

Unique Phenomena in Lake Baikal, Russia Imaged and Studied with SAR and Multi-Sensor Imagery

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Abstract – Lake Baikal in Russia, Eastern Siberia, is the deepest freshwater lake in the world, represents itself specific hydrological/weather regimes as well as different phenomena. Among them are local winds, giant ice rings and oil seeps. These phenomena leave pronounced footprints on the lake surface and in ice cover, and they can be imaged, mapped and studied by remote sensing, in particular by synthetic aperture radar (SAR) and multi-sensor optical imagery. For the first time a number of them were discovered with help of satellite images. In this paper the most pronounced examples are presented and analyzed to emphasize the uniqueness of Lake Baikal. It's concluded that joint use of SAR and multi-sensor images is the best way to study different phenomena occurred in large lakes.

Keywords: Lake Baikal; SAR images; multi-sensor images; local winds; oil seeps; ice rings.

1. INTRODUCTION

Lake Baikal, the lake in Russian Federation, Eastern Siberia, has an area of 31,700 km², a length of about 636 km, and a maximum depth of 1642 m (Figure 1). The lake is estimated to be over 25-30 million years old. It is the largest by volume, containing at least 20% of fresh water of the Earth, and the deepest freshwater lake. Biodiversity of the lake includes the floral and faunal species, many of them are endemic, and it represents a unique ecosystem. The lake is surrounded by the mountain ridges, which often modulate a background wind field and produce very variable local winds of different strength and directions.

The lake is located in the Baikal Rift Zone filled up by multi-kilometer sediments. This accumulated matter is the source of gas and oil in the lake (Khlystov et al., 2007); for example, methane seeps in the lake have been known for a long time. The Baikal rift zone is tectonically and seismically active.

The lake is divided into the Southern, Central and Northern Basins that is important from a hydrological point of view. These three basins differ in their origin, morphology and structure; the deepest is the Central Basin. Selenga River is the main lake's river; it forms a large delta between the Central and the South Basins and is a major source of organic material and bottom sediments.

Baikal is a dimictic lake, i.e., with mixing twice a year; within the upper layer there are seasonal changes in temperature. One of the important features of the lake is the fact that it is frozen during 4-5 months in the year.

Different natural phenomena leave pronounced footprints both on the lake surface and in the ice cover. These phenomena can be imaged, mapped and studied by remote sensing, in particular by

synthetic aperture radar (SAR) and multi-sensor optical imagery. For the first time, most of them have been discovered in satellite images and studied with their help. In this paper a number of recent results are presented, discussed and reviewed with purpose to emphasize the uniqueness of the Lake Baikal' environment.

2. LOCAL WIND FIELD AND LOCAL WINDS

Lake Baikal represents itself very complicated regime of variable and treacherous local winds (Burman, 1969). The weather in this region sometimes is so unique and complex that meteorologists have to use more than 30 names for these winds, mostly taking them from local people. The Baikal's winds suddenly appear and blow in various directions, both along and across the lake (Figure 1). The mountain ranges surrounding the lake produce very strong bora-type winds. Among them the strongest, most severe and dangerous of Baikal winds, is the NW wind or mountain wind. One of its specific varieties, *Sarma* blows from the river valley of the same name, where it can reach hurricane strength, up to 30-40 m/s. Other severe easterly wind, *Barguzin* blows from the northeast also from river valley of the same name. All these winds leave footprints on the lake surface, as local winds do, e.g., bora in the coastal zones of the Adriatic Sea and Black Sea (Alpers et al., 2009, Alpers et al., 2010). The sea surface roughness patterns associated with these wind events captured by SAR can yield information on the spatial extent and the fine-scale structure of these winds. Quantitative information on the wind field can be derived from the SAR images by using the CMOD4 wind scatterometric model dealing with converting radar backscatter values into wind speed fields.

Many SAR images with manifestations of local winds have been acquired in 2005 during the monitoring campaign. Acquired SAR images have been analyzed and interpreted based on approach by Alpers et al. (2009) and Alpers et al. (2010).

One of 'footprints' of the Baikal' local winds on the Envisat ASAR images is shown on Figure 2a. This image was acquired in Image Mode over the Middle Baikal on 4.11.2005 at 03:22 UTC (11:22 local time) during a strong wind event. The pattern visible on the image consists of many wind jets, which are practically normal to the coastline and generated by winds blowing through the coastal mountain Primorskii Ridge, and which extend until the eastern Baikal coast. These features are very typical for bora wind events occurring at the eastern coasts of the Adriatic Sea and Black Sea (Alpers et al., 2009, Alpers et al., 2010). Other SAR images (not represented here) show manifestations of katabatic winds and local wind *Barguzin*.

The best way to extract information from SAR images of the lake surface that show surface manifestations of local atmospheric phenomena is to combine them with ground observations.

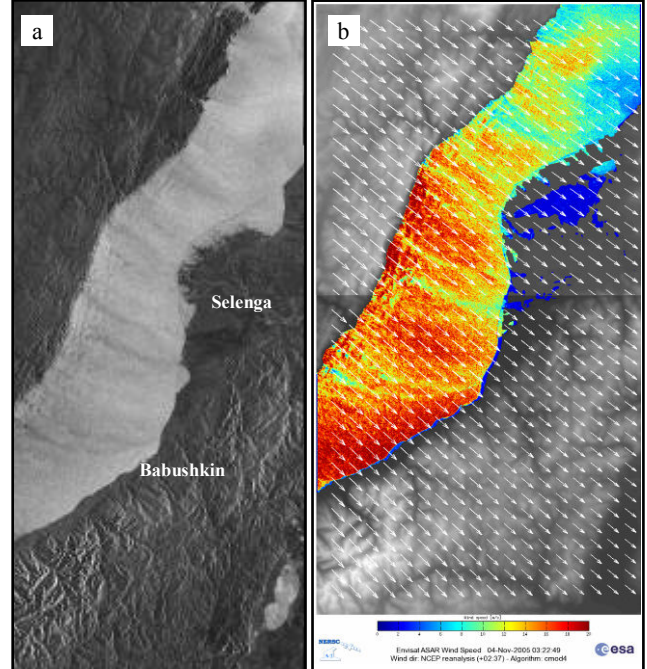
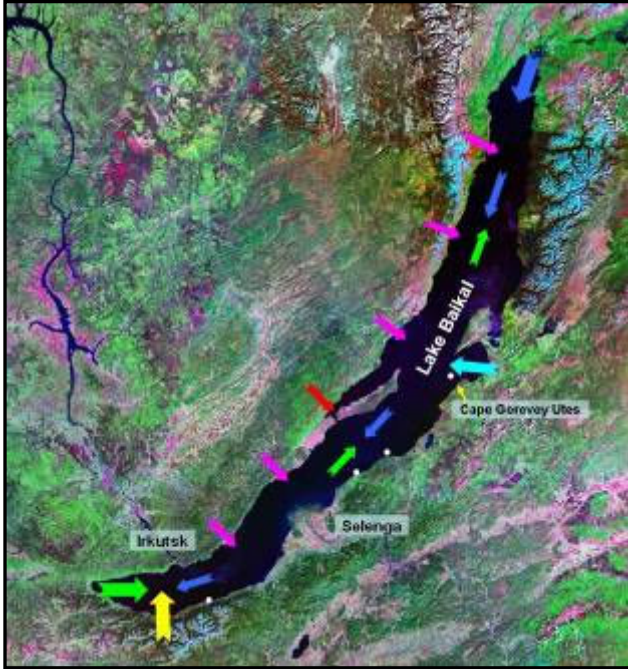


Figure 1 (left): Satellite map of Lake Baikal with general directions of the main local winds and with locations of known oil seeps (white circles). Figure 2 (right): *a* – Envisat ASAR image with manifestations of NW mountain wind on 4.11.2005 at 03:22 UTC. © ESA. *b* – near-surface wind field retrieved from this image; wind direction from the NCEP/NCAR reanalysis is used. Courtesy: K.-F. Dagestad, NERSC.

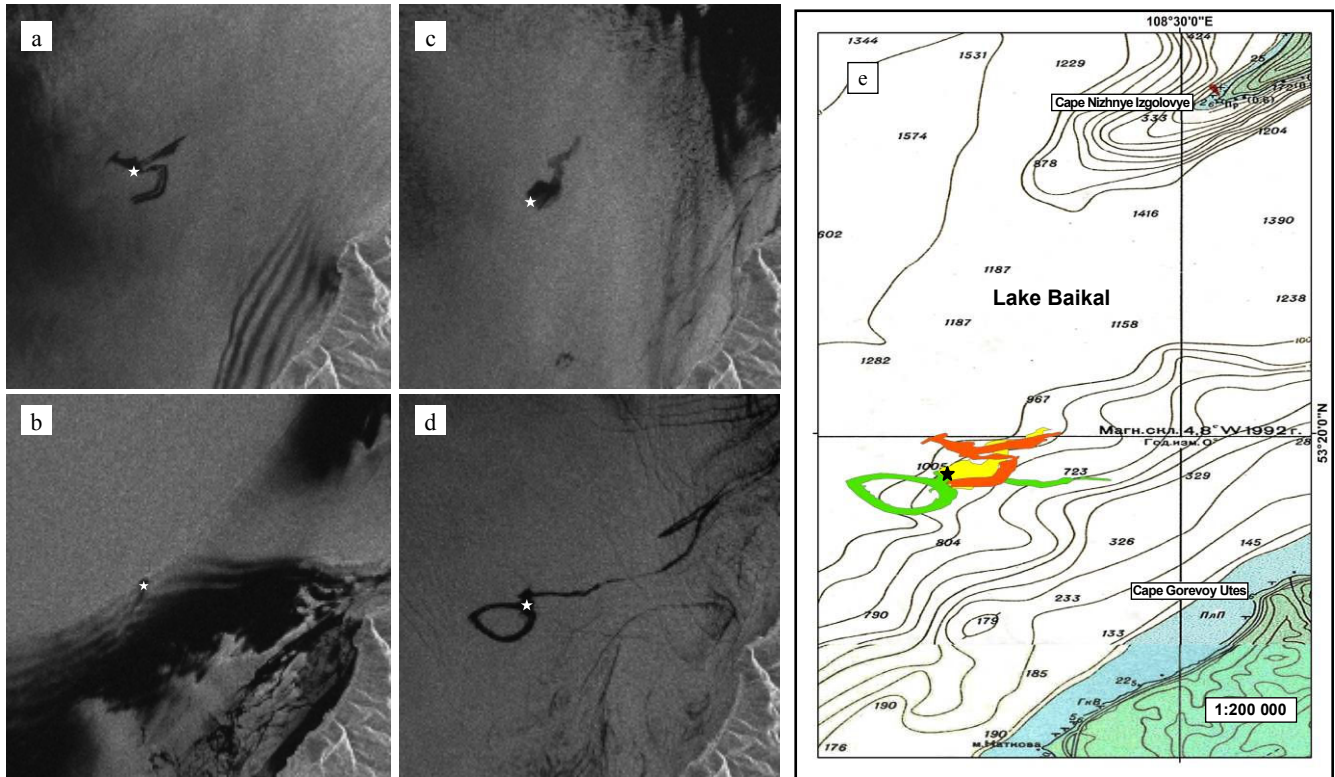


Figure 3: 20 x 20 km subscenes of the ERS-2 SAR images with seepage oil slicks acquired on 28.05.1998 (*a*) and 2.07.1998 (*b*), and Envisat ASAR images acquired on 30.06.2005 (*c*) and 4.08.2005 (*d*), where white stars show the emission points. © ESA; *e* – A GIS window with seep slicks detected in the SAR images on a background of the nautical chart: 28.05.1998 (red), 30.06.2005 (yellow) and 4.08.2005 (green); black star shows the position of the oil seep on the floor at depth ~870 m.

Meteorological data at time close to the time of the SAR image acquisition available from the weather station at Babushkin (eastern coast, 51°43' N, 105°51' E) on 3-6.11.2005, show an abrupt change of wind speed and direction from 0-2 to 9-10 m/s and from E to W, drop of air temperature (up to -10°C), as well as drop and then rise of atmospheric pressure.

From this SAR image a wind field map has been generated (Figure 2b) by using the CMOD4 wind scatterometer model and by inferring the wind direction from the NCEP/NCAR reanalysis. The wind field map depicted on Figure 2b shows several wind jets, where the wind speed fluctuated between 12 and 20 m/s. The western coast of Lake Baikal is bordered by coastal the mountain range of variable height having many mountain gaps and narrow river valleys through which northwesterly airflow can be funneled onto the lake. When the NW winds are strengthened by atmospheric forcing, e.g., by passing of atmospheric disturbances in highland or mountainous areas, and when they have speed above 15 m/s, enhanced by funneling and topography, they can be considered to be bora-type winds.

This phenomenon associated with bora events is well known to the local people. Its local name is *Gornaya*, and this is the strongest of Baikal winds and the most dangerous for navigation. It blows along the western coasts of the lake, from the mountainous passages of Primorskii and Baikalskii Ridges and can reach speed more than 30-40 m/s (Burman, 1969).

3. OIL SEEPS

Signs of oil and gas in Lake Baikal are known from the beginning of XVIII c. Oil, bitumens and gases in coastal deposits were found out for the first time by local hunters and fishermen. Individual researchers undertook attempts of definition of the nature of this phenomenon, but till now this question is open. In the literature such data began to appear owing to researchers of Siberia since 1724. Today oil seepage from bottom sediments in Lake Baikal, are known in the mouth of Stvolovaya River (depth 10 m), near Cape Tolsty (250 m) and near Cape Gorevoy Utes (850 m) (Figure 1); properties of these oils were studied by Khlystov et al. (2007), where a reader can find information about origin of the Baikal's oils as well. On Figure 1 known oil seeps are depicted by small white circles.

To study oil seep in Lake Baikal four ERS-2 and Envisat SAR images (Figure 3a-d) were collected as standard products from ESA; their subscenes are on Figure 3. Processing of the SAR images included: calibration, 8-bit transformation, filtering, georeferencing and thresholding of oil slick candidates. The discrimination between dark formations or look-alikes and seep oil slicks was performed based on the Offshore Basin Screening (www.npagroup.com) or the Seep Screening (www.infoterra.co.uk) methodologies, which are remote sensing techniques for reducing interpretation risk by identifying natural hydrocarbon seepage in offshore basins using SAR images.

For discrimination the great help can also give a GIS-approach, in which geographic information about water basin, industrial and other context are used (Ivanov and Zatyagalova, 2008). To analyze the spatial distribution of seepage slicks a GIS has been created based on the nautical map of scale 1:200 000 (Figure 3e). By applying above mentioned techniques dark formations firstly interpreted as oil slicks finally were finally interpreted as seepage slicks.

Figure 3a-d shows subscenes of the ERS-2 SAR and Envisat ASAR images, acquired on 28.05.1998 03:43 UTC, 2.07.1998 03:43 UTC, 30.06.2005 03:13 UTC and 4.08.2005 03:13 UTC, where oil slicks are visible. As seen these patches have characteristic emission points (white stars) that definitely determine them as seepage slicks.

The GIS window with detected oil slicks is shown in Figure 3e. It is clearly seen how the slicks group at the same place. Evidently this is because they originated from the same bottom source. Moreover, the emission points of two of them are coincided very well. This point, marked by the black star, is considered to be a location of the seep on the floor.

On the basis of the patch's areas measured in GIS and certain assumptions about film thickness, rough estimates of volume of oil floating on the surface can be obtained (Ivanov, 2011) by using an approach of the Bonn Agreement Manual (Bonn Agreement, 2007). According to airborne visual observations the color of the seepage slicks varies from rainbow ($0.30 \cdot 10^{-3}$ mm) around emission point to silver sheen ($0.04 \cdot 10^{-3}$ mm) on periphery (Bonn Agreement, 2007). Thus, assuming: (1) the layer thickness is $0.04 \cdot 10^{-3}$ to $0.3 \cdot 10^{-3}$ mm for oil visible (from rainbow to silver sheen), and 40-300 litres per km^2 for the volume of oil, (2) the density of Baikal petroleum is 960-980 kg/m^3 , (3) oil films exist on the surface about 24 hrs, and (4) the single volume estimate persists for a year. Then, if the slick areas vary from 3.32 to 4.57 km^2 , the min and max annual estimates of hydrocarbon flux from the Lake Baikal' interior are 48 to 480 tonnes per year due to oil (Ivanov, 2011). These estimates exceed the estimate by Khlystov et al. (2007) by one-two orders.

4. ICE RINGS

Since May 2009 scientific community has been raised by information about giant rings in the ice cover of Lake Baikal detected by remote sensing satellites (Figure 4). Many publications mostly referred to the rings observed by MODIS onboard the Terra and Aqua satellites. Probably the rings in the Lake Baikal ice are not a new phenomenon. For the first time they were detected on the NOAA AVHRR image, acquired in late April 1999; this was a ring at the Cape Krestovskii. It seems similar circular patterns to be documented by astronauts in the central part of the lake during the Shuttle missions in 1985 and in 1994.

Studies of the Baikal rings were carried out based on the analysis of satellite images acquired from remote sensing satellites such as MODIS images available from EOStation in Irkutsk (<http://eostation.irk.ru>), NOAA AVHRR, Landsat-5/7 and SPOT-2/4 imagery available from USGS Earth Explorer. SAR images were available from the ESA AO projects.

Visibility of ice rings in visible/IR range is quite different from the SAR imagery due to physical mechanisms involved. In visible bands (reflected sunlight) an ice ring consist of white ice center, where ice is thicker, and a ring proper (dark circular band) where ice is thinner. This is in agreement with field findings by Granin (2009), whose measurements of ice thickness show 70 cm in the ring center and 40-45 cm in the dark ring itself. If the ring is well developed and energy-exchange between ice and water exists, the ring is also observable in thermal IR channel. SAR images are the results of surface/subsurface scattering on the ice. While there was one event, when a well-developed ring has been observed as a dark feature in the Envisat ASAR image, in most cases rings are not

discernible at all, that suggests that the melting/thinning of the ice is going from the beneath (Kouraev et al., 2011).

According to the collected remote sensing data set, the ice rings on Baikal are not formed every year: after first definite detection in 1999, the well-developed ice rings were detected in 2003, 2005, 2007, 2008 and in 2009. But there were no them in 2000-2002, 2004 and in 2006. Also there were no rings in the cold season of 2010. However, in 2008 the rings appeared simultaneously in two parts of the lake: near Cape Krestovskii (close to the ring locations in 1999, 2003 and 2005) and for the first time near Turka settlement (Figure 4). In April 2009 one ring was detected at the Cape Nizhnye Izgolovye, Peninsula Svyatoy Nos (Central Basin) and another one – in the southern end of the lake (Figure 4). To sum it up, the rings were observed mainly in 4 places (Figure 4) of the lake, at different times and in different years. Some places, such as Cape Krestovskii in the Middle Baikal, have a high reiteration. As a rule, the rings located over the deepwater regions: when the centers of the ice rings were inserted into GIS, it became clear that they located over deep or very deep waters, typically over the depths of 800-1500 m.

Most frequently rings appeared in late April (when ice is thin and snow cover is absent), but they may appear as early as January 31 and as late as May 26 (Kouraev et al., 2011). For example, the ring near Cape Nizhnye Izgolovye in 2009 was visible on a sequence of MODIS images through March and April (Kouraev et al., 2011). It seems it to appear when ice cover became stable, and then disappear as ice melts. This feature was last observed on the MODIS image on April 29, 2009 as a hole of open water.

Typical radius of the rings is 2.5-3 km, with extreme values from 1.4 to 5.5 km (Kouraev et al., 2011). The ring width (450 m \div 2 km) depends on the ice cover and snow conditions; typical width is 800-1000 m (Kouraev et al., 2011). The latest ring has a diameter of 4.4 km, and this is reason, why they can be seen on satellite images only.

Mechanisms involved in the ring formations in the ice cover are not well understood. There are a number of contradictory explanations for their origin, such as: gas emission, heat flux, circular subsurface currents and mega bubble formation (Kouraev et al., 2011). But none of them is able to explain the phenomenon in whole. To explain formation of this phenomenon a detail study of many things including tectonic, seismic and hydrothermal activity, bottom gas hydrates and gas seeping as well as winter under-the-ice hydrology and water dynamics are necessary. However, even this qualitative study shows that analysis of satellite multi-sensor images allow getting closer to understanding origin and formation mechanisms of this unique phenomenon.

5. CONCLUSION

Collected and analyzed multi-sensor imagery including SAR and optical images provide both a new insight into these phenomena and new information helping to understand their nature. Further studies and monitoring of these phenomena using satellite observations and in situ measurements could be very useful.

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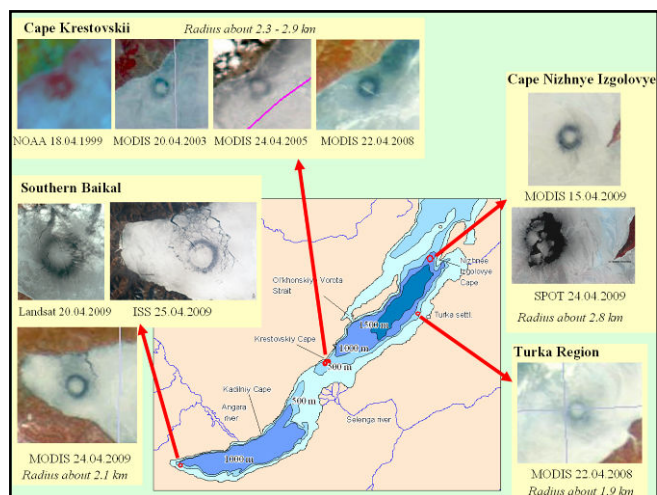


Figure 4: Map of Lake Baikal with locations of the rings in the ice cover detected in multi-sensor satellite images (NOAA AVHRR, Terra/Aqua MODIS, Landsat TM+ and SPOT HRV) in 1999, 2003, 2005, 2008 and 2009. Courtesy: A. Kouraev, University of Toulouse/LEGOS

REFERENCES

- W. Alpers, A. Ivanov, and J. Horstmann, "Observations of bora events over the Adriatic Sea and Black Sea by spaceborne synthetic aperture radar", *Mon. Wea. Review*, 137, pp. 1150-1161, 2009.
- W. Alpers, A.Yu. Ivanov, and K.-F. Dagestad, "Observation of local wind fields and cyclonic atmospheric eddies over the Eastern Black Sea using Envisat synthetic aperture radar images", *Issl. Zemli iz Kosmosa*, 5, pp. 46-58, 2010.
- Bonn Agreement Aerial Surveillance Handbook. <http://www.bonnagreement.org/eng/doc/Aerial%20Surveillance%20Handbook%202004%20-%20English%20version.pdf>.
- E.A. Burman, "Local winds", Leningrad, USSR: Gidrometeoizdat (in Russian), 1969.
- N.G. Granin, "The ringed Baikal", *Science First Hands*, 2, pp. 26-27, 2009.
- A.Yu. Ivanov, "Oil seep in Lake Baikal imaged and studied with the ERS-2 and Envisat SAR", *Proc. ESA Living Planet Symposium*, 28 June - 2 July 2010, Bergen, Norway (ESA SP-686), 2010.
- A.Yu. Ivanov, and V.V. Zatyagalova, "A GIS approach to mapping of oil spills in a marine environment", *Int. J. Rem. Sens.*, 29(21), pp. 6297-6313, 2008.
- O.M. Khlystov, A.G. Gorshkov, A.V. Egorov et al., "Oil in the lake of the world heritage", *Doklady Akademii Nauk*, 414, pp. 656-659 (in Russian), 2007.
- A. Kouraev, M. Shimaraev, F. Remy, A. Ivanov et al., "Giant rings on ice of the Lake Baikal: A look from space and from beneath", *Proc. ESA Living Planet Symposium*, 28 June - 2 July 2010, Bergen, Norway (ESA SP-686), 2010.