SENSITIVITY OF THE BASIN-SCALE INTERNAL WAVE STRUCTURE IN A PREALPINE LAKE TO WIND DISTRIBUTION

Giulia Valerio[1], Marco Pilotti[1], Antonio Cantelli[2], Paolo Monti[3] & Giovanni Leuzzi[3]

(1) Dipartimento DICATAM, Università degli Studi di Brescia, Brescia, Italy; (2) Dipartimento DIMA, Università di Roma La Sapienza, Roma, Italy; (3) Dipartimento DICEA, Università di Roma La Sapienza, Roma, Italy.

KEY POINTS

- *Wind distribution plays a fundamental role in lake dynamics, but its representation is a challenging task in alpine areas due to the strong influence of the topography on the wind regime.*
- *We propose to couple an high resolution meteorological model to a 3D hydrodynamic model to simulate the basin-scale internal wave structure in Lake Iseo.*
- *The improved distributed description of the wind stress over the lake surface leads to a significant enhancement of the representation of the main basin-scale internal wave motion.*

1 INTRODUCTION

Wind distribution plays a fundamental role in lake dynamics and mixing processes can't be effectively reproduced without an adequate representation of the space and time variable wind field. This fact has been clearly shown by the results of 3D hydrodynamic simulations which highlight that a uniform wind does not allow to correctly reproduce the surface lake currents (e.g. *Shilo* et al., 2007; *Strub and Powell,* 1986; *Lemmin and D'Adamo*, 1997), the inter-basin exchange rates (*Rueda et al.* 2005), the upwelling structure of the baroclinic basin-scale dynamics (*Appt et al*., 2004), and the excitation of the higher horizontal modes (*Lemmin et al.*, 2005; *Valerio et al.,* 2012).

In medium-size lakes in the alpine and pre-alpine regions, taking into account the space and time variability of the wind field is a challenging task due to the strong influence of the topography on the wind regime (*Petenko et al.*, 2011). In these geographical areas, the flow is mainly determined by the differential heating-cooling processes and is characterized by a complex interaction between up-slope winds and lake breezes. The complexity of the resulting flow field was shown for example numerically by *Giovannini et al.* (2014), with reference to the Adige Valley, and by *Lemmin and D'Adamo* (1997) on the basis of the analysis of sparse anemometric data in Lake Geneva.

In order to evaluate the sensitivity of the basin-scale internal wave structure in a deep, stratified pre-alpine lake to wind distribution, we used a moored lake station to tune a high resolution meteorological model that provides the wind and air temperature field to a 3D hydrodynamic model of lake Iseo.

2 MATERIALS AND METHODS

Lake Iseo is a deep, oligomictic Italian lake located in the pre-alpine area of east-central Lombardy (45°44'N 10°04'E) at 185 m a.s.l., which represents well the features of other large lakes located south of the Alps. The lake covers a surface area of 60.9 km^2, has a maximum depth of 256 m and is characterized by steep banks and a large island that separates the central plateau from the eastern 100 m deep channel. The area surrounding the lake is subjected to a temperate climate and to slope winds, characterized by a daily inversion due to periodic heating-cooling of the mountain sides ; their predominant directions are aligned with the north-south lake axis. The wind structure induces basin-scale internal waves characterized by a regular daily periodicity, amplitudes around 5 m in the stratified period (*Valerio et al.*, 2012) and epilimnetic speed in the order of a few centimeters per second. Lake Iseo has been monitored since 1995 on a monthly basis, while high-resolution data suitable for hydrodynamic modeling are available since 2010 (*Pilotti et al.*, 2013).

In this work, we modeled the wind field over lake Iseo numerically through the Weather Research and Forecasting (WRF) model (*Skamarock et al.*, 2008) in the period 11-18 July 2010. The horizontal domain considered for the simulations consisted of five two-way nested grids covering all spatial scales, from synoptic to local scales. A detailed and smoothed topography having a 3-arc seconds resolution was used in the area surrounding the lake. The performance of the simulations were successfully tested by comparisons with observations collected in a meteorological station moored on the lake surface and three other stations located along the shoreline (see Fig. 1). The resulting 2D wind field was used as a boundary condition for the 3D hydrodynamic model ELCOM, which solves the Reynolds averaged Navier Stokes equations with the Boussinesq approximation for density differences using a semi-implicit formulation on a finite-volume framework (*Hodges et al.*, 2000). We used an horizontal grid with cells 160 x 160-m large, combined with 74 vertical layers, having the higher resolution in the area with the maximum temperature gradient. The performance of the simulations were evaluated by comparing the modeled temperature time series in the first 30 m with the corresponding temperature measured at the northern and southern end of the lake (LDS and TC2 in Fig. 1) in the period 13-17 July 2010.

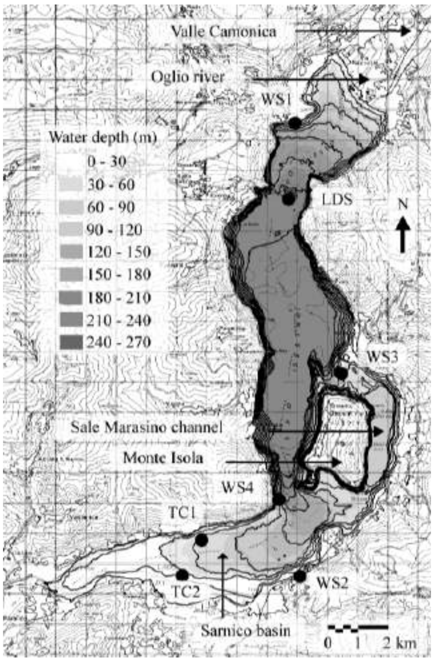

Figure 1. Bathymetry of Lake Iseo, represented with isodepth lines at 30-m spacing, and location of the measurement stations: thermistor chains (TC), wind stations (WS), and lake diagnostic system (LDS). The coordinates for the location in the bottom-left corner of the map are 45.63°N, 9.94°E. (Bathymetric data source: Regione Lombardia)

3 RESULTS AND DISCUSSION

To study the sensitivity of the basin-scale internal wave structure to wind distribution, we compared the results obtained by forcing the model with uniform wind fields measured at the anemometric stations shown in Fig. 1, and with spatially varying wind field obtained through the bilinear interpolation of all the measured data (cfr. *Valerio et al.*, 2012) and with the one simulated by the meteorological model.

In the period under consideration, a thermal stratification typical of the summer season was present, with mean temperature ranging from 24.5 °C at the surface and 6.4 °C at the bottom. The internal wave activity under this forcing is dominated by a basin-scale internal wave of vertical and horizontal modes 1 (V1H1), characterized by a regular 24-hours periodicity. The comparison between the measured and simulated average profiles and isotherms oscillations are shown in Fig. 2 with reference to the most representative simulations.

The results obtained by uniform wind fields measured at each anemometric station were not satisfactory. The internal wave amplitudes resulted greatly underestimated and more than 1 hour out of phase in the southern basin when forced by WS2 and WS3 station. Moreover, the surface mixed layer was much thinner and warmer with respect to the measured one in all the stations. A better fit of the oscillatory pattern in term of phase resulted by using WS1 and WS4 stations, but the amplitudes appeared still greatly underestimated.

On the contrary, the application of the on-lake LDS wind over all the lake surface provided notable discrepancies between the measured and simulated temperature in the southern basin, due to overestimated deepening of the surface layer and larger internal waves amplitudes. These results showed that the wind at WS2 and WS3 locations is not sufficient to energize the internal waves and to mix the surface layer, where most of the shortwave radiation remains trapped close to the surface. WS1 and WS4 instead, provide a wind that is in phase with the effective wind energizing the lake, but affected by the reduction of velocity along the shore. LDS wind, instead, seemed to overestimate the average energy transferred by the wind to the lake.

Most of these limitation were overcame by forcing the model with a spatially-varying wind. The wind field obtained from the meteorological model led to the best fit of the measured data, further improving the fit of the spatially-varying interpolated wind. With regard to the thermal structure the numerical wind field allowed to minimize the RMSE with respect to the mean temperature profile (0.64 and 0.70 °C at LDS and TC2), by improving the reproduction of the average surface layer deepening. With regard to the oscillatory pattern, it led to notable improvements especially in the southern area. Here, the numerical wind field was the only one that allowed a correct reproduction of the gradual increase of the first horizontal and vertical V1H1 amplitudes between 5 and 30 m of depth, which is a peculiar feature of the internal wave field measured by TC2.

The significant enhancement of the modeled main basin-scale internal wave motion based on the physically based distributed description of the wind stress over the lake surface confirms the importance of an accurate representation of the wind in physical limnology. Moreover, the presented coupled approach provides important insights for setting up more simplified conceptualization of the wind field and for the comprehension of the 3D hydrodynamic processes.

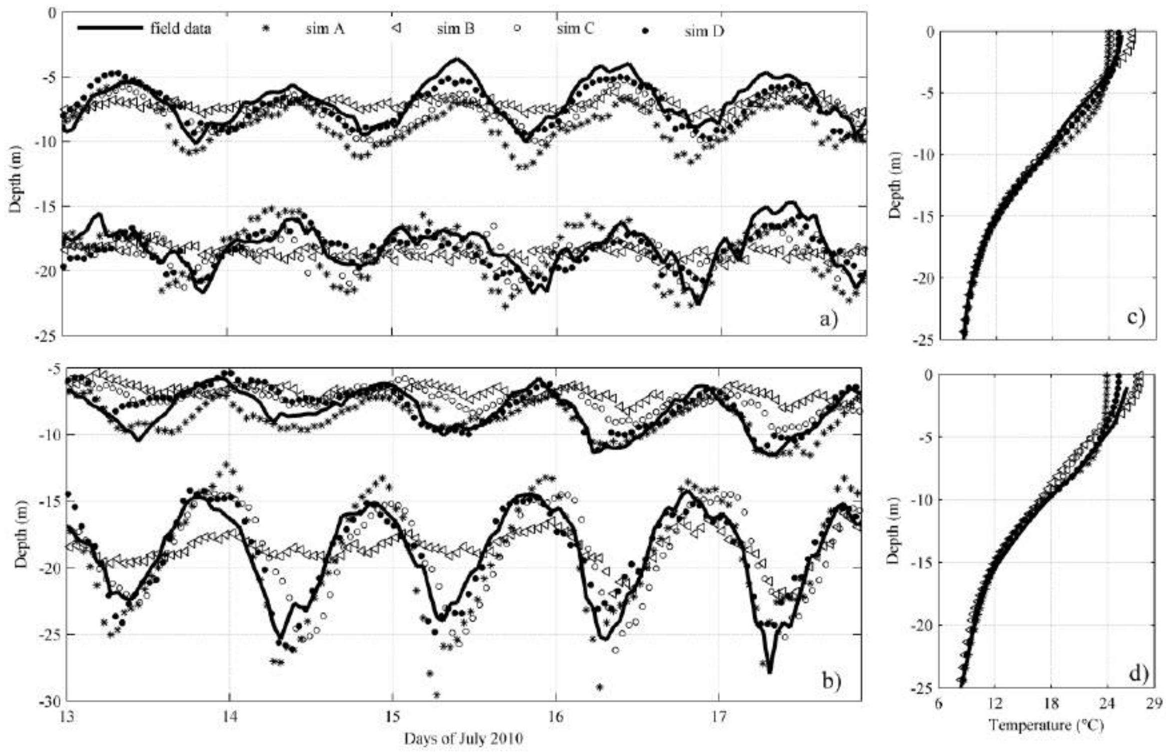

Figure 2. Time series of the (a, b) and vertical displacements of the 10°C and 20°C isotherms recorded at (a) the northern (LDS) southern and (b) the southern (TC2) thermistor chain. The continuous line show the measured values, while the markers indicate the results of the simulations forced by (sim A) the uniform LDS wind, (sim B) the uniform WS2 wind, (sim C) the interpolated wind and (sim D) the simulated wind. (c, d) Comparison of the average temperature profile simulated and measured at (c) LDS and (d) TC2).

4 REFERENCES

Appt, J., Imberger & J., Kobus, H. Basin-scale motion in stratified Upper Lake Constance, Limnol. Oceanogr., 2004, 49(4), 919-933.

Giovannini, L., Zardi, D., de Franceschi, M. & Chen, F. Numerical simulations of boundary-layer processes and urban-induced alterations in an Alpine valley, Int. J. Climatol., 2014, 34, 1111–1131.

Hodges, B.R., Imberger, J., Saggio, A. & Winters, K. Modeling basin-scale internal waves in a stratified lake. Limnol. Oceanogr., 2000, 45, 1603–1620.

Lemmin, U. & D'Adamo, N. Summertime winds and direct cyclonic circulation: observations from Lake Geneva. Annales Geophysicae, 1997, 14, 1207–1220.

Lemmin, U., Mortimer, C. H. & Bauerle E. Internal seiche dynamics in Lake Geneva. Limnol. Oceanogr., 2005, 50, 207–216.

Petenko, I., Mastrantonio, G., Viola, A., Argentini, S., Coniglio, L., Monti, P. & Leuzzi, G. Local circulation diurnal patterns and their relationship with large-scale flows in a coastal area of the Tyrrhenian Sea, Boundary-Layer Meteorology, 2011, 139, 353-366.

Pilotti, M., Valerio, G. & Leoni, B. Data set for hydrodynamic lake model calibration: a deep pre-alpine case. Water Resources Research, 2013, 49, 7159–7163.

Rueda, F., Schladow, S.G., Monismith, S. & Stacey, M. On the effects of topography on wind and the generation of currents in a large multi-basin lake. Hydrobiologia, 2005, 532, 139–151

Shilo, E., Ashkenazy, Y., Rimmer, A., Assouline, S., Katsafados, P. & Mahrer, Y. Effect of wind variability on topographic waves: Lake Kinneret case. J. Geophys. Res., 2007, 112(C12024).

Skamarock, W.C. & Klemp, J.B. A time-split nonhydrostatic atmospheric model for weather research and forecasting applications, Journal of Computational Physics, 2008, 227 (7), 3465-3485.

Strub, P.T. & Powell, T.M. Wind-driven surface transport in stratified closed basins: Direct versus residual circulations. J. Geophys. Res., 1986, 91(C7), 8497-8508.

Valerio, G., Pilotti, M., Marti, C.L. & Imberger, J. The structure of basin scale internal waves in a stratified lake in response to lake bathymetry and wind spatial and temporal distribution: Lake Iseo, Italy. Limnol. Oceanogr., 2012, 57, 772-786.