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The Cryosphere Discussions

Interactive comment on "Trends and spatial variation in rain-on-snow events over the Arctic Ocean during the early melt season" *by* Tingfeng Dou et al.

Tingfeng Dou et al.

doutf@ucas.ac.cn

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Dear Editor, We have studied the valuable comments from yourself and the reviewers carefully, and made further revisions in the manuscript that address your and the reviewers' concerns. Our detailed response to the reviewers' comments follows below. - Response to reviewer#2's comments: This study evaluates the performance of four reanalysis datasets (ERA-I, JRA-55, MERRA2, and ERA5) in representing the timing of ROS events and the phase change of precipitation during the spring melt season over the Arctic Ocean. Comparing with observations at 15 Arctic coastal weather stations, the authors find that the date of the first ROS events in ERA-I is closer to the obser-

vations than that in the other three products, while ERA5 better represents the phase change of precipitation associated with ROS events in spring. The study then investigates trends and spatial variations of ROS events and rain-precipitation-ratio (RPR) over the Arctic Ocean during the melt season. The results show trends towards earlier spring ROS events over most of the Arctic Ocean in recent decades, with the most negative trends in the marginal seas. There has been a clear transition from solid to liquid precipitation over the Arctic Ocean from Match to June, consistent with more ROS events in spring. General Comments This is an interesting study and fits well to The Cryosphere. Overall the paper reads well, however, I have one major concern, which is the weak justification of the use of ERA-I and ERA5 for trend analyses. In addition, the structure of the paper is not always clear. Outlined in the comments below are some suggestions that will hopefully improve the final version of the paper. 1) Why the four reanalysis products (ERA-I, JRA-55, MERRA2, and ERA5) are chosen for the study? Especially MERRA2 instead of MERRA? Boisvert et al. (2018) suggested that precipitation in MERRA was realistic but there were large biases in MERRA2. In their abstract: "When compared with drifting ice mass balance buoys, three reanalyses (ERA-Interim, MERRA, and NCEP R2) produce realistic magnitudes and temporal agreement with observed precipitation events, while two products [MERRA, version 2 (MERRA-2), and CFSR] show large, implausible magnitudes in precipitation events."

Response: Thank you for your comments. This study was conducted based on the global reanalysis datasets those can distinguish between solid and liquid precipitation. According to the results of Boisvert et al. (2018), we select three representative datasets: ERA-I, JRA-55 and MERRA. ERA5 represents the new generation of ECMWF atmospheric reanalyses, which was included in this study since it has not been evaluated in previous studies. Boisvert et al. (2018) have evaluated the advantages and disadvantages of MERRA and MERRA-2, and compared their performance in simulating the precipitation changes in the Arctic Ocean. In order to avoid unnecessary repetitive work, this study chose one of them as the representative of NASA products according to Boisvert et al. (2018) and our own analysis. We compared their performance in simulating the first rainfall date and RPR. Results show that the average value and spatial distribution of the first rainfall date are basically the same in these two reanalysis datasets, which is consistent with the results of Boisvert et al. (2018), in their work, they suggested that the two datasets have highly consistent descriptions of the rainfall days in the Arctic Ocean. In addition, both of the datasets overestimate snowfall and underestimate rainfall in the Arctic Ocean (Fig. 5, and Fig. 11-12 in Boisvert et al., 2018), leading to an underestimation of RPR in the Arctic Ocean (Fig. R1 and Fig. 4). This situation is more serious in MERRA-2 (Fig. R1). As response to the second comment from the Reviewer#1, we have rechecked the data used in this work, and found that we actually used MERRA data in this study. We mistakenly wrote it as MERRA-2 in the original MS. As show in Figure R1, MERRA-2 gives a lower RPR because it overestimates the snowfall too much and underestimated the rainfall in the Arctic Ocean. We corrected this in the revised MS and added a discussion about the results of Boisvert et al. (2018). Please see details at L83-90 in the revised MS with trace of changes. "Boisvert et al. (2018) evaluated the performance of various reanalysis datasets in simulating the precipitation in the Arctic Ocean, and showed that Modern-Era Retrospective analysis for Research and Applications (MERRA version 2, Gelaro et al. 2017) significantly overestimates the total precipitation compared to MERRA (Rienecker et al., 2011), ERA-I and JRA-55. They further pointed out that MERRA and MERRA-2 have both overestimated snowfall, especially for MERRA-2. In contrast, they have a significant underestimation of rainfall (both for rainfall amount and rainfall days), leading to an underestimation of RPR in the Arctic Ocean. Accordingly, we chose MERRA for the analysis in this study since its underestimation is relatively slight." Figure R1ïijŽTime series of monthly rainfall precipitation ratio (RPR) averaged over the Arctic Ocean for MERRA and MERRA-2.

2) Observations from 15 coastal stations are used to assess the performance of the reanalysis in this study. In my opinion, the observations at the coastal stations may be representative of nearby marginal seas, but unlikely to be representative of the central Arctic Ocean. Therefore the justification of using ERA-I for ROS events and ERA5

for RPR analyses is rather weak in the paper. The authors should at least provide a summary of evaluation results from previous studies, i.e. Boisvert et al. (2018). In addition, it is critical for the reanalysis products to be consistent over time (1980-2017) for trend analyses. Please verify this in the paper.

Response: Thank you for your suggestion. Current long-term precipitation observation data only exist in the land area of the Arctic, and the limited records obtained by IMB buoy in sea ice area cannot be used to verify the long-term trends of precipitation. Therefore, this study applied the precipitation data from the coastal stations closest to the sea ice area to validate the reanalysis dataset. According to the reviewer's suggestion, we have included a summary of evaluation results from Boisvert et al. (2018) in the revised MS. Please see the response to your first comment. Thank you for your reminder, we have checked the time series used in the full text, including those for trend analysis, and modified Fig. 4d and related content in the revised MS.

Specific comments Section 2.1, Please provide a bit more detail about the reanalysis products, such as the resolutions. Map in Fig. 2(b) is somewhat blurry, is that due to the coarser resolution of JRA-55 relative to the other three products?

Response: Thank you for your suggestion. More detailed description has been included in the revised MS (L92-100): "ERA-I uses the ECMWF forecasting model [version cycle 31r1 (CY31r1)] with a horizontal resolution of T213 ($\sim$78 km). ERA5 is the fifth generation reanalysis from ECMWF. It provides several improvements compared to ERA-I, as detailed by Hersbach and Dee (2016). The analysis is produced at a 1-hourly time step using a significantly more advanced 4Dvar assimilation scheme with a horizontal resolution of approximately 30km. JRA-55 is the ïňĄrst atmospheric global reanalysis dataset and covers a period extending back to 1958. It is based on the TL319 (55km$\times$55km) spectral resolution version, with linear Gaussian grid, of the JMA global spectral model (GSM) with 4DVAR and also incorporates TOVS and SSM/I satellite data. MERRA uses the Goddard Earth Observing System Data Assimilation System (GEOS-5) (Rienecker et al. 2008). It applies the GEOS-5 AGCM dynamical atmospheric model, which includes a finite-volume dynamical core and a native latitude–longitude horizontal resolution of 1/2°×2/3°." Regarding the problem in figure2b you mentioned, we found that the "blurry" is caused by the selected format of image when it was generated by NCL. We have corrected this figure in the revised manuscript. Thank you so much for your reminder.

L83-84, are the results sensitive to the 0.5 mm threshold used to determine the occurrence of rainfall? I suggest the authors do some tests on this if haven't already. Ideally, the results shouldn't be too sensitive to the threshold.

Response: Thank you for your suggestion. The reanalysis data generally overestimates the number of trace precipitation (Dai et al., 2006; Boisvert et al., 2018), so the frequency and occurrence time of precipitation event in the reanalysis are sensitive to changes in the precipitation threshold. For this study, different precipitation thresholds may mainly have an impact on the date of the first rainfall event. We have tried different precipitation thresholds, and found that when the threshold exceeds 0.5mm/day, the changes of different precipitation thresholds have negligible effect on the timing of first ROS event and the spatial distribution of its trend in various reanalysis datasets, including MERRA. Our analysis showed that when the threshold is set to 0.5mm/day, the date of first ROS event given by MERRA is consistent with the results of ERA5 and JRA-55, and the spatial pattern of trend of first ROS date is similar with ERA-I and JRA-55. Therefore, we use this value as a threshold in this study. As in the response to review#1, we clarified this in the revised MS (L181-186): "Changing the threshold of precipitation events may affect the determination of the date of the first rainfall to a certain extent, especially for the reanalysis with more frequent trace precipitation, such as MERRA and MERRA-2 (Boisvert et al. al., 2018). Therefore, a lower precipitation threshold may result in an earlier ROS event in these reanalysis datasets, while a higher threshold may result in a later ROS event. However, different thresholds will not have a fundamental impact on the spatial distribution of the trend of the first rainfall timing." Reference: Boisvert, L. N., Webster, M. A., Petty, A. A. et

al.: Intercomparison of precipitation estimates over the Arctic Ocean and its peripheral seas from reanalyses, J. Clim., 31, 8441–8462, 2018. Dai, A., 2006: Precipitation characteristics in eighteen coupled climate models. J. Climate, 19, 4605–4630, https://doi.org/10.1175/JCLI3884.1.

L97-98, "The sea ice extent is calculated from SIC using a threshold of 15%", please provide a reference.

Response: Thank you for your suggestion. We have included an earlier study that used the threshold of 15% in the revised MS. "Gloersen, P., Campbell, W. J., Cavalieri, D. J., Comiso, J. C., Parkinson, C., and Zwally, H. J.: Satellite passive microwave observations and analysis of Arctic and Antarctic sea ice, 1978-1987, Annals of Glaciology, 17, 149-154, 1993."

Section 2.3, Please explain why observations at other weather stations are not included, such as those along the coast of European Arctic.

Response: Thank you for your comment. The precipitation observations along the coast of European Arctic available to us are mainly located in the Nordic arctic region-northern Norway, Sweden, and Finland, including the arctic islands Svalbard and Jan Mayen (Førland et al., 2020; Vikhamar-Schuler et al., 2016). The stations in Svalbard region are located on the west coast of Spitsbergen or on the south to Spitsbergen. During our study period, there was no sea ice near the stations in the Nordic arctic region. Thus, they are not included in this study. However, we added a discussion on the results of previous studies in Svalbard in the revised MS (L307-313). "There is also an increasing trend close to sea ice edges in the Atlantic sector, especially in the Nordic arctic region. A recent study based on the station observations in Svalbard demonstrates that the solid precipitation has decreased at a rate of 2.3-6.5 % per decade in this region during the past decades, while the liquid precipitation has increased at a rate of 0.6-9.4 % per decade during the same period (Førland et al. 2020). This is generally consistent with our results in the Atlantic sector (Fig. 4-5)." Reference: Førland,

E. J., K. Isaksen, J. Lutz, I. Hanssen-Bauer, T. V. Schuler, A. Dobler, H. M. Gjelten, and D. Vikhamar-Schuler, 2020: Measured and Modeled Historical Precipitation Trends for Svalbard. J. Hydrometeor., 21, 1279–1296, https://doi.org/10.1175/JHM-D-19-0252.1. Peeters B, Pedersen ÅØ, Loe LE, Isaksen K, Veiberg V, Stien A, Kohler J, Gallet J-C, Aanes R, Hansen BB. 2019. Spatiotemporal patterns of rain-on-snow and basal ice in high Arctic Svalbard: detection of a climate-cryosphere regime shift. Environmental Research Letters. 14 015002, https://doi.org/10.1088/1748-9326/aaefb3. Vikhamar-Schuler D, Isaksen K, Haugen JE, Tømmervik H, Luks B, Schuler T, Bjerke J. 2016. Changes in winter warming events in the Nordic Arctic Region. Journal of Climate 29, doi: 10.1175/JCLI-D-15-0763.1.

Fig.2, it would be helpful to provide some comments about the positive/later trends occurring in (a)-(c), but not in (d).

Response: During the transition period between spring and summer, the earlier ROS events in most parts of the Arctic Ocean (Fig. 2) could be attributed to the rapid warming of the Arctic. During this period, the climate began to warm up, and the local temperature rose to around melting point by May and June. Therefore, the precipitation phase during this period is very sensitive to climate warming. However, we cannot explain the reason for the unusual delay of the first ROS event in Atlantic and Pacific sectors in ERA-I, MERRA and JRA-55 because the air temperature rise is significant in these areas. In-depth study is needed in the next step.

Section 3.2, I'd suggest to move the first paragraph to the Introduction. I think this would make the paper tighter and make it easier for readers to have a better understanding of the linkages between different components of the paper.

Response: Thank you for your suggestion. However, is it better to keep this paragraph here because Section 3.2 is short enough? We have flipped the order of the first two paragraphs since Paragraphs 1 and 3 cover similar ground and could be condensed a little if consecutive. Please see details at L214-232, or see our response to the

comment for section 3.2 by Reviewer#1.

Fig.3, I wonder if the significant correlations between EMO and ROS are due to the fact that they are both correlated with surface air temperature (SAT)? SAT was used to indicate melt onset on sea ice in previous studies. Dou et al. (2019) suggested that the year-to-year variability of the timing of first spring ROS was closely tied to the timing of persistent warming events.

Response: Thank you for your comment. In the early period, people generally believed that the temperature rise was the main factor resulting in the sea ice melt onset. With the enrichment of observational data, people found that there is no good correspondence between sensible heat (warm air) and melt onset, although their long-term trends are consistent (e.g., Persson, 2012; Mortin et al., 2016 ; Dou et al., 2019). Moreover, liquid precipitation did not always occur during every warm event (Vikhamar-Schuler et al., 2016). Therefore, there is not a good correspondence between SAT and ROS events too. In recent years, the melt onset was found to be triggered by moist, warm air masses associated with synoptic-scale weather systems that augmented the atmospheric energy ïňĆuxes to the surface (Persson, 2012). Mortin et al. (2016) further showed that melt onset over Arctic sea ice is initiated by positive anomalies of water vapor, clouds, and air temperatures that increase the downwelling longwave radiation (LWD) to the surface. The earlier melt onset occurs; the stronger are these anomalies. When melt occurs early, an anomalously opaque atmosphere with positive LWD anomalies preconditions the surface for weeks preceding melt. In contrast, when melt begins late, clearer than usual conditions are evident prior to melt. However, the previous studies have not evaluated the impact of rainfall (ROS event) on the melt onset. Note that ROS events may occur alongside abundant water vapor and clouds (e.g., Bieniek et al., 2018). In other words, while the LWD generated by clouds and water vapor continues to heat the ground, it may also be accompanied by ROS events that could initiate the sea ice ablation (Dou et al., 2019). Our study estimated the sensitivity of sea ice melt onset to on large spatial scale or the possible connection between them. Further research on the exact role of liquid precipitation in triggering sea ice melt onset is needed based on large-scale observations of precipitation and melt onset. Reference: Dou, T., Xiao, C., Liu, J. et al.: A key factor initiating surface ablation of Arctic sea ice: earlier and increasing liquid precipitation, The Cryosphere, 13, 1233–1246, https://doi.org/10.5194/tc-13-1233-2019, 2019. Mortin, J., G. Svensson, R. G. Graversen, M.-L. Kapsch, J. C. Stroeve, and L. N. Boisvert: Melt onset over Arctic sea ice controlled by atmospheric moisture transport, Geophys. Res. Lett., 43, 6636–6642, doi:10.1002/ 2016GL069330, 2016. Persson, P. O. G. : Onset and end of the summer melt season over sea ice: Thermal structure and surface energy perspective from SHEBA, Clim. Dyn., 39(6), 1349–1371, doi:10.1007/s00382-011-1196-9, 2012. Vikhamar-Schuler, D., Isaksen, K., Haugen, J.E., Tømmervik, H., Luks, B., Schuler, T., Bjerke, J.: Changes in winter warming events in the Nordic Arctic Region. Journal of Climate 29, doi: 10.1175/JCLI-D-15-0763.1, 2016.

L195, FRD is not defined.

Response: Thank you for your reminder. The definition of 'FRD' has been included in the section of 'Methods' in the revised MS (L152).

Section 3.3, I'd suggest move the first paragraph to the Introduction, see above.

Response: We merged part of the content in the first paragraph into the second paragraph and deleted the rest. Please see details at L250-259. "The amount of rainfall depends on the total precipitation and the portion of total precipitation occurring as rainfall, as quantified by the rain precipitation ratio, RPR (see section 2.5). Below, we evaluated and compared changes in RPR across four different reanalysis products. The RPR averaged over the Arctic Ocean is overall higher for all spring months in ERA-I than in the other three reanalysis datasets (Fig. 4)."

L317, ESAO is not defined.

Response: This has been defined at L295 in the revised MS.

L321-330, "ERA5 more reasonably reproduces the observed RPR and its trends than ERA-I compared with station observations. Several new techniques have been incorporated into ERA5: : :", this seems to be in contrast with the large negative bias for first ROS events in ERA5 relative to ERA-I and observations shown earlier (L150), can you explain why?

Response: Thank you for your comment. The first rainfall date can be determined even if a light rain occurs. Therefore, an earlier ROS event does not mean a greater rainfall during the early melt season, because the amount of rainfall in a time window often depends on several large precipitation events, which is not directly related to the timing of first rainfall.

Fig.5, I'd prefer to have maps in May on the upper panel and June on the bottom panel. Please include the name of the reanalysis product used for the results in Fig.3 and 7 in the captions.

Response: Done.

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