the radar "blind zone". So surface precipitation phase refers to ground-level. But the precipitation rate at ground level is not corrected in any way - it is the precipitation rate derived from the first usable bin above the surface (~1.2 km above ground level).

l.189 : "assimilates" > uses, is based on
Thank you, this sentence has been reformulated, p.11 (l.236).

l.199 : "while CloudSat started in 2007" this should be said earlier, when describing the CloudSat dataset.
Yes, this is now said earlier in the text, in the section concerning CloudSat, (p.9, l.185).

l.206 : "based on the Kapos et al. (2000) definition" : could the authors summarize the criteria that define a mountainous terrain ?
We have tried to summarize their technic in the text adding more explanation but their technique was quite complicated so it was difficult to add a general description (p.12, l.257-260).

l.233 : "In spite of these differences, the geographical distribution of mountain snowfall is similar between CloudSat and all the reanalyses" : as mentioned above in my major comment, I disagree, we see large differences between the different datasets, and these spatial differences might be part of the reason why the absolute amount of snowfall differs between them.

Yes, this point is now clarified, and more analysis has been added to the text for Figure 2, and a Figure 3 commenting some of the differences between the datasets has been added, (p.13-14, l. 297-313).

l.258 to 261: does this mean that the CloudSat estimate, which is already high, is probably a lower bound, because it might miss some large events? if so, this should be said in the text.
CloudSat may be missing a few large events but as this analysis over many months and years, the effect of these few events should still be limited. This has now been clarified in the text, (p.16, l.349-350).

l.268: "To ease the comparison between the different datasets" I don't understand why the amounts are normalized; to me it makes things more difficult to understand, with very different y axes. Are the authors sure it is the best way to represent this?
We understand your point but without normalization the results were hard to interpret. The snowfall estimates are so different between the different datasets that we needed to include the normalization by grid points. For example, for some datasets, you can have the same amount of snow over an area, however, for one dataset it snows on much more grid points than other ones and it snows less than the other dataset. So, we needed a way to compare how the amount of snow was distributed over the area examined.

Table 1 : I don't understand the row entitled "Global" : for example, 1763/43403 means that when the four continents are put together, 1763 cubic km per year of snow falls in the mountains (i.e. the sum of the rates for the four continents, which is not always exactly the case by the way...), but I don't understand the number "43403"; does it include Greenland and Antarctica? it is much bigger than the sum of all the snowfall amounts. Please clarify.
Yes, Global includes Greenland and Antarctica. This was indicated in the text in the Section 2 but this is clearly not enough so now it is also indicated in the legend of Table 1, p.31, l.687-688).

Figure 4 : How is this frequency computed exactly and how comes this is so different between the different continents ? Please clarify.
For each grid box, we counted every instance of time (call this total events). we also created a separate variable to count up every instance of time where snow > 0 (call this snow events). At the end of iterating through every instance of time, for each grid box, we computed the ratio of snow events to total events (snow events / total events).
The difference between continents in frequency of occurrence of snowfall is due to numerous factors. These differences could be due to proximity to bodies of water, the spatial coverage of mountain ranges (x vs. y on a map; the Andes, for example, are much narrower in the 'y' direction), possibly height of mountain ranges, latitude probably plays a factor as well., prevailing winds, synoptic weather patterns, climate-scale oscillations, terrain gradient, etc. could also influence the results.

Typos:
l.57 : "the response of" can be removed
Thank you, it has been removed, (p.3, l.53).
l.288 : "for MERRA-2", remove "for"
Thank you, it is corrected, (p.17, l.376).
l.312 : "for researchers for"
Thank you, it is corrected now, (p.19., l.423)
l.317 : that THEY have difficulties ?
Thank you, it is corrected, (p.19, l.429).

Figure 4, y axis, upper left panel : occurence > occurrence
Thank you, this has been corrected in the text.

How much snow falls in the world's mountains?

A first look at mountain snowfall estimates in A-train observations and reanalyses.

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Abstract

CloudSat estimates that 1773 cubic km of snow falls, on average, each year over the world's mountains. This ~~volume of snow~~ amounts to five percent of the ~~volume of~~global snowfall accumulations ~~globally~~. This study ~~provides a synthesis of~~synthetizes mountain snowfall estimates over the four continents containing mountains (Eurasia, North America, South America and Africa), comparing snowfall estimates from a new ~~observation~~ satellite cloud radar based dataset to ~~similar snowfall estimates~~those from four widely used reanalyses: Modern-Era Retrospective analysis for Research and Applications (MERRA), MERRA-2, Japanese 55-year Reanalysis (JRA-55) and European Center for Medium-Range Weather Forecasts Re-Analysis (ERA-Interim). Globally, the fraction of snow that falls in the world's mountains is very similar between all these independent datasets (4-5%), providing confidence in this estimate. The fraction of ~~mountain snowfall for~~snow that falls in the ~~different continents~~mountains compared to the continent as a whole is also very similar between the different datasets. However, the ~~magnitude~~total of ~~snowfall estimates differs substantially~~snow that falls globally and ~~for~~over each continent – the critical factor governing freshwater availability in these regions – varies widely between datasets. The consensus in fractions and the dissimilarities in magnitude could indicate that large-scale forcings ~~are similarly represented~~may be similar in the five datasets while local orographic enhancements at smaller scales ~~there might be large discrepancies~~may not be captured. This may have significant implications for our ability to diagnose regional trends in snowfall and its impacts on snowpack in the rapidly evolving alpine environments.

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1. Introduction

~~The advent of satellite-borne instruments capable of detecting falling snow and of reanalysis products that diagnose snowfall have made possible a global examination of how snowfall is distributed and its contribution to atmospheric and surface processes.~~ Falling snow transfers moisture and latent energy between the atmosphere and the surface. Snow impacts the surface radiant energy transfer by modifying albedo and emissivity. Accumulated snow can also act as a thermal insulator that modifies sensible heat fluxes and how ~~the response of~~ surface temperature responds to changes in atmospheric conditions. Furthermore, it acts as a surface water storage reservoir (Rodell et al., 2018), providing seasonal runoff that provides fresh water supplies for both human populations and water-dependent ecosystems. Billions of people around the world depends on these resources. These water supplies are recognized as being at risk from climate change and rising global temperatures (Barnett et al., 2005; Mankin et al., 2015).

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The advent of satellite-borne instruments capable of detecting falling snow and of reanalysis products that diagnose snowfall have made possible a global examination of how snowfall is distributed and its contribution to atmospheric and surface processes. Precipitation gauge measurements of snowfall for meteorological and hydrological purposes provide valuable data but have historically suffered shortcomings related to spatial sampling and gauge performance (Kidd et al., 2017). Shortcomings in the accuracy of such measurements and methods to improve that accuracy have been the focus of a number of studies (Goodison et al., 1998; Kochendorfer et al., 2018). Beyond accuracy issues, these gauge networks are necessarily of limited spatial coverage potentially biasing climatologies over large domains. Coverage of ocean regions is not possible. Over land, gauges tend to be located near inhabited areas, leading to spare or nonexistent coverage

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in more remote locations (Groisman and Legates, 1994). These remote locations include areas such as the high latitudes and mountains, where snowfall can be the dominant form of precipitation. Even when these areas have relatively dense gauge networks such as the CONUS (Contiguous United States) mountains, gridded datasets have their limitations, most notably gauge under catchment issues and large snowfall accumulation gradients in complex terrain that are often insufficiently sampled by existing in situ networks (Henn et al., 2018).

Given these shortcomings in snowfall surface observations, studies on snowfall in remote locations commonly rely on reanalyses (e.g. Bromwich et al., 2011). Reanalyses utilize numerical weather prediction models to integrate observations of large-scale geophysical fields (e.g., temperature and water vapor). One strength of reanalysis datasets is their continuous spatial and temporal coverage. However, the veracity of reanalysis snowfall datasets depends strongly on the underlying model and the assimilated datasets, which often ~~exhibit~~exhibits systematic and varied biases (Daloz et al. 2018). In addition, their low spatial resolutions can be a limitation especially in regions of complex topography and reanalyses should therefore be used with caution. For example, Wrzesien et al. (2019) showed that reanalyses have large biases in terms of snow water equivalent (SWE) over North America ~~but their representation of snowfall is more realistic. In this current study, four reanalysis datasets will be examined: Modern-Era Retrospective analysis for Research and Applications (MERRA), MERRA-2, European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) and Japanese 55-year Reanalysis (JRA-55).~~. Wang et al. (2019) compared the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5th generation (ERA5) and ERA-Interim snowfall estimates over Arctic sea ice and showed higher snowfall in ERA5 compared to ERA-Interim resulting in a thicker

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snowpack for ERA5. Orsolini et al. (2019) focused on the Tibetan Plateau and evaluated snow depth and snow cover estimates from reanalyses (ERA-5, ERA-Interim, Japanese 55-year Reanalysis (JRA-55), and Modern-Era Retrospective analysis for Research and Applications 2 (MERRA-2)), in situ observations and satellite remote sensing observations. They showed that reanalyses can represent the snowpack of the Tibetan Plateau but tend to overestimate snow depth or snow cover. Snow accumulation measurements from automatic weather stations are compared to reanalysis datasets (ERA-Interim and National Center for Environmental Prediction -2 (NCEP-2)) over the Ross Ice Shelf in Antarctica in Cohen and Dean (2013). While both reanalysis datasets miss a number of accumulation events, ERA-Interim is able to capture more events than NCEP-2. Liu and Magulis (2019) evaluated snowfall precipitation biases over Hign Mountain Asia in MERRA-2 and ERA-5. The results show that, at high altitudes, snowfall is underestimated in both reanalyses. In this current study, four reanalysis datasets will be examined: MERRA, MERRA-2, ERA_Interim and JRA-55.

As an alternative to reanalyses, snowfall rates can now be assessed using satellite observations (with sufficient spatio-temporal coverage) provided by CloudSat's Cloud Profiling Radar (CPR). CloudSat observations, nearly continuous since 2006 (Stephens et al., 2002, 2008), have been applied to produce near-global estimates of snowfall occurrence and intensity (Liu 2008; Kulie and Bennartz, 2009; Wood and L'Ecuyer, 2018). The resulting datasets have been examined extensively from local to global scales (Liu 2008; Kulie and Bennartz, 2009; Hiley et al., 2011; Palerme et al., 2014; Smalley et al., 2015; Chen et al., 2016; Behrangi et al., 2016; Norin et al., 2015; Milani et al., 2018~~).~~; Lemonnier et al., 2019a, b). CloudSat has substantially extended the spatial extent of precipitation measurements compared to existing gauge or radar networks. In

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particular, these instruments have greatly enhanced the observations of light precipitation including snowfall over oceans, over remote high latitude regions and over inaccessible land areas (e.g., Behrangi et al., 2016; Milani et al., 2018; Smalley et al., 2015; Norin et al., 2017~~).~~; Lemonnier et al. 2019a, b).

However, satellite-based retrievals also have inherent uncertainties related, for example, to their limited temporal coverage. For instance, they might miss some heavy events such as atmospheric rivers in Western North and South America (Ralph et al., 2005; Neiman et al., 2008; Viale and Nunez, 2011). Therefore, CloudSat snowfall retrievals have been extensively assessed against a wide range of independent ground-based measurements. Hiley et al. (2011) seasonally compared CloudSat snowfall estimates with Canadian surface gauge measurements, showing better results for higher versus lower latitudes - especially lower latitude coastal sites. They speculated that the latitudinal~~ comparison~~ differences might be due to CloudSat sampling (more observations at higher latitudes), snow microphysical differences associated with warmer snow events that could affect CloudSat estimates (e.g., wetter snow, rimed snow, and/or mixed phase precipitation), or precipitation phase identification issues associated with snow events in the 0-~~4C~~4°C temperature range. CloudSat's 2C-SNOW-PROFILE (2CSP) product also displayed excellent light snowfall detection capabilities when compared against the National Multi-Sensor Mosaic QPE System (NMQ) dataset, a hydrometeorological platform~~,~~ which assimilates different observational network~~, but~~. Still, CloudSat did not produce higher snowfall rates as frequently as NMQ (Cao et al., 2014). Further comparisons between CloudSat and the National Centers for Environmental Prediction (NCEP) merged NEXRAD and rain gauge Stage IV dataset illustrated consistent CloudSat-Stage IV performance when near-surface temperatures are below freezing

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(Smalley et al., 2014). The CloudSat 2CSP product was also compared to a ground-based radar network in Sweden, showing consistent agreement in the 0.1 – 1.0 mm h^{-1} snowfall rate range (Norin et al., 2015). However, 2CSP snowfall rate counts were lower above the 1 mm h^{-1} threshold. 2CSP retrievals have also been rigorously compared to ground-based profiling radars in Antarctica, with CloudSat outperforming ERA-Interim grid-averaged results when MRR-derived retrievals are used as a reference dataset (Souverijns et al., 2018). Comparisons between CloudSat and existing reanalysis datasets are however scarce, and mostly limited to the ~~Poles~~poles (Palerme et al., 2014, 2017; Milani et al., 2018; Behrangi et al., 2016). Together, these independent analyses provide confidence that CloudSat observations may deliver realistic accumulations on seasonal scales. The CloudSat snowfall dataset has also been proven useful for isolating distinct modes of snowfall variability on global scales. For instance, over-ocean convective snow has been comprehensively studied using CloudSat products (Kulie et al., 2016; Kulie and Milani, 2018). CloudSat also exhibits enhanced snowfall observational capabilities in mountainous regions compared to ground-based radar networks, partially due to scanning radar beam blockage issues (Smalley et al., 2014).

In spite of the noted shortcomings in snowfall datasets from gauge, radar and reanalyses, mountain snowfall has not yet been thoroughly studied using multiple reanalyses and the CloudSat data set. In this study, we derive mountain snowfall from five datasets (CloudSat 2CSP, MERRA, MERRA-2, ERA-Interim and JRA-55) to answer the following questions:

1. How much snow falls on the World’s mountains?
2. What percentage of continental snow falls on mountainous regions?

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Given the challenges in retrieving snowfall from single-frequency radar observations, especially in complex terrain, the CloudSat estimates are not treated as the “reference” dataset, though we note that they are the only estimates derived directly from observations. All five sources are treated as providing valid independent estimates of the fraction of snow that falls in mountainous compared to all continental regions to document the current state of knowledge in this field. The next section presents the different datasets employed in this study, as well as methodological information such as the mountain and continental masks. Section 3 compares mountain snowfall fraction and magnitudes between the different datasets while the following section, Section 4 discusses the differences in absolute magnitude of snowfall estimates. Finally, Section 5 summarizes the results of this study and offers concluding remarks.

2. Data and Methodology

2.1 Satellite observations

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For this work, the CloudSat data are spatially gridded onto a 1^{o} x 3^{o} (lat/lon) grid. The nadir-pointing CPR onboard NASA’s CloudSat satellite is the first spaceborne W-band (94-GHz) radar. CloudSat’s high inclination orbit (98^{o}) provides a unique coverage of observed global snowfall (Kulie et al., 2016). In addition to providing near-global sampling, the CPR has a minimum detectable radar reflectivity of approximately -29 dBZ and is consequently sensitive to lighter precipitation events (Tanelli et al., 2008). The CPR has a fixed field of view pointed at near-nadir and measures over a spatial resolution of approximately 1.7 km along-track and 1.4 km cross-track (Tanelli et al., 2008). The orbit is such that CloudSat revisits particular locations every 16 days. While this observing strategy limits sampling on short time-scales, CloudSat has observed more than 120 million snowing profiles over its 10+ year mission providing a rich dataset from

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which to derive snowfall frequency and cumulative snowfall over the large domains analyzed here. CloudSat data are available from 2007.

CloudSat's 2CSP snowfall product, version R04 (Wood et al., 2013), provides estimates of instantaneous surface snowfall rates (S) for each of these pixels derived from the observed vertical profiles of radar reflectivity (Z). ~~For this work, the data are spatially gridded onto a 1°x3°~~A version R05 is now available however, the snow retrieval status variable is evaluated in the same way in the two versions of the product. The global snowfall amount is very similar in R04 and R05 so the results should only differ slighly with the new version of CloudSat. The data are spatially gridded onto a 1° x 3° (lat/lon) grid to ensure robust sampling by the narrow CloudSat ground track. This means that the satellite data are sampled onto the spatial grid desired and then averaged within each grid. The product derives instantaneous data twice per month from an optimal estimation retrieval (Rodgers, 2000~~) retrieval~~). They are then applied to individual reflectivity profiles to obtain vertical profiles of snow microphysical properties. Ground clutter affects radar bins nearest the surface, so the retrieval is applied only to the clutter-free portion of the profile, i.e., that portion of the profile that is above the extent of likely ground clutter effects, typically about 1.2 km over land. Surface snowfall rate is estimated as the rate in the lowest clutter-free radar bin. The cumulative snowfall presented here are, thus, not true surface snowfall rates. ~~Clutter also~~Grazioli et al. (2017) compared the vertical profile of precipitation from the ECMWF Integrated Forecasting System (IFS) model with satellite-borne radar measurements. They showed some noticeable differences between the different datasets in the vertical structure. Clutter limits CloudSat's ability to detect shallow snow events or capture strong variations in snow profiles near the surface (Maahn et al, 2014; Souverijns et al, 2018; Palerme et al, 2017). While this introduces

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uncertainty in the snowfall estimates presented here, the analysis of ground-based vertically-pointing radar in ~~mountainous regions~~East Antarctica and in Svalbard (Norway) by Maahn et al. (2014) show that the effects of this observing system limitations ~~are somewhat~~may be compensated by the competing effects of evaporation and undetected shallow snowfall. It should also be noted that on November 1 2011, there was a change in CloudSat's operating mode, leading to daytime-only operations, which can lead to some uncertainty in the snowfall estimates.

Snow and rain are discriminated based on the CloudSat 2C-PRECIP-COLUMN product (Haynes et al., 2013), which applies a melting layer model driven by the ECMWF analyses temperature profiles. Snow particles are assumed to melt following the model of melted mass fraction described by Haynes et al. (2009). All profiles with melted fractions less than about 15% at the surface (<1.2km) are considered snowing. Those with melted fractions greater than 90% are considered raining. Melted/frozen fractions between 15-90% are labeled "mixed" category considered to be a catch-all uncertainty for profiles that cannot be unambiguously classified as rain or snow using W-band reflectivity alone. Only snowing profiles are considered in this study.

2.2 Reanalyses

This study also considers four modern reanalyses: MERRA, MERRA-2, ERA-Interim and JRA-55. MERRA (Rienecker et al., 2011; 0.67° x 0.5° x 42 levels) uses the Goddard Earth Observing System version 5 (GEOS-5) and the data assimilation system (DAS). MERRA-2 (Gelaro et al., 2017; Bosilovich et al., 2015; 0.635° x 0.5° x 42 levels) was recently introduced to replace MERRA. ERA-Interim (Dee et al., 2011; 0.75° x 0.75° x 37 levels) is developed by the ~~European Center for Medium Range Forecasts (ECMWF).~~ECMWF. ERA-Interim replaced the previous reanalysis dataset from the ECMWF, ERA-40. The Japanese Meteorological Agency

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(JMA) has recently developed their second reanalysis dataset after JRA-25: JRA-55 (Kobayashi et al., 2015; 0.56° x 0.56° x 60 levels). Both MERRA (Rienecker et al., 2011) and MERRA-2 (Gelaro et al., 2017) use 3D variational assimilation systems, where JRA-55 (Kobayashi et al., 2015) and ERA-Interim (Dee et al., 2011) use 4D. The spatial and temporal modeling of snowfall alone is different in these reanalyses, as are some of the physical mechanisms within. The MERRA-2 reanalysis ~~assimilates~~is based on an updated version of the GEOS-5 atmospheric model. Reichle et al. (2017) showed that the snow amounts are generally better represented in MERRA-2 than MERRA. However, MERRA-2 precipitation has a known deficiency over high topography due to issues in categorizing precipitation mode as large-scale instead of convective (Gelaro et al., 2017). The results from these previous studies make the comparison between MERRA and MERRA-2 particularly interesting in this case. JRA-55 assimilates the same observations that were used for the predecessor to ERA-Interim, ERA-40, as well as archived observations from JMA. Both JRA-55 and ERA-Interim use their own forecast models.

CloudSat has not been assimilated in any of the four reanalyses so it can be considered as independent. All datasets used in this study are bilinearly interpolated from their native resolution to match the ~~1°x3~~1° x 3° (lat x lon) grid of CloudSat. The data are examined over the time period 2007-2016 with a monthly temporal resolution. The production of MERRA data ended in February 2016, as MERRA-2 is now the preferred dataset while CloudSat started in 2007.

2.3 Masks and definitions

Snowfall estimates from all sources are partitioned between the different continents using the "continental mask" shown in Figure 1a. The continental mask was first used in L'Ecuyer et al.

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(2015). Then, the mountain and non-mountain regions are separated using the “mountain mask” presented in Figure 1b. Based on the Kapos et al. (2000) definition, grid cells are classified as mountainous based on elevation, slope, and local elevation range. ~~The original mask was produced using the USGS GTOPO30 digital elevation model,~~They used the global digital elevation model GTOPO30 and ARC-INFO to identify areas above particular altitudes and generate grids containing the slope and the local elevation range. Then, they combined these variables, with adapted criteria, to define mountainous regions. The original mask was produced using with a spatial resolution of 30 arc-seconds (~1 km). Our version of the mountain mask has been aggregated to 1°~~x3~~ x 3° (lat/lon) grid to match the spatial resolution of the gridded CloudSat 2SCP. The combination of these two masks is used to subdivide the snowfall estimates over the four continents that contain mountains: North America, South America, Eurasia and Africa.

In this article, total mountain snowfall is equal to the cumulative snow falling over North America, South America, Africa and Eurasia. Greenland and Antarctica are considered as ice sheets and therefore do not qualify as continents with mountains. Global snowfall is the cumulative snow falling over all lands in the world, which includes the four continents already cited plus Greenland, Australia and Antarctica.

3. Mountain snowfall estimates in CloudSat observations and reanalyses

3.1 Global spatial distribution of mountain snowfall

Table 1 shows the snowfall estimates for mountain and non-mountain snowfall for CloudSat and the reanalyses, over each continent and globally. According to CloudSat observations, 1773 cubic km of snow falls over global mountains per year. This number is an

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average over the volume of snow falling during the time period from 2007 to 2016. From CloudSat estimates, 5% of global snowfall is within mountainous areas. It is encouraging that the fraction of snow falling in the mountains occupies a narrow range from 4% for MERRA's reanalyses and JRA-55 to 5 % for ERA-Interim and CloudSat. This good agreement between the different datasets (Table 1) allows us to state with some confidence that 5% of all continental snow falls in the mountains globally. In the reanalyses, while the fraction of snow within the mountains is similar across all datasets, the amount of snow falling over the mountains varies depending on the dataset examined (cf. Table 1). MERRA and MERRA-2 global mountain snowfall estimates are close to CloudSat with 1763 and 1891 cubic km per year, respectively, while ERA-Interim and JRA-55 show much lower amounts, with 1041 and 489 cubic km per year, respectively.

To ~~understand~~visualize where the snow is falling, Figure ~~2a~~2 presents the geographical distribution of the mountain snowfall estimates in CloudSat and the reanalyses. As expected, in all datasets a majority of the mountain snow falls in the Northern Hemisphere (Himalayas and Rockies; 95-99%), with little snowfall (<5%) in the Southern Hemisphere.

~~In the reanalyses, while the amount of snow falling over the mountains varies depending on the dataset examined, the fraction of snow within the mountains is similar across all datasets. MERRA and MERRA-2 global mountain snowfall estimates are close to CloudSat with 1763 cubic km per year and 1891 cubic km per year, respectively, while ERA-Interim and JRA-55 show much lower amounts, with 1041 cubic km per year and 489 cubic km per year, respectively.~~The geographical patterns exhibited by MERRA, MERRA-2 and CloudSat seem to resemble each other while ERA-Interim and JRA-55 tend to show different geographical distributions with generally

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lower snow rates. However, when focusing on specific regions, we can see that MERRA-2 has also major differences compared to MERRA and CloudSat: For example, over South America or Eastern Russia, MERRA-2 produces much more snow than all the other datasets. Another interesting difference appears when comparing the datasets over North America versus Asia. ERA-Interim has higher snow rates in the Rockies compared to the Himalayas while for the other datasets they are comparable. To go deeper into the comparison of the datasets, Figure 3 presents the differences in geographical distribution of mountain snowfall between CloudSat and the reanalyses over the High-mountain Asia. This figure clearly shows very large differences between CloudSat and the reanalyses, reaching +/- 10 mm/month/gridbox at some locations. In general, both ERA-Interim and JRA-55 present much lower snow accumulations compared to CloudSat. On the other hand, MERRA and MERRA-2 present lower snow accumulations on the southern part of the domain and higher on the northern part. These differences in snowfall distribution have major implications in terms of mountain runoff, millions of people in the surrounding regions depend on these resources. The systematically lower mountain snowfall estimates in ERA-Interim and in JRA-55, as well as the tendency for MERRA-2 to produce higher mountain snowfall rates over some continents will be further discussed below. ~~In spite of these differences, the geographical distribution of mountain snowfall is similar between CloudSat and all the reanalyses (Fig. 2).~~

~~It is encouraging that the fraction of snow falling in the mountains occupies a narrow range from 4% for MERRA's reanalyses and JRA-55 to 5 % for ERA-Interim and CloudSat. This good agreement between the different datasets (Table 1) allows us to state with some confidence that 5% of all continental snow falls in the mountains globally.~~

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3.2 Contribution of mountain snowfall to continental snowfall

Table 1 also shows the contribution of mountain snowfall to total snowfall for CloudSat and each reanalysis over each continent. To get a better sense of the contribution of orography to snowfall, the percentage of mountainous grid points over each continent is provided in the last column of the table. Eurasia has the highest fraction of mountainous grid boxes with 33% of its grid boxes considered as mountains. North and South America have a quarter of their grid boxes covered with mountains and only 14% of the African continent is considered mountainous. The contribution of mountain snowfall does not vary substantially between continents. For Eurasia, South America and Africa, it is around 10 % while for North America it represents around 5% of the snow falling over the continent. Over all the continents, the agreement between the reanalyses and CloudSat observations is very good with differences under 4%.

Coherently with the previous section, the magnitude of mountain snowfall estimates over the four continents vary a lot depending on the datasets examined. MERRA's datasets and CloudSat present similar magnitude in terms of mountain and continental snowfall while ERA-Interim and JRA-55 present much lower estimates than the other datasets. For example,~~ for mountain snowfall:~~ over Eurasia the values for mountain snowfall vary between 379 for JRA-55 and 1440 cubic km per year for CloudSat. Over North America, it varies from 105 cubic km per year for JRA-55 to 378 cubic km per year for MERRA-2 and for South America from 5 for JRA-55 to 86 cubic km per year for MERRA-2. Unfortunately, the high range of differences observed for mountain snowfall also applies for the magnitude of total snowfall over each continent. In all cases, JRA-55 shows the lowest magnitude estimates and MERRA-2 the highest. It is also interesting to point out that CloudSat is always part of the higher range of snowfall estimates for each continent. Due to its limited temporal coverage, it might be missing some heavy snow events such as atmospheric rivers in Western North America (Rutz and Steenburgh, 2012; Lavers and Villarini, 2015; Molotch et al. 2010). These few events contribute to a large part of the water year precipitation but as the analysis has been done over several years, this should have a limited impact on the total accumulated snow.

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4. Examination of the differences in snowfall magnitude

The previous section showed a very good agreement between all the datasets in terms of mountain snowfall fractions. However, the spatial maps presented in Figure 2 and the absolute snowfall amounts in Table 1 showed substantial differences in magnitude between the different datasets. This is further demonstrated in Figure ~~3~~4 that summarizes the snowfall estimates in mm/month/grid box over Eurasia, North America, South America and Africa and its partitioning between mountainous (blue) and non-mountainous areas (yellow) for the five datasets. To ease the comparison between the different datasets, here the snowfall amounts are normalized by the number of mountain and non-mountain grid boxes respectively. There is some consistency in the relative behavior of the various datasets between the regions. Consistently with the results in Section 3, JRA-55 always has the lowest estimates of snowfall per grid box (cf. Table 1). For example, over North America and Eurasia, JRA-55 produces 68% less snowfall than the average of the four other datasets (Fig. ~~3~~4). Even so, when looking at Figure ~~4~~5, which presents the frequency of snowfall occurrences for each continent for all datasets, the frequency of snowfall occurrences for JRA-55 is very close to the other products. This indicates that JRA-55 underestimates the intensity of many snowfall events. ERA-Interim also tends to be on the lower end of the spectrum concerning snowfall, compared to the other datasets (Fig. ~~3~~4). This can be at

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least partly attributed to its systematic lower frequency of snowfall occurrences (cf. Figure ~~4~~5). With the exception of North America, MERRA-2 generally has the highest total snowfall compared to the other datasets (Fig. ~~3~~4). Again, this is consistent with the results shown in the previous section. This overestimate is related to the way this dataset represents the frequency of snowfall events. MERRA-2 produces much more snowfall events than the other datasets (cf. Figure ~~4~~5). This bias might be similar to the bias identified for precipitation in climate models, producing too frequent and too lightly-precipitating events, referred to as “perpetual drizzle” (Stephens et al., 2010). This could be happening for ~~MERRA-2, for~~ snowfall events in MERRA-2.

The differences in snowfall among datasets is especially prominent over Africa and South America. Over Africa (Fig. ~~3d~~4d), both MERRA and MERRA-2 produce much more snow than the other datasets, with MERRA-2 producing nearly twice as much snowfall as MERRA. MERRA produces 75% more snowfall than the average of the three remaining datasets (ERA-Interim, JRA-55 and CloudSat) while ~~for~~ MERRA-2 produces 85% more. For the same reasons, over South America MERRA-2 produces 73% more snowfall than the average of the other datasets. Furthermore, it highly exceeds the mountain and non-mountain snowfall compared to the other datasets. However, as most of the snow over South America is mountainous, the excess in mountainous snowfall has a stronger impact on the differences in total accumulated snowfall. The seasonal cycle of mountain snowfall over South America (not shown) provides another interesting explanation for this specific bias. From January to December, MERRA-2 overestimates the other datasets but ~~behave similarly, however~~with a similar seasonal cycle in the first part of the year. However, during the second part ~~of the cycle~~ (after June), the behavior of MERRA-2 is very different~~. Instead~~ – instead of a decrease in mountain snowfall, snowfall accumulations remain very high and steady. This is clearly a major contributor to the high snowfall estimates of MERRA-2 over South America.

Overall, these results are coherent with previous studies comparing different reanalysis datasets (Daloz et al. 2018, Sebastian et al. 2016, Thorne and Vose 2010). They all show that reanalyses are able to represent some general patterns but also show very important differences. For example, Sebastian et al. (2016) compared atmospheric budgets for the computation of water availability in different reanalyses. They showed considerable variations in the individual components of the different budgets and suggested that part of these variations could be attributed to differences in the representation of clouds and convective schemes for precipitation. Furthermore, Daloz et al. (2018) showed significant differences in the representation of clouds in the reanalyses examined in this article, confirming the hypothesis of Sebastian et al. (2016). More specifically, they showed that JRA-55 exhibits some strong deficiencies in the representation of clouds and that MERRA-2 introduces some biases that were not evident in MERRA. These results may partly explain the deficiencies observed for these two datasets.

5. Summary and conclusion

Snowfall plays an important role in a number of atmospheric and surface processes that impact energy and hydrological cycles and can influence Earth's climate. To understand these processes, and how they will be influenced by future climate change, it is imperative to have reliable observations of present-day mountain snowfall. This study is a preliminary step towards

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an estimate of mountain snowfall from CloudSat satellite observations and four reanalyses (MERRA, MERRA-2, JRA-55 and ERA-Interim). In this work we answer the following questions:

1. How much snow falls on the World's mountains?

1773 cubic km per year of snow falls on the World's mountains in CloudSat observations, 1763 cubic km per year in MERRA, 1891 cubic km per year in MERRA-2, 1041 cubic km per year in ERA-Interim and 489 cubic km per year in JRA-55 (cf. Table 1).

2. What percentage of continental snow falls on mountainous regions?

4 to 5% of snow falls over the mountains (cf. Table 1).

One aim of this research is to provide context for researchers ~~for~~ who want to use snowfall estimates globally or on specific continents from reanalyses and/or satellite observations. The results of the discussion clearly emphasize the necessity of using several datasets, including different platforms such as reanalyses and satellite observations. Results presented here can help future analyses select validation datasets for specific continents, since we show that some datasets behave differently than the others for continental snowfall estimates. For ~~this reason, as well as the acknowledgement by~~instance, modelers ~~that~~ have difficulties accurately representing snowfall over South American mountains (Gelaro et al., 2017), and it is suspected that MERRA-2 is not the optimal dataset to use for this continent. However, this study and Wrzesien et al. (2019) showed that over North America, MERRA-2 is certainly a realistic dataset with substantial skills. Generally, there is no good or bad dataset, however some datasets may outperform others over certain continents. These different abilities in the reanalyses and satellite products can lead to issues when validating climate models, for example. ~~It is~~We therefore ~~recommended~~recommend to use an ensemble of the products just like it is recommended to use several models or simulations.

This study also suggests that estimates of the fraction of snow that falls in the mountains compared to all-continental snowfall may be more reliable than estimates of the absolute magnitude of mountain snow accumulations. A hypothesis behind this result could be that the datasets presented here have a similar representation of the large-scale forcings but differences at local/smaller scales, which could be due to ~~uncertainties in the microphysics.~~differences in the physical parameterizations of the models, subgrid-scale parameterizations of orographical effects. Indeed, even if the reanalyses are based on different models, they should simulate similar and realistic large-scale forcings. For CloudSat, its ability to capture these forcings would come from its relatively good level of temporal and spatial coverages. This could explain the consensus between the different datasets in terms of snowfall fractions. On the other hand, at smaller scales, both types of datasets experience different limitations which would explain the dissimilarities in snowfall magnitude. For example, for CloudSat, its spatial coverage could lead it to miss some heavy snow events like atmospheric rivers.

In the future, this work will expand in several directions. First, a deeper and more process-oriented analysis of the differences observed during the different datasets should be done over each continent. While this study is confined to mountain snowfall produced by CloudSat and reanalysis datasets, it also serves as a foundation for studying cloud microphysical and dynamical processes operating within snow-producing clouds forced by orography. Because different modes of snowfall have varying impacts on the environment and potentially unique remote sensing fingerprints, identifying specific types of snowfall could lead to better measurements of snowfall. In addition, this could also improve forecasting by representing different snowfall modes more realistically within numerical weather models. Also, to evaluate the ability of climate models to

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represent snowfall estimates, this same analysis could be realized for climate models such as the CMIP5 ensemble, or the forthcoming CMIP6 ensemble.

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National Oceanic and Atmospheric Administration or U.S. Government position, policy, or decision.

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Tables

Snowfall estimates	MERRA	MERRA-2	ERA-Interim	JRA-55	CloudSat	Percentage of mountain grid boxes per continent
Eurasia	1416 /11176 **11%**	1426 / 13104 **10%**	808 /8112 **9%**	379 / 3916 **9%**	1440 / 10764 **12%**	33%
North America	312 / 4500 **6%**	378/5800 **6%**	223 /3450 **6%**	105 / 1725 **6%**	303 / 7325 **4%**	24%
South America	30 / 270 **10%**	86 / 662 **12%**	10 / 100 **9%**	5 / 46 **10%**	30 / 236 **11%**	21%
Africa	0.5 / 6 **8%**	0.8 / 11 **7%**	0.1 / 1 **9%**	0.07 / 0.5 **12%**	0.2 / 2 **9%**	14%
Global	1763/ 43403 **4%**	1891/47127 **4%**	1041/21363 **5%**	489/11288 **4%**	1773/35027 **5%**	

Table 1: The table summarizes the snowfall estimates of mountain and non-mountain snowfall for MERRA, MERRA-2, ERA-Interim, JRA-55 and CloudSat for the time period 2007-2016, for Eurasia, North America, South America, Africa and globally. Global snowfall is the cumulative snow falling over all lands in the world, which includes the four continents already cited plus Greenland, Australia and Antarctica. For each area and dataset, a table cell shows: the amount of mountain (top left), non-mountain snow (top right; cubic km per year) and the contribution of mountain snow to the total amount of snow falling over a continent (bottom, %). The last column shows the percentage of grid boxes considered as mountain by the mountain mask over each continent.

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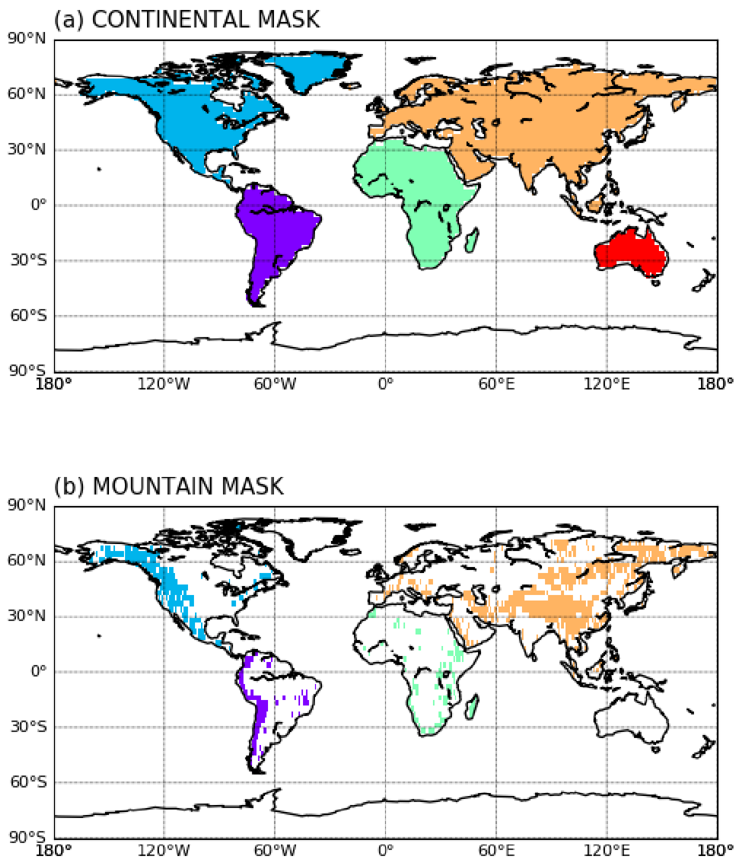

Figure 1: Spatial maps of the continental mask (a) with specific colors for each continent: blue for North America, pink for South America, orange for Eurasia, green for Africa, red for Australia and white for Antarctica; and the associated mountain mask (b) for each continent containing mountains.

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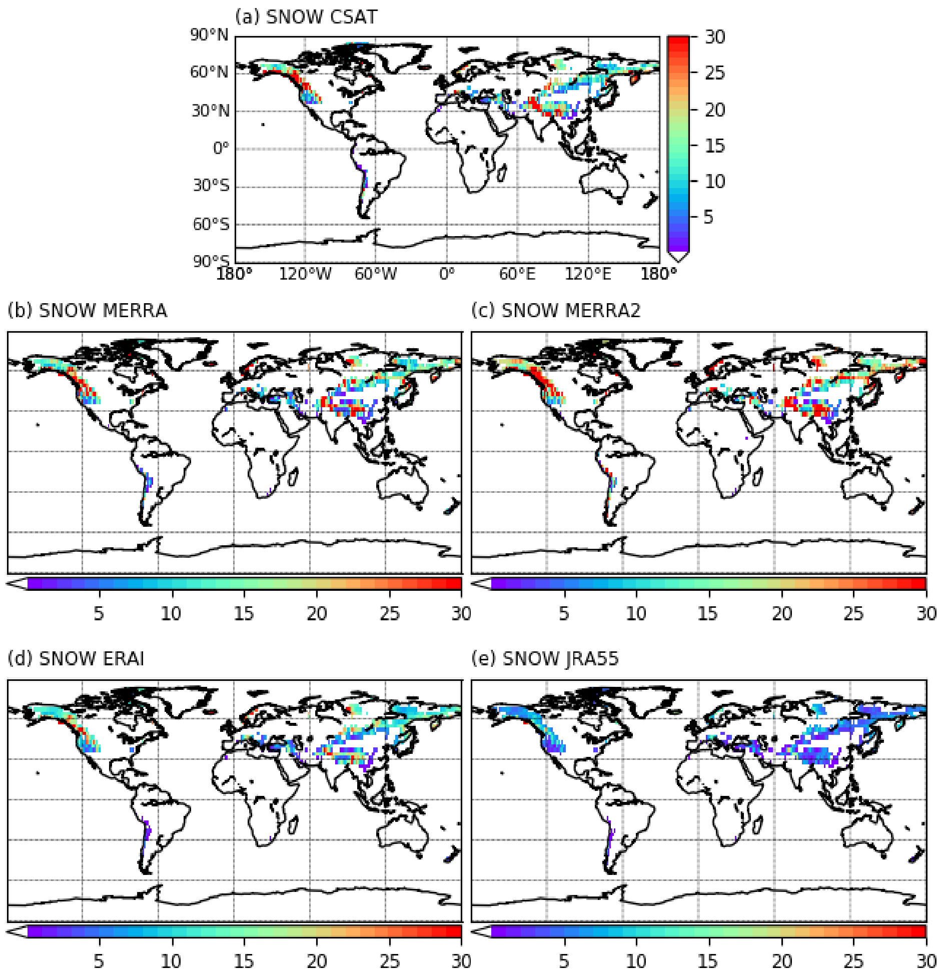

Figure 2: Spatial maps of global cumulative mountain snowfall (mm/month/gridbox) for a) CloudSat, b) MERRA, c) MERRA-2, d) ERA-Interim and d) JRA-55, averaged over the time period 2007-2016.

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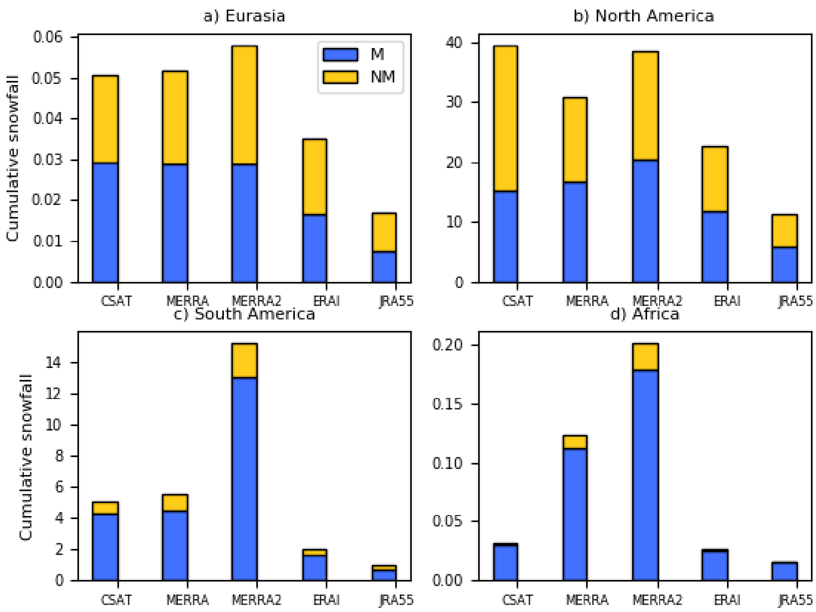

~~Figure 3~~

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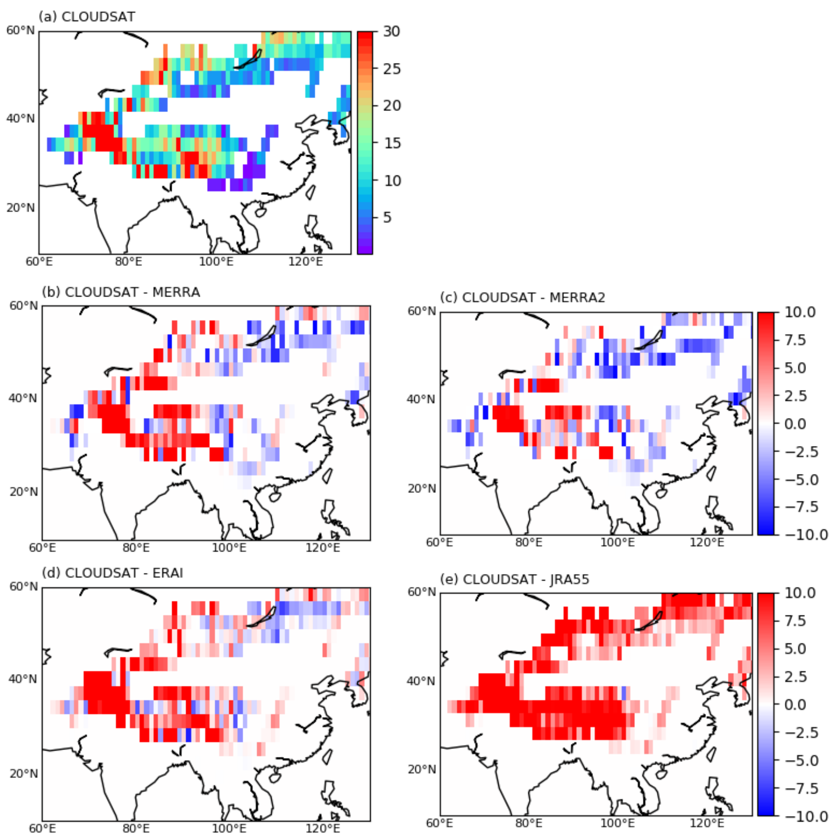

Figure 3: Spatial maps of the global cumulative mountain snowfall (mm/month/gridbox) over the High-mountains Asia for a) CloudSat, b) CloudSat minus MERRA, c) CloudSat minus MERRA-2, d) CloudSat minus ERA-Interim and d) CloudSat minus JRA-55, over the time period 2007-2016.

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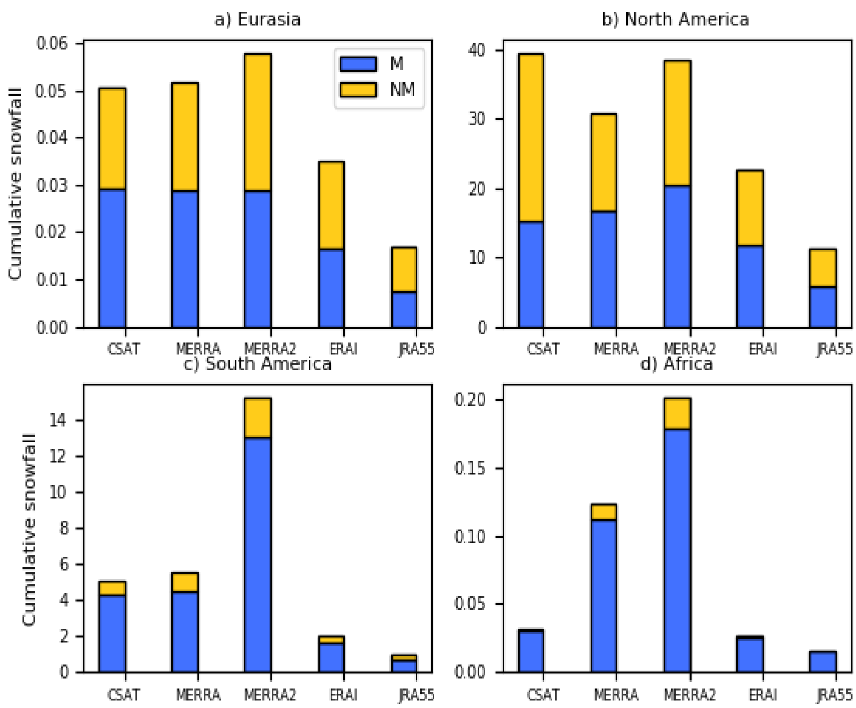

Figure 4: Snowfall estimates (mm/month/grid box) over: a) Eurasia, b) North America, c) South America and d) Africa for CloudSat, MERRA, MERRA-2, ERA-Interim and JRA-55 over the time period 2007-2016. Mountain snow is in blue and non-mountain snow is in yellow.

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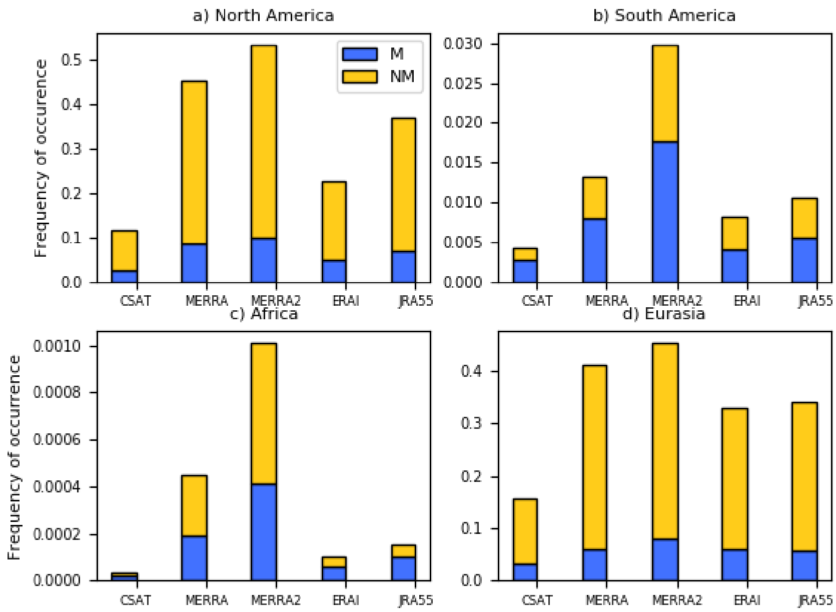

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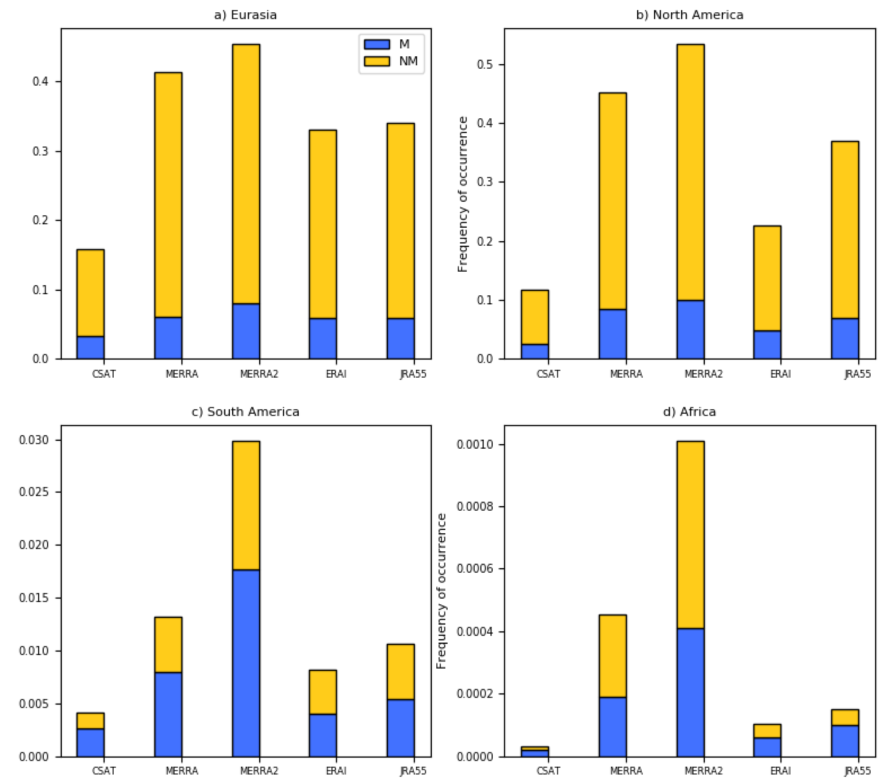

Figure 45: Frequency of occurrence of snowfall estimates over: a) Eurasia, b) North America, c) South America and d) Africa for CloudSat, MERRA, MERRA-2, ERA-Interim and JRA-55 over the time period 2007-2016. Mountain snow is in blue and non-mountain snow is in yellow.