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Reply to: Detecting long-term Arctic surface water changes

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REPLYING TO I. Olthof et al. *Nature Climate Change* https://doi.org/10.1038/s41558-023-01836-9 (2023)

Our pan-Arctic analysis based on the Moderate Resolution Imaging Spectroradiometer (MODIS) superfine water index (SWI) suggested that permafrost thaw is driving widespread surface water declines[1]. Olthof et al.[2] question the reliability of SWI-derived surface water trends because (1) there is a weak relationship between MODIS SWI (at 500 m resolution) and a Landsat-based surface water product[3] (30 m resolution) over Canada; (2) the SWI is sensitive to land surface changes other than water area[2]; and (3) the negative surface water trends we reported contradict trends derived from two Landsat-based products[3,4] over Canada[2]. Here we show that: (1) Landsat-based products have their own uncertainties and limitations that preclude their use as a true reference; (2) decreasing trends in surface water inferred from the SWI are unlikely to be caused by confounding variables (for example, vegetation change or turbidity); and (3) our conclusion of a net decrease in surface water across the Arctic is supported by independent evidence. We also offer a broader view of the uncertainties in analysing Arctic surface water change through remote-sensing techniques, and highlight that this is an unresolved, ongoing field of research.

Comparison between surface water products

The Landsat archive (30 m) has been employed in many regions across the Arctic to estimate surface water trends, but different processing methods may yield directionally opposite lake area trends, even in the same region[5]. For example, both ref. 6 (1984–2015) and ref. 7 (1999–2014) used Landsat images to map surface water change in Alaska but employed different change detection methods. Both studies identified the Arctic Coastal Plain as an area of extensive change, but ref. 7 reported decreasing lake area whereas ref. 6 reported increasing surface water. Similarly, in the eastern Hudson Bay of Canada, a Landsat-based analysis reported net lake area declines[7] (1999–2014), a finding that is similar to the surface water reductions reported in the same area by Pickens et al.[4] (1999–2018) and in our SWI-based study[1] (2000–2021). In contrast, Olthof and Rainville[3] (1984–2019) report a net increase in surface water in this region (see the Methods for additional details).

Such interstudy differences in the observed direction and magnitude of surface water change indicate that there is no consensus on how Landsat data should be analysed to estimate surface water change, and that processing methods have a large impact on study outcomes. Further, our MODIS SWI trends are directionally similar to another large-scale Landsat-based study that quantified lake area trends across four large regions of the Arctic[7]. Therefore, directionally opposite results between the Landsat-based trends produced by Olthof et al.[2] and the MODIS SWI-based surface water trends we reported[1] do not necessarily imply that the latter are inaccurate. Instead, the factors leading to inconsistencies among Landsat-based surface water datasets may also contribute to differences between the Landsat-based products analysed by Olthof et al.[2] and our MODIS SWI-based results.

One potential cause of the inconsistencies described above—between different Landsat-based studies, or between Landsat-based and MODIS-based studies—is differences in water detection methods. In many regions of the Arctic, inundated vegetation and mixed land/water pixels are common[8,9], and binary classification schemes such as those highlighted by Olthof et al.[2] may misclassify these pixels. Landsat-derived binary approaches have performed poorly in these environments, and in some regions captured only 40% of surface water area mapped with higher-resolution images[10]. Although our analysis of surface water change was based on coarser-resolution MODIS pixels, we did not adopt a binary approach. We instead implemented a continuous SWI-based approach, which can detect sub-pixel changes in surface water (for example, water bodies mapped using imagery with 0.5–3 m resolution) across time and space[1].

The weak correlation between the Olthof and Rainville[3] Landsat product and the MODIS SWI (see fig. 1 in Olthof et al.[2]) may also be due to differences in image acquisition timing. Arctic surface water extent varies intra- and interannually due to the timing and amount of rainfall, snowmelt and evaporation[11–13]. The repeat interval of Landsat (8–16 days), combined with frequent cloud cover in the Arctic, can therefore result in large errors: Landsat-based products underestimate seasonal variation by up to 50% (ref. 12). In comparison, MODIS has a

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1 day repeat interval, and we controlled for seasonal variation by analysing trends in the July SWI. Olthof et al.[2] analysed annual maximum water extents, which are error-prone (due to Landsat's relatively patchy temporal coverage) and not comparable to the July SWI, when surface water extent is lower than the maximum water extent[12]. Olthof et al.[2] argue that temporal mismatches cannot explain the differences they reported between Landsat and MODIS products because seasonal shifts in Arctic lake boundaries are typically <10 m (ref. 12). However, a 10 m shift would result in a binary misclassification of ~1/3 of Landsat shoreline pixels, which could contribute to the weak correlation between the Landsat surface water mask[3] analysed by Olthof et al.[2] and the MODIS SWI.

As with any satellite-based product, there are uncertainties in the MODIS SWI product we analysed[1]. However, the above considerations also indicate large uncertainties in the Landsat products analysed by Olthof et al.[2] Considering the strengths and weaknesses discussed above, there is at present no basis to consider binary Landsat-based surface water products more reliable than MODIS SWI for detecting pan-Arctic surface water change.

Sensitivity of the SWI to land surface changes

Both vegetation and surface water changes have been documented across the Arctic[5,14], and in many locations, these changes co-occur[15]. The fact that near-infrared radiation is strongly absorbed by water and reflected by vegetation suggests that both the SWI and vegetation indices (for example, the normalized difference vegetation index (NDVI) or the enhanced vegetation index (EVI)) will be influenced by changes in both surface water and vegetation. Surface water is a known confounding factor in understanding vegetation trends[14], and the reverse is also probably true to some extent. This does not, however, imply that inferences about surface water (or vegetation) trends derived from the SWI (or NDVI/EVI) are erroneous. Just as vegetation indices are optimized for vegetation but are influenced by non-vegetative land surface changes[14], the SWI is optimized for surface water but is influenced by non-water land surface changes[1,2].

In the Arctic, vegetation greening is associated with reductions in surface water at the local to pan-Arctic scale[15]. Lake drainage, as well as more spatially diffuse decreases in surface water, can lead to increased vegetation growth[15]. Conversely, vegetation expansion in and around water bodies can lead to decreases in surface water[15]. Olthof et al.[2] argue that a negative correlation between the NDVI and SWI arises from how the indices are defined spectrally. We suggest that a more balanced view should acknowledge that: (1) there are uncertainties in both the SWI and NDVI (and other vegetation indices); and (2) regardless of these uncertainties, a negative correlation is expected from real processes on the ground[15].

Olthof et al.[2] suggest that post-fire vegetation regrowth, combined with spectral overlap between the NDVI and SWI, contributed to the negative SWI trends we reported. Another likely cause of negative SWI trends within fire scars is real declines in surface water due to fire-induced melting of ground ice, which is an important driver of Arctic lake area change[16].

We used publicly available fire products[27–30] (which were, to our knowledge, the best available in 2020–2021 when we performed our analysis) to remove burned pixels from North American and Eurasian fires from 1995–2021 and 2000–2021, respectively, from our original analysis. However, Olthof et al.[2] demonstrated that some burn scars remained in our analysis area, which could be due to differences in the products analysed (that is, the National Burned Area Composite used by Olthof et al.[2], which did not include the years before 2004 at the time of our analysis[21] versus the National Fire Database we used; both products are produced by the Canadian National Forest Service) as well as manual delineation performed by Olthof et al.[2], which we did not implement because this method is impractical at the pan-Arctic scale.

All large-scale fire products include errors of omission and commission. To evaluate the potential impact of incomplete fire masking on our results, we repeated our original analysis, this time without excluding any burned area across our pan-Arctic study region. The revised mean SWI trend was $-0.00096\ \mathrm{yr}^{-1}$, which is similar to the original result ($-0.0009\ \mathrm{yr}^{-1}$)[1]. It is therefore unlikely that an incomplete masking of burned area qualitatively affected our pan-Arctic results.

We agree with Olthof et al.[2] that changes in surface water turbidity could influence the SWI. However, we are not aware of any large-scale analyses documenting multidecadal trends in surface water turbidity, and the relative importance of these changes for pan-Arctic SWI trends is unknown. While retrogressive thaw slumps, a source of turbidity in lakes[17], are initiating and expanding at record rates[18], different processes may dominate in river deltas, which were also a considerable portion of our study domain. For example, sediment export from Russian Arctic rivers has decreased over recent decades[19], which could decrease turbidity (and increase the SWI) in these river deltas. Despite this, our study shows decreasing SWI in the largest Arctic river delta (the Lena Delta), consistent with Landsat-based lake area trends in the same region[7].

Independent evidence for surface water decline

A recent multi-sensor, global study of lake water storage found widespread storage declines in large lakes, including in the Canadian and pan-Arctic permafrost zones[20]. Similarly, a review of 139 sites from 57 publications tracking Arctic lake area change with remote-sensing images (primarily Landsat) showed that 63% of sites in the discontinuous permafrost zone exhibit decreasing lake area, whereas reports of increasing and decreasing lake area were nearly equal in the continuous zone[5]. Observations of near-equal lake area increases and decreases in the continuous permafrost zone are similar to our finding of a near-zero median SWI trend in the same zone (fig. 2 of Webb et al.[1]). Similarly, the prevalence of reported lake area declines in the discontinuous zone is consistent with the SWI declines we reported in this zone[1].

Another line of evidence in support of widespread surface water declines is the relationship between albedo and surface water. Multiple independent studies and sensors have documented albedo increases in July across the Arctic–boreal terrestrial zone[22–24]. Not all of these studies examined surface water change, but the albedo increases they reported are consistent with albedo changes expected from surface water declines[24–26]. Surface water is the most important control over the spatial and temporal variation in Arctic–boreal snow-free summer albedo[24–26], so increasing July albedo suggests decreasing surface water[24]. An analysis that gave statistical precedence to vegetation change and fire found surface water change to be the dominant driver of July albedo trends in the Arctic–boreal region[24]. Thus, July albedo increases support our finding of widespread surface water declines.

Conclusion

Our original Article reported widespread surface water declines across lake-rich regions of the Arctic[1]. Although Arctic surface water mapping and trend detection are characterized by methodological uncertainties, which should be addressed by further research, multiple lines of independent evidence suggest that our finding of widespread Arctic surface water declines is robust. This evidence includes increasing albedo trends across the Arctic–boreal terrestrial zone[24], a meta-analysis showing diminishing lake area across the permafrost zone[5] and a recent multi-sensor analysis reporting declines in lake area across our study region[20].

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01837-8.

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Data availability

The analysis in this study relied on datasets from the following sources, all of which are freely available to the public. Webb et al.[1] SWI trends are available at: https://arcticdata.io/catalog/view/doi:10.18739/A2NK3665N. Olthof and Rainville[3] surface water trends are available at: https://open.canada.ca/data/en/dataset/62de5952-a5eb-4859-b086-22a8ba8024b8. Pickens et al.[4] surface water trends are available at: https://glad.umd.edu/dataset/global-surface-water-dynamics. Nitze et al.[7] lake area trends are available at: https://doi.pangaea.de/10.1594/PANGAEA.894755. Yao et al.[20] lake water storage trends are available at: https://zenodo.org/record/7946043.

Code availability

Google Earth Engine code used to calculate the net changes in surface water in eastern Canada from different data sources is available here: https://code.earthengine.google.com/0edfaa0327c018b68f1ab8aab2e32f98. Google Earth Engine code used to isolate lake water storage trends over Canada and pan-Arctic permafrost zones is available here: https://code.earthengine.google.com/75a7ea6f5b35252e4a55fb4972da1aec.

Author contributions

E.E.W. wrote the manuscript with assistance from J.W.L. and all authors provided feedback.

Competing interests

The authors declare no competing interests.

Additional information

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