

Summary

The submitted article is clearly written and addresses an important topic, adding largely missing detailed insight on how much should Greenland precipitation change in a warming future. Besides suggesting several missing relevant citations and questioning the likely important future model treatment of sea ice decline in Greenland precipitation change, I take issue mainly with the magnitude of the precipitation sensitivity to temperature, arguing that the conclusion of $\sim 5\%/K$, being considerably lower than theory ($\sim 7\%/K$) appears to me more due to the research design than reality given there exist research finding $7\%/K$ using observation-based approach.

I am a fan of the work that deserves to be published, especially on working with my comments. Upon successful addressing of my comments, I think the work will deserve nomination for a highlight by the EGU (is a question reviewers are asked in this review form).

Thank you for your positive and constructive feedback.

high level critique in no particular order of importance...

Precipitation feedbacks with changing sea ice appear to be a key consideration, deserving perhaps a whole new section in this study. The following is relevant to incorporate in discussion: Stroeve, J. C., Mioduszewski, J. R., Rennermalm, A., Boisvert, L. N., Tedesco, M., and Robinson, D.: Investigating the local scale influence of sea ice on Greenland surface melt, *The Cryosphere*, 11, 2363–2381, <https://doi.org/10.5194/tc-11-2363-2017>, 2017.

REPLY: Good point. We will add the following paragraph to the discussion:

“A reduction in Arctic sea ice cover, due to increases in atmospheric CO_2 , can enhance transfer of heat and moisture between the ocean and the atmosphere leading to an increase in temperature and precipitation over Greenland (Stroeve et al., 2017; Noel et al., 2014). This increase in temperature will increase the ice melt and thereby decreasing the surface albedo creating a positive feedback loop, resulting in a warmer atmosphere with the capacity to hold more water vapor and thereby intensifying the hydrological cycle (Zeitz et al., 2021).”

Noël, B., Fettweis, X., van de Berg, W. J., van den Broeke, M. R., and Erpicum, M.: Sensitivity of Greenland Ice Sheet surface mass balance to perturbations in sea surface temperature and sea ice cover: a study with the regional climate model MAR, *The Cryosphere*, 8, 1871–1883, <https://doi.org/10.5194/tc-8-1871-2014>, 2014.

230 "7% increase per degree warming", the idea of warmer atmosphere, more water vapor appears as a statistically robust feature of observational data, specifically N Atlantic SST and Northern Hemisphere near-surface air temperatures correlation with Greenland snow accumulation, matching theory articulated by Treberth (doi: 10.3354/cr00953), see <https://doi.org/10.1175/JCLI-D-12-00373.1> figure 9a, Table 3 and related discussion. The *J. Clim.* article finds the expected $7\%/K$ sensitivity using observations, in the following Figure 9 comment, I suggest ways to possibly find a more credible result after all the *J. Clim.* article has more observation constraint. As is, the conclusion of "4.9%, 5.1% and 4.5% increase in precipitation per Kelvin for HIRHAM, MAR and RACMO," I fear may be misleading...

REPLY: Using the information from the 2013 Box et al. paper, we did an analysis using the northern hemisphere change in t_{as} (using the forcing GCMs) and we still got values around 5% per degree. The Box et al.

paper did their analysis for the period 1880–1962 during which the temperature increase was low (less than +1) and during which changes in general circulation or natural variability could have also impacted this precipitation increase vs temperature increase. In the current study, the temperature increase is significantly larger (therefore the trend is likely more robust) and the GCMs do not suggest any general circulation change (Delhasse et al., 2020), therefore it is normal that our rate is different. Moreover, +5%/K is in agreement with other studies based on models over the Greenland ice sheet.

Therefore, we will add the following text to the paragraph beginning at line 280:

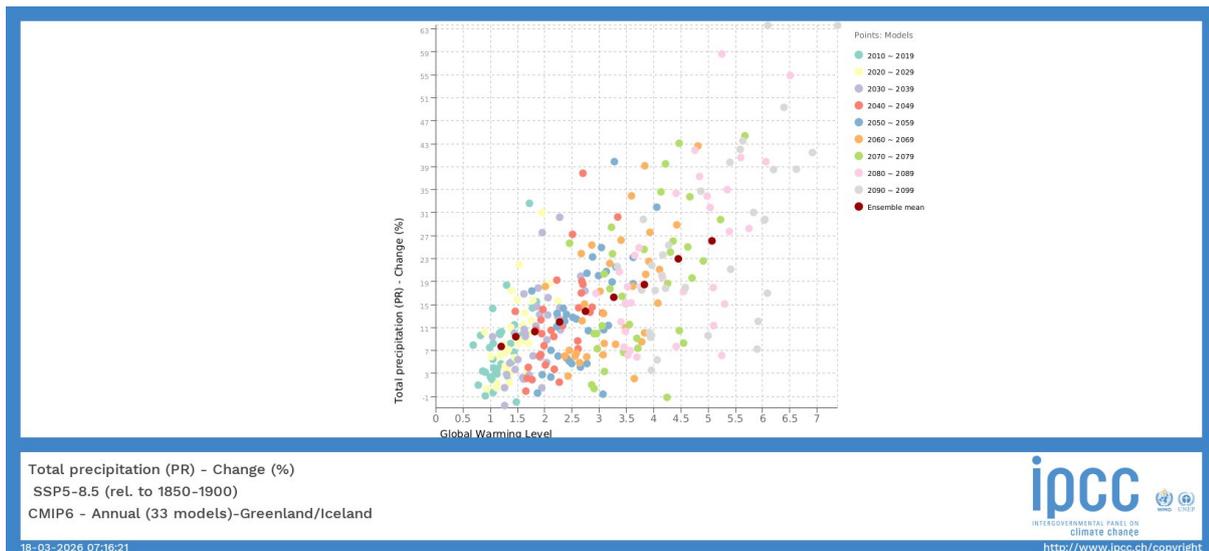
“There are several ways of determining the relationship between temperature and precipitation changes. Frieler et al. (2014) used a wide range of methods for Antarctica and derived a combined sensitivity of $5 \pm 1\% K^{-1}$. The individual forcing models in this study give similar values. However, Box et al. (2013) found the theoretically expected $7\% K^{-1}$ using reconstructions of snow accumulation from ice cores together with the average near-surface air temperature in the Northern Hemisphere for the period 1880–1962 during which the temperature increase was relatively low (less than +1°C) and during which changes in general circulation or natural variability could have also impacted this precipitation increase vs temperature increase.”

Figure 9: Ensemble median... is there a GCM that is arguably more reliable? Grouping ALL models may obscure a more realistic result. I'm wondering which models given 7%/K and if those are of a model class that is arguably more reliable? If so, a new figure could feature that more credible model result. at line 206 you get into the issue "dependency on the choice of GCM."

REPLY: We have investigated the individual models and they all give similar numbers (4-5% per K). Previous studies, using model data (RCMs/GCMs) for different emission scenarios, seem to agree on values close to 5%/K. (see reply above).

...Well ok at line 285 "Bochow et al. (2024) used 32 GCMs within the CMIP6 project and found a mean value of $6\% K^{-1}$ ", but I just hope you can build an even more convincing argument why or why not the actually should be drier than theory! If it's something about dynamics, then I think you need to do more sensitivity analysis, i.e. burden of proof on this study.

REPLY: The correct sentence is in fact "Bochow et al. (2024) used 32 GCMs within the CMIP6 project and found a mean value between 3 and $6\% K^{-1}$ following the scenario used". As we can see over the IPCC AR6 Atlas over Greenland and Iceland (<https://interactive-atlas.ipcc.ch/>), the ensemble mean changes are close to $5\% K^{-1}$ (e.g. +26%/+5°C; +23%/+4.5°C) similar to what we found although there are significant differences between models. For example, in a +5°C world precipitation increase varies between +7% and +59%.



...286-299 "A 5% increase in precipitation per degree warming over the GrIS were found by Gregory and Huybrechts (2006) and by Fettweis et al. (2013)." Do they provide a credible explanation why the sensitivity is lower than 'observed' by <https://doi.org/10.1175/JCLI-D-12-00373.1> ?

Whatever extent IPCC AR6 examines future Greenland precipitation change warrants treatment here.

REPLY: See our previous response discussing the precipitation increase in Box et al. (2013) vs our rates.

Figure 8: Annual sum of precipitation nonlinearity for rain is striking, deserves highlight in abstract and conclusions and has important implications you get into lines 256-261 that can be further elaborated, more citations, more to the point text... some thoughts, partly redundant...driving snow metamorphic (albedo decline) feedbacks and potential firn heating at depth (ONLY IF HEAVY RAIN AND LOW TEMPERATURE SNOW <https://doi.org/10.1029/2023GL103654>), if rain is light, it does not infiltrate and instead the heat radiates away

<https://doi.org/10.1029/2021GL097356>

REPLY: The second to last sentence in the abstract will be changed to:

"The change in precipitation phase shows a non-linear increase in rainfall with temperature, particularly along the outer edge and the southern part of the ice sheet."

The second sentence in the Conclusions section will be changed to:

"The fraction of rain relative to the total precipitation increases exponentially with temperature during the 21st century."

The paragraph on lines 256-261 will be rewritten as:

"The precipitation phase is important because rainfall serves as a crucial climate indicator in polar regions and plays a multifaceted role in cryospheric processes. When heavy rain falls on low temperature snow or ice surfaces, its infiltration not only contributes directly to surface melt, but also initiates a sequence of physical changes in the snowpack (Box et al., 2022). The freezing of rainwater within the firn releases latent heat, which further enhances snowpack collapse by warming the surrounding ice and snow (Harper et al.,

2023). In addition, rainfall events lower the surface albedo making the surface more susceptible to future melting due to increased absorption of solar radiation (Noël et al., 2022; Firn Symposium team, 2024; Gilbert et al., 2025).”

line 260 "rainfall events lower the surface albedo", <https://doi.org/10.1029/2021GL097356> cites relevant detail. Another is Colbeck, S.: Theory of metamorphism of wet snow, 1973.

REPLY: The Box et al. paper will be included.

at the first mention of runoff, I was thinking, why? I mean this is a precipitation change study. Then at line 264 "Glaude et al. (2024) however, show from some of the same simulations as we analyse here, that the melt and runoff is projected to increase by a much larger"... again, runoff is beside the point. I recommend you keep the study focused on precip change and not do other mass balance terms and so avoid needing to add yet more (irrelevant) citations.

REPLY: Good point! We will remove the melt/runoff parts in the text.

PLEASE use "ice sheet" instead of "GrIS" once it's obvious the geographic focus is Greenland. having read though, there are really few places where an abbreviation would be needed. Therefore, clearly it's not.

REPLY: We will change the wording.

** lower level critique **

KEY: "io" means "instead of", NUMEBRS: line numbers

32 "projected increase in snowfall, compensating for increased runoff", consider also <https://doi.org/10.1029/2024GL110121>

REPLY: The paper will be cited.

40 "higher temperature of rain compared to melt water", surprisingly insignificant for surfaces that are already at melting point, see section 3.6 in <https://doi.org/10.1002/met.2134> and supporting citations, the exception being HEAVY rain only LOW TEMPERATURE firn, see Harper et al 2024?

GRL <https://doi.org/10.1029/2023GL103654>

REPLY: Thanks for pointing this out! We will change the sentence to:

“During the right conditions (heavy rain on low temperature firn), the higher temperature of rain compared to melt water can also transport energy deeper into the firn, warming it and reducing refreezing potential (Harper et al., 2023).”

43-44 "washing away surface debris" shown by what study? citation needed

REPLY: Thanks, we have not found reference about this and we will therefore remove this sentence.

Table 1, CARRA 1971–2000 but CARRA data start in 1991?

REPLY: Yes, CARRA starts in 1991 as stated in the caption. We will add an asterisk to the CARRA value.

105-106 "previously used to evaluate climate models" also <https://doi.org/10.1002/met.2134> and <https://doi.org/10.1029/2021GL092942>

REPLY: We will cite the two papers.

106 and new GEUS AWS data citation <https://doi.org/10.5194/essd-2025-687>

REPLY: We will add the citation to the text.

108 "hard to compare with precipitation in a climate model" true :-) for CARRA data, in addition to the Yang et al citation, pls include

Schyberg, H., Yang, X., Køltzow, M. A. Ø., Amstrup, B., Bakketun, Å., Bazile, E., Bojarova, J., e., B., Dahlgren, P., Hagelin, S., Homleid, M., Horányi, A., Høyer, J., Johansson, Å., Killie, M. A., Körnich, H., Le, Moigne, P., Lindskog, M., Manninen, T., Nielsen, Englyst, P., Nielsen, K. P., Olsson, E., Palmason, B., Peralta, Aros, C., Randriamampianina, R., Samuelsson, P., Stappers, R., Støylen, E., Thorsteinsson, S., Valkonen, T., and Wang, Z. Q.: Arctic regional reanalysis on single levels from 1991 to present, <https://doi.org/10.24381/cds.713858f6>, 2020.

REPLY: The paper above will be cited.

118 "outperforms ERA5 when comparing the two datasets with in-situ observations", for rainfall using ON-ICE observations, not only CARRA but other models, <https://doi.org/10.1002/met.2134>

REPLY: We will add a citation to the study.

Figures 3 and 7, like the figures!, but the colors need to change, avoid bright yellow and no greens. Orange, magenta and could also be dashed lines, and why not box plots using seaborne or violin plots to make a great plot even better? Instead of 1,2,3... use names like NE, all

REPLY: The figures will be updated with better colors and box plots for figure 7. The numbers 1-7 in Fig.3 refers to the stations in figure 1a.

Figure 4 important results. Comments on sea ice decline effect for change in precipitation needed if not already there.

REPLY: See our 1st reply.

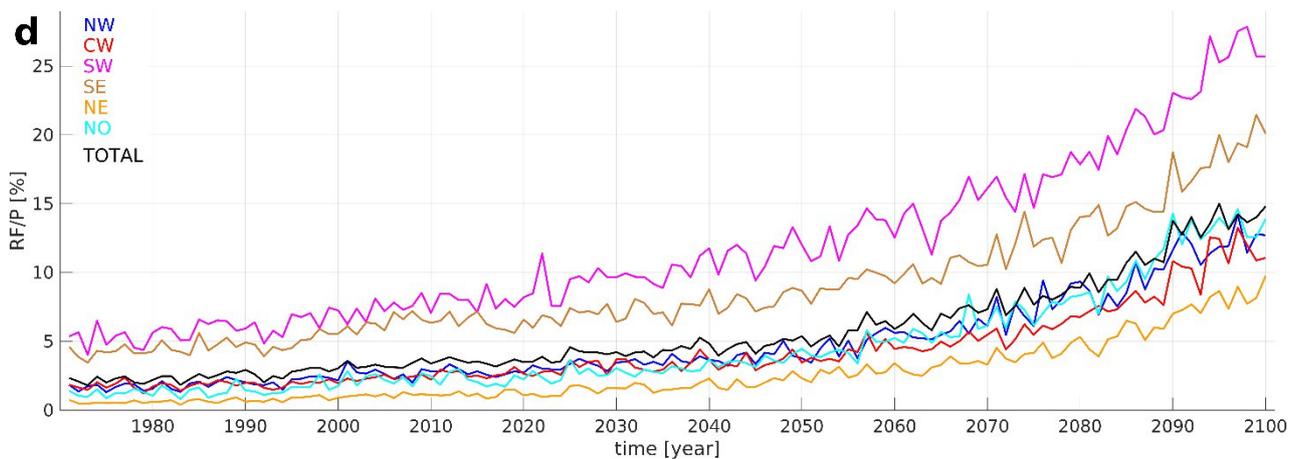
198 "a large fraction", include a quantity

REPLY: (See reply below with the added time-series plot) We will change the text to:

"Figure 6d shows how the rainfall fraction of total precipitation for the six drainage basins changes with time. For the historical period, the mean rainfall fraction is around 5% for basins SW and SE while the other basins show mean values below 2%. At the end of the century for the SSP5-8.5 scenario, we see that a large fraction of the precipitation is rainfall (total ice sheet: around 15%) , especially basins SW (above 25%) and SE (around 20%)."

Figure 6 using a colorblind sensitive color palette? Seems not. I'm not color blind (at least I don't think so), but it's the norm anyway to not combine green and red-sh colors. And thin rain fraction of total precip is more standard than snow fraction of total precip. Really want a number for the whole ice sheet within the ice mask, and a time series graphic

REPLY: We are using the IPCC color palette for all of our map plots and we would like to stick to this if ok. We will change to showing rainfall fraction, add numbers to the text and add the panel below showing a time series (ensemble median):



249 "robust across most models." or "consistent across all models"... is there a statistical test to help here?

REPLY: The sentence will be changed to:

“Results from the GCM ensemble from CMIP6 (cf. Figure 5) show that the north east signal is robust across all models while the south east signal is positive for 28 out of the 34 models for the end of the century (cf. Figure 5f).”

254 "we find increases" io "we see positive changes"

REPLY: Text will be changed.

274 "CARRA has shown clear advantages to other reanalysis products (Køltzow et al., 2022)" include the Greenland specific study reaching this conclusion <https://doi.org/10.1002/met.2134>

REPLY: We will cite this study as well.

275 "performs better in other regions." better than ___?, could be something like "has smaller differences relative to observations in other regions."

REPLY: We will change the first part of the paragraph to

“CARRA has shown clear advantages to other reanalysis products (Køltzow et al., 2022; Box et al., 2023) and CARRA performs well when compared with station observations outside the GrIS (cf. Figure 3). Compared with our RCM ensemble (cf. Figure 7) over the ice sheet, CARRA overestimate precipitation for all basins except NO and NW.”

276 "located in or near" io "located in"

REPLY: We will change the wording.

283 "However,", see the %/K points above in this review.

REPLY: see our previous replies about this issue.

293 "(Doyle et al., 2015)"? io "(Doyle et al., 2014)"

REPLY: Indeed, it is Doyle et al. (2015): Doyle, S., Hubbard, A., van de Wal, R. et al. Amplified melt and flow of the Greenland ice sheet driven by late-summer cyclonic rainfall. *Nature Geosci* 8, 647–653 (2015). <https://doi.org/10.1038/ngeo2482>

299 something like "Our work, consistent with theory, finds that the GrIS faces a wetter future in all regions," io "The GrIS faces a wetter future in all regions,"

REPLY: Text will be changed.

301 avoid/spell out abbreviations in conclusions, "SSP".

REPLY: Text will be changed to "shared socioeconomic pathway (SSP)".