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Landsat-based lake distribution and changes in western Alaska permafrost regions between the 1970s and 2010s

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Abstract

Lakes are an important ecosystem component and geomorphological agent in northern high latitudes and it is important to understand how lake initiation, expansion and drainage may change as high latitudes continue to warm. In this study, we utilized Landsat Multispectral Scanner System images from the 1970s (1972, 1974, and 1975) and Operational Land Imager images from the 2010s (2013, 2014, and 2015) to assess broad-scale distribution and changes of lakes larger than 1 ha across the four permafrost zones (continuous, discontinuous, sporadic, and isolated extent) in western Alaska. Across our 68 000 km^2 study area, we saw a decline in overall lake coverage across all permafrost zones with the exception of the sporadic permafrost zone. In the continuous permafrost zone lake area declined by −6.7% (−65.3 km^2), in the discontinuous permafrost zone by −1.6% (−55.0 km^2), in the isolated permafrost zone by −6.9% (−31.5 km^2) while lake cover increased by 2.7% (117.2 km^2) in the sporadic permafrost zone. Overall, we observed a net drainage of lakes larger than 10 ha in the study region. Partial drainage of these medium to large lakes created an increase in the area covered by small water bodies <10 ha, in the form of remnant lakes and ponds by 7.1% (12.6 km^2) in continuous permafrost, 2.5% (15.5 km^2) in discontinuous permafrost, 14.4% (74.6 km^2) in sporadic permafrost, and 10.4% (17.2 km^2) in isolated permafrost. In general, our observations indicate that lake expansion and drainage in western Alaska are occurring in parallel. As the climate continues to warm and permafrost continues to thaw, we expect an increase in the number of drainage events in this region leading to the formation of higher numbers of small remnant lakes.

1. Introduction

Over a quarter of lakes on Earth are located in northern high latitudes (Lehner and Döll 2004). This is due in part to the presence of permafrost which forms an aquitard close to the ground surface, inhibiting drainage (Smith *et al* 2007, Grosse *et al* 2013). Ongoing warming is currently causing changes in permafrost ground temperature and active layer depth (Biskaborn *et al* 2019, Romanovsky *et al* 2019a), but how this will influence near surface hydrology in Arctic and sub-Arctic is poorly understood.

Climate warming is amplified in the Arctic compared to lower latitudes (Serreze and Barry 2011) and since 1971 mean annual air temperature in the Arctic has increased by 2.7 °C (Box *et al* 2019). Consequently, permafrost temperatures have warmed throughout the region particularly during the last two to three decades and mean annual ground temperature has increased by 0.4 °C–0.8 °C per decade within the continuous permafrost zone (Biskaborn *et al* 2019, Romanovsky *et al* 2019a). The subsequent impact of permafrost degradation on lakes is varied and includes instances of initiation, expansion, and both gradual and catastrophic drainage (Yoshikawa and Hinzman 2003, Smith *et al* 2005, Roach *et al* 2013, Jones and Arp 2015, Jones *et al* 2020a). Temporal and spatial heterogeneity in lake area change also is driven by regional and temporal variations in environmental characteristics such as permafrost extent and thickness, topography, and ground ice content (Smith *et al* 2005, Riordan *et al* 2006, Chen *et al* 2014, Nitze *et al* 2017). Recent work has also highlighted the potential influence of wildlife ecology in lake dynamics as the return of beavers to Arctic Alaska appears to be influencing lake distribution (Jones *et al* 2020b).

In northern high latitudes, lakes play an important role both within the natural environment and socioeconomically. Thaw lake formation exerts an important influence over ecology (Schuur and Mack 2018), and both nutrient and carbon cycling (Walter *et al* 2007, Jones *et al* 2012, Walter Anthony *et al* 2014, Fuchs *et al* 2019). Repeated cycles of lake formation and drainage result in a complex and dynamic topography across much of the unglaciated Arctic (Frohn *et al* 2005, Jorgenson and Shur 2007, Arp and Jones 2009, Swanson 2019). Subsequently changes in lake area and distribution across the landscape can drive abrupt and drastic shifts in vegetation (Jorgenson *et al* 2001), hydrology (Rowland *et al* 2011) and both aquatic and terrestrial habitat distribution (Clark *et al* 2010, Jorgenson *et al* 2010). Lakes are also important socioeconomically, often providing indigenous communities with fresh drinking water sources, as well as facilitating subsistence hunting and fishing (Eisner *et al* 2009). Lakes and ponds have also been used as a source of fresh water for industrial applications, such as ice road construction (Alessa *et al* 2008, Jones *et al* 2009, Arp *et al* 2019). Recent work has also highlighted how lake basins can influence local hydrology post-drainage, through snow dam outburst floods (Arp *et al* 2020).

In this study we used medium resolution (60–30 m) Landsat images to understand lake distribution and change in six lake districts spanning a gradient of continuous to isolated permafrost in western Alaska. The main objectives of this study are to (a) understand broad-scale lake distribution along a permafrost gradient; (b) investigate changes in lake area in the region since the 1970s; and (c) investigate how changes in lakes may vary between different permafrost zones of that region.

2. Study area

The six study regions cover a total area of 68 830 km^2 and represent four permafrost extent zones located in western Alaska: In the southern fringe of the continuous permafrost zone, (1) the Baldwin Peninsula and (2) Beringia; at the continuous-discontinuous permafrost zone boundary, (3) the Central Seward Peninsula and (4) the Selawik area; and at the isolated-sporadic permafrost boundary, (5) the Kobuk Delta and (6) Yukon-Kuskokwim Delta (YK Delta) (figure 1). Permafrost characteristics in our study regions were extracted from the digital dataset from Jorgenson *et al* (2008) based on a map scale of 1:7200 000. Permafrost type varies from continuous extent in the north to isolated extent in the south (figure 1, table S1 which is available online at stacks.iop.org/ERL/16/025006/mmedia). Permafrost temperatures are coldest in the northern areas with a mean annual ground temperature of −3.3 °C at 20 m depth recorded at the Kotzebue borehole on the Baldwin Peninsula in 2015 (Romanovsky *et al* 2019b). The study regions contain extensive loess deposits in the uplands and sandy or silty alluvial and fluvial deposits in the river floodplains and delta regions that contain a wide range of ground ice volumes (table S2, figure S1). Other types of geologic deposit found are sand dunes, old glaciolacustrine deposits, glaciofluvial outwash, modified moraine and volcanic deposits (table S3, figure S2). Ground ice content varies between our regions, and is high in Beringia due to the presence of yedoma, moderate in the Kobuk Delta, moderate to high on the Central Seward Peninsula, the Baldwin Peninsula, and Selawik, and low to high in the YK Delta (Jorgenson *et al* 2008) (table S2, figure S1). Mean annual air temperature in the entire region is characterized by a south to north gradient with temperatures ranging from 0 °C to −6 °C (Jorgenson *et al* 2008). Between 1950 and 2010 air temperature has warmed with thawing degree day values increasing by approximately 200 °C and freezing degree day values increasing by approximately 175 °C (figure S3).

The study regions encompass various types of lakes; thermokarst lakes are the most common type (Jones *et al* 2011), while oxbow and delta lakes are also widely distributed in the river floodplains and delta regions. Additional lake types include maar (Begét *et al* 1996), tidal, and coastal lakes. Thermokarst lakes are most prevalent in the Beringia and Baldwin Peninsula study areas. Beringia also has multiple large maar lakes of an average size of ~1000 ha. Maar lakes form due to explosive volcanic eruptions that create depressions that are subsequently infilled by groundwater and or precipitation. The Kobuk Delta and Selawik study areas have a mix of thermokarst, delta, and oxbow lakes. In the YK Delta, there are many thermokarst, delta, oxbow, and tidal flat lakes of all sizes as well as some small maar lakes. All lake types mentioned above were mapped as part of this study.

3. Data and methods

3.1. Data

We collected Landsat L1T-processed, terrain-corrected images acquired during two different time periods (MSS, 60 m resolution, from 1972, 1974, and 1975; and OLI, 30 m resolution, from 2013, 2014, and 2015) from the USGS Landsat repository (http://earthexplorer.usgs.gov) (table S4). The selection criteria included imagery with less than 10% cloud cover acquired during the lake ice-free summer periods (July–August with some exceptions in June

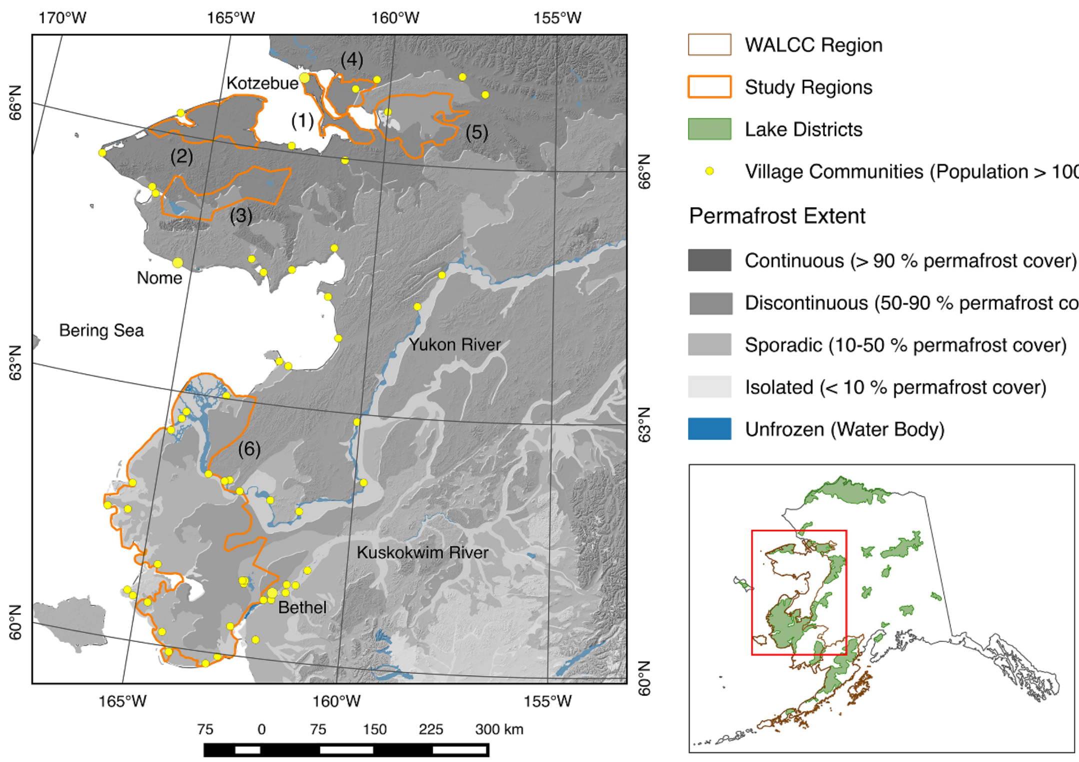

Figure 1. Study areas in the northern and central western Alaska LCC Region with permafrost extent types and village locations in the region (with population >100, major villages Kotzebue, Nome and Bethel are shown in large yellow dots): (1) the Baldwin Peninsula, (2) Beringia, (3) the Central Seward Peninsula, (4) Kobuk Delta, (5) Selawik, and (6) Yukon-Kuskokwim Delta.

and September) of the 1970s and 2010s. Altogether, we used 12 Landsat Multispectral Scanner System (MSS) image tiles covering a total land surface area of 377 400 km^2 and 14 Landsat Operational Land Imager (OLI) image tiles covering a total land surface area of 435 540 km^2 to extract lakes for these two time steps. To understand the role of permafrost extent on lake area changes in the study regions we used the digital permafrost map for Alaska by Jorgenson *et al* (2008).

Due to the time periods that we were focusing on the discrepancy in spatial resolution between the satellite datasets used in this study was unavoidable. Prior studies using MSS data for lake change either relied on its comparability (Plug *et al* 2008), down-sampled their higher resolution data to MSS (60 m: Karlsson *et al* 2013) or even lower spatial resolutions (150 m: Smith *et al* 2005), or they only investigated larger lakes in their study areas (⩾1.2 ha: Smith *et al* 2005, Hinkel *et al* 2007, Plug *et al* 2008, Karlsson *et al* 2013). However, direct comparison of lake areas derived from same-day MSS and 30 m TM data (Rover *et al* 2012) indicates very high correlation coefficients for lake areas derived from both sensors, carefully indicating their suitability also for cross-sensor time-series. Others (e.g. Lantz and Turner 2015) compared lake areas derived from high-resolution imagery with lake areas based on the same imagery down sampled to TM and MSS spatial resolutions. They find deviations in the lower percentage (up to 1.2% for TM resolutions, between 1% and 16% for MSS resolutions, compared to the lake areas from the high-resolution base imagery). We therefore consider the difference in spatial resolution between the MSS and OLI imagery overall as small. For medium, large, and very large lakes the uncertainty is even negligible as the resolution difference is mostly relevant for shoreline (lake perimeter) pixels while the area to perimeter ratio increases substantially with lake size, essentially diluting the effect substantially.

3.2. Lake mapping

We mapped lakes greater than 1 ha in Landsat images by applying a semi-automated lake classification using object-based image analysis (OBIA) methods in the commercial software package eCognition™ Developer 8. OBIA consists of two steps: (a) image segmentation, i.e. aggregation of homogenous image pixels based on their spatial and spectral homogeneity into meaningful clusters known as image objects, and (b) classification of image objects (Blaschke and Strobl 2001, Navulur 2006). Rather than identifying a surface feature simply based on spectral pixel information in a single step as in a traditional classification technique, OBIA requires users to decompose an image into meaningful objects, organize them in a conceptual hierarchy based on their relationships and integrate object semantics in classification rulesets in an iterative fashion until the target objects are identified more accurately (Blaschke and Strobl 2001, Navulur 2006, Blaschke *et al* 2008).

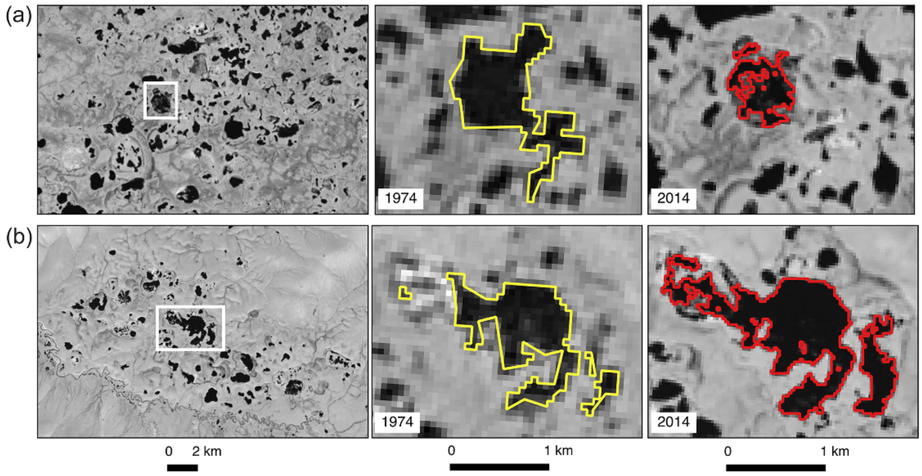

Figure 2. Examples of (a) partial lake drainage in the Selawik region and (b) lake area expansion in the Baldwin Peninsula region.

Prior to image segmentation, we performed spectral transformation on visible and infrared bands utilizing principal component analysis (PCA) on all images for image enhancement and better spectral separation of water bodies from various surface features (Mather and Koch 2011). For further analysis, we only used the first two PC bands that carried the most variance (>99%).

We implemented OBIA techniques that involved segmentation of the original set of image bands and the first two PC components followed by a classification of image objects based on a range of classification rulesets. The Normalized Difference Water Index (NDWI) and Modified Normalized Difference Water Index (MNDWI) guided the waterbody identification on Landsat MSS and OLI images, respectively (Mcfeeters 1996, Xu 2006, Li *et al* 2013). NDWI and MNDWI were calculated using the following equations (for further information see supplementary materials):

For Landsat MSS:

$$\mathrm{NDWI} = \frac{G - \mathrm{NIR}}{G + \mathrm{NIR}}. \quad (1)$$

For Landsat OLI:

$$\mathrm{MNDWI} = \frac{G - \mathrm{SWIR2}}{G + \mathrm{SWIR1}}. \quad (2)$$

(Definitions of bands: G—Green, NIR—Near Infrared, SWIR-2—Short-Wave Infrared 2.)

Since no SWIR bands exist for Landsat MSS it was not possible to calculate a MNDWI for data from this sensor. In general, our Object Based Image Analysis classification for imagery from either sensor did not rely on specific multi-spectral indices such as NDWI or MNDWI but used all available bands plus the first two bands from a PCA transformation based on all bands. NDWI was used as a visual validation tool for Landsat MSS and MNDWI for Landsat OLI to fine-tune the OBIA segmentation to capture lake surfaces.

We used the U.S. Geological Survey National Elevation Dataset (NED DEM) and a derived hillshade raster to remove misclassified non-water objects associated with terrain shadows, which appear dark similar to water surfaces in imagery. Manual assessment, correction, and removal of rivers, streams and channels were conducted to remove misclassifications of lake water bodies. To visualize changes in lake numbers and total lake area over the large study domain we calculated and plotted these changes per 100 km^2 using a 10 × 10 km grid across the study domain.

4. Results

The study region as a whole experienced a net loss in lake cover (figures 2–5). Between 1970's and 2010's the net change in lake cover was −34.6 km^2, which equates to −0.05% of the total landscape analyzed and a −0.38% decline in the area covered by lakes compared to the 1970s. Lake area change was found to be variable between study areas with an observed a mix of lake expansion and lake drainage in all study regions (examples of lake drainage and expansion shown in figures 2 and 3). Here we break down these observations by study region and explore the high amount of variability between regions with contrasting permafrost extent.

4.1. Regional lake change in four permafrost zones (1970s–2010s)

4.1.1. Continuous permafrost zone: a net decrease in lake area but net increase in lake number

Between 1970s and 2010s, within the continuous permafrost zone, the total area covered by lakes declined by −6.7% (−65.3 km^2). This is the largest area loss observed among all permafrost zones (figures 4 and 5, table 1). Size class contributions to this value were +7.1%, −8.8%, −10.5%, −10.1% for lakes that were <10 ha (small), 10–50 ha (medium), 50–100 ha (large), and >100 (extra large) respectively, with the

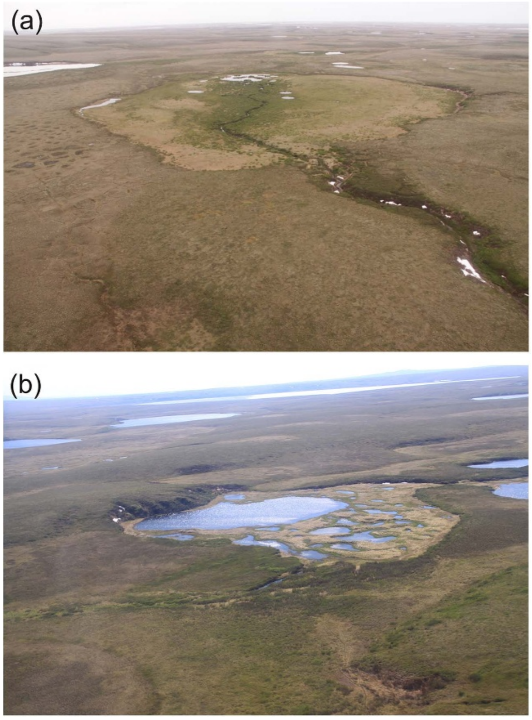

Figure 3. Field photos from the Beringia study region showing lateral drainage of lakes caused by formation of a drainage channel. (a) Photo showing a complete drainage, note the deep drainage channel and (b) showing partial drainage with the formation of remnant ponds (Photo credit G. Grosse).

small lakes being the only class that increased in cover. The number of lakes across all continuous permafrost areas increased in number by 9.4% (615 lakes). This increase was driven by small lakes alone which increased by 804 lakes (16.5%) relative to the 1970s. All other lake classes declined in their numbers: medium lakes by −139 lakes (−10.5%), large lakes by −26 lakes (−12.9%), and extra large lakes by −24 lakes (−15.6%) (table 1).

4.1.2. Discontinuous permafrost zone: a net decrease in lake area but a net increase in lake number

Overall, the area covered by lakes in the discontinuous permafrost zone decreased by −1.6% (−55 km^2) between 1970s and 2010s (figures 4 and 5, table 1). Medium size lakes were responsible for the majority of this change. The area covered by medium lakes changed by −8.1%, and large lakes by −6.8%. Increases in lake area were observed for both the largest and smallest classes with changes of 0.6% and 2.5% respectively (figures 4 and 5, table 1). Extra large lake extent probably increased due to lake expansion, while small lake extent primarily increased due to drainage events and remnant pond formation.

The overall number of lakes in the discontinuous permafrost zone increased by 6.7% ($n = 1538$) (table 1). The number of small lakes increased by 1861 lakes (10%), or 8.2 lakes 100 km^{-2}. The number of lakes in the medium size class decreased by −265 lakes (−7.4%), or −1.2 lakes 100 km^{-2}. The number of large lakes (50–100 ha) and extra large lakes declined by less than −1 lake 100 km^{-2} with a loss of −35 lakes (−7.6%) and −23 lakes (−5.8%), respectively (figures 4 and 5, table 1).

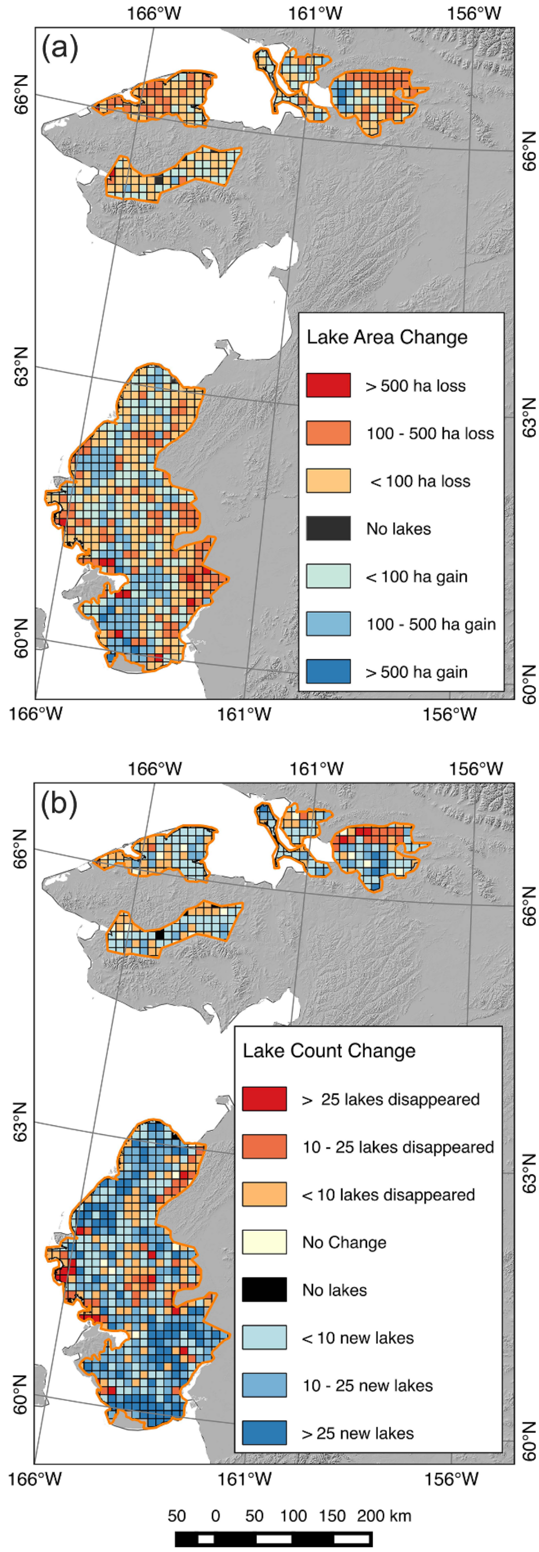

Figure 4. Maps showing gridded (10 × 10 km = 100 km^2 grid cells) lake area and lake count change.

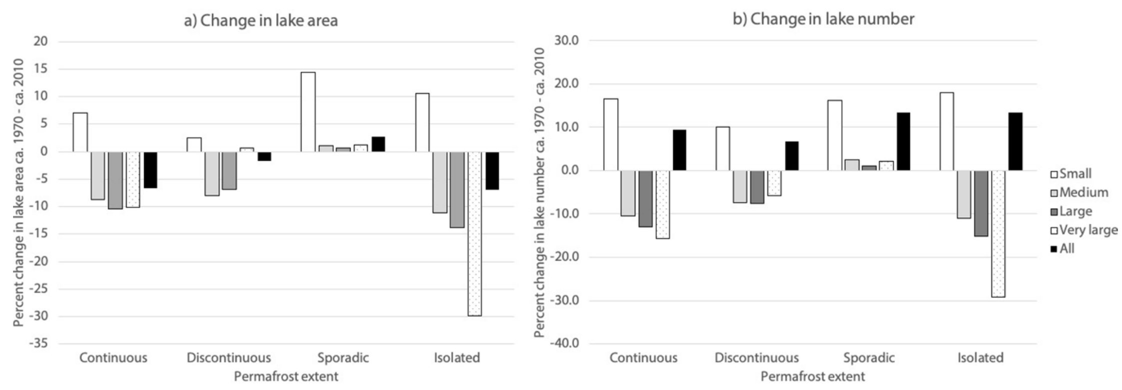

Figure 5. Summary of lake area (a) and number (b) changes across the different permafrost zones in the study domain from ca. 1970s to 2010s.

4.1.3. Sporadic permafrost zone: net increase in lake area and lake number

The sporadic permafrost zone is only present in the YK Delta region and at the start of our study period this landscape had the highest percent lake cover of all permafrost zones of 24%. Between the 1970's and 2010's, in contrast to other permafrost zones, there was a net increase in lake abundance and lake surface area in the sporadic permafrost zone for all lake size classes (figures 4 and 5, table 2). Within the sporadic permafrost zone, we found a net increase in the total lake surface area of 2.7% (117 km^2) (figure 4(a), table 1). The largest increase in surface area was observed for small lakes, which increased by 14.4% (75 km^2) (figures 4(a) and 5(a), table 1). The total area of lakes increased by 1.0%, 0.7%, and 1.2% for medium, large, and extra large lake classes respectively (table 1).

Within the sporadic permafrost zone the number of lakes increased by 13.3% (2760 lakes, or 15.2 lakes 100 km^{-2}) (figures 4(b) and 5(b), table 1). The largest increase in lake number was observed for small lakes, which increased by 2663 lakes (16.2%), or 14.6 lakes/100 km^2 (figure 4(b), table 1). The number of lakes for medium, large and extra large size classes increased by 82 (2.5%), 5 (1.0%), and 10 (2.1%), respectively.

4.1.4. Isolated permafrost zone: a net decrease in lake area but a net increase in lake number

The isolated permafrost zone is present only in the YK Delta region and had the lowest lake cover (5%) of all permafrost zones at the start of our study period. The isolated permafrost zone region of the study area experienced a net loss of lake surface area of −6.9% (−32 km^2) accompanied by a net increase in lake number of 13.4% (829 lakes, or 10.2 lakes 100 km^{-2}) (figures 4 and 5, table 1).

Within the isolated permafrost zone, small lakes saw the only net positive change of all size classes with an increase in area of 10.5% (17.2 km^2). All other lake size classes saw a decrease in extent: −11.1%, −13.9% and −29.9% for medium, large and extra large lake classes respectively (figures 4 and 5, table 1). The number of lakes in the isolated permafrost zone increased by 829 (13.4%). As with other permafrost zones, this was driven by an increase in the distribution of small water bodies, probably due to remnant lake formation. Small water bodies increased in number by 942 (17.9%). Larger water bodies decreased in number by −87 (−11%), −12 (−15.2%), and −14 (−29.2%) for medium, large and extra large lake classes respectively (figures 4 and 5, table 1).

4.2. Intra-permafrost zone variability: a comparison between study regions with the same permafrost extent

4.2.1. Study areas characterized by continuous permafrost

Both the Beringia and Baldwin Peninsula study regions are characterized by continuous permafrost and the two regions show very different patterns of lake change (figures 4 and 5, table 2). Beringia exhibited a large net decrease in lake area (−15.3%) which stands in stark contrast to the Baldwin Peninsula which experienced a small net increase in lake area of 3.9%. Interestingly both regions were characterized by an increase in lake number, 6.4% in Beringia and 27.1% on the Baldwin Peninsula. In Beringia, all lake size classes saw a decrease in area with the exception of lakes less than 10 ha in size: 6.5%, −15.4%, −14.4%, and −23.2% for small, medium, large and extra large lake classes respectively. On the Baldwin Peninsula, we observed an increase in lake area for all lake classes with the exception of large lakes. Changes in lake area on the Baldwin Peninsula were 16.8%, 0.1%, −20.4%, and 15.0% for small, medium, large and extra large lake classes respectively (table 2).

4.2.2. Lake change in study areas characterized by a mix of continuous and discontinuous permafrost

A mix of continuous and discontinuous permafrost characterizes three of our study regions: the central Seward Peninsula, the Kobuk Delta, and Selawik.

Table 1. Lake change by permafrost zone. Note that Limnicity is a land area index normalized by describing the total lake area for a certain lake size category per km^2.

		1970s			2010s			Change			
Permafrost extent	Size class	Count	Surface area (km^2)	Limn-icity	Count	Surface area (km^2)	Limn-icity	% Count change	% Area change	Count change	Area change (km^2)
Continuous	<10 ha	4879	177.032	0.8	5683	189.589	0.9	16.5	7.1	804	12.557
	10–50 ha	1322	272.683	1.2	1183	248.729	1.1	−10.5	−8.8	−139	−23.954
	50–100 ha	201	135.534	0.6	175	121.333	0.5	−12.9	−10.5	−26	−14.201
	>100 ha	154	393.83	1.8	130	354.155	1.6	−15.6	−10.1	−24	−39.675
	All lakes	6556	979.079	4.4	7171	913.806	4.1	9.4	−6.7	615	−65.273
Discontinuous	<10 ha	18 576	609.783	1	20 437	625.26	1	10	2.5	1861	15.477
	10–50 ha	3572	733.158	1.2	3307	674.006	1.1	−7.4	−8.1	−265	−59.152
	50–100 ha	463	318.381	0.5	428	296.646	0.5	−7.6	−6.8	−35	−21.735
	>100 ha	395	1683.867	2.8	372	1694.317	2.8	−5.8	0.6	−23	10.45
	All lakes	23 006	3345.189	5.5	24 544	3290.229	5.4	6.7	−1.6	1538	−54.96
Sporadic	<10 ha	16 484	518.197	1.1	19 147	592.806	1.3	16.2	14.4	2663	74.609
	10–50 ha	3259	684.154	1.5	3341	691.148	1.5	2.5	1	82	6.994
	50–100 ha	497	347.975	0.7	502	350.445	0.8	1	0.7	5	2.47
	>100 ha	471	2862.817	6.1	481	2895.926	6.2	2.1	1.2	10	33.109
	All lakes	20 711	4413.144	9.5	23 471	4530.325	9.7	13.3	2.7	2760	117.181
Isolated	<10 ha	5251	163.544	0.4	6193	180.756	0.4	17.9	10.5	942	17.212
	10–50 ha	791	157.59	0.3	704	140.139	0.3	−11	−11.1	−87	−17.451
	50–100 ha	79	53.538	0.1	67	46.109	0.1	−15.2	−13.9	−12	−7.429
	>100 ha	48	79.798	0.2	34	55.96	0.1	−29.2	−29.9	−14	−23.838
	All lakes	6169	454.47	1	6998	422.964	0.9	13.4	−6.9	829	−31.506

Table 2. Lake change for specific study areas. Region acronyms are as follows: Baldwin Peninsula, BAP; Beringia, BER; Central Seward Peninsula, CSP; Kobuk Delta, KD; Selawik, SEL; and Yukon Kuskokwim Delta, YKD.

			1970s			2000s			Change between 1970s and 2000s			
Focus regions	Pf extent	Size class	Total lake count	Total lake surface area (Ha)	Limn-icity	Total lake count	Total lake surface area (Ha)	Limnicity	Lake area (%)	Area (ha)	Lake count (%)	Lake count
BAP	C	<10 ha	447	1542	1.18	602	1801.64	1.01	+16.84	+259.64	+34.68	+155
BAP		10–50 ha	106	2098.7	1.37	106	2101.42	1.37	+0.13	+2.72	0.00	0
BAP		50–100 ha	13	868.84	0.45	11	691.65	0.57	−20.39	−177.19	−15.38	−2
BAP		>100 ha	3	800.7	0.60	4	920.41	0.52	+14.95	+119.71	+33.33	1
BER	C	<10 ha	1866	6771.83	1.16	2144	7209.96	1.23	+6.47	+438.13	+14.90	+278
BER		10–50 ha	491	9914.91	1.70	406	8389.18	1.44	−15.39	−1525.73	−17.31	−85
BER		50–100 ha	81	5275.07	0.90	68	4516.29	0.77	−14.38	−758.78	−16.05	−13
BER		>100 ha	73	19 294.76	3.30	53	14 823.02	2.54	−23.18	−4471.74	−27.40	−20
CSP	C,D	<10 ha	1133	3873.17	0.65	1318	4171.04	0.70	+7.69	+297.87	+16.33	+185
CSP		10–50 ha	237	4912.67	0.83	234	4646.81	0.78	−5.41	−265.86	−1.27	−3
CSP		50–100 ha	26	1943.33	0.33	24	1760.31	0.30	−9.42	−183.02	−7.69	−2
CSP		>100 ha	17	42 074.84	7.09	15	35 683.72	6.01	−15.19	−6391.12	−11.76	−2
KD	C,D	<10 ha	1152	4071.05	2.12	1192	4265.4	2.22	+4.77	+194.35	+3.47	+40
KD		10–50 ha	373	8181.22	4.25	363	8029.03	4.17	−1.86	−152.19	−2.68	−10
KD		50–100 ha	64	4410.28	2.29	58	4272.41	2.22	−3.13	−137.87	−9.38	−6
KD		>100 ha	49	11 189.15	5.81	47	11 668.6	6.06	+4.28	+479.45	−4.08	−2
SEL	C,D	<10 ha	3793	14 630.07	2.30	4142	13 715.2	2.16	−6.25	−914.87	9.20	349
SEL		10–50 ha	1091	22 318.9	3.51	872	18 212.68	2.87	−18.40	−4106.22	−20.07	−219
SEL		50–100 ha	131	8946.52	1.41	113	7796.42	1.23	−12.86	−1150.10	−13.74	−18
SEL		>100 ha	59	40 747.75	6.41	58	43 560.02	6.86	+6.90	+2812.27	−1.69	−1
YKD	D,S,I	<10 ha	37 080	117 058.15	2.51	42 434	128 965.93	2.76	+10.17	+11 907.78	+14.44	+5354
YKD		10–50 ha	6754	139 691.77	2.99	6658	136 058.66	2.92	−2.60	−3633.11	−1.42	−96
YKD		50–100 ha	937	64 904.76	1.39	923	64 196.19	1.38	−1.09	−708.57	−1.49	−14
YKD		>100 ha	886	437 292.36	9.37	857	433 648.83	9.29	−0.83	−3643.53	−3.27	−29

As with the study regions underlain by continuous permafrost only, we observed different patterns of change between these three areas (figures S4–S9). A net loss in lake area was observed in both the Selawik and the central Seward Peninsula study areas of −3.9% and −12.4% respectively. In the Kobuk Delta region we observed a net gain in lake area of 1.4%. All areas saw an increase in lake number, the greatest occurring on the central Seward Peninsula with an increase of 12.6% ($n = 178$). The Kobuk Delta and Selawik areas saw an increase of 1.3% ($n = 22$) and 2.2% ($n = 110$) respectively.

Lake size classes responded differently between discontinuous permafrost study areas (table 2). In the central Seward Peninsula area, small lakes were the only size class to increase in area, by 7.7%. All other size classes saw a decrease in area of −5.4%, −9.4%, and −15.2% for medium, large and extra large lake classes respectively. In the Kobuk Delta area, both the smallest and extra large lake size classes saw an increase of 4.8% and 4.3% respectively. Medium and large size lakes saw a decrease in area by −1.9% and −3.1% respectively. In the Selawik area all lake size classes except the extra large lake class saw a decrease in area of −6.3%, −18.4%, and −12.9% for small, medium, and large classes respectively. The largest lake size class (>100 ha) saw an increase in area of 6.9%. Since the YK Delta study area was the only one characterized by isolated and sporadic permafrost, no comparisons were conducted for these permafrost zones.

5. Discussion

Our assessment of lake distribution and changes using Landsat images from the 1970s to 2010s in six major lake-rich regions covering an area of 68 830 km^2 in western Alaska shows widespread lake area loss. Many large lakes drained and declined in area while the abundance of small lakes increased for all permafrost types most likely due to partial drainage of large lakes creating numerous remnant ponds. Lake area increase was observed in some areas of the continuous permafrost zone but lake area loss was significantly higher in other areas, leading to a regional net lake area loss of −6.7% in the continuous permafrost zone. Through our mapping efforts, we observed that partial lake drainage dominated the non-continuous permafrost zones. These trends show that both lake expansion and drainage are phenomena taking place in parallel in western Alaska but that drainage is dominating regional net lake area trends.

Our findings on lake area change in the continuous permafrost zone differ from trends described in some previous studies. Smith *et al* (2005) reported an overall lake area increase in the continuous permafrost zone and a decrease in the non-continuous permafrost zones across their study region covering an area of 515 000 km^2 in Siberia for the time period between the 1970s and 2004. In contrast, our study saw an overall lake area loss between 1970s and 2010s within the continuous permafrost zone. A decrease or negligible change in lake area has been reported from other regions of Alaska and Siberia for smaller study regions in the continuous permafrost zone (Riordan *et al* 2006, Labrecque *et al* 2009, Jones *et al* 2011, Swanson 2019). Recent findings suggest that large numbers of new ponds and lakes on the Baldwin Peninsula have been created in recent years by beavers which ecosystem-engineered drained lake basins and narrow erosional gullies with their dams (Jones *et al* 2020b). These differences in observations show that the direction of lake area change can be variable from one region to another across same permafrost types due to spatial heterogeneity in lake characteristics and local environmental factors (Riordan *et al* 2006, Karlsson *et al* 2013, Roach *et al* 2013, Chen *et al* 2014, Nitze *et al* 2017).

Other research efforts have also highlighted a loss in lake area in northwestern Alaska. Our findings of lake area loss in general agree with those of Jones *et al* (2011) who analyzed lake changes in the continuous permafrost zone on the northern Seward Peninsula. They found that numerous significant lake drainage events have occurred since ca. 1950, primarily to lakes over 40 ha in area at an average rate of −2.3 lakes year^{-1} (Jones *et al* 2011). Our findings also agree with Swanson (2019) who documented a significant decline in surface water between 1984 and 2018 in northwestern Alaska, which they attribute to thermoerosion of lake outlets. Swanson (2019) suggests that the thermoerosion of outlets was driven by a combination of warm mean annual air temperature and fluctuations in summer precipitation. Recent work by Nitze *et al* (2018) highlights large scale trends across northern and western Alaska and for the continuous permafrost zone found a lake area loss of −0.62% (a combination of a gross increase of 3.31% and a gross decrease of −3.94%) between 1999 and 2014, although lake change in general was highly diverse across the continuous permafrost zone. In contrast to our study, Nitze *et al* (2018) found a greater loss in lake area within discontinuous versus continuous permafrost (−11.39% and −3.45% respectively compared to −1.6% and −6.7% respectively in our study region).

We observed a net decrease in lake area in the continuous permafrost zone due to major lake drainage events in the Beringia (−63 km^2) and Selawik (−34 km^2) study regions. In the continuous permafrost zone, lateral drainage of thermokarst lakes can occur due to bank overflow, subsequent development of the drainage network by ice wedge degradation, headward erosion, or lake tapping by another water body such as lake, river or sea (Hopkins 1949, Mackay 1988, Hinkel *et al* 2007, Marsh *et al* 2009, Jones *et al* 2011, 2020a, Grosse *et al* 2013, Jones and Arp 2015). Therefore, it is possible that areas of relatively stable continuous permafrost show variable lake change patterns depending on the adjacent landscape features, local geomorphology, stages of thaw, and the timing of the observation.

Observations from this study support previous findings that partial drainage of lakes is becoming increasingly common in areas of discontinuous permafrost. In Alaska, declining lake surface area was reported for numerous discontinuous permafrost regions including the southern Seward Peninsula, the Interior, and the Yukon Flats (Yoshikawa and Hinzman 2003, Riordan *et al* 2006, Rover *et al* 2012, Chen *et al* 2014, Nitze *et al* 2017). This suggests that as the Arctic warms and the continuous-discontinuous permafrost zone boundary shifts northwards (Jafarov *et al* 2012), lake shrinkage may eventually become a more prominent phenomenon than lake expansion.

We observed an overall increase in lake area for the sporadic permafrost zone in the YK Delta. This stands in contrast to observations from the sporadic permafrost zone in West Siberia where lake area loss was prevalent (Smith *et al* 2005). The overall increase in lake area we observe in the YK Delta could be due to the dominant surficial geology and the distribution and structure of hydrological networks. Lake dynamics within low-lying delta regions are influenced by expansive and complicated systems of water channel distributaries both at the surface and in the subsurface (Burn 1995, Stephani *et al* 2020). In the sporadic permafrost zone, underground connectivity of lakes to the groundwater system may also be enhanced and lakes can be recharged from better-developed ground water aquifers as this can significantly affect lake water levels and lake areas in non-continuous permafrost zones more so than in continuous permafrost regions (Chen *et al* 2014). For the YK Delta, permafrost distribution beneath lakes and the hydraulic head gradient of lakes relative to the groundwater table may be a potential driver for heterogeneous, though clustered, spatial patterns of lake changes.

In the isolated permafrost zone of the study region lake area drainage is again greater than lake expansion. We suggest that this may be due to large lakes located close to larger water channels drained by stream or river tapping. Using our Landsat data set, we observed that the formation of new drainage channels or expansion of pre-existing water channels promoted lake area loss. In addition, headward erosion of stream channels and erosion of narrow land between coastal lakes and the sea caused nearby lakes to drain. Similar patterns of lake drainage due to coastal erosion have been reported earlier for the Alaska North Slope (Hinkel *et al* 2007, Jones and Arp 2015).

6. Conclusions

We combined Landsat MSS and OLI images from the 1970s and 2010s with OBIA to assess broad-scale distribution and changes of lakes larger than 1 ha across the four permafrost zones (continuous, discontinuous, sporadic, and isolated extent). Overall, we observed a net drainage of lakes larger than 10 ha across the western Alaska study region. Partial drainage of these medium to large lakes created an increase in small water bodies <10 ha, in the form of remnant lakes and ponds, leading to an increase of up to 27% in the total number of lakes in all regions. We found this trend to be most pronounced in areas of continuous permafrost with regional variations between study sites with similar permafrost extent.

Lake area change varied between areas of different permafrost extent. Areas of continuous and isolated permafrost experienced the greatest loss in lake area (−6.7% and −6.9% respectively). In contrast areas of sporadic permafrost were characterized by a net increase in lake area (2.7%). While this variability could be attributed in part to permafrost extent it is likely that other factors such as local geomorphology, ground ice content and surficial geology (tables S2, S3, figures S1 and S2) play a critical role in drainage dynamics.

Our results demonstrate that the selection of a specific study region can have an impact on observed patterns of lake change. Fine-scale observations from small study regions may show clear lake area loss or gain trends but only a broad-scale observation of a larger study regions is likely to show regional trends that exceed localized noise from environmental variables. Our findings highlight the dramatic and important changes in hydrology and habitat that are already occurring across permafrost-affected landscapes due to changes in lake dynamics and permafrost extent.

Data availability

Data that support the findings of this study can be accessed at https://doi.pangaea.de/10.1594/PANGAEA.847703.

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Author contributions

Prajna R. Lindgren developed the method, performed analysis and co-lead manuscript writing. Louise M.

Farquharson provided expertise regarding permafrost dynamics and surficial geology in the western Alaska and co-lead manuscript writing. Guido Grosse and Vladimir Romanovsky conceived this study. Guido Grosse provided significant input during the development of the method, data analysis and result interpretation. All the coauthors contributed to writing and editing of the manuscript.

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