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Giant ice rings on lakes Baikal and Hovsgol: Inventory, associated water structure and potential formation mechanism

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Abstract

Observations of giant ice rings on Lake Baikal (Russia) have recently sparked scientific and public interest. However, there is still no clear consensus on their origins. Here, we provide an inventory of the ice rings based on satellite imagery and photography for 1974–2014. We have identified 45 rings on Lake Baikal (compared with 13 previously known) and also for the first time four rings for the neighbouring Lake Hovsgol (Mongolia). The results of our hydrographic surveys beneath the ice rings in Lake Baikal in 2012–2014 and in Lake Hovsgol in 2015 show the presence of warm double-convex lens-like eddies before and during manifestation of ice rings. We suggest that these eddies are the driving factor for the formation of ice rings in these lakes. We reassess the existing hypotheses of ice ring formation and discuss the potential mechanisms of eddy formation.

Since 2009 the scientific community and the public have been intrigued by news of giant rings on Lake Baikal ice ("Circles in thin ice." 2009; Granin 2009; Hsu 2009; "Ring-like structures" 2009; "Strange Circles…" 2009; Kouraev et al. 2010a,b; "Ice rings." 2013; Granin et al. 2015). These are rings of dark (thinner) ice with a typical diameter of 5–7 km and width of 0.9–1.3 km (Fig. 1), surrounding white ice. The circular form of these rings and the unclear origins of this natural phenomenon represent a puzzle and a challenge for scientific research.

Potential explanations of the ice rings' origin include a wide variety of hypotheses ranging from atmospheric influence and biological activity in the upper water layer to UFO activity and hoaxes (crop circles etc.). However, among the more scientific explanations (Granin 2009; Balkhanov et al. 2010; Kouraev et al. 2010a,b; Granin et al. 2015) the most cited is the hydrothermal activity of Lake Baikal, namely extremely high-intensity gas venting (methane) from bottom sediments. As Lake Baikal was formed in an ancient rift, increased thermal flux from the lake sediments and temperature gradients can lead to intensive gas seeping. In shallow waters methane is normally released into the water column by gas seeps and mud volcanoes at locations near bottom faults, and creates steam-throughs (small patches of open water of size ranging from several meters to tens of meters) in the ice cover. But at larger depths, methane can be released mainly from gas hydrate deposits that occur at depths in excess of 500 m in the South and Central Basins of Lake Baikal (Granin et al. 2010).

How exactly the rings could be formed after the gas release is still not well understood. One hypothesis (Granin 2009; Granin et al. 2015), based on the in situ observations in April–May 2009 on the ice ring near the Southern tip of Lake Baikal (see Fig. 1b) and numerical modelling, is that local upwelling of the deep waters after gas emission from a point source is affected by the Coriolis force, leading to the formation of a dome-shaped density structure and an anticyclonic (clockwise) geostrophic ring current. Other gas-related hypotheses include formation of toroidal convection bringing warmer water to the surface (Balkhanov et al. 2010), or the formation of a mega-bubble of gas trapped under the ice cover, thus isolating the central part and increasing heat exchange on the outer

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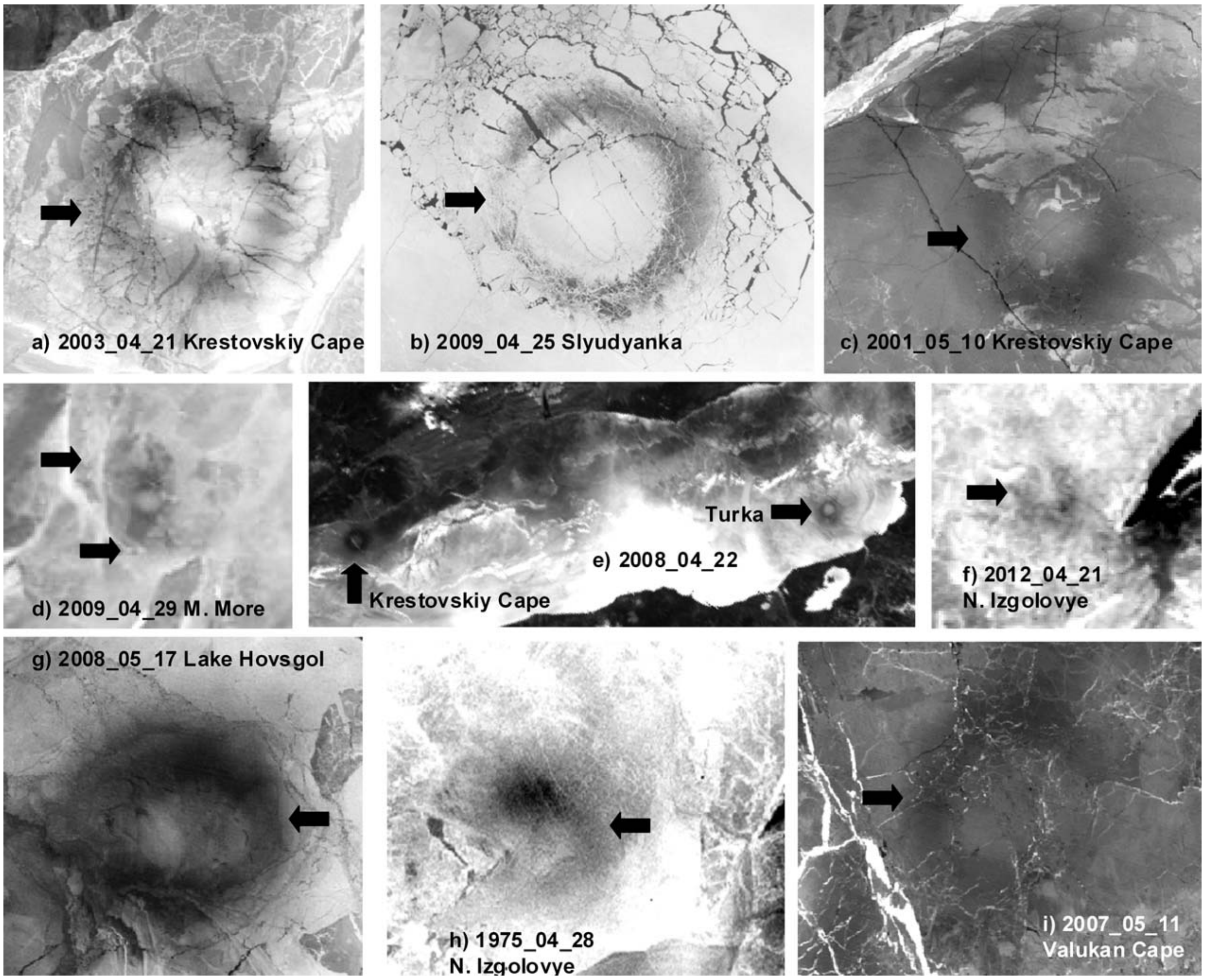

Fig. 1. Examples of ice rings for Lakes Baikal and Hovsgol. Data are from Landsat 1–7 (**a**, **c**, **g**–**i**), MODIS/Terra (**d**–**f**) and ISS (**b**) imagery. All images except (**e**) are aligned to North. For exact location and parameters see Fig. 2 and Table 1.

boundary of the mega-bubble (Kouraev et al. 2010a,b). Other researchers (Bordonskiy and Krylov 2014) suggest that ice ring formation is explained by deformations and heterogeneity of ice cover and self-organisation of ring-like structure with the incoming solar energy as the main source. However, as will be seen later on, all these hypotheses are tentative, and do not adequately explain the formation of the ice rings.

To better understand the phenomena responsible for the formation, development and disappearance of ice rings, we have: (1) processed satellite imagery and photography archives to get as full as possible an inventory of the ice rings and their parameters; (2) conducted field hydrographic surveys (2010–2015) in the regions of the ice ring formation that led us to (3) reassess existing hypotheses of the origins of ice rings.

Natural conditions of lakes Baikal and Hovsgol

Lake Baikal is the deepest lake in the world and contains 20% of the world's unfrozen surface freshwater. The lake bottom is separated into three parts (Fig. 2): deep depressions in the southern and central parts (maximum depths 1461 m and 1642 m, correspondingly), and a less deep one (maximum depth 904 m) in the northern part. High-altitude Lake Hovsgol (also known as Khubsugul or Khuvsgul) in north-western Mongolia is located 250 km south-east of Lake Baikal at an altitude of 1645 m above sea level (1200 m higher than Lake Baikal). It is part of the Baikal rift system and the lake has steep (25–50 m/km) bathymetry with depths of more than 250 m. Continental climate conditions with long cold winters result every year in complete freeze-up for 5–6 months (December–January to May) for Lake Baikal (Verbolov et al. 1965; Galaziy 1993; Kouraev et al. 2007a,b) and for 6–7 months (November to May–June) for Lake Hovsgol. At longer time scales, ice formation, development and decay are influenced by air temperature, wind, snow cover etc, and at shorter time scales by ice temperature changes and spatial heterogeneity of heat flux from water to ice.

The distribution and state of the ice cover and snow on the ice affect the hydrophysical structure, spring bloom of

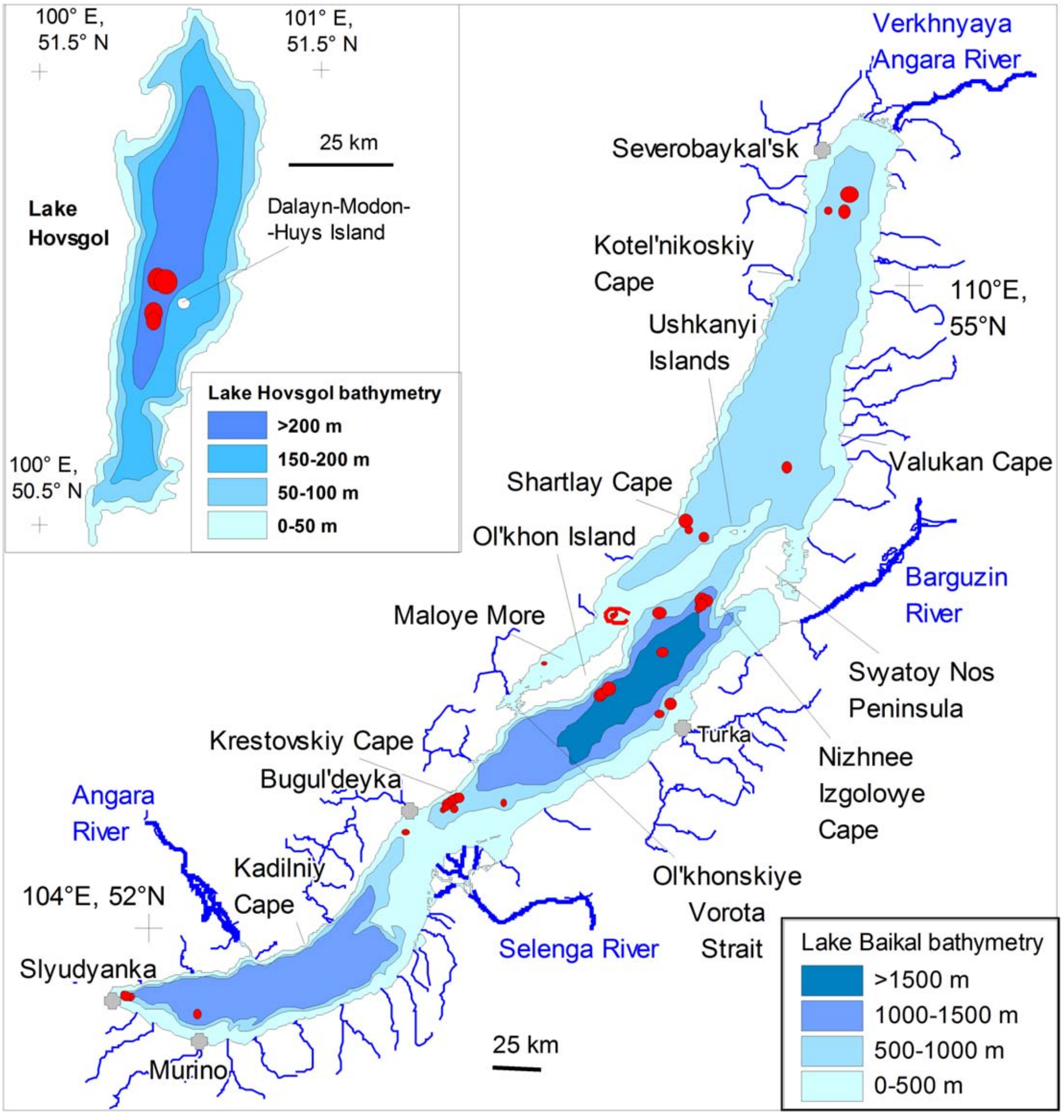

Fig. 2. Overview map of lakes Baikal and Hovsgol. Lake bathymetry (m) and location and size of ice rings (red circles) are shown. The scale is different for the two lakes and is indicated on the maps.

diatoms and primary productivity (Granin et al. 1999; Semovski et al. 2000; Mackay et al. 2003, 2005; Moore et al. 2009), as well as the living conditions of the only Baikal mammal—the endemic Baikal seal (*Pusa Sibirica, Phoca Sibirica*). For both lakes, ice is also important for establishing transport on ice, for fishing activities and tourism. In the winter, the ice is strong enough (more than 1 m thick) to support motorcycles, cars and even heavy vehicles.

Changes in air temperature lead to contraction or expansion of ice and the formation of "main cracks" (also called "stanoviye sheli" in Russian). When travelling on the ice, these main cracks are relatively easy to detect (expansion cracks are seen as areas of hummocks and contraction cracks as leads with open water), and ice thickness is similar to other neighbouring areas (except in the direct vicinity of the cracks). Ice rings, on the contrary, are not easily visible for travellers, at least not in the final stage of ice ring development. Ice cover here has the same visual aspect as the surrounding areas, but the ice is much thinner.

In this respect, better detection and potential forecasting of location, size and properties of zones of weak ice cover associated with ice rings is of paramount importance for ensuring security of transportation and fisheries on lake ice in winter and spring.

Ice ring detection and inventory

Ice ring detection

We have processed and visually analysed optical and infra-red satellite imagery from MODIS (Moderate Resolution Imaging Spectroradiometer 2002–2015) (Irkutsk RICC

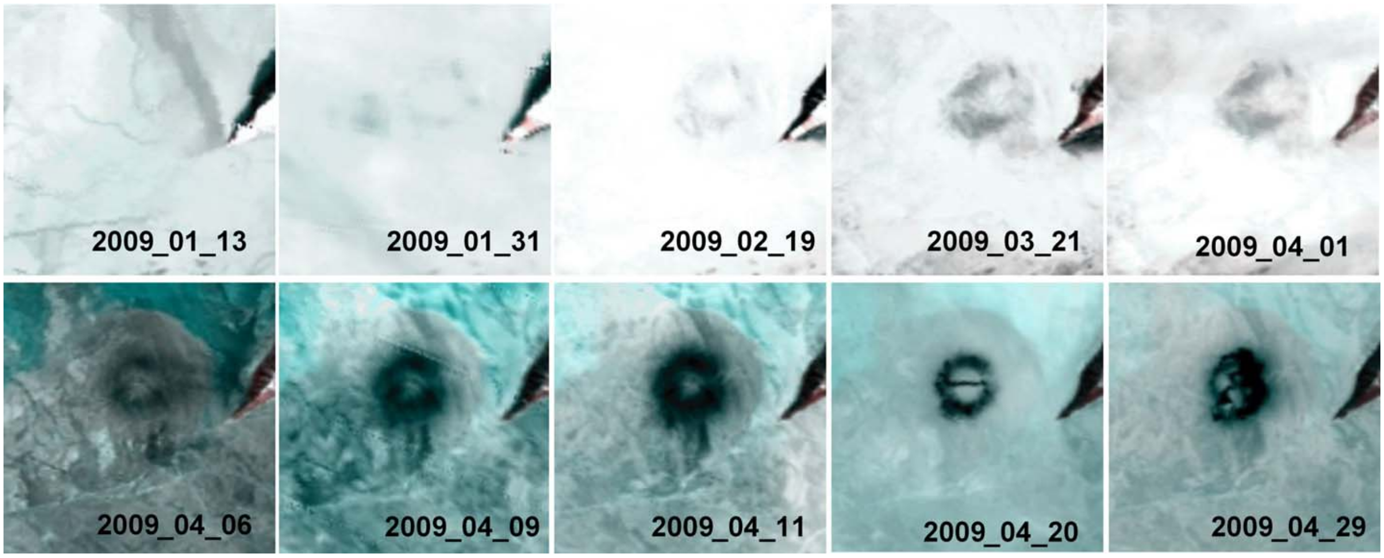

Fig. 3. Chronological sequence of MODIS images showing formation, development and disappearance of the ice ring (diameter 6.6 km) in the vicinity of Cape Nizhneye Izgolovye (Middle Baikal) in January–April 2009.

website 2015; LAADS web site 2015), Landsat (1972–2015) (Earth Explorer web site 2015) and NOAA AVHRR (for Cape Krestovskiy in spring 1999, spatial resolution 1 km). MODIS instruments onboard the Terra and Aqua satellites (daily observations since 2002) provide imagery (with a spatial resolution of up to 250 m in the visible range), with scenes entirely covering Lake Baikal. Landsat images (with spatial resolution depending on sensor: 80 m for MSS, 30 m for TM and 15 m for ETM+ and OLI) enhance the analysis by providing images with higher spatial resolution and extending back as early as 1970s. The Landsat scene size is about 185 by 185 km, and the exact repeat period is 16 d (18 d for MSS), so all available scenes for 1972–2015 from different passes covering Lake Baikal (10 scenes for passes 131–134 for each cycle) and Hovsgol (4 scenes for passes 136–137 for each cycle) have been analysed. Both MODIS and Landsat have sun-synchronous orbits and they revisit each place at the same local time (at about 3 or 4 h UTC for Lake Baikal, which corresponds to local late morning—GMT+8). We have also analysed satellite photography (with different spatial resolution and time coverage, 1983–2009) from the International Space Station (ISS) and US Space Shuttle (Evans et al. 1992; Circles in Thin Ice 2009; The Gateway to Astronaut Photography of Earth 2013).

We define an “ice ring” as a circular (or near-circular) pattern, seen as a dark circle (ring) on the ice cover, with a diameter of several kilometres. Once the rings have been identified from visual analysis, geographical coordinates and ring diameter were measured and ring shape was classified. There are several possible manifestations of the rings on lake ice. Depending on the ice structure (and probably also on snow cover on ice) it can be a full (Fig. 1a) or open ring (Fig. 1f). In some cases, there is a more pronounced dark feature in some part of the ring making it look like a diamond ring or a dark patch (Fig. 1h). In other cases a ring can be surrounded by a halo with a much larger diameter (Fig. 1d or Fig. 3 from 06 April 2009 to 29 April 2009).

Once an ice ring is observed on a satellite image, this feature persists until the ice break-up. A sequence of satellite images for the region near Cape Nizhneye Izgolovye (Fig. 3) shows a typical example of the appearance and development of an ice ring in 2009. By 13 January stable ice cover was formed. The first observation of the ice ring was 2 weeks later—31 January, when lake ice was still thin. Then the ring gradually became more and more visible. By mid-April the ring was well formed, very dark and wide. By 19–20 April, the ring had broken into two parts and then it gradually melted until the full ice break-up (03–04 May).

Because no ring has been observed so far in November–December, we designated each winter as the year in which winter ends (such as 2010 for winter 2009/2010). To name the location of the ice rings we used the name of the nearest settlement or geographic feature (capes, islands etc.).

The ring lifetime was determined as the difference (in days) between the first cloud-free observation and the last one (usually just before ice break-up, one or several days later). When the ice ring was still visible in the drifting ice fields during ice break-up, it was considered that the ice ring was still defined.

Cloud cover represents an obstacle for detection of ice rings from satellite imagery. Although the presence of cloud cover varies from one winter to another, we made an estimation of cloud frequency for the region where the ice ring near Cape Nizhneye Izgolovye was observed for a long time

Table 1. Inventory of ice rings and their characteristics.

Winter	Name	Diameter, km	Lon E	Lat N	First seen*	Last seen*	Duration, days†	Depth, m	Form‡
1974	Shartlay C.	8.2	108.25	53.90	03/01	03/01	(1)	850	R
1974	Kotel'nikovskiy C.	2.4	109.14	55.02	03/01	03/01	(1)	850	DR
1975	N. Izgolovye C.	5.4	108.36	53.50	04/28	04/28	(1)	1550	DR
1975	Hovsgol	2.5	100.40	50.97	05/19	05/20	(2)	>200	R
1977	Krestovskiy C.	3.6	106.42	52.55	05/06	05/06	(1)	1050	DR
1985	N. Izgolovye C.	7	108.42	53.52	04/29	05/06	(1)§	1450	OR
1994	N. Izgolovye C.	6	108.38	53.51	04/10	04/16	(7)	1450	OR
1999	Krestovskiy C.	6.4	106.42	52.60	04/18	04/18	(1)	900	R
2000	Slyudyanka	5.6	103.83	51.68	04/27	04/27	(1)	750	R
2000	Severobaykalsk	5.4	109.37	55.35	05/15	05/15	(1)	750	R
2001	Krestovskiy C.	4.4	106.34	52.55	04/21	05/10	(20)	850	DR
2002	M. More North	7.6	107.70	53.46	04/19	04/26	(8)	400	E
2002	M. More South	3.4	107.14	53.24	04/19	04/26	(8)	60	R
2002	Olkhon East	7.6	107.58	53.09	04/26	04/26	(1)	1550	R
2003	Krestovskiy C.	5.2	106.45	52.60	04/03(4)	04/28(4)	26	950	R
2003	Off Krestovskiy C.	4.4	106.81	52.58	04/17(7)	05/08(1)	22	950	R
2003	Hovsgol	2.9	100.42	51.04	06/13	06/13	(1)	>200	R
2004	Krestovskiy C.	6	106.42	52.59	04/21(5)	05/02(3)	12	900	R
2005	Krestovskiy C.	5.6	106.45	52.61	04/15(1)	05/01(3)	17	900	R
2005	M. More North	4.6	107.68	53.46	05/01(3)	05/13(2)	13	370	R,H
2005	Olkhon East	7	108.07	53.29	05/13(5)	05/23(1)	11	1550	OR
2005	Ushkanyi Islands	6.4	108.40	53.83	05/21(4)	05/23(4)	3	650	R
2007	Murino	6	104.40	51.60	04/11(2)	04/24(2)	14	1150	R
2007	Valukan C.	5.4	109.01	54.16	05/11(5)	05/16(1)	6	770	R
2008	Hovsgol	2.2	100.40	50.95	05/17	06/02	17	>200	OR
2008	Turka	4.6	108.04	53.00	04/15(5)	04/22(11)	8	670	R
2008	Krestovskiy C.	5.4	106.39	52.59	04/10(2)	04/23(10)	14	850	R
2008	Slyudyanka	4.4	103.81	51.69	04/16(1)	04/30(3)	15	650	R
2009	N. Izgolovye C.	6.6	108.37	53.53	02/01(5)	05/03(1)	92	1350	R
2009	Slyudyanka	5.2	103.88	51.67	04/04(3)	04/27(2)	24	1050	R
2009	M. More North	3.8	107.70	53.47	04/04(3)	05/04(2)	31	370	R,H
2009	Turka	7.6	108.13	53.05	04/09(2)	04/29(4)	21	500	R,H
2010	Severobaykalsk N	7.6	109.55	55.42	01/31(9)	04/27(2)	87	750	R
2010	Severobaykalsk S	6	109.50	55.34	01/02(0)	05/07(4)	126	750	R
2010	Krestovskiy	4.6	106.35	52.57	04/21(2)	05/11(6)	21	950	R,H
2010	Bugul'deyka	4.8	106.04	52.45	04/21(2)	05/16(1)	26	450	R,H
2011	N. Izgolovye C.	8	108.38	53.53	04/15(2)	05/02(3)	18	1150	R
2011	Olkhon East	8	107.64	53.12	04/13(3)	04/26(5)	14	1350	R
2011	Krestovskiy C.	6.2	106.36	52.57	03/31(4)	04/27(4)	28	850	R
2012	N. Izgolovye C.	6	108.39	53.52	04/06(3)	04/28(1)	23	1450	R
2012	Olkhon East	7.6	107.59	53.09	04/06(11)	04/21(3)	16	1550	R
2012	Krestovskiy C.	6.8	106.37	52.58	04/06(7)	04/21(3)	16	850	R
2013	Krestovskiy C.	4.8	106.36	52.56	04/18(2)	05/04(2)	17	900	R,H
2013	Sv. Nos - Olkhon	7.6	108.04	53.47	04/29(5)	05/13(2)	15	750	R
2013	Shartlay C.	5.4	108.27	53.85	05/07(3)	05/19(2)	13	850	OR
2014	Krestovskiy C.	6	106.47	52.61	04/17(1)	04/22(4)	9	850	DR

TABLE 1. Continued

Winter	Name	Diameter, km	Lon E	Lat N	First seen*	Last seen*	Duration, days†	Depth, m	Form‡
2014	N. Izgolovye C.	7	108.38	53.50	04/01(2)	04/23(3)	23	1450	R
2015	Valukan C.	5.6	109.18	54.13	05/08(1)	05/10(3)	3	650	OR
2015	Hovsgol	6.2	100.45	51.03	05/20	05/29	(10)	>200	OR

C., Cape; N. Izgolovye, Nizhneye Izgolovye; M. More, Maloye More; Sv. Nos, Svyatoy Nos. Rings that already have been identified in previous publications are marked (year is bold).
*Date format is (MM/DD); numbers in brackets—days since last ring-free scene for first ring seen, and days to first ring-free scene after last ring observation.
†Duration is defined as difference between the first observation and the last one. For observations based on non-MODIS imagery, duration is put in brackets, meaning "at least X days)," although ring could have existed longer.
‡R, ring; DR, diamond ring; OR, open ring; H, halo; E, ellipse.
§Exact date of the image taken during the Shuttle STS 51B mission (29 April 1985–06 May 1985) is not known.

in 2009. For the total period of ice presence (128 d, 04 January–11 May), clouds completely masking the region of ice rings were observed on 47 daily MODIS scenes (37%), and for the period of ice ring presence (92 d, 01 February–03 May) clouds were observed on 35 scenes (38%). However, the error in detecting ice ring appearance and disappearance dates for 2009 is zero (cloud-free images are available for the day before and the day after both events). For other rings observed with MODIS images uncertainty in the definition of dates ranges mostly from 0 to 3–4 d.

Ice ring inventory

The size of the ice rings makes them impossible to observe while on the ice or on the shore. In this respect, satellite imagery is a unique tool providing the means for their identification and monitoring on a large-spatial scale. Existing publications ("Circles in thin ice." 2009; Granin 2009; Hsu 2009; "Ring-like structures" 2009; "Strange Circles…" 2009; "Ice rings." 2013; Granin et al. 2015) refer to a total of 13 rings (Table 1) in Lake Baikal based mostly on data from MODIS. To our knowledge, until now no ice rings had been observed outside Lake Baikal.

We have been able to identify 45 ice rings (including the above mentioned) for 1974–2014 for Lake Baikal. We have also analysed numerous large water bodies (lakes and reservoirs) in Eurasia and Northern America and—for the first time—we found four ice rings for Lake Hovsgol (Table 1; Fig. 2). Observation of ice rings for Lake Hovsgol in this respect is very important, as it shows that this phenomenon is not limited to Lake Baikal and that there may be similar physical phenomena leading to ice ring formation elsewhere.

Our inventory shows that ice rings are also observed in regions that are shallower than depth of occurrence of gas hydrates (such as Maloye More in Lake Baikal—300–400 m or Lake Hovsgol—200–250 m) or in regions without known gas emission sources. This rules out gas release as an universal explanation of ice ring formation.

Due to the higher frequency of observations (daily for MODIS vs. every 18 d or 16 d for Landsat) many more rings have been identified after 2002 (start of our MODIS dataset). Moreover, in many cases not all Landsat images are available in the archive. Thus, prior to winter 2002/2003 many ice rings are probably still not identified, and those identified have often been observed only once per winter (but apparently they existed longer). As a result we can not draw any conclusions about the temporal evolution (interannual variability) of frequency of ice ring appearance, and datasets before and after winter 2002/2003 should be treated separately. There are also cases (such as the whole winter 2005/2006) when despite daily image availability from MODIS and the moderate presence of clouds, no ice rings were observed. To assess uncertainties related with ring date detection, for rings with daily availability of MODIS images (Lake Baikal, since winter 2002/2003), we provide number of days between last ring-free scene and first ring observation, as well as number of days between last ring observation and first ring-free scene (for both parameters the median value is 3 d).

Figure 2 shows that ice rings have been observed in all parts of Lake Baikal from its southern to its northern part. The regions with the highest number of ice ring observations are the Krestovskiy (12 observations, with ring center position changing about 4–6 km in various years) and Nizhneye Izgolovye Capes (7 observations, less than 3 km changes in ring position) (see Fig. 2). In 2009, an ice ring near Cape Nizhneye Izgolovye was observed for a very long time (92 d, see Fig. 3). For Lake Hovsgol ice rings are observed near the Dalayn-Modon-Huys Island in the middle of the lake (twice north-east and twice south-east of the island, with distance between the two of about 8 km). The earliest observed ice rings for both lakes date back to 1974 and 1975, so even though recently documented, this is not a recent phenomenon.

The duration of ring observations in our dataset varies from 1 d (due to availability of satellite images and/or cloud cover) to 126 d; the typical duration is 5–10 d. Most frequently ice rings are observed in the second half of April

Table 2. Water structure parameters and ice cover properties for ice rings in 2012–2015.

Year	2012	2013	2014	2015
Region	N. Izgolovye C.	Shartlay C.	N. Izgolovye C.	Hovsgol
CTD date	06 Apr	04 Apr	03–04 Apr	31 Mar
Ice ring first observed	06 Apr	07 May	01 Apr	20 May
Thermocline depth outside of the ring, m	40–45	35–40	40–45	45
Undisturbed isopicnal level, m	45	55	50	30
Undisturbed isopicnal density, kg/m^3	1000.17	1000.225	1000.22	1000.15
Typical water properties in the ring				
T (°C)	1.2–1.4	1.2–1.3	1.2–1.4	1–1.2
Sp. Cond. (μS/cm)	120.5–121.5	119.5–120.5	120.5–121.5	263–265
Difference between water column in the ring and outside				
T (°C), 0–30 m depth	0.6	0.3	0.4	0.1–0.2
T (°C), 80–90 m depth	−1.3	−0.6	−1.1	−0.4
Sp. Cond. (μS/cm), 0–30 m depth	1	1	1	0.4
Sp. Cond. (μS/cm), 80–90 m depth	−1	−1	−1	−1
Surface conditions	0–1 cm snow, ice crust on surface	Transparent crystalline ice, with some patches of snow (0–2 cm)	0–1 cm snow, ice crust on surface	1–1.5 cm snow, up to 4–5 cm at station 7
Ice thickness (cm)—ring center	65–72.5	n.a.	49–65.5	n.a.
Ice thickness (cm)—ring border	68.5–74	105	32–61	87–102
Ice thickness (cm)—outside	80–91	108.5–122	61–73	94–99
Ring radius	3	2.7	3.5	3.1
Baroclinic Rossby radius, km (ring center/outside of the ring)	2.8/3.25	2.34/2.55	2.95/3.04	2.9/3.16

(when snow cover is absent or minimal) before the ice break-up, but they have been observed as early as 31 January and as late as 26 May.

The inventory presented in Table 1 is the most complete existing dataset on the location, size, timing of the appearance and disappearance and other parameters of ice rings in lakes Baikal and Hovsgol. However, it is not an exhaustive list, and further exploration using SPOT, AVHRR and other satellite archives will potentially provide new observations of this phenomenon.

Hydrological structure beneath the ice rings

From ringspotting to ring hunting: field measurements

To get a better understanding of the phenomena responsible for the formation, development and disappearance of ice rings we conducted dedicated field measurements in the regions where ice rings have been observed previously. In the framework of French-Russian-Mongolian cooperation every spring (March–April) since 2010, we conduct yearly field observations of ice cover in the central part of Lake Baikal and since 2014 in Lake Hovsgol. Measures include observations of ice thickness and snow depth (using a hand drill and a ruler), as well as ice structure and roughness. Since 2012 using the YSI CastAway CTD probe operating down to 100 m depth these observations have been complemented by vertical profiles of temperature (accuracy 0.05°C, resolution 0.01°C) and conductivity (accuracy 0.25% ± 5 μS/cm, resolution 1 μS/cm). Since 2014, we have also performed semi-quantitative estimations of currents by defining direction and current strength (weak, moderate, or strong) from CTD cable inclination. The existing dataset contains more than 250 stations located along the tracks of radar altimetry missions (Kouraev et al. 2015), in the regions of known ice ring observations and other regions with interesting features. For the region near the Nizhneye Izgolovye Cape our sampling strategy is to do a transect(s) covering the region of ice ring locations known from the previous years, and for other regions of known ice rings observations to do at least one or several stations when possible. The winter of 2013/2014 was warmer than usual, the ice was thinner and already on 01 April 2014 an ice ring had been clearly identified on the MODIS image prior our field survey. Knowing the exact location of the ring we were thus able to perform 2 d later (03 April 2014–04 April 2014) a dedicated study with high spatial sampling.

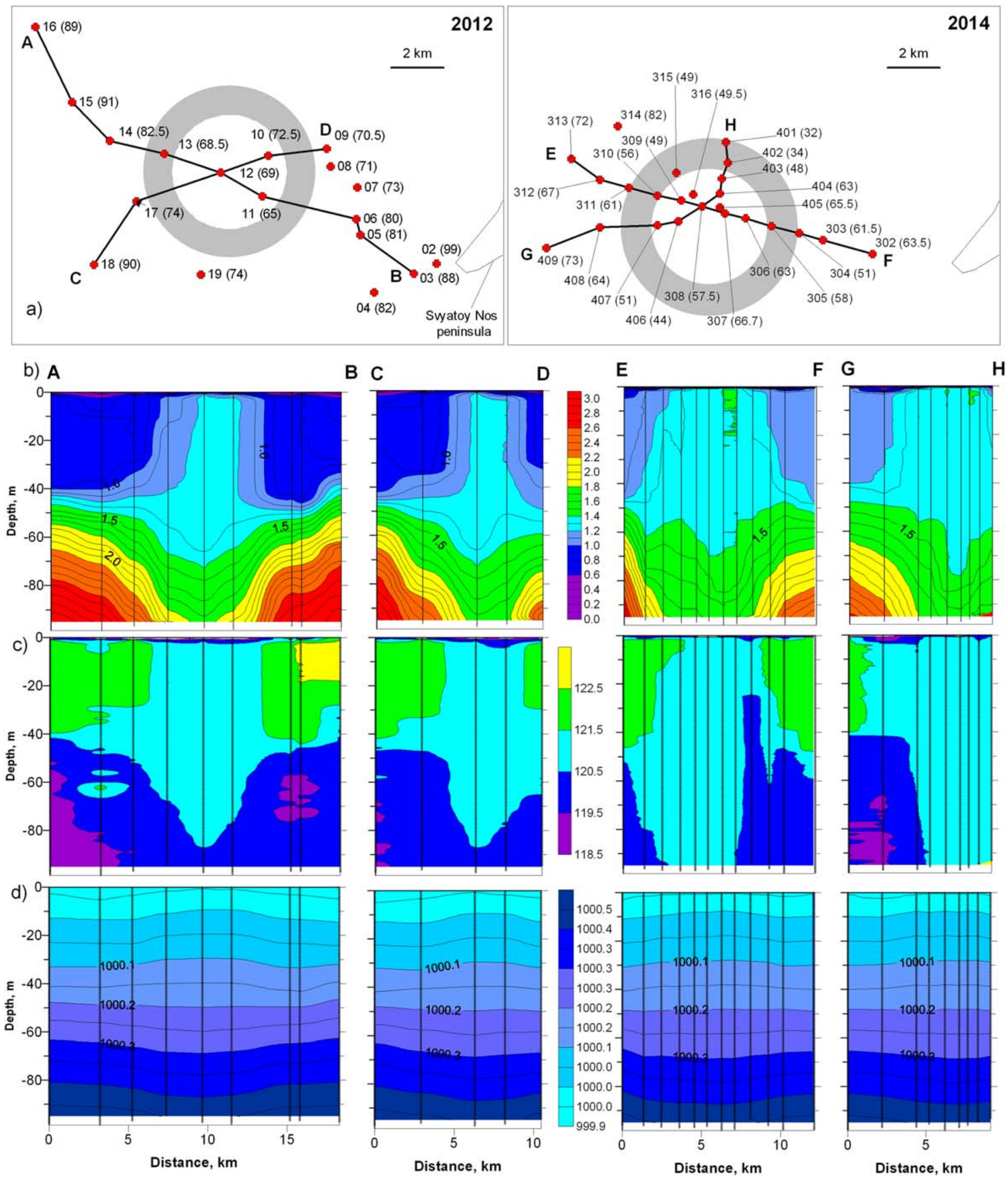

Fig. 4. Hydrographic measurements on 06 April 2012 (transects A–B and C–D, left panel) and on 03 April 2014 and 04 April 2014 (transects E–F and G–H, right panel) in the region of Nizhneye Izgolovye Cape, Lake Baikal. (**a**) maps of stations with their numbers (for 2014 the first number is the day—03 April or 04 April, and the next two numbers—station number), ice thickness (cm, in brackets), transects (black lines) and location of the ice rings (as identified from satellite images on 21 April 2012 and on 24 April 2014) shown in grey. Vertical sections of (**b**) water temperature (°C), (**c**) specific conductance (μSi/cm) and (**d**) density (kg/m^3, TEOS-10) are shown along the transects (vertical lines—station positions). All horizontal distances are to scale.

Water structure and ice surface characteristics associated with ice rings

As a result we have now four datasets of field hydrographic measurements in the regions where ice rings has been observed (Table 2). For the region of the Nizhneye Izgolovye Cape, measures in 2012 and 2014 represent situations when an ice ring was already visible on satellite images. These datasets (Fig. 4) are the most detailed and provide two transects across each of the ring structures. Observations in 2013 (Cape Shartlay, Lake Baikal) and 2015 (Lake Hovsgol) (Fig. 5) are less detailed but still reveal water structure prior (20–35 d) to ice ring appearance.

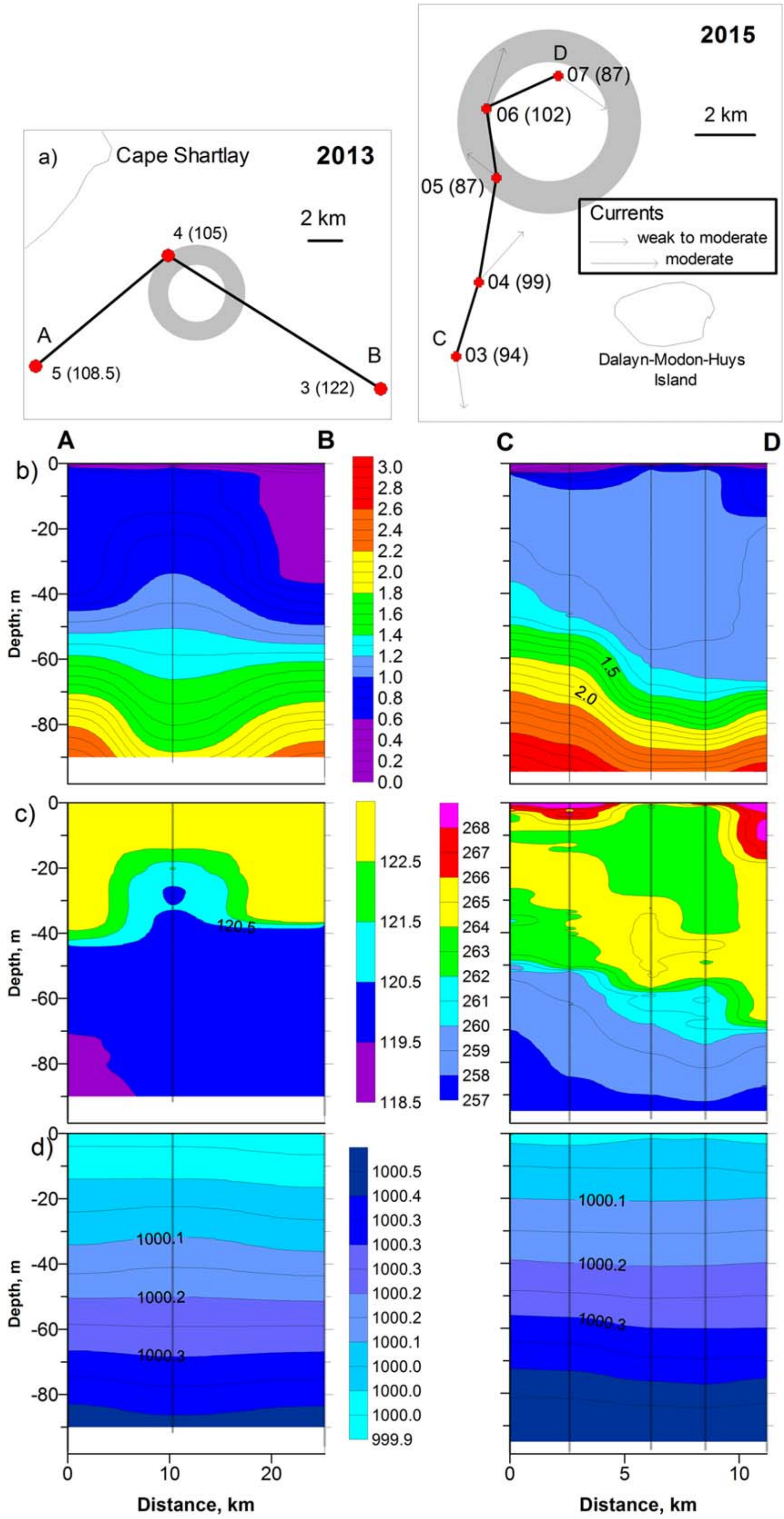

Fig. 5. Same as Fig. 4, but hydrographic measurements on 04 April 2013 (Lake Baikal, Cape Shartlay) and on 31 March 2015 (Lake Hovsgol). For Lake Hovsgol, the map of stations shows also current strength and direction. Ring locations as identified on satellite images for 05 May 2013 (Cape Shartlay) and 21 May 2015 (Lake Hovsgol). The horizontal scales are different for each lake.

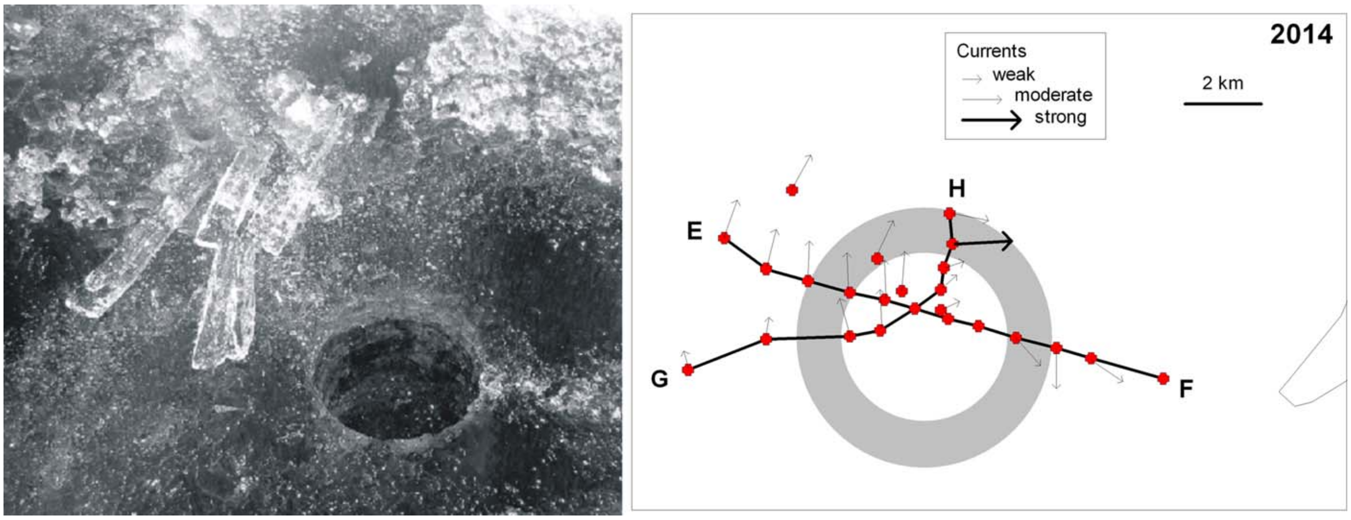

Fig. 6. (**a**) Needle ice crystals from ice bottom (hole diameter—11 cm, crystals size—10–12 cm long, 2–3 cm thick) at station 401, 03 April 2014; (**b**) currents strength and direction for ring near Cape Nizhneye Izgolovye on 03 April 2014–04 April 2014.

All these hydrographical sections (Figs. 4, 5) reveal lens-like structures (double-convex form) in temperature, specific conductance and density fields. These lens-like structures are located at depths (defined as position of undisturbed isopicnal level) of 45–55 m for Lake Baikal and 30 m for Lake Hovsgol with density values of 1000.15–1000.225 kg/m^3 (Table 2) and correspond to the location of ice rings (already existing or yet to be manifested). The core of the lens-like structures has fairly uniform values of temperature (1–1.4°C, which at depth 0–30 m is 0.1–0.6°C warmer and at depths 80–90 m 0.4–1.3°C colder than surrounding water) and specific conductance (119.5–121.5 μS/cm for Lake Baikal and 263–265 μS/cm for Lake Hovsgol). For Lake Hovsgol specific conductance values show a more complicated distribution than for Lake Baikal, indicating potential lateral intrusion of more mineralised (264–266 μS/cm) water at depths 30–50 m, although there are not enough observation points to draw a firm conclusion. Comparison of water structure in the ring and outside shows that upward and downward extension of isolines in the lens-like structure region result in warmer (+0.1–0.6°C) and more mineralised (0.4–1 μS/cm) water in the upper 30 m below the ice cover, and colder (−1.3: −0.4°C) and less mineralised (−1 μS/cm) water at depths 80–90 m.

This three-dimensional spatial structure of temperature, specific conductance and density is typical for oceanic anticyclonic lens-like eddies (Dugan et al. 1982; Armi and Zenk 1984; McWilliams 1985; Kostianoy and Belkin 1989). Eddies in ice-covered lakes have been observed previously. Forrest et al. (2013) observed a cyclonic eddy in the ice-covered Lake Pavilion in British Columbia, Canada (maximal depth 61 m) that has a morphological structure similar to Lake Baikal: a long narrow shape, with three basins separated by narrow sills. Using an autonomous underwater vehicle they observed in February 2008 a cylindrical density anomaly with a radius of about 110 m, affecting depth up to 14 m. The authors state that this radius is smaller than the internal Rossby radius of deformation (200 m) and suggest that it is a result of cyclostrophic balance between centrifugal, Coriolis, and pressure forces. Cyclonic circulation resulted in a double-concave structure (opposite to the one observed in Lakes Baikal and Hovsgol), i.e., a deepening of isolines in the upper layers (colder and more mineralised water compared with surroundings) and rising of isolines in the bottom part (warmer and less mineralised water).

In the northern part of Lake Kilpisjarvi, Finland (mean depth 19.5 m, maximum depth 57 m), in 2013 and 2014 horizontal density anomalies were observed below ice cover with vertically paired cyclonic and anticyclonic rotating circulations (Graves 2015; Kirillin et al. 2015). In 2013, they resulted in a warm anomaly in the central part of the lake, with radius of 350 m and height of 22 m. The authors hypothesise that this anomaly is linked to warmer and denser water flowing down the slopes, converging in the center of the lake and leading to upwelling of warmer water. The internal Rossby radius of deformation was estimated to be much smaller (about 160 m) and authors suggest that the warm anomaly was modified by the earth's rotation and was in either geostrophic or cyclostrophic balance.

Our observations for Lake Baikal in 2012 and 2014 show water structure similar to the one found below the ice ring in 2009 (Granin et al. 2015) for temperature (core values 1–1.25°C). However for the conductivity/salinity this similarity is only partial. Granin et al. (2015) found less mineralised water in the center than at the periphery of the ring (this is similar to our observations), but from the depth of 40 m downward their observations show no increase of salinity. This observation apparently led the authors to conclude that this anomalous structure results from upwelling of deep

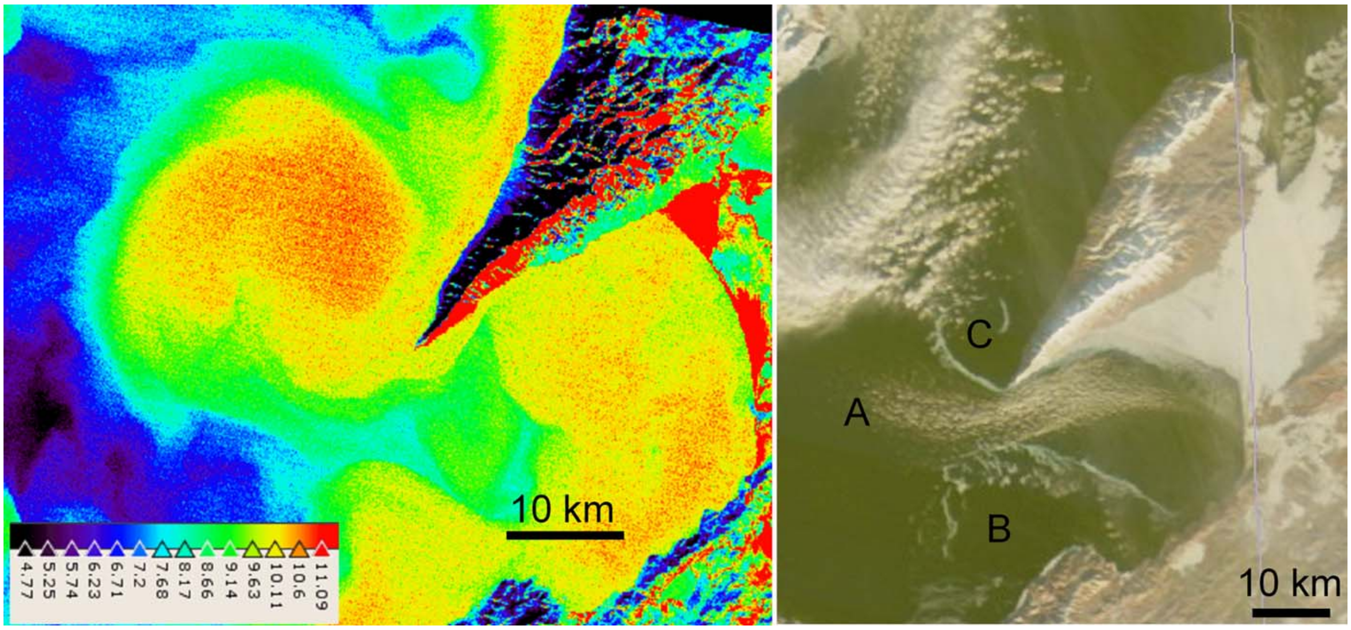

Fig. 7. Water dynamics in the region of the Nizhneye Izgolovye Cape. Left: Landsat thermal (°C) image of water surface temperature from 26 September 2002, showing formation of an anticyclonic warm eddy. Right: MODIS image from 31 December 2011 showing strong wind blowing out of Barguzin Bay (A, observed by a field of clouds directed to the lake), generates a dipole structure in lake waters revealed as two lines of drifting ice patches—a cyclone moving south-west (B) and an anticyclone (C).

waters (with lower mineralisation and higher temperature) through the thermocline, and is potentially related to the presence of gas hydrates in bottom sediments. However, our observations of specific conductance for the four datasets (Figs. 4, 5) show no such feature; water in the eddy center always has higher mineralisation than water at lower depth and we observe upward and downward extension of water with specific conductance typical for the eddy core (same as for water temperature). A well-developed eddy (such as the one in 2014, Fig. 4, right panel) may show homogeneous mineralisation in the upper 100 m in the central part of the eddy. This is not water coming from deeper layers, but less mineralised water pushed up- and downward from the undisturbed isopicnal layer. This, and the fact that rings were observed over relatively small depths and in regions without known gas sources (see "Ice ring detection and inventory" section) contradict gas-related hypotheses of ice ring formation discussed in the Introduction.

Our observations of water structure for different transects along the ring regions in 2012 and 2014 has very similar pattern, showing that the observed lens-like eddies have an isolated circular form and radial symmetry. The observed anomalous water structure both before (2013 and 2015) and during (2012 and 2014) ring appearance shows that such lens-like structures are directly associated with ice rings, that they exist before and continue to exist during ice ring appearance and development, and that an ice ring is a surface manifestation of dynamical processes going on below the ice cover. This contradicts the hypothesis of ice ring formation related to ice structure heterogeneities (Bordonskiy and Krylov 2014).

Depending on ice formation in the beginning of winter, its drifting, deformation and consequent growth, ice thickness is not spatially homogeneous and ice melting related to dynamical processes going below ice cover will result in different rate of ice melting and thus different ice thickness. This is also illustrated by different manifestations of ice rings (such as open rings, diamond rings etc., see Table 1) related to different types of ice fields presented in the regions of ice ring formation. Measures of ice thickness in the region of the ice ring in Southern Baikal in 2009 (Granin 2009; Granin et al. 2015) show increased ice thickness in the ring center (74 cm) and outside of the ring (70 cm), and much thinner ice (43 cm) in the ring itself. Our datasets for 2013 and 2015 (Fig. 5) representing situations 20–35 d before ice ring manifestation are too coarse to draw definite conclusions on ice thickness spatial distribution inside and outside of ice rings. However our observations (Fig. 4) for 2012 (when ice ring has been faintly seen) and especially 2014 (when an ice ring was well manifested) clearly show the spatial distribution of ice thickness.

For all four datasets ice was black and crystalline (with some ice crust and/or snow on the surface, see Table 2) and without impurities. No water was observed on ice and no gas bubbles were presented in the upper water column. In 2012, the ice was thicker (80–91 cm) outside the ring, while in the ring and in its center it was already thinner (65–74 cm). In 2014, the ice was thick outside (61–73 cm) and less thick in the center of the ring (49–65 cm), while in the ring itself it was much thinner (32–61 cm), especially at the two stations of the northern part of the transect G-H (32 cm for station 401 and 34 cm for station 402). At these two stations we observed large needle ice crystals (up to 12 cm long and 2–3 cm thick, Fig. 6a) at the bottom of the ice. Neighbouring stations 315 and 316 presented no needle ice on the bottom, but ice was water-laden from a depth of 30–35 cm. This northern part of the ring represents an advanced stage of ice melting and metamorphism that will later on be typical for other regions of the ring. Further ice ring development will lead to thinner ice in the ring, metamorphism, fracturing, the appearance of leads and finally break-up of the ice (Figs. 1i, 3).

Currents in 2014 (Fig. 6b) and 2015 (Fig. 5a) confirm typical anticyclonic (clockwise) direction of eddy rotation, with currents oriented approximately 30–45° to the left of the ring direction. This is consistent with geostrophic flow subject to frictional stress although the nature and mechanisms of the associated frictional stress remain to be identified. Another issue could be influence of larger scale currents field. Currents in the center of the ring in 2014 are absent or weak, the strongest velocity is observed for northern part of the ring (especially for station 402—one of the two stations with minimal ice thickness). This indicates that current speed (and thus intense heat exchange between ice and water), rather than presence of warmer water in the ring center, is the main driver related to ice melting and metamorphism.

The diameter of the ice rings is comparable to the Rossby baroclinic internal radius of deformation for a two-layered fluid, calculated as:

$$L_{\mathrm{i}} = \frac{\sqrt{\frac{g^{*}\Delta\rho}{\rho_{\mathrm{a}}} * \frac{h_1 {}^{*} h_2}{h_1 + h_2}}}{f},$$

where g is gravity acceleration, $\Delta\rho$ is the density gradient between the two layers, ρ_0 is the reference water density of 1000 kg/m^3), h_1 and h_2 are thicknesses of the upper and lower layers, and f is the Coriolis acceleration (Kirillin et al. 2012). The Rossby radius of deformation calculated using water profiles outside and inside the rings (Table 2) is 2.8–3.25 km. The ice ring radius varies between 2.7 km and 3.5 km.

Discussions and conclusion

The most complete existing ice ring inventory made from analysis of satellite images and photography contains 45 ice rings for Lake Baikal and—for the first time—four ice rings for Lake Hovsgol. Although recently documented, the ice rings are not a recent phenomenon, as they have been observed as early as 1974–1975.

Ice rings are a surface manifestation of water dynamics under ice cover, namely lens-like eddies. Our field observations of water structure for four ice rings in lakes Baikal and Hovsgol for 2012–2015 show clear evidence of submerged anticyclonic (at least for these locations) double-convex warm lens-like eddies beneath the ice. They have an isolated circular form and radial symmetry. Their radius is comparable to the baroclinic Rossby radius of deformation and their position coincides with the location of ice rings. They exist before and continue to exist during ice ring appearance and development. Eddies below ice rings are characterised by weak or moderate currents in the central part, and strong currents in the ring region oriented at about 30–45° to the left of the eddy boundary. Increased heat exchange between ice and water at the eddy boundary lead to lower ice thickness compared with the center of ice ring or regions outside the ice ring. These regions of thinner and thus darker ice are seen on satellite images as ice rings.

Ice rings are a surface manifestation of these lens-like eddies, however the proposed mechanism of ice ring formation raises a new set of questions related to location and stationarity of eddies, their lifetime, timing and generation mechanisms.

Concerning the **location** of the ice rings, we can observe that they are mostly associated with regions of strong bathymetry gradients and are often located at the heads of underwater depressions (see Fig. 2). A combination of local conditions: steep bathymetry; coastline shape, wind pattern and river inflow may favour eddy formation and localise the eddy in winter. It is not clear if eddies are quasi-stationary, travel slowly at the same depth after generation, or upwell to the surface from deeper layers during their evolution. Lens-like eddies can be slow moving or quasi-stationary depending on the larger scale circulation. Lens-like eddies in Lake Baikal are too small to self-propagate through the beta-effect. Depending on the initial ice cover structure, quasi-stationary lenses could produce classical "ring" structures in the ice cover whereas advecting lenses would produce dark patches or no effect at all depending on the speed of the advection and depth of the lens.

The **lifetime** of lens-like eddies in Lake Baikal may reach several months, which is a realistic estimate based on the time of observation of ice rings (see Table 1) and the fact that similar features are long-lived in the other lakes or oceans. This phenomenon is consistent with weaker turbulent mixing at intermediate depths compared with the ocean or lake surface.

The **timing** of eddy formation is the most elusive parameter to estimate with field campaigns as it requires long-term monitoring with high spatial and temporal resolution. We can suggest two possibilities. The first is that eddies form under the ice when ice cover is stable. In winter, with synoptic changes of atmospheric pressure, mechanical energy is continuously transferred from the atmosphere through the ice to the water column. As in the ice-free period, seiches, internal waves and surges are generated, and their amplitude is comparable to that observed in the summer and autumn (Pomytkin 1960).

Another possibility is that eddies are formed at some time between the autumnal vertical overturning and ice formation. After the vertical overturning, more colder and lighter water is present at the surface and the eddy descends to its level of neutral buoyancy. Surface layer eddies and ice rings are seldom observed at the beginning of winter (one exception is noted above: the ice ring near the Nizhneye Izgolovye Cape in 2009, see Fig. 3). During the winter, and especially in spring, when the upper water layer starts to get warmer (and thus denser), the eddy moves upward, eventually reaching the ice cover and starting to melt the ice and form an ice ring.

As for **generation** mechanisms, the ice ring inventory and our in situ measurements of water structure rule out gas-related hypotheses as a universal explanation of eddy formation. Heat release from bottom sediments should also play a minor role for deep lakes Baikal and Hovsgol. There are several candidates for potential generation mechanisms: instability of a coastal current, wind forcing before ice formation, seiches induced by the influence of atmospheric pressure on the ice sheet, or river inflow and interaction of a coastal current with the coastline, for example near the Nizhneye Izgolovye Cape. In this region, where we found ice rings and lens-like eddies in 2012 and 2014 (see Fig. 4), it is not uncommon to observe clockwise water currents (anticyclonic eddies) in the autumn or during ice formation (Fig. 7).

There are still several open questions, such as the source and amount of forcing needed to form the eddy and sustain it during winter, the amount of vertical heat flux and associated boundary currents needed to melt the ice, that are outside the scope of this article. This is a task for numerical modelling and further field investigations.

Detection of lens-like eddies requires dedicated and well-timed field campaigns with very fine spatial resolution between CTD stations of the order of hundreds of meters. In the case of lakes Baikal and Hovsgol, the detection and study of eddies is facilitated by the presence of stable ice cover that makes it possible to observe their manifestation as giant circular ice rings.

The discussion is still going on and we welcome new ideas. Further studies and monitoring of ice rings and lens-like eddies based on satellite observations, in situ measurements and numerical modelling will hopefully provide new insights for a better understanding of this intriguing phenomenon.

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