Response to Referee #2

Review of the Manuscript 'Warm and moist atmospheric flow caused a record minimum July sea ice extent of the Arctic in 2020' by Ling et al. submitted to The Cryosphere.

Summary:

Liang et al. aims to investigate the July 2020 extreme sea ice melt event in terms of physical mechanisms. They look at the prior late spring-early summer 2020 to explain that anomalous warm air intrusion and cyclone activity set up favorable conditions for sea ice melt in July 2020. I find the idea interesting and well suited for The Cryosphere journal and the methods generally appear sound, however the presentation of their results and the significance of the findings need a bit more elaboration before I could recommend the paper for publication.

Reviewer comments

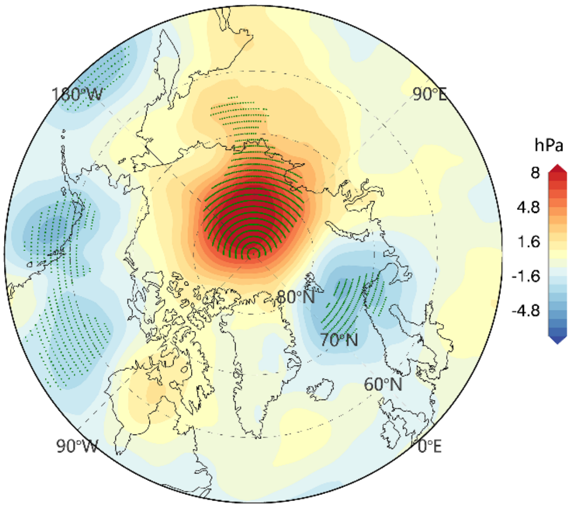
R.1. I find the Introduction a bit hard to follow. The authors might consider reorganizing it a little bit via discussing the contents of the current second paragraph before starting to talk about the 2020 SIE extent and referring to Figure 1. From row 30 it reads like it is already the description of the Results. I understand the reasoning behind it; the authors want a succinct Introduction to go with their very specific and well-defined goal in the paper, however I think they could do better in setting up the research question.

Especially, I suggest that the authors discuss more thoroughly the current understanding of oceanic and atmospheric drivers of summer sea ice melt, especially the physical mechanisms, as their objective in this paper is to reveal the underlying mechanisms leading to the record melt in July 2020. For example, in the current introduction the authors only mention surface wind driven sea ice drift as dynamical forcing on sea ice, however in recent years anticyclonic circulation anomalies caused vertical motion (warming and moistening descending air) is also a key component of atmospheric forcing on sea ice (see e.g., Ding et al. 2019; Topal et al. 2020). This local atmosphere-sea-ice coupling mechanism is further linked to large-scale circulation changes and forcing from the tropics especially over the enhanced melt period between 2007 and 2012 (Screen and Deser 2020; Warner et al. 2020; Baxter et al. 2019). Therefore, the well-known thermodynamical factors causing sea ice melt may be better linked with known dynamical sources besides surface wind drift, which is far from being the only dynamics causing sea ice variations in the Arctic. In this way the authors may set up their research question a bit more connected to existing literature and highlight that their goal is to complement the existing knowledge of dynamical drivers of sea ice loss which can well be exemplified via a case study in July 2020. June-August 2020 was dominated by a high-pressure anomaly in the Arctic, which could have acted in concert with the prevailing spring conditions to cause the sea ice extreme melt. I wonder if the authors could provide more discussion on how they distinguish their results or link together with previous literature either in the Introduction or in their Discussion part.

Response: We sincerely appreciate the constructive and detailed comments by Referee #2. These comments helped us improve our manuscript, and provided important guidance for our future research.

a. The Introduction will be reorganized as suggested. Before analyzing the severe event of sea ice loss in July 2020, we will discuss thoroughly the current understanding of atmospheric drivers of sea ice melt, especially the relevant physical mechanisms and refer to the previous studies. The scientific question of the present research will be set up afterward.

b. Although the September SIE of 2020 did not shatter the previous lows to be a new record, September 2020 had the second-lowest SIE since 1979, stood at 3.74×10^{6} km^2, which is merely 1% higher than the lowest SIE. A prominent high-pressure anomaly dominated the Arctic in June-August 2020 (especially in July-August, the figure below). Previous studies elaborated that the recent summertime sea ice depletion is broadly associated with the anticyclonic atmospheric circulation pattern which can increase the downwelling longwave radiation above the ice by warming and moistening the lower troposphere (Ogi and Wallace, 2012; Ding et al., 2017; Bi et al., 2021). This kind of variation in local atmospheric circulation patterns is further linked to large-scale circulation changes and forcing from the tropics through teleconnections (Baxter et al., 2019; Screen and Deser, 2019; Warner et al., 2020). The combination of low-pressure anomaly persistent in April-June (favoring moisture and energy inflow) and anticyclonic atmospheric circulation pattern (leading to adiabatic warming) may contribute to the particularly low SIE of September 2020, the mechanisms of which would be the potential candidates for future studies. The present study is dedicated to elucidating that anomalous high inflow of total energy and moisture from lower latitudes to the Arctic in spring caused severe sea ice loss of July 2020. The above arguments about the anticyclonic atmospheric circulation pattern therefore will be added to the Discussion and Conclusions part when mentioning the September SIE of 2020.



Supplementary Figure. Spatial patterns of sea level pressure anomalies (shading) during July to August 2020. The anomalies are computed as the difference between the averaged fields of the three months (April-June) and the corresponding climatology over the past four decades (1979-2020). Stipplings represent the values where the anomaly exceeds 1.5 standard deviations.

c. Several existing literature pointed out similar mechanisms with ours (Graversen et al., 2011; Vázquez et al., 2017; Kapsch et al., 2019; Horvath et al., 2021). Our results serve to augment more evidence to the mechanisms that drive sea ice loss through transporting moisture and energy into the Arctic via a case study in July 2020. Here we argued that the unusual atmospheric energy and moisture transport favored by large-scale circulation and cyclones in Spring 2020 effectively reduce ice extent under the circumstance of more thin, first-year ice, which is a novel result. These points distinguishing our research from previous literature will be added to the revised version.

R.2. I would encourage the Authors to use either SIE or SIC in the Introduction, the current version has both of them. Also, in Figure 1, I do not see any gray lines, which would refer to the 2000-2020 SIC climatology. Maybe it would aid the interpretation of Fig. 1 if it had multiple panels instead of the contour lines. The authors might consider plotting the SIC climatologies with shading in Fig 1 b for example.

Response: Indeed, sea ice extent (SIE) and sea ice concentration (SIC) are two similar parameters describing the areal coverage of sea ice, while the former denotes the “boundary” and the latter represents the "spatial fraction". As suggested, we will use SIE in the Introduction. SIC will be used only once when showing the spatial pattern of sea ice cover anomalies to detect the regions where severe ice loss occurred in July 2020 (Fig. 1.). Besides, Fig. 1 has been modified to aid the interpretation. We plot spatial patterns of SIC anomalies and the SIEs in different panels instead of superimposing the contour lines onto the shading (figure attached below).

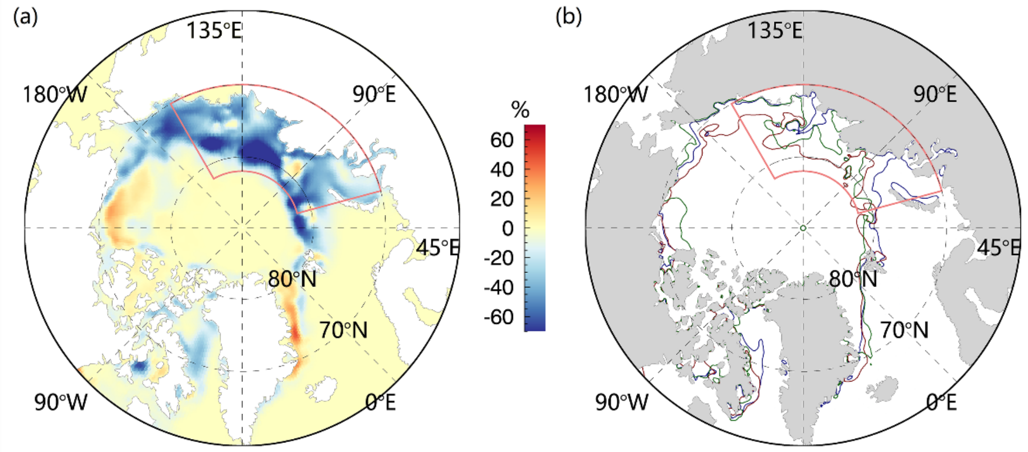


Figure 1. (a) Spatial patterns of SIC anomalies (shading), and (b) the SIEs in typical years (bold lines). The red line represents the SIE in July 2020. Green and grey curves within denote the SIE in July 2012 and the 20-yr average of the recent period 2001-2020, respectively. The anomalies are computed as the difference between the fields in July and the corresponding climatology over the past four decades (1979-2020). Pink polygons encapsulate areas where substantial sea ice cover loss (60° E-165° E, 70° N-82° N) occurred in July 2020, which represents the study area of this paper.

R.3. In general, in the figure captions it would be helpful not to use abbreviations.

Response: We will add the full names of the abbreviations in the figure captions.

R.4. In many cases, the significance of the anomalies are not clear. In Fig 2, Fig. 4 and Fig.5 it would be necessary to include significance as stippling for the anomalies. In Fig. 6, I do not see the significance of the results (nor statistically or literally). For example, in lines 237-240, the energy convergence should start early March and peak in June in each year corresponding with solar irradiation seasonality. How are the results presented in Fig 6 differ from the climatology? e.g., a histogram of all 42 years' melt start date could help to point out that 2020 May melt start was statistically significantly earlier than usual. Polishing the discussion of Fig. 6 would be essential to help the reader arrive at the conclusions that the authors set forth.

Response: Thanks for the insightful comments on the significance test. The significance of the figures and results is an essential issue when drawing a conclusion. Following the suggestion, we have added striplings to denote anomalies that are significant (e.g. greater than two standard deviations) in Fig 2, Fig. 4, and Fig.5. Accordingly, we will polish the discussion part of these figures (Fig 2, Fig. 4, and Fig.5) for better clarification. The significance of the results shown in Fig.6, including the magnitudes of different anomalies will be stated literally in the paragraph of its analysis. Besides, we produce a bar plot of all 42 years' early melt date to distinguish the particularly early melt onset in 2020. The revised figures are shown below.

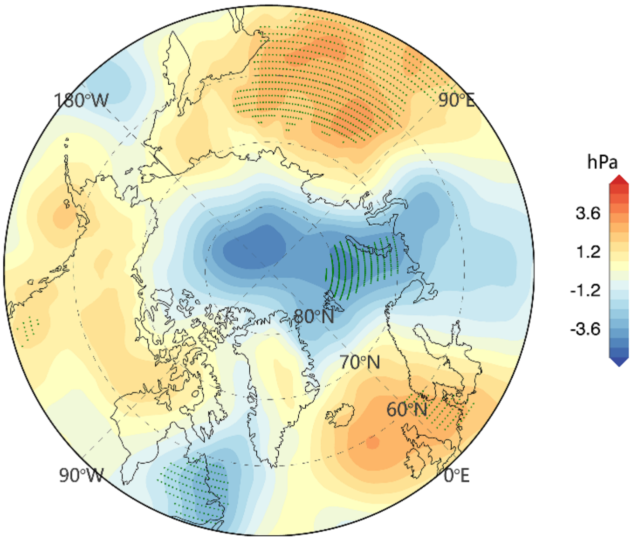


Figure 2. Spatial patterns of sea level pressure anomalies (shading) during April to June 2020. The anomalies are computed as the difference between the averaged fields of the three months (April-June) and the corresponding climatology over the past four decades (1979-2020). Stipplings represent the values where the anomaly exceeds 1.5 standard deviations.

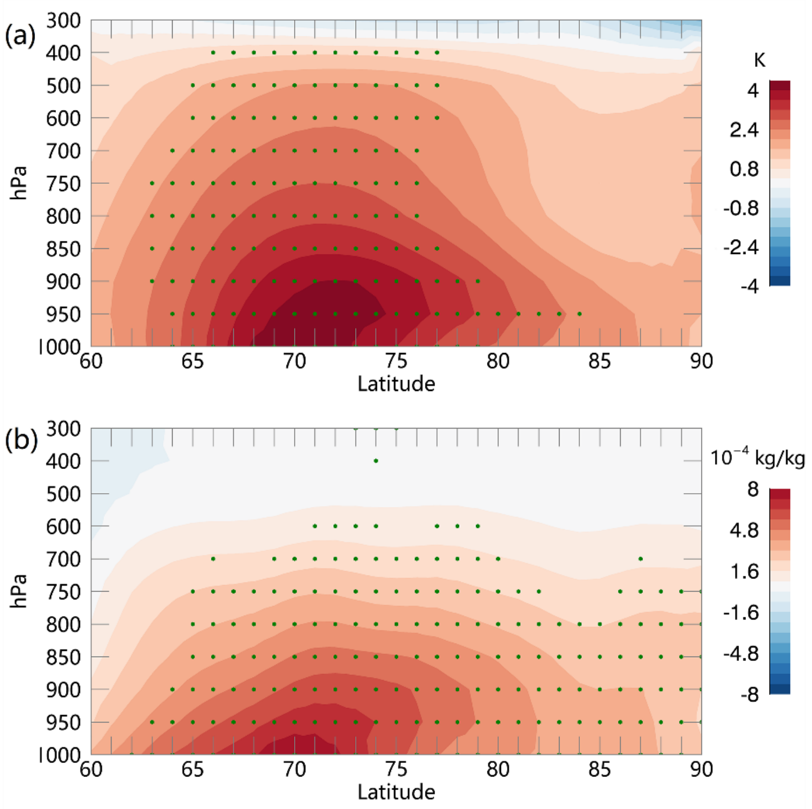


Figure 4. Vertical cross-sections of zonal averaged (a) air temperature and (b) specific humidity anomalies, as a function of latitude and pressure level, during the spring months (April–June) of 2020 spanning the regions with significant energy and moisture convergence (60° E-165° E, 60° N-90° N). The anomalies are calculated as the difference between the averaged fields of the three months (April-June) and the corresponding climatology over the past four decades (1979-2020). Stipplings represent the values where the anomaly exceeds 2 standard deviations.

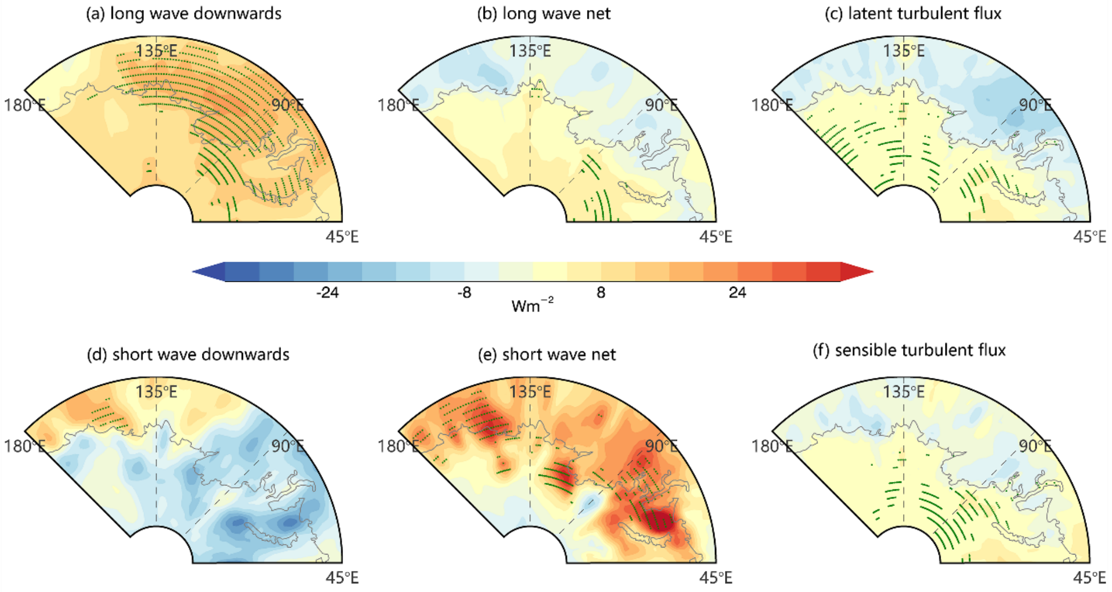


Figure 5. Anomalies of surface (a) downwelling and (b) net longwave radiation, (d) downwelling and (e) net shortwave radiation, as well as sensible (c) and latent (f) heat fluxes. The anomalies are relative to the climatology

with monthly resolution from the years 1979-2020 and averaged over the spring months (April–June) of 2020. The stippled grids denote those with values where the anomaly exceeds 2 standard deviations.

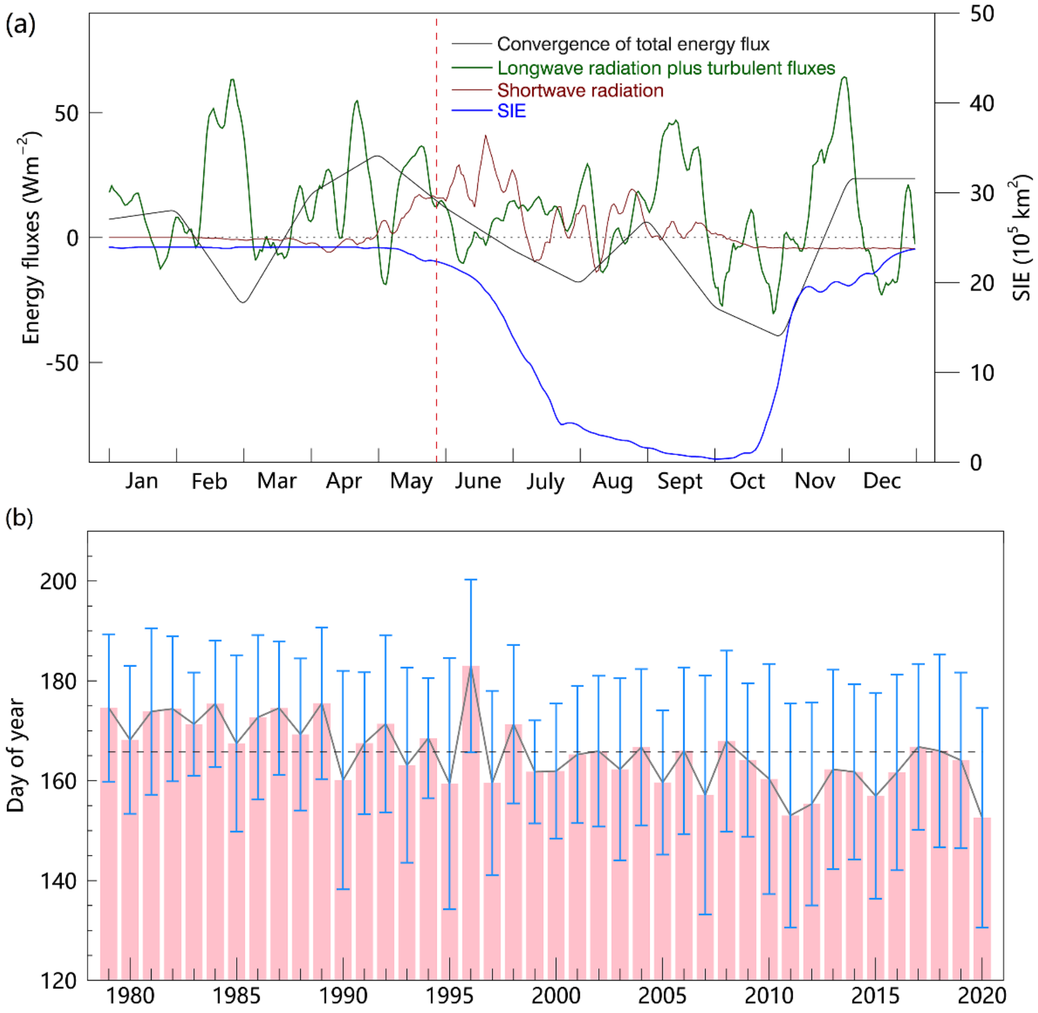


Figure 6. (a) Time series of sea ice extent, the anomalies of atmospheric energy transport convergence and surface energy fluxes over the study area (indicated by the green polygon in Fig. 3c and d) during 2020. The blue curve represents the SIE. The red line denotes the anomalies of net solar radiation. The green line corresponds to the anomalies of the sum of the downwelling thermal radiation and the turbulent (latent plus sensible) flux. The vertical pink line denotes the average melt day (May 28) in 2020, provided by NASA. The anomalies are relative to the climatology of the years 1979-2020. (b) The averaged melt date of the study area during the period 1979-2020. The grey dashed line represents the mean melt date of these four decades. Error bars denote one standard deviation.

L264: significant is what sense? If statistically, please provide the p value.

Also, when stating 99% significance, what was the applied significance testing method?

Response: The decreasing trend detected in the averaged sea ice thickness of the study area in spring during the period 1979-2020 is significant at the 99% confidence level, which is specified at Line 267 in the original manuscript, using a Student's t-test. The significance testing method will be added to the revised paper.

R.4. I think a more thorough discussion of Fig.10a would also improve the paper. Any hints on the seen low-frequency oscillation in the 10-yr trends? Can this be linked with large-scale circulation trends (not SLP, but winds or upper-level geopotential, e.g., 300hPa)?

Response: Intuitively, the low-frequency oscillation in the 10-yr trends will be closely tied with the large-scale circulation trends as the large-scale circulation plays a vital role in regulating cyclones and moisture/total energy flux. We will do some work to look for the upper-level large-scale circulation and try to find out the connection. In the revised paper, we will discuss more thoroughly about Fig.10a.

Reference:

Baxter, I., Ding, Q., Schweiger, A., L'Heureux, M., Baxter, S., Wang, T., Zhang, Q., Harnos, K., Markle, B., and Topal, D.: How tropical Pacific surface cooling contributed to accelerated sea ice melt from 2007 to 2012 as ice is thinned by anthropogenic forcing, Journal of Climate, 32, 8583-8602, 2019.

Bi, H., Wang, Y., Liang, Y., Sun, W., Liang, X., Yu, Q., Zhang, Z., and Xu, X.: Influences of Summertime Arctic Dipole Atmospheric Circulation on Sea Ice Concentration Variations in the Pacific Sector of the Arctic during Different Pacific Decadal Oscillation Phases Journal of Climate, 34, 3003-3019, 10.1175/jcli-d-19-0843.1, 2021.

Ding, Q., Schweiger, A., L'Heureux, M., Battisti, David S., Po-Chedley, S., Johnson, Nathaniel C., Blanchard-Wrigglesworth, E., Harnos, K., Zhang, Q., Eastman, R., and Steig, Eric J.: Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice, Nature Climate Change, 7, 289-295, 10.1038/nclimate3241, 2017.

Graversen, R. G., Mauritsen, T., Drijfhout, S., Tjernstrom, M., and Martensson, S.: Warm winds from the Pacific caused extensive Arctic sea-ice melt in summer 2007, Climate Dynamics, 36, 2103-2112, 2011.

Horvath, S., Stroeve, J., Rajagopalan, B., and Jahn, A.: Arctic sea ice melt onset favored by an atmospheric pressure pattern reminiscent of the North American-Eurasian Arctic pattern, Climate Dynamics, 57, 1771-1787, 10.1007/s00382-021-05776-y, 2021.

Kapsch, M.-L., Skific, N., Graversen, R. G., Tjernström, M., and Francis, J. A.: Summers with low Arctic sea ice linked to persistence of spring atmospheric circulation patterns, Climate Dynamics, 52, 2497-2512, 10.1007/s00382-018-4279-z, 2019.

Ogi, M., and Wallace, J. M.: The role of summer surface wind anomalies in the summer Arctic sea ice extent in 2010 and 2011, Geophysical Research Letters, 39, https://doi.org/10.1029/2012GL051330, 2012.

Screen, J. A., and Deser, C.: Pacific Ocean Variability Influences the Time of Emergence of a Seasonally Ice-Free Arctic Ocean, Geophysical Research Letters, 46, 2222-2231, https://doi.org/10.1029/2018GL081393, 2019.

Vázquez, M., Nieto, R., Drumond, A., and Gimeno, L.: Extreme Sea Ice Loss over the Arctic: An Analysis Based on Anomalous Moisture Transport, Atmosphere, 8, 10.3390/atmos8020032, 2017.

Warner, J., Screen, J., and Scaife, A.: Links between Barents‐Kara sea ice and the extratropical atmospheric circulation explained by internal variability and tropical forcing, Geophysical Research Letters, 47, e2019GL085679, 2020.