We thank Reviewer #1 for the insightful suggestions that have greatly improved the manuscript.

Overall manuscript revisions:

The correlation and trend analysis were repeated for the 925 mb temperatures (ERA5) and downwelling longwave radiation at the surface (APP-x), though only the longwave radiation is included in the final version of the manuscript.

Trend sentences are all group together now, followed by the correlations between the parameters at the pan arctic scale. Correlations between pan-arctic phenology and air temperature / downwelling longwave radiation are focussed on in the regional section. Additional information regarding the phenology timing has been added to each region to enhance the discussion and provide context for the correlations. All correlation numbers have been removed to improve readability, and only trend number remain.

All comments have been responded to below, and line numbers below refer to the tracked changes document with all revisions showing.

Major Concerns

This study looks at relationships between sea ice, snow cover and lake ice timings of retreat/advance from 1997 - 2019 (shorter time-period for lake ice). This is done on a pan- Arctic scale first and then more regional discussions follow. While some relationships between exist based on large-scale warming, earlier snow cover may be expected because of increased atmospheric water vapor from more open water in autumn. Studies have documented that the Arctic atmosphere is now warmer and wetter (i.e. Boisvert and Stroeve, 2015; Serreze et al. 2012), and links with earlier snow on land have been reported (i.e. Ghatak et al. 2012).

We used a citation to Thackery et al., 2019 to explain the warmer wetter atmosphere where relevant in the text, but have now revised to include Boisvert and Stroeve, 2015 as well and to mention Ghatak et al 2010 and 2012 with respect to increased snow fall in the region where we identify earlier trends. Boisvert and Stroeve, 2015, is used in particular now to explain the correlations between ice-on and downwelling longwave radiation at the surface. In so much as the correlation is not saying that freeze is triggered by downwelling longwave, but the feedbacks related to longer open water and increased cloud cover are resulting in increased downwelling longwave radiation during the freeze season.

However, none of these studies are referenced here in the discussion of these linkages, and all relationships are really just discussed in terms of air temperature, which is overly simplistic. Drivers for example for earlier melt onset over sea ice is largely driven by warm/moist air advection into the Arctic (i.e. see papers by Kapsch, Francis, Mortin), especially on the Eurasian side of the Arctic. And thus downwelling longwave has been found to be the primary driver.

We redid the analysis using downwelling Longwave as a parameter to compare to the phenologies – the results show some useful links, though likely mask the local connections since the region are so broad. Some interesting regional patterns in the trends are clear from the new Figure 9 added, so we have added this new analysis throughout the manuscript as it adds some interesting components to the discussion.

Lines 161-174: Downwelling longwave radiation has been linked to melt onset in the Arctic Ocean (e.g., Mortin et al., 2016). To further explore the linkages in the phenology data, downwelling longwave radiation data from the Extended AVHRR Polar Pathfinder (APP-x) was obtained from NOAA National Centres for Environmental Information (https://www.ncei.noaa.gov/data/avhrr-polar-pathfinder-extended/access/)(Key et al., 2019). APP-x data is provided as 25 km EASE grid projection, processed for 0400 and 1400 (LST). Due to large areas of missing data between ~ 59 - 64°N, the mean monthly values were created from the 0400 and 1400 separately to avoid averaging errors where data exist for one time and not the other (to avoid skewing the average with the diurnal differences). Some artificial patterns are evident in the data (e.g., March, Figure 9c, near the pole), however for the purpose of regional comparisons this is not limiting as this region is not used in quantitative comparisons. Downwelling longwave radiation at the surface is calculated using a neural network to simulate a radiative model (see Key and Schweiger 1998; Key et al., 2016). Downwelling longwave radiation was selected from APP-x rather than ERA5 as the APP-x dataset has been determined as 'climate data record quality' and has been validated against in situ data with a bias of only 2.1 Wm-2 and RMSE of 22.4 Wm-2 (with the higher RMSE values attributed to differences in surface snow fall between the sampling site and the 25 km x 25 km area represented) (Key et al, 2016).

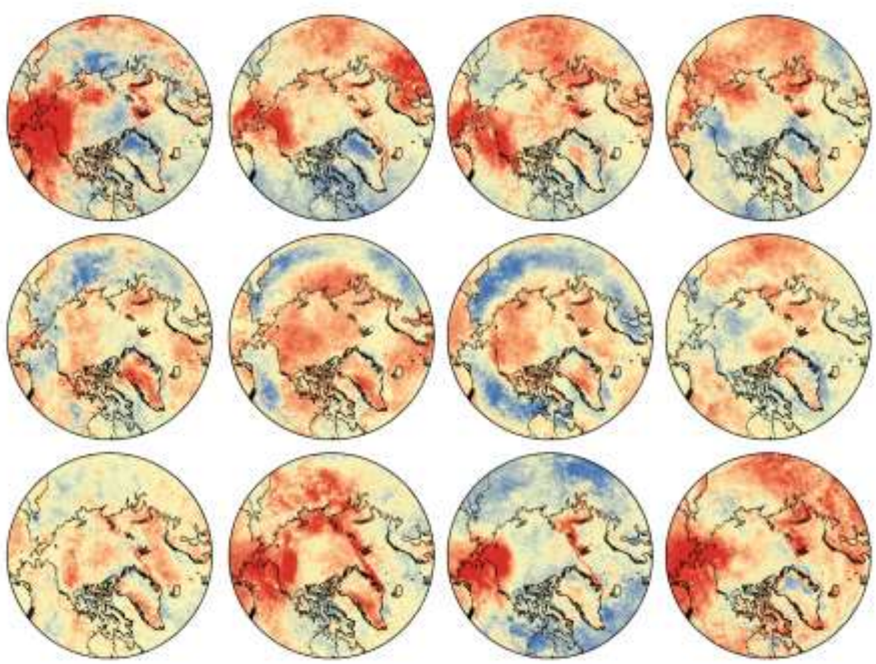

Figure 9: –Trends in downwelling longwave radiation 2004 – 2019 in (a) January , (b) February, (c) March, (d) April € May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December.

And for freeze-up, Steele et al. talked about the importance of mixed layer ocean heat driving the freeze-up and of course many papers have then discussed this heat release to the atmosphere driving the warming air temperatures (i.e. papers by Serreze et al., Screen et al., etc). Thus the maps, while interesting, are analyzed in terms of their inter-relationships only with correlations and air temperature. You may not be aware of a publication by Crawford et al. (2018: JGR-atmosphere) who looked at the relationship between snow retreat and sea ice retreat. The only region with a statistically significant relationship was found in the Laptev Sea with the early retreat of snow over the West Siberian Plain. They discussed the atmospheric mechanisms by which these regions could be linked. Such an analysis could be applied here in a broader context to really understand how these components, sea ice, lake ice and snow cover are interconnected. Just because you have a correlation between two variables doesn't mean you've understood the drivers of the linkages.

Our linkages are in the LISA maps – showing where the sea ice and snow/lake ice are changing similarly. See expanded comment below.

So then I have to ask what are we gaining from this study? The conclusions state that there are trends towards a longer snow and ice-free season, which isn't new knowledge, right? But it is interesting that the ice-free or snow-free season is largest for the sea ice, followed by the lake ice and then the snow cover. So what are the implications of that? And why would sea ice have a longer ice-free season? These are some of the questions that should be answered by this study. Otherwise it just feels like a missed opportunity.

Revised the conclusions to explicitly state the arctic amplification is stronger over the water than land and provide examples from the lakes:

Lines 615-627: … In Eurasia the snow cover trends are stronger in the freeze season, and predominantly towards earlier snow-on, while later lake freeze is occurring on the large lakes. Earlier snowfall occurs through this region and is related to feedbacks from the longer open ocean water, however the contrast in trends between snow and lake ice here show that the heat retained in the mixed layer of the lakes through the longer open water season is enough to delay freeze, despite snow falling earlier in the fall/winter. Overall, stronger trends towards longer open water duration on both the northern oceans and lakes are shown compared to the lack of overall trend in snow-free duration (the earlier snow-off trends are offset by the earlier snow-on trends) (Figure 5). This is in line with stronger Arctic Amplification processes over the Arctic Ocean compared to land (e.g., Miller et al., 2010), with the lower albedo of water allowing for more energy absorption and increased heating than occurs on land. This would apply to lakes as well and is particularly evident in lakes through Alaska with stronger trends towards earlier ice-off and later ice-on compared to snow, as well as in Scandinavia/Northern Europe where strong opposite trends are shown between later lake ice-on and earlier snow-on. Furthermore, feedbacks related to ocean-atmosphere interactions during the longer open water season are contributing to earlier snow-on timing in some regions.

Other Comments

As far as I know, IMS data have never been recommended for use in long-term change studies because of the dependence on analysts interpreting if there is ice or snow there or not. Analysts change and there is always a subjective element to this mapping. How are you accounting for error in your assessment? I would think at minimum checking your results at least for sea ice and snow cover against automated data products would be worthwhile. And some discussion on how your ice/snow on/off dates relate to earlier studies is needed. I realize that your time-period will differ from other studies,

More information from previous studies has been added now regarding IMS comparisons to sea ice, snow and lake ice.

Lines 128 – 141: IMS has been shown to outperform data from traditional passive microwave products (AMRS-E, SSM/I, SSMI-SSMIS) for both the timing and extent of first open water in the Arctic (Brown et al., 2014). For example, through the Barrow Strait in the CAA, the ability of the 4 km IMS data to resolve narrow channels lead to 17% more open water detected than with SSM/I, and 35% more open water than detected with AMSR-E, validated with RADARSAT-1 (Brown et al., 2014). Overall, most pixels compared between IMS and the two passive microwave datasets for first open water were within ± 5 days, with a greater percentage of the pixels in the categories beyond the ± 5 days identifying open water earlier with IMS than the other products (Brown et al., 2014). IMS has been shown to map higher snow cover fractions during the spring melt period than other snow products (Brown et al. 2010; Frei and Lee, 2010), but is reported to have mostly between 80-90% agreement with other snow products during the winter season of non-arctic North America, with better agreement in the later part of the winter season when deeper and more extensive snow cover is present (Chen et al., 2012). For lake ice, the 4 km IMS product occasionally identifies earlier lake ice-on dates in regions of prolonged cloud cover (e.g., northern Quebec, Canada), though both ice-on and -off timing detected using IMS are significantly correlated with, and comparable to, phenology dates extracted from the MODIS Snow Cover product (Brown and Duguay, 2012).

I think it's good to discuss a bit more about your methods for first date of no ice and date when the ice is gone for good until it comes back. Obviously this is a bit problematic for sea ice which is in constant motion. Stammerjohn et al. 2012 and Stroeve et al. 2016 had different ways of computing the retreat/advance of sea ice. This will also play into your determination of the length of the open water period. And of course this influences your trends shown for first ice- off and continuous ice off dates, and why they differ so much between first open water/continuous open water and first freeze/continuous freeze.

Table 1 explains how each phenology parameter was determined. This text was included in a table, rather than the manuscript to save space and make for an easier read. As noted, we did not track intermediate changes between ice/water and land/snow (though this is possible to do in future work, just not with how we configured the search algorithm for this project). More detail has been added including the definition of the open water and snow free timing:

Lines 179-186: Only the first and last change from ice/water and vice versa are tracked for this work, giving first and final dates of change. In sea ice regions dominated by thermodynamics, there is little difference between first and final timing, whereas in more active ice regions there could be a more notable difference between the first and final timings as the ice moves past that pixel. Most lakes are dominated by thermodynamics and return similar first and final dates, however, lakes with more ice motion (e.g., Lake Onega and Ladoga) may show a difference in their timings. For snow, warmer regions where more frequent snowmelt occurs tend to show a larger variation in first and final dates compared to the northern regions where the snow typically remains on the ground for the season. Open water duration and snow-free duration are defined as the time between the final change in the spring to the first change in the fall (WCI_S to FO_S, and last_S_{OFF} to first_S_{ON}).

It is not particularly novel to discuss sea ice retreat/advance or snow off/on as this has been done already in other studies. However, I do like seeing Figures 3 -5 as it's nice to see the land and ocean at the same time. However, talking about mean values for the Arctic as a whole is really meaningless and you rightly point out that there are large regional differences.

Agreed, we have removed the pan-arctic correlations, however, we chose to leave in the 24km and 4km pan-Arctic trends as they 'tell the story' of the large-scale phenology links before delving into the regional specifics.

Best to focus on lags between the ocean and land regions on a regional basis. Thus, in general I think the focus really should be on the regional relationships but then some sort of advanced clustering analysis would be beneficial to first identity the regions with the strongest relationships. Crawford et al. (2018) did show some ways to do this analysis that could be useful here.

Our cluster analysis uses Local indicators of spatial association (Anselin, 1995) and the maps show the areas if statistically significant spatial clusters. The pixels that show statistically significantly clustering were mapped into categories showing the clusters of either earlier or later trends, across the sea ice, snow and lake ice. Clusters crossing the shorelines indicate significantly clustered trends between the phenologies. The aim here was to see if the phenologies are changing similarly in geographic proximity. The LISA maps were not utilized well in the original manuscript and more discussion has been added throughout highlighting the regions where the ocean/land trends are clearly linked. Crawford et al., 2019 use an interesting approach for comparisons, but a detailed regional analysis like this applied to our project is beyond the scope. Our results are focussed on comparing trends changing in the same season, rather than the effects across the season – which would be an excellent addition, but again, beyond the current scope. Our results show limited inland clustering of the snow and sea ice trends (towards earlier ice off and earlier final snow off) retreat in the Laptev Sea area focussed on in Crawford et al., 2018, but do not extend into sub regional correlations. We also show a difference in the snow off trend compared to Crawford et al. 2018.

Revised the methodology sentences to explicitly state how clusters that cross the shorelines indicate regions of spatially significant trends:

Lines 218-220: Clusters of spatially statistically significant trends of high and low trend strengths were mapped. Clusters crossing the shorelines indicate significantly clustered trends between the sea ice and snow or lake ice phenology parameters and show regions of interest where the phenology variables were responding with similar trend strength over the study period.

Line 45: I find this statement to be a bit strange since timing of melt onset, and melt onset trends are latitudinal dependent, so I would expect the CAA to have weaker trends in melt onset and freeze-up. For the most up-to-date trends in melt onst/freeze-up you could reference Stroeve and Notz, 2018.

Unclear what about this statement is strange – there are weaker melt season trends (for clarification - IMS is not detecting melt onset – it is detecting open water) in the CAA than elsewhere, and trends in freeze are towards earlier freeze up dates, see Dauginis and Brown, 2020. The CAA is in a region of less pronounced warming than elsewhere in the Arctic during the recent years and experiencing some cooling trends especially on the eastern side. The updated reference for the trend comparisons has been included now, thank you.

Line 66: on the other hand, once there is liquid water in the snow and/or melt water, passive microwave algorithms underestimate sea ice area, so are you just referring to coastal areas here? Yes there is coastal contamination, resulting in false ice concentrations near the coast, yet in summer you also have the opposing effect of melt water.

Yes, this was referring to the coast regions, for balance we've added:
Line 68-70: … while in contrast it is known that that passive microwave data can underrepresent sea ice coverage when liquid water is present (melt ponds on the ice, or wet snow) (e.g. Meier, 2005).

Line 181: I do not understand your statement that sea ice off dates are most strongly correlated with temperature in September. I assume you're speaking of air temperature so you should specify this. Yet it is well known that air temperature does not drive melt onset or ice retreat (i.e. Mortin et al., 2014; Kapsch et al.). Basically what drives earlier melt onset (which is correlated with ice retreat – Stroeve et al., 2016) is advection of warm moist air masses into the Arctic and the downwelling longwave and sensible/latent heat fluxes associated with those air masses. This is especially true in the eastern Arctic (i.e. Barents and Kara seas). Maybe in the CAA air temperatures are important but this is not true everywhere in the Arctic.

This was phrased poorly originally – the intention was that of the months used to explore freeze, September was the strongest correlation. Not that the strongest correlation over all possible parameters was September air temperature. The entire correlation section has been re-written and now includes the downwelling longwave as well.

Also, why would you expect to have the strongest correlation with September temperatures? Unless it's a feedback that earlier retreat of open water leads to warmer ocean mixed layer temperatures that then of course help keep the atmospheric temperatures warmer. Nevertheless, I think your analysis here is too simplistic and doesn't add anything unless you look at all drivers that influence ice/snow retreat/advance. Thus, the same concerns will apply later on lines 196:200 since if you have earlier retreat of ice you will have later ice advance (i.e. Stroeve et al., 2016; Steele et al. 2016), and of course the release of the mixed layer heat back to the atmosphere will be responsible for the correlation you see (see also papers about Arctic Amplification by Serreze et al. 2009; Screen et al.)

Added some comments about the inherent feedbacks throughout the revised manuscript.

Line 200: I believe your results are consistent with several studies indicating earlier snow fall in autumn in part because of the sea ice loss. This paper comes to mind (Ghatak et al. 2010 – JGR) but I believe Judah Cohen has also written on this.

Thank you, these references have been added.

Line 233: How is the clustering done? This wasn't discussed in the methodology section.

The clustering is explained at the end of the methods section, local indicators of spatial association (LISA). We have expanded on this briefly, as mentioned above.

Lines 423-424: I disagree that delays in freeze-up are consistent with delayed snow onset over land and delayed freeze-onset on lakes. Yes, the lack of sea ice may result in locally warmer air temperatures that influence snow and lake ice formation, yet the lack of sea ice may also lead to earlier autumn snow accumulation. I feel your simple statistical analysis does not really explain the processes for the relationships observed.

This comment was related specifically to the Alaska region in the previous sentence where little to no increases in snow on timing are observed except for the swath of earlier snow through the North Slope. Revised the sentence to read:

Line 610: "Delays in sea ice freeze were also observed here (trends of 8 and 14 days later for first and final freeze) with much stronger trends in the Bering Sea region, along with delayed snow onset over land and delayed freeze onset in lakes across most of Alaska"