RESEARCH LETTER

Key Points:
- River icings are important hydrological and ecological components of many Arctic river systems
- MODIS images from 2000 to 2015 show large changes in temporal persistence and minimum extent of icings in northern Alaska
- Continued decline in river icings would likely result in alterations to hydrology and ecology of Arctic rivers

Correspondence to:
T. M. Pavelsky,
pavelsky@unc.edu

Rapid decline in river icings detected in Arctic Alaska: Implications for a changing hydrologic cycle and river ecosystems

Tamlin M. Pavelsky[1] (iD) and Jay P. Zarnetske[2] (iD)

[1]Department of Geological Sciences, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina, USA, [2]Department of Earth and Environmental Sciences, Michigan State University, East Lansing, Michigan, USA

Abstract Arctic river icings are surface ice accumulations that can be $>10 \, km^2$ in area and $>10 \, m$ thick. They commonly impact the hydrology, geomorphology, and ecology of Arctic river environments. Previous examination of icing dynamics in Arctic Alaska found no substantial changes in extent through 2005. However, here we use daily time series of satellite imagery for 2000–2015 to demonstrate that the temporal persistence and minimum summertime extent of large icings in part of Arctic Alaska and Canada have declined rapidly. We identified 122 large ephemeral icings, and 70 are disappearing significantly earlier in the summer, with a mean trend of $-1.6 \pm 0.9 \, day^{-1}$ for fully ephemeral features. Additionally, 14 of 25 icings that usually persist through the summer have significantly smaller minimum extents ($-2.6 \pm 1.6\% \, yr^{-1}$). These declines are remarkably rapid and suggest that Arctic hydroclimatic systems generating icings, and their associated ecosystems, are changing rapidly.

Plain Language Summary Liquid water emerging from groundwater and flowing through Arctic rivers during the winter often freezes into large ice features, which are called river icings. These icings, which are found in nearly all parts of the Arctic, create wide, gravelly river channels that can be important habitat for animals. When icings melt during the summer, they help keep rivers flowing when other water sources are limited. Up until now, no study has systematically looked at whether these features are changing in response to warming temperatures. We use daily satellite imagery available over northern Alaska from 2000 to 2015 in order to test whether icings are becoming smaller or disappearing earlier in the summer. Of 147 features examined, we found that 84 are either becoming smaller (for those that persist throughout the summer) or are disappearing earlier (for those that fully melt each summer). None are becoming larger or disappearing later. These changes may be directly related to warming temperatures, but they may also be happening because climate change is altering how rivers and groundwater interact. If these trends continue, we may see changes in the form of many Arctic rivers and impacts on the habitat of animals like fish and caribou.

1. Introduction

Over the past two decades, climate change has profoundly impacted Arctic terrestrial, hydrologic, and marine systems [*Hinzman et al.*, 2005; *Schuur et al.*, 2015]. Among the most notable changes are declines in the temporal and spatial extent of ice, including sea ice [*Stroeve et al.*, 2012], lake, and river ice cover [*Prowse et al.*, 2011a; *Cooley and Pavelsky*, 2016], as well as glaciers [*Gardner et al.*, 2011]. However, not all components of the Arctic cryosphere have received such attention. In particular, while river icings exhibit a large influence on river network processes, they are particularly poorly documented [*Li et al.*, 1997]. River icings, sometimes also called aufeis or naled, are surficial ice accumulations formed by water from a spring, river, or other source flowing onto an already frozen surface, where it is exposed to subfreezing temperatures (Figures 1 and 2a). Icings are documented across the Arctic, including in Alaska [*Harden et al.*, 1973], Siberia [*Sokolov and Vuglinsky*, 1997], Canada [*Morse and Wolfe*, 2015], and Greenland [*Yde and Knudsen*, 2005]. River icings are distinct from river ice cover, which forms on the top of most flowing Arctic river channels and generally disappears rapidly during the spring melt season.

Icing formation and spatiotemporal extent are controlled by a combination of climate, geology, hydrology, ground topography, and permafrost dynamics [*Morse and Wolfe*, 2015]. In most cases, icings form from perennial groundwater seepage in or near rivers and streams [*Yoshikawa et al.*, 2003]. In some cases, icings can also form from localized flow resistance in a channel that forces water to the surface through ice cracks
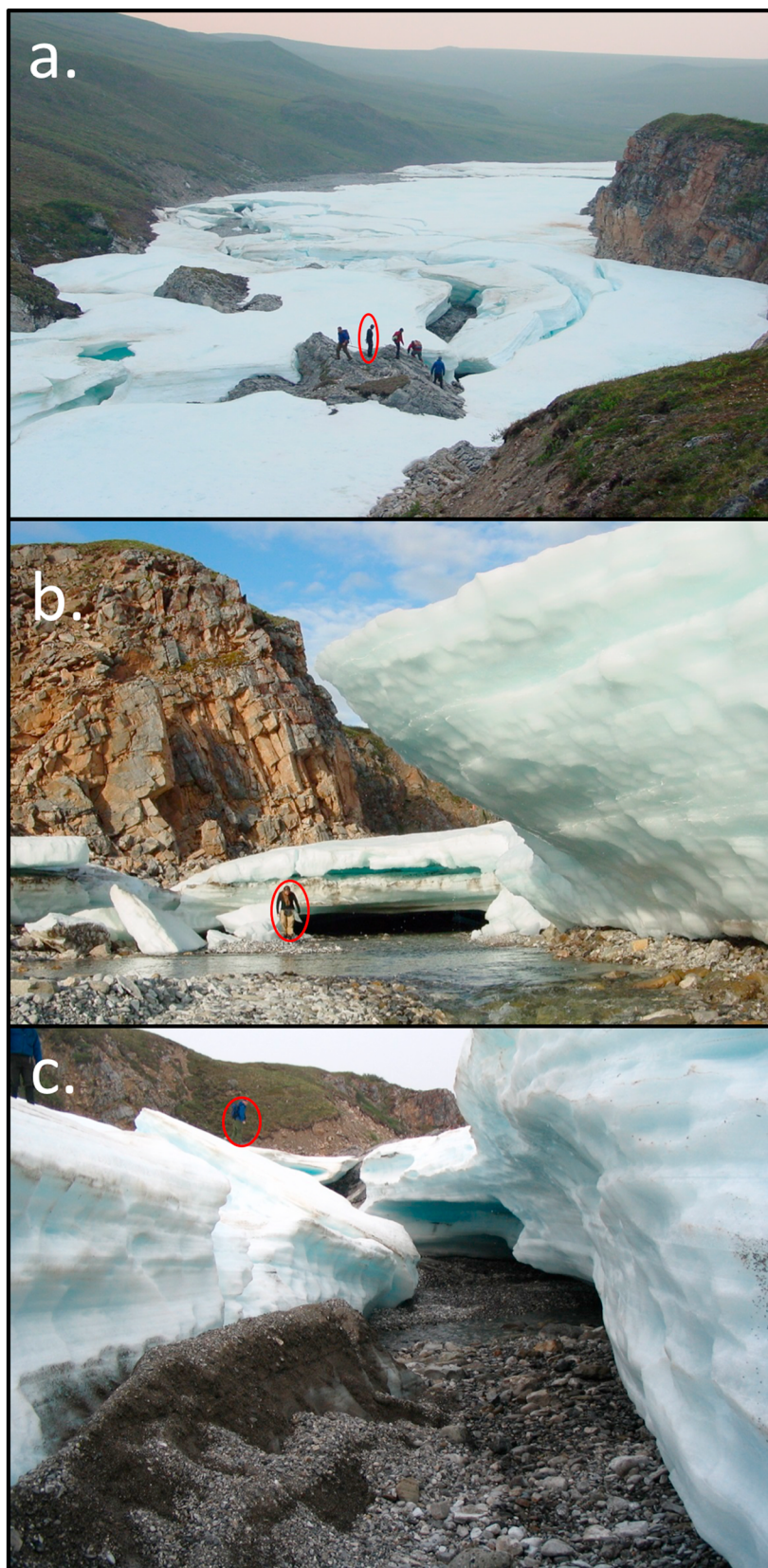
Figure 1. (a and b) Example of a small icing in northern Alaska. (c) The icing is impacting river processes by rerouting the flow of water and sediment. Note the red circles around people for scale.
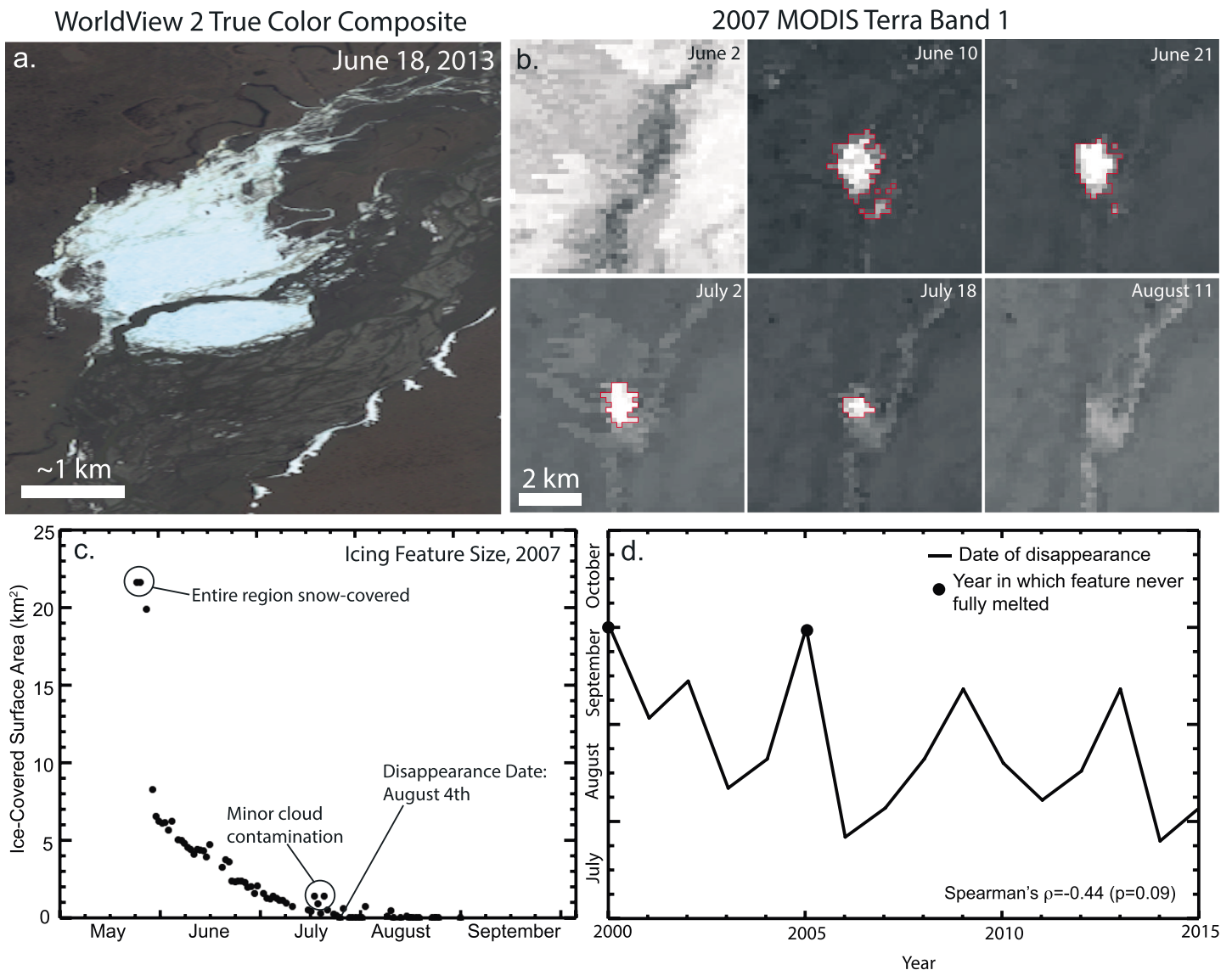
Figure 2. Example of an icing on the Shaviovik River in northern Alaska and the data processing for satellite-detected variations of this icing. (a) A high-resolution true color composite of the icing; (b) MODIS band 1 daily composite images from summer 2007 illustrating the detectability of icing feature area, with pixels considered to be ice-covered outlined in red; (c) variations in total icing area for one thaw season calculated from imagery as shown in Figure 2b; and (d) the detected date of icing feature disappearance in each year from 2000 to 2015.

[*Harden et al.*, 1973]. Entire valley bottoms can be covered with icing thicknesses many times the depth of the open-water channel where groundwater seepage processes continue throughout the winter or where there are many distributed seepage points along a river valley [*Yoshikawa et al.*, 2007] (Figure 1).

River icings are among the dominant forms of ice influencing the hydrogeomorphic conditions of many Arctic rivers. In northern Russia and Alaska, icings can reach tens of kilometers in length, have an average thickness of 1 to 6 m (though thicknesses of >10 m have been observed), and be multiple kilometers wide [*Li et al.*, 1997]. As such, they can dwarf the spatial extents (though not thicknesses) of alpine glaciers in basins where both are present. In some Siberian basins, the basin-wide volume of icings may comprise 25–30% of the annual volume of river discharge [*Harden et al.*, 1973]. Therefore, icings are especially important to Artic rivers during summer low-flow periods, as they can represent a significant reservoir of water accumulated from winter base flows, which is then later made available via melt throughout much or all of the thaw season [*Prowse et al.*, 2011b]. In general, icing formation reduces wintertime base flow and increases thaw season base flow and spring runoff.

Changing icing conditions may have significant effects on arctic river ecosystems and can permit rapid expansion or contraction of habitats for lotic organisms [*Vincent et al.*, 2011]. For example, reduction in the persistence of icings may result in the dominant river channel morphology shifting from braided to single channel [*Bennett et al.*, 1998], which would increase connectivity of the river network above and below the icing location for fish species [*Babaluk et al.*, 2001; *Bradford et al.*, 2001]. Conversely, by decreasing overbank flow, the same morphologic response of a river to icing decline may isolate the floodplain, islands in braided rivers, and riparian ecosystems from the main channel flow. Further, the decline of icings as an important source of meltwater contributing to low-flow periods may mean that the connectivity of river network surface flows could decrease during the thaw season. In turn, this decrease in runoff and surface flow connectivity will regulate river ecosystem functioning (e.g., aquatic habitat, organism dispersal, population connectivity, and carbon and nutrient flux between land and ocean). While it is clear that seasonal temperature variations exert a fundamental control on icing extent and function in valley bottom environments, the influence of longer-term climate variability has not been well studied.

Previous examination of river icing temporal dynamics focused on a small region of northern Alaska [*Yoshikawa et al.*, 2007]. Of the several icings studied using a range of methods, no substantial changes in icing extent or location was detected between the early to middle 20th century and 2005. However, Arctic Canada and Alaska have warmed substantially in the 21st century [*Najafi et al.*, 2015]. Thus, we hypothesize that the temporal persistence and minimum summertime extent of Arctic river icings are now declining. We examine a time series of daily Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery over summers in 2000–2015 to determine whether there are trends in the minimum summertime extent and temporal persistence of large icings in a region of Arctic Alaska and Canada broadly defined by the eastern Brooks Range and the adjacent coastal plain.

2. Methods

Satellite remote sensing has been used to track the locations of Arctic ice features, including icings, for nearly 40 years [*Harden et al.*, 1973]. Remote measurement of icings during the summer is comparatively simple because they reflect much more visible light than do surrounding land cover types such as tundra, taiga, and bare sediment. Most previous remote sensing studies have used relatively high-resolution optical imagery from sensors such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer and Landsat Multispectral Scanner, Thematic Mapper, and Enhanced Thematic Mapper Plus to assess the extent of icings in small subregions of the Arctic [e.g., *Harden et al.*, 1973; *Yoshikawa et al.*, 2007; *Morse and Wolfe*, 2015]. Other studies have used synthetic aperture radar (SAR) imagery to measure icing extent, even under winter conditions [*Li et al.*, 1997; *Yoshikawa et al.*, 2007]. From the perspective of assessing the annual melt of icings over a large portion of the Arctic, however, these sensors have significant limitations. For example, present-day Landsat sensors sample only every 16 days and, because they are affected by clouds, often produce useable observations only a few times per summer. Meanwhile, SAR sensors, though not affected by clouds, usually have repeat times insufficiently fine to characterize temporal patterns in icing degradation. In contrast, the MODIS sensors address these and other deficiencies of earlier remote sensing technologies for observing icings. MODIS is available twice per day, so it has the capability to systematically track the extent of surface ice features on weekly to daily time scales across the Arctic, depending on cloud conditions. The primary limitation of MODIS is its finest nominal resolution of 250 m, which means that its use is limited to the largest icings. Clouds are also a limitation, though a study using MODIS to measure Arctic river ice cover suggests that mean temporal uncertainty due to clouds is ±1.3 days (the study was conducted over different rivers than those observed here) [*Cooley and Pavelsky*, 2016].

Here we use 16 years of thaw season (1 May to 15 September) data from the 250 m MODIS Terra daily surface reflectance imagery and cloud metadata to track seasonal and interannual changes in icing extent for 147 icings in northern Alaska, USA, and Yukon Territories, Canada. Large icings nearly always form in the same locations every year [*Yoshikawa et al.*, 2007], so we use a single static map of icing locations developed via expert interpretation of MODIS and Landsat imagery. Icings were selected to be sufficiently large to be tracked by using MODIS imagery (extent > ~0.25 km^2) and sufficiently distant from other commonly snow- or ice-covered features (e.g., mountains and lakes) to be easily distinguishable. Thus, our identified number of icings is likely substantially smaller than the total number of icing features in the region. The size of
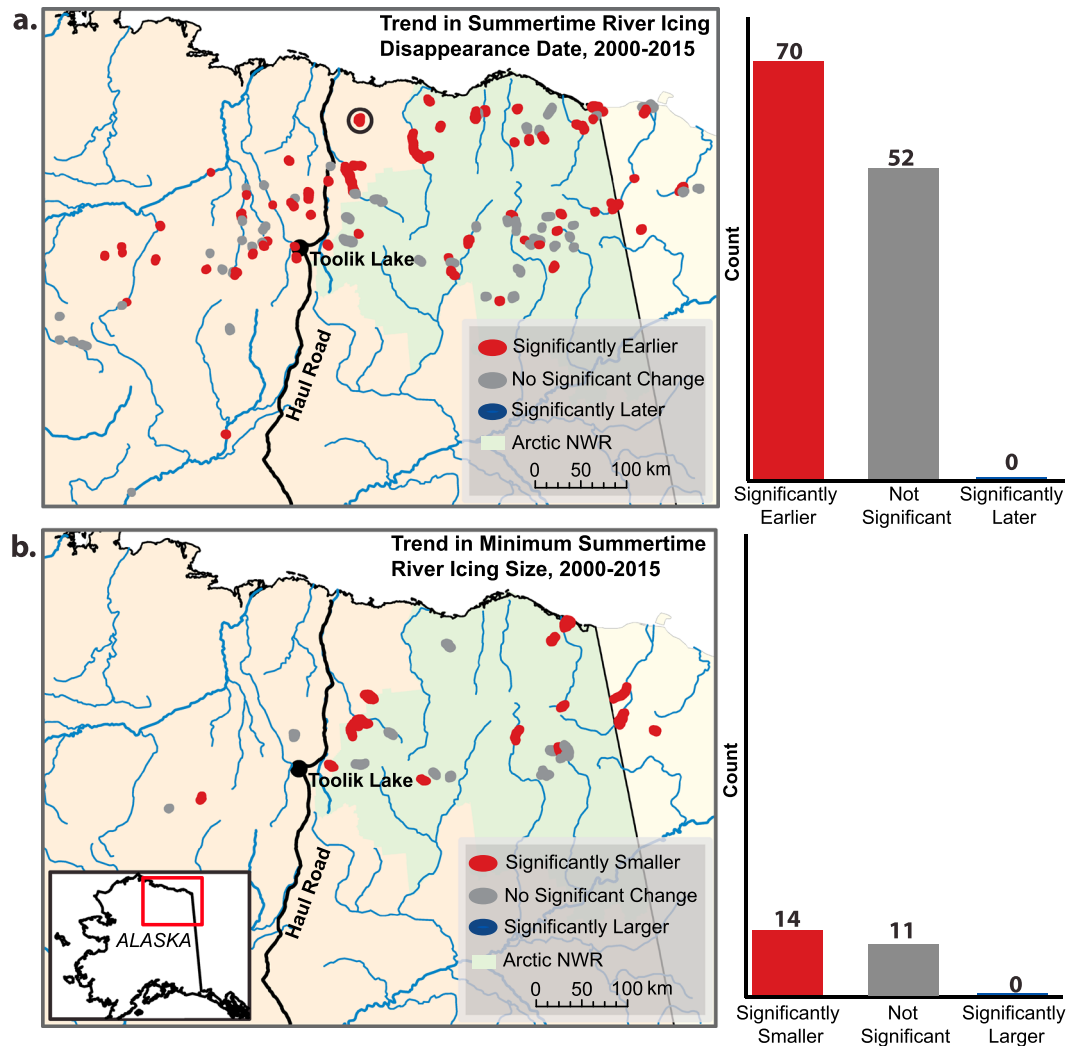
Figure 3. The 2000–2015 trends in (a) timing of disappearance for ephemeral icings that do not persist throughout the entire summer and (b) minimum size of persistent icings that do not completely thaw through the summer. Note the significant trends toward smaller and less persistent icings. The black circle in Figure 3a indicates the river icing shown in Figure 2.

each identified icing is tracked through time via automated thresholding of daily MODIS reflectance composite images acquired during the thaw season of each year (Figure 2). Icing size is calculated as the total area of pixels with MODIS band 1 (620–670 nm) reflectance >0.15 within each feature boundary (e.g., Figures 2b and 2c). We implemented the same technique by using pixels with reflectance >0.10 and >0.20, and while overall feature size changes inversely with the threshold chosen, trends presented here are largely insensitive to the choice of threshold within this range. Cloudy and cloud-adjacent areas are automatically removed on a pixel-by-pixel basis using the MODIS cloud flag, which is included in the metadata of 1 km MODIS daily reflectance imagery. Past studies have identified icing area successfully from Landsat imagery [e.g., *Morse and Wolfe*, 2015], so, as a test, we compared MODIS-derived feature size calculations against comparable Landsat-derived data for 24 features in Northern Alaska. The root-mean-square error of MODIS feature area relative to Landsat is 17%, with a mean bias of 4%, suggesting that, on average, MODIS-derived feature extent is not substantially different from the Landsat-derived extent.

3. Results

Temporal trends in icing disappearance date are shown in Figure 3a for 122 ephemeral features that melt in their entirety during most summers. Similarly, Figure 3b shows temporal trends in minimum feature extent
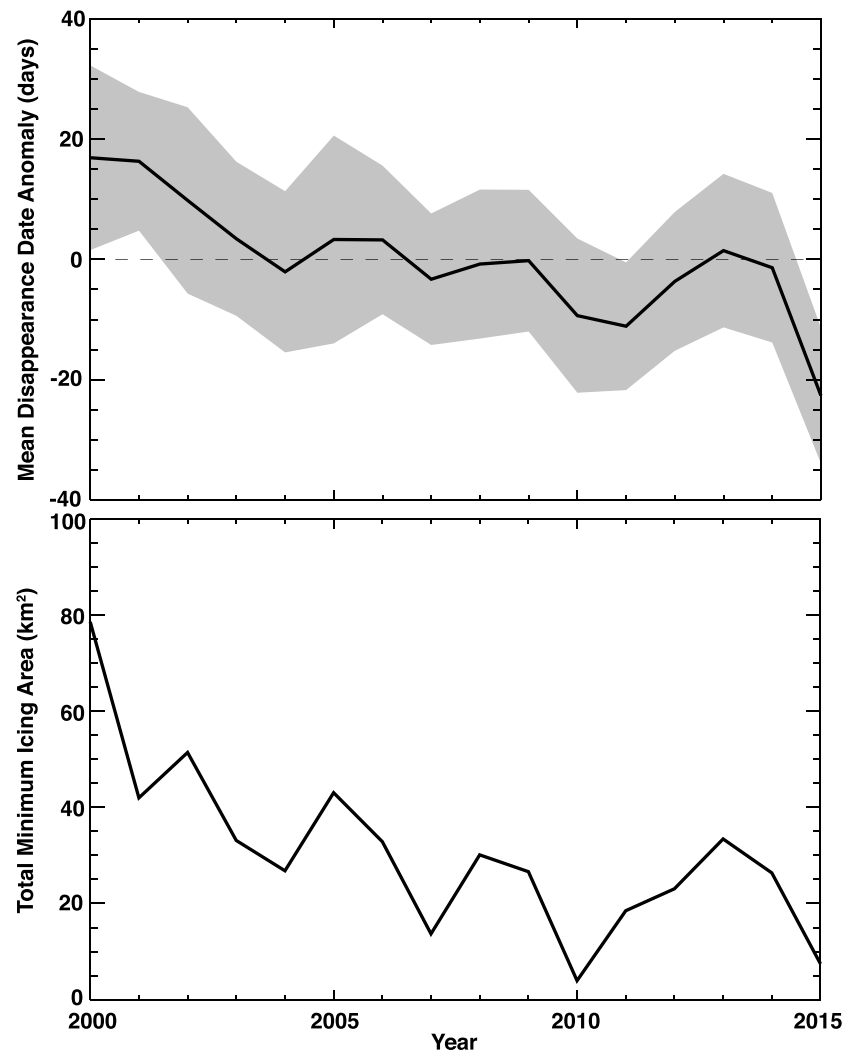
Figure 4. Temporal trends in (a) the 2000–2015 mean feature disappearance date anomalies for 83 features that disappear each year (the black line shows the mean, and the shaded regions show ±1σ), and (b) the total minimum area of all measured icings in each year across the study region.

for the other 25 features that generally persist throughout the thaw season. We use Spearman's ρ [*Spearman*, 1904] to assess statistical significance in order to accommodate the fact that some features switch between ephemeral and persistent from summer to summer. We analyze a feature as ephemeral if it disappears completely in at least 8 of the 16 years observed. All other features are analyzed as persistent.

Of the 122 ephemeral features, 70 are disappearing significantly earlier ($p < 0.10$, H0: $\rho = 0$), while 52 show no significant trend and none are disappearing significantly later (Figure 3a). Overall, these ephemeral icings are disappearing, on average, 1.6 ± 0.9 day yr^{-1} (1σ) earlier in the thaw season (Figure 4a). Note that this trend, and the data shown in Figure 4a, represents only those features that disappear in all years ($n = 83$), as we cannot use linear regression to calculate a trend in disappearance date for those features that sometimes persist through the whole summer.

Icings that persist throughout the summer are, on average, reaching a smaller minimum summertime areal extent, with 14 decreasing significantly in minimum area, 10 showing no trend, and none increasing significantly in area. The average trend in minimum area for persistent icings is -2.6% yr$^{-1} \pm 1.6\%$ yr^{-1} (Figure 3b). We also sum the minimum area of each feature in each year, producing an estimate of the total minimum feature extent (Figure 4b). This summation demonstrates a significant ($r^2 = 0.50$, $p < 0.01$)

decline in minimum icing extent. The resulting areas represent our best estimate of icing extent, but due to the coarse resolution of MODIS imagery and the lack of ground truth data, they should be considered approximate. Finally, we note that 57 of the 62 icings showing no significant trend in either disappearance date (ephemeral features) or minimum size (permanent features) do, in fact, have a negative value of ρ, suggesting that general trends toward later disappearance dates or larger minimum areas are unlikely.

4. Discussion

The exact causes of these apparent declines in temporal persistence and minimum summertime extent of river icings are unclear from the data available to date, but there are two primary mechanisms that could explain the observed trends. First, it is possible that earlier spring thaw and warmer spring and summer temperatures are leading to earlier and more intense melting of icings. A decline in icings due to more intense melting would be consistent with other patterns of changing climate and ice extent in northern Alaska and around the Arctic [*Hinzman et al.*, 2005; *Prowse et al.*, 2011a; *Stroeve et al.*, 2012]. Second, it is possible that less total icing volume is forming annually. This could be due to shortening and substantial increase in air temperatures of the frozen season during which icings accumulate. There is considerable evidence of later river freezeup in the Pan-Arctic [*Prowse et al.*, 2011a], and Arctic wintertime temperatures have increased substantially in the last 15 years [*Pithan and Mauritsen*, 2014]. As a result, less ice may be accumulating simply due to the effects of increasing wintertime air temperature. Additionally, however, there is evidence of more complex processes that could inhibit icing accumulation. Specifically, temperature increases in recent decades may have affected the water cycle in ways that would discourage icing formation. Wintertime streamflow in the Arctic has increased markedly, even in absence of direct human impacts, which suggests the possibility of greater connectivity between surface water and groundwater under warmer temperatures [*Smith et al.*, 2007]. Icings often form downgradient of wintertime groundwater discharge locations, especially where ice-bound channels route this groundwater discharge above and around the main channel [*Harden et al.*, 1973]. It is possible, then, that increased wintertime streamflow may maintain open flow paths within channels, thus reducing the likelihood of groundwater discharge being routed above and outside of the channel, where it forms river icings.

Regardless of the mechanisms behind declines in minimum extent and temporal persistence of river icings, reduced summertime icing extent will impact the hydrology, geomorphology, and ecology of many Arctic river systems. The magnitude of these impacts in not yet known due to the lack of local, regional, and pan-arctic data on icing formation and degradation [*Morse and Wolfe*, 2015]. However, impacts will likely be notable because icings seasonally store substantial volumes of water well into the thaw season, especially in unglaciated basins [*Kane and Slaughter*, 1973; *Reedyk et al.*, 1995; *Li et al.*, 1997]. The observed declines in the summertime temporal and spatial extents of ephemeral and persistent icings mean that the conversion of water stored as ice to river flow is occurring earlier. Earlier melt will likely lead to decreased flow in some rivers during the ecologically critical low-flow period of late summer and fall. Additionally, because icings physical modify the routing of water flows through valley bottom ecosystems, they play a substantial role in defining Arctic fluvial geomorphology [*Harden et al.*, 1973]. A decline in the spatial and temporal extents of icings will likely alter river morphology, which would impact natural habitat and human activities in river floodplains. In particular, icings promote flooding during the annual spring freshet, primarily because they block the transport of meltwater from upstream [*Harden et al.*, 1973; *Zufelt et al.*, 2006], and decreased icing extent could lead to a decline in such flooding. This rerouting of the freshet flows would alter sediment transport and therefore channel morphology. In the presence of river icing, sediment typically aggrades upstream of the icing and leads to braided channels [*Harden et al.*, 1973; *Bennett et al.*, 1998] (e.g., Figure 2a). These sediment deposits and channel morphologies provide a multitude of unique and important ecosystem benefits, including organismal habitat and refugia for key species such as Chinook salmon [*Babaluk et al.*, 2001; *Bradford et al.*, 2001]. Alterations of river flows and deposits associated with icings affect economically important civil infrastructure and recreation opportunities through, for example, roadway and rafting hazards [*Morse and Wolfe*, 2015]. Thus, a decline in river icing extent could lead to changing habitat for a multitude of arctic species, affect civil infrastructure, and impact recreation near rivers, further altering already rapidly changing Arctic ecosystems.

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