



Analysis of the diurnal development of a lake-valley circulation in the Alps based on airborne and surface measurements

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Abstract. This study investigates the thermal structures of the atmospheric boundary layer (ABL) and the near-surface wind field associated with a lake-valley circulation in the south-eastern Italian Alps – the so-called Ora del Garda. Two flights of an equipped motorglider allowed for the exploration of the diurnal evolution of this circulation, from the onset, on Lake Garda's shoreline, throughout its development along the Sarca Valley and Lakes Valley (*Valle dei Laghi*), to the outflow into the Adige Valley. At the same time, surface observations, both from a targeted field campaign and from routinely operated weather stations, supported the analysis of the development of the Ora del Garda at the valley floor.

In particular, in the valleys typical ABL vertical structures, characterized by rather shallow convective mixed layers (~ 500 m) and (deeper) weakly stable layers above, up to the lateral crest height, are identified in the late morning. In contrast, close to the lake the ABL is stably stratified down to very low heights, as a consequence of the intense advection of colder air associated with the Ora del Garda flow (up to 6 m s^{-1}). The combined analysis of surface and airborne observations (remapped over 3-D high-resolution grids) suggests that the lake-breeze front propagating up-valley from the shoreline in the late morning penetrates slightly later at the eastern end of the valley inlet (delay: ~ 1 h), probably due to the asymmetric radiative forcing caused by the N–S valley orientation. On the other hand, in the early afternoon the Ora del Garda overflows through an elevated gap, producing an anomalous, strong cross-valley wind (5 m s^{-1}) at the Adige Valley floor north of Trento, which overwhelms the local up-

valley wind. This feature is associated with a strong deepening of the local mixed layer (from 400 to 1300 m). The potential temperature 3-D field suggests that the intense turbulent mixing may be attributed to the development of a downslope wind across the gap, followed by a hydraulic jump downstream.

1 Introduction

On fair-weather days, especially in the warm season, in areas characterized by complex coastal orography the daytime wind field typically results from the interaction between local sea/lake breezes and slope/valley winds. Both types of circulations are thermally driven – i.e. they originate from the differential heating of adjacent air masses – and are characterized by a reversal of the flow direction twice per day (cf. Defant, 1951; Simpson 1994; Zardi and Whiteman, 2013). When they blow in phase and no orographic blocking occurs, the resulting flow may display stronger intensities and further inland penetration than in plain coastal areas, as an effect of the enhancement of forcing thermal contrasts (Bergström and Juuso, 2006; Mahrer and Pielke, 1977) and/or of the wind channelling, e.g. in a valley (Bastin et al., 2005). This may lead to the formation of “extended” sea/lake breeze circulations, as reported for example by Kondo (1990) for the Kanto Plain (Japan) and by McGowan et al. (1995) and McGowan and Sturman (1996) for the Lake Tekapo basin (New Zealand). The reader is referred to Laiti et al. (2013b) for

a more extensive literature review on the coupling between sea/lake breezes and valley winds.

The present paper investigates a case of interaction between the lake breeze induced by a small lake (surface: 370 km²), lying at the inlet of a deep Alpine valley, and the local valley winds. This circulation, known as Ora del Garda, originates as a lake breeze over the northern shorelines of Lake Garda, in the south-eastern Italian Alps (see Fig. 1). This wind typically arises in the late morning of fair-weather warm-season days, and then channels northward into the nearby Sarca Valley and Lakes Valley (*Valle dei Laghi*), interacting with the local up-valley flow. The northern end of Lake Garda (local width: 4 km) is bounded on both sides by high mountain ranges, reminding of a fjord configuration, and is only open to the north onto the Sarca Valley, which consists of a rather wide (~ 5 km), flat basin. A narrow valley stretch leads to the nearby Lakes Valley to the north. Then, about 20 km north of Lake Garda's shoreline, the orientation of the valley axis shifts from SSW–NNE to WSW–ENE. An elevated pass, the saddle of Terlago, joins the northern end of the Lakes Valley with the adjacent Adige Valley, on the western side of the latter. When the thermal forcing is strong enough, in the early afternoon the Ora del Garda wind overflows into the Adige Valley from this elevated ridge, appearing at the valley floor as a strong and gusty westerly (i.e. cross-valley) wind. The local up-valley wind is then forced to flow at higher levels by the potentially colder (denser) air advected by the Ora del Garda (Schaller, 1936). The Ora del Garda airflow spreads over the valley floor, both northward and southward. The latter branch produces an anomalous down-valley wind that can reach the centre of the city of Trento, a few kilometres south of the Terlago saddle (Giovannini, 2012). The inflow from the Lakes Valley typically persists in the area for a few hours after sunset while gradually weakening (de Franceschi et al., 2002).

Various authors have contributed in the past to the study of the Ora del Garda wind (Defant, 1909; Pollak, 1924; Wiener, 1929; Schaller, 1936; Wagner, 1938). Their attention was captured by the anomalous wind regime observed in Trento in the afternoon. More recently, climatological characterizations of the typical diurnal cycle of this wind have been provided in the preliminary works by Baldi et al. (1999), Daves et al. (1998) and Giovannini et al. (2013b), on the basis of observations collected from surface weather stations deployed along the valley floor. According to these studies, at Lake Garda's shoreline the Ora del Garda typically starts around 11:00–12:00 LST (UTC +1) and ceases around 17:00–19:00 LST (for the April–September period). The typical wind direction and intensity are SSW and 6 m s⁻¹ respectively. On the other hand, the first outbreak of the breeze into the Adige Valley occurs at 14:00–15:00 LST, while its cessation is observed at 19:00–21:00 LST. In general, these timings display a pronounced seasonal variability, with earlier onsets in late spring and early summer, and later cessa-

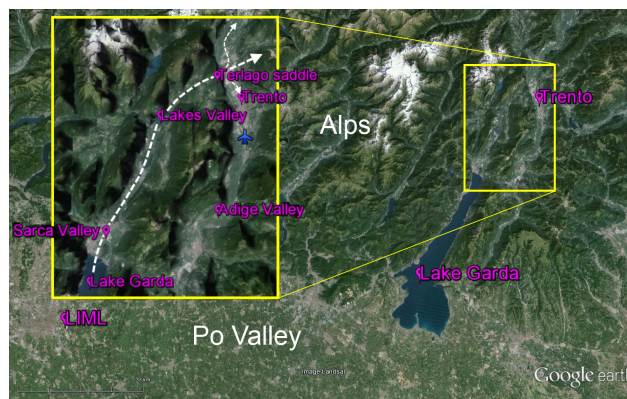


Figure 1. Localization of the study area (small yellow box) near the city of Trento in the south-eastern Italian Alps; Lake Garda and Milan sounding station (LIML) are also indicated. A close-up view on the study area is provided in the large yellow box on the left. Here the dashed white arrow represents the Ora del Garda flowing from Lake Garda's shoreline, along the Sarca and the Lakes Valley, and finally into the Adige Valley across the Terlago saddle (see labels). Background images: ©2014 Google Earth, ©2014 European Space Imaging, ©2014 DigitalGlobe, ©2014 CNES–SPOT Image.

tions (in the lake's shore area) in the warmest months (Giovannini et al., 2013b).

While the typical diurnal cycle of the Ora del Garda at the surface is quite well understood, little is known about the associated structure of the atmospheric boundary layer (ABL). A first contribution, based on both airborne and surface observations, is provided in Laiti et al. (2013b). In particular, that paper examined two flights of an instrumented motorglider (de Franceschi et al., 2003) performed in different weather situations, but with similar timings and flight trajectories. That analysis focused on ABL features characterizing the afternoon phase (i.e. the mature stage) of the Ora del Garda, and on the effects of the different weather conditions on such structures. Thermal structures were recognized that are compatible with the propagation of a lake-breeze front from the shoreline, which had already occurred in the morning (i.e. well before the flights). Moreover, different flow depths, stratifications and asymmetric cross-valley circulations were observed for the two synoptic situations. Laiti et al. (2013b) also speculated about the development of a hydraulic jump associated with the Ora del Garda overflow into the Adige Valley. This hypothesis was formulated on the basis of the observed features of the ABL structure, resembling those found in connection with gap flows in the Alps (as described, among others, by Armi and Mayr, 2007; Flamant et al., 2002; Gohm and Mayr, 2004; Mayr et al., 2007) or with downslope windstorms (see for example Liu et al., 2000). Hydraulic jumps, i.e. flow structures marking the transition from (upstream) supercritical to (downstream) subcritical conditions, are usually identified by isentropes descending on the leeward side (where the flow accelerates) and then

abruptly rising again downstream (where the flow decelerates and recovers ambient conditions; see Liu et al., 2000, in particular their Fig. 17). This behaviour is compatible with the reduced-gravity shallow-water theory for hydraulic jumps in stratified flows (cf. Durran, 1990).

The present paper instead exploits data from two flights performed in the study area on the same day (23 August 2001), when favourable weather conditions allowed for the full development of the Ora del Garda. Differently from Laiti et al. (2013b), here the first flight was performed in the morning and the second in the afternoon, to appreciate the diurnal evolution of the wind. Moreover, the data set also includes intensive surface observations collected during a targeted field campaign in the Terlago saddle area (de Franceschi et al., 2002), as well as standard data from a richer set of routinely operated surface stations than in Laiti et al. (2013b). Indeed, the present study aims at analysing not only the ABL thermal structures associated with the Ora del Garda flow in its mature stage, but also their diurnal evolution. Furthermore, it focuses on the coupled surface and ABL processes occurring in two key areas for the development of the circulation, i.e. Lake Garda's shoreline and the junction between the Lakes and Adige valleys, which were not investigated in detail by Laiti et al. (2013b). These include the lake-breeze front propagation in the Sarca Valley and the phenomena associated with the breeze overflow at the end of the Lakes Valley. The data set presented in this work is indeed unique, for it provides unprecedented observations of wind, temperature and sensible heat fluxes at the surface, as well as observations of the 3-D thermal structure of the valley atmosphere, associated with a lake-valley mountain wind. The potential outreach of the outcomes is twofold. First of all, a good knowledge of local wind and ABL (coupled) processes will be of great importance in order to characterize the climatology and pollution transport and dispersion in the study area, especially for the urban area of Trento in the Adige Valley. Secondly, results may be extended to similar geographic configurations, e.g. other Alpine lakes, or mountain valleys with relatively large water bodies at their bottom.

The paper is organized as follows. The two measurement flights and the surface observations composing the database analysed in this research work are presented in Sect. 2. Section 3 (Results) illustrates the diurnal patterns recorded at the surface weather stations, as well as the dominant vertical structures and the fine-scale 3-D features of the ABL revealed by the airborne measurements. Section 4 discusses the most relevant aspects of the coupled surface and ABL processes characterizing the Ora del Garda development on the flight day, especially in the shoreline area and at the junction of the Lakes and Adige valleys. Finally, Sect. 5 recaps the main findings and provides the conclusions.

2 Experimental data set

2.1 Measurement flights

On 23 August 2001 the Atmospheric Physics Group of the University of Trento performed two flights over the study area by means of an instrumented motorglider. The first flight (no. 1) was carried out in the late morning, and the second (no. 2) in the early afternoon. Onboard instruments recorded position, air pressure, temperature and relative humidity, with 1 Hz sampling frequency (see de Franceschi et al., 2003, for technical details about the measurement platform). The motorglider flew a total of eight spiralling trajectories, oriented along specific vertical sections of the valley atmosphere, and exploring five different sites:

- site A: the flat-bottomed basin facing Lake Garda, i.e. the Sarca Valley;
- site B: the narrow valley stretch joining the Sarca Valley with the lower Lakes Valley;
- site C: the lower Lakes Valley;
- site D: the upper Lakes Valley, close to the ridge of the Terlago saddle;
- site E: the Adige Valley north of Trento, in front of the Terlago saddle.

Flight 1 covered the four sections along the valleys where the Ora del Garda wind blows (sites A, B, C and D) and explored site E twice. Moreover, both along-valley- and cross-valley-oriented flight legs were performed over site A, allowing for an extensive exploration of the local 3-D structure of the valley atmosphere. In contrast, flight 2 focused on the area where the Ora del Garda wind and the Adige Valley wind interact (sites D and E). The flight trajectories are displayed in Fig. 2, and the main characteristics of each spiral are reported in Table 1. Unfortunately, GPS data for the last two spirals of flight 1 (D1 and E1b) are missing. Therefore, only vertical profiles of the measured variables are available for these spirals.

Prior to any analysis, temperature and relative humidity data were corrected to remove the time-lag error due to the time constant of the sensor, as proposed by Rampantelli (2004). The instrumental uncertainties associated with the calculated values of potential temperature (θ) and water vapour mixing ratio (w) are slightly variable upon local conditions, but they were estimated to be not larger than ± 0.09 K and ± 0.26 g kg⁻¹ respectively. Another source of error for temperature data may be adiabatic heating. In principle, the variability of speed and direction of the wind and of the motorglider along the flight path may produce a variable adiabatic heating error. Unfortunately, no wind speed measurements were available to correct for this error. However, the (quasi-horizontal) cross-valley transects characterizing the flight trajectories were performed at almost constant

Table 1. Timings and characteristics of flights 1 and 2 performed on 23 August 2001. Single spirals are labelled according to Fig. 2a. CV and AV respectively indicate whether the trajectory explored a cross- or an along-valley-oriented section. (*) indicates that only altitude data are available. D stands for a descending (downward) flight leg and U for an ascending (upward) leg.

Flight	Take-off	Landing	Spiral	Start	End	Trajectory
No. 1	09:00 LST	12:00 LST	E1a	09:18 LST	09:47 LST	CV U
			A1	09:59 LST	10:42 LST	CV + AV U + D
			B1	10:46 LST	11:06 LST	CV U
			C1	11:08 LST	11:21 LST	CV D
			D1	11:23 LST	11:43 LST	CV(*) U
			E1b	11:43 LST	11:57 LST	CV(*) D
No. 2	14:15 LST	15:30 LST	E2	14:24 LST	14:54 LST	CV U
			D2	14:58 LST	15:17 LST	CV D

velocity ($\sim 30 \text{ m s}^{-1}$). In addition, the cross-valley variations of the wind field in the sampled atmospheric regions were likely to be rather small. Hence the resultant true wind speed around the sensor (and thus the adiabatic heating error) may be reasonably assumed constant for most of the flight time (i.e. except at turning points). Furthermore, the temperature probe (aligned with the flight direction) was equipped with a cap against mechanical stress, specifically aimed at reducing the airflow speed around the sensor and thus adiabatic heating effects (cf. de Franceschi et al., 2003). As a consequence, the magnitude of the error may be plausibly expected to be small. Considering also that cross-valley variations of θ are our primary interest here (rather than absolute values), it can be concluded that adiabatic heating effects do not jeopardize the quality of the results.

Since each spiralling flight leg exploring a single valley section was flown in less than 30 min (with the only exception being spiral A1; cf. Table 1), the temporal variability over the single spiral can be neglected, as no appreciable evolution of the ABL structure took place during the overflight time (cf. Stull, 1988). Accordingly, the dominant vertical structure of the ABL was extracted from w and θ data for each spiral, by means of a simple (i.e. unweighted) moving average (width of the vertical window: 200–250 m). This allowed a strong smoothing of the high-frequency perturbations associated with the local variability of the sampled meteorological fields (i.e. warmer regions associated with convective thermals), which were almost completely filtered out. The resulting “mean” vertical profiles, essentially representative of the valley atmosphere core, will be from here onwards referred to as “pseudo-soundings”.

A residual kriging (RK) method was then used to interpolate the θ observations collected along each spiralling trajectory over a high-resolution regular grid (spacing: $50 \text{ m} \times 50 \text{ m} \times 50 \text{ m}$), in order to visualize the fine-scale 3-D structures of the sampled field. RK foresees the explicit decomposition of the target field into a drift and a residual term, to be estimated separately. In particular, here the aforementioned pseudo-soundings were adopted as a verti-

cal drift term. The interested reader may refer to Laiti et al. (2013a) for full details of RK implementation. Notice that, when representing the regridded θ fields (Figs. 7–10 and 12), we excluded the region close to the lateral slopes and the valley floor, as the motorglider was not able to adequately sample those layers. Based on a scale analysis of data from Schumann (1990), we obtained an estimate of 200 m for the average depth of the slope-wind layer. Accordingly, we removed the values falling within a 200 m buffer around the local orography. We also removed the values in the first 100 m above the valley floor (i.e. a reasonable estimate of the ABL surface layer depth), while above this height we assumed the existence of a mixed layer (ML) when the upper part of such a layer was actually captured by the lowest observations. Accordingly, in RK mapping we extended the pseudo-soundings (except E1a and A1, which show a stably stratified profile down to their lowest point) below the lowest observation height using a constant value (θ_m) for the profile.

2.2 Surface observations

In addition to the flights, surface observations were collected from automated weather stations (AWSs) deployed along the floor of the study area’s valleys and routinely operated by local institutions (see Fig. 2). A list of the AWSs considered in the present study, along with their technical specifications, is given in Table 2. Notice that wind, pressure and radiation data are recorded at some stations only, and that the time resolution of observations varies for the different networks (15 min vs. 1 h averages). Besides routine observations, an intensive field measurement campaign was held from 13 to 24 August 2001 in the area of the Terlago saddle, north of Trento. During this campaign two additional weather stations were operated (see Fig. 2c). The first (MTT) was installed at the end of the Lakes Valley, immediately upstream of the saddle ridge (close to the north-western sidewall, where the maximum wind speed for this section is expected), and recorded 10 min averages of 3 m a.g.l. wind speed and direction. The second (RON2), lying at the Adige Valley floor at the foot of the Terlago saddle,

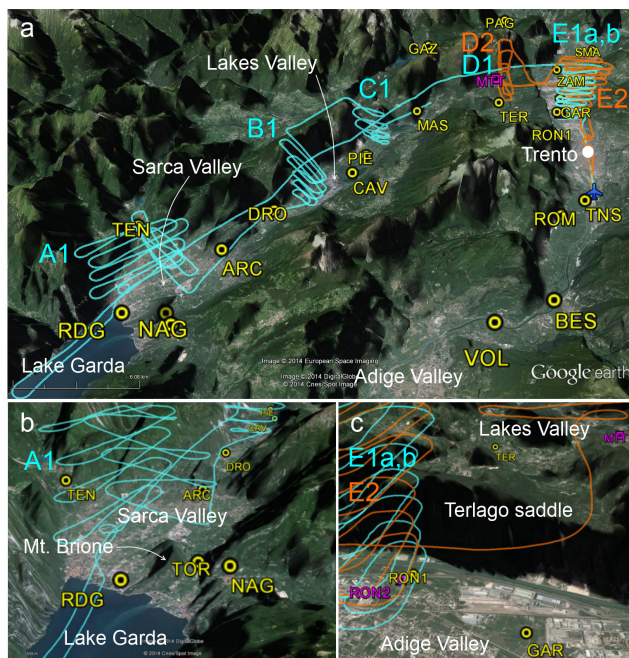


Figure 2. (a) Representation of the flight trajectories (cyan line: flight 1; orange line: flight 2). The names of the single spirals (i.e. sites) are indicated in corresponding colours (see Table 1; notice that spirals D1 and E1b, which lack the GPS data, are also indicated at the corresponding sites). Routinely operated AWSs and intensive surface measurement sites are shown respectively by yellow and magenta place marks (see Table 2). View is from SE. (b) Close-up of the shoreline area and the Sarca Valley (view is from S). (c) Close-up of the area of the Terlago saddle, north of Trento (view is from E). Background images: ©2014 Google Earth, ©2014 European Space Imaging, ©2014 DigitalGlobe, ©2014 CNES–SPOT Image.

was equipped with an ultrasonic anemometer (de Franceschi et al., 2002). Eddy correlation techniques were applied to retrieve the vertical sensible heat flux, adopting an averaging period of 30 min (see de Franceschi and Zardi, 2003; de Franceschi et al., 2009).

3 Results

After a brief description of the weather conditions observed on the flight day (Sect. 3.1), the results are now illustrated separately for three sub-areas – the Sarca Valley (Sect. 3.2), the Lakes Valley (Sect. 3.3) and the Adige Valley (Sect. 3.4) – following the spatial development of the Ora del Garda, from Lake Garda’s shoreline to the Terlago saddle. For each sub-area the results available on the basis of surface observations, airborne pseudo-soundings and RK-interpolated θ fields are also reported separately.

3.1 Weather conditions

On 23 August 2001 clear-sky and weak-wind conditions were observed throughout the day at the crest-level stations PAG and GAZ (respectively 2125 and 1601 m a.s.l.; see Fig. 2a for AWSs’ location). Satellite images indicate that the sky over the study area was completely cloudless in the morning, whereas in the afternoon some cumulus clouds developed at mountain-top level, as a result of the convergence of thermally driven circulations. Reanalyses show a high-pressure ridge elongating over central Europe from the SW, producing a weak northerly synoptic wind across the Alps, as indicated by routine radiosoundings at Milan (see Fig. 1 for the sounding station’s position). Hence, favourable conditions for the full development of thermally driven circulations did occur on the flight day.

3.2 Sarca Valley

3.2.1 Surface data

Figure 3 provides an overview of the wind development during the day at various AWSs. The onset of the lake breeze at RDG at Lake Garda’s shoreline occurs between 09:00 and 10:00 LST, as indicated by an abrupt shift in wind direction, from northerly to southerly (notice that hourly data are backward averages). The lake-breeze onset is accompanied by a temperature decrease (Fig. 4a) and an increase in w (not shown). Then the breeze strengthens to 6.0 m s^{-1} (gust speed: 8.8 m s^{-1}) at 14:00 LST, persists until local sunset ($\sim 18:00$ LST) and then rapidly ceases (Fig. 3). The surface water temperature of Lake Garda (measured at RDG) remains almost constant throughout the day ($\sim 21^\circ\text{C}$), and the diurnal air temperature range close to the lake shore is also limited (only 6.5°C ; Fig. 4a). In particular in the afternoon the temperature curve at RDG is completely flattened around 26.5°C . At TOR and ARC (respectively 1.5 and 5 km inland from the lake’s shoreline; cf. Fig. 2b) a sharp drop in the 15 min resolution temperature series is recorded at 11:00 LST. A similar signal is also seen at NAG and TEN at 11:00 LST (not shown; see Fig. 2b for AWSs’ location). In general, in the afternoon the temperature curve is levelled out at all the AWSs in the Sarca Valley. On the other hand, at TOR, ARC and DRO air temperatures lower than at RDG are observed from 19:00 LST, and a regular land breeze (down-valley wind) is registered at the shoreline during nighttime (Fig. 3). However, contrary to what was expected, the water–air temperature difference observed at RDG does not reverse between day and night.

3.2.2 Pseudo-soundings

The upper part of A1 θ pseudo-sounding (Fig. 5a), taken shortly after the Ora del Garda onset, is in good agreement with 06:00 and 12:00 UTC routine radiosoundings at Milan (in the Po Plain; see Fig. 1). In addition, the A1 profile is

Table 2. List of surface AWSs, named as in Fig. 2 and grouped by geographic area. Operating institution: FEM indicates the Edmund Mach Foundation, Meteot. stands for Meteotrentino (i.e. the Meteorological Office of the Autonomous Province of Trento) and UniTN is the University of Trento. Local terrain height and height of the anemometer (where present) are also reported. (*) indicates anemometers recording only wind speed. (**) indicates the ultrasonic anemometer operated by UniTN. (–) indicates that no anemometer is installed at the AWS.

Area	Station ID	Institution	Terrain height	Time resolution	Anemometer
Sarca Valley	RDG	FEM	69 m a.s.l.	1 h	5 m a.g.l.
	TOR	Meteot.	70 m a.s.l.	15 min	(–)
	ARC	Meteot.	91 m a.s.l.	15 min	(–)
	DRO	FEM	113 m a.s.l.	1 h	(–)
	NAG	FEM	223 m a.s.l.	1 h	(–)
	TEN	Meteot.	405 m a.s.l.	15 min	(–)
Lakes Valley	PIE	FEM	242 m a.s.l.	1 h	3 m a.s.l.(*)
	CAV	Meteot.	245 m a.s.l.	15 min	(–)
	MAS	Meteot.	245 m a.s.l.	15 min	(–)
	TER	FEM	428 m a.s.l.	1 h	3 m a.s.l.(*)
	MTT	UniTN	720 m a.s.l.	10 min	3 m a.s.l.
Adige Valley (S of Trento)	VOL	FEM	175 m a.s.l.	1 h	(–)
	BES	FEM	180 m a.s.l.	1 h	3 m a.s.l.(*)
	ROM	FEM	184 m a.s.l.	1 h	(–)
	TNS	FEM	185 m a.s.l.	1 h	10 m a.s.l.
Adige Valley (N of Trento)	RON1	Meteot.	194 m a.s.l.	15 min	10 m a.s.l.
	RON2	UniTN	194 m a.s.l.	0.04 s	6.5 m a.s.l.(**)
	GAR	FEM	197 m a.s.l.	1 h	3 m a.s.l.
	ZAM	FEM	201 m a.s.l.	1 h	3 m a.s.l.(*)
	SMA	Meteot.	205 m a.s.l.	15 min	(–)

colder at all levels than the pseudo-soundings taken in the upper valley, and, in particular, its lowest part is ~ 2 K colder than B1 and C1. An elevated ML extends between 1500 and 1800 m a.s.l., while the stratification below is stable (θ vertical gradient: 3 K km^{-1}) down to the minimum flying height (i.e. 185 m above Lake Garda's surface). However, surface measurements at RDG indicate that an unstable surface layer is already present at the lake's shoreline. The corresponding A1 w pseudo-sounding (Fig. 6a) shows an almost constant humidity content (10 g kg^{-1}) over the whole valley depth, up to ~ 1750 m a.s.l., while a larger value is recorded at ground level at RDG (13 g kg^{-1}).

3.2.3 RK results

Figures 7 and 8 help in inferring the 3-D thermal structure of the lowest ABL characterizing the Sarca Valley area between 10:00 and 10:45 LST. A colder air mass is displayed at the centre of the valley cross section, while higher θ values (by at least 0.5 K) are detected at both the lateral extremities of the flight trajectory, but especially in the easternmost region below 700 m a.s.l., close to the 300 m high Mt. Brione, where the θ excess reaches 1.25 K (cf. the pattern of 299.00–300.25 K isentropes around 600 m a.s.l. in Fig. 7). On the other hand, almost negligible along-valley gradients

of θ are present over the longitudinal section taken west of Mt. Brione, i.e. within the colder air mass occupying the centre of the valley (see Fig. 8). Only a small warm perturbation – very likely associated with the presence of Mt. Brione – is found downstream of this rocky relief at low level.

3.3 Lakes Valley

3.3.1 Surface data

At PIE (lower Lakes Valley) and TER (upper Lakes Valley) an increasing wind intensity is recorded from 10:00 and 11:00 LST respectively, with a peak at 14:00 and 16:00 LST (maximum hourly average and gust speed values at TER: 3.9 and 8.7 m s^{-1} ; not shown). Intensive wind observations at MTT (not far from TER, close to the north-western valley slopes; see Fig. 2c) reveal a weak up-slope (SE) circulation developing in the morning between 08:30 and 10:30 LST (Fig. 3). Then a gradual clockwise rotation of the wind direction to steady up-valley (SW) occurs, which is completed at 11:50 LST. Between 15:30 and 20:00 LST the up-valley wind at MTT strengthens to 5.5 m s^{-1} (corresponding gust speed: 9.0 m s^{-1}) and then weakens, ceasing completely at 21:50 LST. Also at TER the wind dies out around 22:00 LST (not shown). During the up-valley flow phase described

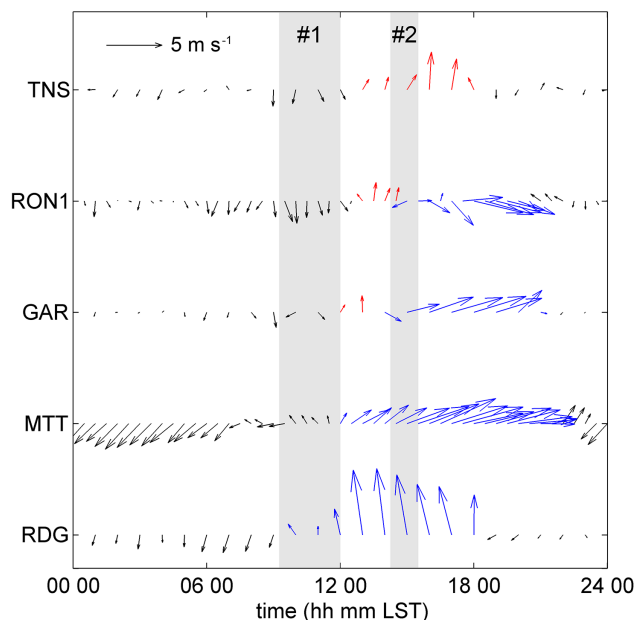


Figure 3. Wind observations for 23 August 2001 at RDG (5 m a.g.l.) in the Sarca Valley, MTT (3 m a.g.l.) at the end of the Lakes Valley, GAR (3 m a.g.l.), RON1 (10 m a.g.l.) and TNS (10 m a.g.l.) in the Adige Valley (see Fig. 2 and Table 2 for name and location of the AWSs). For the sake of clarity, MTT and RON1 data are aggregated as 30 min (backward) averages. Data from RDG, GAR and TNS are 1 h backward averages. Notice that the blue arrows correspond to the Ora del Garda, while the red arrows correspond to the Adige Valley up-valley wind. The duration of flights 1 and 2 is indicated by the grey bands.

above, an evident flattening of the temperature curve around values of 27–28 °C is observed at all the AWSs in the Lakes Valley until 18:00 LST (cf. Fig. 4b).

3.3.2 Pseudo-soundings

Performed in the lower Lakes Valley during the initial stages of the Ora del Garda, spirals B1 and C1 provide θ pseudo-soundings that are more than 0.5 K (potentially) warmer than the 12:00 UTC radiosounding taken at Milan (see Fig. 5a). The two pseudo-soundings are very similar: at both sites a less-than-500 m deep ML is detected above the ground, slightly colder at site B than at C (θ_m : 300.4 and 300.7 K respectively). On the other hand, at the northern end of the Lakes Valley, the D1 profile is on average ~ 1 K warmer than B1 and C1, with a 750 m deep ML at the valley floor displaying a θ_m of 301.8 K (see Fig. 5a). More than 3 h later, at $\sim 15:00$ LST, the ML depth has reduced to 600 m and θ_m has increased by ~ 2 K. At the same time, the θ vertical gradient has decreased from 3.5 to 2.0 K km $^{-1}$ in the layer below 1750 m a.s.l. (cf. D2 pseudo-sounding in Fig. 5b). Moreover, while shortly before noon (D1) the θ observation from the closest AWS is ~ 1 K higher than the corresponding θ_m value, in the afternoon (D2) the two are almost equal (see

Fig. 5b). Unlike the pseudo-soundings further down-valley (i.e. A1, B1 and C1), both D1 and D2 display two distinct elevated MLs around 1500 and 2000 m a.s.l. (i.e. around the height of the south-eastern and north-western lateral crests respectively). Finally, regarding the moisture field, the corresponding w profiles in Fig. 6 show that the water vapour is rather uniformly distributed well above the top of the MLs detected at the valley floor, i.e. up to the average crest elevation.

3.3.3 RK results

In the late morning the vertical section extracted from the θ field regridded around spiral B1 (Fig. 9) reveals a clear cross-valley asymmetry, with the western half of the valley atmosphere warmer than the opposite, by approximately 0.5 K. This horizontal gradient is detectable almost down to the lowest point of the flight trajectory, i.e. 350 m above the local valley floor. On the other hand, further north at the end of the Lakes Valley (about 2 km upstream of the Terlago saddle ridge), in the afternoon an opposite asymmetry is detected at the lowest levels of the valley atmosphere (below ~ 1200 m a.s.l.; see Fig. 10). This plausibly indicates that in this phase the potentially colder air which forms the core of the Ora del Garda current has shifted towards the north-western side of the valley.

3.4 Adige Valley

3.4.1 Surface data

On the flight day a southerly up-valley wind blows in the Adige Valley at TNS (5 km south of Trento) from 13:00 to 18:00 LST, with an average intensity of 2.0 m s $^{-1}$ (see Fig. 3). At the AWSs located south of the city the maximum strength of the up-valley wind is generally recorded around 16:00 LST (peak intensity at BES: 3.9 m s $^{-1}$; not shown), and weak down-valley winds are observed already in the early-evening hours. In contrast, at GAR and RON1 (i.e. the two stations closest to the Terlago saddle and hence most directly affected by the Ora del Garda overflow; see Fig. 2c) the up-valley wind is observed only for a short time, approximately between 12:00 and 14:00 LST (see Fig. 3). Indeed, already at 14:00 LST the wind direction at GAR (which is situated in front of the lowest point of the Terlago saddle) suddenly shifts to WSW (i.e. cross-valley). On the other hand, the 15 min resolution observations collected at RON1 (located ~ 2 km south of GAR) provide a more complex picture: after a short phase of weak up-valley flow (13:00–14:30 LST), from 15:30 LST the wind shows a westerly direction accompanied by an oscillating along-valley component. A steady WNW direction and stronger intensities are observed only from 17:15 LST onwards. In the late afternoon hours, the wind reaches an intensity of ~ 5.0 m s $^{-1}$ at both stations (gust speed at GAR: up to 11.3 m s $^{-1}$;

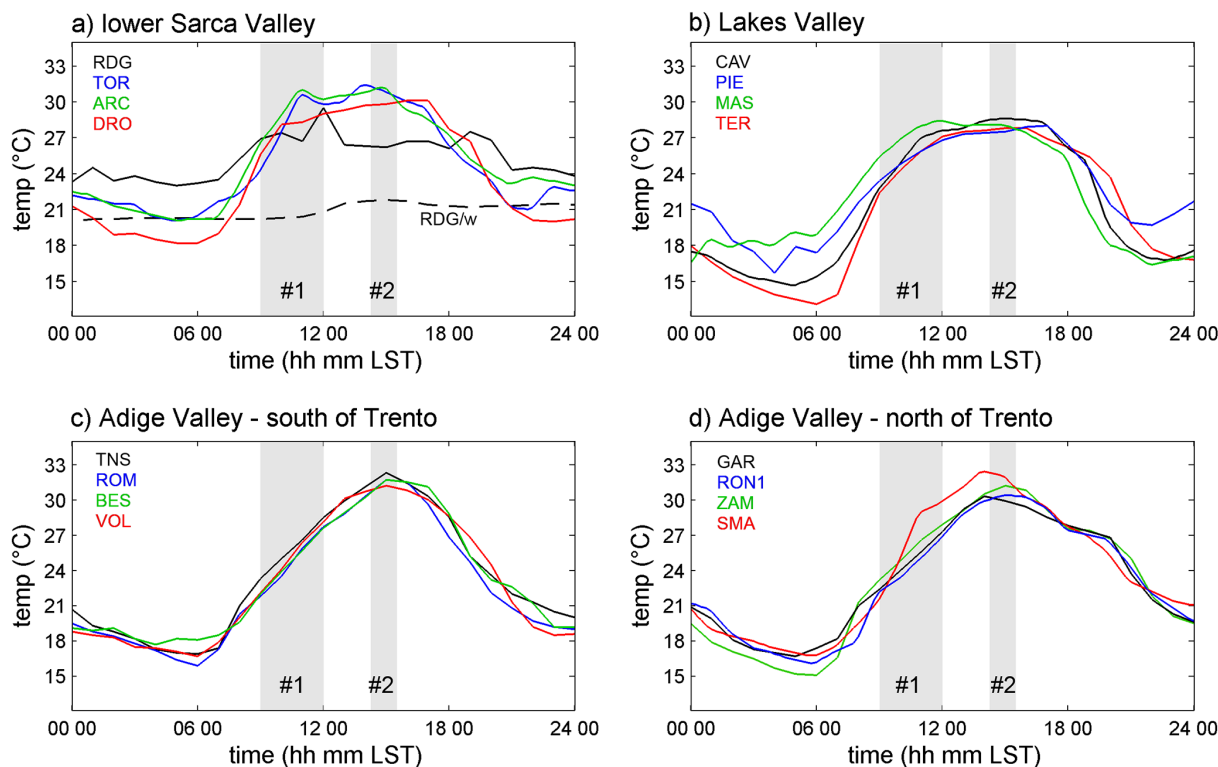


Figure 4. Observations of 2 m a.g.l. air temperature for 23 August 2001, grouped by geographic area. Notice that RDG/w series is the Lake Garda water temperature measured at RDG. See Fig. 2 and Table 2 for names and locations of the AWSs. The duration of flights 1 and 2 is indicated by the grey bands.

not shown), with maximum values being recorded between 16:00 and 19:00 LST. This anomalous flow stops rather suddenly around 21:00 LST at both stations.

As for near-surface temperatures, almost identical diurnal cycles are recorded at the AWSs south of Trento: in the morning the temperature increases, up to a $\sim 32^\circ\text{C}$ peak value (recorded around 15:00 LST), then slowly decreases during the late afternoon and the night (Fig. 4c). In contrast, at the AWSs north of Trento the daily temperature cycle displays specific features (Fig. 4d), different from those observed south of Trento. Indeed, between 15:00 and 17:00 LST lower temperatures are measured north of Trento; in particular, at GAR the air starts to cool down at a quasi-constant rate from 14:00 LST. In contrast, higher temperatures are observed from 18:00 LST, with near-constant values ($\sim 27^\circ\text{C}$) registered until 20:00 LST. According to the temperature patterns described above, in the area north of Trento positive values of the sensible heat flux (up to 70 W m^{-2}) are measured at RON2 starting from 08:00 LST and start decreasing at a rather constant rate from 14:00 LST, i.e. when the anomalous cross-valley wind begins to flow (see Fig. 11). Notice at 16:00 LST a sudden transition to negative values, particularly large (of the order of -100 W m^{-2}) between 17:30 and 20:00 LST, in connection with the maximum wind intensity.

3.4.2 Pseudo-soundings

Three pseudo-soundings are available at site E (Fig. 5b), allowing the assessment of the daytime evolution of the ABL in the area north of Trento. Surface wind observations indicate that each profile is representative of a different wind regime: down-valley wind conditions in the morning (E1a), the transition between down-valley and up-valley wind at noon (E1b) and the anomalous cross-valley wind phase following the Ora del Garda arrival in the early afternoon (E2). Between the first two stages a strongly stably stratified profile is replaced by a shallow ML (depth: 400 m; θ_m : 300.6 K) topped by a slightly stable layer, while between noon and early afternoon the ML depth jumps to 1300 m and θ_m further rises by 3.5 K. The comparison between the θ pseudo-soundings taken at sites D and E within a few minutes from one another shows that in the late morning D1 and E1b are very similar above 1500 m a.s.l. (i.e. above the crest level), while below that height D1 is warmer than E1b by $\sim 1\text{ K}$ (θ_m : 301.8 vs. 300.6 K). In contrast, in the afternoon the upper parts of D2 and E2 pseudo-soundings (range of θ : 305–308 K) seem to be almost rigidly displaced by ~ 300 – 400 m along the vertical axis, resulting in a $\sim 1.5\text{ K}$ difference (E2 warmer than D2). Below 1500 m a.s.l. the two profiles display similar values, with θ_m slightly lower for D2 than for

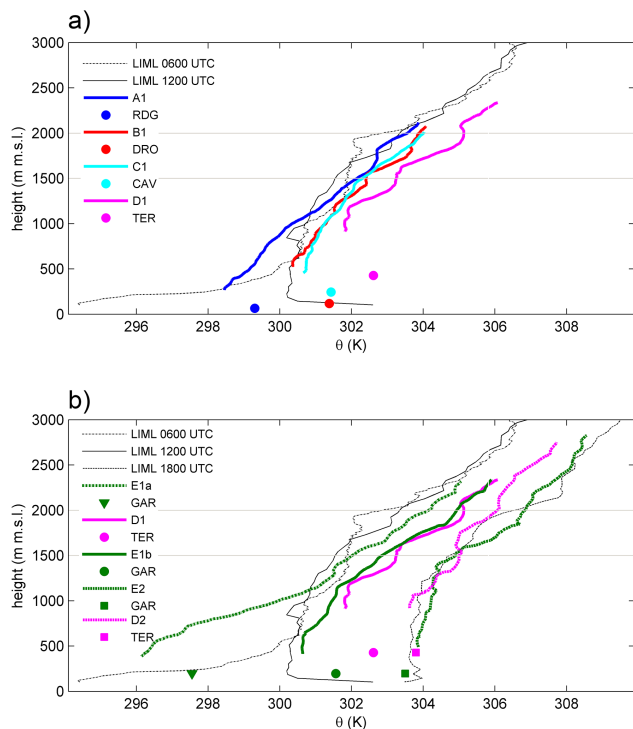


Figure 5. θ pseudo-soundings: (a) profiles for sites A, B, C and D (Sarca and Lakes valleys) from flight 1; (b) profiles for sites D and E (i.e. Terlago saddle area and Adige Valley) from flights 1 and 2 (cf. Table 1). Associated surface observations from the AWS closest to each site are also reported, as representative of local surface layer conditions (see Fig. 2 and Table 2 for station names). Milan (LIML) radiosoundings launched at 06:00, 12:00 and 18:00 UTC (i.e. 07:00, 13:00 and 19:00 LST) are displayed as black lines. The elevation range of the surrounding crests is indicated in grey.

E2. Another relevant difference between flight 1 and flight 2 is that the near-surface θ values at sites D and E are on average ~ 1 K higher than the θ_m values of the associated pseudo-soundings in the morning, but almost equal or slightly lower in the afternoon.

3.4.3 RK results

Moving to RK results, the θ field sampled in the afternoon at site E reveals that the Ora del Garda, overflowing from the Lakes Valley into the Adige Valley, produces a complex ABL thermal structure above the latter valley's floor (see Fig. 12). On the western side the 304.00–304.50 K isentropes (which can be considered as streamlines to a good approximation) bend downward, following the topography of the Terlago saddle. Then, at the centre of the valley cross section (horizontal coordinate: 700–1000 m), they sharply rebound to a higher height, with a quasi-vertical pattern. The structure described seems to be compatible with those resulting from the development of hydraulic jumps in stratified flows in connection with gap flows and downslope windstorms (cf. for exam-

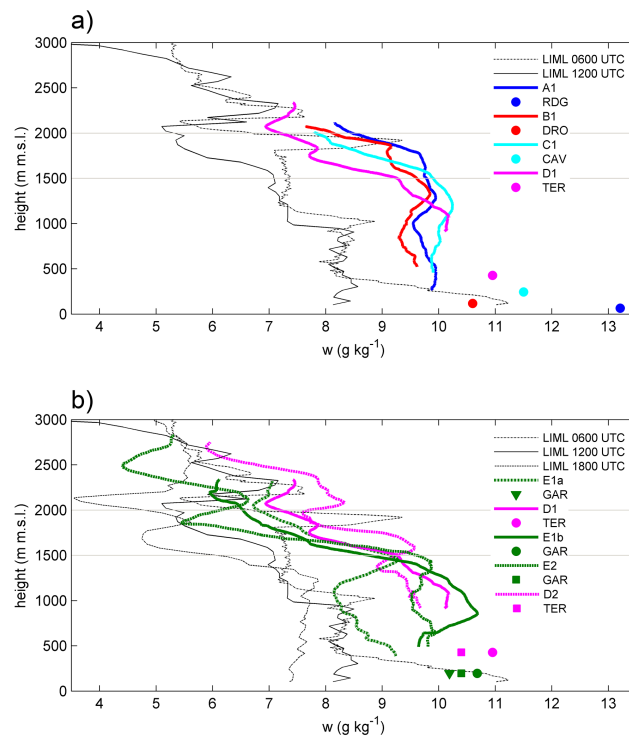


Figure 6. As in Fig. 5 but for w .

ple Liu et al., 2000, their Fig. 17; see also Sect. 1). Moreover, the affected layer – whose depth may be estimated as approximately 1300 m – appears rather well mixed, while between 1500 and 1800 m a.s.l. very dense isentropes are observed. They correspond to a sharp vertical gradient of θ , marking the transition to an upper region of air potentially warmer (by ~ 1.5 K) than air at the same height in the Lakes Valley (cf. Fig. 10).

4 Discussion

Notice that each of Sects. 4.1–4.5 below deals with a specific phase or feature of the Ora del Garda development and associated surface wind and ABL processes. The different aspects are discussed according to their sequence in time and space, i.e. following the different stages of the circulation in time and its development from Lake Garda's shoreline to the Adige Valley.

4.1 The onset of the Ora del Garda

Surface measurements from the Sarca Valley clearly indicate that a small-scale cold and humid front – typical of sea/lake breezes (Simpson, 1994; Zumpfe and Horel, 2007) – forms at Lake Garda's shoreline in the late morning (between 09:00 and 10:00 LST; see Sect. 3.2.1). They confirm the development of a well-defined lake-breeze front at the Ora del Garda onset, as speculated by Laiti et al. (2013b) only on the basis

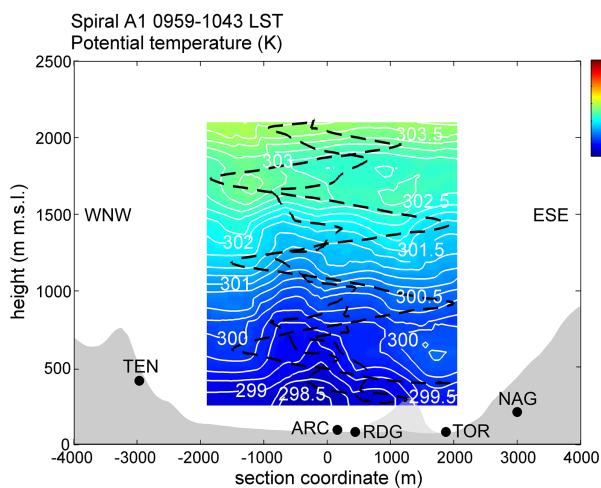


Figure 7. Cross-valley vertical section of RK-interpolated θ field for spiral A1. The contour interval is 0.25 K (in white). The grey shading indicates the valley topography. The horizontal coordinate marks the cross-valley direction. The cross section (along-valley coordinate: 1000 m; cf. Fig. 8) is taken immediately N of Mt. Brione (whose profile is shown by the semi-transparent grey shading). The black dashed line is the projection of the motorglider's trajectory over the considered section. The projection of the position of RDG, TOR, NAG, TEN and ARC is also indicated (black dots). Notice that the RK-estimated standard deviation of the interpolated θ values (i.e. the square root of the RK-estimated variance of the predicted θ residuals; see Goovaerts, 1997) varies between 0.00 K (close to the trajectory) and 0.25 K (at the farthest points from the trajectory) over the fields displayed in Figs. 7–10 and 12.

of local atmospheric thermal structures observed in the afternoon and surface measurements at RDG. Furthermore, the surface data reveal that the inland penetration of the lake breeze in the easternmost part of the Sarca Valley (i.e. between Mt. Brione and the eastern valley sidewall) is delayed with respect to the rest of the basin, by approximately 1 h. Accordingly, the lowest levels of the θ field obtained from spiral A1 (Figs. 7–8) show that, at the overflight time (10:00–10:45 LST), the cold body of the breeze has very likely already propagated in the central part of the Sarca Valley, while the region east of Mt. Brione keeps warmer (Sect. 3.2.3). A plausible reason for this inhomogeneity is the ~ 1.5 h delay between the local sunrise times at the western and eastern extremities of the valley floor (06:05 and 07:45 LST respectively, as determined by a GIS analysis). Indeed, the topographic shadowing of the easternmost region may locally delay the establishment of the water–land temperature contrast promoting the lake breeze. Moreover, the narrow corridor between Mt. Brione and the eastern sidewall (width: ~ 500 m; see Fig. 2c) is known to receive strong drainage flows until late morning. This might also play a role in further delaying the breeze penetration in the area.

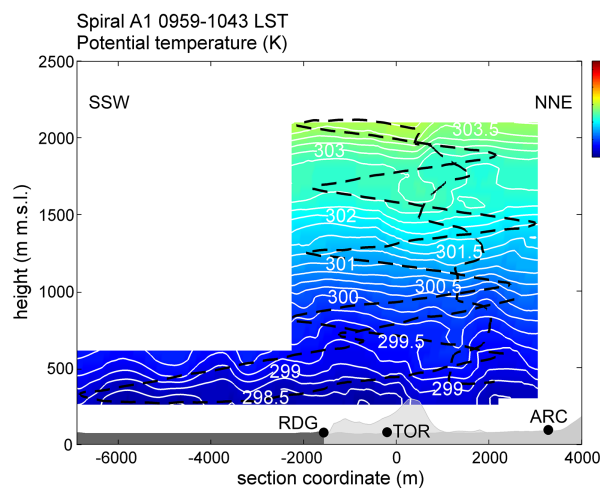


Figure 8. As in Fig. 7 but for a longitudinal (along-valley) vertical section. Dark grey shading indicates Lake Garda's surface. The section is taken immediately W of Mt. Brione (in semi-transparent grey shading), i.e. in the middle of the Sarca Valley (cross-valley coordinate: 500 m; cf. Fig. 7). Accordingly, the horizontal coordinate marks the along-valley direction. The projection of the position of RDG, TOR and ARC is also indicated (black dots).

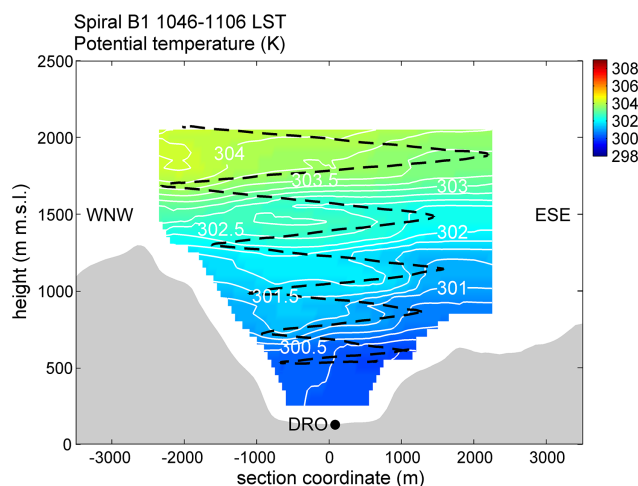


Figure 9. As in Fig. 7 but for spiral B1. The horizontal coordinate marks the cross-valley direction. The projection of DRO's position is also indicated (black dot).

4.2 The flow structure at the junction of the Lakes and Adige valleys

The Ora del Garda reaches its mature stage in the early afternoon around 14:00 LST, when the up-valley wind reinforces all along the Sarca and Lakes valleys, reaching average intensities of $4\text{--}6\text{ m s}^{-1}$ (gust speed: up to 9 m s^{-1} ; see Sects. 3.2.1 and 3.3.1). At the end of the Lakes Valley an asymmetric thermal field (see Fig. 10 and Sect. 3.3.3) and wind observations at MTT and TER (see Sect. 3.3.1) suggest that the cold stream of the breeze is preferentially channelled in the

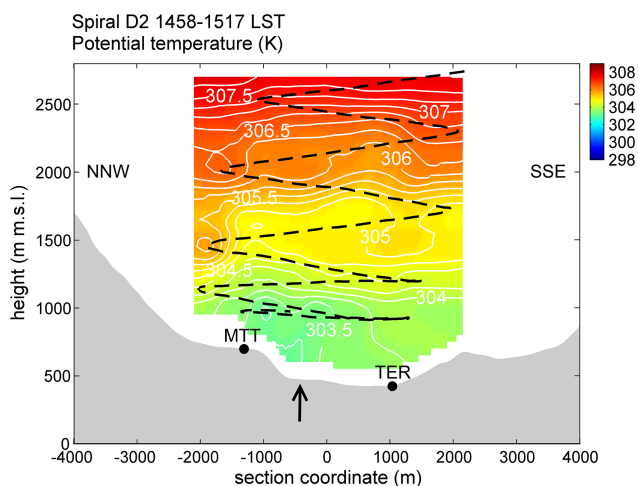


Figure 10. As in Fig. 7 but for spiral D2. The horizontal coordinate marks the local cross-valley direction for the Lakes Valley. The cross section is taken about 2 km upstream of the Terlago saddle ridge, whose lowest point's projection is indicated by the black arrow. The projection of MTT's and TER's position is also indicated (black dots).

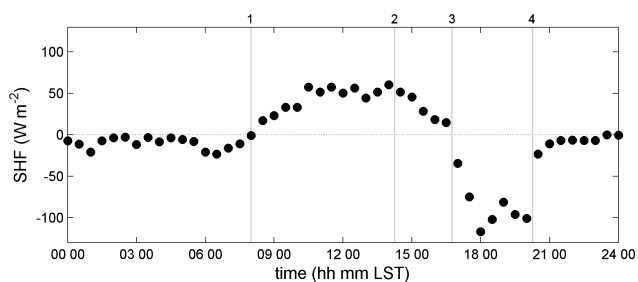


Figure 11. Vertical sensible heat flux (SHF) for 23 August 2001, from eddy covariance analysis of ultrasonic anemometer measurements (averaging interval: 30 min) collected at RON2. The vertical grey lines indicate (1) beginning of the morning heating, (2) beginning of the SHF decrease at the arrival of the Ora del Garda, (3) shift to negative SHF and (4) end of the phase characterized by large negative SHF.

western half of the valley. This westward deflection of the flow may possibly depend on the eastward bending of the valley axis a few kilometres down-valley (i.e. upstream), as previously hypothesized by Laiti et al. (2013b). The phenomenon may be explained in analogy with what was reported by Weigel and Rotach (2004) for the Riviera Valley, where the up-valley current was also displaced laterally towards one of the slopes, as a result of the centrifugal acceleration driven by the local valley curvature. Also at 14:00 LST the Ora del Garda breaks out into the Adige Valley, producing a strong and gusty cross-valley wind in the area north of Trento (see Sect. 3.4.1). The later occurrence of this anomalous wind at RON1 than at GAR, together with the northerly and the southerly component respectively characterizing the

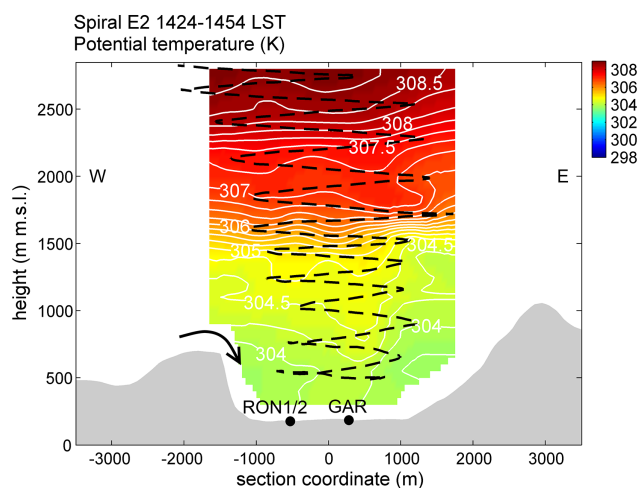


Figure 12. As in Fig. 7 but for spiral E2. The horizontal coordinate marks the local cross-valley direction for the Adige Valley. The black arrow on the left represents the Ora del Garda overflowing from the Lakes Valley through the Terlago saddle into the Adige Valley. The projection of the position of RON1, RON2 and GAR is also indicated (black dots).

flow at the two AWSs, agrees well with the earlier speculations proposed by Schaller (1936). He hypothesized the accumulation of the denser Ora del Garda air at the Adige Valley floor and its propagation not only northward, but also southward, gradually overwhelming the regular up-valley wind in the urban area of Trento. However, no effect associated with the overflow of the Ora del Garda is experienced south of the city (cf. Giovannini, 2012).

Considering the above-described wind field at the surface, the complex pattern of the isentropes below 1500 m a.s.l. observed in Fig. 12 (see Sect. 3.4.3) and the strong deepening of the ML at site E in the afternoon (see Sect. 3.4.2) are plausibly compatible with the development of a hydraulic jump in the Adige Valley. This would mark the transition from supercritical flow conditions upstream (i.e. a downslope current pouring along the eastern wall of the Terlago saddle) to a subcritical regime further downstream (i.e. where the flow decelerates, for it impinges on the floor and the eastern slopes of the Adige Valley), and would be characterized by a highly turbulent region. Indeed, this structure resembles those generated by gap flows (cf. Flamant et al., 2002, their Fig. 16) or by downslope windstorms (cf. Liu et al., 2000, their Fig. 17), but on a smaller scale. The development of such a flow pattern was previously speculated in Laiti et al. (2013b), but only on the basis of the afternoon ABL thermal structure, for in that work no wind data were available for the affected area. In contrast, here (high-resolution) near-surface wind observations and multiple θ profiles for different times of the day finally allow a more robustly supported interpretation of the flow structure determined by the Ora del Garda overflow into the Adige Valley. The fact that above the

well-mixed region the thermal stratification in the Adige Valley seems to be rigidly displaced downward by $\sim 300\text{--}400\text{ m}$ (i.e. by approximately the height of the Terlago saddle) with respect to the Lakes Valley (cf. θ pseudo-soundings E2 and D2 in Fig. 5b) might further support the proposed hydraulic analogy.

4.3 The cessation of the Ora del Garda

While in the area north of Trento the anomalous cross-valley wind persists until the late evening (22:00 LST), south of Trento and at the lake's shoreline regular down-valley winds are observed already in the early evening (18:00 LST; see Sects. 3.2.1 and 3.4.1). The earlier cessation of the Ora del Garda at Lake Garda's shoreline than at the end of the Lakes Valley may be explained by the hypothesis that the lake-breeze and the up-valley wind systems have different response times to the extinction of the radiative forcing. Indeed, following the local sunset, the horizontal (along-valley) gradient in air temperature between the shoreline and the stations further north in the Sarca Valley reverses quickly, accompanied by a sharp shift in wind direction (at RDG), which is typical of the transition from sea/lake breeze to land breeze in the evening (cf. Defant, 1951; Simpson, 1994). Yet, unexpectedly, the difference between air and water surface temperature (observed at RDG) does not reverse during nighttime. This might be explained by an upwelling of deep, colder water at the shoreline, driven by the northerly winds blowing on 17–19 August (not shown). Therefore, the low water temperature measured at RDG may be not truly representative of the lake-surface temperature further offshore. Differently from what occurs in the shoreline area, above the Terlago saddle the air remains potentially colder than the air at the same level in the Adige Valley for a few hours after sunset. As soon as a balance is reached in the late evening, the cross-valley flow at RON1 and GAR ceases; shortly afterwards, the wind at MTT shifts to a steady down-valley direction, with a 3–4 h delay with respect to the Ora del Garda cessation at the lake's shoreline.

4.4 The ABL structure in the Sarca and Lakes valleys

During daytime, the near-surface temperature cycle in the Sarca and Lakes valleys remarkably differs from the cycle typical of a mountain valley (without any lake effect; see Giovannini et al., 2014, in particular their Fig. 9, as an example). In particular, the temperature curve is completely flattened during the warmest hours of the day (see Sects. 3.2.1. and 3.3.1). This suppression of the temperature rise in the lowest atmosphere – as well as the stabilization of the surface layer observed at site D in the afternoon – is clearly attributable to the large source of cold air at the valley inlet, i.e. Lake Garda, and to the up-valley advection by the Ora del Garda. Probably due to the same limiting factor, the rise of θ_m in the Lakes Valley is not as fast as in the nearby Adige

Valley (i.e. ~ 1.5 times faster at E than at D site between 12:00 and 15:00 LST; cf. Sects. 3.3.2 and 3.4.2).

Coherently with the up-valley advection of cold air from above Lake Garda, the valley atmosphere close to the shoreline (site A) is stable down to very low heights (Sect. 3.2.2). On the other hand, different ABL structures are observed further north in the Lakes Valley (sites B, C and D). These consist of rather shallow MLs (of the order of 500 m) at the valley floor and slightly stable layers above. The latter extend almost up to the average height of the lateral crests ($\sim 1500\text{--}2000\text{ m a.s.l.}$) and are topped by one or more (like at site D) elevated MLs, with a depth of a few hundred metres (Sect. 3.3.2). The described ABL structure, which was also observed by Laiti et al. (2013b), is fully compatible with the stratification typically observed in deep mountain valleys (cf. De Wekker et al., 2004; Rotach and Zardi, 2007; Weigel and Rotach, 2004). This is strictly connected with the development in the morning of (multiple) cross-valley circulations, formed by up-slope winds and associated return flows at the crest level (Kuwapata and Kimura, 1995, 1997; Serafin and Zardi, 2010b, in particular their Fig. 9). Also w pseudo-soundings (which were not available in Laiti et al., 2013b) are coherent with this circulation scheme. Unlike in standard convective boundary layer schemes (Stull, 1988; Rampanelli and Zardi, 2004), the water vapour appears rather uniformly distributed nearly up to the crest height (i.e. well above the top of the convective ML; cf. Fig. 6). This is very likely associated with the transport of moisture from the valley floor along the lateral slopes to the valley centre, by the above-cited up-slope winds and return flows (cf. Kuwapata and Kimura, 1995, 1997; Weigel et al., 2007).

The described cross-valley flow pattern induces the subsidence of potentially warmer, stably stratified air from the free atmosphere above the valley centre, which stabilizes the upper part of the θ profile and inhibits the deepening of the convective ML at the valley floor. Local subsidence is also known to be one of the important mechanisms for the early-daytime heating of the valley atmosphere core (cf. Rampanelli et al., 2004; Schmidli and Rotunno, 2010; Serafin and Zardi, 2010a, 2010b, 2011; Schmidli, 2013). As a matter of fact, the daytime heating excess, which is typically found between the air within a mountain valley and over an adjacent plain and is responsible for driving up-valley winds (Zardi and Whiteman, 2013), is observed throughout the whole depth explored by the flights when the study area is compared with the Po Plain. It is found to be of the order of 0.5–1.5 K (see Sect. 3.3.2 and Fig. 5a).

On the other hand, the RK-interpolated θ field at site B reveals that in the morning a more intense heating (and possibly more intense up-slope winds) occurs close to the western sidewall than to the eastern slopes of the lower Lakes Valley (see Sect. 3.3.3). Among the potential reasons for this thermal asymmetry might be the approximately N–S orientation of the valley, which is responsible for an asymmetric radiative forcing in the morning. Moreover, here the rocky and

very steep western sidewall is very likely to produce sensible heat fluxes greater than those produced by the opposite, more vegetated and more gentle slopes, possibly contributing to the above-cited contrast. This may be ascribed not only to the fact that above the rocks there is no partitioning between sensible and latent heat flux, but also to the different steepness of the two sidewalls. A third factor which could potentially explain the asymmetric θ field observed is the presence of an elevated parallel valley on the eastern side of the lower Lakes Valley (cf. the local topography in Fig. 9). Indeed, during nighttime this terrain feature might possibly induce local conditions similar to those associated with nocturnal cooling and cold-air accumulation phenomena above confined elevated plateaus (Zardi and Whiteman, 2013).

4.5 The ABL structure in the Adige Valley

From the aforementioned hydraulic jump development (Sect. 4.2) an intense turbulent mixing is likely to ensue, which may easily explain the strong deepening of the local ML observed at site E between 12:00 and 15:00 LST (cf. Sect. 3.4.2). In fact, it is implausible that such a sudden growth of the ML is driven by surface sensible heat fluxes and thermal convection. On the other hand, concerning the evolution of the lowest ABL in the area north of Trento, while unstable surface layers are observed in the morning, a slightly stably stratified surface layer already develops in the early afternoon. This indicates that the surface sensible heat flux is no longer sustaining the growth of the ML from below. Accordingly, starting from the Ora del Garda outbreak at 14:00 LST, the vertical sensible heat flux measured at RON2 decreases until turning negative at $\sim 17:00$ LST (i.e. when the Ora del Garda establishes steadily at the nearby station RON1; see Sect. 3.4.1). As this change occurs ~ 1 h before the local sunset, it cannot be related to the radiative cooling of the ground. In contrast, it may be plausibly produced by the cold-air advection and the high wind speed associated with the Ora del Garda. As a matter of fact, the largest negative values of sensible heat flux at RON2 are recorded in connection with the climax of the cross-valley wind at RON1 (cf. Figs. 3 and 11). Similarly, the differences between the temperature cycles observed at the valley floor south and north of Trento may also be attributed to the persistent inflow from the Lakes Valley. In particular, in the afternoon the air spilling from above the saddle is potentially colder than the low-level air in the Adige Valley, inducing the earlier temperature decrease and the surface layer stabilization observed at the AWSs north of Trento. On the other hand, in the evening the strong wind may potentially delay the radiative cooling of the valley floor with respect to the rest of the Adige Valley.

4.6 Outlook

In order to identify the dominant mechanisms responsible for the coupled surface and ABL processes discussed in

Sects. 4.1–4.5, high-resolution numerical simulations of the analysed flight day are needed. These will be performed in the near future and will provide the basis for the comparison with the results reported in the present paper. As a matter of fact, the meteorological fields produced by RK inherently provide a degree of spatial detail that is comparable with the resolution of large-eddy simulations, which are able to resolve explicitly the ABL structures typically associated with thermally driven winds (see examples in Catalano and Cenedese, 2010; Catalano and Moeng, 2010; Chow et al., 2006; Lehner and Whiteman, 2012; Weigel et al., 2006). Numerical sensitivity analyses will be also carried out to investigate the effects of the valley orientation and curvature, of land use inhomogeneities and of local topographic features. Furthermore, the modelling will allow open research questions to be addressed, such as the fate of the Adige Valley up-valley current following the interaction with the Ora del Garda, or the phenomena behind the different responses of the breeze to the decline of solar radiation at the shoreline and in the Terlago saddle area.

However, the results presented will be useful for achieving an improved understanding of the typical surface wind and ABL processes affecting air quality (de Franceschi and Zardi, 2009; Gohm et al., 2009; Palau et al., 2005; Pérez-Landa et al., 2007; Rada et al., 2011; Ragazzi et al., 2013; Schnitzhofer et al., 2009), urban weather and climate (Giovannini et al., 2011, 2013a, 2014), turbulent fluxes (de Franceschi et al., 2009) and atmospheric convection leading to precipitation events (Bertò et al., 2004; Kalthoff et al., 2009; Eigenmann et al., 2009; Pucillo et al., 2009) in the study area. For example, in the warm season the Ora del Garda arrival in the afternoon may plausibly be expected to reduce the concentration of (locally emitted) pollutants and mitigate the temperature in the densely populated urban areas north of Trento. The present results may also be extended to complex terrain environments where thermally and dynamically driven local circulations similar to the investigated wind occur.

5 Conclusions

The paper investigated the ABL thermal structures accompanying the development of a coupled lake and valley wind, the Ora del Garda, which blows on warm-season sunny days in the south-eastern Italian Alps. The analyses were based on a composite data set of both surface and airborne observations. The latter were collected during two flights of an instrumented motorglider carried out on 23 August 2001, when weather conditions allowed a vigorous development of the investigated circulation. Compared with previous results contained in Laiti et al. (2013b), this paper added relevant information to the understanding of the ABL and the surface wind processes associated with the investigated circulation. A richer surface data set (including dedicated observations

of wind and sensible heat flux) and measurement flights covering both morning and afternoon provided further details about the different stages of the Ora del Garda. In particular, two key areas, namely the Lake Garda shoreline area and the junction between the Lakes Valley and the Adige Valley, could be explored in detail. The main findings are summarized below.

- At the Ora del Garda onset in the late morning (between 09:00 and 10:00 LST), the up-valley propagation of a well-defined lake-breeze front from Lake Garda's shoreline was documented by wind and temperature observations at the AWSs deployed in the Sarca Valley. Also, a delayed penetration of this front (by at least 1 h) in the easternmost part of the valley (i.e. between Mt. Brione relief and the eastern valley slopes) was suggested by surface data, and further confirmed by the 3-D fields of θ obtained from the airborne data. This feature might be explained by the strongly asymmetric solar irradiation in the morning, as a consequence of the N–S valley orientation.
- In its mature stage (i.e. in the early afternoon) the Ora del Garda reinforced to 6 m s^{-1} at the lake's shoreline and to 5.5 m s^{-1} in the northernmost Lakes Valley, and at 14:00 LST it overflowed into the Adige Valley across the Terlago saddle. This produced a strong cross-valley flow (5 m s^{-1}) in the area north of Trento, which overwhelmed the up-valley wind previously blowing in the area. This anomalous flow regime ceased at around 21:00 LST.
- After the Ora del Garda overflow, a 3-D θ field compatible with the development of a hydraulic jump was observed in the Adige Valley north of Trento. This plausibly marked the transition between an intense downslope wind, developing across the Terlago saddle (supercritical conditions), and a downstream region where the flow decelerated (subcritical conditions), due to the blocking effect of the eastern Adige Valley slopes.
- The Ora del Garda was found to cease earlier at Lake Garda's shoreline (18:00 LST) than in the area of the Terlago saddle (21:00–22:00 LST), with rather different response times to the decline of the radiative forcing.
- The ABL vertical structure typical of deep mountain valleys was observed in the Sarca and Lakes valleys. It consists of shallow convective MLs at the valley floor ($\sim 500 \text{ m}$); deeper, slightly stable layers above; and elevated MLs on top, i.e. around the height of the lateral crests ($\sim 1500 \text{ m a.s.l.}$). This structure plausibly results from the subsidence induced above the valley centre by up-slope winds and associated return flows. On the other hand, the up-valley advection of cold air from above the lake limited the temperature rise in the lowest ABL layers.
- In the Adige Valley the Ora del Garda overflow was followed by a strong increase in the ML depth, from 400 to 1300 m between 12:00 and 15:30 LST. This may be plausibly attributed to the intense turbulent mixing associated with the above-cited hydraulic jump. In addition, in the afternoon lower surface temperatures were recorded north of Trento than south of Trento, and large negative values of sensible heat flux (-100 W m^{-2}) were observed in connection with the Ora del Garda climax between 17:30 and 20:00 LST. In contrast, in the evening the radiative cooling in the area north of Trento was delayed with respect to the area south of the city, possibly due to the anomalous cross-valley wind.

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