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Hydrothermodynamics of Lake Tovel. Part I: Experimental analysis

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SUMMARY - *Hydrothermodynamics of Lake Tovel. Part I: Experimental analysis* - Lake Tovel (Trentino, Italy) is a small, oligotrophic alpine lake, which was subject, until 1964, to a water reddening due to an algal bloom. The present work is part of a multidisciplinary project aimed at understanding the main causes for the establishment of the phenomenon. We have collected temperature, velocity and mixing data during two field campaigns (2002 and 2003) in the Summer-Fall period. In the study we have investigated both the characteristics of the whole lake and that of the Red Bay, a little inlet in the south-western part of the lake, where the reddening phenomenon was mainly occurring. Five temperature sensors chains have been placed along the main axis of the lake in order to study the seasonal stratification cycle. The flow structure has been characterised using an ADCP doppler profiler, an ADV doppler probe and six GPS-equipped drifters. Data collected have been correlated with the wind forcing, the thermal stratification and the underwater inflows. Field measurements highlights the establishment of regular wind driven currents limited to a 1 m surface layer, that during the afternoon feed the Red Bay, with flow reverse in the layer below. The presence of underground springs in the Red Bay produces an intense stratification, such that the diapycnal exchanges becomes negligible.

RIASSUNTO - *Idrotermodinamica del Lago di Tovel. Parte I: analisi sperimentale* - Il Lago di Tovel (Trentino, Italia) è un piccolo lago alpino, oligotrofico e meromittico, caratterizzato fino al 1964 dall'arrossamento delle sue acque, dovuto alla fioritura di una particolare alga. Nell'ambito di un progetto multidisciplinare dedicato all'identificazione dei meccanismi che hanno favorito il verificarsi e poi causato la scomparsa del fenomeno, sono state condotte due campagne di misura (estate-autunno 2002 e primavera-estate-autunno 2003) con l'obiettivo di determinare i processi di riscaldamento e di raffreddamento delle acque del lago, di individuare le correnti che si sviluppano in relazione alle forzanti esterne (vento, afflussi e deflussi ecc.) e di studiare le interazioni tra la Baia Rossa (zona in cui si verificavano gli arrossamenti) e il resto del lago. La caratterizzazione mediante i dati raccolti sul campo ha evidenziato l'influenza degli aspetti topografici, la presenza di sorgenti fredde nella baia e la diversa risposta idrodinamica del bacino al variare della stratificazione. Infine, le misure hanno mostato l'instaurarsi di correnti interne al lago sia per effetto del vento alla superficie sia per differenze di densità (moti baroclinici).

Key words: Tovel Lake, mixing, temperature, seiches
Parole chiave: Lago di Tovel, mescolamento, temperatura, sesse

1. INTRODUCTION

The present work has been developed within the framework of the research project SALTO, a multidisciplinary study on Lake Tovel (Trentino – Italy). The project was aimed at understanding the causes that have led to the disappearence of the reddening phenomenon that was occurring yearly until 1964. In this context with our study we attempt to characterize the hydrodynamic and thermodynamic behaviour of the lake through the collection of data and the subsequent analysis of experimental results. Temperature, velocity and mixing data have been collected during two summer field campaigns performed in 2002 and 2003, focusing mainly on the "Red Bay", a little inlet in the south-western part of the lake, in which the reddening phenomena were particularly frequent and intense.

2. APPLICATION CONTEXT

Lake Tovel is located within the northern Brenta Group (Fig. 1), the wildest part of the Brenta Dolomites; because of its natural beauty, the zone is part of a natural reserve, the Adamello-Brenta Natural Park.

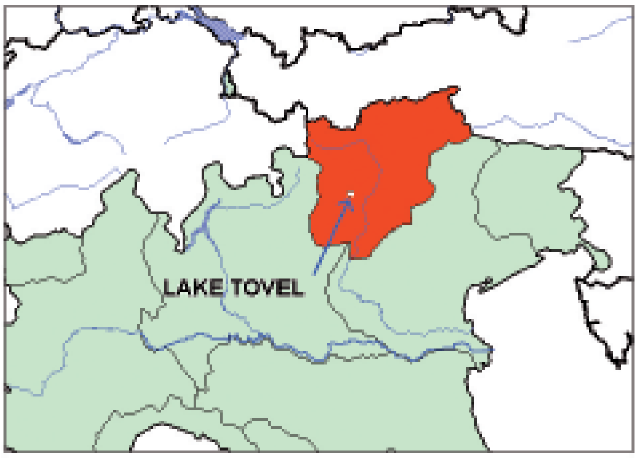

Fig. 1 - Geographic localisation and overview of Tovel Valley.
Fig. 1 - Localizzazione geografica della Val di Tovel.

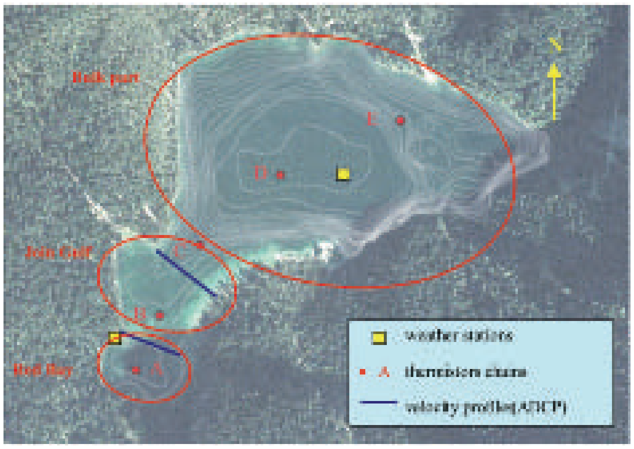

Fig. 2 - Bathymetry of Lake Tovel and location of measurement points: the circles defines the three sub-zone.
Fig. 2 - Batimetria del Lago di Tovel e dislocazione dei punti di misura: i cerchi indicano la suddivisione in tre zone.

Lake Tovel is a temperate, meromictic (with dimictic mixolimnion), oligotrophic mountain lake, known as the *red lake* due to the red colour of its water. The process of reddening, which was occurring yearly in summer due to the presence of a particular alga, whose identification and classification has been an object of the SALTO project, suddenly ceased after the summer 1964. Since then several studies have been developed and many hypothesis have been formulated to explain the extinction of the phenomenon.

The Tovel Valley ranges from the dolomitic Passo Grosté (South-West) to the confluence of streams S. Emerenziana and Tresenga (North-East) at 800 m a.s.l. Its length is about 17 km; the valley is surrounded by two Alpine ridges, whose maximum height reaches 3000 m. The lake is located nearly in the middle of the valley, at an altitude of 1178 m.

The geologic structure is characterized by the presence of several landslides, even of recent formation, that pile up the old glacial moraines and originate the phenomenon of "*marocche*". The origin of Tovel Lake is due to the deposition of collapsed material in the centre of valley.

The lake has an outlet, the Tresenga River, that disappears close to Glare village under the collapsed material and reappears further downstream, creating some small pools which are used to feed two irrigation plants. The tributaries of Lake Tovel are the Rislà creek, whose contribution is small and ephemeral, and the S. Emerenziana creek, that originates in a gorge at an altitude of 1900 m and then disappears, owing to the calcareous-dolomitic nature of the basin, feeding the lake by underground inflows. The catchment area is slightly less than 40 km^2 and the mean elevation of the surrounding rocky crests is about 2500 m a.s.l. Further details can be found in Rizzi & Tonetta 2004 and in Rizzi 2004.

The available bathimetry of the lake indicates isobathes up to a depth of 38 m with respect to the zero level, which corresponds to a lake volume of 7.367.600 m^3, an area of 382.000 m^2 and coast line extension of 3480 m. It is important to note that the pond is characterised by marked seasonal water level fluctuations (3÷5 m): during the summer 2003 (a relatively dry season) the water level drop was more than 3 m.

The lake has a length of roughly 1 km in the NE-SW direction and a width of about 750 m in the NW-SE direction. The mean depth is $z_m = \frac{V}{A} = 19.28m$, while the characteristic length of lake can be computed as $L = \sqrt{2A} = 874m$.

A better schematisation of the lake is obtained dividing the lake into three parts. In fact, Lake Tovel shows a nearly triangular planimetric shape, while the bathimetric map allows one to distinguish three different regions: the SW gulf (called "Red Bay") with maximum depth smaller than 6 m and mild shores, the bulk part (NE part) where the depth reaches a maximum value of 39 m and shores are steep, and an intermediate zone joining the SW gulf to the main lake, through a sharp slope (Fig. 2).

According to historical studies on the lake, the shallowness of the Red Bay has been always considered to play a basic role in the reddening phenomenon. In fact, the process has been typically related to the concurrence of two distinct effects: the former, biological, due to the nature of the algae, and the latter, geophysical, caused by the breeze. The Red Bay

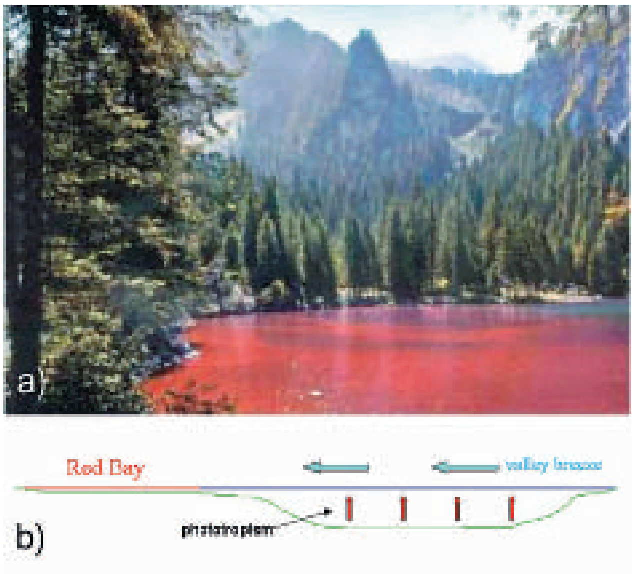

Fig. 3 - a) The Red Bay in a picture of 1963; b) a possible mechanism for the algae accumulation in the bay (Baldi 1941).
Fig. 3 - a) La baia rossa in un'immagine del 1963; b) il meccanismo ipotizzato di trasporto e accumulo delle alghe nella Baia Rossa (Baldi 1941).

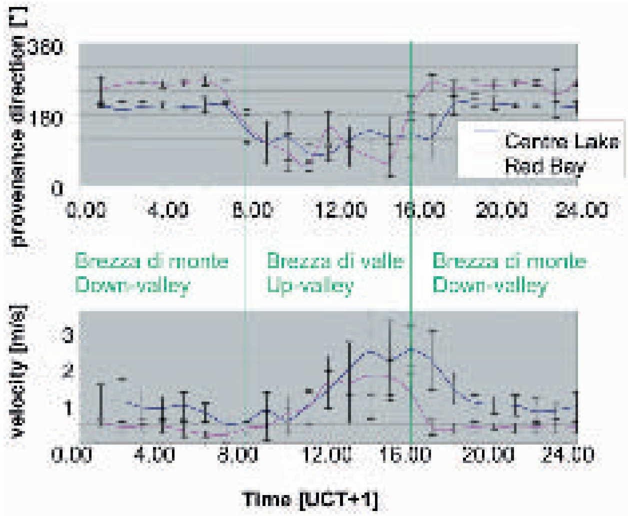

Fig. 4 - Diurnal cycle of up- down-valley breeze: mean value and standard deviation of the wind data collected in the summer 2002 by the two weather stations on Lake Tovel (in the center of the lake and in the Red Bay).
Fig. 4 - Ciclo giornaliero del vento nel periodo estivo (estate 2002): valore medio e deviazione standard della velocità e della direzione nelle due stazioni meteo, a centro lago e nella Baia Rossa. Sono state evidenziate le brezze di monte (notturne) e di valle (diurne).

(Fig. 3) was the most suitable zone for this process to occur (Baldi 1941): in fact, the bay was subject to a large feed of nutrients from underground springs and was able to store algae driven by surface currents. Furthermore, warming of the Red Bay is more intense with respect to the main lake due to its small thermal inertia.

The survey of the meteorological dynamics of the Tovel Valley (de Franceschi & Zardi 2006) has pointed out that the lake area is subject to a typical cycle of up-valley diurnal and down-valley nocturnal breezes along the SW-NE direction; the wind reaches its maximum intensity in the afternoon, approximately at 14:00 (Fig. 4). Such wind is strongly influenced by the net radiation flux on the lake and on the rocky walls in the highest part of the valley, which induces convective motions. It is worth to notice that the micro-climate at Lake Tovel is characterized by a frequent formation of convective clouds, that often trigger short precipitations during the afternoon and a reduction of the incoming radiation (Rizzi 2004).

3. METHODS

Extensive field measurement has been carried out during the periods July-October 2002 and May-October 2003. During the field campaigns five chains of temperature sensors (Handylog DK500) have been positioned along the main lake axis (see Fig. 2). The forty probes employed could cover a temperature range between -20 °C and +80 °C, with a precision of ±0.05 °C; a calibration between 4 °C and 30 °C has been carried out by means of a pt100 probe in a thermostated bath. Further temperature profiles have been collected using another portable probe, to better characterize the temperature distribution in the lake, particularly in the Red Bay. The availability of temperature profiles at different locations has allowed us to identify the seasonal cycle of thermal stratification; furthermore, since the longitudinal axis of the lake coincides with the main direction of the wind, we have used the same set of data to determine the effect of the wind forcing on the isopycnal surfaces. These measurements suggest that in the epilimnion, when the surface wind stress increases, the isopycnal surface at the upwind end rises and deepens at the downwind end. Furthermore, since the stratification is not strong, tilting of the isopycnal surfaces also occurs in the metalimnion: downwelling at the upwind end, due to the wind forcing, produces internal seiches, which are clearly detectable from the isotherms fluctuations.

Flow velocity has been measured by two Doppler based instruments: an ADCP (RDI - Rio grande) profiler, which has been moved at several representative places to obtain velocity profiles on the water column, and a deployed ADV (SonTek – ADVOcean probe), which has been used to get measurements of local currents (coupled with a fluxmeter) and to complete the vertical profiles mainly near the bottom and at the surface, where the ADCP signal is disturbed. Furthermore, in order to get indication about surface main circulations, eight drifters equipped with GPS system have been released during the period August-September 2003, to obtain a continuous monitoring of currents in the surface layer.

More detailed measurements have been performed in the Red Bay, which is the more interesting area for the reddening phenomena, where we have also observed a stronger stratification due to the intense underground water inflows, with a temperature variation of 10 °C concentrate over a depth of 1 m. We have also carried out a specific investigation study on a transect located at the boundary between the Red Bay and the transition zone (see Fig. 2), in order to understand the exchange process across this section.

Another aspect which has been taken into consideration during the field works is the process of vertical mixing in the Red Bay, which can be taken as an indicator of the amount of exchange occurring through the water column. Specific surveys have been carried out in August 2004 using a SCAMP (PME - Self Contained Autonomous MicroProfiler), in order to quantify the vertical diffusivity (k_z [m^2s^{-1}]) from temperature microstructure profiles: the instrument can be moved through the water column at a speed of 0.1 m s^{-1} and collects temperature data with two sensors at a frequency of 100 Hz.

4. RESULTS

4.1. *Thermodynamics*

The thermal data analysis has been performed paying particular attention to the seasonal trend and the diurnal trend; furthermore, a comparison has been performed between data from different chains and temperature profile collected by portable probe.

The chain D, located in the centre of the lake, can be considered as representative of the main seasonal dynamics occurring in Lake Tovel. Results reported in figure 5 suggest that, from May to August, the euphotic layer is clearly distinguishable from the deeper zone where the light can't seep. The diurnal heating cycle manifests only within three meters from the surface. In the region below, it is possible to recognize the gradual deepening of the isotherms due to the seasonal heating. The temperature profiles also show that a deep zone steadily establishes in the whole period: the bottom temperature changes from 4.75 °C to 5.05 °C. This fact, as also confirmed by the data of nutrients concentration, witnesses the occurrence of a

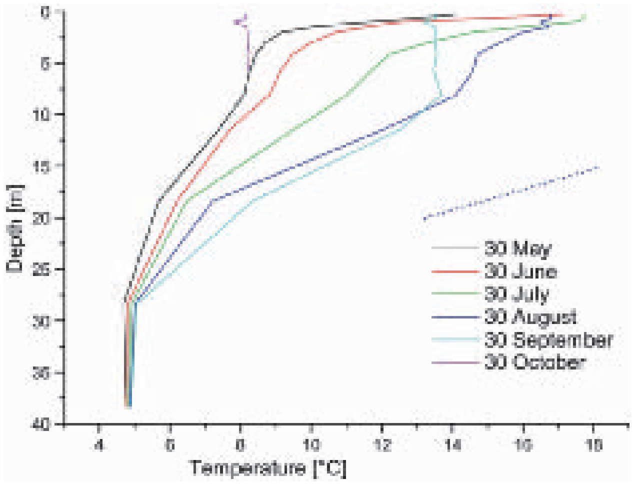

Fig. 5 - Seasonal evolution of the vertical temperature profiles at chain D (dotted line: thermocline conventional slope).

Fig. 5 - Evoluzione dei profili verticali di temperatura durante il periodo estivo e autunnale alla catena D (la linea tratteggiata indica la pendenza del gradiente convenzionale del termoclino).

separate deepest layer where the vertical transport is negligible (monimolimnion). Within the above region the mixolimnion develops, where mixing processes occur. Here temperature changes slowly; in fact, the temperature gradient keeps lower than the conventional thermocline gradient (indicated by a dotted line in Fig. 5) for most of the period of observations. As summer is advancing, the thermocline erosion increases and the limit between hypolimnion and surface mixed layer moves from the depth of 3 m in June to 5 m in July, 8 m in August and 10 m in September.

We may note that an epilimnetic zone, as conventionally defined (Spigel & Imberger 1980), never establishes in Lake Tovel: in fact the wind is too weak to form a well defined mixed layer at the surface and cooling process is required to produce a clearly detectable homogenous layer (Rizzi 2004).

Measured data also suggest that the mechanism of surface heating in May and June follows fairly well the Beer's law:

$$I_z = I_0 e^{-kz} \quad (1)$$

where I_z is the intensity of radiation at depth z and I_0 is the intensity at the surface, with the light extinction coefficient nearly equal to 0.13 m^{-1} (Tonetta 2003).

4.2. *Velocity field*

The data collected with the ADCP in different periods during the summer 2003 near the thermistors

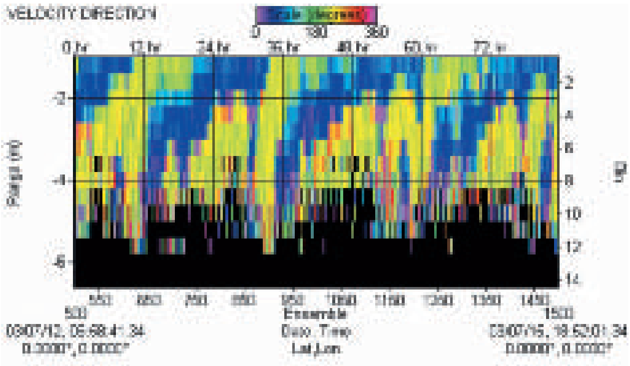

Fig. 6 - Velocity direction measured by ADCP near the temperature chain C in the period July 12th-15th 2003.
Fig. 6 - Direzione delle correnti misurate dall'ADCP dal 12 al 15 luglio 2003 nei pressi della catena di temperatura C.

chain C (see Fig. 2) show a fairly regular dynamics, both for the magnitude and the direction of the fluxes. A similar structure repeats nearly every day as shown in figure 6. It is worth to note that during the night the first layer measured by the profiler moves in direction SW, just opposite to the down-valley breeze. The same phenomenon occurs during the day, when the first layer moves in opposite direction (NE) with respect to the daily breeze. This behaviour can be related to the weak stratification of Lake Tovel, which leads to the establishment of a thin surface mixed layer. Indeed, the circulation inverts its direction very close to the surface, where the ADCP is not able to collect data. This is confirmed by the profiles collected by ADV and fluxmeter which highlights the presence of a thin layer moving according to the wind direction. The trajectories of drifters also suggest that the first surface layer moves in the wind direction, except near the sheltered shores.

Near the surface the velocity magnitude never exceeds 0.05 m s^{-1}, while in the adjacent layer moving against the wind the maximum velocity is nearly 0.03 m s^{-1}.

Below the surface layers a more complex dynamics is observed. In this case a comparative study of wind, temperature and velocity data can provide an information on the fluctuation of the isopycnal surfaces and the related currents (Fig. 7).

The velocity field is conditioned by several factors: the up- down-welling due to the wind, the stratification, the morphology of the bottom and the shores. All these ingredients produce internal waves, which can be investigated by means of spectral analysis of isotherms fluctuation and velocities. Results of such analysis, summarized in figure 8, indicates the occurrence of various events characterised by different periodicity with respect to the wind forcing. At the chosen depth (1.6 m) the spectrum shows a

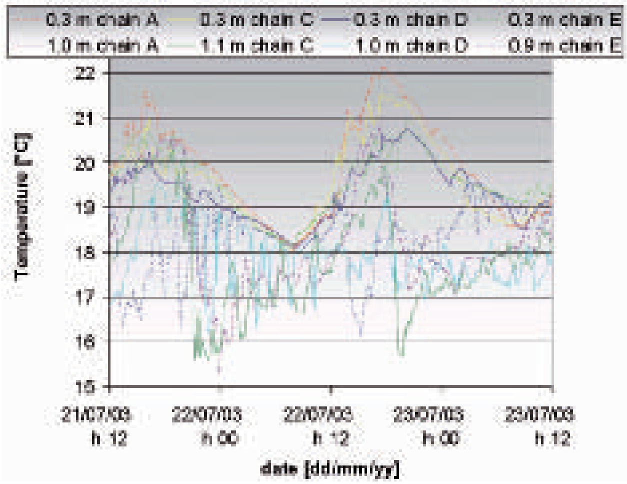

Fig. 7 - Temperature data collected near the surface and 1 m below at the thermal chains A, C, D, E. In the first windy day a strong fluctuation is detected in the evening, whose intensity decreases during the night and in the following sunny day (the black line shows the damping of the seiches).
Fig. 7 - Fluttuazioni di temperatura in superficie e ad 1 m di profondità registrate dai sensori delle catene A, C, D, E. Alla sera del primo giorno (molto ventoso) si notano forti oscillazioni smorzate col trascorrere della notte (la linea nera tratteggiata indica lo smorzamento), mentre per il secondo giorno, caratterizzato da bel tempo, questi movimenti legati alle sesse appaiono con intensità decisamente inferiore.

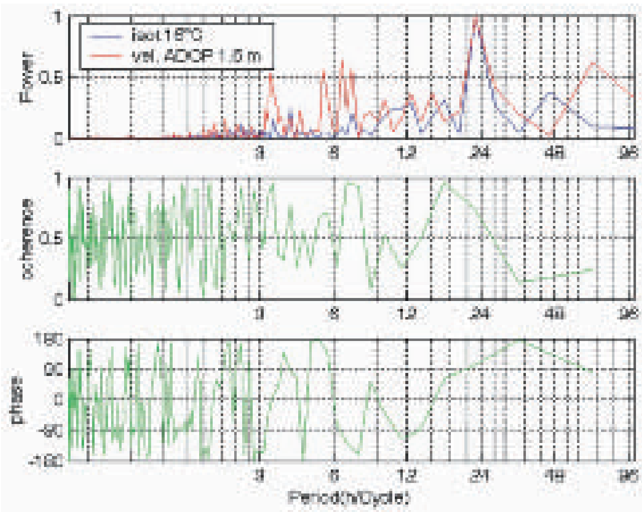

Fig. 8 - a) Spectral analysis of velocities measured by ADCP at 1.6 m depth and 16 °C isotherm in the period July 10th-18th 2003; b) correlation between the two signals; c) phase difference.
Fig. 8 - a) Spettro di energia; b) coerenza; c) differenza di fase, dell'isoterma a 16 °C e della velocità misurata a 1,6 m di profondità con ADCP dal 10 al 18 luglio 2003.

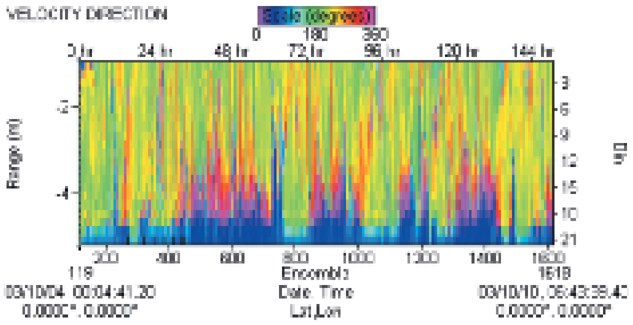

Fig. 9 - Direction of the currents measured by ADCP from October 4th to 10th 2003.

Fig. 9 - Direzione delle correnti misurate dall'ADCP dal 4 al 10 ottobre 2003.

a) b)

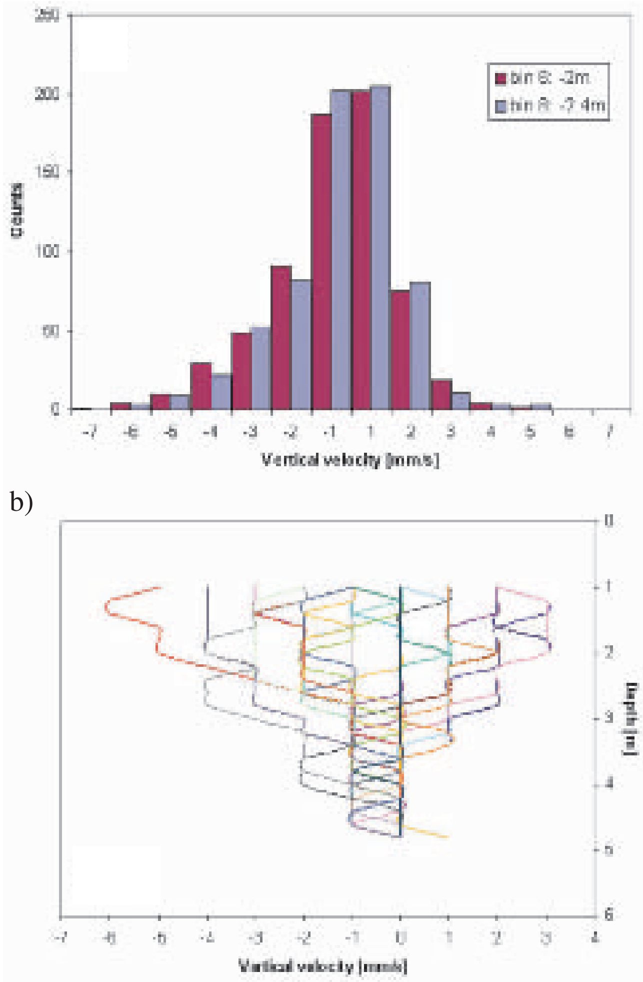

Fig. 10 - Vertical velocities from ADCP measurements (October 4th-10th 2003): a) intensity distribution at 2 m and 2.4 m depth; b) vertical profiles within the core of convective plumes.

Fig. 10 - Velocità verticali misurate dall'ADCP dal 4 al 10 ottobre: a) distribuzione delle intensità alle profondità di 2 m e 2,4 m; b) profili verticali rappresentativi dei nuclei dei pennacchi convettivi.

peak corresponding to 24 hours, which is the wind periodicity.

Moreover, further movements are detected, whose period ranges between 3 and 24 hours. The low value of coherence displayed by peaks falling in the range 8-12 hours witnesses the superimposition of different causes like the heating and cooling processes; on the contrary coherence is higher for peaks corresponding to 7, 6.7, 5.5, 4, 3.5 hours. In these cases velocity and temperature fluctuation are often 90° out of phase, which implies that these movements are related to internal seiches. In fact when the displacement of the internal wave is maximum, the velocity changes its direction, while when the velocity is maximum, the isopycnal surface is roughly at its equilibrium position (Münnich & Wüest. 1992; Rizzi 2004).

The period of cooling begins in September and ends with the ice formation on the superficial layer in November. During this period the ADCP measures a current directed to NE at the bottom (Fig. 9), as also confirmed by measures performed with the ADV positioned near ADCP in October. The main direction of such currents is 60°: as the autumn proceeds, its intensity decreases and direction exhibits a certain scatter. This flow pattern doesn't seem to be influenced by the period of the day. The current, which involves the entire lake, probably arises on a gravity adjustment due to differential cooling, which is stronger in the Red Bay than in main lake (Rizzi 2004).

We may note that the velocity of this baroclinic current can be estimated equating the value of the potential energy losses to the kinetic energy gains of the mass flow (Roget & Colomer 1996), through the following expression:

$$u = \sqrt{2a\Delta Tgh} \qquad (2)$$

where ΔT is the temperature difference between the transition zone and the main lake (see Fig. 2) and h is the vertical distance between the centre of mass of colder part and the depth where the current has been measured. Estimated values of velocity, 0.03-0.04 m s^{-1}, are comparable with those collected near the bottom with the ADV probe.

We also note that in October the ADCP measures relatively high values of vertical velocities. In fact, during the summer vertical velocities never reach $1 \cdot 10^{-3}$ m s^{-1}, while during the events characterised by significant heat loss speed intensities greater than $5 \cdot 10^{-3}$ m s^{-1} are observed. Furthermore, the direction of flux changes alternatively; these movements are caused by the drowning of plumes of cold heavy water. These thermal plumes fall down mainly during the night, when the heat fluxes outgoing from the lake are more intense.

As shown in the histogram reported in figure 10a, the distribution of vertical velocity is asymmetric both in the superficial layer and in deeper zones. In general, downwards plumes exhibit higher velocities with respect to upward plumes, as found in other field observations (Tobias *et al.* 2002). Moreover figure 10b suggests that plumes velocity decreases as the depth is increasing.

The magnitude of such vertical flows can be estimated through a simple energy balance (Imberger & Patterson 1990), which gives:

$$w = \sqrt[3]{\frac{\alpha g h H}{c_p \rho}} \tag{3}$$

where α is the water heat expansion coefficient, h is the cooling layer, H is the outcoming heat flux, c_p is the specific heat at constant pressure and ρ the density of the water. Setting $\alpha = 2.57\ 10^{-4}\ °C^{-1}$, $g = 9.8\ m\ s^{-2}$, $h = 1 \div 4\ m$, $H = -170\ W\ m^{-2}$, $c_p = 4179\ J\ Kg^{-1}\ °C^{-1}$ and $\rho = 998\ kg\ m^{-3}$ we obtain $w = 4 \div 7\ 10^{-3}\ m\ s^{-1}$.

4.3. The Red Bay

Temperature data have revealed the different thermal stratification of the Red Bay as compared with the main lake. The main distinctive features of this region of the lake are the relatively low depth (3-5 m depending on the level of the free surface) and the abundant inflows from underwater springs.

Due to its shallowness, the Red Bay has a lower thermal inertia, such that the diurnal heating is faster: the maximum temperature of nearly 23 °C collected through the chain A during the summer 2002 is the highest in the whole lake, in spite of the sheltered position of the bay. The heating is limited to a thin surface layer due to the continuous incoming of water from the subsoil that keeps the temperature below 6 °C in the lower part of the water column.

An analysis of the fluxes through the transect between the Red Bay and the transition zone (see Fig. 2) has been conducted collecting temperature and velocity data. A detailed study of the temperature field in this area shows the presence of three cold "channels" near the bottom, with water temperature equal to 7-8 °C, as shown in figure 11, and relatively high velocity; for the deepest of these cold currents a NE velocity ranging between 0.1 and 0.15 m s^{-1} has been measured through the ADV probe and the fluxmeter. The total water volume passing through this section has been estimated as equal to15.000 m^3 per day (Rizzi 2004).

We may note that the velocity profiles collected by the ADCP in the Red Bay also suggest that the direction of the flux in the deeper part within the Red Bay is invariably directed out of the bay (60-70°N).

In the surface layer the dynamics conforms to the general behaviour of the lake: figure 12 shows the trajectories of a drifter during the up-valley wind (from 11 am to 4 pm): the path starts from the circle and moves in a counter-clockwise direction.

Microstructure data collected with the SCAMP are used to quantify the vertical mixing, through the estimate of the vertical diffusivity. Its knowledge is relevant to obtain a suitable measure exchange along the water column.

The analysis of the correlation between the two high frequency temperature profiles provided by the SCAMP and the comparison of their spectrum with

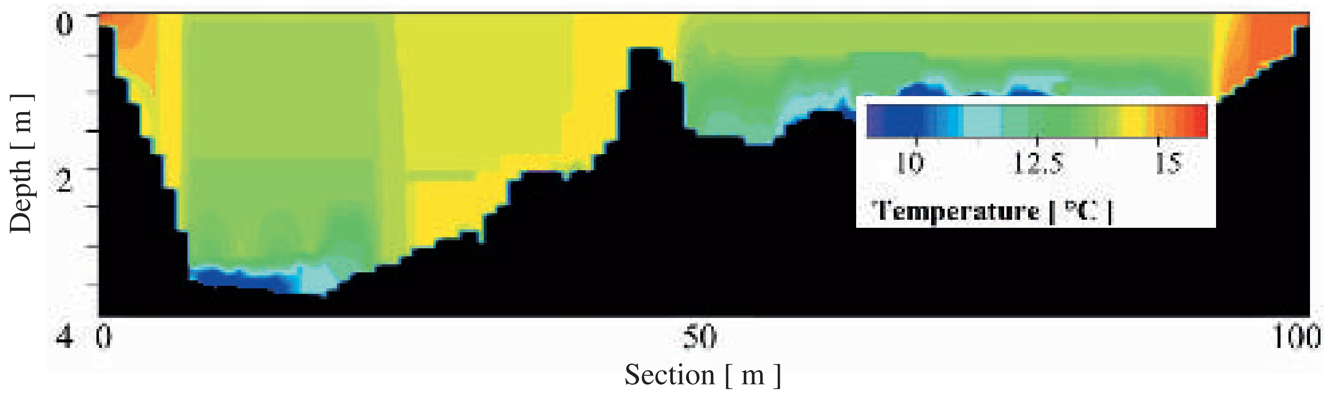

Fig. 11 - Vertical section of temperature field at the transect between the Red Bay and the transition zone of the lake, from east to west (in figure 1 this section lies between the chains A and B): three zones with temperature of about 7 °C are located near the bottom.

Fig. 11 - Sezione verticale del campo di temperatura all'imbocco della Baia Rossa, da est a ovest (in figura 1 corrisponde alla sezione di misura con ADCP tra le catene A e B): sono visibili 3 zone con temperatura di circa 7 °C dove scorrono i canali sul fondo.

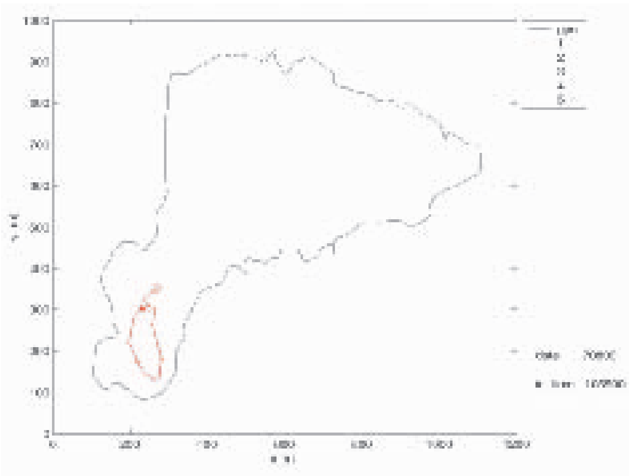

Fig. 12 - Drifter path tracked with GPS data: the drifter has been released at 11 am (circle) and stopped at 4 pm.
Fig. 12 - Percorso di un drifter tracciato con i dati del GPS. La misura ha avuto inizio alle 11 dal punto indicato con un cerchio e è terminata alle ore 16 dello stesso giorno.

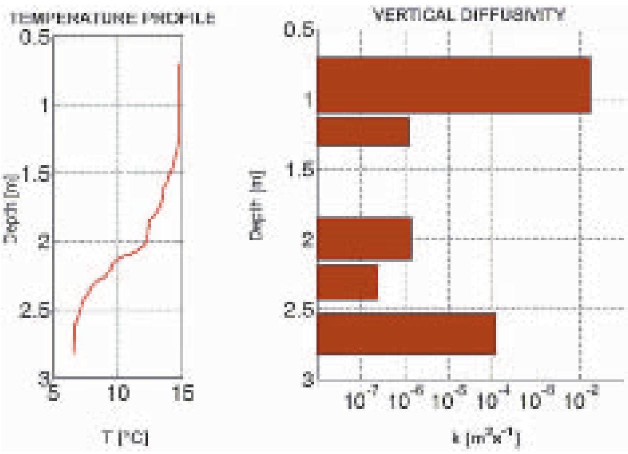

Fig. 13 - Temperature profile collected through the SCAMP profiler in the Red Bay on August 31th 2004 (left) and the vertical diffusivity (right).
Fig. 13 - Profilo di temperatura (a sinistra) in Baia Rossa il 31 agosto 2004 e coefficienti di diffusione turbolenta (a destra) stimati dai microprofili di temperatura ottenuti con lo SCAMP.

the Batchelor theoretical spectrum, allow for an estimate of the dissipation of turbulent kinetic energy (ε) (Luketina & Imberger 1998). We note that only a small fraction (the buoyancy flux) of the rate of energy that transfers to the microscale produces diapycnal exchange: this fraction is computed by many authors through a mixing efficiency $\gamma_{mix} \sim 0{,}15$ (Wüest *et al.* 2000). The change of potential energy due to turbulent diffusion also depend on the stability of the water column, which can be expressed in terms of the Brunt-Väisälä frequency $N^2 = -g\rho^{-1}\partial\rho/\partial z$.

Hence, we can estimate the vertical diffusivity k_z through the following relationship (Osborn 1980):

$$k_z = \gamma_{mix}\varepsilon N^{-2} \qquad (4)$$

Figure 13 shows the vertical profile of temperature and vertical diffusivity evaluated on different segments through the water column in the middle of the Red Bay. In the surface layer and near the bottom recorded high values of diffusivity $k_z = 10^{-2}$-10^{-4} denote an intense turbulent activity, while the strong stratification in the metalimnion suppresses turbulence and limits the vertical exchange leading to smaller values of vertical diffusivity ($k_z = 10^{-6}$-10^{-7}).

5. CONCLUSIONS

Field data collected through two field campaigns performed during the summer-fall season in 2002 and 2003 have allowed us to draw a detailed picture of the main hydrothermodynamic features of Lake Tovel. Such features can be summarized as follows:

- the absence of a clearly detectable epilimnion, as conventionally defined, and the occurrence of a weak stratification limited to the surface layers (1-2 m);
- the establishment of regular circulations induced by the wind forcing, characterised by a thin surface layer flowing in the wind direction and by reverse flow close to the layer beneath, between 1 and 2 m from the surface, and in the sheltered shores;
- the different behaviour of the Red Bay, which is characterized by a strong stratification with a fairly small depth: the presence of underground water inflows induces the establishment of a cold bottom layer and an intense supply of fresh water to the centre of the lake; in the surface layer, during the afternoon, the direction of the fluxes is towards the Red Bay;
- the establishment of an incoming flux within the surface layer of the Red Bay related to the up-valley wind (afternoon);
- the reduction of turbulent exchange in the vertical direction within the Red Bay due to the strong stratification, that leads to values of vertical diffusivity as small as 10^{-6}-10^{-7} $m^2 s^{-1}$.

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