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The thermally driven diurnal wind system of the Adige Valley in the Italian Alps

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The Adige Valley is one of the major corridors connecting the Po Plain with the inner Alps. A series of permanent weather stations and one wind profiler provide a regular monitoring of air temperature, atmospheric pressure, global solar radiation, wind speed and direction over the 140-km valley length and in the adjacent plain. Data from these stations are analysed for a subset of days on which weather conditions favoured a full development of diurnal valley winds in the period 2012-2014. The analysis highlights typical features in the alternating patterns of diurnal up-valley winds and nocturnal down-valley winds. In particular, the wind intensity depends linearly on the along-valley pressure gradient, supporting the concept of a quasi-steady balance between pressure gradient and surface friction. Also, in agreement with previous investigations, the amplitude of the surface pressure cycle increases in the up-valley direction, causing the reversal of the horizontal pressure gradient twice per day. In contrast, no appreciable along-valley variation in the diurnal temperature range is found. The analysis of surface temperature and pressure measurements suggests that the larger pressure perturbations found far into the valley are caused by the increased depth of the atmospheric layer subject to heating and cooling. Local inhomogeneities in the valley cross-section, in particular in the vicinity of a large basin, cause temperature and pressure perturbations that are strong enough to alter the typical cycle of down- and up-valley winds. Similarly, local wind convergence over the major cities during the night are explained in terms of the urban heat island effect.

Key Words: valley winds; thermally-driven circulations; horizontal pressure gradients; temperature daily cycle; Adige Valley

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1. Introduction

Valley wind circulations, which develop mainly on clear-sky days during the warm season, are distinguishing features of mountain valleys. They significantly mark the local wind climatology with a pronounced daily periodicity, as their direction regularly reverses between day and night (Zardi and Whiteman 2013). They usually blow down-valley at night and up-valley during daytime, as a consequence of pressure contrasts between different sections of a valley or between a valley and an adjacent plain. These pressure contrasts have been generally attributed to the larger diurnal temperature range in valleys than over a plain, causing the alternating development of a local pressure low over the plain at night and inside the valley during daytime. The larger daily temperature range in valleys has been commonly explained on the basis of geometric considerations: during daytime a given amount of energy is transferred to a smaller volume of air in a valley than over a plain, thereby enhancing the temperature of the valley air (Wagner 1932; Steinacker 1984; Whiteman 1990). Similarly, energy loss at night affects a smaller air volume in the valley, resulting in lower temperatures therein.

This mechanism is often referred to as the topographic amplification of the daily temperature range at valley sites. A geometrically determined *topographic amplification factor* (TAF) can be computed assuming that no heat and mass transfer occurs between the valley and the overlying atmosphere (Whiteman 1990; Schmidli and Rotunno 2010). However, recent investigations showed that this assumption is generally not valid, at least under strong solar forcing during daytime. Rampanelli et al. (2004) and Serafin and Zardi (2011) highlighted the important role of local subsidence in warming the core of the valley atmosphere in the diurnal phase. This heating process is particularly relevant when the valley atmosphere is stably stratified, and is caused by the sinking motion of potentially warmer air at the center of the valley, that compensates for up-slope flows along the valley sidewalls (Serafin and Zardi 2010). While subsidence heating locally increases temperature in the core of the valley, the net thermal energy budget of the upslope-subsidence circulation typically exports heat upwards to the free atmosphere (Noppel and Fiedler 2002), implying that a large fraction of the heat input along the slopes is deposited out of the valley, above crest height (Serafin and Zardi 2011). Under strong solar forcing, the mass transport operated by the slope wind circulation can actually be responsible for a manifold turnover (up to 5 times) of the valley atmosphere (Leukauf et al. 2015), causing the topographic amplification of the temperature range to be much less than expected on the basis of geometric arguments. Therefore, the largest degree of heat trapping in the valley atmosphere (and, consequently, the largest topographic amplification) occurs when strong thermal inversions are present at low levels (Steinacker 1984), that is, mostly during the winter season.

Geometric considerations were used also by McKee and O'Neal (1989) to evaluate the potential of a valley to develop drainage winds. The authors showed that the nighttime cooling rate is proportional to the width to cross-sectional area ratio (W/A). Decrease of this ratio in the down-valley direction will produce pressure gradients driving the down-valley wind (drainage valleys), while the opposite will produce nocturnal stagnation (pooling valleys).

Recently, the basic mechanisms leading to the development of diurnal valley winds have been widely re-investigated, especially by means of idealised numerical simulations. As mentioned in the previous paragraphs, these studies focused on the causes of the enhanced diurnal heating of the valley atmosphere (e.g. Rampanelli et al. 2004, Schmidli and Rotunno 2010, Serafin and Zardi 2011, Wagner et al. 2015a). Much less attention has been devoted to the evaluation of local thermal and pressure contrasts in real valleys, and to the associated spatial variability in the timing and strength of the valley wind system. In this regard, Rucker et al. (2008) reported observations of enhanced up-valley wind intensities at a narrower section of the Wipp valley, ascribing this behaviour to the stronger horizontal pressure gradient determined by the locally higher heating rate of the valley atmosphere. Similarly, Vergeiner (1983) and Vergeiner and Dreiseitl (1987) detected stronger intensities and stronger pressure gradients in a relatively narrow stretch of the Inn valley. In both studies, the authors used mass continuity arguments to explain the local increase of wind speed.

Zängl (2004) also showed that the strength of down- and up-valley winds is not constant along the Inn valley. On the basis

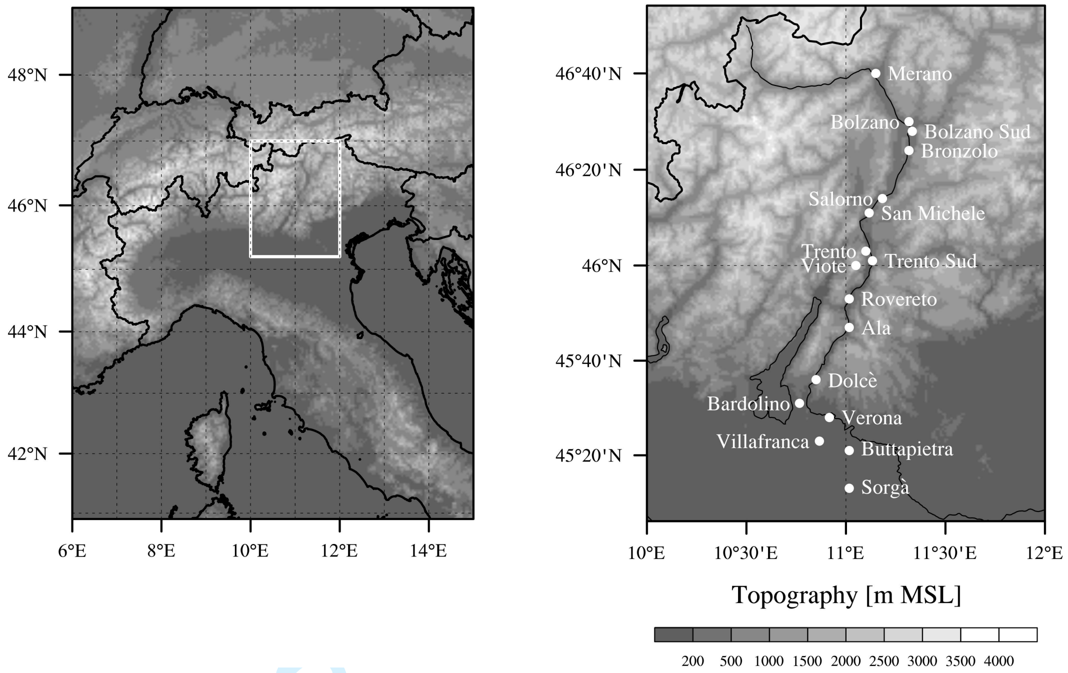

Figure 1. Overview of the study area and of the weather stations used in this work.

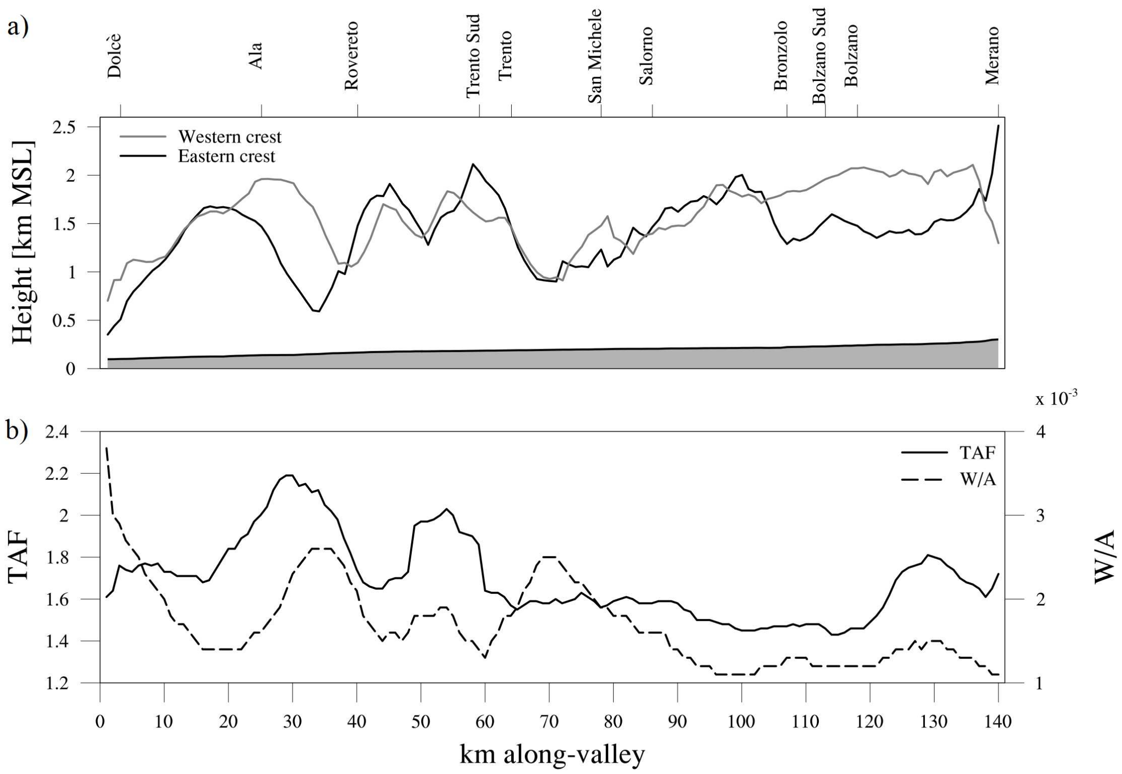

Figure 2. Along-valley variations of (a) valley floor (shadowed) and crests height and (b) Topographic Amplification Factor (TAF) and width to cross-sectional area ratio (W/A). X-coordinate indicates the distance from the mouth of the valley.

of numerical simulations, he suggested that variations in wind intensity are mainly related to tributary valleys, which increase or decrease the mass flux in the main valley. Zängl (2004) also found evidence of an asymmetry between morning and evening wind reversals in the Inn valley: while the morning transition occurred with rather uniform timing along the entire valley, more variability was observed for the evening transition, which appeared to propagate in the valley from the outlet to the inner sections.

Significant asymmetries are generally detected also in the strength of up- and down-valley winds, indicating that temperature contrasts between upper and lower sections of the valley and between the valley and the plain differ between daytime and nighttime. For instance, Egger et al. (2000) showed that the up-valley wind is considerably stronger than the down-valley wind in the Himalayan Kali Gandaki valley. A similar behaviour was found also by Vergeiner and Dreiseitl (1987) in the Inn Valley, by Hennemuth and Schmidt (1985) in the Dischma valley in the Alps and by Khodayar et al. (2008) in the Elqui valley in the Andes. The different intensity of the nocturnal and diurnal along-valley winds reflects different magnitudes of the pressure gradients in some cases (e.g. the Elqui Valley: Khodayar et al. 2008), but not in others (e.g. the Inn Valley, where up- and down-valley winds show different strength despite similar diurnal and nocturnal pressure gradients: Vergeiner and Dreiseitl 1987).

In the present paper the valley wind system developing in the Adige Valley, in the eastern Italian Alps (Fig. 1), is investigated using data from surface weather stations distributed along the valley floor and in the adjacent Po Plain, and from a wind profiler. Besides providing the first systematic characterisation of the valley wind system of one of the major Alpine valleys, the study addresses the following research questions:

- What is the relation between temperature and pressure perturbations along the valley?
- What is the relation between local pressure gradients and the valley wind system?
- What are the most significant differences in the temperature and pressure daily cycles between the valley and the plain?
- How do the valley geometry and land-use differences affect the along-valley wind?
- How does the valley geometry affect the timing of the morning and evening wind reversals?

The paper is organized as follows. Section 2 presents the study area, the dataset and the criteria adopted to select valley wind days. The results of the analysis are presented in Section 3, while Section 4 contains the discussion of the most significant features of the wind system of the Adige Valley, including some considerations on the mechanisms involved and a comparison with findings from similar studies. Conclusions are drawn in Section 5.

2. Study area and dataset

2.1. *Valley morphology*

The Adige Valley is one of the main corridors connecting the Po Plain with the inner Alps. It cuts through mountains reaching an average depth of 1500 m MSL and displays a nearly flat floor along the 140-km path connecting the valley outlet into the Po Plain (near the city of Verona, 91 m MSL) to the upper valley in Merano (310 m MSL), in the eastern Italian Alps (Fig. 1). Mountain peaks in the immediate proximity of the valley reach heights between 2000 and 2200 m MSL in its southern and central stretches, but exceed 3000 m MSL in the northern part. The valley is mostly north/south oriented, with some minor bends up to the city of Bolzano, where the orientation changes to north-west/south-east. The valley floor has a fairly constant width of 2-3 km from the plain up to Salorno. Further north, west of Bronzolo, a secondary valley runs roughly parallel to the Adige Valley for about 15 km. The two valleys are separated by a low hill, reaching an average height of only 300 m above the Adige Valley floor. At this location, the distance between the major mountain ranges flanking the valley becomes considerably larger (approx 8 km). The secondary valley joins the Adige Valley again in the basin of Bolzano, which has a maximum width of about 10 km.

The geometrical features of the Adige Valley can be quantitatively evaluated in terms of TAF and W/A, following McKee and O'Neal (1989). In particular, TAF is defined as the ratio between the air volumes enclosed between the ground and a reference height, respectively over a plain and over a valley. Alternatively, it can be computed as the ratio between the areas of corresponding vertical cross-sections (see e.g. Eq. 2.3 in Whiteman 1990). Since the air volume is smaller in valleys, TAF is always greater than 1. Here, TAF and W/A are calculated at 1-km intervals along the longitudinal axis of the Adige Valley by means of GIS techniques and then 10-km running averages are taken. Figure 2 shows that for most of the Adige Valley TAF ranges between 1.6 and 2, with the exception of a short stretch between Ala and Rovereto (where TAF≈2.2) and of the area of the above-mentioned Bolzano basin (where TAF≈1.4 due to the increased distance between the sidewall crests). W/A varies between $1.5{\cdot}10^{-3}$ and $3{\cdot}10^{-3}$ in the southern and central parts of the valley, while it displays lower and rather constant values south of Bolzano and in the Bolzano basin. Therefore, according to the classification proposed by McKee and O'Neal (1989), the Adige Valley can be identified as a pooling valley, i.e. characterised by weak drainage flows.

2.2. Available data

Several weather stations are deployed along the Adige Valley and in the adjacent Po Plain, providing regular measurements of the main atmospheric variables, such as air temperature, global solar radiation, atmospheric pressure, wind speed and direction. The dataset used to analyze the main features of the local circulation system in the Adige Valley comes from surface weather stations operated by various agencies, as shown in Fig. 1 and Tab. 1, and covers the time period 2012-2014. The southernmost stations are operated by ARPAV, i.e., the environmental protection agency of the Veneto Region and by the Meteorological Service of the Italian Air Force (AM). Those in the middle stretch of the valley belong to the Edmund Mach Foundation (FEM), to Meteotrentino (METTN, the Meteorological Office of the Autonomous Province of Trento) and to the University of Trento (UNITN). Finally, the northernmost stations are operated by the Meteorological Office of the Autonomous Province of Bolzano (METBZ) and by the European Academy of Bolzano (EURAC). As can be seen from Tab. 1, wind measurements at these stations are taken at the standard height of 10 m above ground level (AGL), with the exception of Dolcè and Bolzano Sud, where wind velocity and direction are measured at 2 m AGL. ARPAV, FEM and EURAC provide hourly-averaged data, AM provides 30-min averaged data, while UNITN and METBZ provide 10-min averaged data. To ensure homogeneity, all data were converted to hourly averages for the following analysis. The most recent weather station (Bolzano Sud) was installed in year 2012, therefore setting the beginning of the dataset.

In addition to the surface measurements, data from a pulsed doppler radar wind profiler installed in the vicinity of Trento Sud (see Fig. 1) are analyzed. The profiler, operated by Meteotrentino, is a DEGREWIND PCL1300. The instrument has a vertical resolution of about 70 m and vertical range of about 4000 m. The wind profiler was not operated regularly in 2012-2014 due to frequent malfunctions. As a consequence, data availability is sparse and does not allow the construction of a continuous dataset.

All available data were quality-controlled following the procedures reported in Jiménez et al. (2010) and Chávez-Arroyo and Probst (2013) (see Giovannini et al. 2014a for more details).

2.3. Selection of valley wind days

The present study focuses only on fair weather days with no appreciable synoptic winds, when valley winds can develop without the influence of any external forcing. Following previous climatological investigations of valley winds and sea breezes (e.g. Dreiseitl et al. 1980, Borne et al. 1998), a set of criteria is formulated to objectively select valley wind days. The selection criteria take into account both the typical features of valley winds, especially the wind direction reversals in the late morning and late evening, and the physical mechanisms driving their development. Accordingly, a valley wind day is defined by the following conditions:

1. global daily solar radiation $>$ 50% of the maximum daily radiation measured in the month, to identify days of significant heating of the valley atmosphere;
2. wind blowing up-valley with wind speed (WS) > 2 m s^{-1} for at least 2 hours between 09 and 19 LST (UTC+1), to identify days of well-developed up-valley wind;
3. wind either blowing down-valley or quiescent (WS < 1 m s^{-1}) for most of the period between 00 and 08 LST, to identify days when intense synoptic flows are absent;
4. diurnal pressure range between 2 and 8 hPa. These thresholds were selected on the basis of a preliminary screening of the typical diurnal pressure range at the sites under consideration.

In order to evaluate the typical characteristics of the wind system of the Adige Valley when it is well-developed from the valley mouth to the upper sections, the above criteria were applied to data from Ala, Trento Sud and Bolzano (representative of the southern, central and northern parts of the valley respectively). This procedure identified sixty-two valley-wind days, i.e. satisfying all the criteria at the three weather stations and displaying no gaps in the surface stations dataset. As expected,

Table 1. Weather stations along with their coordinates, altitude, measurements used for the analyses presented and operating institutions. WS = wind speed; WD = wind direction; P = pressure; T = temperature. * indicates wind measurements at 2 m AGL instead of the standard 10 m AGL.

	STATION NAME	COORD. LAT.	COORD. LON.	ALTITUDE (m MSL)	SENSORS WS	SENSORS WD	SENSORS P	SENSORS T	OPERATING INSTITUTION
1	VERONA	45°28' N	10°55' E	91			X	X	ARPAV
2	SORGÀ	45°13' N	11°01' E	24				X	ARPAV
3	BUTTAPIETRA	45°21' N	11°01' E	39				X	ARPAV
4	VILLAFRANCA	45°23' N	10°52' E	68			X	X	AM
5	BARDOLINO	45°31' N	10°46' E	165			X		ARPAV
6	DOLCÈ	45°36' N	10°51' E	105	X*	X*		X	ARPAV
7	ALA	45°47' N	11°01' E	172	X	X	X	X	FEM
8	ROVERETO	45°53' N	11°01' E	170	X	X		X	FEM
9	VIOTE	46°01' N	11°03' E	1490				X	METTN
10	TRENTO SUD	46°01' N	11°08' E	185	X	X	X	X	FEM
11	TRENTO	46°03' N	11°06' E	224			X	X	UNITN
12	SAN MICHELE	46°11' N	11°07' E	204	X	X	X	X	FEM
13	SALORNO	46°14' N	11°11' E	212	X	X	X	X	METBZ
14	BRONZOLO	46°24' N	11°19' E	226	X	X	X	X	METBZ
15	BOLZANO SUD	46°28' N	11°20' E	246	X*	X*			EURAC
16	BOLZANO	46°30' N	11°19' E	254	X	X	X	X	METBZ
17	MERANO	46°40' N	11°09' E	310	X	X	X	X	METBZ

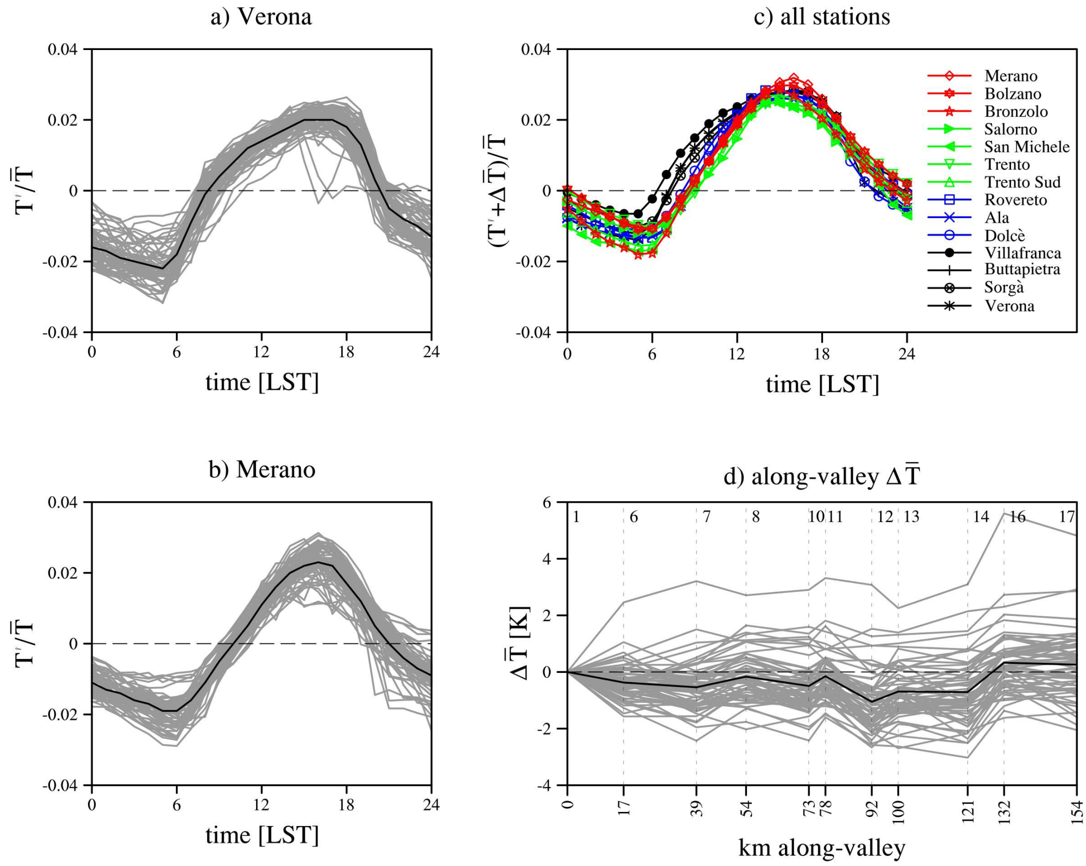

Figure 3. Diurnal cycles of the scaled perturbations $T'/\bar{T}$ at a) Verona and b) Merano; c) average diurnal cycles of the total perturbations $(T' + \Delta\bar{T})/\bar{T}$ at all the weather stations; d) along-valley variation of the daily average temperature differences with the plain $\Delta\bar{T}$. In a), b) and d) gray curves represent the single days analysed, while the thicker black line represents the average over all the valley wind days. In c) only the average diurnal cycles are reported; black, blue, green and red lines and markers are used for stations in the plain, in the southern, central and northern parts of the valley respectively. In d) data from Verona (station 1) have been taken as representative of the plain stations and x-coordinate indicates the distance from Verona. Station numbers (see Table 1) are indicated in d).

these days fall almost completely within the late spring and summer period. Months from May to August cover respectively 23%, 31%, 23% and 13% of the selected days. The sensitivity of the results, and in particular of the average cycles of valley winds and pressure gradients, to variations within a reasonable range of the thresholds adopted in the above criteria was also assessed. No significant variations of the results were found, thus highlighting that the diurnal cycles of valley winds are typically similar, with minor variations in both strength and timing. Wind profiler data are available for 23 out of the 62 selected days.

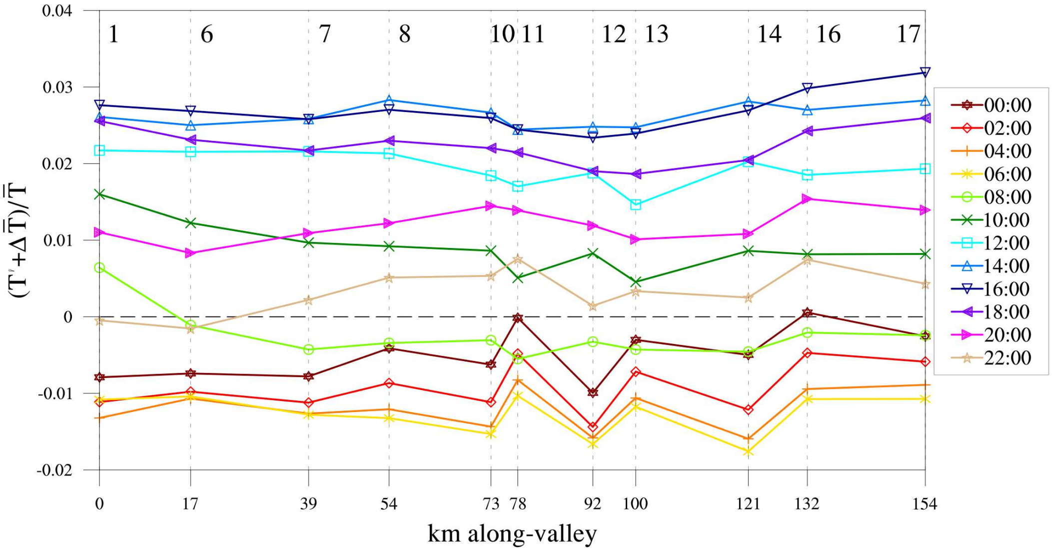

Figure 4. Average horizontal total perturbations $(T' + \Delta\bar{T})/\bar{T}$ versus distance along the Adige Valley for the selected valley wind days. Data from Verona (station 1) have been taken as representative of the plain stations. X-coordinate indicates the distance from Verona. Station numbers (see Table 1) are indicated.

3. Results

This section describes the spatial and temporal variability of the temperature (T) and pressure (p) perturbations related to the Adige Valley wind system, as well as the variability of wind speed and direction. Connections between the variability of different parameters (e.g. temperature and pressure, or pressure and wind speed) are illustrated in detail in Section 4.

To remove their obvious altitudinal dependence, pressure measurements are reduced to the level of a reference station (station 1, Verona). The pressure reduction consists in offsetting each pressure time series by a constant value, corresponding to the long-term average pressure difference between that series and the reference. Pressure measurements are additionally subject to pre-processing, to correct possible discontinuities caused by instrumental recalibration or displacement.

In order to properly compare the variability of the daily cycles of p and T between different days, measurements are normalized by computing scaled perturbations. For any station on any day, these are defined as the ratios between the hourly perturbations (p' and T') from the daily averages ($\bar{p}$ and $\bar{T}$) and the daily averages themselves, where temperatures are absolute temperatures (K). Thus constructed, $p'/\bar{p}$ and $T'/\bar{T}$ are dimensionless and depend on time (LST). A typical value for the extremes of $p'/\bar{p}$ (resp. $T'/\bar{T}$) in this dataset is $\pm 2{\cdot}10^{-3}$ (resp. $\pm 2{\cdot}10^{-2}$), roughly corresponding to 2 hPa (resp. 6 K). Pressure perturbations are one order of magnitude smaller than temperature perturbations, as expected for relatively shallow air motions (Spiegel and Veronis 1960). When comparing data from different stations, the daily average differences with the plain ($\Delta\bar{p}$ and $\Delta\bar{T}$) have been used to obtain the total perturbations $(p' + \Delta\bar{p})/\bar{p}$ and $(T' + \Delta\bar{T})/\bar{T}$, in order to take into account also the spatial variability of pressure and temperature.

3.1. *Temperature*

The typical variability of T on valley wind days is illustrated in Fig. 3. The diurnal patterns of scaled temperature perturbations are remarkably self-similar and variability around the average cycle is relatively small, as apparent in panels 3a and 3b (similar results are found for all other measurement stations). Temperature is higher than the daily average (i.e., $T'/\bar{T} > 0$) between 8 and 20 LST in Verona (Po Plain, Fig. 3a) and between 10 and 21 LST in Merano (upper Adige Valley, Fig. 3b). Maximum temperatures occur around 16 LST at both sites. While the temperature trend between 6 and 16 LST is rather constant in Merano, it has two distinct phases in Verona: an initial period of relatively fast heating until 10 LST, followed by a slower heating trend between 10 and 16 LST. A plausible explanation for this finding is discussed in Section 4.1.

The average temperature cycles at all measurement points along the valley are compared in Fig. 3c. The difference in the heating trend between the stations at the valley bottom (which display a temperature evolution very similar to Merano) and the stations

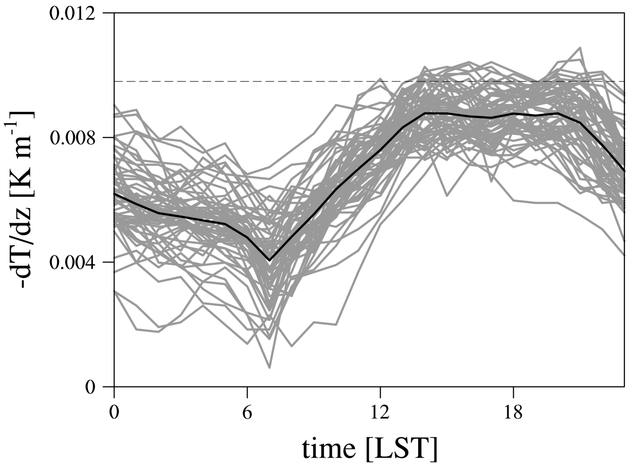

Figure 5. Diurnal cycles of the vertical temperature gradient between Viote (1490 m MSL) and Trento Sud (185 m MSL). The gray curves represent the single days analysed, the thicker black line represents the average over all the valley wind days, while the black dashed line represents the dry adiabatic lapse rate $\Gamma_d = 9.8 \cdot 10^{-3}$ K m^{-1}.

in the plain (which evolve similarly to Verona) can be clearly noticed. On the other hand, the cooling phase presents a similar behaviour for plain and valley stations.

At all stations the amplitude of the temperature cycle is about 0.02 (that is, approximately 6 K). Therefore, contrary to expectations based on the topographic amplification theory, there is no evidence of a significant enhancement of the diurnal temperature range at the floor of the Adige Valley compared to the Po Plain. Also, despite the marked variations of TAF along the Adige Valley (Fig. 2), the daily near-surface temperature cycle maintains approximately the same amplitude everywhere. Moreover, also the daily mean temperature $\bar{T}$ is rather constant along the Adige Valley axis on valley wind days (Fig. 3d). In fact, daily average temperature differences $\Delta\bar{T}$ between the valley interior and the plain are almost negligible on average and within ± 1 K on most days. It is likely that the rather homogeneous land cover of the floor of the Adige Valley contributes to the small temperature differences along the valley. In fact the valley floor is mainly covered by cultivated land, in particular apple orchards and vineyards, with the exception of urban areas.

Figure 4, showing the time- and space-dependent total perturbations, further clarifies the temporal and along-valley variability of temperature fluctuations. No obvious and recurrent spatial behaviours in the temperature perturbations are visible. Appreciable differences in temperature perturbations are present in the morning between Verona (station 1, which is taken as representative of the plain stations) and the valley stations, due to the above-mentioned faster heating rate in the plain in the early morning. On the other hand, temperature perturbations tend to increase with distance along the valley in the evening between Dolcè (station 6) and Trento Sud (station 10).

Reduced amplitude of the temperature cycle, mostly due to higher nighttime temperatures, is clearly evident at three locations, namely Trento (station 11), Salorno (station 13) and Bolzano (station 16). The anomalies in Trento and Bolzano can be explained by the presence of relatively large urban areas, as further discussed in Section 4.4. The smaller diurnal temperature range in Salorno is probably due to the location, next to the north-facing sidewall of a locally west-east oriented section of the valley. This implies that maximum temperatures are lower due to extended shadowing, while minima are higher because the station is less affected by ground-based inversions developing in the valley center.

The evolution of the vertical thermal structure of the Adige Valley atmosphere can be approximately and indirectly reconstructed by evaluating the temperature difference between Viote and Trento Sud (Fig. 5). These two stations are separated by a horizontal distance of only 6 km, but lie at very different altitudes in distinct geographical settings: the valley floor for Trento Sud (185 m MSL), and an elevated plateau slightly below crest height for Viote (1490 m MSL). Figure 5 shows that the bulk estimate of the vertical lapse rate, evaluated from temperature measurements at these two locations, approaches the adiabatic limit ($g/c_p = 9.8 \cdot 10^{-3}$ K m^{-1}) in the afternoon hours. That is, the valley atmosphere tends to evolve towards a convectively mixed situation up to crest height during the afternoon. As for temperature, the day-to-day variability of the temperature lapse rate is rather moderate, and all valley wind days display essentially the same evolution.

3.2. Pressure

Similarly to temperature perturbation cycles, pressure perturbation cycles at individual sites tend to repeat with little variation (Fig. 6ab), although day-to-day variability is somewhat larger at night. Pressure perturbations are much smaller in Verona (Fig. 6a) than in Merano (Fig. 6b), particularly during the afternoon.

The pressure cycle (Fig. 6c) exhibits the same temporal pattern at all stations in the valley, with a maximum around 7-8 LST and a minimum around 17-18 LST. On the other hand, the pressure cycles over the plain are not in phase with those recorded at the valley stations: both the minimum and the maximum perturbation are observed a few hours later than in the valley. The reversal of the valley-plain pressure gradient occurs around 10 LST in the morning and around 22 LST in the evening. Within the valley, the amplitude of the pressure cycle increases towards the north, and the pressure perturbations are larger during the day than at night.

The daily average pressure $\bar{p}$ tends to decrease upvalley during valley wind days (Fig. 6d). A significant degree of variability is apparent (pressure actually increases upvalley in about one third of the selected days), but the average value of the pressure difference between Verona and Merano is 0.7 hPa. This is not negligible in comparison to the diurnal pressure perturbation in the valley, which typically reaches 2 hPa ($p'/\bar{p} = 2 \cdot 10^{-3}$, Fig. 6c).

Figure 7 shows total pressure perturbations in the along-valley direction at different hours of the day, allowing a clearer visualization of the pressure gradients driving the development of down- and up-valley winds. Pressure perturbations are approximately zero at 22 LST: at this time, the along-valley horizontal pressure differences essentially vanish. The change in sign of the gradient occurs rather uniformly along the valley, even though, considering the morning transition, a negative upvalley gradient establishes slightly earlier north of Salorno. The gradient reaches its extreme values between 6 and 8 LST (maximum nocturnal positive gradient going upvalley) and between 16 and 18 LST (maximum diurnal negative gradient going upvalley). In absolute value, the maximum gradient is about three times stronger during the day ($\approx$ 3 hPa/150 km) than at night ($\approx$ 1 hPa/150 km). On the other hand, the pressure differences between Verona (station 1), in the open plain, and Ala (station 7), the southernmost valley station, have approximately the same magnitude (1 hPa) during both daytime and nighttime (as can be seen also from Fig. 6).

The pressure gradient is almost invariably positive upvalley during the night and negative upvalley during the day, but deviations from this pattern are found between Trento Sud and Trento (stations 10 and 11) and between Bronzolo and Bolzano (stations 14 and 16). In both cases, local pressure maxima during the late afternoon and minima during the night occur at the urban stations (resp. Trento and Bolzano), causing a local reversal of the gradient. These pressure anomalies are closely related to the temperature anomalies mentioned in Section 3.1, and are thus regarded as additional evidence of significant local flow modifications induced by urban areas.

3.3. *Surface wind*

Figure 8 presents the diurnal cycles of the along-valley wind component, calculated considering the local orientation of the valley and defined positive with winds blowing upvalley. The diurnal cycles of the along-valley wind at each station display a moderate day-to-day variability, especially during daytime, as can be seen from panels 8a and 8b, which refer to Trento Sud and Merano respectively. This behaviour is found also at the other weather stations. The average daily cycles of the along-valley wind component (Fig. 8c) are similar at all stations between Ala and Salorno. They display weak down-valley wind at night and stronger up-valley wind during the day.

Considerably weaker up-valley winds are found north of Bronzolo, in the upper part of the valley. Only at Dolcè, at the outlet of the Adige Valley, do down-valley and up-valley winds exhibit roughly the same intensity. Here, the up-valley wind is significantly weaker than at the inner sections of the valley, while the down-valley wind is slightly stronger. Comparability of wind speeds between Dolcè and other sites is limited by the wind measurements being taken at 2 m AGL at that location. However, as a matter of fact, the nocturnal and diurnal pressure differences between Ala and Verona (the measurement stations immediately north and south of Dolcè) are similar during the day and the night (Fig. 3), possibly explaining the similar intensity of the up- and down-valley flow at this site.

As clearly visible in Fig. 8d, which shows the average diurnal cycle of the wind vectors at the selected weather stations, the wind direction during the day is aligned with the local orientation of the valley. This is particularly evident in Salorno, located in a short stretch of the valley heading from west to east. The onset of the up-valley wind in the late morning seems to occur roughly

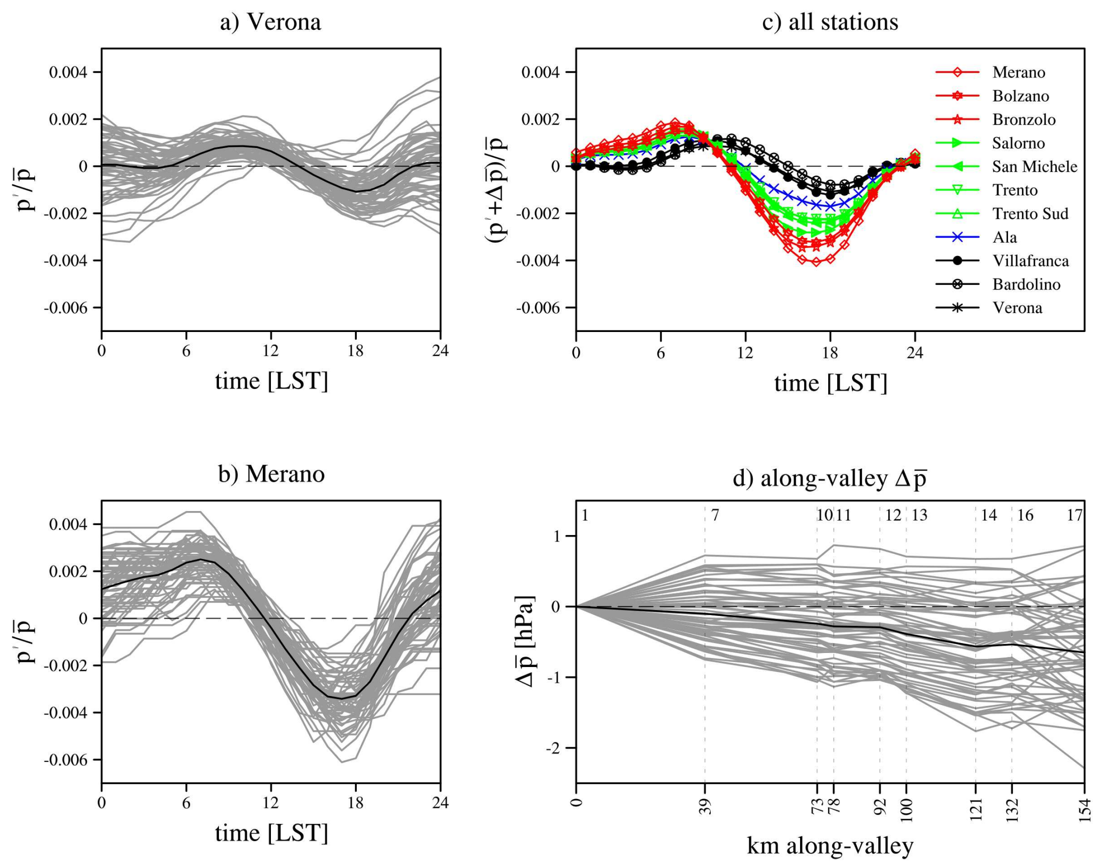

Figure 6. Diurnal cycles of the scaled perturbations $p'/\bar{p}$ at a) Verona and b) Merano; c) average diurnal cycles of the total perturbations $(p' + \Delta\bar{p})/\bar{p}$ at all the weather stations; d) along-valley variation of the daily average pressure differences with the plain $\Delta\bar{p}$. In a), b) and d) gray curves represent the single days analysed, while the thicker black line represents the average over all the valley wind days. In c) only the average diurnal cycles are reported; black, blue, green and red lines and markers are used for stations in the plain, in the southern, central and northern parts of the valley respectively. In d) data from Verona (station 1) have been taken as representative of the plain stations and x-coordinate indicates the distance from Verona. Station numbers (see Table 1) are indicated in d).

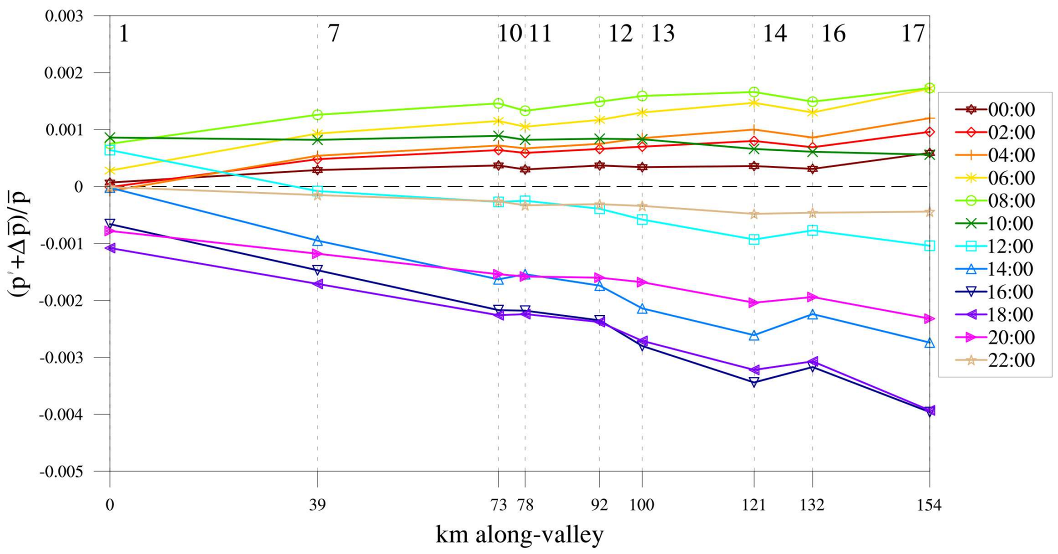

Figure 7. Average total pressure perturbations $(p' + \Delta\bar{p})/\bar{p}$ versus distance along the Adige Valley for the selected valley wind days. Data from Verona (station 1) have been taken as representative of the plain stations. X-coordinate indicates the distance from Verona. Station numbers (see Table 1) are indicated.

at the same time at all stations up to Salorno, probably due to the regularity of the geometry and of the main orientation of the valley and the consequent similar timing in the heating of the valley atmosphere. In this part of the valley, the timing of the morning transition (approx. 11 LST) is in good agreement with the inversion of the pressure gradient (Fig. 6c and 7). On the other hand, north of Salorno, where the valley widens, the up-valley wind sets in slightly earlier, in accordance with the pressure gradients in Fig. 7.

A similar pattern is found for the evening transition, which displays a uniform timing between Ala and Bronzolo (approx. 23 LST, again in good agreement with the evening pressure

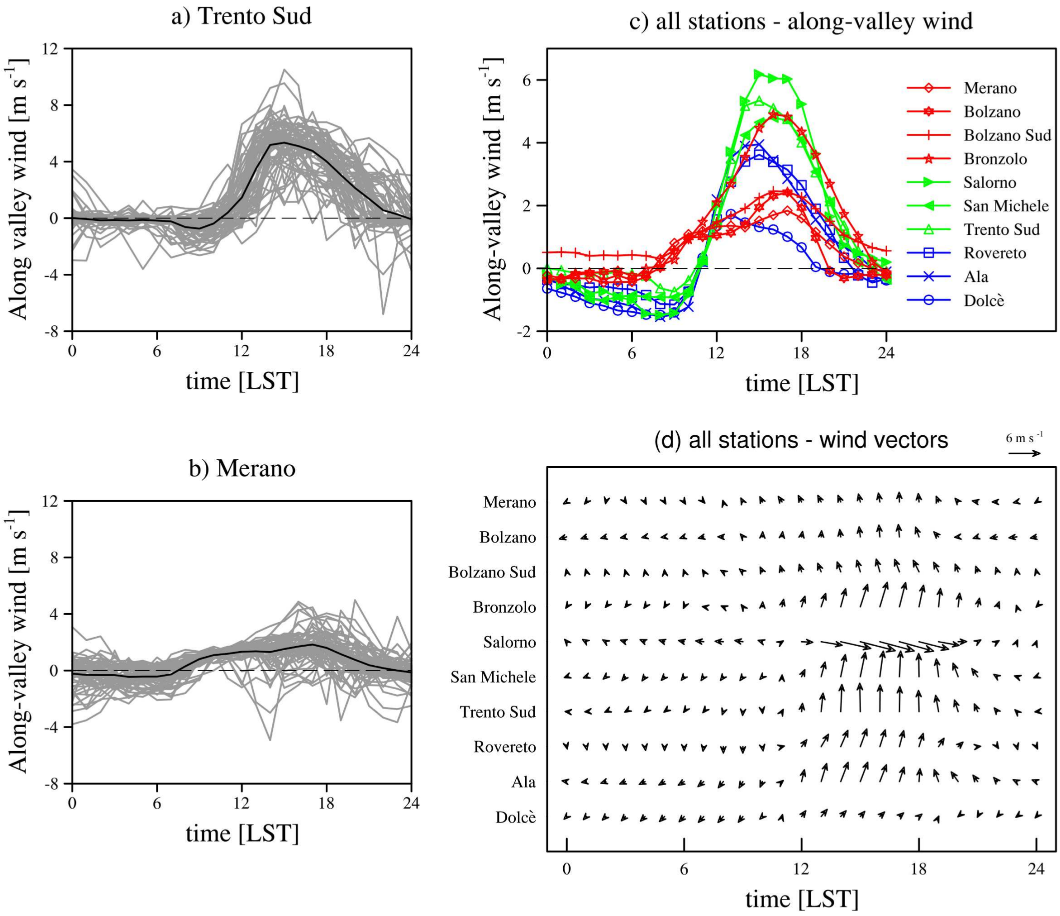

Figure 8. Diurnal cycles of the along-valley wind speed (positive up-valley) at a) Trento Sud and b) Merano; c) average diurnal cycles of the along-valley wind speed and d) average wind vectors at all the weather stations. In a) and b) gray curves represent the single days analysed, while the thicker black line represents the average over all the valley wind days. In c) blue, green and red lines and markers are used for stations in the southern, central and northern parts of the valley respectively.

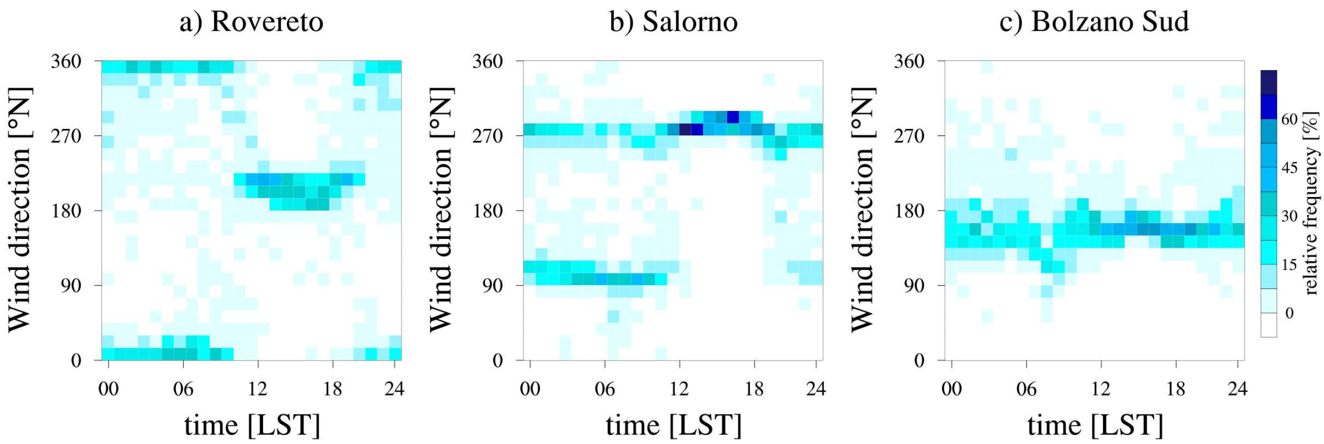

Figure 9. Wind direction as a function of the hour of day at three measurement stations in the selected valley wind days.

gradient reversal in Fig. 6c), but occurs earlier at the southernmost (Dolcè) and northernmost stations (Bolzano and Merano) of the valley. The nocturnal down-valley winds are weak at all weather stations, supporting the ”pooling valley” classification obtained by considering the along-valley variation of W/A (cf. Fig. 2). The breeze is actually almost quiescent in Trento Sud and Bronzolo, while it blows lightly up-valley in Bolzano Sud. Again, local anomalies in the down-valley wind pattern correlate strictly with urban areas.

While Fig. 8d describes the temporal evolution of the average wind direction, Fig. 9 partially illustrates the variability around the average. The wind variability during valley wind days in

Rovereto (Fig. 9a) is representative of that found at most valley sites, namely a well-defined primary daytime wind direction (aligned with the valley orientation, i.e. approximately southerly), and an equally well-defined primary nighttime wind direction (approximately northerly). Wind direction variability is virtually null during the day, and only slightly larger at night.

A few stations, especially in the upper Adige Valley, display a slightly more complex variability pattern, with one primary wind direction observed during the day, and two primary directions observed during the night. These are Bronzolo, Bolzano and Salorno, the latter of which is described in Fig. 9b. At all three of these sites, the nocturnal wind remains predominantly aligned with the valley, but can blow with almost equal probability in either the down-valley or the up-valley direction (resp. easterly and westerly in Salorno). The anomalous behaviour of winds at Bolzano Sud is apparent in Fig. 9c, which shows that winds blow persistently from the south-south-easterly quadrant (i.e. up-valley) even during the night. Similarly to other locations, wind direction variability at night is somewhat larger at this site too.

3.4. Vertical wind profiles

Figure 10 shows the average wind vertical profiles observed at Trento Sud up to 3000 m AGL at two-hour intervals on the basis of the available data for the selected valley wind days. Data at higher levels are not presented here, since they are not relevant for this analysis. The up-valley wind is considerably stronger than the down-valley wind and also extends through a greater vertical depth. The down-valley wind presents average maximum velocities of 2 m s^{-1} between 400 and 800 m AGL and is very weak near the ground, in agreement with the almost quiescent nocturnal winds in Trento Sud (Fig. 8). Considering the up-valley wind, average maximum velocities reach values of 5-6 m s^{-1} up to 1500 m AGL in the afternoon. Maximum up-valley wind velocities shift to increasingly higher levels during the day, following the growth of the well-mixed boundary layer (cf. Serafin and Zardi 2011). Well-developed up-valley wind is present up to the crest level ($\sim$ 1500 AGL, cf. Fig 2), with lower intensities above this height. On the other hand, the down-valley wind is generally confined to much lower heights. Down-valley wind confined to lower heights than the up-valley wind are reported also by Egger et al. (2000) in the Kali Gandaki Valley, and by Ekhart (1944) in the Salzburg Alps. In other cases up- and down-valley wind layers of similar depth were found (e.g. Zängl 2004 in the Inn Valley). The morning transition from down- to up-valley wind occurs roughly at the same time ($\sim$ 12 LST) at all heights, while in the evening the up-valley wind starts weakening from the bottom, due to the progressive cooling of the lowest atmospheric layers, as highlighted also in other studies (e.g. Zängl 2004). As a consequence, the down-valley wind starts to blow first in the layers close to the ground and then thickens during the night. Figure 10 also shows the presence of anti-winds (Buettner and Thyer 1966) both during down- and up-valley wind phases. At night and in the early morning, light up-valley wind blows over the down-valley wind layer (above 1400 m AGL), while in the afternoon down-valley wind is present above 2500 m AGL.

4. Discussion

4.1. Temperature tendency at plain and valley sites

As highlighted in Section 3.1, the diurnal phase of the average temperature cycle displays a markedly different behaviour between the plain sites on one side, and all measurement stations at the floor of the Adige Valley on the other. In particular, in the plain an early stage of rapid temperature increase ($\approx$3 K hr^{-1}) from 6 to 10 LST is followed by one with slower heating rate ($\approx$0.5 K hr^{-1}) from 10 to 16 LST. Conversely, a fairly constant rate of temperature increase ($\approx$1.5 K hr^{-1}) is observed at all valley stations between 6 and 16 LST.

This finding may be interpreted as evidence of the different diurnal heating processes at play at the different locations. In contrast to the valley sites, the plain sites are not shaded by surrounding topography in the early morning. This likely causes the observed early-morning rapid temperature rise on the plain. The positive temperature trend is then strongly damped in the late morning when thermal convection, which efficiently transports heat upwards, develops in response to the surface layer becoming convectively unstable.

The slower morning temperature trend at the valley sites can be related to one or both of two processes, namely the reduction of the energy input due to topographic shading and/or

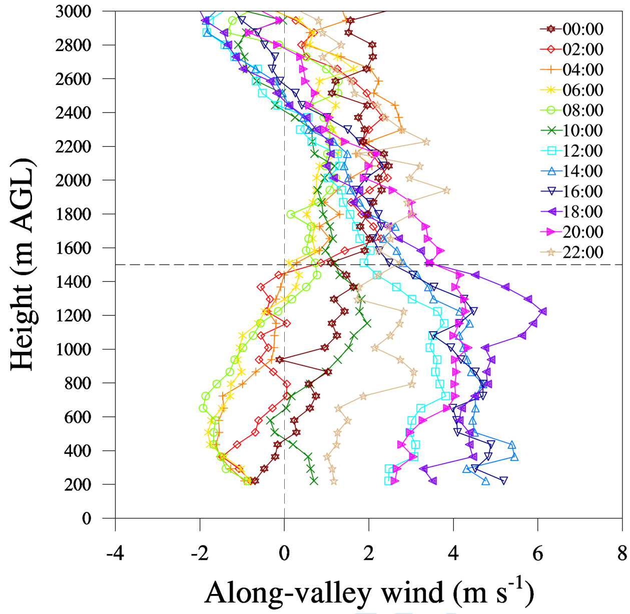

Figure 10. Average vertical profiles of the along-valley wind velocity measured by the wind profiler at Trento Sud during the selected valley wind days. The black horizontal dashed line represents the crest level.

the vertical heat transport continuously operated by upslope winds and mid-valley subsidence. The resulting cross-valley circulation typically responds quickly to solar forcing and develops faster than turbulent convection (Serafin and Zardi 2011). However the actual importance of each process, and whether it really explains the observed difference in temperature cycles between plain and valley or not, still needs to be confirmed by ad-hoc numerical simulations.

4.2. *Relationship between temperature and pressure perturbations*

It was shown in Section 3 that significant horizontal pressure gradients (Fig. 7) are established in the Adige Valley even in the absence of appreciable surface temperature gradients (Fig. 4). This finding can be understood by considering that, in approximate hydrostatic balance, surface pressure depends on the integral of density (or temperature) in the overlying atmosphere. The larger pressure perturbation observed at valley stations can then be explained by assuming that either the air layer subject to heating and cooling gets thicker in the upvalley direction, or that a large fraction of the heat gain or loss in valleys occurs at altitudes well above the valley floor.

The daily cycles of temperature and pressure perturbations (Figs. 3 and 6) are approximately in phase at all valley stations, while pressure minima and, more evidently, maxima are reached some hours later than temperature extremes in the plain. This suggests that temperature in the valley atmosphere reacts quickly to near-surface variations, while a greater inertia is present over the plain. Thus, near-surface temperature perturbations in the valley can be considered representative of the temperature evolution of the valley atmosphere, while the same assumption is not valid in the plain. This suggests that the vertical heat transport created by cross-valley circulations quickly redistributes temperature perturbations from the valley floor and slopes to the valley atmosphere, while the vertical heat transport is less efficient over the plain.

Table 2. Perturbation depths (m AGL) and perturbation heights (perturbation depth plus altitude of the valley bottom, m MSL) obtained from regression lines as in Fig. 11 and rounded to tens of m.

Station	perturbation depth (m AGL)	perturbation height (m MSL)
Ala	880	1060
Trento Sud	1260	1440
Trento	1550	1780
San Michele	1290	1500
Salorno	1880	2090
Bronzolo	1700	1930
Bolzano	1860	2110
Merano	2270	2600

To further evaluate the relation between temperature and pressure perturbations, Fig. 11 shows the joint distribution of $p'/\bar{p}$ and $T'/\bar{T}$ at three different valley sites. In these scatter diagrams, data points (hourly measurements over 62 days) are distributed according to their pressure and temperature perturbations and colored according to the hour of day. A similar analysis is not performed for the stations in the Po Plain, because, as previously mentioned, there is no direct correspondence between near-surface temperature and pressure perturbations. Figure 11 confirms that a certain degree of correlation exists between pressure and temperature fluctuations, and that the correlation coefficient depends markedly on the location.

These findings can be understood on the basis of the vertical momentum equation, compactly written as:

$$\frac{1}{\bar{\rho}}\frac{\partial p'}{\partial z} = g\frac{T'}{\bar{T}} - A \tag{1}$$

Here, the residual term A describes deviations from hydrostatic balance (primarily related to the inertia term dw/dt), and the

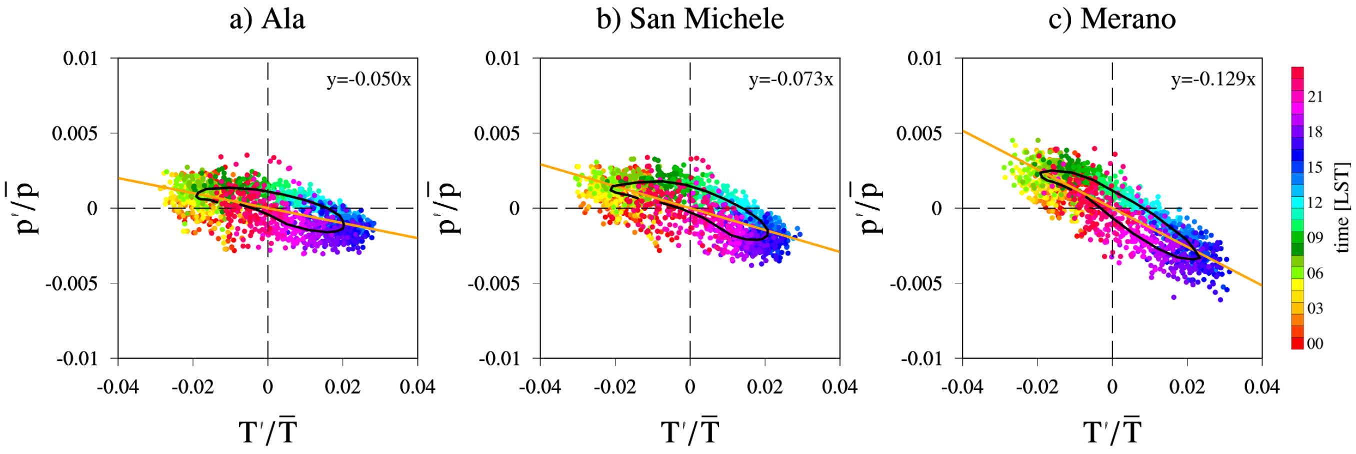

Figure 11. Joint variability of $p'/\bar{p}$ and $T'/\bar{T}$ at a) Ala, b) San Michele and c) Merano. Data points (hourly measurements over the valley wind days) are colored according to the hour of day. Solid black lines connect the hourly-average values. Regression lines (solid orange) and associated equations are also shown.

buoyancy term has been expressed as a function of temperature using the linearized version of the ideal gas law. The latter reduces to $\rho'/\bar{\rho} = -T'/\bar{T}$ because, as shown in Section 3, $|p'/\bar{p}| \ll |T'/\bar{T}|$.

Equation (1) can be integrated vertically over the layer affected by the diurnal perturbations of T and p, which is assumed to have a depth h. For simplicity, we take A to be approximately constant with height and temperature and pressure perturbations to decrease linearly with height below h. That is, $T' = (1 - z/h)T'_0$, where T'_0 is the temperature perturbation at the surface, and similarly for p'.

Using the ideal gas law for the reference state ($\bar{p} = \bar{\rho}R\bar{T}$) and introducing the scale height $H = R\bar{T}/g$, the result of the integration can be expressed as:

$$\frac{p'_0}{\bar{p}} = -\frac{h}{2H}\frac{T'_0}{\bar{T}} + \frac{A}{g}\frac{h}{H} \qquad (2)$$

Equation (2) confirms that a linear relationship is expected between $p'/\bar{p}$ and $T'/\bar{T}$ at the surface (denoted by the subscript 0), and provides an explanation for the slope and intercept parameters in Fig. 11. In particular, the slope is related to the depth h of the layer subject to diurnal heating, while the intercept depends on deviations from the hydrostatic balance A and the depth h. A similar equation appears in Li et al. (2009), and was used to achieve a rough estimate of mixing heights in Owens Valley, California. Li et al. (2009) neglected the non-hydrostatic term in Eq. 2 ($A = 0$) and used the result to explain the cross-valley variability of the boundary-layer depth h. The amplitudes of the diurnal pressure and temperature cycles, and accordingly the boundary-layer depth, were found to increase from west to east down the western valley slope.

With Eq. (2) now at hand, the findings in Fig. 11 are rather straightforward to interpret. Surface pressure and temperature perturbations are distributed around the origin, implying that the base state is in approximate hydrostatic equilibrium.

At all valley stations, perturbations of pressure and temperature lie in the second quadrant ($p' > 0$, $T' < 0$) at night and in the fourth quadrant ($p' < 0$, $T' > 0$) during daytime. The joint variability of $p'/\bar{p}$ and $T'/\bar{T}$ is well explained by a linear relationship, with negative slope becoming steeper proceeding from Ala (Fig. 11a, lower valley) to San Michele (Fig. 11b, mid-valley) and to Merano (Fig. 11c, upper valley). Deviations from the ideal linear relationship are positive during the morning and the early afternoon (when the lowest atmospheric layers expand upon heating, hence $dw/dt > 0$ and $A > 0$) and negative at night, when cooling implies a reduction of specific volume and compression (hence $dw/dt < 0$ and $A < 0$).

A similar evaluation for other valley measurement sites shows that the regression coefficient between $p'/\bar{p}$ and $T'/\bar{T}$ increases rather regularly upvalley, suggesting (on the basis of Eq. (2) and under the hypothesis of linear temperature profiles at all stations along the valley) that the atmosphere is subject to heating or cooling over larger depths proceeding towards the inner Alps. For all valley stations where both pressure and temperature measurements are available, estimates of h from linear regressions are reported in Table 2 (h is retrieved from the regression slope based on Eq. (2), adopting $H = 8800$ m for the scale height). Perturbation depths h range between 880 m in Ala and 2270 m in Merano. These figures agree reasonably well with the typical depths of convective boundary layers in valleys. The upvalley increase of the estimated depths might be explained by Alpine topographic reliefs reaching higher altitudes towards the north, and inducing thicker cross-valley circulations that enhance the vertical redistribution of heat.

The perturbation height estimates in Trento Sud and Trento (resp. 1442 and 1778 m) can be seen to be in fair agreement with the vertical extent of the up-valley circulation in Fig. 10.

4.3. *Relationship between pressure perturbations and surface wind*

The combined analysis of the mean daily cycles of wind and pressure and of average pressure gradients along the Adige Valley highlighted that stronger pressure gradients and, consequently, stronger (up-)valley winds develop during the day than at night, when weaker (down-)valley winds blow. This is clearly demonstrated also by the scatter diagrams in Fig. 12, showing the relation between the horizontal pressure gradients between two stations and the wind speed measured at a third one in between. Three such plots are provided, for the southern (Rovereto, Fig. 12a), middle (San Michele, Fig. 12b) and northern (Bronzolo, Fig. 12c) valley segments. A roughly linear relationship between pressure gradient and along-valley wind speed is found, valid for both nighttime and daytime valley winds (lower-right and upper-left quadrants respectively). This result is seemingly in contrast with findings by Nickus and Vergeiner (1984)'s Figure 1 and Vergeiner and Dreiseitl (1987)'s Figure 13 for the Inn Valley wind system. In those two figures, data from all days included in the periods of analysis (not only data from selected valley wind days) were plotted. Even in the Inn Valley the up-valley wind was found to be considerably stronger than the down-valley wind. However, pressure differences were reported to reach comparable magnitudes in the daytime and nighttime. As a consequence, significantly different linear relations between pressure differences and wind speed emerged for the diurnal and the nocturnal phases of the Inn Valley wind system. The issue of how pressure gradients of the same magnitude can generate up- and down-valley winds of very different intensities was not addressed. Conversely, the picture provided by the present analysis displays an equal proportion between pressure gradient and along-valley wind speed both in the day and at night (independently of sign and direction). This is consistent with recent results from numerical simulations in idealized valleys (Wagner et al. 2015b).

By evaluating the relationship between the pressure gradient and the along-valley wind speed, as done in Fig. 12, the role of friction and the inertia of the valley wind system can be investigated, relying on the horizontal momentum equation for the along-valley wind speed v. Assuming $\partial v/\partial y = 0$ and $(1/\rho)(\partial p/\partial y) = G$, where y is the along-valley coordinate, neglecting the Coriolis terms and denoting the friction term as F, the equation can be written as:

$$\frac{\partial v}{\partial t} = -G + F \tag{3}$$

Friction can be parameterized either as a linear function of wind speed ($F = -k_1 v$, a Guldberg-Mohn friction relationship as in Nickus and Vergeiner 1984), or with a drag relationship ($F = -k_2 v^2$, as in many numerical weather prediction models). Assuming a quasi-steady equilibrium between pressure gradient and friction and thus neglecting the dependence on time, the approximately linear dependence between v and the pressure gradient in Fig. 12 suggests to adopt the linear model, confirming the assumptions made by Nickus and Vergeiner (1984). A linear model for the frictional force was adopted also by Du and Rotunno (2014) to develop an analytical model of the nocturnal low-level jet and by Haurwitz (1947) and Schmidt (1947) in early studies on the sea breeze. Based on the results in Fig. 12, the friction coefficient is taken as a constant.

As can be seen from Fig. 7, the diurnal cycle of the along valley pressure structure can be approximately reproduced as:

$$p(y,t) = P_{vr}(t) + \left.\frac{\Delta p}{\Delta y}\right|_{max} y \sin(\omega t) \tag{4}$$

where $P_{vr}(t)$ is the pressure in Verona, in the plain, $\Delta p/\Delta y|_{max}$ is the maximum along-valley pressure gradient between Merano (uppermost valley station) and Verona, y is the along-valley

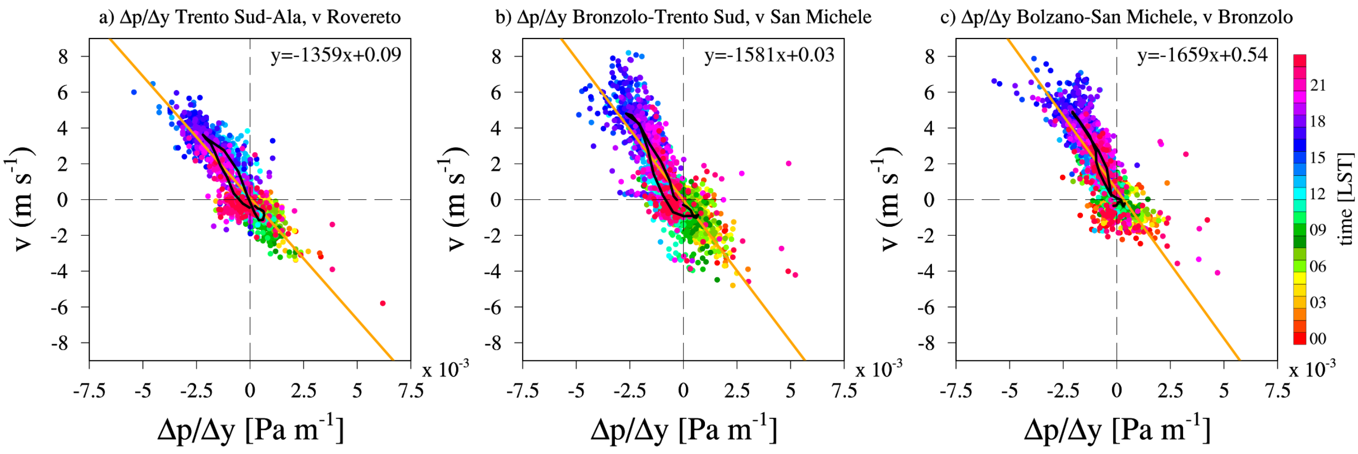

Figure 12. Joint variability of pressure gradients $\Delta p/\Delta y$ and along- valley wind component (v). a) $\Delta p/\Delta y$ between Trento Sud and Ala and along-valley wind at Rovereto, b) $\Delta p/\Delta y$ between Bronzolo and Trento Sud and along-valley wind at San Michele and c) $\Delta p/\Delta y$ between Bolzano and San Michele and along-valley wind at Bronzolo. Data points (hourly measurements over the valley wind days) are colored according to the hour of day. Solid black lines connect the average hourly values. Regression lines (solid orange) and equations are also shown.

distance from Verona, and $\omega = 2\pi/T$ is the angular frequency, with T = 86400 s. Accordingly, Eq. (3) can be written as:

$$\frac{\partial v}{\partial t} = -B\sin(\omega t) - k_1 v \qquad (5)$$

with $B = (1/\rho)\left(\Delta p/\Delta y|_{max}\right)$. Eq. (5) admits a closed-form solution:

$$v = e^{-k_1 t}\left(v_0 - \frac{B\omega}{\omega^2 + k_1^2}\right) - \frac{B}{\sqrt{\omega^2 + k_1^2}}\sin(\omega t - \phi) \qquad (6)$$

where v_0 is the along-valley wind velocity at $t = 0$ and $\phi = \tan^{-1}(\omega/k_1)$. The solution, which is analogous to the result of Haurwitz (1947) for the sea breeze, is composed of a transient response to initial conditions, which can be neglected when looking at the entire daily cycle, and of a periodic part, characterized by a phase delay ϕ. From Fig. 12 we can assume $\Delta p/\Delta y|_{max} = 2.5 \cdot 10^{-3}$ Pa m^{-1} as a representative value of the maximum pressure gradient during daytime. Therefore, assuming ρ = 1.2 kg m^{-3}, we get $B \simeq 2 \cdot 10^{-3}$ m s^{-2}. The only parameter to be estimated in Eq. (6) is the friction coefficient k_1. In order to obtain a maximum velocity $v_{max} \simeq 4$ m s^{-1}, in accordance with the experimental values in Fig. 8c, k_1 has to be approximately 1/2000 s^{-1}, corresponding to a phase shift $\phi \simeq 30$ min. Looking at the transient part of the solution, the friction coefficient can be also seen as the inverse of a reaction time, which, similarly to the phase shift, turns out to be of about 30 min.

Assuming quasi-steady equilibrium between pressure gradient and friction, the friction coefficient can be estimated also from the slopes of the regression of the relation between pressure gradients and along-valley velocity, as made by Nickus and Vergeiner (1984) and Vergeiner and Dreiseitl (1987). In the present case the slope of the regression line becomes slightly steeper from south to north, while the intercept, as expected, is negligible or small at all stations. Assuming ρ = 1.2 kg m^{-3}, values of k_1 can be estimated from the data in Fig. 12 as roughly 1/1600, 1/1900 and 1/2000 s^{-1} for the lower, central and upper parts of the valley respectively. These values are almost identical to estimates from Eq. 6, corresponding again to reaction times of about 30 min. These are in accordance with Nickus and Vergeiner (1984) and close to the estimates of 40 and 45 min provided by Wagner et al. (2015b) and Vergeiner and Dreiseitl (1987) respectively. This outcome is in agreement with observations during the transition periods of the breeze cycle and supports the hypothesis that the valley wind responds quickly to changes in the horizontal pressure gradient.

4.4. *Local anomalies*

As highlighted in Section 3.2, a reversal of the expected pressure gradient occurs at Trento and Bolzano during both daytime and nighttime (Fig. 7). In particular, while the daily pressure range increases proceeding from the plain to the inner parts of the valley, at Trento and Bolzano the daily pressure range is smaller than at the neighbouring stations.

The smaller daily pressure range in Bolzano is likely caused by the fact that the city lies in a relatively large basin, where the heating and cooling rates of the air are lower than at other segments of the valley. This agrees with results from numerical simulations in idealised valleys (e.g., Serafin and Zardi 2011), which show that temperature increments and pressure perturbations are stronger in narrower valleys. A similar mechanism is likely to occur also for the nighttime cooling. During the night, the reversal of the expected pressure gradient causes light southerly (up-valley) wind blowing from Bolzano Sud towards the basin. Probably for the same reason, the down-valley wind is almost absent in Bronzolo, only a few kilometers south of Bolzano Sud. A similar pattern of nocturnal wind convergence into a valley sub-basin was found by Whiteman et al. (1999) in the Colorado River valley. During daytime, the larger width of this segment of the Adige Valley and the consequent reversal of the pressure gradient between Bronzolo and Bolzano is very likely the primary cause of the considerably weaker up-valley wind recorded north of Bronzolo. Even though the valley narrows again north of Bolzano, the up-valley wind remains weak all along the uppermost valley segment (cf. Fig. 8).

In the vicinity of Trento, the geometry of the valley does not present significant peculiarities and therefore cannot be the cause of the anomalous behaviour of the atmospheric pressure. On the other hand, the lower pressure values measured during the night in the city can be explained by urban effects. Giovannini et al. (2011) showed that a strong urban heat island develops in the city of Trento on nights with clear skies (valley wind days are indeed characterized by clear skies). In particular, temperature differences of the order of 4 K are normally observed between urban and rural areas at night. The urban heat island affects mainly the lowest atmospheric layers. Results from numerical simulations (Giovannini et al. 2014b) highlighted that urban-rural temperature differences vanish at about 100 m AGL. In fact, nearly isothermal vertical temperature gradients are typically present in the lowest 100 m over urban areas at night (cf. Landsberg 1981), while a nocturnal ground-based inversion usually develops over rural areas. Supposing an isothermal vertical temperature distribution over the urban area, a vertical temperature gradient $\Gamma_r = -0.04$ K m^{-1} is required for the rural area to be ~ 4 K colder than the urban atmosphere at the ground and for temperature to be horizontally uniform at 100 m AGL.

In these conditions, the pressure difference at the surface between rural and urban areas Δp_{u-r} can be calculated as follows:

$$\Delta p_{u-r} = p(d)\left[e^{\frac{d}{H}} - \left(\frac{T_{0,r} - \Gamma_r d}{T_{0,r}}\right)^{-\frac{g}{R\Gamma_r}}\right] \qquad (7)$$

Here, d is the depth of the heat island, $T_{0,r}$ is the near-surface temperature in the rural area and $H = RT_{0,u}/g$, with $T_{0,u}$ representing the near-surface temperature in the urban area. The first and second terms in the square brackets in Eq. (7) quantify the downward increase of atmospheric pressure, respectively, in the isothermal urban atmosphere and in the stably stratified rural atmosphere. Applying Eq. (7) to typical values of pressure and temperature and taking d = 100 m, it follows that $\Delta p_{u-r} \approx -0.1$ hPa, which is consistent with observations (cf. Fig. 7).

Contrary to the case of Bolzano, no up-valley wind is observed during the night south of Trento. However, the very weak nocturnal down-valley wind at Trento Sud (Fig. 8d) may be a consequence of this particular urban effect, similar to what happens at Bronzolo. Numerical simulations with the WRF model (Giovannini et al. 2014b) support this hypothesis. ”Urban breezes”, i.e. light winds blowing towards the city due to the presence of the urban heat island, have been observed also in other cases, especially for bigger cities (e.g. Hidalgo et al. 2008). This may cause wind convergence over the city, favourable for the accumulation of air pollutants (Kossmann and Sturman 2004). It is plausible that the city of Bolzano, which is similar to Trento in terms of number of inhabitants and extension of the urban area, produces similar urban effects, adding up to the ”basin” effect and thus contributing to the reversal of the local pressure gradient.

The relatively high pressure at Trento during daytime may be induced by the influence of a local lake breeze, the Ora del Garda (see Laiti et al. 2013, Laiti et al. 2014, Giovannini et al. 2015). The relatively cool lake breeze exits on the Adige Valley from a tributary north of Trento. The outflow of cool air from the Ora del Garda typically extends as far south as the Trento urban area, possibly mitigating the pressure drop in the afternoon there. This explanation was proposed also by Schaller (1936), who found a similar behavior of the along-valley pressure gradient in this area in his investigation of the valley wind system at Trento.

5. Summary and conclusions

Data from surface weather stations and from a wind profiler located in the Alpine Adige Valley and in the adjacent Po Plain were analysed to gain some insight into the main characteristics of the thermally-driven valley wind system in the region. In particular, the relation between valley winds and temperature and pressure perturbations was described, along with the dependence of the wind system on the valley geometry and land use (urban vs. rural). 62 "valley wind days" were selected for the analysis based on a set of objective criteria. The main findings of this work may be summarized as follows:

- The valley wind system of the Adige Valley is characterised at the surface by moderate up-valley wind (generally up to 5 m s^{-1}) during daytime and weak down-valley wind (up to 2 m s^{-1}) at night. Data from a wind profiler highlighted that the up-valley wind is stronger than the down-valley wind also at higher levels, and that the up-valley wind typically extends to a height of about 1500 m AGL, which roughly corresponds to the crest height.
- Pressure gradients between different segments of the valley are stronger during daytime than at night, thus explaining the different strength of up- and down-valley winds. Only at the mouth of the valley are nighttime and daytime pressure gradients of similar magnitude; accordingly, down- and up-valley wind strengths have comparable intensity only at the southernmost weather station in the valley.
- The timing and strength of the valley wind system are similar in the southern and central parts of the valley, that displays uniform geometry and orientation.
- The amplitude of the surface pressure cycle increases in the up-valley direction, while the amplitude of the near-surface temperature cycle is rather uniform. A combined analysis of near-surface temperature and pressure perturbations suggests that the larger pressure cycle far into the valley depends on the thicker air layer affected by heating and cooling.
- The valley wind responds quickly (with a time scale of approximately 30 minutes) to variations in the along-valley pressure gradient.
- Valley winds are anomalous south of the Bolzano basin, where the diurnal up-valley wind is considerably weaker than farther south and light up-valley winds blow even at night. This is likely due to the valley geometry, which causes less intense heating and cooling of the atmosphere within the basin.
- The urban heat islands of the major cities on the valley floor influence the valley wind system at night. Relatively low pressures are registered at night at both Trento and Bolzano (where the urban effect probably combines with the above-mentioned "basin effect"). As a consequence, to the south of the two cities the nocturnal down-valley wind is absent or replaced by weak up-valley flow.

This work provides a basis for a comprehensive understanding of the processes affecting the development and the main features of the valley winds in the Alpine Adige Valley. However, since the analysis is based primarily on surface measurements, which cannot give a complete spatial representation of the phenomena investigated, some questions still remain open. Some deductions elaborated in the present work need to be verified with results from high-resolution numerical models. Modelling results by Giovannini et al. (2014b) support some of the findings of the present paper, in particular the alteration of down-valley winds at night close to urban areas. Additional high-resolution numerical simulations of the thermally-driven wind system of the Adige Valley are underway, and are expected to provide additional insight on the development of temperature and pressure contrasts between different segments of the valley, at ground level as well as in the valley core. Moreover, numerical simulations might be complemented by field studies focusing on the evaluation of vertical profiles of temperature and pressure at different locations along the valley, in order to better understand the physical processes responsible for the differences in the diurnal cycles of pressure perturbations observed at the surface weather stations.

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The thermally driven diurnal wind system of the Adige Valley in the Italian Alps

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Data from weather stations along the Adige Valley are analysed, to evaluate the main characteristics of valley winds. The wind intensity depends linearly on the along-valley pressure gradient, supporting the concept of a quasi-steady balance between pressure gradient and surface friction. The amplitude of the surface pressure cycle increases in the up-valley direction, while no appreciable along-valley variation in the diurnal temperature range is found, suggesting that the larger pressure perturbations far into the valley are caused by the increased depth of the atmospheric layer subject to heating and cooling.