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ORIGINAL PAPER

Intensity, frequency and spatial configuration of winter temperature inversions in the closed La Brevine valley, Switzerland

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Abstract Some of the world's valleys are famous for having particularly cold microclimates. The La Brevine valley, in the Swiss Jura Mountains, holds the record for the lowest temperature ever measured in an inhabited location in Switzerland. We studied cold air pools (CAPs) in this valley during the winter of 2014–2015 using 44 temperature data loggers distributed between 1033 and 1293 m asl. Our goals were to (i) describe the climatic conditions under which CAPs form in the valley, (ii) examine the spatial configuration and the temperature structure of the CAPs and (iii) quantify how often temperature inversions occur in winter using long-term series of temperature from the valley floor. Our results show that CAPs occurred every second night, on average, during the winter of 2014–2015 and were typically formed under cloudless, windless and high-pressure conditions. Strong temperature inversions up to 28 °C were detected between the valley floor and the surrounding hills. The spatial temperature structure of the CAPs varies among the different inversion days, with the upper boundary of the cold pool generally situated at about 1150 m asl. Although mean temperatures have increased in this area over the period 1960–2015 in connection with climate change, the occurrences of extreme cold temperatures did not decrease in winter and are highly correlated with the North Atlantic Oscillation and the East Atlantic indices. This suggests that CAPs in sheltered valleys are largely decoupled from the free atmosphere temperature and will likely continue to occur in the next decades under warmer conditions.

Y. Vitasse and G. Klein contributed equally to the manuscript and are therefore considered to be co-first authors.

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1 Introduction

The vertical temperature lapse rate (the rate at which temperature decreases with height in the atmosphere) varies with time and location. In the mid-latitudes, it varies both diurnally and seasonally, being larger during days and late spring and smaller during nights and winter (Kollas et al. 2014). The lapse rate is also affected by the degree of continentality and by slope exposure and shelter effects (Michalet et al. 2003; Rolland 2003). Even though the environmental lapse rate generally ranges between 0.4 °C 100 m^{-1} in oceanic regions and 0.8 °C 100 m^{-1} in more continental and/or drier areas (Viers 1990), atmospheric inversions (i.e. temperature increases with height) are common in mountain areas, particularly in winter. Multiple processes cause temperature inversions. The two major mechanisms causing inversions are dynamic drainage of cold air from surrounding slopes towards the valley floor (also known as katabatic flow) and in situ cooling of the ground and near-surface air due to infrared radiative energy loss, together with strong sheltering that prevents downward mixing of warmer air from aloft (Sheridan et al. 2014). In the case of katabatic flow, the cold air along the slopes becomes cooler than the adjacent air at the corresponding height. The denser cold air then flows downhill and accumulates in the valley floor. With in situ radiative cooling, the increasing air stability decouples the developing cold air pool (CAP) from external flow and vertical mixing, so that during clear nights, the air near the ground rapidly loses heat at the valley floor. Inversions last longer in areas with significant snow cover, because its high albedo reflects almost all incoming solar radiation, allowing the inversion to persist during daytime. CAPs can significantly affect plant survival and growth (Ailiang 1981; Blennow and Lindkvist 2000) and may even lead to vegetation inversions, in which more cold-tolerant species are found in the valley floor, as described in the central valleys of Japan (Iijima and Shinoda 2000). In particular, CAPs that occur in late winter or early spring are potentially dangerous for temperate perennial plants because their tissues become gradually less resistant to freezing temperature (dehardening phase lasting a few weeks before bud break) (Hänninen 2016; Vitasse et al. 2014).

Current numerical weather prediction models cannot accurately reproduce the formation of CAPs, especially in narrow valleys that are smaller than the spatial resolution at which temperatures are predicted (Vosper et al. 2014). A better description of CAP phenomena at fine scale is therefore important for improving model predictions of temperatures and vegetation distributions in such valleys. CAP formation within small depressions and narrow valleys has been shown to primarily result from the sheltering effect of the surrounding terrain, rather than drainage of cold air from the surrounding hills (Bodine et al. 2009; Gustavsson et al. 1998; Price et al. 2011; Thompson 1986; Vosper and Brown 2008). During the radiative cooling process, the air in the valley floor is decoupled from the external flow and not mixed with warmer air from aloft. In contrast, temperature inversions in large, open and/or deep valleys have been shown to be mostly the result of katabatic flow from the high surrounding hills (e.g. Barr and Orgill 1989; Gudiksen et al. 1992; Schmidli et al. 2009; Zängl 2005). While climate change is expected to reduce the frequency of extreme cold days without necessarily affecting the intensity and duration of CAPs (Kodra et al. 2011), only limited data are available to predict whether the frequency and intensity of CAPs in closed valleys will change with global mean temperature rise and whether narrow sheltered valleys will show different responses compared to large alpine valleys as suggested by Daly et al. (2010).

General patterns of atmospheric pressure may influence the occurrence of temperature inversions in sheltered valleys because the radiative losses that drive these inversions are favoured by clear skies and thus by high and stable atmospheric pressure. The North Atlantic Oscillation (NAO) represents fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high. The NAO has been shown to significantly affect the overall flow variability of the low and mid troposphere over the Arctic and Atlantic oceans (Appenzeller et al. 1998) and across large parts of Europe (Hurrell and Deser 2009; Luterbacher et al. 2004; Wanner et al. 2001). A positive value of the NAO index (low-pressure anomalies over the Icelandic and Arctic regions and high-pressure anomalies across the subtropical Atlantic) is associated with stronger westerlies across middle latitudes leading to lower atmospheric stability. Here, we hypothesise that the frequency of CAPs in the Jura valleys may be related to these indices because if CAP formation occurs predominantly under high and stable atmospheric pressures, it should be favoured under negative NAO index values. Similar correlations might be expected with other large-scale patterns in the northern hemisphere such as the East Atlantic (EA) and the Scandinavian pattern (SCAND). Positive phases of the EA, often interpreted as a southward-shifted NAO pattern, are associated with above-average temperatures and precipitation in central and northern Europe. The SCAND pattern has been shown to block anticyclones, and positive values of SCAND are associated with above-average precipitation in central Europe and thus with lower and more variable atmospheric pressure (Scherrer 2006).

In this study, we examined CAPs in the closed La Brevine valley, which extends roughly over 30 km^2 and spans an altitude range from 1033 to 1308 m asl in the Jura Mountains of western Switzerland. This valley holds the record for the coldest temperature ever measured in Switzerland (−41.8 °C in January 1987), and it frequently records temperatures below −20 °C in winter. Long and intense CAPs have often been studied because their stable atmospheric conditions lead to high levels of fine particulate pollution (e.g. Silcox et al. 2012). In contrast, here we study the spatial configuration, temperature structure and frequency of CAPs in a remote mountain valley with few inhabitants where, in spite of frequent CAPs, air pollution standards are generally met. Here, our aims are as follows:

1. To describe the spatial configuration of CAPs and their temperature structure in the La Brevine valley using 44 temperature loggers located at different elevations during the winter of 2014–2015
2. To identify the main meteorological conditions inducing the formation of CAPs in this valley and their influence on temperature inversion intensity
3. To verify the connections between extreme low temperatures induced by the formation of CAPs over the past decades and large-scale pressure indices such as the NAO, the EA and the SCANDs

4. To discuss the potential evolution of these extreme low temperatures in the context of ongoing climate change with implications for perennial plant species

2 Material and methods

2.1 Study area

The La Brevine valley is a closed valley in the Jura Mountains (centred at 46° 58′ 55″ N, 6° 36′ 25″ E) in the canton of Neuchatel, Switzerland (Fig. 1a). The valley is approximately 20 km long from SW to NE, following the main orientation of the Jura mountains, and 1.5 km wide. The terrain is slightly undulating along the valley floor from 1030 to 1090 m asl. The surrounding hills reach up to 1270 m asl on the northern side of the valley and 1308 m asl on the southern side (Fig. 1a). The slopes of the valley are mostly covered by evergreen forests with *Picea abies* L. and *Abies alba* Mill. as the dominant species, whereas the valley floor is mostly covered by non-irrigated arable land, typically used as meadows for mowing or pasture (Fig. 1b). A small lake of 0.48 km^2 lies on the valley floor in the southern part of the valley (Fig. 1b).

The historical weather station operated by MeteoSwiss is located close to the lowest point of the valley in the village of La Brevine (1050 m). It has recorded the absolute coldest temperature ever measured in Switzerland (−41.8 °C in January 1987), justifying its regional nickname of "Swiss Siberia". During the 1981–2010 reference period computed by MeteoSwiss, the average annual precipitation in La Brevine was 1597 mm and the average annual temperature was 4.9 °C, with the lowest monthly mean values in January (−4.3 °C) and the highest in July (14.1 °C). Maximum temperatures are only 0.5 °C lower than those recorded in La Chaux-de-Fonds, at nearly the same elevation (1018 m asl) on a plateau 18.1 km away. In contrast, annual minimum temperatures differ considerably between these two stations due to the formation of CAPs (3.4 °C lower in La Brevine). The mean winter temperature (DJF) recorded by the MeteoSwiss weather station during the period 1960–2015 was −3.5 ± 0.3 °C (mean ± SE). The study winter (from 1 December 2014 to 28 February 2015) falls well within the range of the long-term mean, with a mean temperature of −3.7 °C. Snowfalls occurred during the first half of December, leading to a thin snowpack (less than 10 cm) that remained on the ground less than a week (Fig. 2). Substantial snowfalls occurred by the end of December, and, except for about 3 days at mid January, the snow covered the ground continuously until the end of the study period, reaching a maximum of 90 cm at the beginning of February (Fig. 2). Air temperature recorded at the valley floor was the lowest

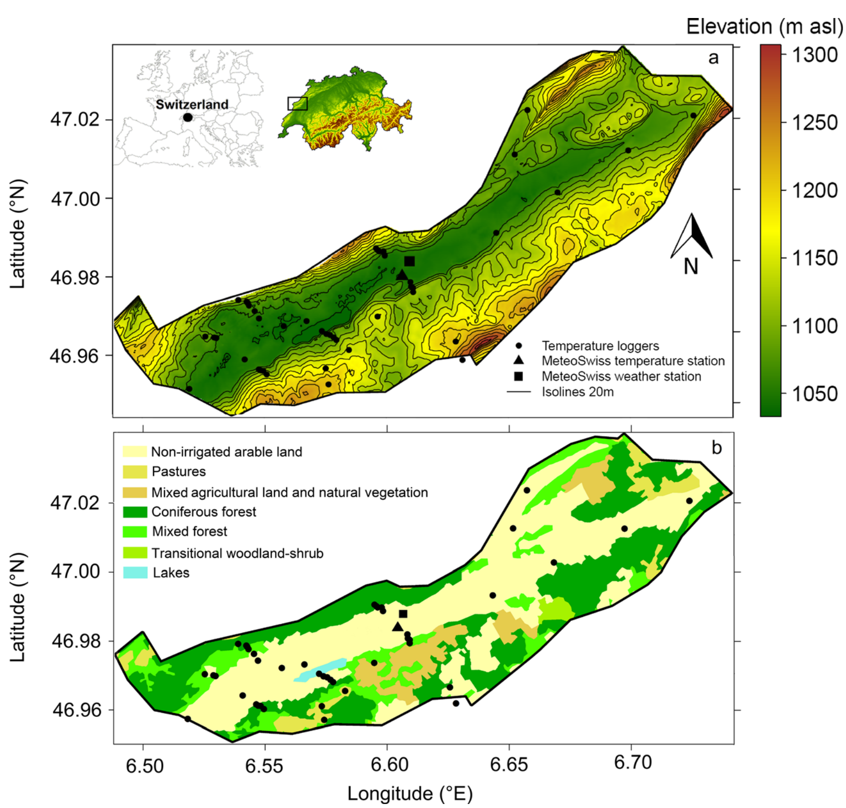

Fig. 1 **a** Topographic map of the La Brevine valley, with inset map indicating the location of the valley in Switzerland. The location of the 44 temperature loggers and the MeteoSwiss weather stations is shown. **b** Map of the La Brevine valley showing the main land cover (source: CORINE Land Cover 2012, version 18.5). The location of the 44 temperature loggers and the MeteoSwiss weather stations is shown

on 28 December (−29.6 °C), and remarkably, daily minimum temperatures were always below 0 °C from 11 January 2015 to 28 February 2015 (Fig. 2).

2.2 Temperature measurements

We recorded temperature every 10 min at 44 sites within the La Brevine valley from 1 December 2014 to 28 February 2015 (i.e. winter, DJF), using 44 data loggers (HOBO U23 Pro v2, Onset Computer Corporation, Bourne, MA, USA) mounted at 2 m height on poles and positioned under white multiple-layered solar radiation shields (RS1, Onset Computer Corporation, Bourne, MA, USA). The temperature loggers were situated at altitudes from 1033 to 1293 m, covering the entire elevation range of the valley (Fig. 1a).

2.3 Data analysis

For each 10-min interval, we subtracted the mean temperature of the five lowest-altitude loggers, all located along the valley floor (between 1033 and 1051 m asl), from the mean temperature of the five highest-altitude loggers (between 1162 and 1293 m asl), mostly located above the CAP whenever a temperature inversion forms. We defined an inversion to have occurred whenever this temperature difference was positive (i.e. whenever the five uppermost stations were warmer, on average, than the five lowermost stations). We grouped together all inversions that occurred during the same 24-h interval, between 1 p.m. on the previous day and 1 p.m. of the current day. We considered an *inversion day* to have occurred when the accumulated inversion duration exceeded 3 h during this 24-h interval, as reported in Table 1. We performed similar analyses using different numbers of stations at the uppermost and lowermost elevations, and they yielded similar numbers of inversion days.

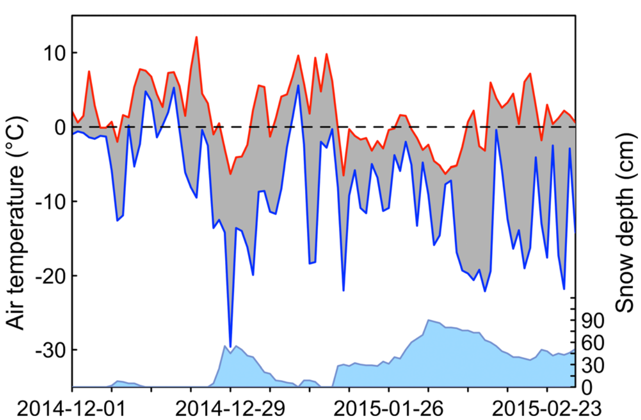

Fig. 2 Daily minimum and maximum air temperature recorded at the MeteoSwiss weather station situated at the valley floor during the winter 2014–2015. Snow depth recorded on the valley floor of a nearby parallel valley (Les Ponts-de-Martel, 9.6 km apart) is shown at the *bottom* of the *graph*

For each 10-min interval of each inversion day, we then subtracted the temperature at each of the 44 stations from their theoretically expected temperature. This theoretically expected temperature was calculated by applying the conventional lapse rate of 0.65 °C 100 m^{-1} to the temperature recorded at the top logger, which we assumed to be above the CAP. We then defined the maximum inversion intensity as the maximum positive theoretical-actual temperature difference, across all stations and 10-min intervals, for the inversion day. Values close to zero are then obtained when no inversion was detected in the valley, whereas high positive values are obtained during strong temperature inversions (that is, when actual temperatures lie well below lapse rate-based theoretical extrapolations), mostly for the lowest-altitude loggers. The temperature lapse rate of 0.65 °C 100 m^{-1} is a classical lapse rate used in climatology studies and roughly corresponds to the mean mid-latitude tropospheric lapse rate (Kunz et al. 2007; Rolland 2003; Scherrer and Appenzeller 2014).

We found that the relationships between elevation and temperature at times of maximum inversion intensity varied among the different inversion days and therefore fitted a polynomial model for each inversion day at its maximum intensity to best represent these relationships. We used the following polynomial model:

$$T(x) = ax^3 + bx^2 + cx + d$$

where T is the temperature of a given station (°C) at the maximum inversion intensity, x is the elevation of the given station and a, b, c and d are fitted parameters of the model. Polynomial models of temperature as a function of elevation combined with interpolations of residual variations of temperature, specific for each inversion, were then used to spatially predict the temperature throughout the valley at times of maximum inversion intensity, using pixels of a 25-m digital elevation model (DEM). We thus generated maps for every inversion day representing the peak of inversion intensity following the methods for daily interpolation of Cianfrani et al. (2015). A third-order polynomial model of temperature as a function of elevation was first calibrated. Then, each daily projection of this fitted model on the 25-m pixels was adjusted by interpolating residuals of the regression from the calibration points over the whole valley according to the inverse distance weighted (IDW) algorithm (Cianfrani et al. 2015).

To explore which climatic parameters favour the formation of CAPs, we correlated the maximum inversion intensity found for each inversion day with different climate parameters such as wind speed, relative sunshine duration, atmospheric pressure, relative air humidity and cloudiness, obtained from the MeteoSwiss weather station situated on the valley floor (see location on Fig. 1a). As a proxy for night cloudiness, we used the relative sunshine duration between 9 a.m. and 10 a.m. on the following morning. We also compared the peak

Table 1 Number, duration and intensity of inversion days observed during winter 2014–2015 in the La Brevine valley, along with the associated minimum temperature recorded during inversions at the lowermost logger

Inversion intensity [°C]	Number	% Of total	Mean duration [h]	Average minimum temperature during inversions [°C]
0–5	1	2	3	−1.4
5–10	8	21	6.7	−9.8
10–15	13	33	11.2	−10.7
15–20	8	21	13.2	−17.3
> 20	9	23	16.6	−18.6
Sum/mean	39	100	11.7	−13.5

We selected only inversions longer than 3 h. The intensity of the inversion corresponds to the maximum deviation found between the temperature value measured at any of the 44 temperature loggers and the expected value using the top logger as reference and a lapse rate of 0.65 °C 100 m^{-1} (cf. Fig. 2)

inversion intensity for each inversion day with the temperature reading at the top logger as a representation of the temperature measured outside of the CAP. We computed the frequency of freezing events below various thresholds (−15, −20 and −25 °C) over the period 1960–2015 using homogenized temperature data provided by MeteoSwiss for the weather station of La Brevine. Homogenization of this long-term series of temperature data has been obtained by using monthly homogeneity adjustments, and daily data were then derived by applying a spline function. The frequencies of these low-temperature events were used as a proxy for CAP frequencies. These thresholds are low enough to mostly exclude low temperatures that would not be the consequence of CAPs and are rather conservative as they may represent only strong CAPs. For instance, during the analysed winter 2014–2015, temperature dropped below −20 °C five times and below −25 °C once, and all of these six events were the consequence of CAP formation. These annual frequency data were tested for serial correlation, which was found to be negligible. The annual frequencies of these low-temperature events were then correlated to three major climate patterns: the winter NAO index, the EA pattern and the SCAND pattern. The NAO-normalized winter index originates from the National Center for Atmospheric Research (Hurrell and NCAR 2015); the EA and SCAND patterns were provided by the National Oceanic and Atmospheric Administration of the USA (NOAA 2016).

All analyses were performed with R 3.1 (R Core Team 2015) using the following R packages: raster, sp, gstat, lattice, maptools and rgdal. Maps were generated both with R 3.1 and ArcMap 10.2.2, using a 25-m high-resolution DEM of Switzerland.

3 Results

3.1 Frequency of inversion days

Over the examined winter period, significant temperature inversions (i.e. uppermost stations recording warmer temperatures than lowermost stations during more than 3 h in a 24-h period) were observed for 43 % of the nights (39 inversions, see Table 1). Among all the selected daily inversions, the vast majority (~77 %) had an intensity higher than 10 °C (Table 1). For 44 %, the intensity exceeded 15 °C, and for 23 % (nine inversions), the intensity was over 20 °C (Table 1) reaching a maximum of 28.0 °C on 13 January 2015. The duration of the inversions was significantly correlated to their intensity (Pearson correlation coefficients $r = 0.61$, $p < 0.001$, data not shown): the longer the duration, the stronger the intensity (Table 1). For weak inversions, i.e. lower than 10 °C, the CAPs lasted on average less than 7 h, vanishing rapidly after sunrise reached the valley floor (Table 2). In contrast, during inversions stronger than 10 °C, the CAPs lasted significantly longer (Table 1) and on a few occasions remained throughout the following day. Noteworthy during the study period, the coldest temperature recorded in the valley was not recorded during the strongest inversion intensity (13 January 2015, intensity 28.0 °C, temperature at the valley floor −19 °C, Figs. 2 and 3) but during a weaker inversion (29 December 2014, intensity 22.2 °C, temperature at the valley floor −30.5 °C).

Table 2 Correlations between the annual frequency of extreme freezing events below −15, −20 and −25 °C recorded at the valley floor using daily homogenized data and the winter North Atlantic Oscillation (NAO), East Atlantic (EA) and Scandinavian (SCAND) indices during the period 1960–2015

	NAO		EA		SCAND	
Threshold [°C]	*r*	*p* value	*r*	*p* value	*r*	*p* value
<−15	−0.20	0.140	**−0.42**	**0.001**	0.04	0.748
<−20	**−0.33**	**0.014**	**−0.45**	**< 0.001**	0.15	0.262
<−25	**−0.34**	**0.010**	**−0.43**	**0.001**	0.07	0.591

Pearson correlation coefficients (*r*) and associated *p* values are shown. Similar results were obtained for Spearman rank correlations (not shown). Significant correlations ($p \leq 0.05$) are highlighted in bold. Winter NAO corresponds to the normalized winter index (extracted from Hurrell and NCAR 2015), and winter EA and SCAND were computed from monthly values from December to February (NOAA 2016)

3.2 Spatial configuration and temperature structure of the CAPs

During inversion days, temperature was positively correlated with elevation, the lowest points of the valley being the coldest. However, the spatial configuration of the CAP differs among the inversion days with, in some cases, a clear upper limit of the cold pool or, in other cases, particularly during strong inversions, a cold pool that completely fills the valley up to the upper elevation of the surrounding ridges (Fig. 3). On average, the temperature increase with elevation during inversions is roughly linear from the valley floor up to ~1100 m asl and then becomes more gradual, finally showing no significant increase over the last 150 m up to the upper ridge (Fig. 4). We attributed the slight differences of temperature among the upper stations to local site effects.

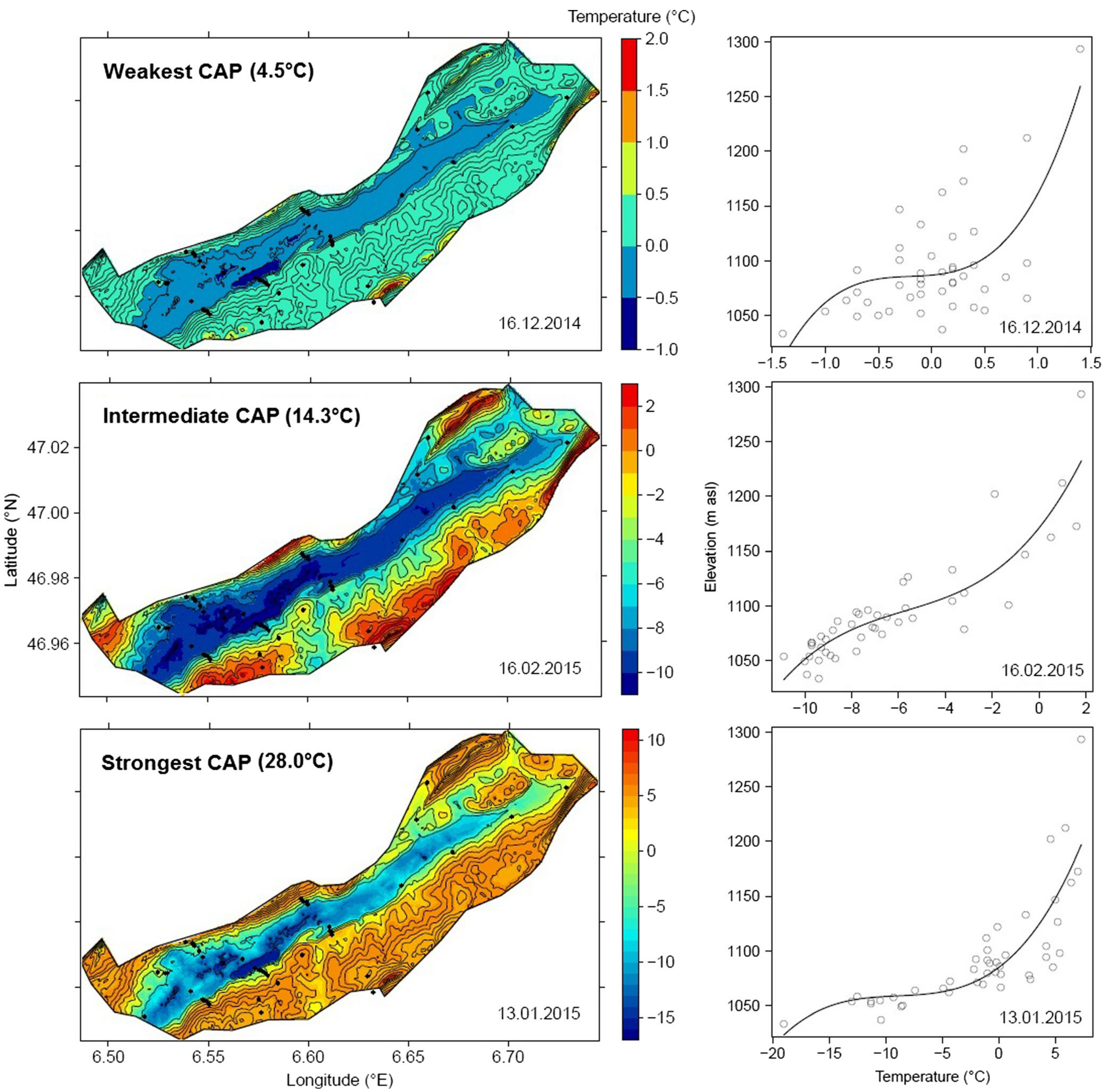

Fig. 3 Spatial distribution of temperatures for the weakest and the strongest and an intermediate temperature inversion during winter 2014–2015, with their corresponding temperature profiles. The *black lines* represent fitted polynomial models. *Black dots* on the map represent the 44 temperature loggers

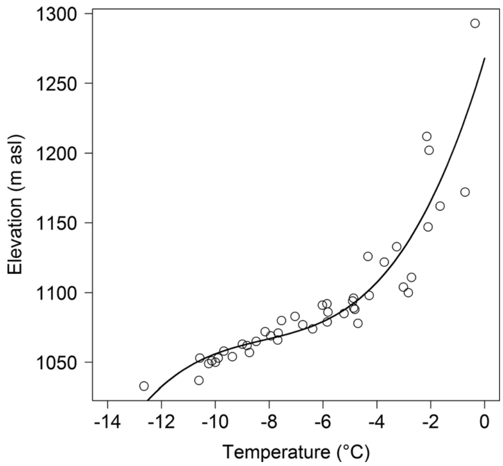

Fig. 4 Mean altitudinal temperature profile during temperature inversions. *Dots* represent, for each station, the mean temperature of all inversions (39) at the moment of its maximum intensity. The *black solid line* represents the fitted polynomial model. Note that temperature ceases to significantly increase with elevation above approximately 1150 m, marking the upper limit of the CAP

Nevertheless, some inversion days presented different temperature distributions with elevation (data not shown), which supports our use of individual polynomial regressions to accurately model each inversion day.

3.3 Observed climatic conditions during temperature inversions

A significant negative correlation ($r = -0.41$, $p < 0.001$) was found between the intensity of the inversions and mean wind speed. While weak inversions or temperature decreases with elevation were observed during both calm and windy nights, most of the CAPs with strong intensity (>20 °C) typically formed during calm nights, i.e. with no wind or winds of less than 10 km h^{-1} on average (Fig. 5a). However, a few inversions of more than 10 °C intensity were still observed with wind blowing on average between 10 and 20 km h^{-1} (Fig. 5a). A significant relationship ($r = 0.35$, $p < 0.001$) was also found between the atmospheric pressure and the intensity of the inversion (Fig. 5b). Inversions with intensity higher than 20 °C were observed only under atmospheric pressure higher than 1015 hPa (Fig. 5b). As for the wind, weak inversions (values close to zero) and non-inverted conditions were found during periods of both low and high atmospheric pressure. Non-inversion conditions occurred during both high and low relative humidity, but more intense inversions tended to occur under lower relative humidity (Fig. 5c). Nevertheless, the correlation was weak ($r = -0.30$, $p = 0.004$) and the relative humidity was mostly high, rarely ranging below 80 %. A clear significant correlation ($r = 0.62$ $p < 0.001$) was found between the intensity of the inversion and the relative sunshine duration on the following morning, as a proxy for the cloudiness during the night (Fig. 5d). Most of the strongest inversions occurred under cloudless conditions, i.e. with 100 % relative sunshine duration on the following morning (Fig. 5d). Finally, the intensity of the inversion was only weakly ($r = 0.21$, $p = 0.049$) related to the measured temperature at the top station, which was usually located above the CAP (Fig. 5e), indicating that strong inversions can occur irrespective of the temperature prevailing in the region.

3.4 Relationship between the formation of CAPs and global atmospheric pressure indices

The annual frequencies of extreme low-temperature events below −15, −20 and −25 °C, likely induced by CAP events, are significantly correlated to the winter NAO (except the −15 °C) and EA indices (Table 2). Lower values of these two indices correlate with higher frequencies of extreme cold temperatures. In contrast, no correlation was found with the SCAND pattern (Table 2). The winter NAO and EA indices are not significantly correlated with one another (data not shown), indicating that they independently influence the frequency of CAP events at La Brevine.

3.5 Frequency and latest winter-spring occurrence of extreme low temperatures since 1960

Although mean annual temperature has shown a statistically significant increase of 0.31 ± 0.05 °C per decade (p value <0.001) over the period 1959–2015 in La Brevine (based on the monthly homogenized series by MeteoSwiss; data not shown), the frequency of extreme freezing events due to CAPs has not significantly declined during this period and remains high at the valley floor (Fig. 6a): temperatures below −15, −20 and −25 °C occur about 23, 12 and 5 times per winter respectively with high interannual variability but no significant trends over the last five decades (Fig. 6a). Similarly, the latest low-temperature events below −20 and −25 °C during late winter and spring time, which could potentially damage perennial plants, have not advanced since 1960 (Fig. 6b), whereas the latest events below −15 °C have slightly advanced (Theil-Sen slope: −0.4 days per decade, $p = 0.045$, Fig. 6b).

4 Discussion

Readings from 44 temperature loggers in the La Brevine valley permitted us to accurately identify the spatial distribution of temperature during CAP formation in this valley. Our study showed that CAPs formed under diverse temperature conditions, with temperature values recorded at the top of the valley (mostly above the CAPs) ranging from −10 to 9.9 °C at the

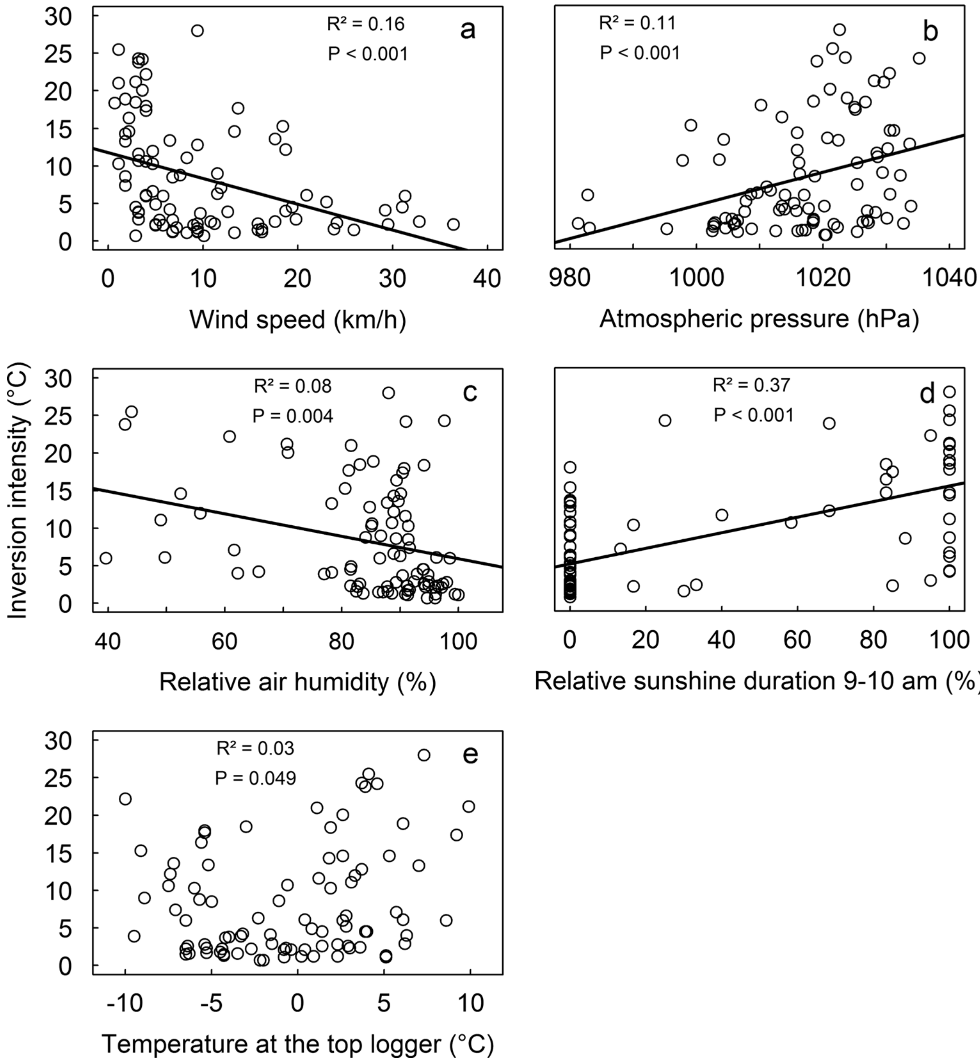

Fig. 5 Correlations between daily maximum temperature inversion (i.e. the temperature that deviates the most from the expected temperature using a lapse rate of 0.65 °C 100 m^{-1} applied from the top station downward) and various climatic parameters. Values close to zero indicate no cold air pooling, whereas high positive values indicate strong temperature inversions. **a** Wind speed; **b** atmospheric pressure; **c** relative humidity; **d** relative sunshine duration; **e** temperature at the top logger. Except for temperature at the top logger, all parameters were measured at the MeteoSwiss weather station located at the bottom of the valley

moment of maximum inversion. We showed that significant inversions occurred during 43 % of the winter nights 2014–2015, and among all the detected inversions lasting at least 3 h, 23 % had an intensity exceeding 20 °C, with the strongest reaching 28 °C. The frequency and intensity of these inversions were correlated with specific climate conditions: most of them occurred during calm and clear nights with high atmospheric pressure. Because the La Brevine valley is closed with mainly evergreen forests covering all the surrounding slopes, strong sheltering effects led to high rates of radiative cooling without air mixing from aloft. Finally, in spite of the statistically significant increase in mean annual temperature observed at La Brevine over the period 1960–2015, no trend was detected in the frequency and intensity of extreme freezing temperatures over the last five decades in this valley, due to the frequent formation of CAPs. However, the frequency of extreme low temperatures was negatively correlated with the NAO and EA indices, confirming the strong dependence of CAPs on atmospheric pressure rather than on the current atmospheric temperature.

4.1 The formation and development of CAPs in the La Brevine valley

Our study showed that strong CAPs formed during calm, clear nights under high atmospheric pressure, which is consistent with previous studies, especially those conducted in narrow and sheltered valleys as in the present study (Daly et al. 2010; Smith et al. 2010). Temperature inversions have been shown to occur under dry conditions (Whiteman et al. 2007; Williams and Thorp 2015). Likewise, stronger inversions tended to occur under drier conditions at La Brevine. However, the relative humidity values seemed rather high even during strong inversions because saturation humidity dramatically decreases when temperature drops below freezing. In fact, the absolute humidity contained in the air during the cooling process substantially decreased, likely resulting into the formation of either fog or ice crystals. We hypothesise that in the vast majority of winter CAPs at La Brevine, the removal of humidity as the consequence of temperature decrease most likely occurs through the formation of ice crystals

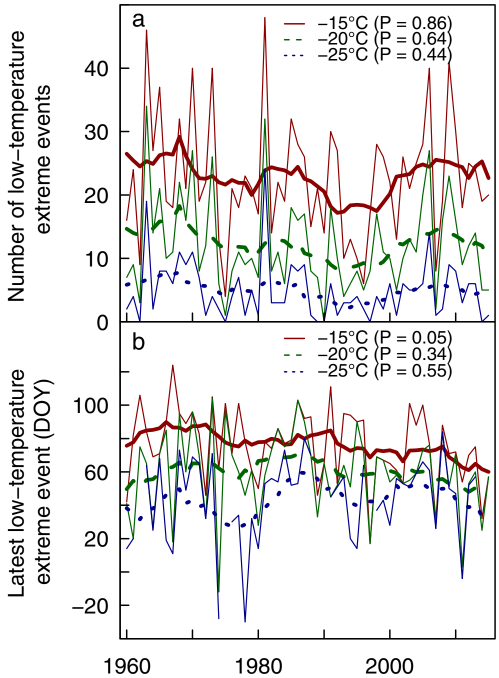

Fig. 6 **a** Frequency of extreme freezing events recorded at the valley floor during the period 1960–2015 during the winter months (DJF). **b** Latest occurrence of extreme freezing events recorded at the valley floor during the period 1960–2015 during the winter and spring months (DJF-MAM). *Solid line* shows frequency of temperatures below −15 °C, *dashed line* shows frequency of temperatures below −20 °C and *dotted line* shows frequency of temperatures below −25 °C, all as 10-year moving windows from 1960 to 2015. *DOY* day of year. No occurrences of temperature below −25 °C were found during 6 years and are therefore accounted for as missing values in Fig. 5b (1962, 1975, 1989, 1990, 1997 and 2014). *p* Values were calculated from Mann-Kendall tests

rather than fog, which would otherwise limit further radiative cooling and probably prevent the temperatures from reaching the extreme low values typically observed in this valley. The analyses of fog observations in this valley during the period 1966–1996 (the only available period of record) supports this hypothesis, as fog was detected in about 22 % of the days during the winter months (DJF), and this percentage remained as low as 23.5 % under high atmospheric pressure conditions (here considered as a proxy for the likelihood presence of CAPs).

Cooling trends were usually observed simultaneously all along the valley, suggesting that the CAPs form mainly as a result of in situ cooling with very limited mixing with air from aloft, rather than as a result of advective cooling. Moreover, in contrast to valleys in the Alps, the La Brevine valley lies on a large plateau at about 1000 m asl, with no surrounding high relief. The topography of this closed valley confers a strong sheltering effect, increasing the in situ radiative cooling of the air over the ground surface, since there is no path for cold air to be evacuated towards lower elevations. Forests dominated by evergreen conifer species (*Picea abies* and *Abies alba*) cover all the slopes of the valley and may enhance the sheltering effect by reducing the wind speed and consequently the vertical mixing, as has been previously reported for other sites (e.g. Blennow 1998; Bodine et al. 2009; Gustavsson et al. 1998; Karlsson 2000).

Radiative cooling rates are highly dependent on cloud cover, as outgoing longwave radiation loss is higher under clear sky conditions (Gustavsson 1995; Whiteman et al. 2004). Consistent with this relationship, our results showed that the intensity of inversions was strongest under clear sky conditions and high atmospheric pressure. We found high inversion intensities of more than 25 °C over a very short elevational range (less than 300 m), which is typical for a narrow valley with strong sheltering effects and low vertical air mixing (Miller et al. 1983; Vosper et al. 2014).

Snow cover is an important factor influencing the cooling rate and therefore the inversion intensity. Snow cover provides an insulating layer that limits the upward ground heat flux that would normally counter longwave radiation losses from the surface (Whiteman et al. 2004). Except during December, a rather thick snow pack covered the valley floor, which we would expect to enhance CAP formation compared to other seasons, when herbaceous vegetation covers the ground, decreasing surface albedo. Further studies would be necessary to characterize the seasonal variation and intensity of CAPs during an entire year.

The lack of connection between the temperature measured above the CAP and the intensity of the inversion stands in contradiction to the expectation that very cold conditions should favour stronger CAPs. This may in part be explained by the specific orientation of the valleys in the Jura Mountains: as cold air mostly flows from the North-East, parallel to these valleys, the valleys of the Jura are exposed to windy conditions and air mixing during periods of cold air influx, thus reducing the potential for radiative cooling. Temperature inversions can only intensify again after the new air mass is installed and the wind has calmed down. The temperatures can then be exceptionally cold in the valley floor due to the combination of CAP formation and regionally low temperatures, but the intensity of the inversion is not necessarily exceptional. The lack of correlation between the temperature recorded above the CAP and the intensity of the inversion could thus be specific to the Jura valleys and might not be corroborated in alpine valleys with different geographic orientations, although similar observations have also been reported from another sheltered valley in the Cascade mountains of Oregon (Daly et al. 2010).

4.2 Link with the general climate patterns

The frequency of extreme low temperatures recorded at the bottom of the La Brevine valley (as a proxy for the formation of CAPs) was significantly correlated with the winter NAO and EA indices, corroborating its strong dependence on atmospheric pressure conditions. Positive NAO index values have been shown to be associated with above-normal precipitation over northern Europe and Scandinavia with frequent changes in atmospheric pressure (Hurrell and Deser 2009). Negative NAO index values are therefore more favourable to the development of CAPs in winter in Western Europe because the atmospheric system is more stable, with less cloud cover and precipitation. The correlation with the EA index is not surprising as the EA index is often considered as a southward-shifted NAO pattern, although the strengths of the NAO and EA indices were not significantly correlated with one another during the period 1960–2015 (despite them both being significantly correlated with low temperatures at La Brevine). The absence of correlation with the SCAND pattern shows its weak influence in the study area, as it is expected to impact more northerly parts of Western Europe, Scandinavia and Western Russia.

4.3 Climate change has not affected the frequency of extreme low-temperature events in the La Brevine valley: implications for perennial plants

Characterizing the spatial distribution of temperature is particularly relevant for a better understanding of the vegetation distribution in this valley or in other valleys subject to CAPs. Local but intense CAPs that lead to extreme freezing events in narrow valleys, such as those presented in this study, have substantial impacts on plant fitness (Blennow and Lindkvist 2000), especially if they occur in late spring when vegetation becomes more sensitive to frost (Lenz et al. 2013; Vitasse et al. 2014). A recent study conducted in this valley showed that beech trees that are present in a few spots along the slopes can acclimate to extreme low temperatures of about −40 °C, which have been reached at the valley floor in the past (Lenz et al. 2016). The sporadic distribution of European beech in this valley and its absence at the valley floor might therefore not be caused by extreme low temperatures in winter, but could rather be the consequence of very frequent late spring frosts induced by CAPs at a time when bud tissues are most vulnerable to freezing temperatures (Lenz et al. 2016; Vitasse et al. 2014). Frost damage in the La Brevine valley may increase under ongoing climate change because mean temperature is increasing, leading to earlier spring phenology (and thus to an earlier dehardening phase), while the latest occurrence of extreme low temperature due to CAPs remains unchanged. Some species might be at higher risk than others. For instance, at the upper elevational limits of different tree species in the Swiss Alps, Lenz et al. (2013) reported LT50 values (lethal temperature for 50 % of the considered tissue) for buds ranging between −20 and −10 °C in March for *Prunus avium* and *Fagus sylvatica*, between −30 and −20 °C for *Fraxinus excelsior* and below −35 °C for *Sorbus aucuparia* and *Acer pseudoplatanus*, all these species being present on the slopes surrounding the valley. The two first mentioned species could be at risk of damage during their dehardening phase from stochastic late-spring CAPs. Clearly, more investigation is required to determine the seasonal variation of the CAPs and their intensity in late spring. It is also unclear whether these climatic phenomena will be altered by climate warming (Daly et al. 2010). Although minimum, mean and maximum temperatures have strongly increased since the beginning of the twentieth century (and particularly since the 1970s) in Switzerland as a result of the ongoing climate warming (Rebetez and Reinhard 2008), no trends in minimum temperature or in the frequency of extreme freezing events were observed at La Brevine. The frequencies of temperatures below −15, −20 or −25 °C showed no significant trends since the 1960s but were strongly correlated with the winter NAO and EA indices, corroborating the strong dependence of CAP formation with atmospheric pressure and synoptic-scale air mass stability.

5 Conclusion

The extreme low temperatures recorded in the La Brevine valley result from strong CAPs. Our measurements confirm that in such narrow valleys, CAPs are decoupled from the free atmosphere temperature (Daly et al. 2010; Lundquist et al. 2008) and therefore may not be affected by the regional trend of warming predicted by general circulation models (GCMs). The frequency of CAPs in such narrow valleys in a future warmer climate will therefore depend on how climate change affects global pressure indices such as the NAO, rather than on the degree of warming in these areas. This result has implications for agroforestry because a general increase in mean temperature due to climate warming is likely to release the dormancy of woody species earlier in late winter/early spring, leading to earlier phenology and plant tissue dehardening (Vitasse et al. 2014) at a time when strong inversions due to CAPs can still occur and damage plant tissues.

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