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The Cryosphere Discussions

Interactive comment on "Evidence of recent changes in the ice regime of lakes in the Canadian High Arctic from spaceborne satellite observations" *by* C. M. Surdu et al.

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Response to the 2nd Reviewer

We thank Reviewer 2 for taking the time to read and provide valuable comments on our paper. We have addressed each concern and have revised the manuscript to reflect the suggested changes. Detailed answers to Reviewer 2's comments have been copied below. Comments: Reviewer 2 comment: Page 6225, lines 16-21: (a) it would be interesting to know how the ice on the lake looks like in the field when it can be detected in an image pixel the first time? Response to Reviewer 2's comment: Regrettably we do not have any field pictures of the lakes monitored in this study taken at the

time when satellite observations captured melt onset. However, depending on the number of pixels that capture melt onset and the sensor's resolution, it could be either patches of wet (melting) snow or ponding on top of the ice in areas/on lakes covered by snow to open-water sections in parts of the lake (usually in the shallower parts near shore) where ice completed melted. Below we show a few of melt onset in Arctic lakes taken in the field. Figure 1 shows a picture captured by a digital camera installed on a meteorological station on the shore of Malcolm Ramsay Lake, near Churchill, Manitoba, and a Landsat image acquired on the same date, just 10 minutes after the field picture was taken. Figures 2 and 3 show two pictures taken in the field that capture melt – one in Alaska (Jeffries et al., 2005) and one in the Canadian Arctic (Smol, 2005) that provide a visual portray of what lake ice break-up looks in the field.

Figure 1: Melt onset on Malcolm Ramsaey Lake (Churchill, Manitoba). Top figure from Brown and Duguay (2011), field photo picture provided by C. Duguay.

Figure 2: Oblique aerial photograph of Peters Lake, Alaska (69.33°N, 145.05°W; Jeffries et al., 2005). This photo shows open water in along the lake shore, while the remaining of the lake is still covered by snow ice (S1) and congelation or black ice (S2).

Figure 3: A typical lake from north-central Ellesmere Island, Nunavut, Canadian High Arctic (Smol, 2005; Photo: Bronwyn Keatley, July 2003). This photo shows more advanced melt along the lake shore, with a central ice floe covered by snow.

Reviewer 2 comment: Page 6225, lines 16-21: (b) The terms "summer ice minimum", "WCI", "ice break-up season" should be listed here and explained in more detail: My understanding of "summer ice minimum", e.g., is that ice is present over the entire year and reaches a minimum extent during summer. The analysis presented in section 4.2, however, seems to use this term also for cases in which the ice vanishes during summer. What is the difference between "ice-free" and "WCI"? The "break-up" season covers a time interval from MO to first day of WCI or, in case of perennial ice cover, from MO to first day freeze-up? "Ice-out" (used e.g., on page 6241, line 8) is "ice-free"?

Response to Reviewer 2's comment: To address reviewer 2's comment, we explained in more details the specific ice phenology terms. As such, the text now reads: "In spring, lake ice MO is considered as the first day of the year on which melt is detected in a pixel, observed as ice-free patch(es) on the otherwise ice-covered lake surface and marks the beginning of the break-up season. Gradually, more ice starts to melt until the lake becomes ice free or water-clear-of-ice (WCI). The first day without no ice on the lake surface is considered the end of the break-up season. Consequently, the break-up season extends from MO to WCI. The minimum lake ice cover extent prior to complete melt at the end of summer, also referred to as the summer ice minimum, is generally observed to occur a few days before the lakes become ice free, or in the case of lakes that maintain a multiyear ice cover on occasional years, a few days prior to ice refreezing in the fall." (page 6225) Regarding differences between "ice-free" and WCI – there is none as they both refer to the beginning of the ice-free season, and we only used them as synonyms. Indeed, the break-up season covers a time interval from MO to first day of WCI (now also explained in the manuscript) for the lakes that fully lose their ice cover during the summer, and from MO to the first observed day of freeze-up, for lakes that maintain a multiyear ice cover. By ice-out we do mean ice-free however, in order to eliminate a possible confusion, we amended the manuscript and line 8 on page 6241 now refers to WCI (ice- free).

Reviewer 2 comment: Page 6229, lines 10 and 14: What is meant by "beginning of winter" and "end-of-winter": the corresponding meteorological dates? Or the freezing period?

Response to Reviewer 2's comment: For the purpose of this study both references are associated with the lake ice phenological events – "beginning of winter" with ice formation (freeze-up) and "end-of-winter" with ice melt (break-up). Ice phenology dates do not always follow the actual calendar dates in terms of seasons (e.g., the Arctic winter is considered to last from December to March but most of the High Arctic lakes

start (re)freezing after mid-September into the beginning of October. Artic spring is considered to begin in April but these high-latitude lakes generally start melting in June, thus we can say they do not follow the standard season pattern.

Reviewer 2 comment: Page 6231, lines 4-8: It should be mentioned that the backscattered intensity depends also on the local radar incidence angle.

Response to Reviewer 2's comment: Following reviewer 2's comment, we added the following sentence to the manuscript: "Additionally, backscatter intensity is also dependent on local radar incidence angle (Duguay et al., 2002)."

Reviewer 2 comment: Page 6233, line 10: The criteria that were used to merge the five classes determined in the first step into ice and water need to be explained. Figure 2 indicates that in the specific case shown three segments (blue, light blue, yellow) were merged to class "ice", and two segments (green and red) to class "water". Same page: Since the temporal gaps between successive satellite images can be as large as 13 days, it needs to be explained how the date for an event (e.g., MO) was determined for time gaps > 1day? This is mentioned for WCI on page 6242, lines 13-16 but is important also for MO, considering the images shown in Fig. 9. It should be indicated that the Mann-Kendall test is regarded significant only for values of $\alpha \leq 0.1$ (as the summary indicates. However: on page 6239, lines 13-14 a level > 0.1 is regarded as significant, too. What is the limit?)

Response to Reviewer 2's comment: Following reviewer 2's suggestion, we explained in more detail the merging process of the ice and water classes and added the following text to the manuscript: " In order to account for the different ice classes, the segmentation was set to five clusters. To discriminate between ice and open water clusters in the resulting segmentation maps, each segmentation output was visually assessed against the original SAR image. To additionally evaluate the class-merging accuracy, when available, segmentation results were assessed against optical images (Landsat) acquired on the same date. When ancillary optical data was not available, the backscatter threshold values of the original SAR acquisition were used to verify the segmentation results prior to cluster merging. Once clusters belonging to either ice or open water class have been identified, the resulting five classes were further merged into two classes: one ice and one open-water class in the ENvironment for Visualizing Images (ENVI) software, using the post classification function." The temporal gaps as large as 13 days during melt onset pertain to the SAR images only and existed only during several years. When this was the case, the available Landsat acquisitions during this period reduced the data gaps to less than 5 days between acquisitions thus the accuracy of the MO date estimation for certain years falls within 1-5 days. In order to address reviewer 2's comment, the following explanation was added to the manuscript in section 4.1: "As such, during the few years with larger temporal gaps for the available SAR acquisitions, the complementary optical images reduced the data gaps to less than five days between spaceborne acquisitions thus considerably reducing the uncertainty in estimation of the MO date." To clarify reviewer 2's comment regarding the significance of the Mann-Kendall test for melt onset, we should mention that it is likely a confusing choice of words from our part as by "significant at the > 0.1 level" we actually meant to refer to a significance level greater than 0.1. However, in order to make this clear in the manuscript as well, we rectified the text to reflect this: "…for all other lakes the significance level is greater than 0.1." (page 6239, line 14).

Reviewer 2 comment: Page 6235, line 9: I do not understand the sentence "For the monthly... " Seems that a word is missing.

Response to Reviewer 2's comment: We thank reviewer 2 for noticing this. We corrected the text that now reads: "In order to derive the monthly average LST, daily averages were calculated first."

Reviewer 2 comment: Page 6236: Do MO dates shown in table 3 represent ice break-up in all cases, or is it possible that some dates are biased because of water on ice? (It should be made clear in the introduction that MO means that an ice-free patch appears on the otherwise ice-covered lake surface).

Response to Reviewer 2's comment: Lake ice break-up initiates when the snow cover atop the ice starts to melt and for smaller lakes break-up begins within 3-4 days after snow melted (Jeffries et al., 2005). Indeed, there are cases when melt ponds form on top of the ice as a result of snow melt but those ponds have very low albedo and generally the ice underneath melts within a few days after the snow has melted. Landsat images acquired a few days after SAR acquisitions that indicate melt (or possibly water on ice) show ice-free patches on the lake surface. Based on the above, the dates shown in Table 3 are considered ice melt onset (MO) dates. In order to clarify MO, an explanatory text has been added in introduction and as such, the text now reads: "In spring, lake ice MO is considered as the first day of the year on which melt is detected in a pixel, observed as ice-free patch(es) on the otherwise ice-covered lake surface."

Reviewer 2 comment: Section 4.2, Tables 4 and 5: The use of terms "summer ice minimum" is irritating. If the ice cover vanishes completely it makes no sense to talk about "summer ice minimum". In Table 4, the last day with ice cover is shown (or in case of perennial ice cover, the day of a "real" summer ice minimum?), and in Table 5, the first day with no ice? But differences between corresponding numbers are > 1 in many cases. This should be clarified.

Response to Reviewer 2's comment: We understand reviewer 2's point of view regarding the use of "summer ice minimum". However, the reason we chose to use this term also for cases when the ice cover completely melts is because in this circumstance we are assessing the timing of minimum ice cover extent prior to complete melt at the end of summer, helpful for estimating the break-up and ice cover season length. Regarding Table 4 – the dates shown here are indeed the last observed day when ice cover was present on the lake surface prior to the lake becoming ice free and in the case of multiyear ice, the dates shown represent the timing of minimum ice coverage at the end of summer, prior to refreezing in the fall. As per the days shown in Table 5, as noted, these represent the first observed day with no out ice thus the beginning of the ice-free season. The difference in number of days greater than one day between the timing of the minimum ice cover and its complete disappearance is explained by the frequency of spaceborne observations that are not always available on a daily basis in order to capture the beginning of the ice-free season on the same date it happens. The temporal resolution of observations is discussed in section 3.1, mentioning that during break-up RADARSAT alone provided observations every 2-3 days and was complemented by ASAR and Landsat observations, every 2-9 days. In a few instances the gap between acquisitions of minimum ice and ice free are greater than 2-3 days but knowing the date of minimum ice cover provides a good estimation of the date when the lake becomes ice free as our 15-year data record shows that it takes 1-2 days for ice to completely melt once a minimum was observed. The issue of years with sparse data during break-up and how the ice free date was derived is also discussed on page 6238, lines 18-23. However, in order to clarify this difference in number of days, the following "For years with sparse satellite imagery at the end of break-up, and thus with differences greater than one day between the date of minimum ice cover and the WCI date, the day when the lake became ice free…" was added to the text at the beginning of section 4.3.

Reviewer 2 comment: Page 6241, last paragraph and page 6242, first paragraph: Here it is argued that the lower correlation between the date of 0ËŽ spring isotherm and WCI timing of those lakes occasionally covered by ice during summer is due to the fact that those lakes are more distant from weather stations, and gridded ERA-Interim climate data cannot represent local conditions adequately. However, for example L4 Devon seems to be rather close to a weather station? The problem of not adequately represented microclimate can be valid for all types of lakes, not only for the occasionally ice-covered ones. And can all of the latter ones be regarded as embedded in a localized microclimate environment?

Response to Reviewer 2's comment: Here we are rather discussing the different reasons that might explain the lower correlation between the date of 0ËŽ spring isotherm and WCI timing of those lakes that occasionally maintain a multiyear ice cover, and

the distance from the weather station and/or the likelihood that ERA data could misrepresent local conditions are being considered. Lake 4 on Devon Island, located in a warmer polar-oasis environment, is situated at approximately 218 km distance from the Resolute weather station on Cornwallis Island, a cooler polar-desert environment. Considering the distance between the two, as well as the different dominant climate conditions, we do not consider the Resolute meteorological station data representative of the L4 location on Devon Island. Nevertheless, misrepresentation of local microclimate can be valid for seasonally-covered lakes as well as for those maintaining a multiyear ice cover. Based on existing literature and data we do not rely on the fact that investigated lakes with an occasionally multiyear ice cover are located in microclimate environments.

Reviewer 2 comment: Page 6243, lines 23-28: The two sentences are partly redundant and can be shortened. Response to Reviewer 2's comment: We thank reviewer to for this observation. We reviewed and shortened the text that now reads: "The persistence of ice throughout the summer into early autumn when it starts refreezing (multiyear ice cover) on occasional (cool) years in some lakes could be related to a multitude of factors whose individual and/or combined actions allow the lake ice cover to outlast from one season to another."

Reviewer 2 comment: Section 5.2: From the headline (Lake ice in a changing cryosphere) I expected a discussion of different parameters and environmental conditions influencing the seasonal lake ice evolution. Instead, only the influence of temperature is discussed in great detail. What is the main message to keep in mind?

Response to Reviewer 2's comment: The high-latitude cryosphere is changing mainly as a result of atmospheric conditions, with considerable warmer air temperatures during recent years. As a consequence, other meteorological parameters are changing as well (e.g., timing and amount of precipitation, snowfall, snow depth, evaporation) but since we lack consistent records of these, we decided to focus mainly on the impact of air temperature on the lake ice cover and the historical correlation between teleconnections and ice phenology of Arctic lakes. The assessment of the seasonal lake ice evolution against other environmental conditions (e.g., sea ice, glaciers and ice caps, permafrost) is indeed an interesting discussion but since it would considerably extent the analysis and length of the manuscript, we decided not to include it here and rather have a separate paper dedicated to it. The main message to keep in mind is that the anomalous warm years with a significant greater occurrence than the cool years during the last decade, result in extreme ice phenology events (e.g., later FU, earlier BU and less occurrences of multiyear ice). If the warming trend in the Arctic continues, lakes located in polar desert environments might experience similar ice conditions with those situated in polar deserts and undergo dramatic ice phenology and environmental shifts within a short time span.

Reviewer 2 comment: Page 6247, line 14: What is meant by "extreme ice event"? Intuitively I would guess much ice on the lake...

Response to Reviewer 2's comment: Extreme lake ice events refer to the occurrence of extremes in the timing of the annual formation and/or disappearance of lake ice, as well as that of anomalous thinner/thicker ice. Extreme lake ice phenology events have been associated with warmer or cooler atmospheric conditions that led to later freeze-up and earlier break-up during warmer years (e.g., 1998/99) and earlier freeze-up and later break-up during cooler years (e.g., 2008/09) thus impacting the duration of the ice season. In order to make this clear, the text now reads: "...in 1998 that resulted in extreme ice events (i.e. later ice freeze-up and earlier break-up, and anomalously thin ice) for many of the lakes in the High Arctic (Atkinson et al., 2006)..."

References Brown, L. C. and Duguay, C. R.: A comparison of simulated and measured lake ice thickness using a shallow water ice profiler, Hydrological Processes, 25, 2932-2941, 2011. Jeffries, M. O., Morris, K., and Kozlenko, N.: Ice characteristics and processes, and remote sensing of frozen rivers and lakes. In Duguay, C. R., and Pietroniro, A. (eds.), Remote Sensing in Northern Hydrology: Measuring Environmental Change. Washington: American Geophysical Union, 63-90, 2005. Smol, J. P.:

Tracking Long-Term Environmental Changes in Arctic Lakes and Ponds: A Paleolimnological Perspective, Arctic, 58, 227-229, 2005.

Interactive comment on The Cryosphere Discuss., 9, 6223, 2015.

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Comments:

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Fig. 1.