Responses to Robbie Mallett

Dear Robbie Mallett:

We would like to thank you for the constructive comments to improve this manuscript. We overall agree with the points raised, and the points have been considered in revising the manuscript. In the following, our detailed responses are shown in italic.

Qinghua Yang

On behalf of all the co-authors

General Comments:

1) I read this paper with great interest as a user of CryoSat-2 data, and have a couple of thoughts regarding the authors' use of this data in the spirit of TC discussion.

   It seems that a headline result of this study is that "a sea ice thickness record minimum is confirmed occurring in autumn 2011" (I hope this is fair to say given that it's the second sentence of the abstract and first of the Summary/Discussion). I think to fully make this claim there should perhaps be a deeper consideration of the nature of this metric and the uncertainties in altimetry-derived SIT (particularly over thin ice).

   To state the obvious, SIT is a local property of sea ice, whereas extent and volume are global properties of the ice pack. The impact of this is that mean SIT is sensitive to the area over which it's averaged (unlike the other two metrics). The approach in this paper is to just average over the "area of actual ice coverage" (L37). The decision to average over this area this has many implications.

   For instance, are the authors including the sub-Arctic seas like the Baltic and Okhotsk Seas and Baffin and Hudson Bays? I believe the AWI product includes SIT values for these. If the SIT of these regions contributes to the 'mean SIT' statistic, then how relevant is their interpretation of the 2011 minimum in terms of the dynamic/thermodynamic budget which is only produced for the Arctic Ocean (and also only with reference to 2011-16).

Response: *Thanks for this comment. We found the previous context may not sufficiently describe the region where we compute the mean sea ice thickness. We have now added in more detail: "The mean sea ice thickness is computed within the area of actual ice coverage bounded by the gateways into the Pacific (Bering Strait), the Canadian Arctic Archipelago, and the Greenland (Fram Strait) and Barents Seas (Kwok, 2018; Kwok and Cunningham, 2015)." The region doesn't include the sub-Arctic seas. We have added a new figure to the Supplement of the revised version of our manuscript (as shown in the Figure S1f below).*

About the sub-Arctic seas contributes to the 'mean SIT' statistic, we compared the mean SIT calculated by the whole-Arctic and only for the Arctic Ocean as shown in the Figure S2 below. About the uncertainties in altimetry-derived SIT, we also calculated the uncertainties in CS2SMOS. The mean sea ice thickness in both results in October 2011 was strongly anomalous.

We agree that the SIT is a local property of sea ice and sensitive to the area of actual ice coverage within the boundaries in figure S1. If the SIT is calculated using fixed area instead of the actual area covered by sea ice, then the information reflected by SIT is actually the same as the volume. The influence of sea ice is not just about how much ice volume there is. It is about how that ice is distributed. In 2011 the CS2 data suggest that the ice is unusually thinly distributed as shown in the Figure S1 below, and so that justifies a closer examination of what happened in that year.

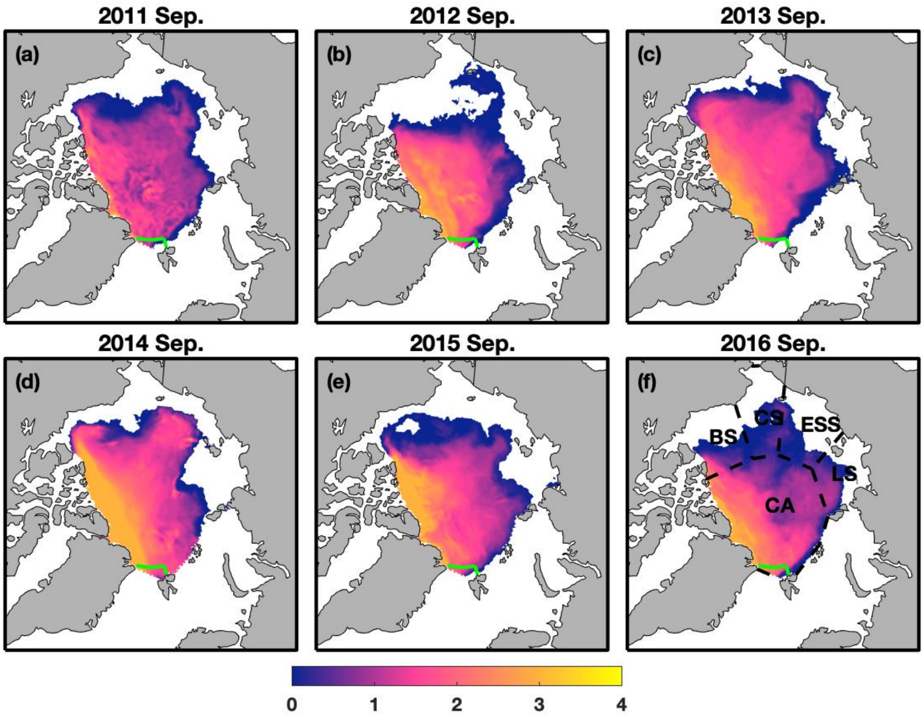

Figure S1. Arctic sea ice thickness in September calculated from CMST (2011–2016). The thick green line represents zonal and meridional sea ice gates to derive sea ice volume flux through the Fram Strait. (f) The mean sea ice thickness is computed within the Arctic basin bounded by the gateways into the Pacific (Bering Strait), the CAA, and the Greenland (Fram Strait) and Barents Seas subdivided into maritime boundaries provided by NSIDC via MAISIE.

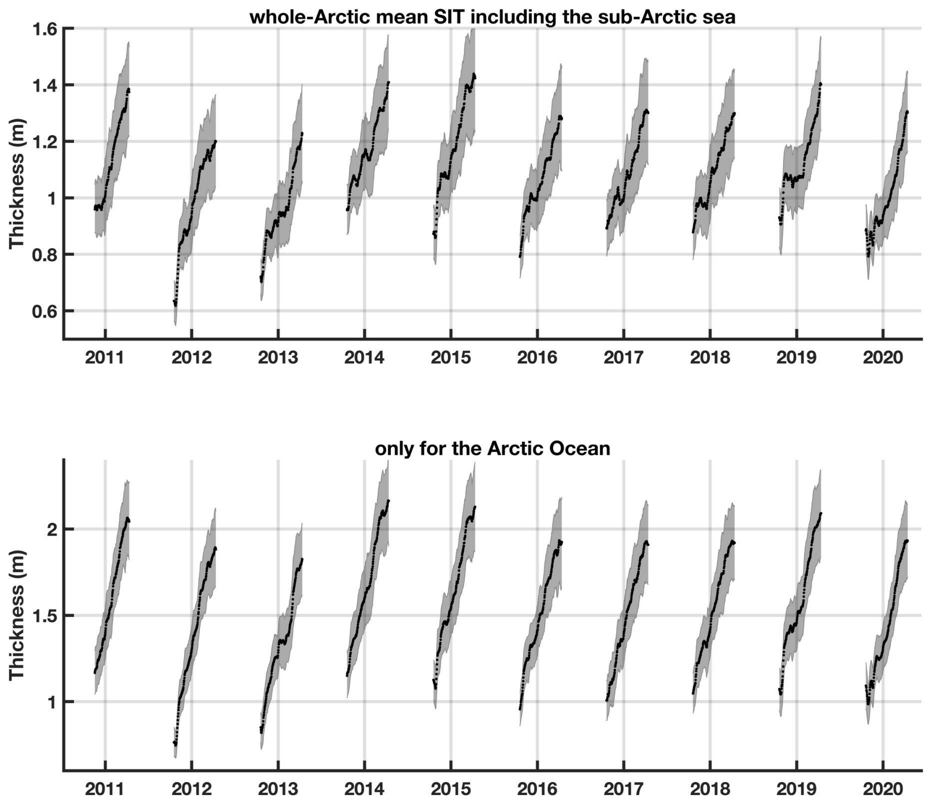

Figure S2: Daily behavior of sea ice thickness and volume based on CS2SMOS dataset from October 2010 through April 2020. (a) Mean sea ice thickness within area of whole-Arctic mean SIT including the sub-Arctic sea. (b) Mean sea ice thickness within area only for the Arctic Ocean. The mean sea ice thickness is computed within the area of actual ice coverage bounded by the gateways into the Pacific (Bering Strait), the Canadian Arctic Archipelago, and the Greenland (Fram Strait) and Barents Seas.

2) Next the authors should probably acknowledge that CryoSat-2 doesn't do a good job of retrieving the thickness of thin ice (<0.5m; see Ricker et al., 2017). This is because this ice protrudes above the waterline by less than 5cm, and even less with snow cover. But here I think the authors are averaging over quite a lot of thin ice to generate their statistic. The merged CS2-SMOS product was developed with this limitation in mind, and (in my opinion) should be the product of choice for this calculation. I particularly think this because the CMST model assimilated this product, so it should perhaps be used for consistency's sake anyway. A related issue is that CS2 simply can't measure ice below a certain thickness. By

just taking the average in places where it can measure, the authors are likely biasing their mean SIT statistic high. The size of this bias will depend on the extent of sea ice with unmeasurably low freeboard. I think they should state what fraction of the total sea ice area (as measured by a scatterometer or radiometer) is covered by the altimetry data under consideration. It's possible that this fraction is very high and my concern isn't warrented, but I think it is relevant.

Response: *Thanks for this comment. The observational CS2 uncertainties of sea ice thickness contain contributions that are associated with speckle noise, sea-surface height estimation, snow depth and densities of ice and snow (Ricker et al., 2014). CS2 data have relatively large errors over the thin ice area, while SMOS has smaller error, and vice versa for the thick ice area (Ricker et al., 2017). As suggested by the reviewer, we replaced the data with CS2SMOS to compare the daily behavior of sea ice thickness and volume from October 2010 through April 2020 and calculated the uncertainties as shown in the Figure S3 below. The retrieval method is based on the evaluation of surface brightness temperature, as measured by the Soil Moisture and Ocean Salinity (SMOS) satellite. The uncertainties over thin ice are significantly smaller than for the altimetry- based retrievals. The SMOS retrieval can contribute valuable information, especially in regions with unmeasurably low freeboard. The complementary character between CS2 and SMOS made up the bias caused by unmeasurably low freeboard. At the same time, the results of ICESAT and CryoSat-2 data are put into Supplementary of the revised version of our manuscript (as shown in the Figure S4 below).*

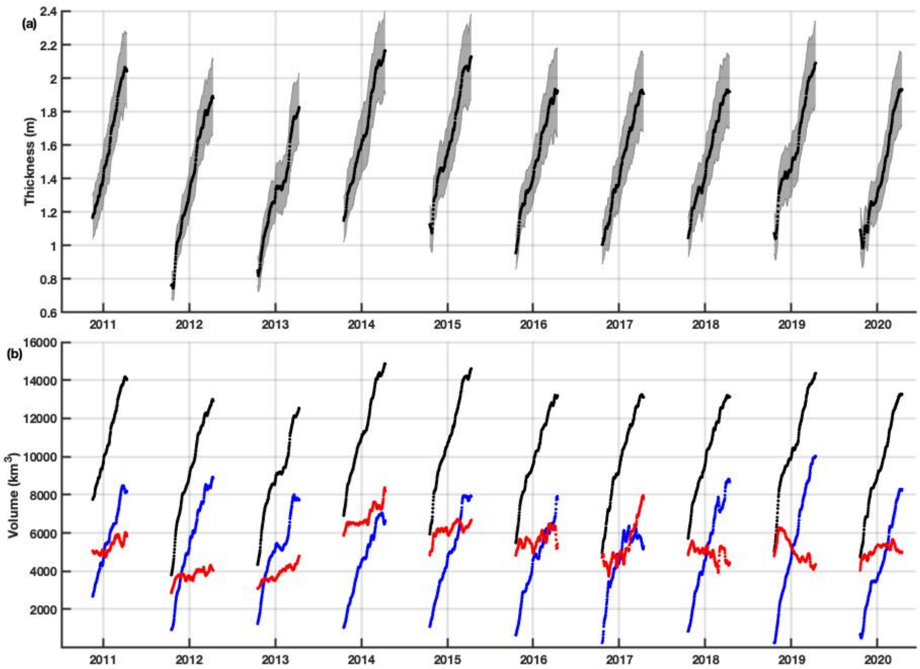

Figure S3: Daily behavior of sea ice thickness and volume based on CS2SMOS dataset from October 2010 through April 2020. (a) Mean sea ice thickness within area of actual ice coverage. (b) Total(black)，first-year(blue) and multiyear (red) sea ice volumes within Arctic basin. The mean sea ice thickness is computed within the area of actual ice coverage bounded by the gateways into the Pacific (Bering Strait), the Canadian Arctic Archipelago, and the Greenland (Fram Strait) and Barents Seas.

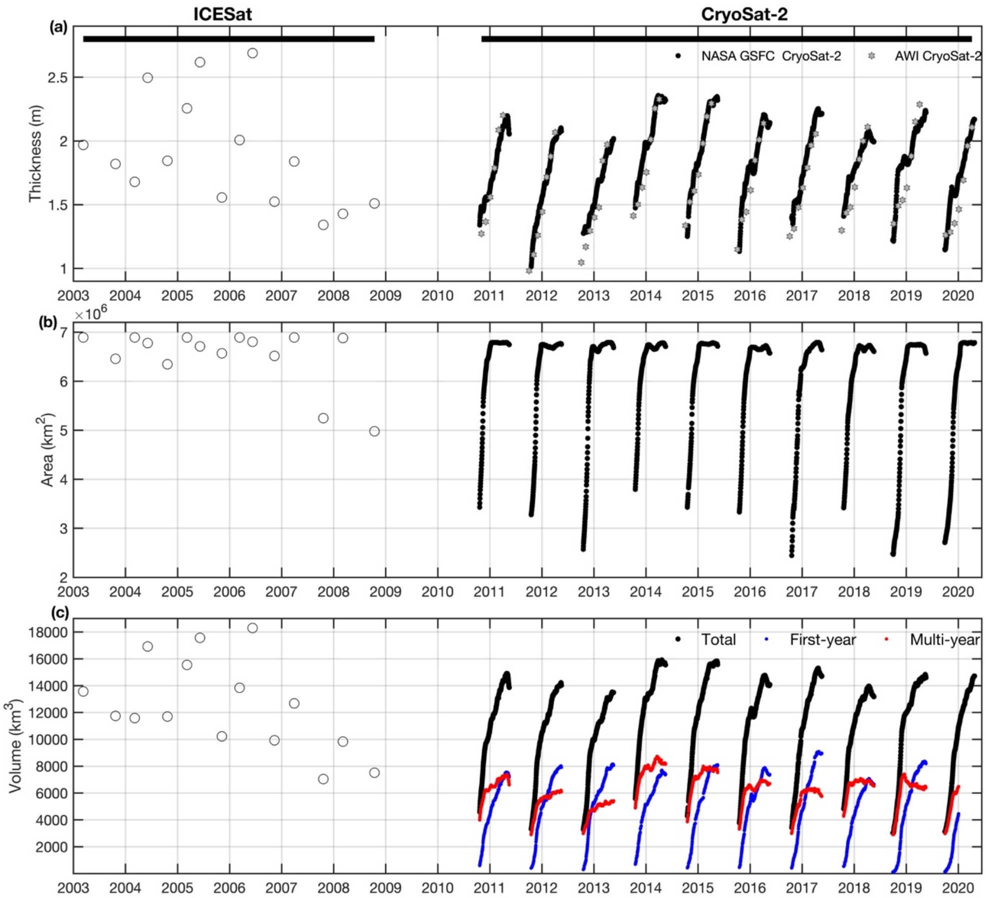

Figure S4: Interannual changes in sea ice volume, area and thickness based on the ICESat (2003–2008) and CryoSat-2 (2011–2020) satellite datasets. (a) Mean sea ice thickness within area of actual ice coverage. (b) Total sea ice area (cumulative area of actual ice coverage) within Arctic basin. (c) Total(black)，first-year(blue) and multiyear (red) sea ice volumes within Arctic basin. Arctic basin volume and area is computed within the bounded by the gateways into the Pacific (Bering Strait), the Canadian Arctic Archipelago, and the Greenland (Fram Strait) and Barents Seas.

3) Finally I'm not really sure what the whole-Arctic mean SIT minimum is supposed to tell us. I can imagine a year where there's an early freezeup and therefore a lot of very thin FYI coverage. So volume could be up, but mean SIT down. (but what if this weren't measurable by CS2?) But I can also imagine a scenario where we're low on MYI, so volume could be down as well as mean SIT. So does whole-Arctic mean SIT mean anything? I think some more consideration of the relationship between the metric and sea ice volume is warranted. (for instance just before the freeze-up there is less sea ice volume than afterwards. But thin FYI proliferates after the freeze-up. So the effect of the freeze-up (I think) is that sea ice volume goes up, but mean sea ice thickness goes down sharply. But then

volume and mean-SIT both grow together). So the minimum occurs after freezeup but before the ice starts thickening in earnest. Does the day of minimum mean-SIT therefore occur before CS2 starts working? I'd be interested to know on what day of the year piomas predicts the minimum in whole-Arctic mean SIT, and for that matter what year has the lowest minimum in that data.

Response: *This point is well taken. As shown in figure S3 and S4, there is no 'minimum' visible in the SIT timeseries. This suggests that the minimum occurs before CS2 starts working. So what we have really identified is a record low for October, not an absolute record low. We have refined the title of our manuscript as: On the 2011 Arctic sea ice thickness: a combination of dynamic and thermodynamic anomalies.*

This figure as shown in the Figure S5 below shows the Interannual changes in mean sea ice thickness based on the PIOMAS (2011–2016). PIOMAS shows that the daily minimum in whole-Arctic mean SIT at the end of October in 2012(0.908m), while the minimum mean SIT in 2011 is on November 1st with 0.911m. The day of PIOMAS predicts the minimum in whole-Arctic mean SIT is disagree with the CS2 and CS2SMOS.

The influence of sea ice is not just about how much ice volume there is. It is about how that ice is distributed. In 2011 the CS2 data suggest that the ice is unusually thinly distributed, and so that justifies a closer examination of what happened in that year. Sea ice thickness (SIT) is a key factor in the study of sea ice variability and their feedback effects, and it can better represent the mass balance of sea ice. Thicker sea ice is more insulated, weakening the coupling between the ocean and the atmosphere. It can limit the heat transfer from the ocean to the atmosphere in winter and affecting the thermodynamics of sea ice. SIT can also control the dynamics of ice; For example, SIT determines whether the ice is ridged or rafted. Finally, thick ice is more likely to survive the melting season, providing an opportunity to predict sea ice status on a seasonal time scale.

The reviewer is broadly commenting that a low SIT anomaly can arise in several ways. We agree with that entirely, which is why we chose to closely examine precisely why the SIT metric was low in this particular year.

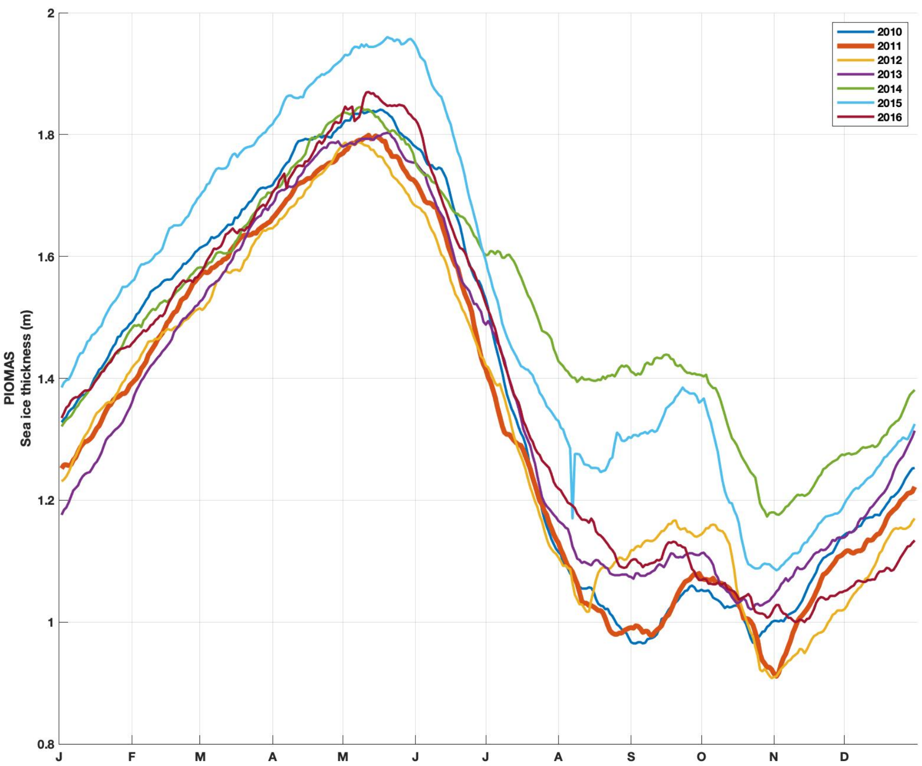

Figure S5: Interannual changes in mean sea ice thickness based on the PIOMAS (2010–2016).

A couple of narrower points:

1) The authors state: “The mean sea ice thickness within the area of actual ice coverage in October 2011 reached the lowest record for that calendar month in any year of the satellite records”. The authors should point out that they have not examined the whole satellite record, which includes pan-Arctic SIT snapshots from ICESAT (2003-2010), and coverage up to 81.5 degrees by Envisat. Would be perhaps worth confirming that 2011 is a record low when also compared to ICESAT derived thickness? In particular I'm thinking about winter 2007-8 after the SIE minimum.

<u>Response</u>: *This is an important point raised by the reviewer and reminds us to check whether 2011 is a record low when compared to ICESAT derived thickness. We have now added a new figure to the Supplement of the revised version of our manuscript (as shown in the Figure S4 below) and compared the sea ice volume, area and mean sea ice thickness based on the ICESat (2003–2008) and CryoSat-2 (2011–2020) satellite datasets The fact that* Kwok (2018) *also has a paper published discussing Arctic sea ice volume in 2011 hit the lowest record from 0ct. to Nov. between 2003 and 2018 in the same Arctic basin means that i) the satellite data are considered worthy of studying and ii) this individual event is worthy of studying.*

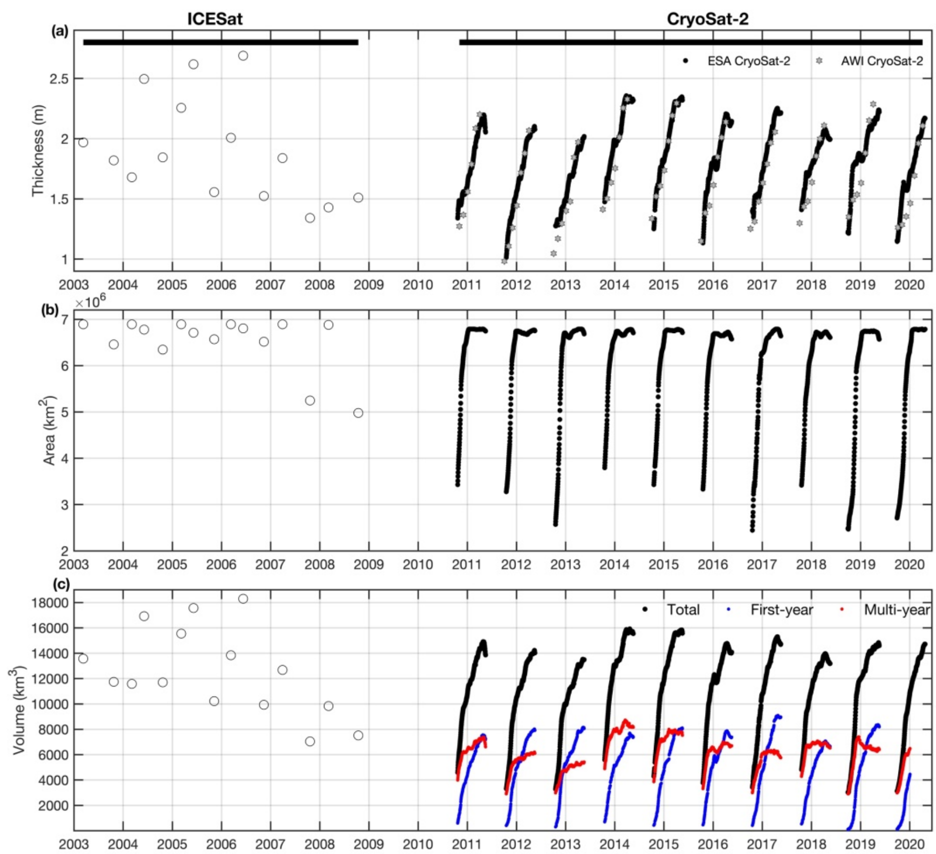

Figure S4: Interannual changes in sea ice volume, area and thickness based on the ICESat (2003–2008) and CryoSat-2 (2011–2020) satellite datasets. (a) Mean sea ice thickness within area of actual ice coverage. (b) Total sea ice area (cumulative area of actual ice coverage) within Arctic basin. (c) Total(black)， first-year(blue) and multiyear (red) sea ice volumes within Arctic basin. Arctic basin volume and area is computed within the bounded by the gateways into the Pacific (Bering Strait), the Canadian Arctic Archipelago, and the Greenland (Fram Strait) and Barents Seas.

2) I'm also not sure that it's right to cite the NSIDC Kurtz & Harbeck data as an ESA product. Given I think both Kurtz and Harbeck were at and still do work at NASA? Could be wrong about this though.

Response: *Thanks for this comment. We refined this description as: To evaluate sea ice variability, we use two CryoSat-2 ice thickness products from 2010 to 2020 and ICESat ice thickness products from 2003 to 2008. The NASA GSFC (Goddard Space Flight Center) CryoSat-2 ice thickness data are available from NSIDC on a 25km polar stereographic grid (Kurtz and Harbeck, 2017). The AWI CryoSat-2 ice thickness data on a 25km EASE2 grid are available at Meereisportal (Ricker et al., 2014). The NASA GSFC CryoSat-2 ice thickness data provided daily from October 2010 to April 2020, while the AWI CryoSat-2 ice thickness provided weekly.*

3) Figure 4(b): It looks a lot like FYI export from the FS is negative for almost all months here? So it's flowing Northwards? Maybe I have the sign convention wrong, but in that case isn't MYI flowing backwards? I think some explanation is warranted about why it looks like there's an ice-type-dependent flow direction.

Response: *Thanks for this comment. Figure 4b has shown the monthly mean arctic sea ice export anomaly at Fram Strait, compared with the average from 2010 to 2016. The positive anomaly represents that more ice was exported at Fram Strait. As shown in Table 1, the FYI、MYI and total sea ice export from the Fram Strait were flowing southwards. Compared with the average from 2010 to 2016, the amount of sea ice exported through the Fram Strait was occupied by more MYI, resulting in the corresponding negative anomaly of FYI.*

4) Figure 5): "Wind anomalies". Does the length of the arrow represent the magnitude of the velocity vector anomaly? Or the magnitude of the wind speed anomaly? These can be quite different. If it's the first then a large arrow can represent wind of the same speed going in a very different direction. If it's the second, then a large arrow can represent wind blowing in the same direction but at a different speed. I suppose it must be the first, because you can't have a negative arrow size? Or maybe it could be, because the arrows could then point backwards. Worth clarifying.

Response: *Thanks for this comment. The wind anomalies in Fig.5 is computed by the 10m wind velocity vector from monthly ERA5 atmospheric reanalysis data. We have carefully checked through this manuscript and rephrased the caption of Fig.5 in the revised: Winds velocity vector anomalies at 10m (m/s) and sea level pressure anomalies (hPa) (bottom row). Positive values indicate convergence, while negative values indicate divergence.*

5) Lastly since this work presents data from CS2 altimetry and a model (which assimilates a related product: the CS2-SMOS data), as a reader I'm interested to know how independent the model and the altimetry are. Does the SIT data 'force' the model behaviour? Or is it a weak influence that can be relatively ignored?

Response: *Thanks for this comment.*

CS2 data have relatively large errors over the thin ice area, while SMOS has smaller error, and vice versa for the thick ice area. The complementary character between CS2 and SMOS motivates this product as pointed in Mu et al. (2018). CMST assimilates CS2 and SMOS sea ice thickness data. So we replaced the data with CS2SMOS for consistency to compare the daily behavior of sea ice thickness and volume from October 2010 through April 2020 and calculated the uncertainties in SIT as shown in the Figure S2.

For a data assimilation (DA) system, at the very beginning, the model generally has systematic errors and deviates from the observations. DA will push the model close to the observation during the so-called "spin-up" period, normally one or two weeks, which depends on the inflation of the ensemble. This process serves as an initialization of the DA system but in a modest way. In that sense, the SIT data force the model. After this "spin-up" period, the model is quite close to the observation. Most of the SIT variations can be simulated now. However, due to systematic error again, there are minor differences still between model simulations and observations. We reconcile the model errors (note that we have an ensemble) and observations errors to obtain the state with the maximum likelihood. During this period, both the model and DA play important roles, but it is difficult to distinguish their effects.