ISSN: 0001-5113
AADRAY

ACTA ADRIAT.,
51(2): 119 - 130, 2010

UDC: 551.465.11(210.7 Mljet)(262.3)

The dynamics of a saltwater marine lake (Big Lake, Island of Mljet, Adriatic Sea) as revealed by temperature measurements

Ivica VILIBIĆ*, Ante ŽULJEVIĆ and Vedran NIKOLIĆ

Institute of Oceanography and Fisheries, P. Box 500, 21000 Split, Croatia

****Corresponding author, e-mail: vilibic@izor.hr***

This paper describes hydrographic and dynamic conditions in the Mljet lakes, through the analysis of high-frequency temperature measurements carried out at an intermediate layer of Big Lake (BL) and Soline Channel during two years (December 2005-October 2007). It appears that the lakes may be colder than the open sea during wintertime by as much as 2-3°C and warmer at the surface during summer by as much as 4°C. Several interesting processes were captured within the series of which we investigated the wintertime cooling that occurred in 2006, diurnal and semidiurnal temperature changes driven by the tides within the connecting channel and the occurrence of turbulence in BL close to the connecting channel. The latter seems to have large implications for the thermocline/pycnocline deepening during the summertime, as incoming open ocean waters are much denser than the BL waters.

Key words: saltwater lakes, water masses, temperature, Adriatic Sea

INTRODUCTION

Small karstic saltwater or seawater lakes, being attached to the oceans or seas through narrow surface or submarine channels, are often characterised by unique and endemic species (GOTOH *et al.*, 2009) adapted to the specific lake conditions such as, for example, hypoxic or anoxic conditions at its deep parts (HAMNER & HAMNER, 1998; HOLMES *et al.*, 1995; JOHNSON & COSTELLO, 2002; MARTIN *et al.*, 2006). There are not many places in the world as unique as the saltwater lakes on the island of Mljet (Fig. 1): from the geological point of view (WUNSAM *et al.*, 1999), over the present hydrography and dynamics (BULJAN & ŠPAN, 1976; PEHARDA & VILIBIĆ, 2008), towards the very specific biological communities such as scyphozoans (BENOVIĆ *et al.*, 2000), bivalves (ŠILETIĆ & PEHARDA, 2003) and corals (KRUŽIĆ *et al.*, 2008b). The uniqueness of the ecosystem had already been recognised by the late 1950s, leading to the one of the first established marine reserves in the world. Namely, both Little Lake (LL) and Big Lake (BL) became a part of the National Park already in 1960, later with an even more strengthened protection level through the Croatian Law on Nature Protection.

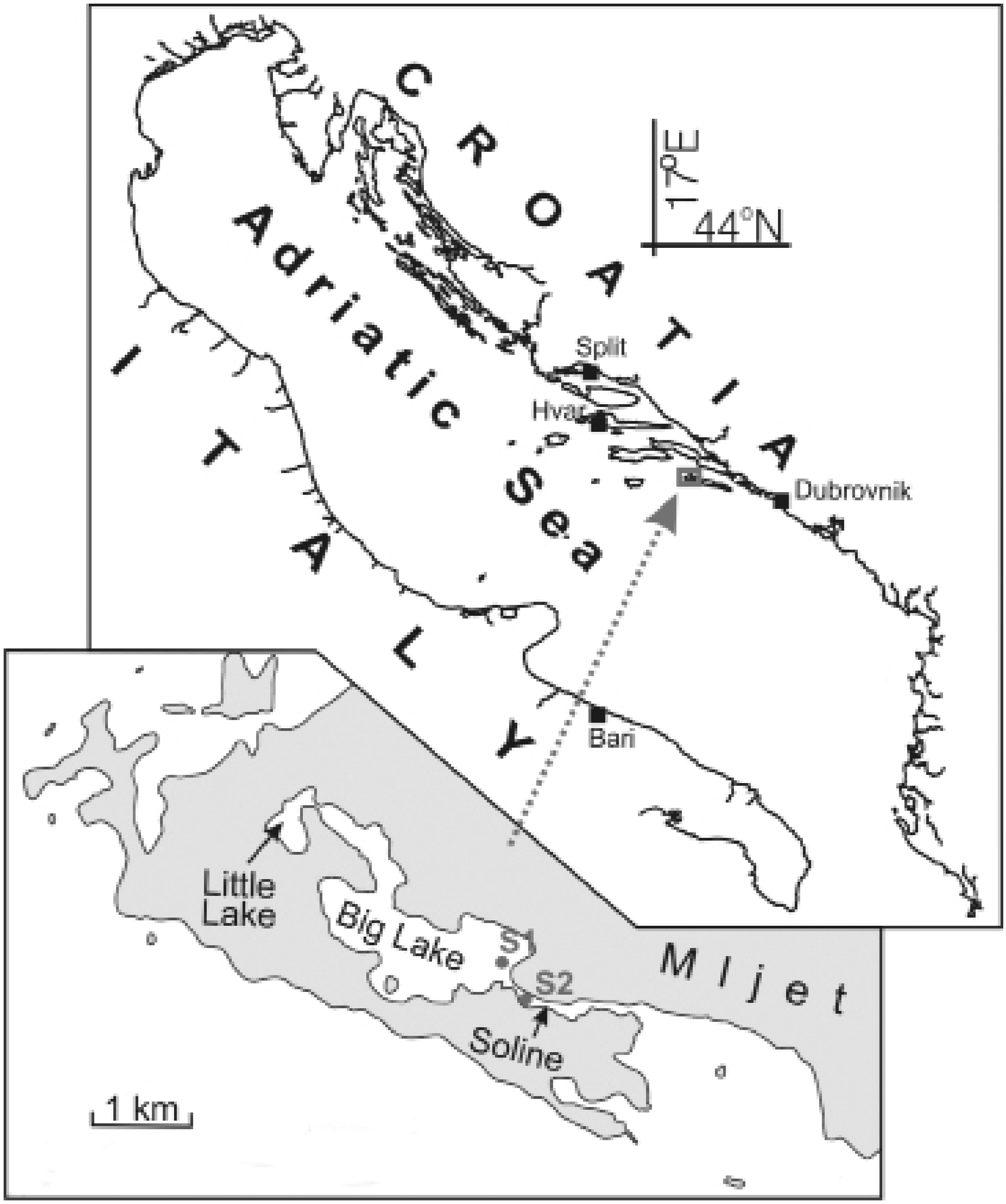

Fig. 1. Geographical characteristics of the investigated area, with the positions of sampling stations indicated

The two karstic depressions had formed in the Mesozoic, first filled by fresh water and then, due to post-glacial sea level rise, intruded upon by marine saltwater through the karst. These submarine karstic connections between the open sea and LL (maximum depth of 29 m) are found to be active today as well (BULJAN & ŠPAN, 1976), being detected on the sub-bottom geological echo profile in the form of a submarine spring (WUNSAM *et al.*, 1999). The connecting channel Soline (Fig. 1, presently 2.5 m to 4 m deep), which enables the exchange of open-ocean water masses with the surface waters in BL (maximum depth of about 50 m), had been formed 5000 years ago while the very shallow (less than 1 m) and narrow (about 2 m) connecting channel between BL and LL has been formed and manually regulated only recently.

Hydrography and water masses of the Mljet lakes have been first documented by ERCEGOVIĆ (1935), followed by VULETIĆ (1953) and BULJAN & ŠPAN (1976). The latter paper is a comprehensive presentation of the measurements carried out mostly between 1951 and 1954. They already found that the lakes have their own dynamics as the residence time is estimated to be on the annual scale (around 8 years). The water exchange through both connecting channels (between LL and BL, and BL and the sea) is dominantly driven by tides, resulting in strong currents (greater than 1 m s^{-1}) and in tidal phase shift between the open sea and both lakes (PEHARDA & VILIBIĆ, 2008). The lakes are much colder during the winter (as low as 8^{o}C) than the outer sea (12-13^{o}C) and warmer at the surface (as high as 28^{o}C) during the summer season with a strong thermocline (up to 4^{o}C/m) at 10-20 m depth. Salinity was restricted to values of 36-37 (in the 1950s) and was much lower then in the outer sea (37.5-38.5). However, an increase in salinity was noticed in the 1990s (BENOVIĆ *et al.*, 2000), being particularly strong in the 2000s. Namely, bottom salinity surpassed 38.5 in 2003 and 2004 (MALEJ *et al.*, 2007) and maintaining those values until 2008 (CUCULIĆ *et al.*, 2009). Through the examination of salinity profiles, BULJAN & ŠPAN (1976) proved the existence of the karstic submarine channel between LL and the outer sea. Furthermore, they documented the anoxic conditions in the bottom layer that lasted for several years, together with high concentrations of hydrogen sulphide H_2S. Such anoxic conditions may be ended during severe wintertime cooling events which homogenise the entire water column (BENOVIĆ *et al.*, 2000). Vertical homogenisation has been noted to occur regularly since 2003, resulting in no anoxic conditions reported for both LL and BL.

As presented, it can be seen that the hydrography of the lakes has been extensively examined, not only because of their uniqueness but also due to constant friendly ocean conditions during sampling. However, we introduce in this paper a long and high-resolution temperature dataset which enabled the assessment of some hydrographic conditions not attainable by the classical CTD or bottle sampling. Sampling strategy and the data is introduced in Section 2, while Section 3 discusses them from the perspective of the hydrography and the dynamics of the lakes-ocean system. The conclusions are given in Section 4.

MATERIAL AND METHODS

Two TidbiT type thermistors were deployed, the first in Big Lake at a depth of 15 m (station S1), and the second in Soline Channel at a depth of 3 m (station S2). The measurements at S1 encompassed the period between 11 December 2005 and 19 October 2007, sampling temperatures at 30 min intervals, while at S2 the sampling interval was set to 15 min and covering the period between 26 November 2006 and 31 October 2007. The instruments recorded the sea temperature with an accuracy of ± 0.2^{o}C. Although the measurements were designed to quantify the ambient characteristics in the area where invasive green alga *Caulerpa racemosa* var. *cylindracea* (Sonder) Verlaque, Huisman et Boudouresque has been found (KRUŽIĆ *et al.*, 2008a), the choice of the sampling locations and the duration of the temperature measurements allowed for new findings and quantification of some known processes related to the BL water masses and the exchange with the open sea.

RESULTS

The full time series of temperatures at stations S1 and S2 are given in Figs. 2 and 3, respectively. A few interesting things can be seen at first glance, such as low temperatures at 15 m depth in BL recorded during wintertime (lower than 11^{o}C) followed by increased diurnal and semidiurnal variability with the approach of summer, and strong temperature variability on a daily scale during the whole year within Soline Channel. We will focus our analysis to these two interesting phenomena characteristic for the Mljet lakes dynamics.

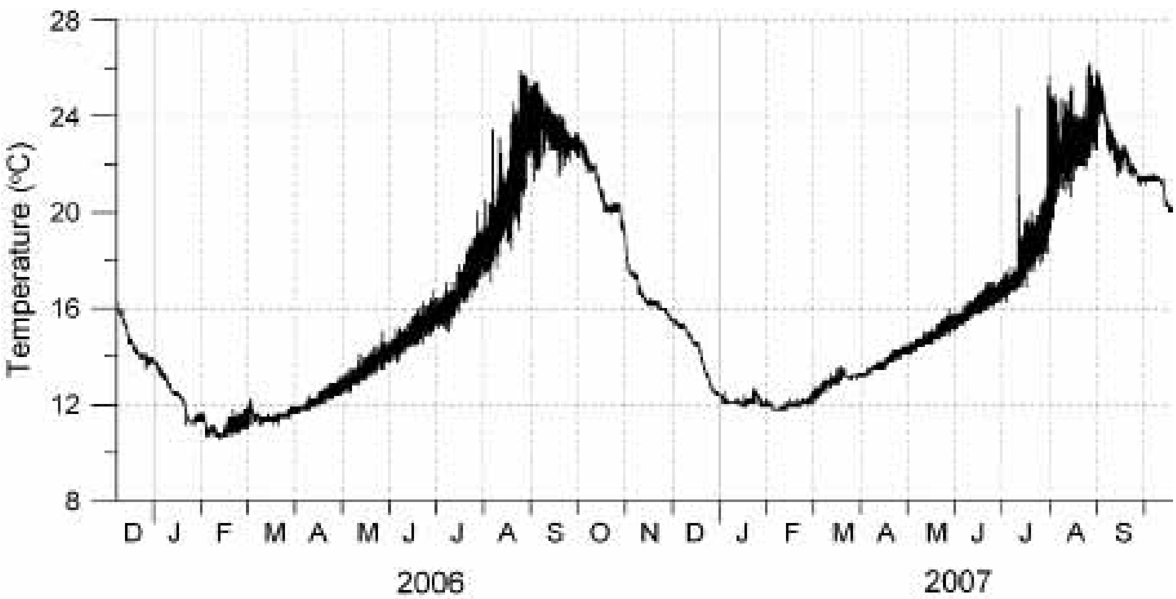

Fig. 2. Temperature time series measured at station S1 at a depth of 15 m

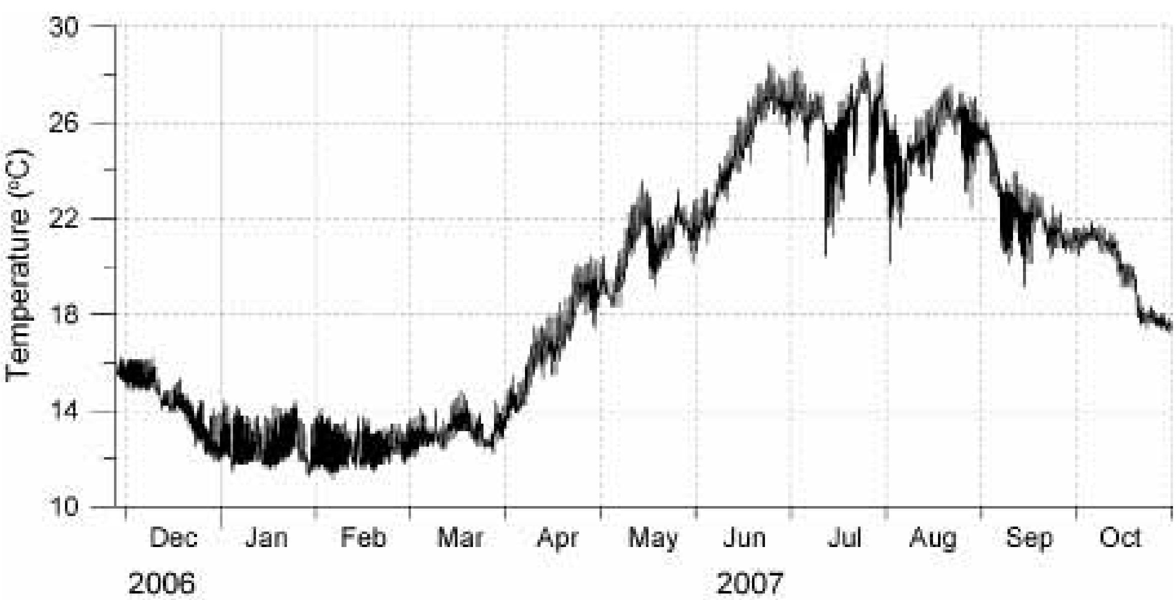

Fig. 3. Temperature time series measured at station S2 at a depth of 3 m

Wintertime cooling in Mljet lakes

It is interesting to note the low temperatures in intermediate BL layers during winter 2006 that followed recently documented wintertime temperatures (e.g. 10-11°C during winters of 1998 and 2004, BENOVIĆ *et al.*, 2000; MALEJ *et al.*, 2007). As earlier measurements, e.g. those in the 1950s (BULJAN & ŠPAN, 1976), document deep BL temperatures to be as low as 8°C, it has been concluded that the wintertime conditions (heat and water flux) over the lakes may significantly change their hydrographic characteristics as they are landlocked and protected from significant mixing with the warmer and saltier open Adriatic waters.

Nevertheless, the temperatures in February 2006 were measured to be as low as 10.5°C (16 February), while in February 2007 they reached just 11.8°C (6 February). It is interesting to note that the temperature in early January was lower in 2007 (about 12°C) than in 2006 (about

13.5°C), which implies better preconditioning for severe cooling in 2007 than in 2006. However, the cooling was more effective in winter 2006 and the reason may be related to the atmospheric conditions and heat losses at the surface of the lakes.

The severity of winter 2006 was already documented over the deep South Adriatic Pit, as some photoautotroph bacteria had been transported rapidly in the deep ocean through open ocean convection (VILIBIĆ & ŠANTIĆ, 2008). Monthly reports issued by the Meteorological and Hydrological Service (MHS, 2007) and Deutscher Wetterdienst synoptic charts (http://www2.wetter3.de/Archiv/archiv_dwd.html, Fig. 4) document the severe bora episodes on 22-25 January and on 5-8 February 2006 when negative air temperatures were present at the coastal meteorological stations (Split, Hvar, Dubrovnik) for several days. Therefore, very strong cooling of the surface, together with strong vertical mixing induced by the wind, is probably a force which may decrease the deep BL temperatures to such low values. Proof may be found by plotting temperature at S1 together with the wind data (Fig. 5) (Bari station is chosen, as the most severe bora blow over the entire Adriatic and reach the western shore – therefore, severe boras in the southern Adriatic can be assessed at the Bari meteorological station in addition to the eastern stations) It may be seen that the cooling happened simultaneously with the severe bora, clearly showing the presence of the two mentioned processes.

At this point it is possible to estimate the surface heat losses that accumulated during those specific episodes. One may apply a simple one box-model, assuming that (i) heat fluxes are uniform over BL, (ii) there is no flow and heat exchange at the boundaries and (iii) the water column is fully homogenised in the whole BL. Therefore, the temperature change ΔT in a box can be estimated by (e.g. GILL, 1982; VILIBIĆ *et al.*, 2004):

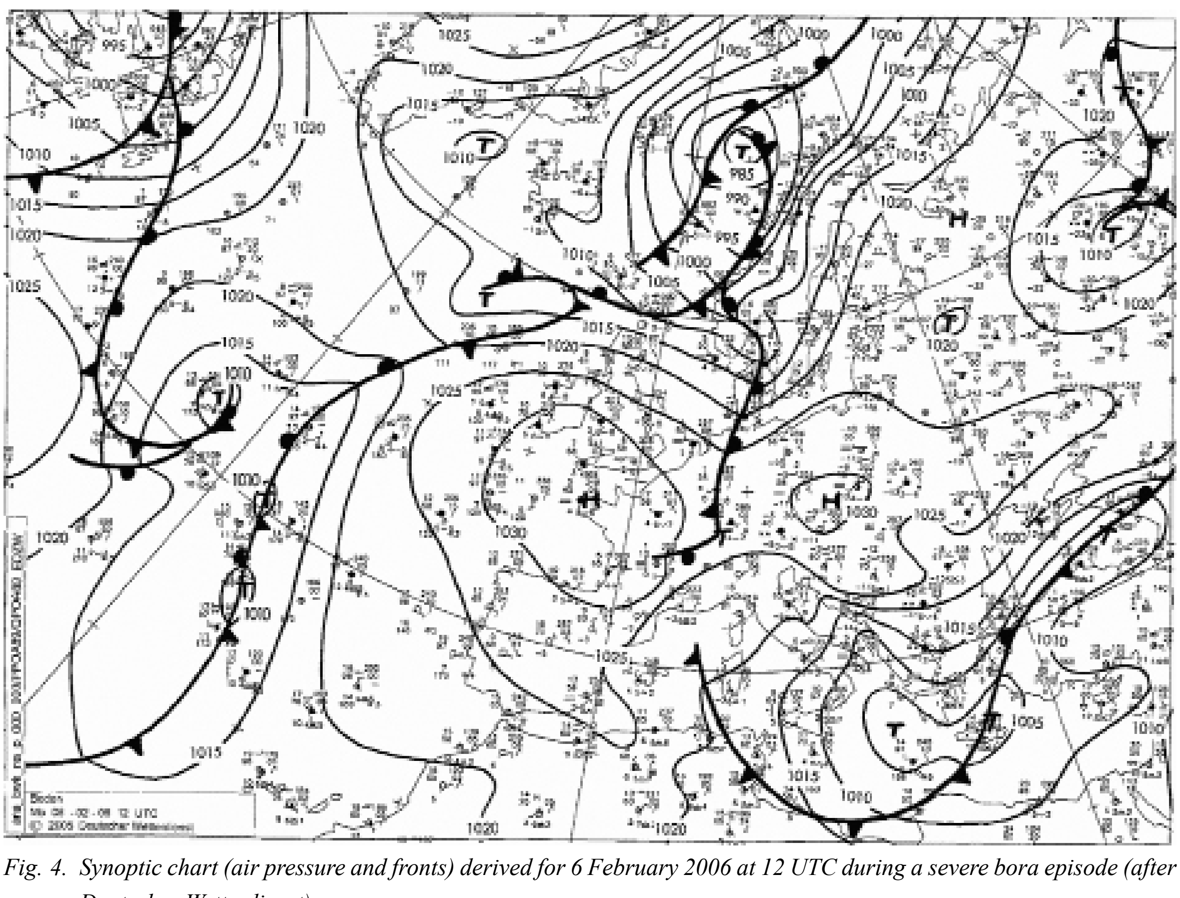

Fig. 4. Synoptic chart (air pressure and fronts) derived for 6 February 2006 at 12 UTC during a severe bora episode (after Deutscher Wetterdienst)

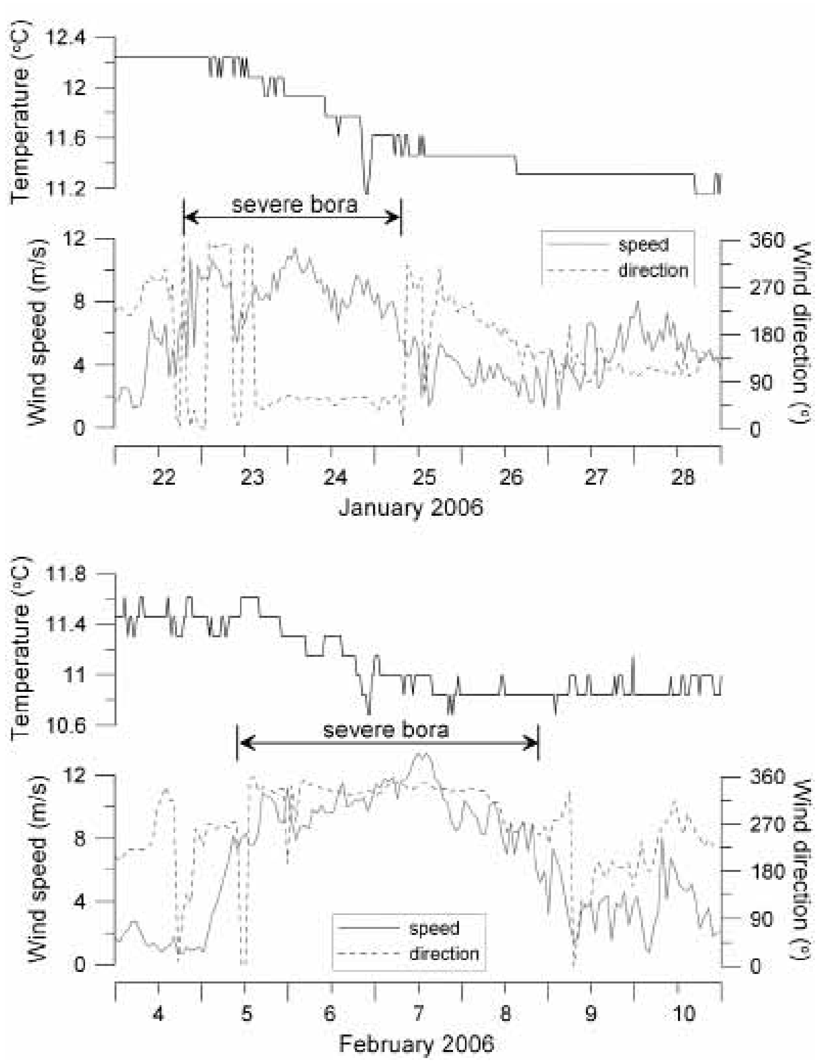

Fig. 5. Temperature at S1 together with wind speed and direction measured at Bari, recorded during two severe boras of winter 2006. The duration of boras used for heat flux estimates is indicated

$$\Delta T = \frac{1}{Hc\rho_0}\int_{t_0}^{t} Q dt = \frac{Q_{cum}}{Hc\rho_0}, \qquad (1)$$

being induced by surface heat loss Q in the time interval between t and t_0 (and having a cumulative value of Q_{cum}), where H is average depth of the water column in BL and taken to be 26 m. The specific heat of sea water c and sea water density ρ_0 was approximated by constant values of 3990 J kg^{-1} K^{-1} and 1028 kg m^{-3}.

We applied (1) to both of the strong bora events, estimating a temperature decrease of 0.8°C between 22 and 25 January 2006, and a decrease of 0.8°C between 5 and 8 February 2006 from the measurements conducted at S1 (Fig. 5). It appears that the first bora event removed heat from the lake at an average rate of 400 W m^{-2}, while the second severe bora removed heat from BL at an average rate of 330 W m^{-2}. These values are realistic compared to the heat loss values estimated for the open South Adriatic Sea during severe episodes, where they are estimated to be as high as 850 W m^{-2} (MANCA *et al.*, 2002). Namely, the Mljet lakes are located on the southern shore and therefore partially protected from the bora influence, resulting in lower heat losses than on the open Adriatic during severe wintertime bora events.

Water exchange at Soline Channel

Although the water exchange through Soline Channel does not allow for the proper ventilation of the lakes, as the water residence time is estimated to exceed a year (BULJAN & ŠPAN, 1976), it is a place where the differences between open sea and BL waters are emerging. The currents are dominantly driven by tides (PEHARDA & VILIBIĆ, 2008), sometimes accelerated by winds and precipitation towards BL or vice versa. High-resolution temperature oscillations measured at station S2 (Fig. 3) indicated the large difference between surface waters throughout the year. By zooming into the series (Fig. 6) one may see that an inflow of open-Adriatic warmer waters, advected from the Ionian Sea by the Adriatic inflowing current (Fig. 7), to the lakes through Soline Channel occurs during wintertime and driven mostly by the tides. Diurnal and semidiurnal temperature oscillations may be quite strong, up to 3°C (Fig. 6). The eulerian temperature oscillations start to oppose the tides sometime during early spring when surface BL waters start to accumulate heat in the surface layer. The difference between BL and open sea temperatures became the largest in July 2007, when tidally-driven temperature changes may surpass 4°C, especially when upwelling-favourable conditions are present off the southern Mljet coast (Fig. 7), bringing colder waters to the surface. It should be added that sea surface temperature (SST) measured by satellite may be significantly greater than the temperature at 3 m (BULJAN & ŠPAN, 1976) - between 1 and 3°C in the period of strong heating and thermocline devel-

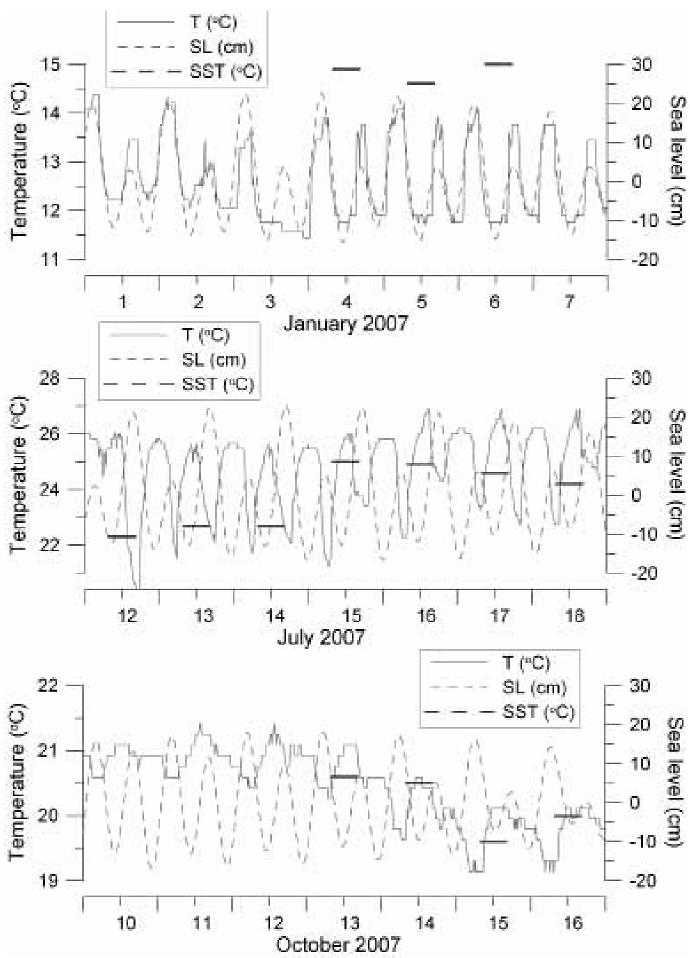

Fig. 6. Three 7-day long time slices of temperature at S2 (red), tidal sea level oscillations at Dubrovnik (which is representative for the Mljet Lakes, blue) and daily sea surface temperature (purple) processed for the closest grid point (taken from http://gos.ifa.rm.cnr.it)

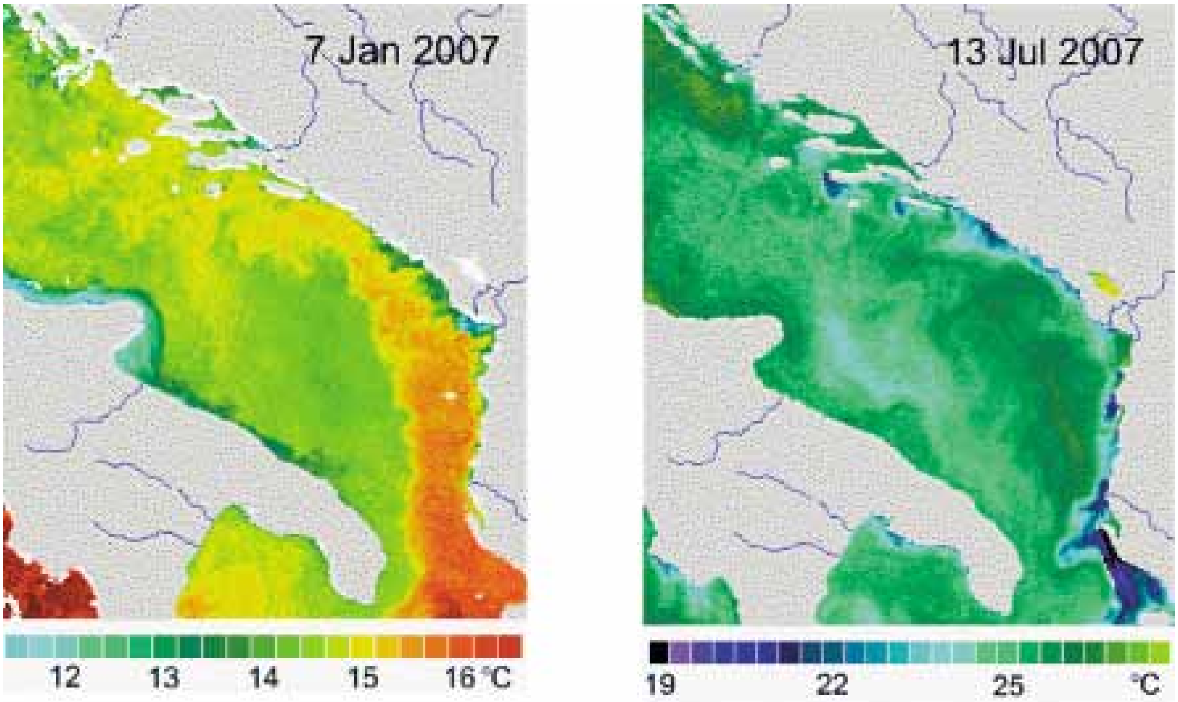

Fig. 7. Sea surface temperature (SST) measured by satellites on (a) 7 January 2007, and (b) 13 July 2007 (taken from http://gos.ifa.rm.cnr.it)

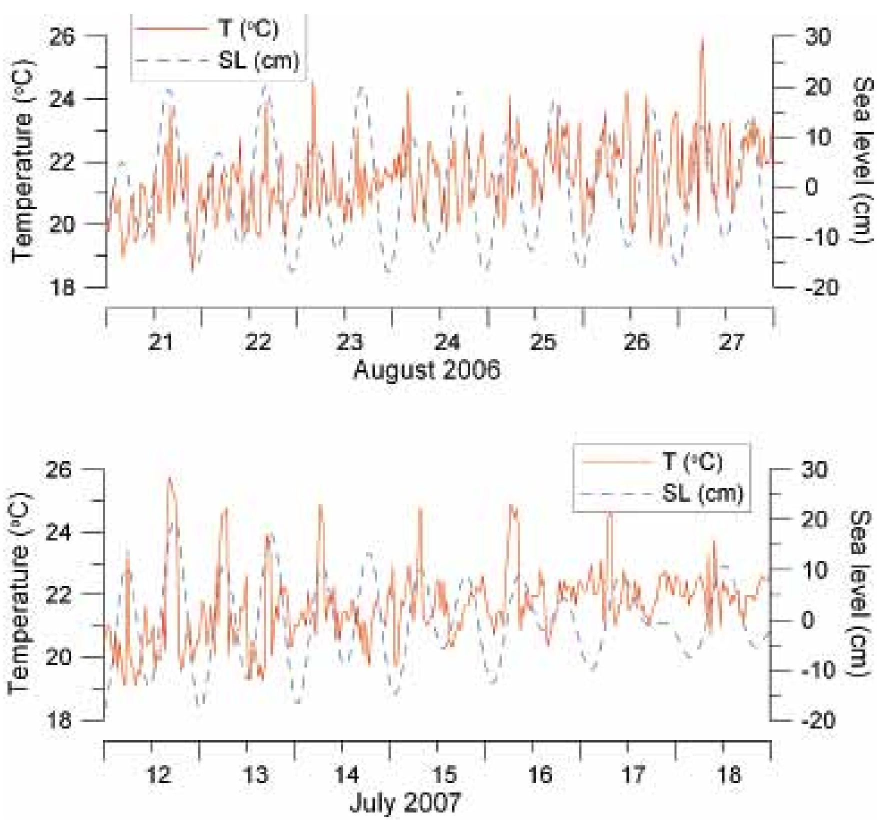

Fig. 8. Two 7-day long time slices of temperature at S1 and tidal sea level oscillations at Dubrovnik

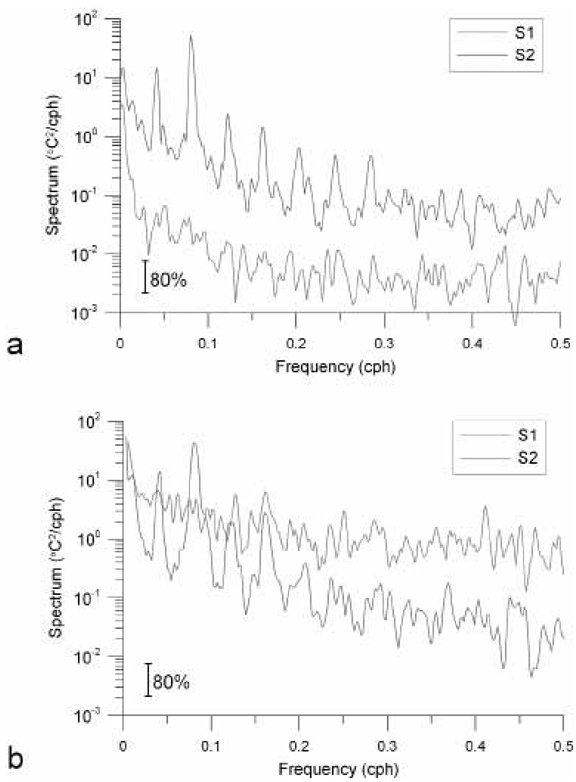

Fig. 9. Spectra derived for the (a) January 2007, and (b) August 2007 temperature series at both S1 and S2 stations

opment (late spring, early summer). The lakes remain warmer until the deepening and dissipation of the thermocline which occurs sometime in October-November.

Another effect may be found in summertime temperature data. As the open sea waters are much colder and saline than the BL surface waters, they are also much denser. Therefore strong turbulence and mixing should be found in BL surface and near-surface layers close to the connecting channel, at least reaching depths equal in density to the open sea waters. Indeed the turbulence may be noted in the S1 summertime series (Fig. 8), thus the mixing occurred in at least the first 15 m of the water column. The maximum temperature is always associated with the high tide, when the open sea waters penetrate most strongly into BL and turbulently mix with the resident waters. Temperature energy content (Fig. 9) clearly shows the existence of the turbulence at S2, as the energy increased by several orders of magnitude with respect to the winter situation. Also, tidal peaks clearly visible in the S2 spectrum vanish in the S1 spectrum as the tidal kinetic energy has been largely relocated towards the turbulence.

Tidal mixing is restricted to the summertime period only; no mixing occurred during the winter period (Fig. 2) as the open Adriatic waters were lighter than BL waters (temperature contribution to the density was stronger than the haline effect).

DISCUSSION AND CONCLUSIONS

Although not designed for the assessment of the hydrodynamic properties of the Mljet lakes, temperature measurements at, and close to, Soline Channel connecting BL to the sea were apparently useful for detecting two interesting phenomena. The first one, the difference of both the surface and deep temperatures between the lakes and the open sea, which appears due to lack of advection and isolation of lake waters, is already documented in the literature though not assessed on the hourly timescale. Daily temperature changes may be as high as 5°C in Soline Channel, both during the winter and during the summer. The wintertime water temperature in BL was measured to be as low as 10.6°C, i.e. 2-3°C lower than the open Adriatic surface temperatures characteristic for the South Adriatic (e.g. VILIBIĆ & ORLIĆ, 2001). Thus the organisms entering the lakes should be accommodated to rapid and strong temperature variations, as well as to temperatures lower than average winter seawater temperatures for the South Adriatic area.

Strong turbulence has been detected in temperature data at S2 during summertime, as that area is affected by the incoming open sea water which is colder and saltier in that period. It is a place where the tidal energy is being largely transformed into the turbulence, which probably contributes to the homogenising of the surface layer and deepening of the pycnocline in the entire BL. In fact, average summertime pycnocline depth in BL (10-20 m, BULJAN & ŠPAN, 1976) is much larger than in similar lakes with no connecting surface channels (e.g. a few meters in

Rogoznica Lake, CIGLENEČKI *et al.*, 2005). However, the quantification of this phenomenon and its propagation within BL should be assessed by numerically modelling the Mljet lakes dynamics and its interaction with the open Adriatic. Also, it probably contributes to the oxygenation of the surface layer and preventing anoxic conditions occurring close to the surface, the latter being restricted to the bottom layers only (BULJAN & ŠPAN, 1976; BENOVIĆ *et al.*, 2000). The implications for benthic organisms are obvious - e.g. the habitat of the coral *Cladocora caespitosa* (Linnaeus, 1767) has been found down to 15 m, i.e. down to the summertime thermocline depth (KRUŽIĆ *et al.*, 2008b).

ACKNOWLEDGEMENTS

Satellite sea surface temperature images were provided by GOS-ISAC and taken from http://gos.ifa.rm.cnr.it/adricosm/index.php. The work has been supported by the MINISTRY OF SCIENCE, EDUCATION AND SPORTS OF THE REPUBLIC OF CROATIA through Grants 001-0013077-1122 and 001-0000000-3203.

REFERENCES

BENOVIĆ, A., D. LUČIĆ, V. ONOFRI, M. PEHARDA, M. CARIĆ, N. JASPRICA & S. BOBANOVIĆ-ĆOLIĆ. 2000. Ecological characteristics of Mljet island seawater lakes (South Adriatic Sea) with special reference to medusa. Sci. Mar., 64(Suppl 1): 197-206.

BULJAN, M. & J. ŠPAN. 1976. Hydrographic properties of the sea water lakes on the Island of Mljet and the adjoining sea in eastern South Adriatic Sea. Acta Adriat., 6(12): 1-227.

CIGLENEČKI, I., M. CARIĆ, F. KRŠINIĆ, D. VILIČIĆ & B. ĆOSOVIĆ. 2005. The extinction by sulphide-turnover and recovery of a naturally eutrophic, meromictic seawater lake. J. Mar. Sys., 56: 29-44.

CUCULIĆ, V., N. CUKROV, Ž. KWOKAL & M. MLAKAR. 2009. Natural and anthropogenic sources of Hg, Cd, Pb, Cu and Zn in seawater and sediment of Mljet National Park, Croatia. Est. Coast. Shelf Sci., 81: 311–320.

ERCEGOVIĆ, A. 1935. Une contribution á la connoissance des conditions hydrographiques et biologiques du lac de l'ille de Mljet (Méléda) (A contribution to the understanding of hydrographic conditions and biology of the Mljet Lakes). Acta Bot., 10: 50-60.

GILL, A.E. 1982. Atmosphere-Ocean Dynamics. Academic Press. Orlando, 662 pp.

GOTOH, R.O., H. SEKIMOTO, S.N. CHIBA & N. HANZAWA. 2009. Peripatric differentiation among adjacent marine lake and lagoon populations of a coastal fish, *Sphaeramia orbicularis* (Apogonidae, Perciformes, Teleostei). Genes and Genetic Systems, 84: 287-295.

HAMNER, W.M & P.P. HAMNER. 1998. Stratified marine lakes of Palau (Western Caroline Islands). Physical Geography, 19: 175-220.

HOLMES, J.A., F.A. STREETPERROTT, T.H.E. HEATON, D.P.F. DARBYSHIRE, N.C. DAVIES & P.E. HALES. 1995. Chemical and isotopic composition of karstic lakes in Jamaica, West Indies. Hydrobiologia, 312: 121-138.

JOHNSON, M.P. & M.J. COSTELLO. 2002. Local and external components of the summertime plankton community in Lough Hyne, Ireland a stratified marine inlet. J. Plankton Res., 24: 1305-1315.

KRUŽIĆ, P., A ŽULJEVIĆ & V. NIKOLIĆ. 2008a. The highly invasive alga *Caulerpa racemosa* var. *cylindracea* poses a new threat to the banks of the coral *Cladocora caespitosa* in the Adriatic Sea. Coral Reefs, 27: 441-441.

KRUŽIĆ, P., A ŽULJEVIĆ & V. NIKOLIĆ. 2008b. Spawning of the colonial coral *Cladocora caespitosa* (Anthozoa, Scleractinia) in the Southern Adriatic Sea. Coral Reefs, 27: 337-341.

MALEJ, A., V. TURK, D. LUČIĆ & A. BENOVIĆ. 2007. Direct and indirect trophic interactions of *Aurelia* sp. (Scyphozoa) in a stratified marine environment (Mljet Lakes, Adriatic Sea). Mar. Biol., 151: 827-841.

MANCA B.B., V. KOVAČEVIĆ, M. GAČIĆ, D. VIEZ-

ZOLI. 2002. Dense water formation in the Southern Adriatic Sea and spreading into the Ionian Sea in the period 1997–1999. J. Mar. Syst., 33-34: 133-154.

MARTIN, L.E., M.N. DAWSON, L.J. BELL & P.L. COLIN. 2006. Marine lake ecosystem dynamics illustrate ENSO variation in the tropical western Pacific. Biol. Lett., 2: 144-147.

MHS. 2007. Meteorological and Hydrological Bulletin. Meteorological and Hydrological Service of the Republic of Croatia, Zagreb, 80 pp.

PEHARDA, M. & I. VILIBIĆ. 2008. Recruitment effect and conservation strategy in small marine protected area: the example of saltwater lake on Island of Mljet (Adriatic Sea). Acta Adriat., 49(1): 25-35.

ŠILETIĆ, T. & M. PEHARDA. 2003. Population study of the fan shell *Pinna nobilis* L. in Malo and Veliko Jezero of the Mljet National Park (Adriatic Sea). Sci. Mar., 67(1): 91-98.

VILIBIĆ, I. & M. ORLIĆ. 2001. Least-squares tracer analysis of water masses in the South Adriatic (1967-1990). Deep-Sea Res. I, 48: 2297-2330.

VILIBIĆ I. & D. ŠANTIĆ. 2008. Deep water ventilation traced by *Synechococcus* cyanobacteria. Ocean Dyn., 58: 119-125.

VILIBIĆ, I., B. GRBEC & N. SUPIĆ. 2004. Dense water generation in the north Adriatic in 1999 and its recirculation along the Jabuka Pit. Deep-Sea Res. I, 51: 1457-1474.

VULETIĆ, A.A. 1953. Structure geologique du fond du Malo jezero et Veliko jezero sur l'isle de Mljet (Geological structure of the seabed in Malo jezero and Veliko jezero on the island of Mljet). Acta Adriat., 6(1): 1-63.

WUNSAM, S., R. SCHMIDT & J. MÜLLER. 1999. Holocene lake development of two Dalmatian lagoons (Malo and Veliko Jezero, Isle of Mljet) in respect to changes in Adriatic sea level and climate. Palaeogeogr. Palaeoclimatol. Palaeoecol., 146: 251-281.

Received: 20 February 2009

Accepted: 7 June 2010

Dinamika slanog morskog jezera (Veliko jezero, Mljet, Jadran) zabilježena pri mjerenjima temperature mora

Ivica VILIBIĆ*, Ante ŽULJEVIĆ i Vedran NIKOLIĆ

Institut za oceanografiju i ribarstvo, pp 500, 21000 Split, Hrvatska

**Kontakt adresa, e-mail: vilibic@izor.hr*

SAŽETAK

Rad opisuje termohalina i dinamička svojstva mljetskih jezera, temeljem analize visokofrekventnih mjerenja temperature obavljanih u intermedijarnom sloju Velikog jezera i kanalu Soline tijekom dvije godine (prosinac 2005. – listopad 2007.). Mjerenja ukazuju da je temperatura jezera niža od temperature otvorenog mora za oko 2-3 ^{o}C tijekom zimskih mjeseci, dok je tijekom ljeta viša oko 4^{o}C u površinskom sloju. Nekoliko zanimljivih oceanografskih procesa je zabilježeno na mjerenjima, od kojih je istraženo hlađenje jezera tijekom zime 2006. godine, dnevne i poludnevne promjene temperature pobuđene plimotvornom silom, te pojava turbulencije u području Velikog jezera bližem kanalu Soline. Mjerenja su ukazala na činjenicu da turbulencija uzrokuje izrazito vertikalno miješanje i poniranje termokline i piknokline za vrijeme ljetnih mjeseci u površinskom i intermedijarnom sloju Velikog jezera, jer vode otvorenog mora posjeduju višu gustoću od voda jezera.

Ključne riječi: slano jezero, vodene mase, temperature mora, Jadran