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Basic hydrology, limnology, and meteorology of modern Lake El'gygytgyn, Siberia

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Abstract A survey of the modern physical setting of Lake El'gygytgyn, northeastern Siberia, is presented here to facilitate interpretation of a 250,000-year climate record derived from sediment cores from the lake bottom. The lake lies inside a meteorite impact crater that is approximately 18 km in diameter, with a total watershed area of 293 km^2, 110 km^2 of which is lake surface. The only surface water entering the lake comes from the approximately 50 streams draining from within the crater rim; a numbering system for these inlet streams is adopted to facilitate scientific discussion. We created a digital elevation model for the watershed and used it to create hypsometries, channel networks, and drainage area statistics for each of the inlet streams. Many of the streams enter shallow lagoons dammed by gravel berms at the lakeshore; these lagoons may play a significant role in the thermal and biological dynamics of the lake due to their higher water temperatures (>6°C). The lake itself is approximately 12 km wide and 175 m deep, with a volume of 14.1 km^3. Water temperature within a column of water near the center of this oligotrophic, monomictic lake never exceeded 4°C over a 2.5 year record, though the shallow shelves (< 10 m) surrounding the lake can reach 5°C in summer. Though thermally stratified in winter, the water appears completely mixed shortly after lake ice breakup in July. Mean annual air temperature measured about 200 m from the lake was –10.3°C in 2002, and an unshielded rain gage there recorded 70 mm of rain in summer of 2002. End of winter snow water equivalent on the lake was approximately 110 mm in May 2002. Analysis of NCEP reanalysis air temperatures (1948–2002) reveals that the 8 warmest years and 10 warmest winters have occurred since 1989, with the number of days below –30°C dropping from a pre-1989 mean of 35 to near 0 in recent years. The crater region is windy as well as cold, with hourly wind speeds exceeding 13.4 m s^{-1} (30 mph) typically at least once each month and 17.8 m s^{-1} (40 mph) in winter months, with only a few calm days per month; wind may also play an important role in controlling the modern shape of the lake. Numerous lines of evidence suggest that the

This is the *second* in a series of eleven papers published in this special issue dedicated to initial studies of El'gygytgyn Crater Lake and its catchment in NE Russia. Julie Brigham-Grette, Martin Melles, Pavel Minyuk were guest editors of this special issue.

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physical hydrology and limnology of the lake has changed substantially over the past 3.6 million years, and some of the implications of these changes on paleoclimate reconstructions are discussed.

Keywords Arctic · Hydrology · Limnology · Lake ice · Climate

Introduction

Lake El'gygtgyn lies inside of a meteorite impact crater dated at 3.6 million year BP (Layer 2000) and holds a promising paleoclimate record within its sediments (Brigham-Grette et al. 2001, 2007; Nolan et al. 2000; Nowaczyk et al. 2002). Located in northeastern Siberia (67.5 N, 172 E), this lake has already yielded the oldest continuous terrestrial climate record in the Arctic, based on a short 13 m long core dated to over 250,000 years BP, as thoroughly described elsewhere in this special issue (Brigham-Grette et al. 2007; Melles et al. 2007; Nowaczyk and Melles 2007). However, little is known in the western world about the physical setting of this lake. The name itself—"El'gygytgyn"— is Siberian Chukchi that has been translated to 'white lake' or 'lake that never thaws', hinting at the intriguing possibility that perhaps within human oral history that it has remained ice covered through the summer; such an ice cover would have a major influence on the physical and chemical dynamics of the lake, as described later. This paper therefore describes some of the basic hydrological, limnological, and meteorologic characteristics of the lake and its crater-watershed, with the goal of providing a context against which other modern-process studies and paleo-conditions can be compared; this paper is the second in a series towards that goal (Nolan et al. 2003). The results described here are based on observations from three US–German–Russian field expeditions (2 May–15 May 1998; 7 Aug–6 Sept 2000; and April–Sept 2003), remote sensing covering roughly the same period, and data from loggers measuring continuously from 2000–2003 located around and within the lake.

Crater hydrology

Lake El'gygytgyn lies within a meteorite impact crater, north of the Arctic Circle, in a region of continuous permafrost in the Russian Far East (Brigham-Grette et al. 2007). The crater is roughly 18 km in diameter and is likely the best preserved on Earth for its size (Dence 1972; Dietz and McHone 1976). The crater lies along the regional continental divide, with the single outlet (the Enmyvaam River) flowing south and east into the Bering Sea, whereas just over the north edge of the crater rim water flows into the Arctic Ocean. The lake is surrounded by continuous permafrost, with local depths likely in the range of 100–300 m (Glushkova 1993). Vegetation is sparse here, dominated by moss tundra (Oacease–Cyperaceae–Artemisia with some prostrate *Salix* spp). At the time of the impact, however, there was no permafrost in this region, and forests extended all the way to the Arctic coast (Brigham-Grette and Carter 1992).

Numerical delineation of stream channels

A digital elevation model (DEM) of the crater region was created by digitizing the contours of commercially available topographic maps with 20 m contour intervals at 1:100,000 scale (Mezyerynnet Q-59-19,20 and Otvegyrgyn Q-59-9.10). The resulting DEM had the usual artifacts associated with such a digitizing process, such as step-like elevations in flat areas and map splice errors, but in general was suitable for basic hydrological study and for ortho-rectification of satellite imagery. This DEM, used in the hydrological analyses here, has a 30 m spatial resolution, 10 m vertical accuracy, and 1 cm vertical resolution.

Using the commercial software RiverTools®, we calculated a number of basic hydrological statistics from this DEM. The entire basin area draining into the lake (including the lake) is 293 km^2, with 183 km^2 of land area draining into the lake itself (lake surface area 110 km^2). Approximately 50 streams drain from the crater rim into the lake. To facilitate research, a common numbering system for these streams was developed during the 2000 field season following upon the work of Glushkova (pers. comm., 2000). These numbers begin with 0 at the outlet stream (southeast corner) and increase clockwise around the lake (Fig. 1). The drainage area and relief for each of these streams was calculated and presented in Table 1. Minor inlet streams exist in between these 50 numbered streams, particularly near their entry into the lake, so the sum of the 50 watershed areas in Table 1 is only about 85% of the total watershed area. Though not labeled on the Fig. 1, it is suggested that future publications refer to these minor streams using decimal notation based on rough percentage distance between two major streams (e.g., use "Stream 16.4" to refer to a stream inlet located about half-way between Streams 16 and 17 but closer to Stream 16, noting the inlet's spatial coordinate if available).

Validation for the drainage areas was completed primarily by comparing computer generated channel networks with Ikonos satellite images (4 m spatial resolution) and with stream vectors taken from the paper topographic maps (presumably derived originally from air photos). The visual correlation between these data sets was excellent, despite the Ikonos image not being ortho-rectified using the DEM and projection differences between the DEM and the topographic maps.

Stream geomorphology

Landcover patterns are typical of arctic terrain. Higher elevations with steeper terrain are dominated by frost-shattered rock. These descend to lower-slope hills dominated by cryoturbation features such as stone stripes and frost boils. As slopes drop below about 5°, they are covered by patches of tussock tundra that become increasingly more contiguous towards the lake. Gravel-bedded streams exist at the bottoms of most valleys, with all but the largest streams being only a few meters across. The rocks in the lake watershed are largely Cretaceous metavolcanics of the Okhotsk-Chukchi volcanic belt and the lake is largely surrounded by the Pykvaam Formation consisting of ignimbrite and tuff (Layer 2000).

The majority of the land surface draining into the lake is located along the broad western shore (Fig. 1). Why the lake itself is offset from the crater rim remains to be fully explained. Informal hypotheses include a low angle impact, pre-impact topographic controls (higher mountains in the west), post-impact tectonic tilting, and more erodable terrain with prograding deltas in the west. While the first two possibilities are outside the scope of this paper, we consider the hydrological aspects of the last two here.

We altered the DEM to synthetically dam the modern outlet stream in the DEM, filled the lake synthetically with more water, and tilted it pseudo-tectonically to look for low spots that may have been outlets previously. We found that the only feasible alternate exit point is a low pass (~36 m above modern lake level) near Stream 36. This area was examined in the field and later with air photos and revealed no signs of ever being a lake outlet, despite the appearance of linear features at roughly this elevation on the hills near Streams 1–3 (Glushkova and Smirnov 2007). Due to millennia of cryoturbation in this area, most evidence of paleo-shorelines has been destroyed and such linear features could also be features of permafrost or locally emphasize structural geology.

The idea of prograding deltas, however, is quite plausible. The Ikonos image in Fig. 2 clearly shows that Streams 12–14 are part of the same delta system, which can also be seen extending underwater as a shallow shelf. Part of the explanation for why the eastern shore is not similarly migrating towards the center may be a geologic control—a fault runs through the southeast corner of the crater and the rock here is more competent, actually outcropping on the shoreline near Stream 48. Seismic measurements made in the lake in 2003 indicate that these deltas continue quite deep into the sediment package beneath the lake (Niessen et al. 2007); these measurements also show that at least 400 m of lake sediment overlie the impact surface. Thus sediment has likely been gradually displacing the lake from both the western shore and from below, suggesting that the original lake volume may have been more than quadrupled in volume (three times as deep and 1.5 times more surface area).

The presence of water tracks on the western shore has several implications for the dominant hydrological processes in effect today. While below the resolution of our DEM, these small

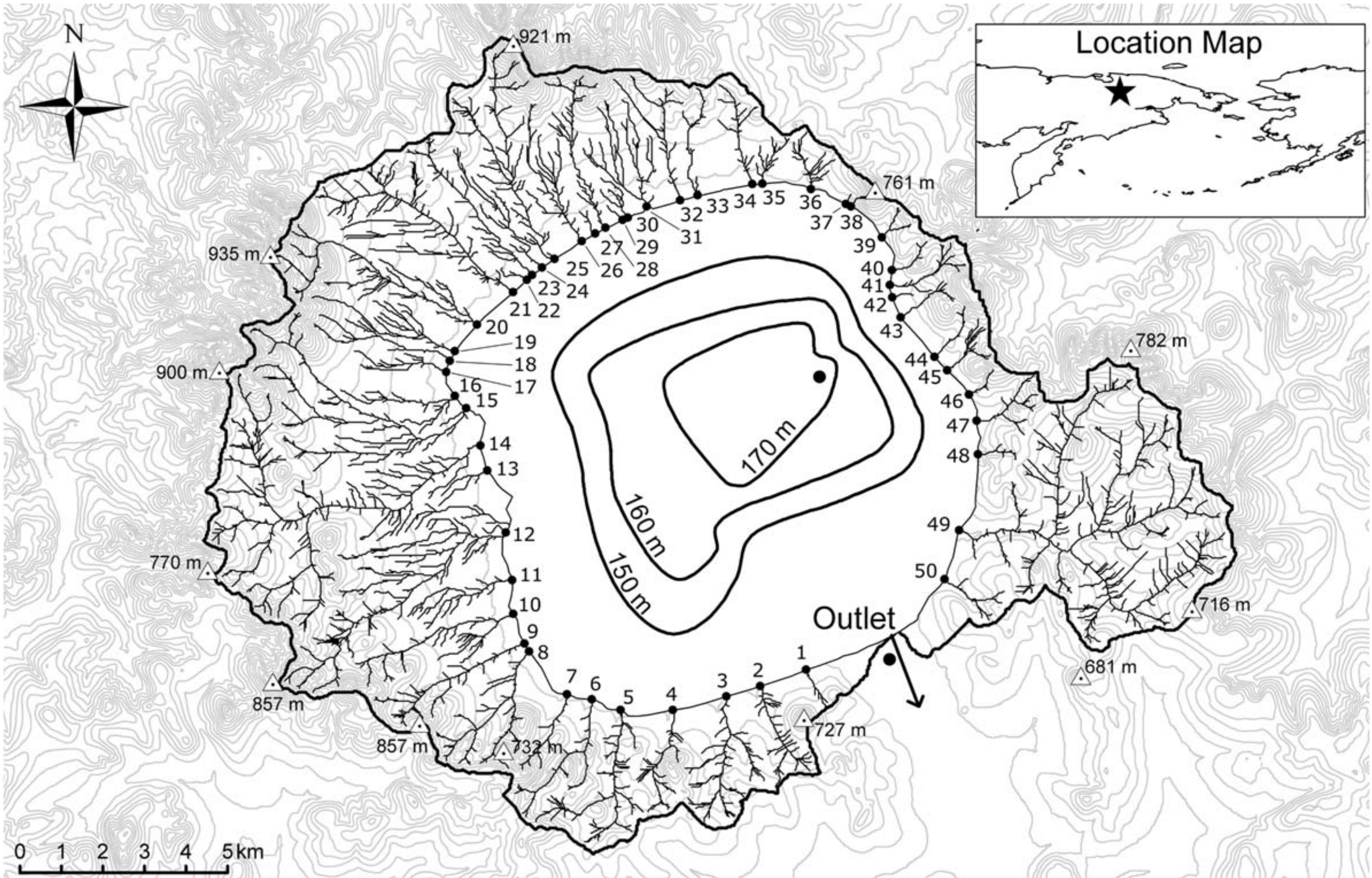

Fig. 1 Location map for Lake El'gygytgyn. Crater watershed area and stream channel network were created from the DEM described in the text. Lake level is roughly 492 m above sea level. Topographic contour interval is 25 m; only three bathymetric contours are shown. Filled circles within 170 m bathymetric contour and near lake outlet are the locations of a thermistor string and weather station, respectively, described in the text

Table 1 Watershed statistics of the 50 major streams draining in Lake El'gygytgyn

Stream number	Area (sq. km)	Relief (m)	Size rank	Lagoon in 2000?	Easting (m)	Northing (m)
1	0.40	85	43	?	548442	7481001
2	2.39	93	20	No	547336	7480608
3	3.97	143	10	No	546522	7480360
4	2.22	147	22	No	545232	7480032
5	4.55	212	8	Yes	543972	7480031
6	2.61	211	18	No	543282	7480286
7	1.32	185	28	Yes	542682	7480409
8	4.44	188	9	Yes	541773	7481442
9	3.41	267	12	?	541657	7481630
10	3.56	244	11	Yes	541386	7482345
11	1.56	51	27	?	541360	7483161
12	**9.92**	**316**	**3**	**Yes**	**541207**	**7484308**
13	0.60	11	39	?	540761	7485801
14	**19.00**	**299**	**2**	**No**	**540595**	**7486402**
15	3.00	134	15	?	540253	7487300
16	**7.21**	**306**	**5**	**Yes**	**539978**	**7487597**
17	1.27	87	31	?	539772	7488172
18	1.70	284	26	No	539861	7488442
19	2.16	264	23	No	539982	7488680
20	5.72	362	7	No	540517	7489317
21	**8.56**	**156**	**4**	**No**	**541385**	**7490098**
22	0.13	10	48	?	541717	7490398
23	2.61	139	19	Yes	541841	7490512
24	0.34	17	45	?	542081	7490691
25	7.18	310	6	No	542381	7490901
26	2.67	176	17	Yes	543037	7491326
27	0.25	9	47	?	543363	7491510
28	3.02	264	14	Yes	543611	7491651
29	0.46	21	41	?	544025	7491838
30	3.33	160	13	?	544149	7491893
31	2.37	160	21	?	544602	7492162
32	2.87	208	16	Yes	545411	7492311
33	0.97	144	33	?	545832	7492432
34	2.00	92	24	?	547151	7492701
35	0.85	39	35	?	547393	7492713
36	1.19	53	32	?	548562	7492582
37	0.02	115	50	?	549403	7492223
38	0.28	167	46	?	549525	7492164
39	0.61	93	38	?	550272	7491416
40	0.53	101	40	?	550515	7490631
41	1.28	152	30	?	550463	7490271
42	0.06	34	49	?	550523	7489971
43	0.69	149	36	?	550722	7489493
44	0.66	159	37	?	551538	7488537
45	0.87	146	34	?	551846	7488214
46	0.36	120	44	?	552371	7487630
47	1.79	162	25	?	552552	7487001
48	0.43	134	42	?	552584	7486192
49	**27.43**	**282**	**1**	**No**	**552133**	**7484360**
50	1.32	109	29	?	551779	7483184

Bold rows indicate the five largest sub-watersheds. Question marks indicate lack of field observations of whether lagoons were present. Coordinates are included here to prevent ambiguities or confusion in the field and indicate location of stream mouth at lake level, reported in the UTM 59 projection

hydrological features are visible on the Ikonos image (Fig. 2) by the slightly different vegetation color, in this case a darker green. Water tracks are a feature found in permafrost terrain across the Arctic and are thought to be related to the immature drainage systems imposed by the frozen ground (McNamara et al. 1998). Little erosion is possible here because snowmelt, typically the

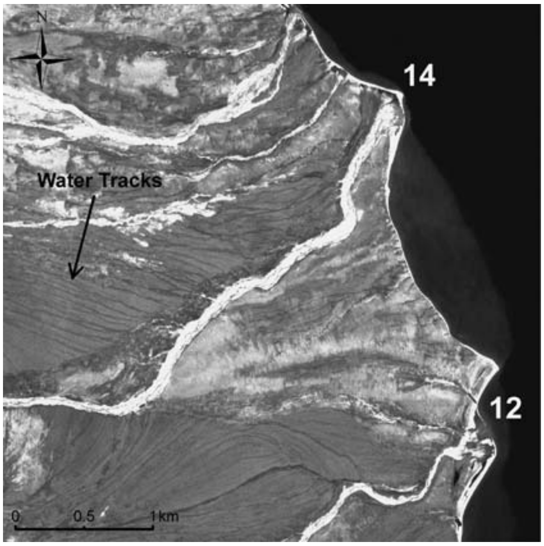

Fig. 2 Example close-up of Ikonos imagery (30 July 2000). Note the prograding delta extending underwater between streams 12 and 14, and the linear drainage features in the tundra called water tracks. It is possible that the toe of this delta formed during lower lake levels and was later submerged

dominant hydrological event of the year in Arctic watersheds (Kane et al. 1992), occurs when the ground is frozen near the surface. Rather than scour soil, these water tracks have the characteristic feature of having slightly thicker vegetation, presumably due to the difference in soil moisture availability there. This vegetation may then serve to slow erosion further. A common characteristic of these water tracks is that they tend to be parallel and follow the steepest gradient, with none of the branching characteristic of drainage systems in non-permafrost terrain. Their existence here confirms that permafrost plays a dominant role in the hydrology of the crater system and that snowmelt is likely the dominant hydrological event of the year.

Stream discharge

During the 2000 field season, we were able to measure the discharge of the outlet stream three times and many of the smaller inlet streams once. In late August, flows in all the inlet streams were less than 1 m^3 s^{-1}, and often just a trickle. As expected, streams with the largest drainage areas (Table 1) had the largest flows, but could easily be crossed on foot. The outlet stream discharge dropped from 19.8 m^3 s^{-1} on August 16, to 14.2 m^3 s^{-1} August 23, and to 11.6 m^3 s^{-1} on September 1. The maximum sill depth at the lake outlet was about 0.6 m, and the outlet was about 30 m wide at the sill. The initial channel deepened to about 1.5 m as it narrowed, before beginning to braid about 200 m downstream. During the 3 weeks of observation, water level dropped approximately 0.12 m. A recently abandoned outlet channel, presumably active during spring runoff, was present several hundred meters east of the present channel, with apparent spring shorelines approximately 1 m higher than the late summer shoreline.

Lagoons

Many of the inlet streams were impounded by gravel bars at the shoreline. Figure 3 shows a cross-section of one such bar. As can be seen, lagoonal deposits are onlapped by gravels thrown inland from the beach presumably during storms, a process observed in the field at other locations along the beach. As the lagoon water depth increases, it either tops over and erodes the bars or seeps out through the porous sand and gravel, or both, as revealed through inspection of about 20 such lagoons. About half of these streams were still impounded in August 2000 (Table 1), and presumably remained impounded until at least the following spring when they likely reach their maximum height due to snowmelt. Total lagoon area in 2000 was 11.5 ± 1.0 km^2, measured from a 1 m pan-chromatic Ikonos image acquired that summer; during snowmelt, this area may double. Lagoon dynamics were observed to be similar in 2003. Longshore drift driven by northernly winds during a 7-day storm in August, 2003, closed off the lake's main outlet, but the lake continued to slowly drain through September via seepage through the gravel berm.

Physical limnology

Bathymetry

Our search revealed two different bathymetric maps of the lake. The first is found on existing paper topographic maps of the region and is

Fig. 3 Cross-section of beach sediments where Stream 14 enters lake towards right. Storm deposited gravels can be seen above lagoon-deposit sediments. Note backpack for scale

highly inaccurate. The second was found inadvertently in Russia with no attributable authorship (Fig. 4a). We brought this map into the field with us, spot checked it with sonar and found it to be as accurate as we could crudely determine with our own sonar and handheld positioning systems; significant errors may yet exist however. We then digitized the contours of this map, gridded them, and merged it with the DEM created earlier. We created the lake-shore contour that splices these two maps together using a lake outline created from the Ikonos image with 4 m spatial resolution.

Using this digital bathymetry and the Ikonos image, we were able to calculate several valuable lake statistics. Lake surface area is 110 km^2, or roughly one third of the total watershed area. Lake volume calculated from the bathymetry using linear interpolation and 10 m horizontal slices is 14.1 km^3 (Fig. 4b). Maximum lake depth is 174 ± 2 m, as measured by several techniques, with inter-annual lake level variations on the order of 1 m. For comparison, a circular lake of constant depth having the same surface area and volume would have a diameter of 11.8 km and a depth of 128 m. Lake surface elevation is approximately 492 m above sea level. The lake bed is characterized by several shallow (< 10 m deep) shelves, remarkably steep sides, and a broad flat bottom (Fig. 4a). The shelves and sides are typically armored by gravels, making gravity coring difficult, but the flat bed is typically a sandy-silt to silt with rare cobbles; these shelves may have been paleo-shore lines. The deepest part of the lake is nearly in its center, but strong vertical relief on the eastern shore, likely due to bedrock outcroppings, puts most of the water towards the eastern side. The steep sides found around most of the remaining basin, likely consisting of sediments and former shorelines, occasionally slump creating debris flows as revealed by seismic measurements (Niessen et al. 2007). Between the shallow shelves and the deep basin (where slopes are less than 1°), typical slopes range 5–15° in the south and west shores and 15–30° in the east and northeast shores; the highest slopes of greater than 40° were found along the eastern shore where bedrock outcrops into the lake. In the absence of lake ice and thermal stratification, the fact that the lake is about 70 times wider than it is deep favors easy mixing of the water column by the strong winds present here.

Lake shape

We hypothesize that the odd, somewhat square shape of the lake is a result of at least several

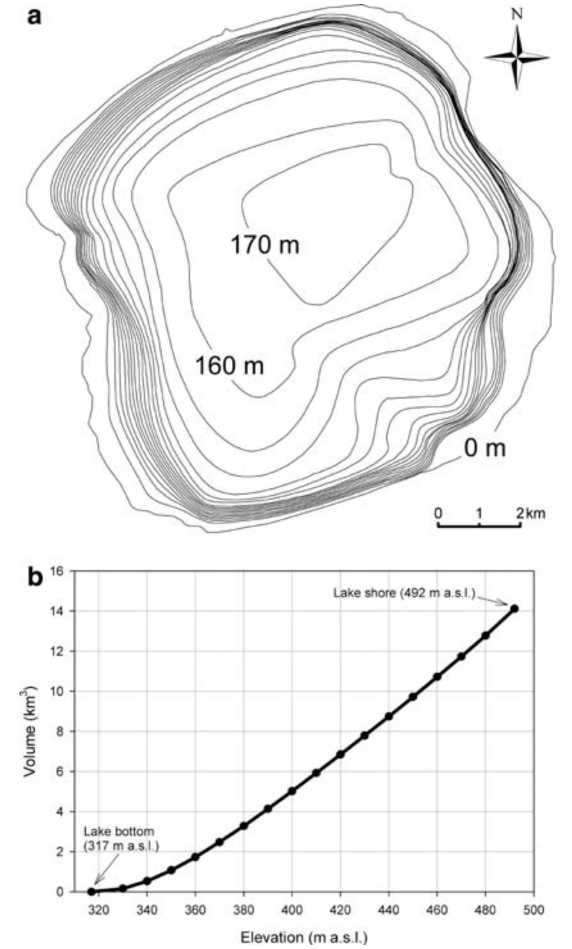

Fig. 4 Lake bathymetry (a) and hypsometry (b). Bathymetric contour interval is 10 m; though we believe this bathymetry to be fairly accurate, substantial errors may yet exist

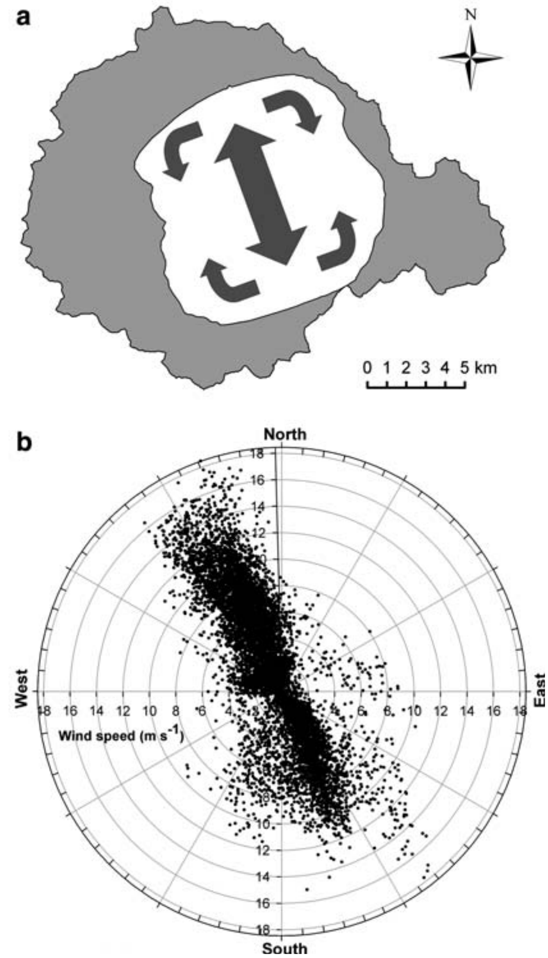

Fig. 5 Surface water dynamics schematic (a) and 2002 hourly wind speeds and directions (b). The orientation of the lake is identical to the dominant wind direction (bearing 335 degrees) to within the measurement accuracy of 5°. How winds help shape the lake is described in the text

factors. If modeled as a square, the north and south shores are exactly perpendicular to the bearings of dominant winds (335°, or 25° west of north), to within the 5° measurement accuracy of both measurements (Fig. 5). Numerous researchers have found that Arctic lakes are often oriented like this to the wind (Burn 2002; Carson and Hussey 1959; Cote and Burns 2002; Harry and French 1983; Rosenfeld and Hussey 1958; Sellman et al. 1975), and others have found that a water-body underlain by deformable sediments in nearly any windy environment will tend to align shorelines in this manner (Cooke 1940; Kaczorowski 1977; Rex 1961). The typical pattern found in smaller lakes is that winds force water along the dominant wind vector, with maximum erosion occurring at the upwind corners and deposition occurring on the downwind edge. This creates elliptically shaped lakes in the easily erodable sediments of the Alaskan Arctic coastal plain, but geological and lacustrine controls likely prevent this shape from developing at El'gygytgyn. For example, a wind from the south piles water up along the northern shore. To maintain mass continuity this water then must return towards the south, balancing gravity and the wind-driven surface current, such that it most likely turns at the corners and follows the shoreline back. This places the highest erosional forces on these corners, rounding them out. On the western shore, elliptical growth is prevented by significant delta formation at Streams 12–14 (Fig. 1). On the eastern shore, it is prevented by bedrock erosion at the outcrops near Stream 45. A similar dynamic results when winds blow from the north. The result is a roughly square lake with rounded corners and a pinched center, oriented with the prevailing winds, which tend to blow either from the north or from the south along a bearing of 335°; this is shown schematically in Fig. 5a. Observations of long-shore drift support these hypothesized lateral return flows (the outlet stream was observed to be closed-off by gravel during a mid-August storm in 2003 and never re-opened, as mentioned above), and observations during storms in 2000 and 2003 revealed a pattern of sediment flow at the water surface that also supports this hypothesis in the open water. Further measurements and modeling are required, however, to be conclusive about the influence of wind on lake shape.

Lake temperature

El'gygytgyn is a cold, oligotrophic lake. We installed a thermistor string in the deepest part of the lake in summer of 2000 which was recovered in-tact in summer of 2003. This string was composed of five Tidbit® dataloggers (Onset Computer Corp) attached to a weighted wire-rope suspended by floats about 4 m below the water surface; the floats were distributed such that if the rope broke at any location, the free portion would float to the surface for later recovery on shore. Records from these thermistors are shown in Fig. 6 for 2002, which was typical of all years. These thermistors show that the water temperatures here did not exceed 4°C during the 3 years of record and that the water is thermally stratified in winter; measurements from another thermistor string on the shallow shelves indicate that water there can exceed 4°C, as warm stream water and solar radiation gain on the sediments warm the lake locally. At least some of the apparent differences in inter-annual winter water temperatures in Fig. 6 are due to changes in water thickness between years (that is, the water and ice surface was closer to the top thermistor in 2003). We did not measure phosphorous or nitrogen contents, but the waters of Lake El'gygytgyn are a clear, deep blue with little algae or vegetation visible in the lake. These features are characteristic of oligotrophy and indicating that the oxygen demand is not high in general (Cremer and Wagner 2003; Hobbie 1984; Wetzel 2001); secchi disk depths were measured to over 20 m.

El'gygytgyn is also a monomictic lake that is fully mixed by late summer, at least during the measurement period 2000–2003 when the thermistors indicate the same seasonal pattern of warming and cooling each year. The warming of the pelagic water column in spring starts at the ice interface shortly after snowmelt begins on the lake in late May (Table 2), probably as a combination of lateral movement of warmer shore-water, vertical percolation of snow-melt through cracks in the ice, and solar gain through the ice once the snow is completely melted as found elsewhere (Ellis et al. 1991, 1997a; Malm et al. 1998; Stefanovic and Stefan 2002). As this warming continues, density differences between layers that are no-longer thermally-stratified become negligible and isothermal mixing likely begins to propagate downward at a steady rate beneath the ice (Fig. 6), in the manner suggested by theory (Matthews and Heaney 1987). Though we have not yet analyzed remote sensing from 2002, a sudden decrease in surface-water temperatures in mid-July (Fig. 6) suggests that the last lake ice melted suddenly at this time (likely due to 'candle ice' tipping over and exposing increased surface area, as is observed on many ice-covered lakes, including Lake El'gygytgyn in 2003) and that within 10 days the entire lake was nearly isothermal. Given that strong winds here are common, as described later, with white-capped waves as high as 1 m across the 12 km fetch, there is little doubt that the lake water is fully mixed during August and September. No significant thermocline or summer stratification was observed by this string or by boat measurements in 2000 and 2003. By early October water temperatures are dropping rapidly and typically ice cover forms by October 20 (Table 2), reducing wind mixing and leading quickly to thermal stratification of the water column.

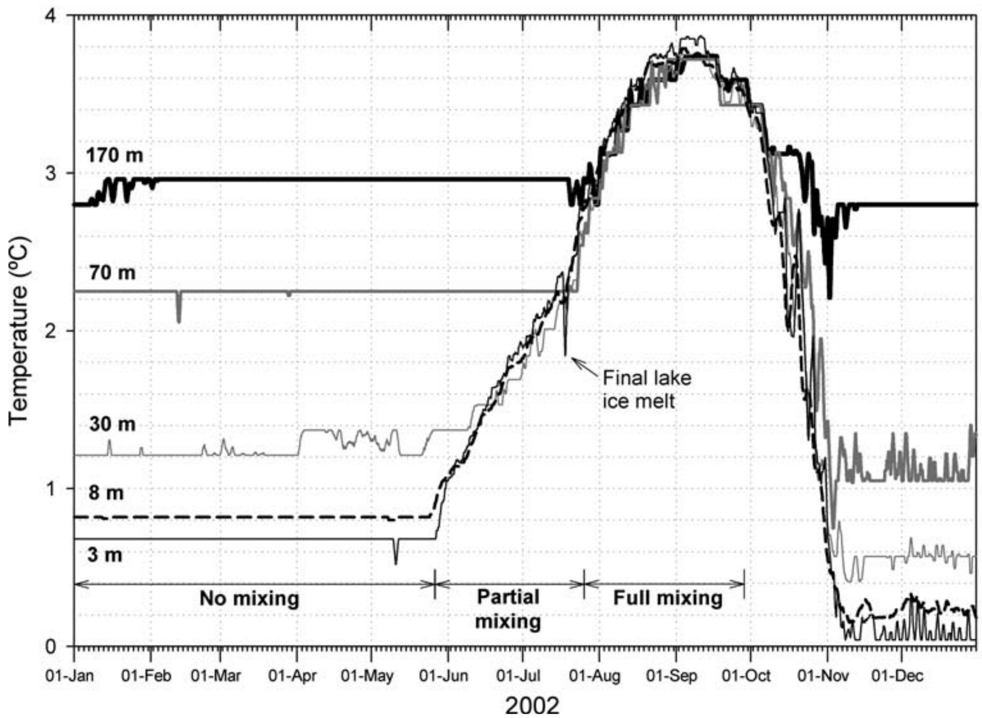

Fig. 6 Lake El'gygytgyn water temperature at five depths in 2002. A 24-point (1 day) running mean has been applied to these data. The lake is thermally stratified during the winter, begins mixing shortly after snow melt begins in mid-May (Table 2), and is completely mixed shortly after the lake ice disintegrates completely in mid-July. Water temperatures at all depths were colder in winter 2002–2003 than the previous one

Table 2 Important dates of lake ice dynamics derived from SAR (Nolan et al. 2003)

Winter	Onset of lake ice freezing	Onset of lake ice snow melt	Completion of lake ice snow melt	Onset of lake ice moat formation	Completion of lake ice melt
1997–1998	No Data	< 8 July	< 8 July	< 8 July	8 July–9 Aug
1998–1999	>6 Oct	17–18 May	31 May–4 June	24 June–4 July	28 July–13 Aug
1999–2000	16–19 Oct	8–11 May	23 June–2 July	23 June–2 July	16–19 July
2000–2001	18–20 Oct	>14 May	No data	No data	No data

Dissolved oxygen

Lake El'gygytgyn's biogeochemical and depositional setting is dominated by the influence of ice cover on the dissolved oxygen level (Melles et al. 2007). Multi-year ice cover can affect dissolved oxygen levels in some lakes by sealing the water from the atmosphere, allowing biota within the lake (particularly in the lake sediments) to gradually consume it; indeed, even seasonal ice covers are known to lead to massive fish-kills in smaller lakes (Ellis et al. 1991, 1997b; Ellis and Stefan 1989). Preliminary core analyses (Brigham-Grette et al. 2001; Cosby et al. 2000; Nowaczyk et al. 2002) clearly shows anoxic conditions during glacial cycles at the core-site in the deepest part of the lake, indicating that the presence or absence of lake ice cover throughout summer is the single largest driver of the biogeochemical environment there (Brigham-Grette et al. 2007; Melles et al. 2007).

In the modern environment, the lake appears fully saturated with dissolved oxygen. During the 1998 winter coring expedition, small larvae were found in the lake sediments at 170 m depth, indicating that there is currently some mid-winter supply of oxygen there. Crude chemical test-strips indicated 7 mg/l at the top of sediment core in May 1998 and in summer 2000 digital measurements indicated the water was fully oxygen-saturated throughout the pelagic column (Cremer and Wagner 2003). Remote sensing (Nolan et al. 2003) also indicates a high level of biological productivity near the deepest part of the lake, as described next.

Lake ice and biological productivity

Satellite Synthetic Aperture Radar (SAR) observations have yielded several insights into both lake ice dynamics and biological productivity (Nolan et al. 2003), as well as possible mid-winter mixing dynamics. Nolan et al. (2003) modeled the interaction between weather, snow melt, and lake ice breakup, using NCEP globally-gridded weather data (Kalnay et al. 1996) and SAR observations as validation with good success; remote sensing from 1998–2001 indicates a consistent annual pattern where lake ice forms in late-October, snow melt begins in mid-May, a moat forms around the lake in mid-June, and the lake is clear of ice by mid-July (Table 2). Perhaps more interestingly, these SAR measurements revealed that the spatial distribution of bubbles within the lake ice is non-uniform, and that they consistently form most heavily over the shallow shelves and the deepest part of the lake (Fig. 7). Nolan et al. (2003) argued that these brightness contrasts can only be explained as differences in bubble content observed by microwave penetration through the dry winter snow, as the pattern disappears as soon as snow-melt begins, preventing microwave penetration. Over the shallow shelves, it is clear that the warmer sediments there (as measured in the field and caused by increased solar gain) support higher rates of biological productivity and higher associated rates of respiration and decomposition, which leads to the increase in bubble generation there.

Three plausible explanations were postulated for the central concentration of bubbles (Nolan et al. 2003), but data from other researchers acquired since then likely rule out two of them. The

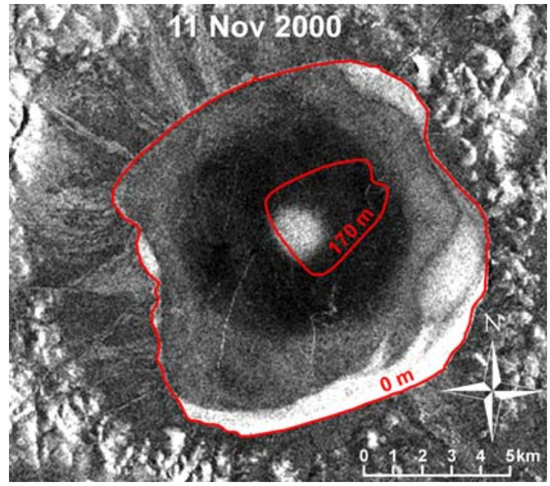

Fig. 7 Radarsat SAR scene with several overlaid bathymetric contours (as marked). This image was acquired within about a week of lake ice formation. Differences in brightness of the lake are related to the distribution of lake-ice bubbles, as described in the text. Note the close correspondence of the central bright spot with the deepest part of the lake (~175 m). In general, the bubble concentration reflects bathymetric features and some of the brightest regions of the shore may correspond to land that was recently submerged by rising lake levels

unresolved issue at that time was the structure of the impact crater underlying the lake. Large impact craters often have either central uplift features (conically shaped) or uplifted ring structures with or without a central uplift. Recent seismic measurements (Gebhardt et al. 2006) suggest that a ring structure is likely, and that any uplift features (ring or cone) are located several kilometers further west than the deepest part of the lake. This finding decreases the likelihood of the two hypotheses from Nolan et al. (2003) that depended on the uplift structure being located directly beneath this deepest part of the lake to describe the gaseous-source of the lake-ice bubbles found there.

Thus the most likely explanation currently for these central-lake bubbles is a toroidally shaped convection cell within the lake that supplies warm (4°C) water to the deepest part of the lake, where higher rates of respiration and decomposition can then be supported compared to the surrounding area, similar to the dynamics on the warmer shelves that are the source of the water. In early winter, shelf sediments release heat causing the water to increase in density and to sink, as has been found in many ice-covered lakes (Ellis et al.

1991, 1997a; Hondzo and Stefan 1993; Likens and Ragotzkie 1965; Matthews and Heaney 1987; Stefanovic and Stefan 2002). This prior research suggests that these currents would be limited to <1 mm/s with a thickness of <0.4 m along the sediment interface. To our knowledge, though this toroidal convection cell has been postulated many times on other lakes, no one has ever measured the upwelling that must occur at the center to supply the return flow, thus our SAR observations may be the strongest support for such an upwelling yet described. There is some possibility that if this convection cell does exist here that it could be substantially shallower than 175 m and exist just below the ice surface; however we then have no explanation for why the bubble pattern mimics the 170 m bathymetric contour so well (Fig. 7), and we thus believe it to be an unlikely possibility. Water chemistry measurements in 2000 also indicate that the water below 170 m in depth is characteristically different than the bulk water column (Cremer and Wagner 2003), further supporting a deep-water convection cell. Note that because the flows are so shallow and slow that this does not conflict with the observations of a thermally stratified water column (Fig. 6) for the bulk of the lake water, however further research is required to validate the existence and dynamics of this mixing.

Local weather

In summer of 2000, we installed several weather stations around the lake. The main station is located near the outlet stream on old fluvial gravel beds a few meters above lake level, and measures air temperature and relative humidity at two heights in shielded housings, wind speed and direction, net solar radiation, barometric pressure, rainfall via an unshielded tipping bucket, snow depth via sonic ranger, and soil temperatures and moisture down to approximately 0.6 m. The unit is powered by deep cycle batteries and solar panels and was designed to run unattended for at least 3 years. Unfortunately, the day after our departure from the lake in 2000 the datalogger was permanently ‘‘disabled’’ by a recreational ‘‘hunter’’ from the nearest town (200 km away); this event was not discovered by us until the following summer. At that time we replaced the datalogger and the station logged continuously until it was downloaded in September of 2003, recovering more than 2 years of data, with 2002 being the only complete calendar year to date; the station was left running in 2003 with several years of data capacity. Two other stations were established, one on the north side of the lake at shore level, and another on a peak approximately 300 m above lake level on the south side; these measured rainfall and air temperature. Unfortunately these units stopped working within several months of deployment, apparently caused by combinations of lightening, bear attacks, and faulty components.

Air temperature

The crater region is cold, but apparently getting warmer over the last half-century. Our local measurements show mean annual air temperature (MAAT) at the lake in 2002 was –10.3°C (Fig. 8a). Extremes in 2002 ranged from –40°C in winter to as high as +26°C in summer, with occasional mid-winter warming approaching 0°C. We compared these local measurements with the nearest grid-cell of the 2002 NCEP reanalysis data (Kalnay et al. 1996) for this region, which indicates a MAAT of –8.3°C. Such discrepancies are typical for reanalysis data, which use a wide variety of sources to arrive at a globally gridded data set with 2.5° (geographic) resolution cells to represent all of the points within that large cell. However, the reanalysis data does capture the trends in temperature reasonably well; thus while comparisons between NCEP and local data in terms of absolute values may not be worthwhile, trend analysis of the multi-year NCEP data would likely have value at the local level. Figure 8b plots the entire 1948–2002 NCEP record, with daily averages, minimums, and maximums for each day of the year; average MAAT during this period was –10.4 ± 1.1°C. However, closer inspection of this long-term record (Fig. 9) shows that 11 of the of 15 warmest years on record have occurred since 1989 and that the past 3 years (2000, 2001, and 2002) have seen MAATs greater than two standard deviations (about 2°C) warmer than the

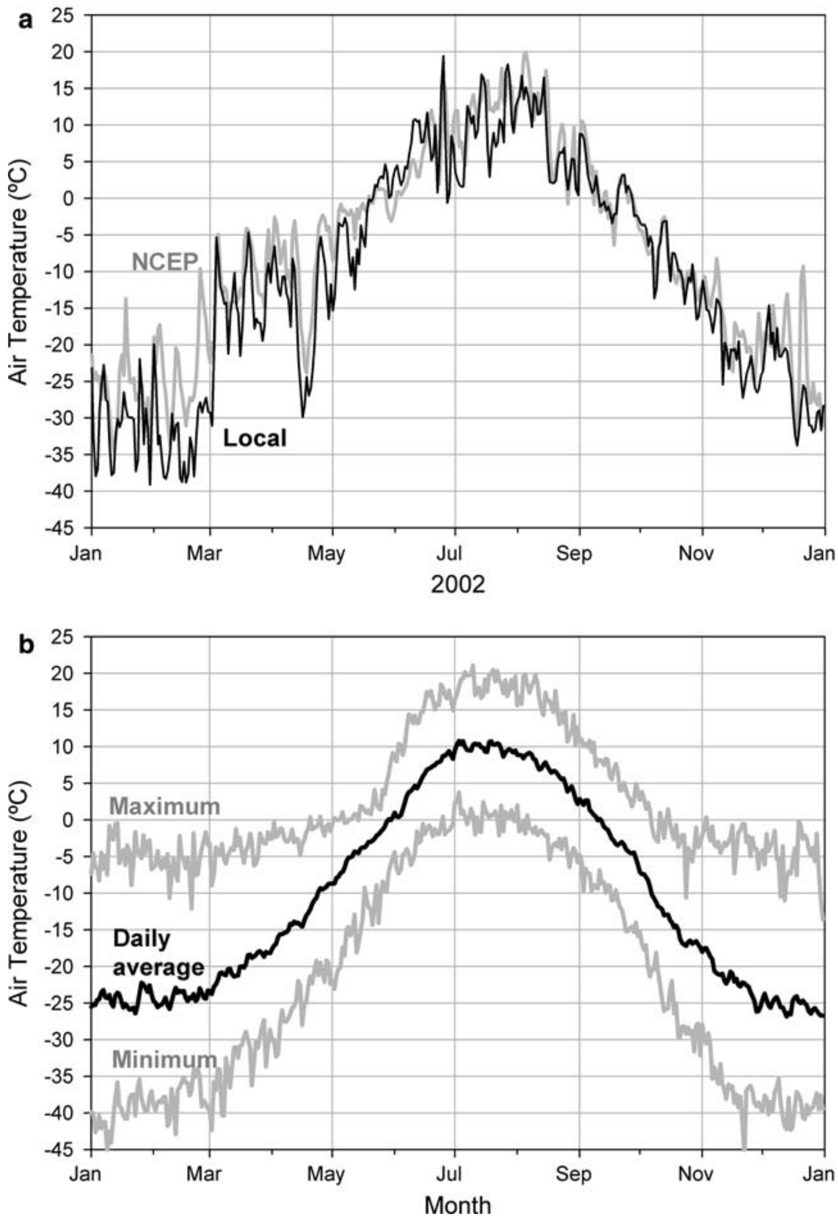

Fig. 8 (**a**) Comparison of mean daily air temperatures measured locally with air temperatures from the NCEP reanalysis. Trends compare well, though NCEP indicates slightly warmer temperatures. (**b**) Mean daily average, daily minimum, and daily maximum air temperatures derived from NCEP reanalysis data 1948–2002. Actual temperatures may have been slightly colder, as indicated in (**a**)

long-term mean. It is unknown whether some of this trend may be accounted for by changes in the amount or quality of assimilation data through time used to create the gridded data here.

These warmer MAATs are explained by warmer winters. Shown in Fig. 9 are negative, positive, and net degree-days. Positive degree days (dd) were calculated by summing daily average temperatures on all days in 2002 when the average daily air temperature was above 0°C, negative degree days by summing negative daily temperatures, and net degree days by adding positive and negative degree days together. The degree-day method is a useful way to quantitatively compare temporal and spatial trends in temperature because it does not depend on arbitrary determinations of which months or days are considered winter or summer (e.g., June–July–August is typically considered 'summer' in many climatologies) and quantitatively describes the magnitude of

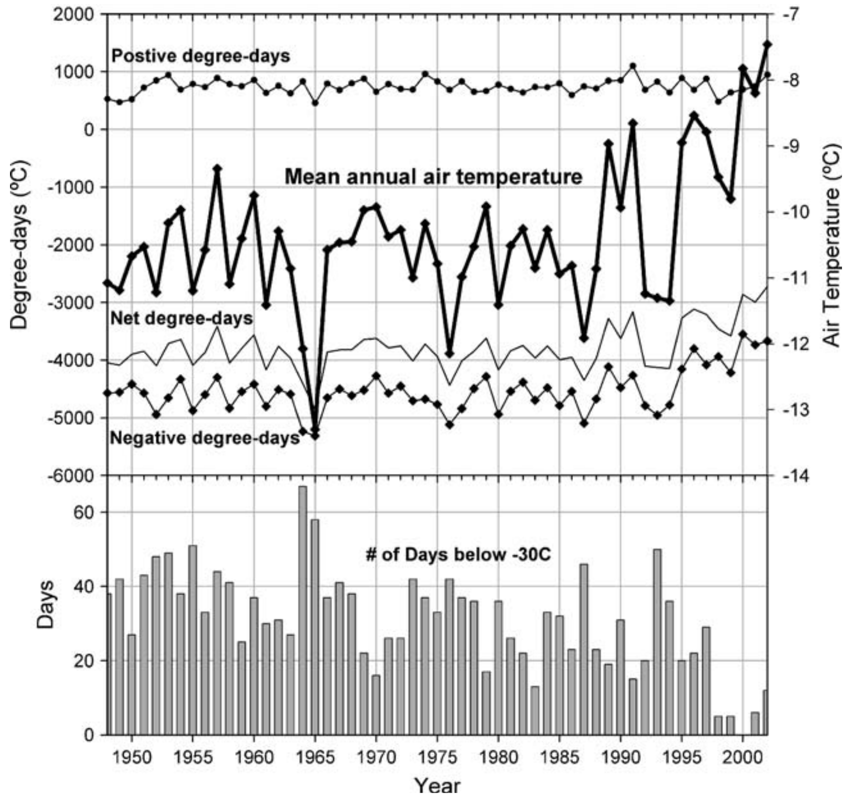

Fig. 9 Time-series of air temperature data derived from NCEP reanalysis. Note that warmer winters (negative degree-days) rather than warmer summers (positive degree-days) seem to be responsible for the increase in mean annual air temperatures over the past 15 years

winter coldness or summer warmness in a single number. The degree-day method is also used in our lake-ice models and is a simple proxy for estimating lake ice growth and decay and comparisons between regions. As can be seen, there has been no long-term trend in positive degree-days, which has been +739 ± 127 dd for the entire record. Prior to 1989, there was no trend in negative degree-days, which had been –4648 ± 251 dd. Since 1989, however, the 10 warmest winters on record have occurred, with values reaching –3549 dd, which is *more than four standard deviations higher* than the pre-1989 mean. This *change* in negative degree-days is greater in magnitude than the *total* positive degrees. The reason for the warmer negative degree-days seems to be related to a steadily declining number of days below –30°C (there was no trend in numbers of days between –20 and –30°C) as shown in Fig. 9; that is, the winter's are not as extreme and are becoming more moderate. Because rootstocks are sensitive to the extremes of cold weather, such a decrease in extremes may allow less hardy rootstocks to survive in winters here, perhaps facilitating a new vegetative succession that has not been seen for at least 50 years. Thus, assuming the reanalysis data are reliable, the trend of warmer temperatures and increasing variability found throughout the Arctic since 1989 (Chapman and Walsh 1993) seems to have a related manifestation at Lake El'gygytgyn.

Precipitation

The El'gygytgyn crater has a dry environment, typical of the Arctic. An unshielded tipping bucket near the main weather station recorded 70 mm of rainfall in 2002, all between mid-May and late-September when air temperatures were near or above freezing. In summer of 2000, we observed at least four separate snowfall events in August and September, and in 2002 the sonic ranger showed transient snowfalls greater than 5 cm beginning in mid-July and lasting the rest of the summer; it is therefore likely that some of the tipping bucket catch was snow that melted into the bucket. This combined with the strong and regular winds likely led to undercatch at the tipping bucket. End of winter snow accumulation in 2002 was 0.40 m, as measured by the sonic ranger on the weather station; this value is no doubt somewhat influenced by drifting caused by the station, but our observations at end of winter in 1998 indicate that 0.3–0.5 m snow depths are typical here, as in much of the Arctic (Hinzman et al. 2000). We did not measure snow density, but assuming that 0.27 g/ml is a reasonable and conservative value, as it is on the North Slope of Alaska (Liston and Sturm 2002), end of winter snow water equivalent is about 108 mm at the weather station. Thus the total precipitation estimate of 178 mm from end of summer 2001 to end of summer 2002 is likely conservative; these values are slightly lower than those made on the North Slope of Alaska (Bowling et al. 2003; Liston and Sturm 2002), which may be reasonable considering that weather patterns cause the two regions to have quite different moisture source areas. In 2002, snow melt at the weather station occurred quickly once air temperatures approached freezing, lasting less than 1 week (24–29 May) to melt the snow and expose the bare ground.

Our automated lake stage measurements also indicate that our 2002 precipitation measurements are likely conservative. If we assume that the average end of winter snowpack across the 183 km^2 crater watershed was 108 mm water equivalent, then we should expect a maximum of 179 mm rise in lake level if no evaporation or sublimation occurred $(183\,km^2 \div 110\,km^2 \times 108\,mm)$. During snowmelt in 2002, lake level rose by about 200 mm according to a pressure transducer submerged with the thermistor string and corrected for barometric pressure changes using the weather station's barometer. This pressure record gradually increased over the winter (before breakup and the 200 mm increase), by an amount that corresponds to about 150 mm of water, presumably due to snow loading of the ice. Thus this stage record suggests that our snow measurements at the weather station (108 mm w.e.) are lower than the average for the crater watershed and further that there is little storage of snowmelt on the land surface, as seems reasonable for frozen ground with no lakes. Because there is no evidence of glacial activity here (Glushkova 1993), it is likely that winter precipitation during glacial times was substantially less than today and/or that it melted completely during summer, as even a 50 mm annual accumulation would lead to sizable glaciers over 10,000 years. Evidence for extreme aridity across western Beringia during full glacial conditions is widespread (Brigham-Grette et al. 2004).

Wind

El'gygytgyn is also windy. Winds are dominantly either from the north or south (Fig. 5), with wind speeds exceeding 13.4 m s^{-1} (30 mph) every month in 2002 and exceeding 17.8 m s^{-1} (40 mph) in six of the months. In 2002, the mean hourly wind speed was 5.6 m s^{-1} (12.5 mph), the maximum mean hourly wind speed was 15.6 m s^{-1} (34.9 mph), and the maximum wind speed recorded was 21.0 m s^{-1} (47 mph). The strongest winds are typically in winter, and there were only a handful of calm days in 2002. While these winds are strong, they are not extreme. What is perhaps most relevant to understanding the lake is that they are strong *and persistent*, and this likely plays an important role in controlling lake shape, as discussed previously.

Relevance to paleoclimate reconstructions

We now have a reasonable understanding of the modern environment of El'gygytgyn crater, and this presumably should aid in our understanding of paleoclimate reconstructions, even if it is by pointing towards research gaps that still need to be filled.

Currently the hydrology of the crater is characteristic of permafrost terrains found elsewhere in the Arctic, but this was likely not always the case. Peak discharges in the modern environment typically occur during snow melt over an immature drainage system consisting largely of water tracks leading to gravel-bedded streams in the valley bottoms. Cryoturbation and sedimentation has obscured many clues as to the paleoenvironment, but the wide valleys along the crater-rim may have been formed in warmer climates that pre-date the initiation of glacial–interglacial cycles 2.6 million years ago and the wide-spread formation of permafrost. At this time, the crater-lake was likely more than four times larger in volume, and the center of the lake at that time is now buried beneath more than 500 m of sediments on what is now the western shore. That more sediments exist here than in the deepest part of the current lake-center suggests a higher sedimentation rate and therefore an increased temporal resolution of cores taken from what is now land. Further, a core taken from this location would presumably regularly switch between lake-deposited to river-deposited sediments, which may yield new or complementary information to a core taken from the current lake environment, perhaps even recovering vegetation in situ.

The lagoons found in the modern environment could have played an important role in the lake's biogeochemical cycling throughout time. Water temperature in the shallow lagoons (< 1 m water depth typically) was often >8°C, substantially warmer than the lake itself (~3°C). Fish fry were observed in several lagoons, and algae and diatoms are also present. Lagoon beds were typically composed of fine sediments. Thus these lagoons appear to act as settling and warming ponds, as well as comparatively warm and safe havens for small creatures. In spring, when lagoons are fullest, the influx of warm water from the lagoons to the lake likely plays a role in both moat formation around the lake ice and the destruction of any thermal bars (Wetzel 2001) within the lake water that would otherwise prevent wide-scale mixing and warming of the lake. Then, throughout the summer, the constant influx of warm water likely continues to help drive thermally-induced lake-water circulation by warming the lake margin water up to 3.9°C (the density maximum) and forcing it to sink towards the deepest part of the lake. Because the processes that create these lagoons (initiated by wind-driven currents) have likely been present for much of the lake's history, care should be taken when interpreting sediment core proxies, as some of these proxies may have characteristics inherited from within the lagoons inhabited by biota preferring higher temperatures then those inhabiting the lake itself.

Our air temperature, water temperature, and remote sensing data provide some clues as to lake dynamics during glacial times. They suggest that mixing of the lake-water would be greatly reduced during glacial times when a permanent ice cover was present (Melles et al. 2007), as even in the modern environment a strong stratification forms beneath winter ice covers. However, moat formations and solar absorption through the snow-free ice may have led to low-volume convection cell caused as sediments release heat to the water into winter, as appears to be occurring today beneath the ice. Determining whether such density flows could have reached the deepest part of the lake requires further modeling and field work, as it depends sensitively on the balance between thermal conductivity, heat storage, and thermal diffusivity within the lake (i.e., the dynamics of "thermal bars"). However, that this warming begins well before the ice cover disappears (as seen in our data) suggests that a similar warming may have occurred to some depth during glacial summers, and therefore caused an increase in biological productivity in the lake during that time.

Whether the entire water column, or just the water–sediment interface, became anoxic in the past remains an open question, as several pathways exist for oxygenation of ice-covered lakes, and evidence suggests that at least part of the El'gygytgyn water column remained oxygenated during the last 250,000 years. The lake is currently inhabited by several non-migrating salmonoid species: *Salvelinus boganidae* (length ~800 mm), *Salvelinus elgyticus* (~200 mm), and *Salvethymus svetovidovi* (~300 mm); these species are unique to the lake (Bely and Chershnev 1993; Skopets 1992) and indicate that life and a reliable food chain have persisted here through perhaps several glacial periods despite the continuous ice cover and anoxic conditions near the bottom. There are at least three possibilities to explain this. (1) Benthic demand was insufficient to consume all of the dissolved oxygen, perhaps due to the lack of mixing. Most of the oxygen in lake water is consumed within the sediments, not the water column (Wetzel 2001). In still, thermally stratified water beneath an ice cover, however, oxygen consumption within the sediments can effectively drop to zero, as a thin anoxic boundary layer develops between the sediments and the pelagic water column that severely reduces biological productivity within the sediments due to lack of oxygen (Ellis and Stefan 1989); that is, the consumption of dissolved oxygen is partly a function of mechanical mixing and re-supply of dissolved oxygen to the benthos. (2) Photosynthesis in summer continued beneath the ice in the uppermost water layers. This would require much of the lake to be free of snow in glacial summer (Ellis and Stefan 1989; Ellis et al. 1991; Stefanovic and Stefan 2002). In May1998 we directly observed that large areas of ice were blown free of snow on the north end of the lake (this was confirmed for several years using remote sensing (Nolan et al. 2003)), so the possibility of a completely snow-free surface during much drier glacial conditions seems reasonable (Brigham-Grette et al. 2007; Melles et al. 2007). (3) Oxygen resupply occurred during glacial episodes when summer-time moats were open around the lake. The snow-free, dark-colored rocks and sediments would have heated in the Arctic summer sun even in glacial times and tended to warm or melt ice in contact with it, leading to moat formation. Modern data from the permanently ice-covered lakes in the Dry Valleys of Antarctica indicate a super-saturation of oxygen there, as streams carrying water and oxygen into the lake via moats, but the water eventually sublimates via the lake ice leaving the oxygen behind (Wharton et al. 1986). These possibilities make it difficult to explain the causes of anoxic paleo-conditions based on modern-process data alone.

Had lake levels varied substantially in the past, however, anoxic conditions might be easier to explain due to lower water volumes and increased benthic productivity due to exposure to sunlight on the broad flat bottom, and any altered-chemistry conditions easier to explain due to increased concentrations of solutes. Sublimation rates of lake-ice in the Dry Valleys have been measured at 35 cm a^{-1} (Clow et al. 1988); in the absence of any annual water inputs to the lake, such a sublimation rate would completely dry up El'gygytgyn in only 500 years. Several core-proxies lead to interpretations of peak cold and dry conditions at Lake El'gygytgyn lasting much longer than this (Melles et al. 2007), and even with an order of magnitude less net water loss (i.e., 3.5 cm a^{-1}), it would only take 5000 years to completely dry up the lake. Decreased lake levels would clearly explain the existence of the cobble-covered shallow shelves surrounding the lake as old shorelines and river deltas that have been recently submerged; lakes in the Dry Valleys are currently showing similar trends, as warmer conditions there are leading to increased inputs to the lake systems from glacier melt (Bomblies et al. 2001). Many of these same Antarctic lakes show signs of their former size in terms of water chemistry—the water in the deeper pockets is substantially different chemically and therefore in density, preventing mixing with more recent fresh water that floats on top of it. At El'gygytgyn, we noticed substantial differences in water chemistry in the bottom few meters of water. Slumping of sediments into or within the lakes, as observed seismically (Niessen et al. 2007), might also be easier to explain with a variable water-level, as wave-undercutting of a shallow lake and watering–dewatering processes on exposed slopes might lead to the fairly steep side bathymetry leading from the current shelves to the flat bottom. Close inspection of the ice-bubble pattern in (Fig. 7) hints that the regions of brightest bubble concentrations at the margins may indicate areas where land has been recently claimed by rising lake levels. Thus the possibility of substantial variations in lake levels, even to the point of nearly complete loss of water, should not be overlooked when interpreting core proxies over the past 3.6 million years, though sediment cores from the lake dating back to 250 ka show no evidence of complete desiccation (Melles et al. 2007).

In summary, in the 3.6 million years since Lake El'gygytgyn was formed, substantial changes have likely occurred to the crater's physical hydrology and limnology, and these changes will complicate interpretations of changes in the local and regional climate, which are the ultimate goal of the project. However, we now have a reasonable understanding of this physical setting and how it may have changed over time. Thus while further research is necessary to understand the dynamics of these physical changes, such research is reasonably straightforward and should continue to improve the interpretations of sediments cores retrieved from this unique and interesting location in the Arctic.

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