RESEARCH ARTICLE

Cyclonic circulation and upwelling in Lake Baikal

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Abstract We investigated upwelling events in the pelagic area of Lake Baikal that developed during summer stratification (July–November) using a combination of in situ and satellite observations. These upwellings appear in the centres of local cyclonic macrovortices with compensatory downwelling located on their periphery in coastal areas. The average duration of upwelling events was 5 weeks, with an observed maximum of 16 weeks. The most stable upwellings in Southern Baikal and over the Academician Ridge covered areas of up to 4,400 km^2 (59 % of Southern Baikal's surface) and 1,550 km^2, respectively. Water was ascending in the upwelling zones at velocities of 1×10^{-4} to 1.2×10^{-2} cm s^{-1}. Temperature differences of 1–4 °C and 2–13 °C were observed between the downwelling and upwelling zones in the epilimnion and metalimnion, respectively. On the surface of the lake, water temperature can drop 4–7 °C for water ascending from depths of 10–75 m, but the observed thickness of the layer within which water was ascending reached a depth of 280 m in August–September and 380 m in October; i.e. the ascending water included the entire upper layer (0–300 m). Geostrophic currents reached up to 24–38 cm s^{-1} on the boundary between up- and downwelling zones (usually 5–7 km offshore), but did not exceed 6–10 cm s^{-1} in the centres of upwelling zones.

Comparison with other large lakes of the world is carried. This study is important for understanding the upwelling process that develops in Lake Baikal during summer stratification and can influence the heterogeneity of nutrients and primary production.

Introduction

Physical processes such as upwelling can strongly modify physical and chemical conditions (e.g., the distribution of water temperature, salinity, density, chemical water composition and water pollution) and thus influence biological processes (e.g., life cycles of bacteria and phytoplankton) in lake ecosystems. It is known that upwellings can develop in coastal and pelagic areas. Coastal upwellings have been studied extensively in lakes Michigan, Ladoga, Onega, and Tanganyika (references in Bell and Eadie 1983; Boyarinov and Petrov 1991; Plattner et al. 2006; Corman et al. 2010, respectively).

Upwellings in the pelagic areas of lakes have been less investigated. Csanady (1977) described a simple conceptual model that explained the generation of upwelling events in the pelagic part of a lake and compared the modelling results with observations in Lake Ontario. Beletsky and Schwab (2001) achieved a reliable description of the annual cycle of circulation and thermal structure of Lake Michigan using an adapted version of the Princeton Ocean Model. Upwellings in the centre of the cyclonic circulation in Lake Issyk-Kul were studied using in situ temperature data, dissolved oxygen concentrations and estimates of velocities of geostrophic currents and

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ascending water masses (Romanovskiy and Shabunin 1981). The authors found that upwellings in the pelagic area of the lake lead to an increase in dissolved oxygen in the surface layer (Romanovskiy and Shabunin 1981, 2002) that is inversely distributed during summer stratification (Karmanchuk 2002). Later, in a study of vertical water exchange using temperature, conductivity, pressure, dissolved oxygen and light transmission data, Kipfer and Peeters (2002) and Peeters et al. (2003) described upwelling in the upper 200-m layer of the water in the central part of Lake Issyk-Kul. Corman et al. (2010) analysed upwellings in Lake Tanganyika induced by longitudinal winds and their influence on changes in water temperature and concentrations of nutrients and phytoplankton. The results obtained by Corman with his co-authors showed a significant increase in nutrients, chlorophyll *a* concentrations and phytoplankton biomass due to upwellings in the pelagic area of the lake.

Lake Baikal is one of the largest lakes in the world and is located in the Baikal Rift Zone in the southern part of East Siberia. According to recent reanalysis (Sherstyankin et al. 2006), the surface area of the lake is $31,722 \text{ km}^2$ and its volume is $23,615 \text{ km}^3$, which corresponds to $\sim 20 \%$ of the world's unfrozen freshwater reserve. The Buguldeika and Academician Ridges divide Lake Baikal into three basins: Southern Baikal (mean depth 853 m, maximum depth 1,461 m), Central Baikal (857, 1,642 m) and Northern Baikal (598, 904 m).

Water exchange processes in Lake Baikal during summer stratification have been described, but require further detailed analysis. As a result of increased stability of the metalimnion below the surface mixed layer (Schmid et al. 2007), vertical mixing decreases during the summer period. Major factors influencing vertical exchange processes during summer stratification can include vertical movements of water masses within cyclonic currents driven by the winds (Shimaraev and Ladeyshchikov 1986) as well as horizontal heterogeneity of water temperature and density. At the beginning of summer stratification (late June–early July), the cyclonic currents are weak and unstable. They intensify gradually due to wind strengthening and inhomogeneous warming of the surface water layer resulting in the formation of a stable system of cyclonic currents in late August–early September (Krotova 1970; Verbolov 1996). This is characterised by the presence of macrovortices in each basin of the lake. The resulting large cyclonic macrovortices create physical forces driving the ascension of water (upwelling) in their centres and downwelling in the coastal and convergence areas (Csanady 1977).

Vereshchagin (1927) was the first to characterise coastal upwelling in Lake Baikal. He measured water temperatures (*T*) and dissolved oxygen concentrations in the coastal surface water that corresponded to values observed in the

pelagic areas at depths of 50–200 m. Long-term maps of average surface water temperatures (Verbolov et al. 1965) showed regions with low surface water temperature T_{surf} in the centres of cyclonic vortices in the pelagic areas. Later, it was theoretically predicted that cyclonic circulation causes upwelling in the centres of the lake basins (Shimaraev and Ladeyshchikov 1986; Shimaraev et al. 1994). Upwellings were also detected in the coastal areas of Northern Baikal according to NOAA/AVHRR satellite images (Semovski et al. 2001). Exploring the influence of air mass circulation above the northern hemisphere on the seasonality of water temperature in Lake Baikal, Katz et al. (2011) supposed that jet stream variability is one factor affecting local water dynamics in the lake, in particular, coastal upwelling. Shimaraev et al. (2012) undertook the first quantitative estimates (maximum changes in *T*, duration, depths of upwelling development, and vertical velocities) of coastal upwellings in Southern Baikal.

An effect of upwelling on the plankton distribution in Lake Baikal was reported in some studies. Kozhov (1962) observed strong upwelling in Maloye More Strait and the adjoining areas of the lake after a severe NW storm on 4–9 September 1951. The surface water temperature decreased from 12–13 °C to 7–7.5 °C in Maloye More Strait and to 8–9 °C near the eastern shore of Olkhon Island. Plankton "was very sparse, and relatively uniformly distributed in the upper 100 m" after this event. In August 1963 (Kozhov et al. 1970), strong NW winds near Bolshye Koty (Southern Baikal) led to upwelling of 5–6 °C water from the depths to the surface. Zooplankton biomass decreased to 1.2 g m^{-2} compared to mean annual values of $40–50 \text{ g m}^{-2}$. Afanaseva (1977) also showed that vertical movements of water in an upwelling zone can transport nauplii of the copepod *Epishura baikalensis* from deep water layers to the surface water. Based on phytoplankton measurements and SeaWiFS satellite observations in 2001–2003, Heim et al. (2005) concluded that reduced chlorophyll *a* concentrations along the eastern shore of Northern Baikal were associated with upwelling events. Notably, chlorophyll *a* concentrations can increase after upwelling relaxation, as was noted by Verbolov et al. (1992) during complex hydrophysical studies at a site near Cape Elokhin (the western shore of Northern Baikal) in August 1988. Upwelling is one of the processes that leads to the vertical advection of water masses, nutrients, etc. Peeters et al. (2000) used inverse modelling to demonstrate that the annual velocities and water volumes seen in upwelling by common vertical advection transport in certain basins of Lake Baikal are consistent with expectations. At a depth of 400 m, the velocities are $\sim 21 \text{ m year}^{-1}$ in Southern Baikal, 9 m year^{-1} in Central Baikal, and 29 m year^{-1} in Northern Baikal, where the flows are 110, 70 and $290 \text{ km}^3 \text{ year}^{-1}$, respectively. Fluxes of nitrogen, phosphorus and silica from

the deep water to the surface estimated separately in Southern and Northern Baikal are N = −93 and −34 mmol m^{-2} year^{-1}, P = −5 and −3 mmol m^{-2} year^{-1} and SiO$_2$ = −630 and −460 mmol m^{-2} year^{-1}, respectively (Müller et al. 2005). Apparently, upwelling developing in the upper water layer supplies nutrients to the surface from deep-water layers near the bottom.

The aim of this work was to determine quantitative characteristics of upwelling (locations, duration, horizontal and vertical dimensions, temperature changes and area) developing in the pelagic area of Lake Baikal during summer stratification using annual in situ measurements and remote sensing data.

Materials and methods

We used data obtained on 16–24 August, 2002, 13–23 August, 2004, 23 September–7 October, 2009, 25–29 October, 2010, and 9–19 September, 2012, all periods containing upwelling events (Table 1). Measurements were obtained on transects of the Marituy–Solzan River, Listvyanka–Tankhoy and Cape Kadilny–Mishikha River during all expeditions; additional measurements were made from the Malye Vorota Strait–Boldakova River and Cape Ukhan–Cape Tonky in 2009; Cape Krasny Yar–Kharauz Channel in 2010; and Cape Tolsty–Snezhnaya River and Peschanaya Bay–Istok in 2012 (Fig. 1). Vertical profiles of T (absolute ±0.002 °C and relative 0.0003 °C accuracy) were measured with a Sea-Bird SBE-25 probe.

In addition, weekly observations of T obtained along a transect of Listvyanka–Tankhoy (Fig. 1) in August–

October of 1971–1992 were included in the analysis. Measurements were carried out using reversing thermometers (accuracy ±0.02 °C) at depths of 0, 5, 10, 15, 25, 50, 75, 100, 150, 200, 250, 300 m and then every 100 m to the local lake bottom.

Furthermore, daily NOAA/AVHRR satellite data were analysed for 25 May–16 November 1996–1999 and for 15 July–15 October 2000–2012 to determine the location, length, width and area of each upwelling zone. According to the method described by Mogilev et al. (2001), images were processed with the XV-HRPT program (Zakharov et al. 1995) and radiometric correction was done using calibration factors derived by the NOAA–NASA AVHRR Pathfinder Calibration Working Group (Kidwell 1991). The average daily water surface temperature T_{surf} was calculated using available images for cloudless areas based on the infrared spectral bands 10.5–11.5 and 11.5–12.5 μm. Water surface temperatures for areas covered with clouds were interpolated from cloudless areas. When the entire lake was covered with clouds, the water surface temperature was interpolated between cloudless days. Altogether, 5,479 images were processed, including 2,628 (48 %) with cloudless or partially cloudy (<50 % of the lake area) skies over Lake Baikal, and 2,851 (52 %) with cloudy skies.

The velocities of geostrophic currents were calculated with a dynamic height method (Ayers 1956; Krotova 1970). An equation of state (Chen and Millero 1986) was used for the calculation of specific volume and dynamic heights. The reference level for August–September was 250 m and for October it was 300 m (Shimaraev and Troitskaya, 2005). The average error in the velocity calculation was 0.90 cm s^{-1} in August–September and

Table 1 Information on the in situ data (dates of expedition, name of transects, number of stations and date of measurements at transects)

Transect	Number of stations (date of measurements)					
	1971–1992	16–24 August 2002	13–23 August 2004	23 September–7 October 2009	25–29 October 2010	9–19 September 2012
Southern Baikal						
Marituy–Solzan River		10 (22–23 Aug)	9 (14 Aug)	18 (23–24 Sept, 6–7 Oct)	8 (26 Oct)	22 (11, 15 Sept)
Cape Tolsty–Snezhnaya River						22 (11–12, 15–16 Sept)
Listvyanka–Tankhoy	235 (Aug–Oct)	9 (23–24 Aug)	9 (15 Aug)	18 (24–25 Sept, 5–6 Oct)	8 (25–26 Oct)	22 (12–13, 16–17 Sept)
Cape Kadilny–Mishikha River				18 (25–26 Sept, 5 Oct)	7 (26–27 Oct)	22 (13, 17–18 Sept)
Peschanaya Bay–Istok						22 (14, 18 Sept)
Central Baikal						
Malye Vorota Strait–Boldakova River				10 (27–28 Sept)		
Cape Ukhan–Cape Tonky				9 (28 Sept)		
Total number of stations	235	19	18	73	23	110

Fig. 1 Scheme of measurement stations on transects in Lake Baikal (*dotted line*). The profiles were taken in 1971–1992 at 3 and 7 km from both shores, and in the centre (central station—CS), in 2002, 2004, 2009, 2010—at 1, 3, 5, and 7 km from the shores and at CS, in 2012—the same stations as in the 2000-s and, additionally, at 10 km offshore
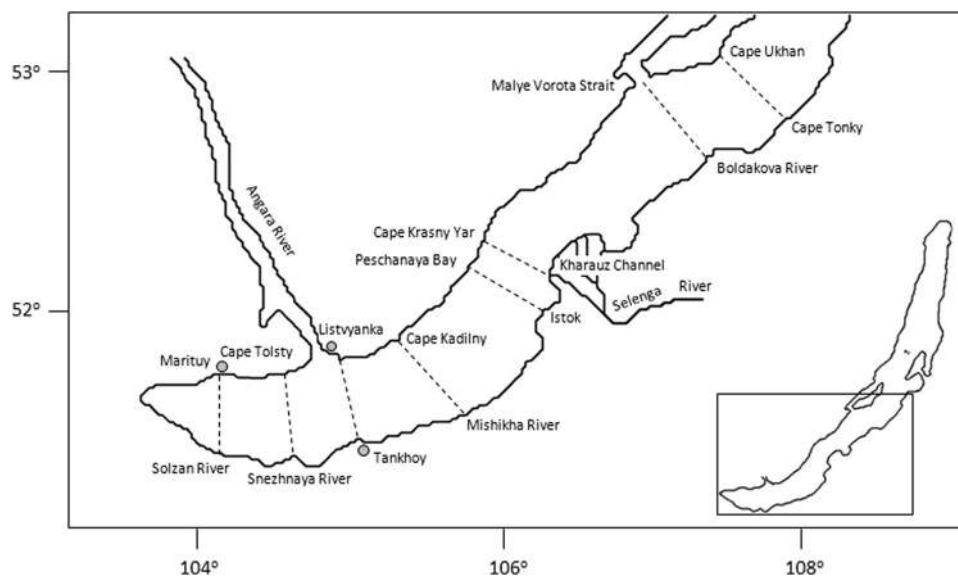
1.15 cm s^{-1} in October, the relative error was 7 % for high and 140 % for low velocities (Krotova [1970]; Shimaraev and Troitskaya [2005]).

In 2009 and 2012, during our field work in Southern Baikal, we carried out repeated water temperature measurements. The time interval between measurements in September–October 2009 was 13 days for the transverse transect of the Marituy–Solzan River, 11 days for Listvyanka–Tankhoy and 10 days for Cape Kadilny–Mishikha River. In September 2012, the interval was 4 days for all measured transects (Marituy–Solzan River, Cape Tolsty–Snezhnaya River, Listvyanka–Tankhoy, Cape Kadilny–Mishikha River, and Peschanaya Bay–Istok). Analysis of daily NOAA/AVHRR satellite data for these years showed that a zone of upwelling in the pelagic area of Southern Baikal was present throughout the entire period of our field work. Evaluation of differences in surface water temperature between upwelling and downwelling zones based on satellite data showed they varied during the field work within 2.95–3.4 °C in 2009 and 4.6–5.1 °C in 2012 (Fig. 2). Moreover, the wind speed and direction above Southern Baikal observed during these periods of field work (prevailing SES winds with average speeds of 3.6 and 2.5 m s^{-1} in September–October 2009 and September 2012, respectively) maintained a cyclonic circulation in the lake. Since the zones of upwelling in the pelagic area and downwelling zones near the shores were maintained, this allowed us to estimate the vertical velocity W using a simple method. It is based on the fact that having repeated temperature measurements at the same depth on a transect allowed us to calculate W from $W = \Delta z / \Delta \tau$, where $\Delta \tau$ is the time interval between individual observations and Δz is the change in depth of specific isotherms during $\Delta \tau$ (Boyarinov and Petrov [1991]).
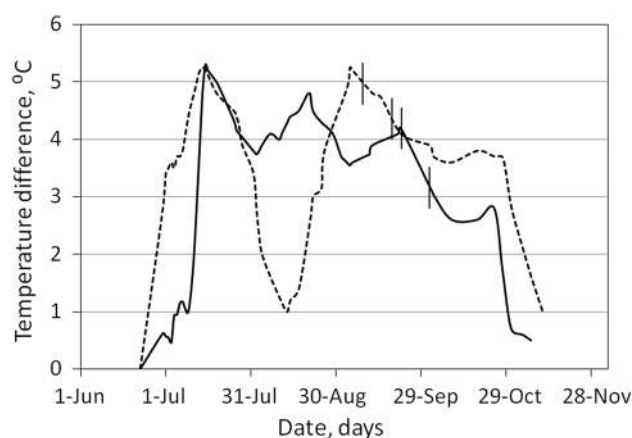

Fig. 2 Differences in surface water temperature between upwelling and downwelling zones in July–October 2009 (*solid line*) and 2012 (*dashed line*). The *vertical solid lines* show dates of field work in these years

Results

Remote sensing data

Seventy upwelling events were identified in the pelagic area of Lake Baikal using lake surface temperature maps from 1996–1999, 2002, 2004, 2009, 2010 and 2012 compiled from NOAA/AVHRR satellite data (Fig. 3; Table 2). The locations of upwelling zones generally coincided with the centres of cyclonic macrovortices (Fig. 3).

The individual pelagic upwelling events lasted for 38 ± 23 days. Figure 3b–f shows an example of T_{surf} distribution and its evolution during one of the longest upwellings in Southern Baikal. Two locations were distinguished by having the longest upwelling events.
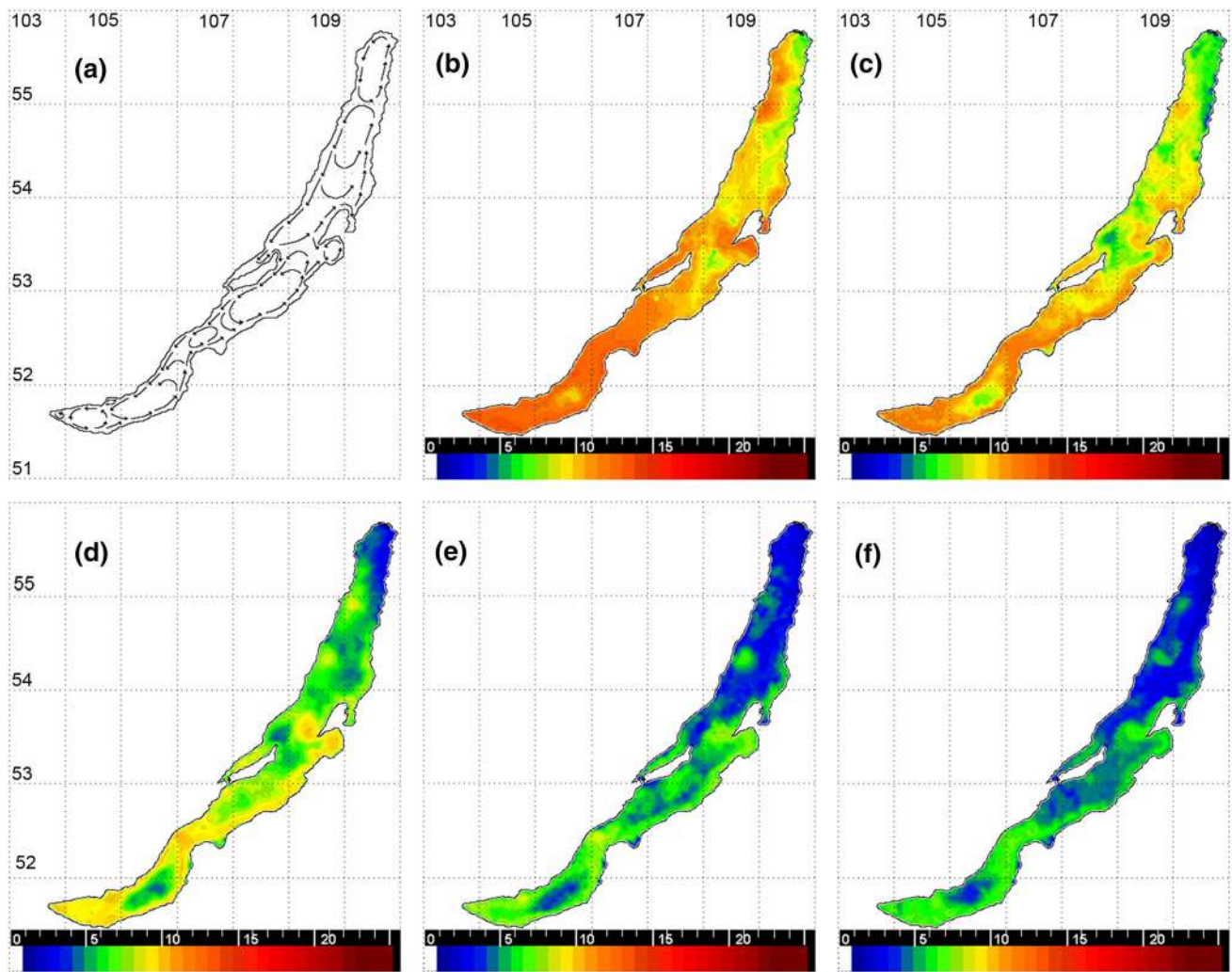
Fig. 3 Development of upwellings in the pelagic area of Lake Baikal within the field of cyclonic currents: **a** a scheme of summary currents in Lake Baikal (Verbolov 1996); **b–f** changes of surface water temperature in Lake Baikal derived from NOAA/AVHRR satellite data (Remote sensing group ISTP SB RAS, http://ckm.iszf.irk.ru) during the upwelling development in the north-eastern part of Southern Baikal in 1999: **b** 26 August, **c** 16 September, **d** 1 October, **e** 13 October, and **f** 24 October

Table 2 Average dimensions of pelagic upwellings in Lake Baikal derived from NOAA/AVHRR satellite data in May–November 1996–1999 and July–October 2002, 2004, 2009, 2010, 2012 (maximum observed values are given in parentheses)

Dimension	Number of events	Length (km)	Width (km)	Area (km²)	Duration (days)
Southern Baikal	28	46 (120)	19 (38)	1,072	(4,400)
41 (111)					
Central Baikal	24	44 (84)	23 (40)	873	(2,160)
43 (72)					
Northern Baikal	18	46 (71)	31 (47)	1,019	(1,550)
29 (52)					
Entire lake	70	45	24	985	38

One of them was in the north-eastern part of Southern Baikal (up to 16 weeks) and the other was located over the Academician Ridge (up to 10 weeks). As a rule, upwellings with maximum duration started to develop in those areas in early August and persisted until October–early November, when the summer stratification is destroyed by cooling–induced convective mixing.

The average length of upwelling zones in all basins of the lake was similar and varied from 44 to 46 km (Table 2). The maximum length differed by up to 1.7 fold and decreased in size from Southern to Northern Baikal (Table 2). The average and maximum widths decreased from Northern to Southern Baikal and depended, apparently, on the width of the basin in which the upwelling developed (Table 2).

The average area of the upwelling zones (Table 2) covered, in the mean, 14, 8, and 7 % of Southern, Central and Northern Baikal, respectively; in extreme cases, the areas reached 59, 20, and 11 % of the total, respectively. The largest areas with the most stable upwelling zones were 4,400 km^2 in Southern Baikal and 1,500 km^2 over the Academician Ridge. The spatial dimensions of upwelling zones (Table 2) show that their form strongly depends on the basin's morphometry. The upwelling zone is oval in the narrow Southern Baikal but almost round in Northern Baikal. The ratio of length to width is 2.4, 1.9 and 1.5 in Southern, Central and Northern Baikal, respectively.

During the development of upwelling, the water surface temperature decreased from 5–18 °C before the onset of upwelling to 4–7 °C in 66 % of the upwelling events. These values corresponded to water temperatures at depths of 10–75 m (Table 7.3.2 in Shimaraev et al. 1994). The remaining upwelling events were characterised by a smaller T_{surf} decrease (from 11–17 °C to 7–10 °C), corresponding to temperatures at depths of 5–25 m.

In situ data

The in situ data (2002–2012) indicated 11 upwelling events on 24 transects: one in August 2002, two in August 2004, four in September–October 2009, two in October 2010 and two in September 2012 (Figs. 4, 5 show examples of temperature transects and distributions of surface water temperature). An upwelling zone was observed in the western part of Southern Baikal four times (data from Marituy–Solzan River and Cape Tolsty–Snezhnaya River), another was detected in the north-eastern part of Southern Baikal (Listvyanka–Tankhoy, Kadilny–Mishikha and Peschanaya Bay–Istok) five times, and two were found in Central Baikal in the Malye Vorota Strait–Boldakova River and in Cape Ukhan–Cape Tonky.

The upper boundary of the metalimnion in the upwelling zone was recorded in the near-surface layer (1–4 m) in the August 2004, October 2009 and September 2012 events, but it was deeper (6–30 m) in August 2002, September 2009, and October 2010. The maximum horizontal differences in water temperature between zones of upwelling and downwelling in the near–surface layer reached 2.8 °C (1–2 m) in August, 3.5 °C (2 m) in September and 3 °C (2 m) in October. The corresponding maxima in the metalimnion were 13.0 °C (15 m), 9.1 °C (22 m) and 4.7 °C (38 m), respectively.

To estimate the thickness of an upwelling zone layer, we determined the depth where the difference between the vertical and average water temperature was equal to or less than 0.02 °C (more than an order of magnitude greater than the absolute accuracy of water temperature measurement

with a CTD-probe). The water ascended 280 m in August–September and from 380 m in October. Downwelling water near the steep western shore descended to 260–315 m in August to September, and reached 500 m in October. The depth of the downwelling zone was 200–250 m near the less steep eastern shore.

In-situ data collected during 1971–1992 on the Listvyanka–Tankhoy transect showed the development of upwelling in Southern Baikal in October–November (Fig. 6). This is a regular phenomenon due to intensification of cyclonic currents forced by strong winds at this time of the year (Verbolov et al. 1965; Verbolov 1996). Mean annual wind speeds in October–November were 5–6 m s^{-1}. Wind speeds >8 m s^{-1} occurred 20 % of the time, while speeds >15 m s^{-1} occurred 5 % of the time (Verbolov et al. 1965). This leads to high velocity cyclonic currents that can reach 60–70 cm s^{-1} (Verbolov 1996).

Calculated geostrophic currents and vertical velocities

The calculation of the geostrophic currents showed that their direction mostly coincided with that of the cyclonic water circulation. They were from NE to SW along the western shore and from SW to NE along the eastern shore (Fig. 7; Tables 3, 4). In addition, velocities in the centres of upwelling zones were generally small (max 6–10 cm s^{-1}) and increased towards the periphery of upwelling zones, reaching 38 cm s^{-1} (Tables 3, 4).

The spatial distribution analysis of water temperature and velocities of geostrophic currents allowed us to hypothesize that a zone of maximum horizontal temperature and the largest values of geostrophic current velocities is a boundary (Tables 3, 4) between warm sinking water near the shore and ascending cool deep water in the pelagic area. On that assumption, we suggested that the boundary of up- and downwelling zones occurs 5–7 km offshore in 41 % of cases near the western and eastern shores, 1–3 and 3–5 km offshore in 17 and 21 % of cases, respectively, and 7–10 km offshore in 25 and 17 % of cases. We also considered that the intensification of geostrophic currents at this boundary is one of the factors determining the position of the maximum velocities of summary currents that were detected from the measurement data (Aynbuend 1988).

Upwelling water W_{up} values varied within 0.1–6.3×10^{-3} in 2009, and 0.3–12×10^{-3} cm s^{-1} in 2012. Values of water sinking W_{down} in downwelling zones were of the same order of magnitude, i.e., 0.1–5.1×10^{-3} and 0.3–8.2×10^{-3} cm s^{-1} in 2009 and 2012, respectively. According to the comparison of maximum calculated W the intensities of the upwelling and downwelling zones were 1.5–2 fold higher in 2012 than in 2009.

Fig. 4 Spatial distribution of water temperature on transects, °C; Cape Kadilny–Mishikha River on: **a** 21–22 August, 2002 and **b** 13 September, 2012; Listvyanka–Tankhoy on: **c** 15 August, 2004 and **d** 25 October, 2010
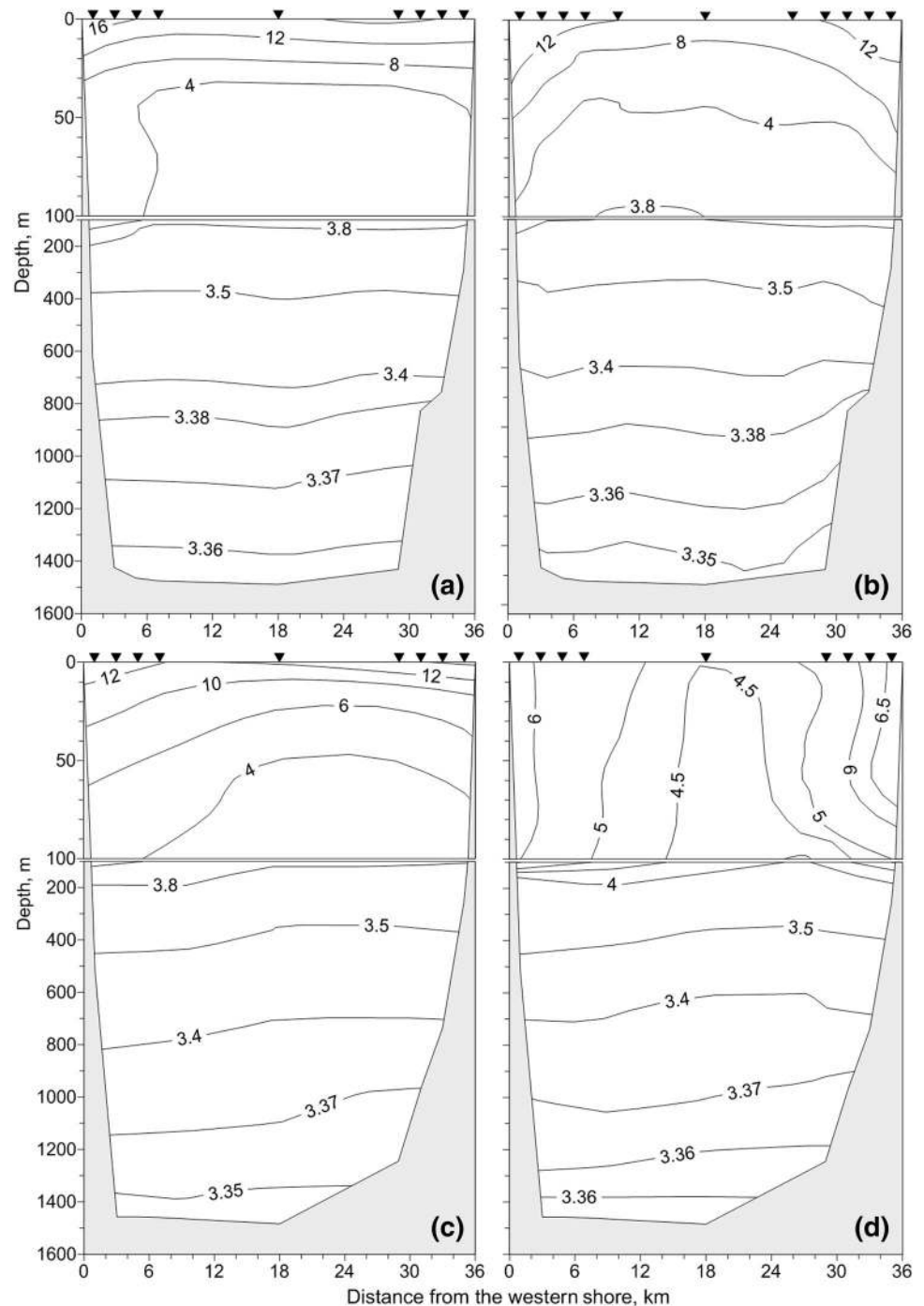
Discussion

In this paper, the first results on identifying developing zones of upwelling in the pelagic area of the lake and where they develop most often are represented. Areas of upwelling and vertical velocities were estimated on the basis of in situ and satellite data. The upwelling durations, the temperature differences between up- and downwelling zones, the layer where vertical water movements were observed, and

geostrophic velocities were refined compared to the results reported by Shimaraev et al. (2012). For the first time, a comparison of upwelling in the pelagic area of Lake Baikal and other large lakes is described (see below).

Lake Baikal

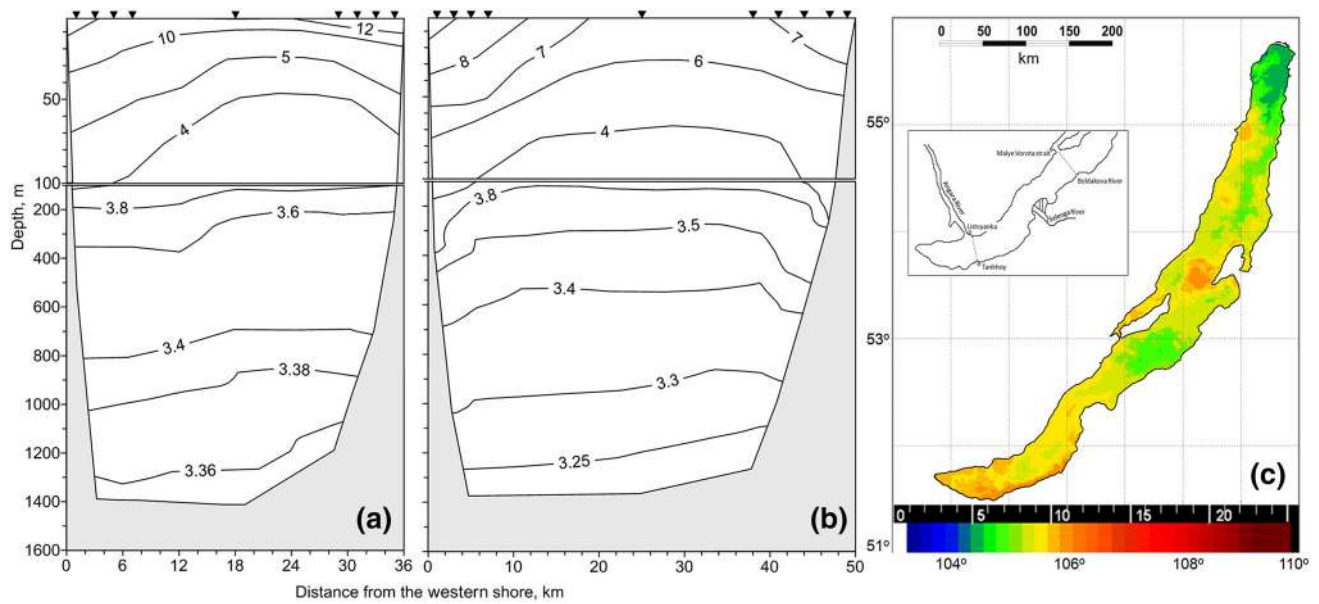The prevailing winds over Lake Baikal are the major factor influencing water cyclonic circulation within the

Fig. 5 Comparison of in situ and NOAA/AVHRR satellite data on water temperature (°C) on transects in 2009: **a** Listvyanka–Tankhoy on 24–25 September, **b** Malye Vorota Strait–Boldakova River on 27 September and **c** distribution of surface water temperature on 27 September

Fig. 6 Evolution of spatial temperature distribution during upwelling development on Listvyanka–Tankhoy transect on: **a** 2 October 1975, **b** 5 November 1975 and **c** 18 November 1975
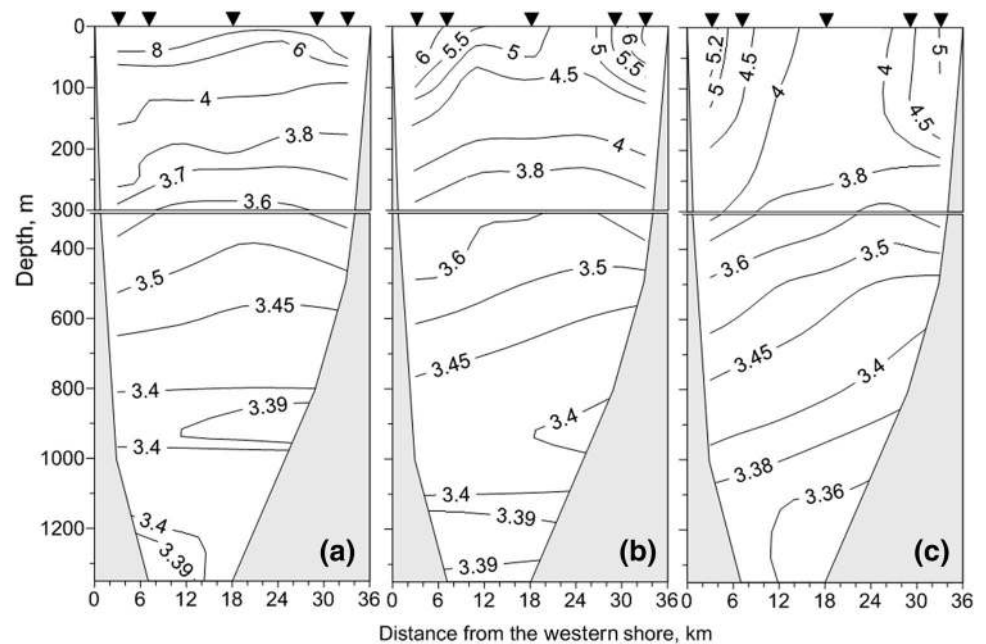
lake. The long-term average wind speed in July–October is 3.9, 4.1 and 3.0 m s^{-1} in Southern, Central and Northern Baikal, respectively (Shimaraev et al. 1994). It is notable that wind conditions over Southern Baikal are the most stable and, as a consequence, the cyclonic currents in this part of the lake are the most persistent. Wind conditions above Central and Northern Baikal are less stable, and this is manifested in a reduced stability of the current scheme. Water flow by the major river inflow into their outfall areas (Selenga River, Barguzin River and Upper Angara River) also plays an appreciable role in current maintenance.

As noted earlier, the location of most upwelling zones coincides with cyclonic circulation centres in separate basins. One of the longest upwellings develops in the centre of the major cyclonic macrovortex in the north–eastern part of Southern Baikal. Another one develops over Academician Ridge, where a complex dynamic situation is observed (Verbolov 1996). The cyclonic macrovortices are located northwest and southeast from Academician Ridge,
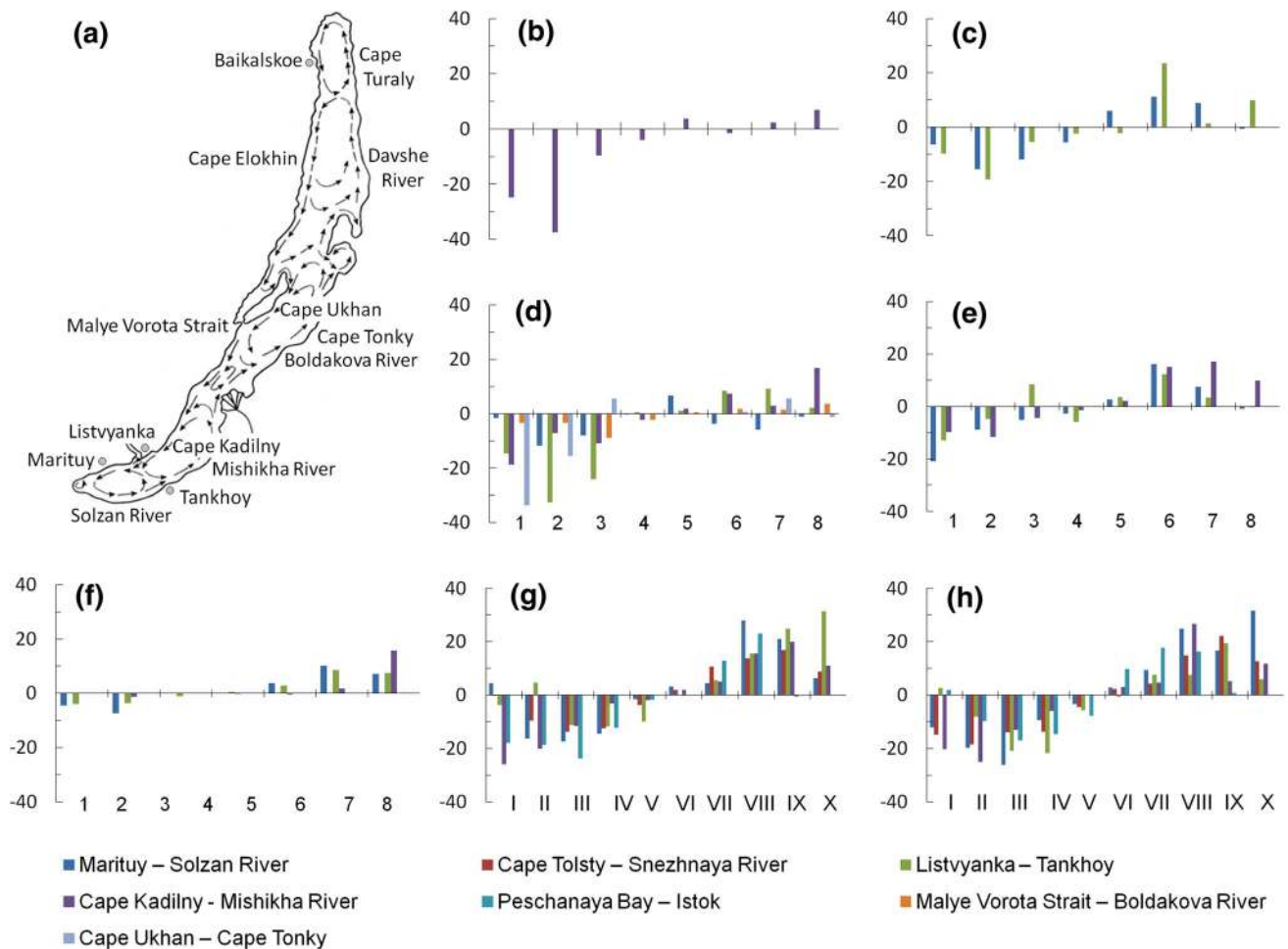
Fig. 7 Scheme of summary currents **a** in Lake Baikal (Verbolov 1996) and velocities of surface geostrophic currents on transects in: **b** August 2002, **c** August 2004, **d** September 2009, **e** October 2009, **f** October 2010, **g** September 2012 (*1*) and **h** September 2012 (2). *X*-axis—distance between transect stations: *1*, 1–3 km; *2*, 3–5 km; *3*, 5–7 km and *4*, 7 km—central station from the western shore and *5*, central station—7 km; *6*, 7–5 km; *7*, 5–3 km; *8*, 3–1 km from the eastern shore. 2012: *I* 1–3 km, *II* 3–5 km, *III* 5–7 km, *IV* 7–10 km and *V* 10 km—central station from the western shore and *VI* central station—10 km, *VII* 10–7 km, *VIII* 7–5 km, *IX* 5–3 km, *X* 3–1 km from the eastern shore. *Y*-axis—velocity of geostrophic currents, cm s^{-1} (positive values are the current direction from southwest to northeast; negative values are the opposite)

between them is situated an area where the prevailing current directions are typical of a divergence zone. To determine exactly which conditions promote upwelling will require more detailed information about meteorological conditions and the currents in this part of the lake.

It was revealed that water ascends from a depth of 10–75 m to the surface in the pelagic area of Lake Baikal during upwelling, but the layer in which ascending water is detected reaches a depth of 280 m in August–September and 380 m depth in October. So, water ascending in the pelagic area includes the entire active layer (0–300 m). The depth of compensating sinking water remains practically constant near the less steep eastern slope (200–250 m), and near the steep western slope it increases up to a depth of 500 m at the end of autumn. Observations on water temperature in 1971–1992 indicated a preservation of the

vertical water movement's structure (upwelling in the centre and downwelling near the shores) within the field of cyclonic circulation until the summer stratification is destroyed in late autumn (Fig. 6). It promotes breakup of the metalimnion in near shore areas and creates favourable conditions for penetration by surface water intrusions into the deep layers as far as the local bottom in December–January, which were described by Schmid et al. (2008). Moreover, the estimated W_{down} (10^{-3} cm s^{-1}) was two orders less than the observed time scales (10^{-1} cm s^{-1}) of cold intrusions (Schmid et al. 2008).

As the metalimnion did not appear on the surface during our measurements, the largest horizontal temperature differences (up to 13 °C) were observed at some depth (15–40 m). This is due to the fact that the metalimnion crosses this depth separating sinking warm surface water in the

Table 3 Velocities of geostrophic currents (cm s^{-1}) in separate parts of transects in different years (positive values correspond to current directions from southwest to northeast, negative values are the opposite)

Transect	Distance from							
	Western shore (km)				Eastern shore (km)			
	1–3	3–5	5–7	7–cs	cs–7	7–5	5–3	3–1
	August 2002							
Cape Kadilny–Mishikha River	−24.8	**−37.5**	−9.7	−4.0	3.7	−1.5	2.4	**6.9**
	August 2004							
Marituy–Solzan River	−6.4	**−15.4**	−11.9	−5.6	6.0	**11.2**	8.9	−0.7
Listvyanka–Tankhoy	−9.7	**−19.3**	−5.5	−2.4	−2.3	**23.6**	1.4	10.0
	September 2009							
Marituy–Solzan River	−1.5	**−11.8**	−8.1	−0.3	6.7	−3.8	**−5.9**	−1.1
Listvyanka–Tankhoy	−14.7	**−32.6**	−24.1	0.5	1.2	8.5	**9.1**	2.2
Cape Kadilny–Mishikha River	**−18.8**	−7.1	−10.9	−2.3	1.9	7.3	2.9	**16.9**
Malye Vorota Strait–Boldakova River	−3.3	−3.4	**−9.0**	−2.3	0.5	1.9	1.5	**3.6**
Cape Ukhan–Cape Tonky	**−33.6**	−15.6	5.5	0.1	–	0.8	**5.6**	−1.2
	October 2009							
Marituy–Solzan River	**−21.0**	−8.8	−5.2	−2.7	2.7	**16.1**	7.5	−0.9
Listvyanka–Tankhoy	**−12.9**	−4.8	8.4	−5.9	3.5	**12.3**	3.3	−0.4
Cape Kadilny–Mishikha River	−9.8	**−11.6**	−4.5	−1.5	2.1	15.0	**17.1**	9.9
	October 2010							
Marituy–Solzan River	−4.6	**−7.4**		0.1	0.2	3.7	**10.1**	7.1
Listvyanka–Tankhoy	**−3.9**	−3.7		−1.1	0.5	2.8	**8.5**	7.4
Cape Kadilny–Mishikha River	–	**−1.3**		0	−0.2	−0.4	1.8	**15.7**

The boundary between the up- and downwelling zones is marked with bold type

cs central station of transect

downwelling zones from ascending cool deep water in the upwelling zone.

In our paper we did not consider the occasional appearance of a vast upwelling in Northern Baikal detected with satellite data and mentioned by Semovski et al. (2001) and Heim et al. (2005). It is observed in late August–September and covers the eastern part of Northern Baikal. Its development begins from the eastern shore and rapidly extends in area to also cover the pelagic area of the lake. The area encompassed by the zone of upwelling is 15–20 % (maximum ∼80 %) of Northern Baikal's surface. The water temperature decreases from 10–14 °C to 4–5 °C corresponding to the appearance on the surface of water from depths of 25–75 m. Its duration is 4 ± 1 weeks. A possible reason for the development of this upwelling is a long–continued strong ENE wind. To study this type of upwelling in detail, complex investigations using satellite data, meteorological and hydrophysical measurements are needed.

Comparison with other lakes

A comparison of the results on Lake Baikal with those from other large lakes shows that upwelling in the pelagic area of large lakes is predominantly due to the prevailing winds over their surfaces. These cause the development of cyclonic currents in the Great Lakes (Csanady 1977), Lakes Ladoga and Onega (Boyarinov and Petrov 1991) and Lake Issyk-Kul (Romanovskiy and Shabunin 1981) or drift surface water over a wide distance offshore covering the pelagic part of Lake Tanganyika (Corman et al. 2010).

The thickness of the upwelling zone layer in large lakes of the world can vary from 10 to 20 m in Lake Onega (17 m, Boyarinov and Petrov 1991) to several tens of metres in Lake Tanganyika (60–66 m, Corman et al. 2010) and up to hundreds of metres in Lake Issyk-Kul (100–200 m, Romanovskiy and Shabunin 1981; Kipfer and Peeters 2002; Peeters et al. 2003) and Lake Baikal (300–400 m, present paper). The temperature differences between up- and downwelling zones on the water surface of temperate lakes is similar, varying within 5–8 °C in July–September (Romanovskiy and Shabunin 1981, present paper) and decreasing by up to 1–1.5 °C in October–November (Romanovskiy and Shabunin 1981, Fig. 6 in this paper).

Values of geostrophic current velocities estimated using a dynamic height method for Lake Baikal (present paper)

Table 4 Geostrophic current velocities (cm s^{-1}) in separate parts of transects in September 2012 (positive values correspond to current directions from southwest to northeast, negative values are the opposite)

Transect	Distance from									
	Western shore (km)					Eastern shore (km)				
	1–3	3–5	5–7	7–10	10–cs	cs–10	10–7	7–5	5–3	3–1
Marituy–Solzan River 1	4.5	−16.3	**−17.3**	−14.5	−1.5	3.2	4.4	**28.0**	21.0	6.2
Marituy–Solzan River 2	−12.1	−19.7	**−26.1**	−9.3	−3.3	2.9	9.3	24.8	16.6	**31.6**
Cape Tolsty–Snezhnaya River 1	−0.3	−9.5	**−13.8**	−12.5	−3.8	2.0	10.6	13.8	**16.8**	8.9
Cape Tolsty–Snezhnaya River 2	−14.9	**−18.5**	−13.9	−13.8	−4.4	2.2	4.3	14.8	**22.2**	12.7
Listvyanka–Tankhoy 1	−3.7	4.6	−11.2	**−11.8**	−9.9	0.1	5.5	15.6	24.8	**31.4**
Listvyanka–Tankhoy 2	2.7	−8.1	−20.9	**−21.7**	−5.7	−0.6	7.6	7.6	**19.4**	6.0
Cape Kadilny–Mishikha River 1	**−26.0**	−20.2	−11.5	−3.2	−1.9	2.0	5.1	15.6	**20.0**	11.1
Cape Kadilny–Mishikha River 2	−20.3	**−25.0**	−13.1	−6.0	0.1	3.0	4.6	**26.6**	5.2	11.7
Peschanaya Bay–Istok 1	−17.9	−18.6	**−23.7**	−12.2	−1.8	0	12.8	**23.0**	−0.6	
Peschanaya Bay–Istok 2	1.9	−9.8	**−17.1**	−14.7	−7.8	9.8	**17.7**	16.3	0.9	

The boundary between the up– and downwelling zones is marked with bold type

cs the central station of transect

and Lake Issyk-Kul (Romanovskiy and Shabunin 1981) during upwelling are similar. They are not high in the centres of the upwellings: 1–10 cm s^{-1} in Lake Baikal and 8–12 cm s^{-1} in Lake Issyk-Kul, increasing on the periphery of the upwelling up to 38 and 78 cm s^{-1}, respectively.

The values of W_{up} calculated for Lake Baikal (Verbolov and Shimaraev 1972, present paper) cover quite a wide range (1×10^{-4} to 1.2×10^{-2} cm s^{-1}). The values of W_{up} estimated using different methods for other lakes are also in this range: 1.3×10^{-3} cm s^{-1} for Lake Issyk-Kul (Romanovskiy and Shabunin 1981, 2002) and $0.6–8.5 \times 10^{-2}$ cm s^{-1} for Lakes Ontario, Upper and Onega (Boyarinov and Petrov 1991). It seems such a range of W_{up} is typical of temperate lakes and depends on the wind stress.

Based on the study by Verbolov et al. (1992) showing an increase in chlorophyll *a* concentrations after an upwelling event subsided in Northern Baikal, as well as by analogy with the observations in the coastal and pelagic areas of other large lakes (Rinke et al. 2009; Corman et al. 2010), we can infer that plankton are transferred from the centre of an upwelling to its periphery and nutrients are lifted to the surface layer by the upwelling flow. Eventually, an increase in productivity and chlorophyll *a* concentrations in the pelagic area of Lake Baikal could be expected after the upwelling event.

To investigate the influence of external factors (e.g., air pressure, wind speed and direction) on the initiation of upwellings in the Lake Baikal pelagic area and estimate the influence of upwelling on hydrochemical conditions and biological processes, it will be necessary to develop further combined studies of pelagic upwelling with measurements of meteorological, hydrophysical, hydrochemical and biological parameters.

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