Dear editor,

We thoroughly thank you and the three reviewers for taking the time to review our paper and providing very detailed and useful comments. We have considered all of the comments in our rebuttal, and our responses are detailed below (reviewer in black, response in blue). The main changes relative to the original manuscript are:

a. We added the original appendix figure to the main text.
b. We reformulated the title.
c. We added multiple new references to provide a broader perspective on the topic of study and limitations of CloudSat and CESM.
d. We substantially expanded the discussion and provided more comparison to existing studies, and added a paragraph on the relevance for this study for existing future radar missions.

Below our response, please find a version of the manuscript highlighting the differences between revised and original manuscript.

We thank you for your consideration, and we hope this revised manuscript is suitable for publication in The Cryosphere.

All the best,

Jan Lenaerts and co-authors

Reviewer #1

Lenaerts et al. use precipitation frequency observations from CloudSat to evaluate the accuracy of the Community Earth System Model (CESM) across the Greenland Ice Sheet. They find that CESM is able to reproduce present-day spatial patterns and seasonality of precipitation frequency fairly well. This lends confidence to their assessment of future precipitation frequency changes by 2080-2095. Overall, the paper is well-organized and easy to follow. The methods are clearly articulated and the results are thoroughly described. The discussion recognizes the limitations of CloudSat and the biases in CESM and presents a very insightful explanation about how we can use Earth System Models to make precipitation forecasts for the Greenland Ice Sheet. I have a few suggestions that would improve the manuscript which I detail below. The main ones are to tidy up the first three paragraphs of the introduction and describe a bit more about how this study will actually aid future satellite planning campaigns. If the authors can address my relatively minor comments, I would be happy to endorse publication in The Cryosphere.

Title: I would urge the authors to consider replacing "satellite observations" with "Cloud-Sat" and "Earth System Model" with the "Community Earth System Model" in the title. Being more specific would probably make the paper more searchable.

We changed the title accordingly.

P1 L16: "Clearly" is vague, how do we know that mass loss has accelerated? Models? GRACE?

We changed this sentence to 'observations indicate that GrIS mass loss has accelerated'

P1 L19-20: Consider adding a reference that supports this statement.

We added a new reference to support this statement: the new IMBIE assessment of Greenland Ice Sheet mass balance (Shepherd et al., 2020)

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., et al. (2020). Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature, 579*(7798), 233–239.

P2 L3-4L: According to observations, precipitation decreased in western Greenland between 1996 and 2016 (Lewis et al. 2019; https://doi.org/10.5194/tc-13-2797-2019). Consider clarifying that this statement refers only to models.

Thanks, we added 'climate modeling indicates that' and added the Lewis et al., 2019 to the statement 'with only an increase over parts of the interior'.

P2 L7-9: There are two nice papers that were recently published in Science Ad- vances that investigated this feedback. Consider referencing Noël et al. (2019; https://advances.sciencemag.org/content/5/9/eaaw0123) and Ryan et al. (2019; https://advances.sciencemag.org/content/5/3/eaav3738).

Both references are added to the revised manuscript.

P3 L5-6: I was interested to learn about the "implications for future radar missions" but was disappointed that this was absent from the discussion and conclusions. Either remove this statement or discuss the implications for future radar missions in the manuscript. I would urge the latter to round off a very nice paper.

We agree with the reviewer (as well as the other reviewers) that a discussion of this is a welcome addition to our paper and increases its significance. Therefore we added this paragraph to the discussion:

"In addition to understanding the impact of changing precipitation frequency on the GrIS surface, our methodology can be used to assess what a future CloudSat-style mission would observe in terms of changes in GrIS precipitation. Cloud radars are, and will remain, essential to continually monitor polar precipitation, for a variety of reasons. Firstly, they measure at the right frequency: cloud radars (94 GHz such as CloudSat) provide the only spaceborne radar observations of high-latitude precipitation that have ever been made. Future missions currently will have this frequency: ESA's EarthCARE (https://earth.esa.int/web/guest/missions/esa-future-missions/earthcare ; to be launched 2021) and NASA's ACCP mission (https://science.nasa.gov/earth-science/decadal-accp). In contrast, lower frequency precipitation radars (e.g., TRMM, GPM) cannot detect light precipitation, which commonly occurs at high latitudes, including Greenland (as shown in this study). Secondly, CloudSat regularly samples the high latitude regions, whereas precipitation radars typically do not sample high latitude regions. Future cloud radar missions should continue to consider (near-)polar orbits to include high latitudes. Thirdly, co-locating spaceborne cloud radar with spaceborne lidar can help with assessment of light precipitation and precipitation phase. While our study only focused on CloudSat, future work should complement CloudSat radar retrievals with collocated CALIPSO lidar information to study high latitude precipitation. Both the future EarthCARE and ACCP missions plan to include complimentary radar and lidar retrievals.

Unfortunately, CloudSat only provides a 'curtain view' of cloud and precipitation vertical structures at high latitudes, and still provides relatively limited temporal coverage. Creative ways to combine CloudSat-like observations with meteorology can help isolate process-based relationships (e.g., Morrison et al. 2018; Gallagher et al. 2020). However, long-term (decadal or longer) data records are likely needed to isolate change from internal variability. For planning future Earth-observing missions, satellite simulators can give a preliminary peek into potential findings, and provide initial assessments of how long a data record is needed to detect Greenland precipitation changes due to climate change. We suggest that future work leverages these tools, which has already been done for non-polar regions (e.g., Takahashi et al. 2019)."

New references:

Morrison, A. L., Kay, J. E., Chepfer, H., Guzman, R., & Yettella, V. (2018). Isolating the Liquid Cloud Response to Recent Arctic Sea Ice Variability Using Spaceborne Lidar Observations. Journal of Geophysical Research: Atmospheres, 123(1), 473–490. https://doi.org/10.1002/2017JD027248

Gallagher, M. R., Chepfer, H., Shupe, M. D., & Guzman, R. (2020). Warm Temperature Extremes Across Greenland Connected to Clouds. Geophysical Research Letters, 47(9), e2019GL086059. https://doi.org/10.1029/2019GL086059

P3 L24: "heavy precipitation" do the authors mean "heavy rainfall"?

We refer both to snow and rain here, so precipitation seems to be valid to use.

P8 L3-13: Might some of these uncertainties be explained by surface air temperatures in CESM being too warm/cold? If so, please discuss.

We would argue that, although surface air temperatures partly determine the precipitation phase (and frequency as well), many factors control precipitation formation (e.g. cloud microphysics, thermodynamics of full atmospheric column, advection, etc.). We think that is clearly beyond the scope of this study to perform a detailed evaluation of CESM1 precipitation formation mechanisms.

P9 L2-4: The authors miss an opportunity here to describe the future climate of Greenland according to an Earth System Model and how it differs from the present-day

cli- mate. What is the difference in mean average air temps? Is the seasonality of air temps weaker?

The goal of this study is not to provide a general overview of the future climate on the Greenland ice sheet, but to focus on precipitation phase and frequency chases in particular. Other studies have focused on using various versions of CESM to characterize future changes in Greenland climate, e.g. Vizcaino et al., 2014; Muntjewerf et al., 2020. These references are added to the discussion: "Also, this study focuses on future changes in precipitation only, and does not give a more general overview of future climate change on the GrIS that is provided by other studies using different versions of CESM (e.g. Vizcaino et al., 2013; Muntjewerf et al., 2020)."

New references added:

Vizcaíno, M., Lipscomb, W. H., Sacks, W. J., & van den Broeke, M. (2013). Greenland Surface Mass Balance as Simulated by the Community Earth System Model. Part II: Twenty-First-Century Changes. Journal of Climate, 27(1), 215–226. https://doi.org/10.1175/JCLI-D-12-00588.1

Muntjewerf, L., Petrini, M., Vizcaino, M., Ernani da Silva, C., Sellevold, R., Scherrenberg, M. D. W., et al. (2020). Greenland Ice Sheet Contribution to 21st Century Sea Level Rise as Simulated by the Coupled CESM2.1-CISM2.1. Geophysical Research Letters, 47(9), e2019GL086836. https://doi.org/10.1029/2019GL086836

Figure 7b: Why would there be differences in the grid cell area between CloudSat and CESM? Please clarify.

We acknowledge that 'grid cell area' is confusing; this is simply the total area in each bin. We have changed this to 'Area' instead and divided the number by 10^3 to improve readability of the labels.

Reviewer #2

The manuscript presents a comparison between precipitation frequency as observed by CloudSat and as modeled by the Community Earth System Model for the last 15 years (2006-2020) and once determined that the model can simulate fairly well the pattern and the seasonal variability of precipitation, it extends the simulation to the last 15 years of the 21st Century. The results show a general decrease on snowfall frequency over the Greenland Ice Sheet except for the inner most elevated region where the snowfall frequency actually increases by 10%. Rainfall frequency is supposed to increase over the entire Greenland and will extend over higher elevation compared to present-days. These changes will affect climate and mass balance of the Greenland Ice Sheet with dramatic consequences on the snowpack. The paper follows a pretty straightforward line of reasoning, clearly describing data, methodology and results. Here are few suggestions to clarify few points:

We thank the reviewer for their positive feedback. We provide a response to all items below.

The whole paper is about precipitation frequency so I suggest to explicitly describe what you mean with it (#precipitating pixels/#total pixels I suppose), especially because you also partition snow and rain and there could be confusion between the snow (rain) frequency over all pixels or over only precipitating pixels for example.

Good point, we added to the first paragraph of the data and methods section: "We define precipitation frequency as the ratio between the number of time steps with precipitation and the total number of time steps. If averaged across an area, such as the ice sheet or elevation bin, frequency is defined as the average frequency of all grid cells contained within that area."

P4 L2: add a sentence to tell what RCP is (a forecast model? A future scenario? . . .)

We added: "using the worst-case Representative Concentration Pathway (RCP) 8.5 greenhouse gas emissions scenario."

Section 3.1: describing present-day precipitation from CloudSat it is worth mentioning that there could be some biases due to the daylight operational mode CloudSat is operating on since 2011. The winter descending orbits over Southern Greenland for example do not provide any data. There are ongoing studies that will eventually quantify

the biases but nothing has been published yet. I would suggest to mention the issue and just advice that no bias correction have been applied in the present study.

Thanks for pointing that out. We have added this to the Data and methods section:" Since CloudSat has been operating on daytime only mode since 2011, which might potentially introduce biases that are not considered in this study."

P5 L10-11: does the fact that areas below 2000m are actually a low percentage compared to other eleva- tions affect precipitation frequencies? Describe a bit more how those variables are connected in your study.

Yes, it does, and this sentence aims to address exactly that: "This implies that, although all areas below 2000 m a.s.l. experience rain, all these elevation bands combined only occupy ≈ 38% of the ice sheet area."

P5 L19 and following: it is not really clear from your wording that you are calculating the difference between CESM and CloudSat frequencies. I would suggest to make this more explicit both here and on fig.5 caption.

Good point, we added a sentence to start the paragraph: "We first present the CESM precipitation frequencies (Figure 4), and then compare them directly to CloudSat (Figure 5)." In the caption of Figure 5, we more explicitly state that these map shows CESM-CloudSat: "Present-day, annual (left) and seasonal (DJF, MAM, JJA, SON, from left to right) mean snowfall (top) and rainfall (bottom) frequency difference between CESM (2006--2020) and CloudSat 2CPC (2006--2016). Positive values indicate that CESM overestimates precipitation frequency relative to CloudSat."

Figure 3 caption: the "grid-cell" area concept is not really clear, is it the total area of the GrIS for each elevation bin? I feel like this "grid-cell" is a bit misleading.

We acknowledge that 'grid cell area' is confusing; this is simply the total area in each bin. We have changed this to 'Area' instead and divided the number by 10^3 to improve readability of the labels.

P9 L1-4: as a curiosity, have you tried to compare different intervals like only 10 years or for example 15 years around 2050? Just to see if there is a dependence on the actual interval of years used for the comparison or if we can extend the results independently on that.

We have not done that. The 15 years is chosen because it is a compromise between having sufficient number of years to filter out much of the internal variability, and to stay as close to the end of the 21st century to see the largest signal.

In general I feel like the conclusion section is a bit weak, some more information could be added about the mass balance and what to expect for future satellite missions here. Better describing the consequences of your results would absolutely help making the paper stronger.

We agree, and have added new text to discuss the relevance for future satellite missions.

Minor comments:

In the abstract you mention RCP8.5, I suggest to explicitly write "Representative Concentration Pathway 8.5 Scenario" as you did for CESM earlier.

Done.

P2 L8: why the snow layer "needs" to be melted away?

Changed to 'is melted away'

P2 L29: remove the first "the" from "CloudSat is the currently the. . ."

Done.

P2 L30: there aren't so many papers about the observational assess- ment of Antarctic Ice Sheet precipitation rates, so I would mention all of them, including Milani et al 2018 that considered also the surrounding oceans and the ground clutter corrections.

Thanks, added Milani et al., 2018 and Lemonnier et al., 2020 references to revised paper.

Milani, L., Kulie, M. S., Casella, D., Dietrich, S., L'Ecuyer, T. S., Panegrossi, G., et al. (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. https://doi.org/10.1016/j.atmosres.2018.05.015

Lemonnier, F., Madeleine, J.-B., Claud, C., Palerme, C., Genthon, C., L'Ecuyer, T., & Wood, N. B. (2020). CloudSat-Inferred Vertical Structure of Snowfall Over the Antarctic Continent. Journal of Geophysical Research: Atmospheres, 125(2), e2019JD031399. https://doi.org/10.1029/2019JD031399

P3 L21: "gridded observations", can you give some details about the grid you used for this work?

This grid is a 1x1 degree grid in which all CloudSat 2C-PRECIPITATION-COLUMN are aggregated. This is added to the text.

P3 L21: "2CPC", for a reader not familiar with CloudSat this acronym does not make much sense, explicitly mention 2C-PRECIPITATION-COLUMN product so they know what to look for.

Done.

P6 L4: you probably forgot to say "in winter".

Added.

P8 L5: Is Figure A1 an appendix figure? It is not clear at the end of the manuscript that there is an appendix, shouldn't this figure just be included as a regular figure since there is no in-depth description in a real supplemental section?

We added this figure as a separate regular figure in the revised manuscript.

P8 L7: what is GIMP and what is its grid? The full name is provided in fig. 3 caption, I would suggest to include it in the text as well.

Done.

P9 L14-21: I guess you are referring to figure 9, please cite it.

Done.

 P10 L2: "the increase of light frequency", add "light rain frequency".

Done.

Reviewer #3

Review of tc-2020-31

This manuscript examines the current state of precipitation around the Greenland Ice Sheet (GrIS) using precipitation products from CloudSat (CS). It partitions the frequency of the snowfall into regions of the GrIS as well as looks at impacts based on elevation. The manuscript looks at both snow (moderate and light) and rain (light only) and compares to both CESM findings of current day and future projections. In general, CESM overestimates the rainfall frequency, but reproduces the spatial and seasonal variability when compared to CS. Under future warming conditions, the authors find that rainfall will increase at higher elevations of the GrIS, whereas snow only increases in the highest elevations (>2500 MASL).

Overall, this is a well-written and organized manuscript. I believe that the material is novel and will add to our understanding of future impacts of precipitation to the GrIS. I have only some minor comments and suggestions of added references in some areas where I think they would help broaden or support the manuscript. These are listed below:

We thank the reviewer for their positive assessment. We provide a point-by-point response below.

* The introduction could benefit with a little more background and citations (especially the first three paragraphs). For example, please cite: . . ."equivalent to 7.3 meter sea 15 level equivalent." (P1, L15), . . ."driven by a progressively declining SMB." (P1, L20). Also, could you add any comments on recent data from GRACE or IceSat2/IceBridge in constraining some of these measures of SMB somewhere in the Intro?

Thanks for this suggestion. We have added several new references to the intro.

Morlighem et al., 2017 - to support the 7.4 m sea level rise equivalent claim.

Shepherd et al., 2019: to support 'progressively declining SMB'

Montgomery et al., 2020: Constraining SMB using IceBridge in SW Greenland

Fettweis et al., 2020: model intercomparison of Greenland SMB

New references

Morlighem, M., Williams, C. N., Rignot, E., An, L., Arndt, J. E., Bamber, J. L., et al. (2017). BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation. Geophysical Research Letters, 44(21), 11,051-11,061. https://doi.org/10.1002/2017GL074954

Montgomery, L., Koenig, L., Lenaerts, J. T. M., & Kuipers Munneke, P. (2020). Accumulation rates (2009-2017) in Southeast Greenland derived from airborne snow radar and comparison with regional climate models. Annals of Glaciology, 1–9. https://doi.org/10.1017/aog.2020.8

Fettweis, X., Hofer, S., Krebs-Kanzow, U., Amory, C., Aoki, T., Berends, C. J., et al. (2020). GrSMBMIP: Intercomparison of the modelled 1980--2012 surface mass balance over the Greenland Ice sheet. The Cryosphere Discussions, 2020, 1–35. https://doi.org/10.5194/tc-2019-321

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., et al. (2020). Mass balance of the Greenland Ice Sheet from 1992 to 2018. Nature, 579(7798), 233–239. https://doi.org/10.1038/s41586-019-1855-2

* Could you please add McIlhattan et al. (2019 TCD – in revisions) as well at "and GrIS precipitation rates (Bennartz et al., 2019)" (P2, L31)? McIlhattan et al. also ex- amines the frequency and rates of snowfall over the GrIS (https://www.the-cryosphere-discuss.net/tc-2019-223/tc-2019-223.pdf)

Done.

McIlhattan, E. A., Pettersen, C., Wood, N. B., & L'Ecuyer, T. S. (2019). Satellite Observations of Snowfall Regimes over the Greenland Ice Sheet. The Cryosphere Discussions, 2019, 1–40. https://doi.org/10.5194/tc-2019-223

* This comment relates to what you say on P2, L33: "In particular, CloudSat radar reflectivity profiles are contaminated by ground clutter in the bottom kilometer of the atmosphere. . ." Both Bennartz et al. (2019) and McIlhattan et al. (2019) examine the impact of the ground clutter and the accuracy of the lowest available bin on snow rate information. McIlhattan et al. found that up to 25% of the light snow-producing mixed-

phase clouds are likely being missed by CS, when compared to studies at Summit Station (Pettersen et al., 2018 (ACP)). It might be good to have some discussion of this in the data and methods section. I do not think that it fits in the introduction and I do not think it will detract from the overall narrative, but I think some discussion or inclusion of the ground clutter/detection issues in the Data and Methods section would be helpful. It might also be helpful to show the definitions of "light" versus "regular" snow and rain in the methods (I did find it in Kay et al., 2018, but it would be nice to include here as well).

Thanks for pointing that out. We added to the Data and methods, after the first sentence "In addition, CloudSat suffers from ground clutter, which leads to, for example, missing up to 25% of the light snow producing mixed-phase clouds over central Greenland (Bennartz et al., 2019; McIlhattan et al., 2019)."

We also added the thresholds to the text in the Data and methods.

* P4, L9-11 I would add some citations of previous precipitation studies that agree with these findings. For example, "to >30% over Southeast Greenland" is con- sistent with previous studies, such as: Schuenemann et al., 2009; Hakuba et al., 2012; Berdahl et al., 2018. And "The interior experiences snowfall most fre- quently in the summer (JJA, >20%)," is in line with ground-based studies from Summit Station, so I suggest noting that and adding the citations: Castellani et al., 2015 (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015JD023072) and Pettersen et al., 2018 (https://www.atmos-chem-phys.net/18/4715/2018/acp-18-4715- 2018.pdf). Throughout this paragraph, it would be helpful to note previous work that is consistent with these findings (similar with the rain frequencies).

Thanks once again for providing these references, these are useful to put our results into a perspective. To clearly separate our own results and the discussion, we have added a brief discussion on the comparison/agreement with existing studies to the discussion (first paragraph), adding the references suggested by the reviewer: "Our CloudSat results align well with previous studies. The snowfall frequency maximum of >30% over Southeast Greenland is consistent with various modeling results (Schuenemann et al., 2009; Hakuba et al., 2012; Berdahl et al., 2018). The summer maximum in snowfall in the GrIS interior is confirmed by ground observations at Summit station (Castellani et al., 2015; Pettersen et al, 2018)."

New references

Castellani, B. B., Shupe, M. D., Hudak, D. R., & Sheppard, B. E. (2015). The annual cycle of snowfall at Summit, Greenland. Journal of Geophysical Research: Atmospheres, 120(13), 6654–6668. https://doi.org/10.1002/2015JD023072

Hakuba, M. Z., Folini, D., Wild, M., & Schär, C. (2012). Impact of Greenland's topographic height on precipitation and snow accumulation in idealized simulations. Journal of Geophysical Research: Atmospheres, 117(D9). https://doi.org/10.1029/2011JD017052

Pettersen, C., Bennartz, R., Merrelli, A. J., Shupe, M. D., Turner, D. D., & Walden, V. P. (2018). Precipitation regimes over central Greenland inferred from 5 years of ICECAPS observations. Atmospheric Chemistry and Physics, 18(7), 4715–4735. https://doi.org/10.5194/acp-18-4715-2018

Berdahl, M., Rennermalm, A., Hammann, A., Mioduszweski, J., Hameed, S., Tedesco, M., et al. (2018). Southeast Greenland Winter Precipitation Strongly Linked to the Icelandic Low Position. Journal of Climate, 31(11), 4483–4500. https://doi.org/10.1175/JCLI-D-17-0622.1

Schuenemann, K. C., Cassano, J. J., & Finnis, J. (2009). Synoptic Forcing of Precipitation over Greenland: Climatology for 1961–99. Journal of Hydrometeorology, 10(1), 60–78. https://doi.org/10.1175/2008JHM1014.1

* Figure 3 caption implies there should be dashed lines, but they are not shown. It does say "not shown" in the text (P5, L7). I think it would be nice to show these. Also, this is in agreement with what McIllhattan et al. found (see figure 7).

We revised Figure 3 accordingly.

* P6, L1: You say "In contrast, interior GrIS summer snowfall frequency is slightly lower in CESM than in CloudSat." Both Pettersen et al. (2018) and McIlhattan et al. found that mixed-phase clouds were the dominate cloud type producing snowfall in the summer (as opposed to deep, frontal clouds). CS misses many of these lightly precipitating mixed-phase clouds (especially over the interior where CS was compared to Summit Station instrumentation). Is it worth noting this point? Either here or in the discussion? It could be that CS is missing some of this summertime precipitation that is actually being modeling correctly?

That is a fair point, but if we understand correctly, this would actually aggravate the CESM bias, since the model produces even less light snowfall than CloudSat (which - as the reviewer indicates - misses a fraction of these events). Since we already mentioned that CloudSat potentially fails to detect such events in the Data and methods section, we would argue that this topic has been addressed sufficiently.

* Figure 6: just a comment that not only does the heavier snow seem to have less of a seasonal cycle, it seems to be completely missing the uptick in SON that is due to the firing up of the NA storm track. Just a comment – but does CESM not accurately capture the NA storm tracks impinging the GrIS?

We are not aware of a study that analyzes the CESM1 storm track seasonality in/around the North Atlantic region, but this is potentially the case. Since this topic is out of the scope of our study, and would require substantial additional analysis, we prefer to refrain from mentioning it.

* P8, L3-4: "A part of these discrepancies between CESM and CloudSat may be ascribed to CESM (at its horizontal resolution of 1 degree) not resolving the steep topog- raphy and related surface climate and precipitation gradients of the marginal GrIS" – also, Bennartz et al., (2019) showed that CS additionally has a very difficult time re- solving the precipitation accurately in the steep topographic regions (as well as other studies focused on CS and GPM orographic impacts). Could it also be that both CESM and CS have difficulties here? Might be worth noting – I am not sure I would say it is all CESM.

Good point. We added to the discussion: "The differences between CESM and CloudSat are, at least partly, ascribed by the limited horizontal resolution (around 1 degree) of both products. Here we show that topography smoothing in CESM leads to underestimated precipitation frequency along the GrIS edges. While the native resolution of CloudSat is much higher (around 1 km), the aggregation of these observations in a 1 x 1 grid, along with ground clutter issues in steep topography, likely degrades the quality of this CloudSat product in accurately representing precipitation in the coastal regions of the GrIS (Bennartz et al., 2019)."

* P9, L9 -10: "The increase in GrIS interior snow frequency is consistent throughout all seasons, and most prominent in winter (DJF)" – any speculation as to why? Is it temperature driven, moisture? (either here or in the discussion).

We added in the discussion (second paragraph): "The strongest increase in snow frequency occurs in winter, which is the season with the strongest simulated

temperature increase in CESM (Peings et al., 2017). Snowfall and temperature are strongly correlated at low temperatures, since the Clausius-Clapeyron relationship dictates that the atmospheric saturation vapor pressure exponentially increases with temperature."

New reference

Peings, Y., Cattiaux, J., Vavrus, S., & Magnusdottir, G. (2017). Late Twenty-First-Century Changes in the Midlatitude Atmospheric Circulation in the CESM Large Ensemble. Journal of Climate, 30(15), 5943–5960. https://doi.org/10.1175/JCLI-D-16-0340.1

* Figure A1 is not really in an appendix. Is it worth just adding it as a regular figure? Or adding a proper Appendix with some verbiage?

We have added this figure as a regular figure in the revised manuscript.

* Final comment – Much of the above comments/citations could be added either where I noted or in the discussion. I think adding some of the above gives the paper more context.

Present-day and future Greenland Ice Sheet precipitation frequency from ~~satellite~~ CloudSat observations and ~~an~~ the Community Earth System Model

Jan T. M. Lenaerts[1,*], M. Drew Camron[1,*], Christopher R. Wyburn-Powell[1], and Jennifer E. Kay[1, 2]

[1]Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, CO 80309
[2]CIRES, University of Colorado Boulder, Boulder, CO 80309
[*]These authors have contributed equally to this work.

Correspondence: Jan Lenaerts (Jan.Lenaerts@colorado.edu)

Abstract. The dominant mass input component of the Greenland Ice Sheet (GrIS) is precipitation, whose amounts and phase are poorly constrained by observations. Here we use spaceborne radar observations from CloudSat to map the precipitation frequency and phase on the GrIS, and use those observations, in combination with a satellite simulator to enable direct comparison between observations and model, to evaluate present-day precipitation frequency in the Community Earth System Model (CESM). The observations show that substantial variability of snowfall frequency over the GrIS exists, that snowfall occurs throughout the year, and snowfall frequency peaks in Spring and Fall. Rainfall is rare over the GrIS, and only occurs in regions under 2000 m elevation and to the peak summer season. Although CESM overestimates the rainfall frequency, it reproduces the spatial and seasonal variability of precipitation frequency reasonably well. Driven by a high-emission, worst-case ~~RCP8.5~~ Representative Concentration Pathway (RCP) 8.5 scenario, CESM indicates that rainfall frequency will increase considerably across the GrIS, and will occur at higher elevations, potentially exposing a much larger GrIS area to rain and associated meltwater refreezing, firn warming, and reduced storage capacity. This technique can be applied to evaluate precipitation frequency in other climate models, and can aid in planning future satellite campaigns.

1 Introduction

The Greenland Ice Sheet (GrIS) contains the largest volume of ice on the Northern Hemisphere, equivalent to ~~7.3~~ 7.4 meter sea level equivalent (Morlighem et al., 2017). While the GrIS has been losing mass since the 1970s, and likely also in earlier episodes in the 20th century (Kjeldsen et al., 2015; Kjær et al., 2012), observations indicate that GrIS mass loss has ~~clearly~~ accelerated since the mid-1990s to early 2000s (Van den Broeke et al., 2016; Mouginot et al., 2019).

Mass loss is equivalent to a negative ice sheet mass balance (MB). Negative MB, in turn, implies that the ice sheet surface mass balance (SMB) is lower than the total flux of ice across the GrIS grounding line (D, (Lenaerts et al., 2019)). The aforementioned enhanced GrIS mass loss has been predominantly driven by a progressively declining SMB (Shepherd et al., 2020). In contract, D has remained relatively constant since the 2000s, despite interannual (Enderlin et al., 2014) and seasonal variations (King et al., 2018).

1

GrIS SMB is predominantly governed by the difference between precipitation (snowfall and rainfall) and meltwater runoff from snow and ice melt, with surface and blowing snow sublimation an order of magnitude lower (Lenaerts et al., 2012). Recent GrIS SMB decrease is driven by enhanced surface melting and runoff (Van den Broeke et al., 2016; Trusel et al., 2018), caused by increasing atmospheric temperatures (Van Angelen et al., 2014; Fettweis et al., 2012) and persistent anomalously high large-scale atmospheric blocking over the GrIS (Fettweis et al., 2013; Belleflamme et al., 2015). In contrast, climate modeling and airborne radar observations indicate that GrIS precipitation has remained relatively constant ~~(Van den Broeke et al., 2016)~~ (Van den Broeke et al., 2016; Montgomery et al., 2020; Fettweis et al., 2020), with only ~~a small~~ an increase over parts of the interior ~~(Csatho et al., 2014)~~(Csatho et al., 2014; Lewis et al., 2019). Throughout the remainder of the 21st century, sustained atmospheric warming is expected to cause continued GrIS mass loss (Pattyn et al., 2018), but the potential role of increasing precipitation on mitigating that GrIS mass loss is highly uncertain.

The amount of precipitation that falls on the GrIS ablation zone (areas where local SMB < 0) during winter determines the depth of the snow layer that ~~needs to be~~ is melted away, and thereby, controls the timing of bare, low-albedo ice exposure in summer (Noël et al., 2019; Ryan et al., 2019). For example, the 2017-2018 winter was a very wet winter on Greenland, delaying the ice exposure onset to late in the summer season, which led to anomalously low melt and runoff, and high SMB, in 2018. Additionally, snowfall events during the melt season can significantly limit subsequent melting (Noël et al., 2015). In the GrIS accumulation zone (where local SMB > 0), the depth of the winter snowpack controls the availability of 'cold content', i.e. energy to refreeze and locally store surface meltwater that percolates into it, thereby preventing runoff of that water into the ocean. In regions of very high snow accumulation, such as Southeast Greenland, the winter snowpack can also act to thermally insulate warm firn containing liquid water below (the firn aquifer, Forster et al. (2014)) from the cold atmosphere aloft.

Despite its importance for the GrIS mass balance and firn processes, it is notoriously challenging to retrieve direct observations of precipitation on the GrIS. Precipitation gauges struggle from undercatching snowfall, and those gauges that overcome these issues are large and expensive, and hence difficult to deploy in the field. Alternatively, snow accumulation rates can be derived from firn cores, ground-based and airborne snow radar, and cosmic ray counters, but these observations do not allow to separate precipitation from other surface mass balance processes such as sublimation, vapor deposition, and blowing snow redistribution (Lenaerts et al., 2019). Moreover, precipitation amounts vary greatly across the GrIS and across seasons and years, indicating the need of distributed and long-term observations to capture the full extent of GrIS precipitation. The phase of the precipitation on the GrIS is even more uncertain, as precipitation phase is determined by complex thermodynamic and cloud micro-physical processes that are poorly constrained over much of the Polar Regions.

Over the last decade, new satellite remote sensing technology has enabled the direct observation of precipitation in Polar Regions, including over the GrIS. Specifically, the CloudSat satellite has an active cloud-profiling 94-GHz radar and has been observing polar clouds and precipitation since 2006 (Stephens et al., 2002). Unlike precipitation radars such as TRMM and GPM, which are designed to target heavy tropical precipitation, CloudSat is sensitive to the light precipitation and snow that falls at high latitudes. Due to its orbit and its sensitivity, CloudSat is ~~the~~ currently the only radar in space that measures precipitation at high latitudes. CloudSat observations have been used to assess Antarctic Ice Sheet precipitation rates ~~(Palerme et al., 2014, 2016; Boening et al., 2012)~~ (Palerme et al., 2014, 2016; Boening et al., 2012; Milani et al., 2018; Lemonnier et al., 2

and GrIS precipitation rates (Bennartz et al., 2019). While CloudSat observations are unique in their measurement of polar precipitation, they are not without limitations. In particular, CloudSat radar reflectivity profiles are contaminated by ground clutter in the bottom kilometer of the atmosphere, which limits their ability to assess surface precipitation. In addition, converting CloudSat reflectivity observations into precipitation amount requires assumptions about the drop size distribution and shape.

5   To circumvent these limitations, many precipitation studies have applied thresholds to CloudSat's near-surface radar reflectivity to estimate near-surface precipitation frequency (Haynes et al., 2009; Ellis et al., 2009; Smalley and L'Ecuyer, 2015). Recently, these near-surface radar reflectivity derived precipitation frequencies have been compared to climate model output in a scale-aware and definition-aware framework (Kay et al., 2018). Here, we use this framework to compare present-day GrIS precipitation frequency between observations (CloudSat) and an Earth System Model (CESM). After understanding present-

10   day biases, we assess future 21st century changes in precipitation frequency over the GrIS, and discuss the implications for future radar missions. We start this paper with a presentation of our framework for comparing models and observations and a description of the model simulations (Section 2), followed by results (Section 3). Section 4 presents a discussion and conclusions.

2   Data and methods

15   **2.1   Scale-aware and definition-aware framework for evaluating simulated precipitation frequency**

Evaluating precipitation simulated by Earth System Models with satellite observations is challenged by the scale differences (model grids are ∼100 km, while CloudSat footprints are ∼1 km), and because of inherent differences in the definition of precipitation between models and observations. In addition, CloudSat suffers from ground clutter, which leads to, for example, missing up to 25% of the light snow producing mixed-phase clouds over central Greenland (Bennartz et al., 2019; McIlhattan et al., 2019)

20   . To address these challenges, the science community has developed a software package called Cloud Feedbacks Model Intercomparison Project (CFMIP) Observational Simulator Package (COSP, Bodas-Salcedo et al. (2011)). COSP contains a subcolumn generator and instrument forward models, called simulators, to convert raw model output at the model grid scale into pseudo-satellite observations at the satellite footprint. As such, COSP outputs can be directly compared to equivalent satellite observations in a scale-aware and definition-aware framework. For this study, we use the Quickbeam radar simulator ~~(Haynes et~~

25   ~~al., 2007)~~ (Haynes et al., 2007) to simulate modelled CloudSat reflectivity profiles. Subsequently, following Kay et al. (2018), we calculate near-surface precipitation frequency based on thresholding the modeled near-surface CloudSat reflectivity. Using this framework, we are able to directly compare modelled and observed CloudSat near-surface precipitation frequency. The observations we use are gridded observations of 2C-PRECIPITATION-COLUMN (2CPC hereafter) CloudSat near-surface precipitation frequency (Ellis et al., 2009) during 11 years (June 2006 - May 2016). This grid has a 1 x 1 degree horizontal

30   resolution that aggregates all CloudSat 2CPC observations. Since CloudSat has been operating on daytime only mode since 2011, which might potentially introduce biases that are not considered in this study. The model and the observations use the same reflectivity thresholds ~~(see Table 2 in Kay et al. (2018))~~ (Kay et al., 2018) for assessing near-surface precipitation frequency. Here we use the 'light snow' ~~,~~ (near-surface (960–1,440 m above the surface) attenuated radar reflectivity (dBZ)

3
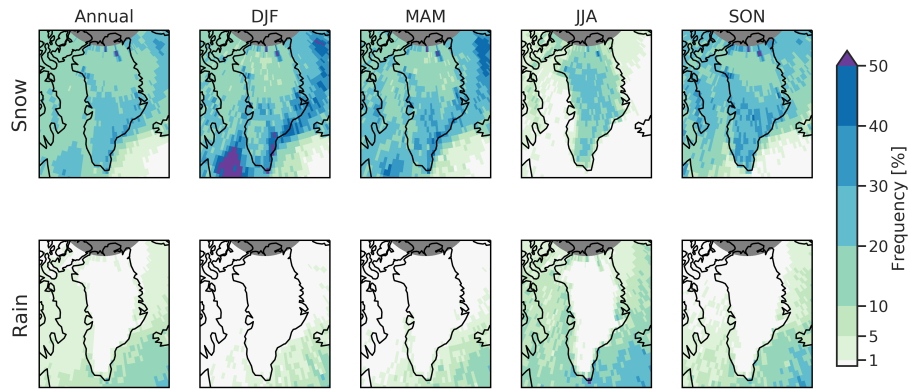
Figure 1. Annual (left) and seasonal (DJF, MAM, JJA, SON, from left to right) mean ~~snowfall~~ total snow (light snow + snow, top) and ~~rainfall~~ total rain (light rain + rain, bottom) frequency derived from CloudSat cloud-profiling radar (2CPC: 2006–2016).

between -15 and -5 and near-surface air temperature (T) < 273 K), 'snow' (dBZ > -5 and T < 273 K), 'light rain' (-15 < dBZ < -5 and T > 275 K), and 'rain' (dBZ > -5 or heavily attenuated, and T > 275 K) categories, as heavy precipitation (as defined by Kay et al. (2018)) does not occur on the GrIS. We define precipitation frequency as the ratio between the number of time steps with precipitation and the total number of time steps. If averaged across an area, such as the ice sheet or elevation bin, frequency is defined as the average frequency of all grid cells contained within that area. For more details regarding the methodology, refer to Kay et al. (2018).

2.2 Model simulations with CloudSat near-surface precipitation frequency diagnostics

We assess GrIS precipitation simulated by the Community Earth System Model (CESM) version 1 with the Community Atmosphere Model version 5 (CESM1-CAM5, CESM hereafter, Hurrell et al. (2013)). CloudSat near-surface precipitation frequency diagnostics were implemented in COSP version 1.4 (Kay et al., 2016b, 2018). While this study uses COSP1.4, the CloudSat-based diagnostics described here are also available for the broader scientific community within the latest COSP version, COSP 2 (Swales et al., 2018).

In order to evaluate present-day GrIS precipitation and to assess GrIS precipitation in a warmer future world, we ran CESM using the worst-case Representative Concentration Pathway (RCP) 8.5 greenhouse gas emissions scenario. The simulations span 90 years (2006 to 2095) and was initialized in 2006 from member 1 of the CESM1 Large Ensemble (Kay et al., 2015). The same simulation has been used to assess the influence of global warming on rising cloud heights (Takahashi et al., 2019).

4

3 Results

3.1 Present-day precipitation from CloudSat

First we explore the present-day spatial and temporal precipitation frequency patterns that have been observed by CloudSat from 2006 to 2016. Figure 1 shows the observed annual and seasonal mean spatial patterns of total snowfall (i.e. the sum of 'light snow' and 'snow') and rainfall (the sum of 'light rain' and 'rain') frequencies on the GrIS. The annual mean snowfall on the GrIS varies from ~10% in the dry, high-elevation northern GrIS, to >30% over Southeast Greenland. The interior experiences snowfall most frequently in the summer (JJA, >20%), whereas most snow in the coastal regions falls in winter (DJF), and to a less extent in Spring (MAM) and Fall (SON). Observed snowfall frequency over the oceans surrounding the GrIS is highest in the winter, particularly in the Labrador Sea (southwest of the GrIS), where winter snowfall frequency exceeds 50%. In summer, snowfall does not occur over the oceans around the GrIS. Rainfall over the interior of the GrIS is negligible throughout the entire year. Rain occurs in summer, albeit rarely ($< 10\%$),over the marginal, low-elevation zones of the GrIS. Summer rainfall frequency is largest over the North Atlantic ocean, southeast of the GrIS (>30%). Averaged across the GrIS, light snow and snow show similar seasonal cycles (Figure 2), and vary from 6% in summer to ~10% over the rest of year, with peaks in spring and fall. Light rain does not occur on the GrIS, and rain only occurs from June to September, with maximum values (~2%) in July and August.

A unique perspective on the CloudSat precipitation frequency climatology across the GrIS can be offered by analyzing their gradients with respect to surface elevation (Figure 3). Snow frequency varies moderately with elevation, and the highest snow frequencies (>20%) are found at the lowest elevations (< 200 m above sea level (a.s.l.)) as well as between 1500 and 2000 m a.s.l.. The latter maximum can be explained by the strong topographically forced snowfall in Southeast GrIS, where the maximum snowfall occurs at these elevations. When classifying the snow frequency, heavier snow peaks at these elevations and otherwise decreases with elevation, while light snow frequency clearly increases with height and dominates heavy snow above 2000 m a.s.l. (not shown). Rainfall frequency (which is dominated by rain, as light rain is almost zero everywhere (not shown)) does not exceed 2% anywhere on the GrIS, and rain is never observed above 2000 m a.s.l.. Note that, due to the hyperbolic shape of the GrIS and steep surface slopes along the margins, low-elevation areas occupy a very small fraction of the ice sheet, while higher-elevation areas occupy a much larger fraction. This implies that, although all areas below 2000 m a.s.l. experience rain, all these elevation bands combined only occupy $\approx 38\%$ of the ice sheet area.

3.2 Present-day precipitation from CESM

~~The patterns of precipitation frequency across the GrIS as simulated by CESM are mostly consistent with those derived by CloudSat~~ We first present the CESM precipitation frequencies (Figure 4), and then compare them directly to CloudSat (Figure 5). The highest snowfall frequencies produced by CESM are found in the oceanic regions neighbouring the GrIS, the North Atlantic and Baffin Bay along the southwest GrIS coast, in concert with what CloudSat shows. On the ice sheet, snowfall frequency is highest in the south (>40%), and decreases northward to low values of <20% in the high-elevation interior. CESM simulates a clear seasonal cycle in snowfall frequency, with highest frequency in winter and lowest in summer. CESM
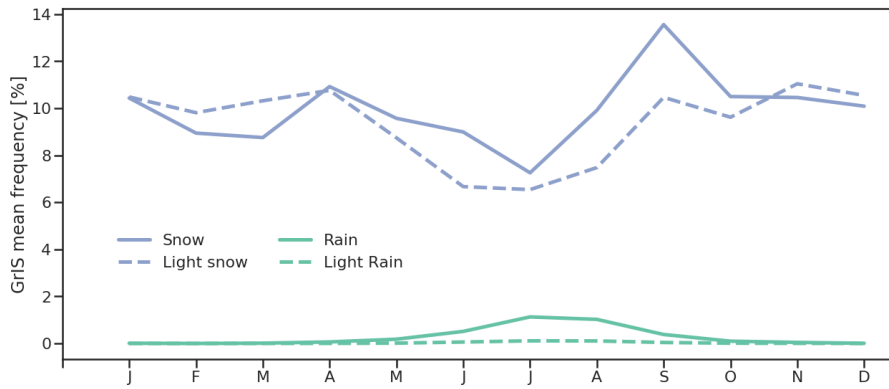
Figure 2. Seasonal cycle (January to December) of Greenland Ice Sheet averaged snowfall, light snowfall (blue: solid, dashed) and rainfall, light rainfall (green: solid, dashed) frequency obtained by CloudSat cloud-profiling radar observations (2CPC: 2006–2016).
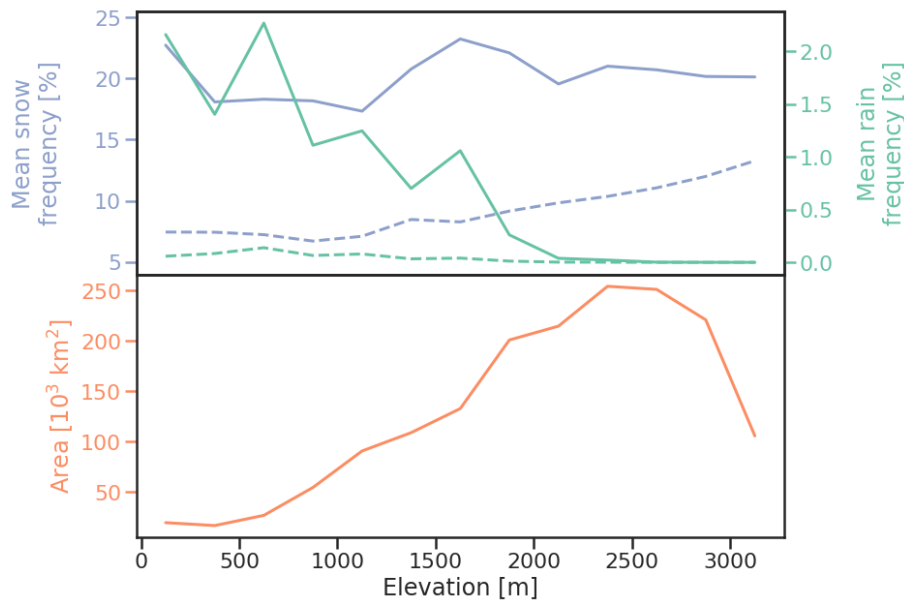

Figure 3. Top: CloudSat 2CPC (2006–2016 average) Greenland Ice Sheet snow, light snow (blue: solid, dashed) and rain, light rain (green: solid, dashed) frequency in 250-m elevation bins based on Greenland Ice sheet Mapping Project (GIMP, Howat et al. (2014)) topography. Bottom: total ice sheet grid-cell surface area in each of these elevation bins according to GIMP.

produces rainfall on the oceans around Greenland during most of the year, while GrIS rainfall is constrained to the summer season, and limited to the coastal regions.

Next, we compare the CESM simulated precipitation frequency on the GrIS to the frequencies derived by CloudSat (Figure 5). Snowfall frequency over the GrIS is generally overestimated by CESM, especially in winter and fall (>15%). Over the
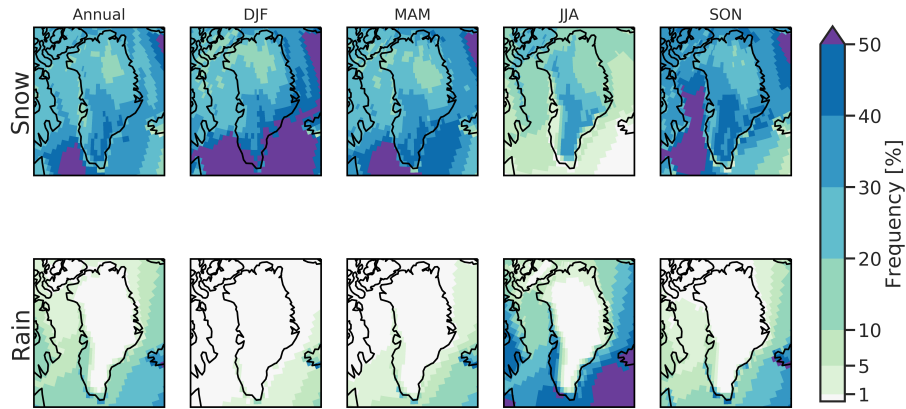
Figure 4. Present-day, annual (left) and seasonal (DJF, MAM, JJA, SON, from left to right) mean total snowfall (light snow + snow, top) and total rainfall (light rain + rain, bottom) frequency as simulated by CESM (2006–2020).
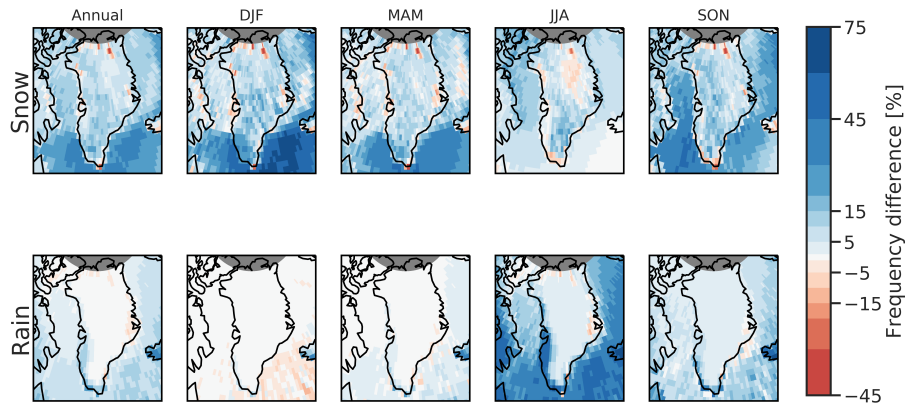

Figure 5. Present-day, annual (left) and seasonal (DJF, MAM, JJA, SON, from left to right) mean snowfall (top) and rainfall (bottom) frequency as simulated by difference between CESM (2006–2020) relative to and CloudSat 2CPC (2006–2016). Positive values indicate that CESM overestimates precipitation frequency relative to CloudSat.

surrounding oceans, CESM clearly produces more frequent snowfall than CloudSat, with up to 75% more frequent snowfall in the North Atlantic in winter. In contrast, interior GrIS summer snowfall frequency is slightly lower in CESM than in CloudSat. In contrast with CloudSat, CESM only produces rainfall in the low-elevation GrIS coastal zones, and in summer, but the rain frequencies are clearly overestimated, especially over the western GrIS ablation zone and the oceans. CESM produces slightly lower rain frequencies in the North Atlantic compared to CloudSat in winter.

The seasonal cycle of precipitation frequency averaged over the GrIS, as shown in Figure 6, highlights seasonal variations in light snow and light rain frequencies as simulated by CESM. In summer, the only season in which light rain occurs according to CESM, the simulated light snow frequency is smaller than in the other seasons. Throughout most of the year, the simulated
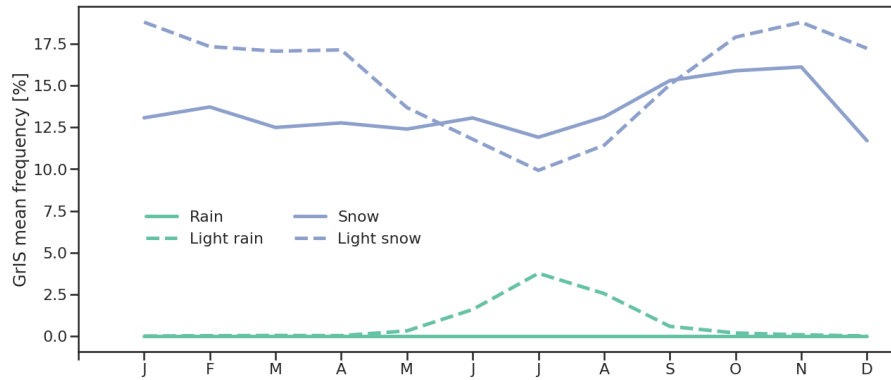
Figure 6. Present-day, Greenland Ice Sheet averaged snowfall, light snowfall (blue: solid, dashed) and rainfall, light rainfall (green: solid, dashed) frequency as simulated by CESM (2006–2020).
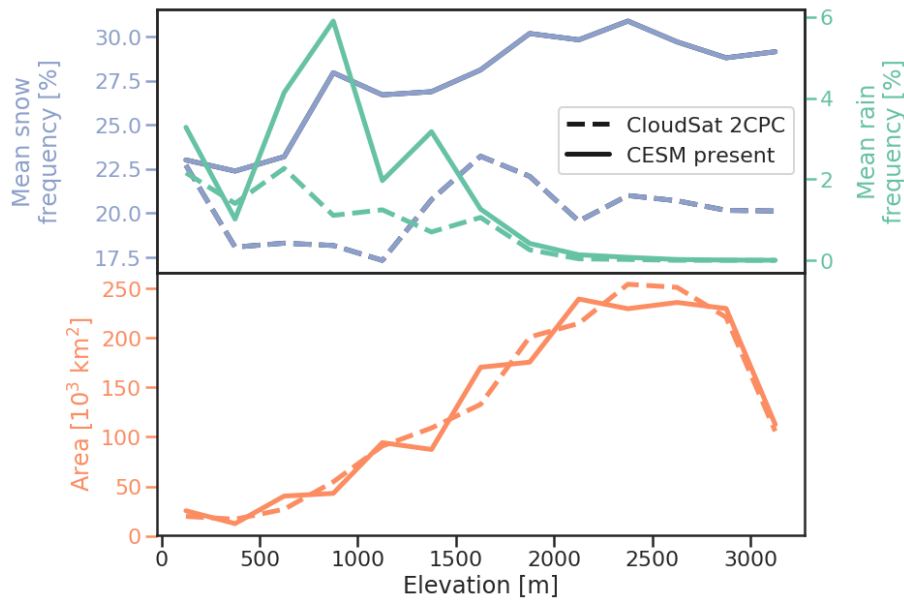
Figure 7. Top: Present-day, Greenland Ice Sheet averaged total snow (blue) and total rain (green) frequency in 250-m elevation bins based on GIMP topography, according to CloudSat 2CPC (dashed, 2006–2015) and CESM (solid, 2006–2020). Bottom: total ice sheet grid-cell surface area in each of these elevation bins according to CloudSat (dashed) and CESM (solid).

light snow contributes more to the total snowfall frequency than the heavier snow. This heavier snow also exhibits less of a seasonal variability than the light snow. Similarly, light rain dominates the total rainfall across the Greenland ice sheet, as heavier rain does not occur.
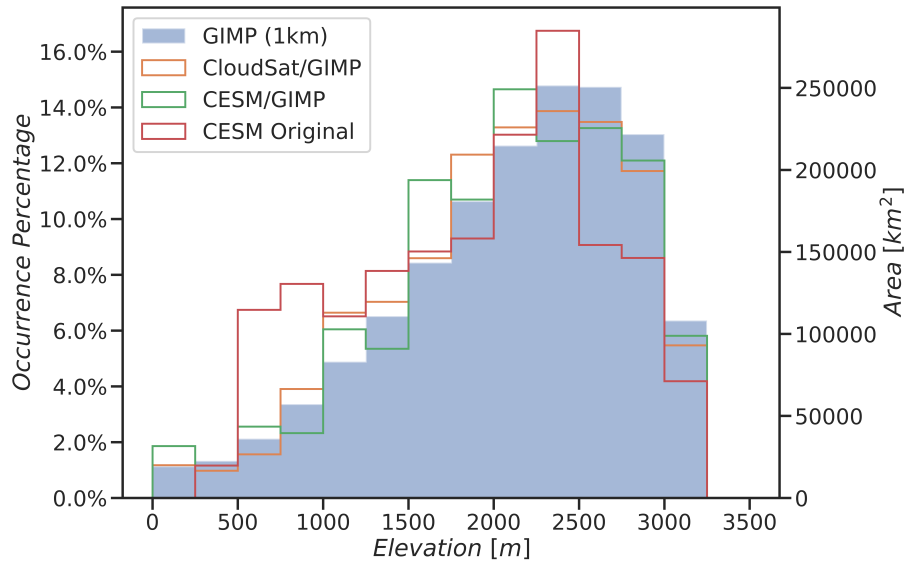
Figure 8. Comparison of GrIS hypsometry in GIMP (grey), CloudSat regridded to GIMP (orange), CESM regridded to GIMP (green), and original CESM (red).

Analyzing the differences between CESM and CloudSat with respect to elevation across the GrIS (Figure 7), we see that CESM overestimates snowfall frequencies with 5 to 10% at all elevations. CESM also produces an increase of snow frequency with elevations from the coast to 2000 m a.s.l., which is not confirmed by CloudSat. With regards to rain, CESM clearly produces too high frequencies at lower elevations (double to triple the CloudSat frequency). On the other hand, the model
5 correctly simulates the clear decrease in rain frequency above 1500 m a.s.l., and agrees with CloudSat in that it simulates no rain above 2000 m a.s.l..

A part of these discrepancies between CESM and CloudSat may be ascribed to CESM (at its horizontal resolution of 1 degree) not resolving the steep topography and related surface climate and precipitation gradients of the marginal GrIS. This is illustrated in Figure 8, which shows that the original CESM grid overestimates the extent of low-elevation areas and
10 underestimates the extent of high-elevation areas of the GrIS. While we have attempted to correct for this by regridding the CESM results to the ~~GIMP grid~~ Greenland Ice sheet Mapping Project grid (1 x 1 km), which virtually removes this bias (green line in Figure 8), this implies that the CESM atmospheric model 'feels' a lower topography of the coastal GrIS than in reality, enhancing atmospheric and surface temperatures and rain in these elevations. However, since the model also produces too much snow at these elevations, we conclude that CESM tends to exaggerate the precipitation frequency of both snow and
15 rain across the GrIS, rather than attributing the incorrect phase to precipitation. While acknowledging these model biases in absolute precipitation frequencies, we argue that, overall, CESM reproduces the spatial patterns and seasonal cycle of snow and rain frequency satisfactorily well. This allows us to use CESM to analyze future changes in precipitation frequency on the GrIS.
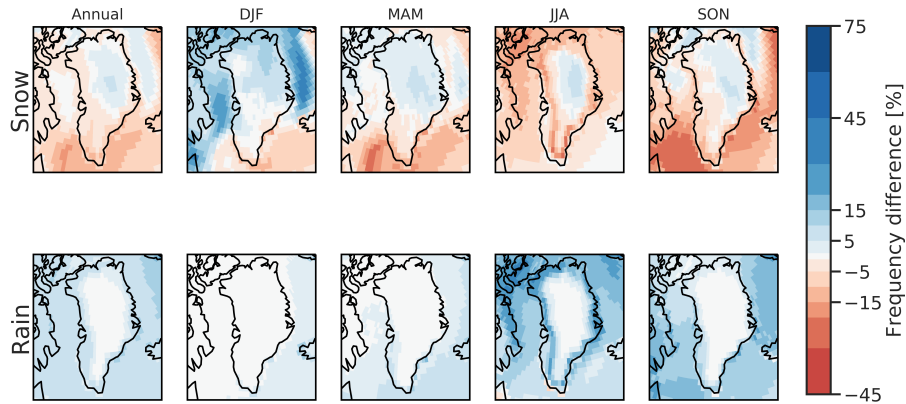
Figure 9. Annual (left) and seasonal (DJF, MAM, JJA, SON, from left to right) mean snowfall (top) and rainfall (bottom) frequency difference from present to future over the Greenland Ice Sheet simulated by CESM (present: 2006–2020 and future: 2080–2095).

3.3 Future changes in precipitation frequency

Next we use CESM with the radar simulator to analyze 21st century changes in the GrIS precipitation characteristics. To do so, we compare the final 15-year period (2080-2095) of our simulation (referred to CC future) to our baseline CC present period (2006-2020).

5   The 21st century changes in precipitation frequency, as depicted in Figure 9, are substantial over the entire ice sheet. Across the south and much of the coast of the GrIS, annual snowfall frequency decreases by up to 10%. This contrasts the interior of the ice sheet, where annual snowfall frequency increases by up to 10%. This coastal decrease and interior increase is most clearly present in the summer (JJA), when coastal decreases in snow frequency exceed 20% to up to 40% in the southern GrIS. The increase in GrIS interior snow frequency is consistent throughout all seasons~~, and most prominent in winter~~

10 ~~(DJF). Snowfall~~ . The strongest increase in snow frequency occurs in winter, which is the season with the strongest simulated temperature increase in CESM (Peings et al., 2017). Snowfall and temperature are strongly correlated at low temperatures, since the Clausius-Clapeyron relationship dictates that the atmospheric saturation vapor pressure exponentially increases with temperature.Snowfall frequency over the oceanic regions surrounding the GrIS decreases throughout much of the year, although strong increases to the north are noted in winter, and to a lesser extent, in spring and fall. This snowfall increase is

15 potentially associated with sea ice loss in these regions in the 21st century. More open water leads to enhanced atmospheric instability, condensation, and precipitation.

Rain frequency change shows a much more homogeneous signal across the GrIS and neighboring oceans (Figure 9). Annual rain frequency increases with 5-15% across the entirety of coastal GrIS, which essentially leads to a doubling of the present-day CESM rain frequency in these regions. While the winter season is still too cold for any rain on the GrIS at the end of the 21st

20 century, rainfall occurs more frequently in spring, summer, and fall, and this frequency increase peaks in summer.
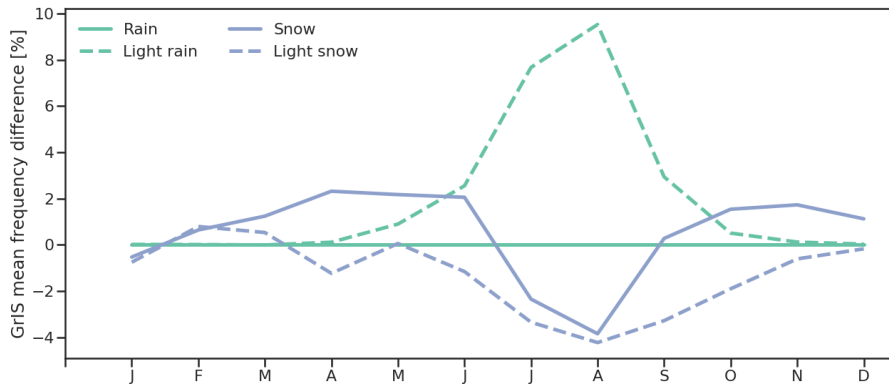
Figure 10. Greenland Ice Sheet averaged snowfall, light snowfall (blue: solid, dashed) and rainfall, light rainfall (green: solid, dashed) frequency difference between future (2080–2095) and present (2006–2020), as simulated by CESM.

Averaged over the GrIS (Figure 10), the change in heavier snow frequency is slightly positive (0 to 2%) in winter, and negative in summer (down to -4% in August). Light snow frequency only changes substantially from June to October, with a decrease that also peaks in August (-4%). While heavier rain still doesn't occur on the GrIS at the end of the 21st century, light rain clearly increases, and dominates the change in snow frequency. At the end of the 21 century, light rain occurs in all months

5 outside the core winter (November to March), which suggests that the rain-occurring season is extended with about 4 months relative to the present (Figure 6). In summer, the increase of light rain frequency peaks at almost 10%, which implies that rain frequency more than triples in summer relative to the present.

The increase in (light) rain frequency is apparent over most of the GrIS (Figure 11), with roughly a tripling of rain frequency at all elevations below 2500 m a.s.l.. End of the 21 st century rain frequency varies between 7 to 13% at elevations between

10 0 and 1500 m a.s.l., and decreases sharply above that elevation. However, the area of the GrIS that experiences at least some rain clearly extends inward and to higher elevations. Rain is projected to occur at elevations up to 2500 m a.s.l., in comparison to <2000 m a.s.l. in the present-day period. This exposes an additional area of >250,000 km^2 (>15%) of the GrIS to liquid precipitation. In comparison to the rain changes, the changes in snow frequency are relatively small, with a small (0-2 %) decrease in snow frequency below 2500 m a.s.l., and a small increase (up to 2%) above that elevation, on the high GrIS interior.

15 The relative minor change in snow frequency indicates that the increase in rain frequency is not completely compensated for a decrease in snow frequency. This finding signals that overall precipitation frequency is increasing over the GrIS, with an increase of rain dominating over the entire ice sheet but the highest elevations, where rain does not occur and snow frequency increases.
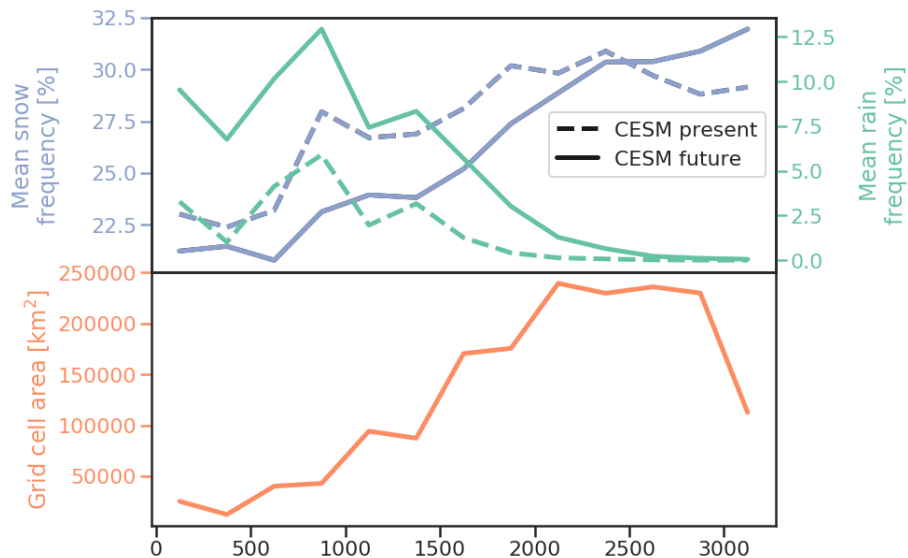
Figure 11. Top: Future (2080–2095) (solid) and present (2006–2020) (dashed) Greenland Ice Sheet snow (blue) and rain (green) frequency in 250-m elevation bins based on GIMP topography, as simulated by CESM. Bottom: total ice sheet ~~grid-cell~~ surface area in each of these elevation bins according to GIMP.

4   Discussion and conclusions

In this paper, we used observations derived from active radar remote sensing (CloudSAT) and simulations with the Community Earth System Model to characterize precipitation frequency over the Greenland Ice Sheet. For the present-day climate, the observations show that snowfall occurs frequently over the GrIS, with variations (1) in snowfall classification (light and heavier snow occur approximately equally frequently), (2) temporally throughout the year, and (3) spatially across the ice sheet. Rainfall, on the other hand, is rare, and only occurs in summer and at elevations below 2000 m a.s.l.. Our CloudSat results align well with previous studies. The snowfall frequency maximum of >30% over Southeast Greenland is consistent with various modeling results (Schuenemann et al., 2009; Hakuba et al., 2012; Berdahl et al., 2018, e.g.,). The summer maximum in snowfall in the GrIS interior is confirmed by ground observations at Summit station (Castellani et al., 2015; Pettersen et al., 2018).

These observations were subsequently used to evaluate precipitation frequency output generated by CESM. The model is equipped with a satellite simulator, which allows for a consistent 'apples-to-apples' comparison with the observations. The results showed that, while CESM overestimates precipitation frequency on the GrIS overall, the model shows a realistic seasonal cycle and spatial gradients. The differences between CESM and CloudSat are, at least partly, ascribed by the limited horizontal resolution (around 1 degree) of both products. Here we show that topography smoothing in CESM leads to underestimated precipitation frequency along the GrIS edges. While the native resolution of CloudSat is much higher (around 1 km), the

12
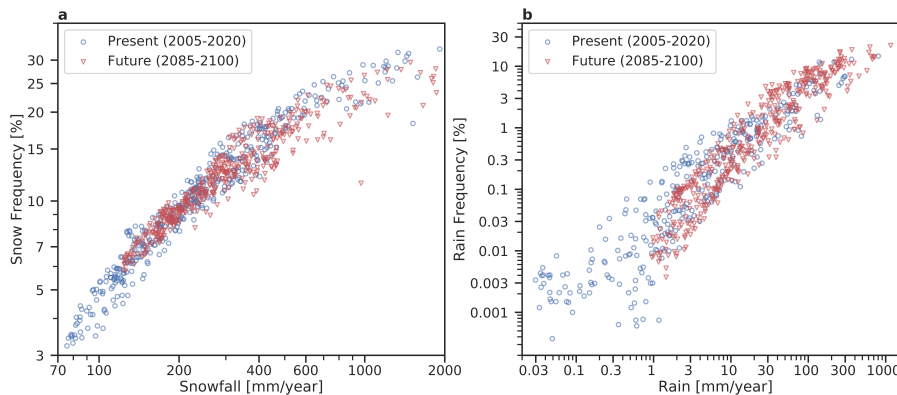
Figure 12. CESM simulated snowfall frequency (a) and rainfall frequency (light rain only, b) versus CESM simulated snowfall and rainfall rates in the present (2006–2020, blue circles) and future (2080–2095, red triangles).

aggregation of these observations in a 1 x 1 grid, along with ground clutter issues in steep topography, likely degrades the quality of this CloudSat product in accurately representing precipitation in the coastal regions of the GrIS (Bennartz et al., 2019).

To then analyze future changes in GrIS precipitation frequency, we analyzed CESM output for the end of the 21st century. The model suggests dramatic changes in the occurrence of rainfall, with rain occurrence extending in time (from April to

5   October) and at much higher elevations (up to 2500 m a.s.l.). In contrast, snow frequency changes only marginally, and only increases across the high-elevation GrIS.

The comparison between CESM and CloudSat revealed clear biases in the simulated snow and rain frequency. This result is consistent with the work of McIlhattan et al. (2017), who showed that the overestimated CESM snowfall frequency is potentially related to a exaggerated growth of cloud ice in expense of supercooled cloud liquid water in the model. The lack of

10   supercooled liquid in polar clouds in CESM has been reported on previously (Miller et al., 2018; Kay et al., 2016a), and leads to substantial biases in surface downwelling longwave radiation and surface temperature (Kay et al., 2016a), and GrIS surface melting.

Carefully recognizing these CESM biases, caution is warranted when quantitatively assessing simulated changes in the precipitation frequency throughout the 21st century. Doing so, we suggest to focus particularly on relative changes simulated

15   by CESM, which are likely more robust than the absolute changes. For example, while the absolute change in rainfall frequency is likely biased because the present-day rainfall frequency is overestimated, the simulated tripling of GrIS rainfall frequency is potentially a more robust change. In addition, this study only uses one climate model and one climate change scenario; to further test the robustness of our findings, future work should focus on using other models, with a satellite simulator embedded, and apply various climate change scenarios. Also, this study focuses on future changes in precipitation only, and does not give

20   a more general overview of future climate change on the GrIS that is provided by other studies using different versions of CESM (e.g., Vizcaíno et al., 2013; Muntjewerf et al., 2020).

Interpreting the relevance of these 21st century changes in precipitation frequency for the GrIS climate and mass balance, an outstanding question is how frequency relates to mass. For example, as rainfall frequency increases, does that imply that there is more mass of rain added to the GrIS surface? As we do not have reliable observations of precipitation fluxes from CloudSat, we use CESM to analyze the relation between snow and rain frequency and the representative precipitation fluxes
5 (Figure 12). Interestingly, for both snow and rain, the relation between precipitation frequency and rate apparent, with a near-linear increase in flux with frequency at low frequencies, and a much larger increase of flux with frequency as frequencies are higher. This relation, as suggested by CESM, indicates that even for small changes in precipitation frequency, precipitation rates change considerably; for example, an increase of snow frequency from 10 to 15% is associated with an approximate doubling in snowfall rate (200 to 400 mm per year). That implies that a dramatic increase in rainfall frequency, as suggested
10 by CESM, will be associated with much more rain on the GrIS. This has potential dramatic consequences for the GrIS surface conditions. In the GrIS ablation zone, slightly less snow in winter, and more rain in the transition seasons, will lead to more rapid degradation of the winter snowpack, expediting exposure of bare ice in Spring and delaying ice burial in Fall. Rain falling on ice will decrease surface albedo, further enhancing melt, and the rain water will collect in surface lakes and streams that eventually end up in the ocean. In the percolation zone, less snow and much more rain will affect the storage capacity of the
15 firn, and near-surface ice layer formation will lead to more rapid runoff of melt water. As CESM suggests an up- and inward migration of the zone where rain occurs, a much larger area of the GrIS will be prone to summer runoff. Finally, the areas above 2500 m a.s.l., where our results indicate that snowfall increases slightly and rain still does not occur, will likely experience slight surface thickening.

In addition to understanding the impact of changing precipitation frequency on the GrIS surface, our methodology can be
20 used to assess what a future ~~CloudSat~~ CloudSat-style mission would observe in terms of changes in GrIS precipitation. Cloud radars are, and will remain, essential to continually monitor polar precipitation, for a variety of reasons. Firstly, they measure at the right frequency: cloud radars (94 GHz such as CloudSat) provide the only spaceborne radar observations of high-latitude precipitation that have ever been made. Future missions currently will have this frequency: ESA's EarthCARE (https://earth.esa. int/web/guest/missions/esa-future-missions/earthcare; to be launched 2021) and NASA's ACCP mission (https://science.nasa.
25 gov/earth-science/decadal-accp). In contrast, lower frequency precipitation radars (e.g., TRMM, GPM) cannot detect light precipitation, which commonly occurs at high latitudes, including Greenland (as shown in this study). Secondly, CloudSat regularly samples the high latitude regions, whereas precipitation radars typically do not sample high latitude regions. Future cloud radar missions should continue to consider (near-)polar orbits to include high latitudes. Thirdly, co-locating spaceborne cloud radar with spaceborne lidar can help with assessment of light precipitation and precipitation phase. While our study only
30 focused on CloudSat, future work should complement CloudSat radar retrievals with collocated CALIPSO lidar information to study high latitude precipitation. Both the future EarthCARE and ACCP missions plan to include complimentary radar and lidar retrievals. Unfortunately, CloudSat only provides a 'curtain view' of cloud and precipitation vertical structures at high latitudes, and still provides relatively limited temporal coverage. Creative ways to combine CloudSat-like observations with meteorology can help isolate process-based relationships (e.g., Morrison et al., 2018; Gallagher et al., 2020). However, long-term (decadal
35 or longer) data records are likely needed to isolate change from internal variability. For planning future Earth-observing mis-

sions, satellite simulators can give a preliminary peek into potential findings~~.~~, and provide initial assessments of how long a data record is needed to detect Greenland precipitation changes due to climate change. We suggest that future work leverages these tools, which has already been done for non-polar regions (e.g., Takahashi et al., 2019).

~~Comparison of GrIS hypsometry in GIMP (grey), CloudSat regridded to GIMP (orange), CESM regridded to GIMP (green), and original CESM (red).~~

10 *Competing interests.* The authors declare no competing interests.

References

Belleflamme, A., Fettweis, X., and Erpicum, M.: Recent summer Arctic atmospheric circulation anomalies in a historical perspective, The Cryosphere, 9, 53–64, https://doi.org/10.5194/tc-9-53-2015, https://www.the-cryosphere.net/9/53/2015/, 2015.

Bennartz, R., Fell, F., Pettersen, C., Shupe, M. D., and Schuettemeyer, D.: Spatial and temporal variability of snowfall over Greenland from CloudSat observations, Atmospheric Chemistry and Physics Discussions, pp. 1–32, https://doi.org/10.5194/acp-2018-1045, https://www.atmos-chem-phys-discuss.net/acp-2018-1045/, 2019.

Berdahl, M., Rennermalm, A., Hammann, A., Mioduszweski, J., Hameed, S., Tedesco, M., Stroeve, J., Mote, T., Koyama, T., and McConnell, J. R.: Southeast Greenland Winter Precipitation Strongly Linked to the Icelandic Low Position, Journal of Climate, 31, 4483–4500, https://doi.org/10.1175/JCLI-D-17-0622.1, https://doi.org/10.1175/JCLI-D-17-0622.1, 2018.

Bodas-Salcedo, A., Webb, M. J., Bony, S., Chepfer, H., Dufresne, J.-L., Klein, S. A., Zhang, Y., Marchand, R., Haynes, J. M., Pincus, R., John, V. O., Bodas-Salcedo, A., Webb, M. J., Bony, S., Chepfer, H., Dufresne, J.-L., Klein, S. A., Zhang, Y., Marchand, R., Haynes, J. M., Pincus, R., and John, V. O.: COSP: Satellite simulation software for model assessment, Bulletin of the American Meteorological Society, 92, 1023–1043, https://doi.org/10.1175/2011BAMS2856.1, 2011.

Boening, C., Lebsock, M., Landerer, F., and Stephens, G.: Snowfall-driven mass change on the East Antarctic ice sheet, Geophysical Research Letters, 39, https://doi.org/10.1029/2012GL053316, http://dx.doi.org/10.1029/2012GL053316, 2012.

Castellani, B. B., Shupe, M. D., Hudak, D. R., and Sheppard, B. E.: The annual cycle of snowfall at Summit, Greenland, Journal of Geophysical Research: Atmospheres, 120, 6654–6668, https://doi.org/10.1002/2015JD023072, https://doi.org/10.1002/2015JD023072, 2015.

Csatho, B. M., Schenk, A. F., van der Veen, C. J., Babonis, G., Duncan, K., Rezvanbehbahani, S., van den Broeke, M. R., Simonsen, S. B., Nagarajan, S., and van Angelen, J. H.: Laser altimetry reveals complex pattern of Greenland Ice Sheet dynamics., Proceedings of the National Academy of Sciences of the United States of America, 111, 18 478–83, https://doi.org/10.1073/pnas.1411680112, http://www.ncbi.nlm.nih.gov/pubmed/25512537http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4284527, 2014.

Ellis, T. D., L'Ecuyer, T., Haynes, J. M., and Stephens, G. L.: How often does it rain over the global oceans? The perspective from CloudSat, Geophysical Research Letters, 36, https://doi.org/doi:10.1029/2008GL036728, https://doi.org/10.1029/2008GL036728, 2009.

Enderlin, E. M., Howat, I. M., Jeong, S., Noh, M. J., Van Angelen, J. H., and Van Den Broeke, M. R.: An improved mass budget for the Greenland ice sheet, Geophysical Research Letters, 41, 866–872, https://doi.org/10.1002/2013GL059010, http://doi.wiley.com/10.1002/2013GL059010, 2014.

Fettweis, X., Franco, B., Tedesco, M., van Angelen, J. H., Lenaerts, J. T. M., van den Broeke, M. R., and Gallée, H.: Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR, The Cryosphere, 7, 469–489, https://doi.org/10.5194/tc-7-469-2013, http://www.the-cryosphere.net/7/469/2013/tc-7-469-2013.htmlhttps://www.the-cryosphere.net/7/469/2013/, 2012.

Fettweis, X., Hanna, E., Lang, C., Belleflamme, A., Erpicum, M., and Gallée, H.: &lt;i&gt;Brief communication&lt;/i&gt; &quot;Important role of the mid-tropospheric atmospheric circulation in the recent surface melt increase over the Greenland ice sheet&quot;, The Cryosphere, 7, 241–248, https://doi.org/10.5194/tc-7-241-2013, https://www.the-cryosphere.net/7/241/2013/, 2013.

Fettweis, X., Hofer, S., Krebs-Kanzow, U., Amory, C., Aoki, T., Berends, C. J., Born, A., Box, J. E., Delhasse, A., Fujita, K., Gierz, P., Goelzer, H., Hanna, E., Hashimoto, A., Huybrechts, P., Kapsch, M.-L., King, M. D., Kittel, C., Lang, C., Langen, P. L., Lenaerts, J. T. M., Liston, G. E., Lohmann, G., Mernild, S. H., Mikolajewicz, U., Modali, K., Mottram, R. H., Niwano, M., Noël, B., Ryan, J. C.,

Smith, A., Streffing, J., Tedesco, M., van de Berg, W. J., van den Broeke, M., van de Wal, R. S. W., van Kampenhout, L., Wilton, D., Wouters, B., Ziemen, F., and Zolles, T.: GrSMBMIP: Intercomparison of the modelled 1980–2012 surface mass balance over the Greenland Ice sheet, The Cryosphere Discussions, 2020, 1–35, https://doi.org/10.5194/tc-2019-321, https://www.the-cryosphere-discuss.net/tc-2019-321/, 2020.

5 Forster, R. R., Box, J. E., van den Broeke, M. R., Miège, C., Burgess, E. W., Van Angelen, J. H., Lenaerts, J. T. M., Koenig, L. S., Paden, J., Lewis, C., Gogineni, S. P., Leuschen, C., and McConnell, J. R.: Extensive liquid meltwater storage in firn within the Greenland ice sheet, Nature Geoscience, 7, 95–98, https://doi.org/10.1038/ngeo2043, http://www.nature.com/doifinder/10.1038/ngeo2043http://www.nature.com/articles/ngeo2043, 2014.

Gallagher, M. R., Chepfer, H., Shupe, M. D., and Guzman, R.: Warm Temperature Extremes Across Greenland Connected to Clouds, Geo-
10 physical Research Letters, 47, e2019GL086059, https://doi.org/10.1029/2019GL086059, https://doi.org/10.1029/2019GL086059, 2020.

Hakuba, M. Z., Folini, D., Wild, M., and Schär, C.: Impact of Greenland's topographic height on precipitation and snow accumulation in idealized simulations, Journal of Geophysical Research: Atmospheres, 117, https://doi.org/10.1029/2011JD017052, https://doi.org/10.1029/2011JD017052, 2012.

Haynes, J. M., Marchand, R. T., Luo, Z., Bodas-Salcedo, A., and Stephens, G. L.: A Multipurpose Radar Simulation Package: QuickBeam,
15 Bulletin of the American Meteorological Society, 88, 1723–1728, https://doi.org/10.1175/BAMS-88-11-1723, https://doi.org/10.1175/BAMS-88-11-1723, 2007.

Haynes, J. M., L'Ecuyer, T. S., Stephens, G. L., Miller, S. D., Mitrescu, C., Wood, N. B., and Tanelli, S.: Rainfall retrieval over the ocean with spaceborne W-band radar, Journal of Geophysical Research: Atmospheres, 114, https://doi.org/doi:10.1029/2008JD009973, https://doi.org/10.1029/2008JD009973, 2009.

20 Howat, I. M., Negrete, A., and Smith, B. E.: The Greenland Ice Mapping Project (GIMP) land classification and surface elevation data sets, Cryosph., 8, 1509–1518, https://doi.org/10.5194/tc-8-1509-2014, http://www.the-cryosphere.net/8/1509/2014/tc-8-1509-2014.html, 2014.

Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., Lamarque, J. F., Large, W. G., Lawrence, D., Lindsay, K., Lipscomb, W. H., Long, M. C., Mahowald, N., Marsh, D. R., Neale, R. B., Rasch, P., Vavrus, S., Vertenstein, M., Bader, D., Collins,
25 W. D., Hack, J. J., Kiehl, J., and Marshall, S.: The Community Earth System Model: A framework for collaborative research, Bulletin of the American Meteorological Society, 94, 1339–1360, https://doi.org/10.1175/BAMS-D-12-00121.1, 2013.

Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J. M., Bates, S. C., Danabasoglu, G., Edwards, J., Holland, M., Kushner, P., Lamarque, J. F., Lawrence, D., Lindsay, K., Middleton, A., Munoz, E., Neale, R., Oleson, K., Polvani, L., and Vertenstein, M.: The community earth system model (CESM) large ensemble project : A community resource for studying climate change in the
30 presence of internal climate variability, Bulletin of the American Meteorological Society, 96, 1333–1349, https://doi.org/10.1175/BAMS-D-13-00255.1, 2015.

Kay, J. E., Bourdages, L., Miller, N. B., Morrison, A., Yettella, V., Chepfer, H., and Eaton, B.: Evaluating and improving cloud phase in the Community Atmosphere Model version 5 using spaceborne lidar observations, Journal of Geophysical Research: Atmospheres, 121, 4162–4176, https://doi.org/10.1002/2015JD024699, 2016a.

35 Kay, J. E., Wall, C., Yettella, V., Medeiros, B., Hannay, C., Caldwell, P., and Bitz, C.: Global Climate Impacts of Fixing the Southern Ocean Shortwave Radiation Bias in the Community Earth System Model (CESM), Journal of Climate, 29, 4617–4636, https://doi.org/10.1175/JCLI-D-15-0358.1, 2016b.

Kay, J. E., L'Ecuyer, T., Pendergrass, A., Chepfer, H., Guzman, R., and Yettella, V.: Scale-Aware and Definition-Aware Evaluation of Modeled Near-Surface Precipitation Frequency Using CloudSat Observations, Journal of Geophysical Research: Atmospheres, 123, 4294–4309, https://doi.org/doi:10.1002/2017JD028213, 2018.

King, M. D., Howat, I. M., Jeong, S., Noh, M. J., Wouters, B., Noël, B., and van den Broeke, M. R.: Seasonal to decadal variability in ice discharge from the Greenland Ice Sheet, The Cryosphere, 12, 3813–3825, https://doi.org/10.5194/tc-12-3813-2018, https://www.the-cryosphere.net/12/3813/2018/, 2018.

Kjær, K. H., Khan, S. A., Korsgaard, N. J., Wahr, J., Bamber, J. L., Hurkmans, R., van den Broeke, M., Timm, L. H., Kjeldsen, K. K., Bjørk, A. A., Larsen, N. K., Jørgensen, L. T., Færch-Jensen, A., and Willerslev, E.: Aerial Photographs Reveal Late–20th-Century Dynamic Ice Loss in Northwestern Greenland, Science, 337, 569 LP – 573, https://doi.org/10.1126/science.1220614, http://science.sciencemag.org/content/337/6094/569.abstract, 2012.

Kjeldsen, K., Korsgaard, N., Bjørk, A., Khan, S., Box, J., Funder, S., Larsen, N., Bamber, J., Colgan, W., van den Broeke, M., Siggaard-Andersen, M.-L., Nuth, C., Schomacker, A., Andresen, C., Willerslev, E., and Kjær, K.: Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since AD 1900, Nature, 528, 396, https://doi.org/10.1038/nature16183http://10.0.4.14/nature16183, 2015.

Lemonnier, F., Madeleine, J.-B., Claud, C., Palerme, C., Genthon, C., L'Ecuyer, T., and Wood, N. B.: CloudSat-Inferred Vertical Structure of Snowfall Over the Antarctic Continent, Journal of Geophysical Research: Atmospheres, 125, e2019JD031 399, https://doi.org/10.1029/2019JD031399, https://doi.org/10.1029/2019JD031399, 2020.

Lenaerts, J. T. M., van Den Broeke, M. R., van Angelen, J. H., van Meijgaard, E., and Déry, S. J.: Drifting snow climate of the Greenland ice sheet: a study with a regional climate model, The Cryosphere, 6, 891–899, https://doi.org/10.5194/tc-6-891-2012, 2012.

Lenaerts, J. T. M., Medley, B., van den Broeke, M. R., and Wouters, B.: Observing and Modeling Ice Sheet Surface Mass Balance, Reviews of Geophysics, 57, 376–420, https://doi.org/10.1029/2018RG000622, 2019.

Lewis, G., Osterberg, E., Hawley, R., Marshall, H. P., Meehan, T., Graeter, K., McCarthy, F., Overly, T., Thundercloud, Z., and Ferris, D.: Recent precipitation decrease across the western Greenland ice sheet percolation zone, The Cryosphere, 13, 2797–2815, https://doi.org/10.5194/tc-13-2797-2019, https://www.the-cryosphere.net/13/2797/2019/, 2019.

McIlhattan, E. A., L'Ecuyer, T. S., and Miller, N. B.: Observational Evidence Linking Arctic Supercooled Liquid Cloud Biases in CESM to Snowfall Processes, Journal of Climate, https://doi.org/10.1175/JCLI-D-16-0666.1, 2017.

McIlhattan, E. A., Pettersen, C., Wood, N. B., and L'Ecuyer, T. S.: Satellite Observations of Snowfall Regimes over the Greenland Ice Sheet, The Cryosphere Discussions, 2019, 1–40, https://doi.org/10.5194/tc-2019-223, https://www.the-cryosphere-discuss.net/tc-2019-223/, 2019.

Milani, L., Kulie, M. S., Casella, D., Dietrich, S., L'Ecuyer, T. S., Panegrossi, G., Porcù, F., Sanò, P., and Wood, N. B.: 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, https://doi.org/10.1016/j.atmosres.2018.05.015, https://doi.org/10.1016/j.atmosres.2018.05.015, 2018.

Miller, N. B., Shupe, M., Lenaerts, J. T. M., Kay, J., de Boer, G., and Bennartz, R.: Process-Based Model Evaluation Using Surface Energy Budget Observations in Central Greenland, Journal of Geophysical Research: Atmospheres, https://doi.org/10.1029/2017JD027377, 2018.

Montgomery, L., Koenig, L., Lenaerts, J. T., and Kuipers Munneke, P.: Accumulation rates (2009-2017) in Southeast Greenland derived from airborne snow radar and comparison with regional climate models, Annals of Glaciology, pp. 1–9, https://doi.org/10.1017/aog.2020.8, https://www.cambridge.org/core/product/identifier/S0260305520000087/type/journal_article, 2020.

Morlighem, M., Williams, C. N., Rignot, E., An, L., Arndt, J. E., Bamber, J. L., Catania, G., Chauché, N., Dowdeswell, J. A., Dorschel, B., Fenty, I., Hogan, K., Howat, I., Hubbard, A., Jakobsson, M., Jordan, T. M., Kjeldsen, K. K., Millan, R., Mayer, L., Mouginot, J., Noël, B. P., O'Cofaigh, C., Palmer, S., Rysgaard, S., Seroussi, H., Siegert, M. J., Slabon, P., Straneo, F., van den Broeke, M. R., Weinrebe, W., Wood, M., and Zinglersen, K. B.: BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam

5   Echo Sounding Combined With Mass Conservation, Geophysical Research Letters, 44, 051–11, https://doi.org/10.1002/2017GL074954, http://doi.wiley.com/10.1002/2017GL074954, 2017.

Morrison, A. L., Kay, J. E., Chepfer, H., Guzman, R., and Yettella, V.: Isolating the Liquid Cloud Response to Recent Arctic Sea Ice Variability Using Spaceborne Lidar Observations, Journal of Geophysical Research: Atmospheres, 123, 473–490, https://doi.org/10.1002/2017JD027248, https://doi.org/10.1002/2017JD027248, 2018.

10 Mouginot, J., Rignot, E., Bjørk, A. A., van den Broeke, M., Millan, R., Morlighem, M., Noël, B., Scheuchl, B., and Wood, M.: Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018, https://doi.org/10.1073/pnas.1904242116, https://www.pnas.org/content/early/2019/04/16/1904242116http://www.pnas.org/lookup/doi/10.1073/pnas.1904242116, 2019.

Muntjewerf, L., Petrini, M., Vizcaino, M., Ernani da Silva, C., Sellevold, R., Scherrenberg, M. D. W., Thayer-Calder, K., Bradley, S. L., Lenaerts, J. T. M., Lipscomb, W. H., and Lofverstrom, M.: Greenland Ice Sheet Contribution to 21st Century Sea Level Rise as Simulated

15   by the Coupled CESM2.1-CISM2.1, Geophysical Research Letters, 47, e2019GL086 836, https://doi.org/10.1029/2019GL086836, https://doi.org/10.1029/2019GL086836, 2020.

Noël, B., van de Berg, W. J., van Meijgaard, E., Kuipers Munneke, P., van de Wal, R. S. W., and van den Broeke, M. R.: Evaluation of the updated regional climate model RACMO2.3: summer snowfall impact on the Greenland Ice Sheet, The Cryosphere, 9, 1831–1844, https://doi.org/10.5194/tc-9-1831-2015, http://www.the-cryosphere.net/9/1831/2015/, 2015.

20 Noël, B., van de Berg, W. J., Lhermitte, S., and van den Broeke, M. R.: Rapid ablation zone expansion amplifies north Greenland mass loss, Science Advances, 5, eaaw0123, https://doi.org/10.1126/sciadv.aaw0123, http://advances.sciencemag.org/content/5/9/eaaw0123.abstract, 2019.

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, http://www.the-cryosphere.net/8/1577/2014/, 2014.

25 Palerme, C., Genthon, C., Claud, C., Kay, J. E., Wood, N. B., and L'Ecuyer, T.: Evaluation of current and projected Antarctic precipitation in CMIP5 models, Climate Dynamics, pp. 1–15, https://doi.org/10.1007/s00382-016-3071-1, http://dx.doi.org/10.1007/s00382-016-3071-1, 2016.

Pattyn, F., Ritz, C., Hanna, E., Asay-Davis, X., DeConto, R., Durand, G., Favier, L., Fettweis, X., Goelzer, H., Golledge, N. R., Kuipers Munneke, P., Lenaerts, J. T. M., Nowicki, S., Payne, A. J., Robinson, A., Seroussi, H., Trusel, L. D., and van den Broeke, M.: The

30   Greenland and Antarctic ice sheets under 1.5 °C global warming, Nature Climate Change, 8, 1053–1061, https://doi.org/10.1038/s41558-018-0305-8, 2018.

Peings, Y., Cattiaux, J., Vavrus, S., and Magnusdottir, G.: Late Twenty-First-Century Changes in the Midlatitude Atmospheric Circulation in the CESM Large Ensemble, Journal of Climate, 30, 5943–5960, https://doi.org/10.1175/JCLI-D-16-0340.1, https://doi.org/10.1175/JCLI-D-16-0340.1, 2017.

35 Pettersen, C., Bennartz, R., Merrelli, A. J., Shupe, M. D., Turner, D. D., and Walden, V. P.: Precipitation regimes over central Greenland inferred from 5 years of ICECAPS observations, Atmospheric Chemistry and Physics, 18, 4715–4735, https://doi.org/10.5194/acp-18-4715-2018, https://www.atmos-chem-phys.net/18/4715/2018/, 2018.

Ryan, J. C., Smith, L. C., Van As, D., Cooley, S. W., Cooper, M. G., Pitcher, L. H., and Hubbard, A.: Greenland Ice Sheet surface melt amplified by snowline migration and bare ice exposure, Science Advances, 5, https://doi.org/10.1126/sciadv.aav3738, https://advances.sciencemag.org/content/5/3/eaav3738, 2019.

Schuenemann, K. C., Cassano, J. J., and Finnis, J.: Synoptic Forcing of Precipitation over Greenland: Climatology for 1961–99, Journal of Hydrometeorology, 10, 60–78, https://doi.org/10.1175/2008JHM1014.1, https://doi.org/10.1175/2008JHM1014.1https://journals.ametsoc.org/doi/pdf/10.1175/2008JHM1014.1, 2009.

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., Whitehouse, P., Briggs, K., Joughin, I., Krinner, G., Nowicki, S., Payne, T., Scambos, T., Schlegel, N., A, G., Agosta, C., Ahlstrøm, A., Babonis, G., Barletta, V. R., Bjørk, A. A., Blazquez, A., Bonin, J., Colgan, W., Csatho, B., Cullather, R., Engdahl, M. E., Felikson, D., Fettweis, X., Forsberg, R., Hogg, A. E., Gallee, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B., Hanna, E., Harig, C., Helm, V., Horvath, A., Horwath, M., Khan, S., Kjeldsen, K. K., Konrad, H., Langen, P. L., Lecavalier, B., Loomis, B., Luthcke, S., McMillan, M., Melini, D., Mernild, S., Mohajerani, Y., Moore, P., Mottram, R., Mouginot, J., Moyano, G., Muir, A., Nagler, T., Nield, G., Nilsson, J., Noël, B., Otosaka, I., Pattle, M. E., Peltier, W. R., Pie, N., Rietbroek, R., Rott, H., Sandberg Sørensen, L., Sasgen, I., Save, H., Scheuchl, B., Schrama, E., Schröder, L., Seo, K. W., Simonsen, S. B., Slater, T., Spada, G., Sutterley, T., Talpe, M., Tarasov, L., van de Berg, W. J., van der Wal, W., van Wessem, M., Vishwakarma, B. D., Wiese, D., Wilton, D., Wagner, T., Wouters, B., and Wuite, J.: Mass balance of the Greenland Ice Sheet from 1992 to 2018, Nature, 579, 233–239, https://doi.org/10.1038/s41586-019-1855-2, https://www.nature.com/articles/s41586-019-1855-2, 2020.

Smalley, M. and L'Ecuyer, T.: A Global Assessment of the Spatial Distribution of Precipitation Occurrence, Journal of Applied Meteorology and Climatology, 54, 2179–2197, https://doi.org/10.1175/JAMC-D-15-0019.1, https://doi.org/10.1175/JAMC-D-15-0019.1, 2015.

Stephens, G. L., Vane, D. G., Boain, R. J., Mace, G. G., Sassen, K., Wang, Z., Illingworth, A. J., O'connor, E. J., Rossow, W. B., Durden, S. L., Miller, S. D., Austin, R. T., Benedetti, A., and Mitrescu, C.: The Cloudsat Mission and the A-Train, Bulletin of the American Meteorological Society, 83, 1771–1790, https://doi.org/10.1175/BAMS-83-12-1771, http://journals.ametsoc.org/doi/10.1175/BAMS-83-12-1771, 2002.

Swales, D. J., Pincus, R., and Bodas-Salcedo, A.: The Cloud Feedback Model Intercomparison Project Observational Simulator Package: Version 2, Geoscientific Model Development, 11, 77–81, https://doi.org/10.5194/gmd-11-77-2018, https://www.geosci-model-dev.net/11/77/2018/, 2018.

Takahashi, H., Lebsock, M. D., Richardson, M., Marchand, R., and Kay, J. E.: When Will Spaceborne Cloud Radar Detect Upward Shifts in Cloud Heights?, Journal of Geophysical Research: Atmospheres, 124, 7270–7285, https://doi.org/10.1029/2018JD030242, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018JD030242, 2019.

Trusel, L. D., Das, S. B., Osman, M. B., Evans, M. J., Smith, B. E., Fettweis, X., McConnell, J. R., Noël, B. P. Y., and van den Broeke, M. R.: Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming, Nature, 564, 104–108, https://doi.org/10.1038/s41586-018-0752-4, https://doi.org/10.1038/s41586-018-0752-4, 2018.

Van Angelen, J. H., van den Broeke, M. R., Wouters, B., Lenaerts, J. T. M., Broeke, M. R., Wouters, B., Lenaerts, J. T. M., van den Broeke, M. R., Wouters, B., and Lenaerts, J. T. M.: Contemporary (1960–2012) Evolution of the Climate and Surface Mass Balance of the Greenland Ice Sheet, Surveys in Geophysics, 35, 1155–1174, https://doi.org/10.1007/s10712-013-9261-z, http://link.springer.com/10.1007/s10712-013-9261-z, 2014.

Van den Broeke, M. R., Enderlin, E. M., Howat, I. M., Kuipers Munneke, P., Noël, B. P. Y., van de Berg, W. J., van Meijgaard, E., and Wouters, B.: On the Recent Contribution of the Greenland Ice Sheet to Sea Level Change, The Cryosphere, 10, 1933–1946, https://doi.org/10.5194/tc-10-1933-2016, 2016.

Vizcaíno, M., Lipscomb, W. H., Sacks, W. J., and van den Broeke, M.: Greenland Surface Mass Balance as Simulated by the Community Earth System Model. Part II: Twenty-First-Century Changes, Journal of Climate, 27, 215–226, https://doi.org/10.1175/JCLI-D-12-00588.1, 2013.