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Atmospheric boundary layer structures associated with the *Ora del Garda* wind in the Alps as revealed from airborne and surface measurements

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ABSTRACT

The paper investigates a coupled lake-breeze and valley-wind system, known as *Ora del Garda*. The latter typically originates on clear-sky days over the northern shore of Lake Garda in the Alps. After channelling into the nearby Sarca Valley and Lakes Valley, this airflow finally breaks out, through an elevated saddle, into the adjacent Adige Valley, where it strongly interacts with the local valley wind. Two flights of an instrumented motorglider explored, under different synoptic conditions, the thermal structure of the atmospheric boundary layer (ABL) associated with this wind at selected vertical sections—namely over the lake shore, at mid-valley, and at the junction with the Adige Valley. Data from airborne measurements, as well as from weather stations disseminated along the valley floor, provided the basis for mapping 3D fields of potential temperature over high-resolution grids by means of a Residual Kriging (RK) technique. This representation allowed the identification of site-specific ABL features associated with the *Ora del Garda*. In particular, a typical daytime coastal-breeze structure is detected in the lake shore region, where the advection of colder air tends to stabilize the atmosphere throughout the ABL depth. Mid-valley vertical profiles from both flights display shallow convective mixed layers, surmounted by deeper weakly stable layers. On the other hand, RK-gridded temperature maps show cross-valley thermal asymmetries, amenable to the complex topography and to the inhomogeneous surface coverage, as well as to a curvature of the valley axis. Finally, in the area where the upper Lakes Valley joins the Adige Valley, specific features associated with the complex interaction between the *Ora del Garda* and the local up-valley wind are found.

1. Introduction

Daily-periodic local circulations typically arise under fair-weather conditions along coastal regions, originated by the differential heating of neighboring water and land surfaces. They play a leading role in determining local weather and climate, as well as related atmospheric boundary layer (ABL) processes, such as pollution transport from mesoscale down to local scale (Boyouk et al., 2011; Lyons and Olsson, 1973). For this reason sea and large-lake breezes have been extensively investigated, both theoretically and by means of field observations and numerical simulations (see, among others, the reviews by Atkinson, 1981; Crosman and Horel, 2010, 2012; Pielke, 1984; Simpson, 1994). On the other hand, less attention was paid to thermally-driven winds arising over small lakes, i.e. lakes whose characteristic width is less than 50 km, according to the survey of observational studies on small lakes provided by Segal et al. (1997).

A variety of daily-periodic, thermally-driven winds is also observed in mountainous regions. These airflows develop as an

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organized and interacting system of air motions, including regional scale circulations (such as mountain-plain winds), mesoscale flows (such as valley winds), and local scale currents (such as slope winds): cf. Zardi and Whiteman (2013) for a recent review. These winds deeply affect ABL processes as well (Rotach and Zardi, 2007; de Franceschi et al., 2009), including local air pollutant transport (de Franceschi and Zardi, 2009; Ragazzi et al., 2013). They may also trigger the initiation of deep convection for the convergence of moist air they produce along the mountain crests (Barthlott et al., 2006; Gladich et al., 2011; Kalthoff et al., 2009; Pucillo et al., 2009). The basic mechanisms of mountain winds are well understood, especially since the increasing capabilities of numerical models allowed considerable progress in the simulation of the related atmospheric processes (De Wekker, 2002; De Wekker et al., 2004; Rampanelli et al., 2004; Schmidli and Rotunno, 2010, 2012; Schmidli et al., 2011; Serafin and Zardi, 2010a,b, 2011).

Further challenging situations arise from the combination of a shoreline with an adjacent complex terrain, where coastal breeze systems interact with topography-driven circulations. As an example, idealized numerical simulations by Kondo (1990) provide evidence of an effective enhancement of the sea breeze in connection with a valley outlet in front of the coast, even at many kilometres distance, leading to a regional-scale unified flow, the so-called *Extended Sea Breeze*. Similarly, detailed observations around the small Lake Tekapo in New Zealand outlined the development of a complex lake–valley wind system, referred to as the *Extended Lake Breeze* (Kossmann et al., 2002; McGowan et al., 1995; McGowan and Sturman, 1996). Indeed, a variety of site-specific phenomena arise from different combinations of coastal and orographic factors. Lidar observations in the Salinas Valley (California) documented the morning development of a shallow sea breeze, evolving into a deeper unified up-valley circulation in the afternoon (De Wekker et al., 2012). During the ESCOMPTE project, Bastin et al. (2005) reported the different behavior accompanying the diurnal development of local winds in two large valleys facing the Mediterranean Sea in the area of Marsille (France): the Rhône Valley and the Durance Valley. While the former does not modify significantly the sea breeze development, the narrower Durance Valley always affects the channelled sea breeze by accelerating the flow. Indeed, Bergström and Juuso (2006), by means of numerical simulations over idealized topography, provided evidence that a lake acts as a continuous source of cold air at a valley bottom, leading to stronger up-valley winds. Furthermore, Bischoff-Gauß et al. (2006), in their investigation of the impact of a new storage lake on the arid environment of the Elqui Valley in the Andes, found that, even if a real lake breeze circulation may fail to develop, the presence of the small lake significantly modifies the surface energy budgets, and consequently the local airflows.

All the above situations are associated with complex thermal and dynamical atmospheric structures, reflecting the horizontal inhomogeneity of the underlying terrain, which makes the resulting processes remarkably different from those commonly found over plain uniform terrain (Rotach and Zardi, 2007). To explore in detail the fine-scale variability of the above structures, a particularly suited tool is nowadays offered by light airplanes equipped with specifically designed platforms (cf. de Franceschi et al., 2003). Indeed, the flights performed during the field campaigns of the DISKUS experiment (Hennemuth, 1985, 1986; Hennemuth and Schmidt, 1985), the MAP-Riviera project (Weigel and Rotach, 2004), the ALPNAP project (Gohm et al., 2009; Harnisch et al., 2009; Schnitzhofer et al., 2009), the ESCOMPTE experiment (Hasel et al., 2005; Puygrenier et al., 2005), and the COPS project (Kalthoff et al., 2009) provided a unique opportunity to extensively explore atmospheric dynamics and transport phenomena associated with local winds in coastal and/or valley environments. Similarly, Finkele et al. (1995) characterized a complete sea breeze circulation cell on the basis of measurements from an instrumented light aircraft. Measurements with light airplanes definitely provide, thanks to the inherent manoeuvrability of the measurement platform, a suitable basis to obtain detailed representations of the spatial distribution of temperature, wind, moisture and other atmospheric quantities, such as turbulent fluxes (Druilhet and Durand, 1997) and air pollutants, including trace gases (Hasel et al., 2005) and aerosols (Baumgardner et al., 2011). However, to get high-resolution 3D pictures of any variable out of airborne observations taken along flight trajectories, data need to be appropriately interpolated over the explored atmospheric volume. To accomplish this purpose, various mapping techniques may be used, such as interpolation methods based on distance between points (Egger, 1983; Hennemuth, 1985) or on Delaunay triangulations (De Wekker, 2002; Weigel and Rotach, 2004). More recently Laiti et al. (2013a) proposed a different approach, based on the geostatistical technique called Residual Kriging (RK; Ahmed and de Marsily, 1987; Goovaerts, 1999; Odeh et al., 1995), to map potential temperature fields over vertical slices of a valley atmosphere. RK gridding allowed a deeper insight on the thermal structure associated with valley winds, and in particular outlined 3D local features, mainly amenable to complex topography or surface inhomogeneities, that would not be revealed by simple vertical profiles of observations.

All of the above issues meet in the present work, which examines a peculiar case of lake and valley breeze interaction in the south-eastern Italian Alps, the so-called *Ora del Garda* wind. Between 1998 and 2001 some targeted measurement flights were carried out by means of an instrumented motorglider (de Franceschi et al., 2002, 2003), providing the database for this work. Accordingly, results contained in this paper provide an insight into the thermal structures associated with the *Ora del Garda* circulation based on the combined analysis of surface and airborne measurements. The paper is organized as follows. In Section 2 a concise introduction to the study area where the *Ora del Garda* develops and an overview of the observational framework are provided. Section 3 illustrates the results from the analysis of the airborne dataset, as for dominant vertical structure and fine-scale 3D structure of the valley ABL associated with the *Ora del Garda* development, while Section 4 discusses these findings in detail. Finally, Section 5 provides some conclusions and an outlook on possible future developments.

2. The target area and the observational framework

2.1. The target area and the Ora del Garda

The target area for the present investigation is the corridor connecting the region north of Lake Garda with the Adige Valley in the south-eastern Italian Alps (Fig. 1). Lake Garda