Response to Referee #1

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:

The authors are exploring the atmospheric conditions during spring that might have led to the low sea-ice extent in July of 2020. In their analysis the authors focus on the transport and convergence of moist and warm air masses and associated changes in the surface energy balance. Using a cyclone tracking algorithm, they connect the increased energy transport in spring 2020 to anomalies in the cyclone activity. Thereby, the study follows up on a range of previous studies, which identified the spring atmospheric conditions to be the major driver of a low summer sea-ice extent. While the topic is very relevant and interesting, the analysis lacks explanations and potentially also extensions.

General comments:

The analysis is rather comprehensive but the methods and supporting information are not always clear, hence, it is hard to arrive at the drawn conclusions. One of the main problems is that the study area contains a lot of land points, but the focus of interest is sea-ice variability. Why did the authors choose this study area and did not e.g. exclude land points or even focus on the area that showed the largest SIE anomalies in 2020 from Fig. 1.? Another point is the cyclone detection and conclusions drawn. It is not clear how robust the results are.

Response:

a. First of all, thanks a lot for the advice on this manuscript which helps us to improve the research. In the present study, we use a range of latitudes and longitudes to define a relatively regular study area (60° E-165° E, 70° N-82° N) for the convenience of plotting. However, in the analysis, the retrieved values are averaged over the oceanic grids by applying a land mask and SIE is defined as areas that have an ice concentration of at least 15% (Fig. 6 and 7).

b. The nature that extratropical cyclones are characterized by great complexity (asymmetric structure, differ rather more in size, multi-centers and occur in very diverse synoptic situations) indicate that there is no single commonly agreed upon scientific definition of an extratropical cyclone, and there exists a range of ideas and concepts regarding how to identify and track them (Murray and Simmonds, 1991; Serreze et al., 1993; Serreze, 1994; Sinclair, 1994; Pinto et al., 2005; Wang et al., 2006; Wernli and Schwierz, 2006). Methods differ in a number of aspects including variables used, tracking parameters, and post-processing. Different approaches each have their strengths and weaknesses, hence one cannot "judge" the algorithms to be "right" or "incorrect" (Neu et al., 2013). In the present study, we use a revised automatic cyclone identification and tracking algorithm developed originally by Serreze et al. (1993) to diagnose and track the cyclones from the 6-hourly mean sea level pressure (MSLP) data (Serreze et al., 1993; Serreze, 1995; Serreze et al., 1997; Wu et al., 2006a; Wang et al., 2013). The method was used by the National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences (NOAA–CIRES) Climate Diagnostics Center (CDC) to diagnose storm tracks for the period 1948 and 2004. Besides, Neu et al. (2013) conducted an intercomparison experiment involving 15 commonly used detection and tracking algorithms for extratropical cyclones. The results revealed that cyclone characteristics that are robust between different schemes and our algorithm agrees well with the others in terms of spatial distribution, interannual variability and geographical linear patterns of the cyclones. To some extent, these facts give credence to the method utilized in this study.

Specific comments:

1) Figure 1: It is not possible to see the colored line indicating the July SIE of 2021 (red) and not possible to distinguish between the others (green, gray). Please choose different colors or a thicker linewidth, as this figure is important for the following analysis.

Response: 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).

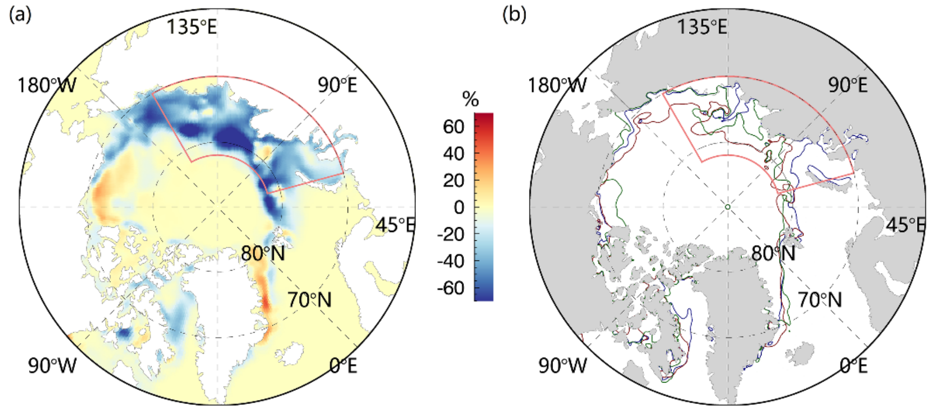

Figure 1. (a) Spatial patterns of SIC anomalies (shading), and (b) the SIEs in typical years (bold lines). The red line represents the SIE in July 2020. Green and grey curves within denote the SIE in July 2012 and the 20-yr average of the recent period 2001-2020, respectively. The anomalies are computed 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.

2) Section 2.2.3: Crawford et al, 2021 (https://doi.org/10.1175/mwr-d-20-0417.1) have investigated the dependence of spatial and temporal resolution on a realistic detection of cyclone tracks in ERA-5. How does your algorithm differ from theirs? Do you experience an unrealistic break up of cyclones? The cyclone tracks in Fig. 9 are hard to identify and many end up over land (while you are interested in what happens over the ice), which makes me wonder how robust your whole analysis on the cyclone tracks is. Maybe backwards trajectories would be easier to interpret?

Response:

a. Crawford et al. (2021) aim to test the sensitivity of the cyclone tracking method to the spatial and temporal resolution of ERA5 sea level pressure fields. The cyclone detection and tracking algorithm they used was introduced by Crawford and Serreze (2016) and builds on the method originally designed by Serreze et al. (1993). Coincidentally, we use a revised automatic cyclone identification and tracking algorithm which is based on the same scheme developed by Serreze et al. (1993). The main difference is that they explicitly identify multicenter cyclones as well as splitting and merging events. While in our algorithm, the exact center is determined as the grid with the largest local Laplacian of SLP when multiple cyclone center candidates are found within a radius of 1200 km.

b. In the present study, the ERA5 6-hour SLP fields were interpolated to a 50-km version of the NSIDC EASE-grid, prior to the application of the algorithm. As suggested by Crawford et al. (2021), we used a common search distance (7×7 array of grid points) when detecting minima in sea level pressure and did not experience an unrealistic break up of cyclones.

c. Some studies corroborated the fact that synoptic cyclones play a crucial role in regulating the poleward moisture and energy fluxes (Jakobson and Vihma, 2010; Dufour et al., 2016; Villamil-Otero et al., 2018). As a cyclone represents a dynamical process and concerning its fundamental nature in holding moisture and energy, all poleward cyclones may play a non-negligible role in transporting energy and water vapor to the Arctic in the form of a relay. Thus, rather than just confining cyclones that occurred over the ice, we take all poleward cyclones into account when inspecting the underlying effects of the cyclones on the poleward transport of energy/moisture in spring 2020. As a consequence, some cyclones in Fig.9 had their tracks end over land. Tracking cyclones backwards from their lysis to form trajectories may be more straightforward in this study. However, within the scope of our knowledge, there exist no backward-tracking schemes of an extratropical cyclone. It may be an innovative path for future research.

3) Line 157: A low-pressure anomaly over the central Arctic dominates the spring of 2020. Similar anomalies were detected in spring of years with a low summer sea ice in Kapsch et al., 2019 (https://doi.org/10.1007/s00382-018-4279-z) and Horvath et al., 2021 (https://doi.org/10.1007/s00382-021-05776-y). Both of the studies pointed out that a similar pattern was associated with summers of low sea ice and an early melt onset in the Kara/East Siberian Sea. You should relate to these studies, as your findings for 2020 are a confirmation their findings.

Response: We have read the recommended literature and will relate these two studies in our study.

4) Fig. 6: the total convergence of energy is heavily smoothed. Why using a different temporal resolution for the different variables? Please clarify. A higher spatial resolution can also give an idea about the persistence of atmospheric circulation patterns that lead to the enhanced energy transport, which was found to be of importance for the summer sea ice in previous studies.

Response: We have no idea why the hourly REA5 convergence of total energy flux fields are rather noisy (Figure below, grey dashed line), the reasoning behind it demands further evaluations. Hence it is a compromise to utilize the monthly mean of the convergence fields.

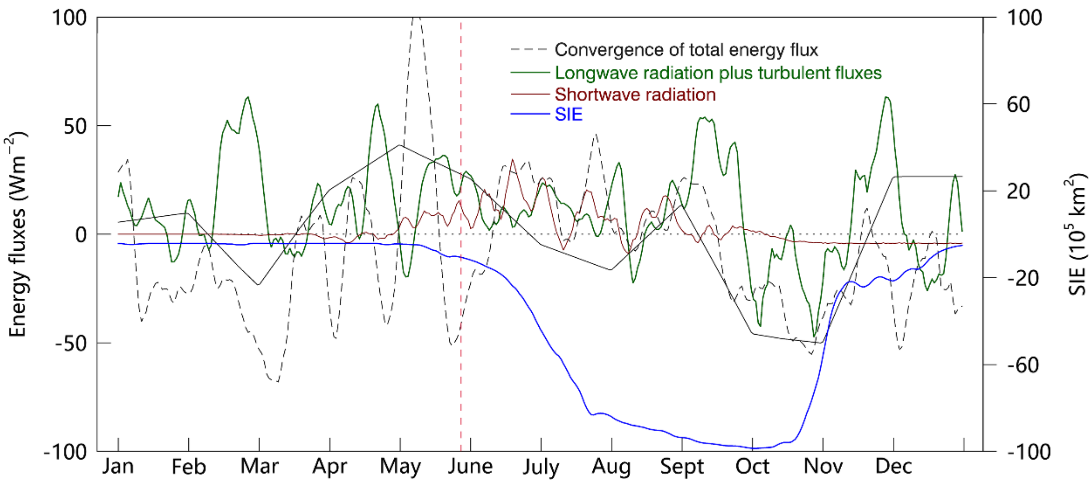

Figure 6. Time series of SIE, the anomalies of atmospheric energy transport convergence and surface energy fluxes over the study area (indicated by the green polygon in Fig. 3c and d) during 2020. The blue curve represents the SIE. The red line denotes the anomalies of net solar radiation. The green 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.

5) Line 46: '… various disciplines.' – like which? Line 87: Schweiger et al outlined a less than 0.1m difference and a high pattern correlation. How different are the data sets over the area of interest?

Response:

a. The scientific studies about the causes of Arctic sea ice shrinkage encompass various disciplines, including atmospheric (Deser et al., 2000; Wu et al., 2006b; Wang et al., 2009; Ogi et al., 2016) and oceanic (Årthun et al., 2012; Miles et al., 2014; Zhang, 2015; Årthun and Eldevik, 2016) sciences. This paper aimed to assess the impact of the variations in atmospheric transport of total energy and moisture on sea ice loss in spring 2020, the second paragraph in the introduction, therefore, discusses the current understanding of relevant mechanisms.

b. In the Laptev and East Siberian Seas, ICESat and PIOMAS ice thickness fields show a close agreement with the spatial pattern of ice thickness. The PIOMAS thickness fields are about

0.2-0.7 m small than that of ICESat for February–March (Schweiger et al., 2011).

6) Line 119: You claim that the results of your energy flux estimates are similar to those of ERA-5. If the moisture flux exists in ERA-5, why estimating it?

Response: Indeed, the ERA5 fields of the total energy and moisture flux experience an update and some corrections during the period we processed the data. To ensure that our research continues, we calculate the moisture flux when the corresponding field from ERA5 was in an upgrade state. Once the ERA5 field is prepared, we compared our estimated results with ERA5 and decided to directly utilize the ERA5 fields of the total energy and moisture flux.

7) Fig. 5: Might be an optical illusion due to the projection, but for me it seems that the study area slightly differs from the one indicated in Fig. 3. It seems that there are more land points in Fig. 5. However, see comment on excluding land points from the analysis.

Response: All the fields obtained from ERA5 have a spatial resolution of 1.0° ×1.0° in longitude and latitude. For better illustration, the anomalies of different meteorological variables as well as cyclone characteristics are displayed on a polar stereographic projection (Figs. 1, 2, 3, 5, 7, 10, and 11). The spatial patterns of variations of surface radiative and turbulent fluxes shown in Fig.5 are not the optical illusion but indeed a true phenomenon exists in the data. The figure attached below shows the same anomalies, which have coincident patterns with Fig.5. Besides, the plotted domain of Fig.5 is slightly bigger than the study area in order to display. In the analysis, the retrieved values are averaged over the oceanic grids within the study area by applying a land mask and SIE is defined as areas that have an ice concentration of at least 15% (Fig. 6 and 7).

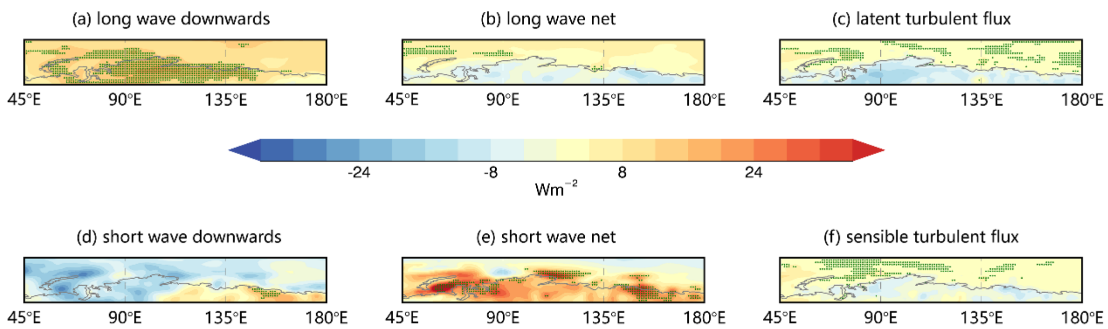

Figure 5. Anomalies of surface (a) downwelling and (b) net longwave radiation, (d) downwelling and (e) net shortwave radiation, as well as sensible (c) and latent (f) heat fluxes. The anomalies are relative to the climatology with monthly resolution from the years 1979-2020 and averaged over the spring months (April–June) of 2020. The

stippled grids denote those with values where the anomaly exceeds 2 standard deviations.

8) Line 284: I don't see how calculating the cyclones from ERA-Interim gives more credibility in the methods and results. It might be worse to take a more independent reanalysis for such credibility check. Again, a discussion on the method and previous findings is necessary (see point Section 2.2.3).

Response: We sincerely appreciate the valuable comments on the credence check of the cyclone identifying and tracking algorithm. In a previous study of our team, the retrieved cyclones from ERA-Interim SLP fields are used to discuss the impact of cyclones on the sea ice area flux through the Baffin Bay with respect to dynamical processes (Liang et al., 2021). For convenience, we compared the cyclone systems diagnosed from the ERA5 SLP with those from ERA-Interim, which may be problematic. We will delete these sentences when preparing the revised manuscript and refer to the results of the intercomparison between 15 different algorithms in Neu et al. (2013).

9) Line 361: Ice motion in response to the circulation patterns and cyclones should be discussed a bit more in detail, as it is an important process. It also should be related to previous studies. There have also been other studies, elaborating on some of the processes that lead to an earlier melt onset (e.g. increased liquid precipitation).

Response: The main driver of sea ice motion is the surface wind, which can explain more than 70% of the variance of the ice velocity in the central Arctic Ocean. Sea ice tends to move with a speed of about 2% of the surface wind and about 45° to the right of the wind (Thorndike and Colony, 1982). That is to say, variations in large-scale circulation patterns and cyclones would inevitably change the ice drift pattern. We will discuss the ice motion in more detail in the revised paper and add the related references. Besides, the literature elaborating the consistent mechanisms with the present study which lead to an earlier melt onset will be added to the discussion part of Fig.6 (Line 240-252 in the original manuscript).

10) Line 415: A very relevant study related to an early melt onset in years of low summer sea ice in the study area is also Mortin et al., 2016 (https://doi.org/10.1002/2016GL069330) as well as several studies by Stroeve et al.

Response: We have read the recommended literature and will refer to them in our study.

11) Line 427: It should be mentioned much earlier, probably in the introduction, that the September SIE was not a record in 2021. It might be interesting for the reader to know why this study explores the July SIE instead of the September SIE.

Response: We clarified the fact that the September SIE of 2021 did not hit the record earlier in the introduction (Line 30-31 in the original manuscript). In 2020 however, Arctic sea ice experienced the lowest July extent recorded since 1979, which is ~21% lower than the average July SIE over the period 2000-2020. This study aims to disentangle the mechanisms that drive this extreme event.

Technical corrections:

1) Line 102: 'replacing ERA-Interim'

Response: We replace the sentence with "ERA5 is a new reanalysis product which improves on its predecessor (ERA-Interim). ERA5 benefits from a decade of developments in model physics, core dynamics, and data assimilation.".

2) Line 175: remove parenthesis behind Kara Sea.

Response: Revised as suggested.

3) Line 188: 'unusual conditions with higher'

Response: Revised as suggested.

4) Fig. 1, 2, 3, 7, 10, 11: It might be worse to use one projection (including latitude range) for the plots.

Response: As the regions of interest in this study are located in the Arctic, I think it is better to plot the geographical patterns of different variables on a polar stereographic projection. Moreover, all figures that demonstrate spatial distributions have the same projection for the sake of uniformity of presentation.

5) Fig. 4: Line 200: 'spanning the with significant' – something missing here. The whole caption would benefit from a revision.

Response: The expression has been changed into "spanning the regions with significant".

6) Line 282: 'we identify and track cyclone'

Response: Corrected as suggested.

7) In many places there is no space between text and the following parentheses, e.g. Line 205, 256,

279, 283, 398, 419, 421 … In general, it would be good to check for spelling and language related issues.

Response: Following the suggestion, the space between text and the following parentheses will be added. We will also further polish the original manuscript and remove the inappropriate expressions.

Årthun, M., Eldevik, T., Smedsrud, L., Skagseth, Ø., and Ingvaldsen, R.: Quantifying the influence of Atlantic heat on Barents Sea ice variability and retreat, Journal of Climate, 25, 4736-4743, 2012.

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algorithm: individual tracks and climatology, Meteorologische Zeitschrift, 14, 823-838, 2005.
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Serreze, M. C.: Climatological aspects of cyclone development and decay in the Arctic, Journal of Atmosphere, 33, 1-23, 1995.
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