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Internal wave weather heterogeneity in a deep multi-basin subalpine lake resulting from wavelet transform and numerical analysis

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ABSTRACT

The internal wave-field of a Y-shaped lake (Lake Como, North Italy) was investigated over a 3-year long period applying wavelet time–frequency analysis to temperature and wind data time series, recorded at the edge of each of the three arms. The comparison with the results from a modal model allowed to identify the presence of both first and second vertical modes of oscillations. The field data analysis underlined a heterogeneous baroclinic response with the eastern arm decoupled from the remaining part of the lake constituted by the northern and western arms (north–south west transect). This disjoined response is expected to enhance the water exchange between the northern and the western arm, with relevant consequences on the inter-basins water exchanges and on the distribution of chemical and biological species. In the north–south west transect the analysis of the low power signals in winter underlined a residual internal wave activity ascribed to the first vertical free mode of oscillation (*V1H1*).

1. Introduction

Stratification in lakes and reservoirs plays a crucial role in the overall ecology of the lake water body [5,18,37]. In a fresh water ecosystem the stratification of the water column is generally due to thermal stratification [32,56] resulting from the combination of different meteorological stressors such as solar heating, radiative cooling and wind stirring. The vertical variation of water density, associated with these changes in temperatures, support internal wave motions forced by wind-generated pressure gradients [50]. Internal wave activity is ubiquitous in stratified lakes and provides one of the main driving forces for vertical and horizontal transport under the wind mixed layer (e.g. [31]). Internal waves have an important role on the lake biogeochemistry and their impact on lake ecology [36] has recently been the subject of different papers. Internal waves have been demonstrated to enhance the nutrient fluxes from the hypolimnion to the epilimnion (e.g. [30]) and the light availability at which phytoplankton cells are exposed thus influencing phytoplankton community composition and primary production (e.g. [4]). More recently Pannard et al. [37] demonstrated the role of internal waves in controlling the phytoplankton community by the contrasting gradients of light and nutrients that enhanced the metalimnetic community of cyanobacteria in a small lake. Similar results have been found by Cuypers et al. [15] in a deep alpine lake where internal waves showed a direct impact on the light availability and an indirect influence on both the vertical and horizontal distribution of the cyanobacteria community proliferating in the metalimnetic layer.

Internal wave motions can be classified according to the number of nodal points in term of both vertical (*Vi*) and horizontal (*Hm*) modes where *i* and *m* are the number of nodal points. The most observed mode [34] is the *V1H1*, but many observations of higher horizontal and vertical modes were documented in the literature (e.g. [25,26,35]).

The spatial and the temporal structure of internal waves in lakes is constrained by both the density gradients and by the geometric properties of the inclosing basin [45]. The baroclinic response to wind has been extensively investigated in single-basin

Abbreviations: *CWT*, continuous wavelet transform; *GWS-Amplitude*, global wavelet spectrum-amplitude; *GWCS-Amplitude*, global wavelet coherence spectrum-amplitude; *GWCS-Phase*, global wavelet coherence spectrum-phase; *GXWS-Amplitude*, global cross wavelet spectrum amplitude; *GXWS-Phase*, global cross wavelet spectrum-phase; *IDD*, isotherm depth difference; *IPE*, integrated potential energy; *MWCT-Amplitude*, mean wavelet coherence time series-amplitude; *MWCT-Period*, mean wavelet coherence time series-period; *MWCT-Phase*, mean wavelet coherence time series-phase; *MWT-Period*, mean wavelet time series-period; *MXWT-Amplitude*, mean cross wavelet time series-amplitude; *MXWT-Period*, mean cross wavelet time series-period; *MXWT-Phase*, mean cross wavelet time series-phase; *WTC*, wavelet coherence transform; *XWT*, cross wavelet transform.

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lakes, where it may be traced back to the theoretical solutions for simplified geometries [2]. In more complicated multi-basin lakes, field and numerical studies have investigated the role of local bathymetric features on the free mode structure and their excitation by wind, such as embayments (Lake Tahoe [43], side sub-basin (Lake Constance [3], Clear Lake [44]), islands (Lake Iseo [53]), changes in orientations of lake thalweg with respect to wind (Lake Biwa [48]), narrows and/or sills (Lake Zug [27], Lake Banyoles [41], Amisk Lake [19]). The common observations of higher horizontal modes in these works seem to confirm the insight of Mortimer that the presence of constrictions between basins may offer an impedance to the first whole-lake mode [20,34], with relevant biogeochemical implications on the inter-basin exchange rates [42]. In this context, multi-arms lakes, made by narrow arms connected by contractions, sills or changes in orientations, have received less attention [24].

Furthermore, most of these studies focused on a relatively short period (from few days to months) during summer. Only few studies have been conducted outside the summer stratification [43,44] or over a complete year [1]. None of them present a multi-year continuous analysis of field data. The relatively shortness of the field analysis conducted so far can be ascribed to two principal issues: the scarcity of long-term high-frequency temperature data time series and the intrinsic difficulties in the analysis of signals whose frequency varies over time with varying intensity of thermal stratification [26]. In this regard an interesting contribution to the study of non-stationary signals has recently come from the development of the wavelet transform. Wavelet transform has been widely applied in hydrology (e.g. [21,46]) and meteorology (e.g. [14]) to analyze long term time series.

The first applications of the wavelet transform in physical limnology date back to early 2000s [2,8,43]. Antenucci et al. [2], in particular, used the continuous wavelet transform (*CWT*) to differentiate groups of gravitational waves from a complete spectrum of signals. A seasonal wavelet transform analysis was conducted by Vidal et al. [55] which provided a description of the dominant vertical modes in a deep reservoir and by Bernhardt and Kirillin [6] that described the seasonal pattern of rotation-affected internal seiches in a small temperate lake. Accordingly, the long time, high-resolution series of temperature measured in the three arms of Lake Como, forming its peculiar Y-like shape (Fig. 1), provides a contribution to the understanding of the internal wave structure in narrow, multi-arms bathymetries.

Investigations on the physics of Lake Como started recently and only few hydrodynamic studies have been developed [10,22,23,33]. A surface seiches analysis was conducted by Buzzi et al. [10] and provided clear indications of relevant differences on the periods of oscillation between the eastern and the two other arms. Based on theoretical considerations a similar behavior was supposed for the internal wave motions. The authors, however, were unable to confirm this hypothesis because of the lack of experimental data. A subsequent study identified the *V1H1* as the dominant internal seiche mode [23]. *V1H1* period was estimated over discrete periods between 4.4 (early autumn) and 8 (winter) days depending on the strength of the thermal stratification. The presence of higher vertical modes was mentioned in Laborde et al. [22] but no specific paper has analytically studied this aspect. Upwelling of deeper waters at the northern end of the lake was also identified and ascribed to the action of strong northerly winds [23,49].

The main objective of this paper is to describe the internal wave-field in Lake Como, a Y-shaped, deep lake, providing an original insight to the knowledge of the internal waves development in narrow, multi-arms lakes. The study is based on a wavelet time–frequency analysis conducted using multi-year high frequency temperature and wind data collected in three lake locations. A numerical modal model was used to provide an interpretation of the nature of the identified signals. The impact of the principal modes of oscillation on the distribution of chemical and biological species at the lake basin scale is also discussed.

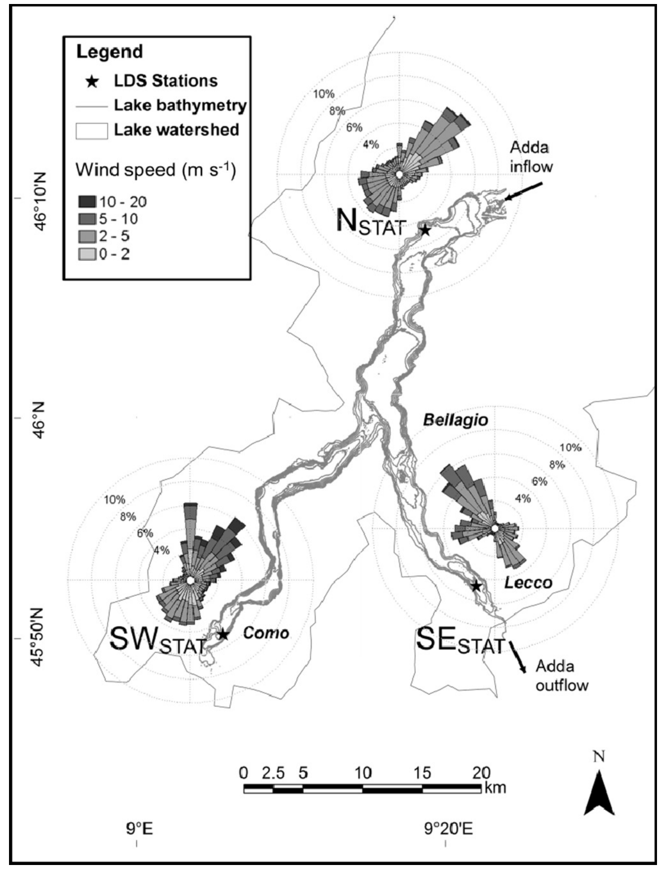

Fig. 1. Lake Como map (100 m bathymetric interval) showing the location of the floating stations (black star) provided with wind sensor and thermistor chain. For each station (SW_{STAT}, N_{STAT} and SE_{STAT}) the wind rose (2007–2009) is shown.

2. Material and methods

2.1. Field site and data

Lake Como is a natural regulated lake located at the southern edge of the Alps in Northern Italy (Lombardy Region). It is the deepest (maximum depth = 425 m) and the third largest Italian lake with a surface area of 145.5 km^2, a volume of 22.5 km^3 and a catchment area of 4524 km^2 [54]. The lake is composed by 3 basins (Fig. 1). The northern basin is fed by the two main tributaries: the Adda (mean annual flow = 88 m^3 s^{-1}) and the Mera (mean annual flow = 22 m^3 s^{-1}) rivers that cover respectively 50% and 20% of the total inflow to the lake [13]. The northern basin extends 20 km south from the mouth of the Adda to the city of Bellagio, where it diverges in two distinct arms. The eastern arm extends southeast to the city of Lecco, where the Adda outflow is regulated by a dam (mean annual flow = 155 m^3 s^{-1}). The western arm is a closed basin and extends southwest to the city of Como (Fig. 1). Higher water residence times and nutrient loads make the western basin the portion of the lake more vulnerable for water quality-related issues, with particular respect to its southern edge [33] where recurrent algal blooms are observed [9].

The wind regime on Lake Como is characterized by two alternative dominant winds. In the early morning the “Tivano” wind blows north-easterly, with higher intensities at the southern end