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

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Rebetez, Martine; University of Neuchatel, Institute of Geography |
| Keywords:     | Climate change, Cold air pools, NAO index, radiative cooling, sheltering, temperature inversions, temperature lapse rate, valley cooling |
Intensity, frequency and spatial configuration of winter temperature inversions in the closed La Brevine valley, Switzerland

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Short title: Winter cold air pools in a closed valley
Abstract

Some valleys in the world are famous for having a particularly cold or hot microclimate. The La Brevine valley, in the Swiss Jura Mountains, recorded the lowest temperature ever measured in an inhabited location in Switzerland. Here, we conducted a fine-scale microclimatology study using 46 temperature data loggers distributed in the valley from 1033 to 1293 m asl during the winter of 2014-2015. We aimed at (i) describing the climatic conditions under which Cold Air Pools (CAPs) form in the valley, (ii) examining the spatial configuration and the temperature structure of the CAPs and (iii) quantifying how often temperature inversions occur in winter. Our results show that CAPs occurred every second night, on average, during winter, and are typically formed under cloudless, windless and high atmospheric pressure conditions. Strong temperature inversions up to 27.8 K were detected within a few kilometres between the bottom of the valley and the surrounding hills. The spatial temperature structure of the CAPs is consistent between distinct nights irrespective of the intensity of the inversion. Although temperature has increased in this area over the period 1964–2015 in connection with climate change, the occurrences of extreme cold temperatures recorded in the valley and the intensity of temperature inversions did not decrease in winter but they are highly correlated with the North Atlantic Oscillation (NAO) index. This suggests that the formation of CAPs in sheltered valleys is decoupled from the free atmosphere temperature and will likely not follow the general warming trend expected in the coming decades.

Keywords Climate change, cold air pools, NAO index, radiative cooling, sheltering, temperature inversions, temperature lapse rate, valley cooling
1. Introduction

The temperature lapse rate (the rate at which atmospheric temperature decreases with increasing altitude within the atmospheric boundary layer) varies with time and location. In the mid-latitudes it varies both diurnally and seasonally, reaching minimum values during nights and winter, and maximum values during days and late spring (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 K 100 m\(^{-1}\) in oceanic regions to -0.8 K 100 m\(^{-1}\) in more continental and/or drier areas (Viers, 1990), temperature inversions leading to positive lapse rates are common in mountain areas, particularly in winter. Multiple factors cause temperature inversions. The two major mechanisms causing inversions are dynamic drainage of cold air from surrounding slopes towards the bottom of the valley (or katabatic flow) and in-situ cooling of the ground and near-surface air due to infra-red radiation, together with strong sheltering preventing downward mixing of warmer air from aloft (Sheridan et al., 2014). In the case of katabatic flow, the cold air near the ground gets cooler along the slopes than the surrounding air at the corresponding height. The denser cold air flows downhill and accumulates in the valley bottom. With in-situ radiative cooling, the topography of the valley restricts external flow and reduces vertical mixing, so that, during clear nights, the air near the ground rapidly loses heat at the valley bottom. Inversions are reinforced in areas with significant snow cover because the snow’s high albedo reflects almost all incoming heat. Thus, the air above the snow is often warmer because it holds the reflected energy (Miller, 1956). CAPs can significantly affect plant
survival and growth (Ai-liang, 1981; Blennow and Lindkvist, 2000) and may even lead to vegetation inversions as described in the central valleys of Japan (Iijima and Shinoda, 2000).

Current numerical weather prediction models cannot accurately reproduce the formation of CAPs (Vosper et al., 2014), especially in narrow valleys smaller than the grid scale used for temperature data. Yet, a better description of such phenomena at fine scale is important for improving model predictions of temperature in such valleys. CAP formation within small depressions and narrow valleys has been shown to primarily result from the sheltering effect of the topography of the surrounding terrain or even the surrounding, rather than drainage of cold air from the surrounding hills, which would on the contrary reinforce vertical mixing (advective cooling, Bodine et al., 2009; Gustavsson et al., 1998; Price et al., 2011; Thompson, 1986; Vosper and Brown, 2008). During the cooling process, the air on the bottom of the valley 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 (Meehl et al., 2000), 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).

The atmospheric pressure in western Europe has been shown to be connected to the general
Atlantic pressure system for which the North Atlantic Oscillation (NAO) index is a good proxy, as it reflects the pressure difference between the Arctic and the subtropical Atlantic. The NAO may therefore affect the formation of CAPs in large and narrow European valleys since CAPs are favoured under more stable atmospheric conditions (Daly et al., 2010).

Here we examined CAPs occurring in the closed La Brevine valley, which extends roughly over 30 km² from 1033 m to 1308 m asl in the Jura Mountains in the western part of Switzerland. This valley holds the record for the coldest temperature ever measured in Switzerland in an inhabited place, and it frequently records temperatures below –20°C in winter. The purpose of this paper is

1. to describe the main climatic conditions inducing the formation of CAPs in the La Brevine valley,
2. to characterize the spatial configuration of these CAPs using 46 temperature loggers located at different elevations in the valley,
3. to quantify how often such conditions occurred in winter over the last five decades and check a potential relationship between the frequency of CAPs and the NAO index
4. finally to discuss the potential evolution of these extreme low temperatures in the context of ongoing climate change.
2. Material and Methods

2.1. Study area

The La Brevine valley (Figure 1) is a closed valley located in the Jura Mountains (middle point at 46° 58′ 55″ N, 6° 36′ 25″ E) in the canton of Neuchatel, Switzerland. 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 slopes of the valley are fully covered by forests with *Picea abies* L. as the dominant species. The terrain is slightly undulating along the thalweg 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. A small lake of 0.48 km² lies on the bottom southern part of the valley.

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 values in January (-4.3°C) and the highest values in July (14.2°C). Maximum temperatures do not differ significantly from those recorded in La Chaux-de-Fonds, at nearly the same elevation (1018 m asl), on a Plateau 18.1 km away (0.5 K lower in La Brevine). In contrast, annual minimum temperatures differ considerably due to the formation of CAPs (3.4 K lower in La Brevine). Note that we
use Kelvin units [K] when referring to temperature deviations, in order to avoid confusion with absolute temperature values [°C].

2.2. Temperature measurements

We recorded temperature every 10 minutes at 46 sites within the La Brevine valley from 1 December 2014 to 28 February 2015 (i.e. winter, DJF) using 46 data loggers (HOBO U23 Pro v2, Onset Computer Corporation, Bourne, MA, USA) mounted at 2 m height on a pole and positioned under a white multiple-layered ventilated solar radiation shield (RS1, Onset Computer Corporation, Bourne, MA, USA). The temperature loggers were located at various elevations from 1033 m to 1293 m (Fig. 1).

We also used 10-minute data from the MeteoSwiss weather station of La Brevine, including wind speed, relative sunshine duration, atmospheric pressure, relative air humidity and 10-minute air temperature data from a 500 m distant MeteoSwiss air temperature station (Location of the MeteoSwiss installations is shown in Fig. 1).

2.3. Data analysis

For each day from December to February (from 12 noon on the previous day to 12 noon), we applied linear regressions between temperature values of our 46 temperature loggers and their elevation at the time when temperature is coldest at the bottom logger. We
considered the inversion as *significant* when the slope of the regression line over the 46 temperature loggers was significantly higher than zero ($p < 0.01$). We considered the lapse rate to be *normal* when the slope of the regression line was significantly lower than zero ($p < 0.01$). We obtained an average value for the *normal* lapse rate of -0.58 K per 100 m of elevation increase (Table 1), which is in the range of the environmental lapse rates typically observed in these areas (Rolland, 2003; Scherrer and Appenzeller, 2014).

Based on the temperature value measured at the *top logger* over the valley, we applied this average atmospheric lapse rate of -0.58 K per 100 m of elevation increase for *normal* atmospheric conditions to compute the *expected (or theoretical) temperature* at the *bottom logger* (Fig. 2). Whenever a CAP forms, a positive temperature lapse rate is found with elevation instead of a negative one. We computed the *deviation* between the temperature value *measured* at the *bottom logger* and the *expected* value to define the *intensity of the temperature inversion* at the time of minimum temperature at the *bottom logger* (Fig. 2). At that time of minimum temperature, we computed the linear regression of the temperature of the 46 temperature loggers on their elevations. Then, the intercept and the residuals were extracted and summed, so that each logger became a calibrating point (Cianfrani *et al.*, 2015). These points were finally predicted using the inverse distance weighting interpolation method, on each valley pixel with a 25m Digital Elevation Model in order to generate daily maps showing the temperature distribution according to elevation (Cianfrani *et al.*, 2015).

As several short inversions may occur during one single night or one inversion may last more than one night, we quantified all inversions that lasted at least 3 hours based on the
deviation between the expected and measured temperatures at the bottom station. For each inversion we then computed the mean cooling rates (K h\(^{-1}\)) from the beginning of the inversion until its maximum intensity and classified them by intensity classes (Table 2).

For each day, we correlated the maximum intensity of the inversion with other climate parameters (data at 15 min resolution), such as wind speed, relative sunshine duration, atmospheric pressure, relative air humidity and cloudiness, obtained from the MeteoSwiss weather station situated in the valley (see location on Fig. 1). As a proxy for night cloudiness, we used the relative sunshine duration between 9 and 10 am on the following morning. We also compared the temperature value 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 (-20°C, -25°C and -30°C) over the period 1958–2014 using temperature data recorded at the MeteoSwiss weather station of La Brevine. The rainfall data was tested for serial correlation and was found to be absent. The North Atlantic Oscillation index (NAO) originates from the National Center for Atmospheric Research (Hurrell and NCAR, 2015) and was correlated with these frequencies. Finally we used the MeteoSwiss long-term homogenized monthly temperature data series for 12 weather stations in Switzerland for comparison with the available data in La Brevine since 1964.

All analyses were performed using 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 25m high-resolution Digital Elevation Model (DEM) of Switzerland.
3. Results

3.1. Frequency of temperature inversions

Over the examined winter period, significant temperature inversions (i.e. significant positive lapse rates) were observed for 48% of the nights, whereas significant negative lapse rates were found for 29% of them (Table 1). The mean lapse rate for significant inversions was $+4.93 \text{ K} \text{ 100 m}^{-1}$. Statistically significant negative lapse rates had a mean value of $-0.58 \text{ K} \text{ 100 m}^{-1}$ (Table 1), i.e., in the range of environmental lapse rate classically found in central Europe.

3.2. Observed climatic conditions during temperature inversions

A significant negative correlation ($p<0.001$) was found between the intensity of the inversions and mean wind speed. While normal lapse rates were observed during both calm and windy nights, most of the CAPs with strong intensity typically formed during calm nights, i.e., with no wind or winds of less than $10 \text{ km h}^{-1}$ on average (Fig. 3a). However, a few inversions of more than $10 \text{ K}$ intensity were still observed with wind blowing on average between 10 and $20 \text{ km h}^{-1}$ (Fig. 3a). A significant relationship ($p=0.001$) was also found between the atmospheric pressure and the intensity of the inversion (Fig. 3b).

Inversions with intensity higher than $15 \text{ K}$ were observed only under atmospheric pressure higher than $1010 \text{ hPa}$ (Fig. 3b). Normal (negative) lapse rates occurred during both high and low atmospheric pressure conditions. More intense inversions tended to occur under lower atmospheric humidity (Fig. 3c), but the correlation was weak ($R^2=0.08$, $p=0.005$) and
the relative humidity was mostly high, rarely ranging below 80%. A significant correlation (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. 3d). Most of the strongest inversions occurred under cloudless conditions, i.e. with 100% relative sunshine duration on the following morning (Fig. 3d). Finally, the intensity of the inversion was not related to the measured temperature at the top station (Fig. 3e), indicating that strong inversions can occur irrespective of the temperature prevailing in the region.

3.3. Temporal patterns of the formation of CAPs, duration and cooling rates

Among all the inversions that lasted at least 3 hours during the considered period (n=70), about half of them had an intensity higher than 5 K (Table 2). For 29 % the intensity exceeded 10 K and for 6 inversions it exceeded 20 K (Table 2). On average, inversions lasted about 15 hours. The duration of the inversions was significantly correlated to their intensity and the temperature reached at the bottom station (R^2=0.69 and P<0.001; R^2=0.33 P<0.001 respectively, data not shown): the longer the duration, the stronger the intensity and the colder the temperature in the valley (Table 2). For weak inversions, i.e., lower than 5 K, the CAPs lasted on average less than 7 hours, vanishing rapidly after sunrise reached the bottom of the valley (Table 2). In contrast, during inversions stronger than 15 K, the CAPs lasted significantly longer and remained on the following day (Table 2). The mean cooling rate from the beginning to the maximum of the inversion was 0.8 K h^{-1} and the most rapid cooling rate detected was 4.4 K h^{-1} during an inversion of 12 K intensity (Table 2). No apparent relationship was found between the cooling rate and the intensity of the
3.4. Spatial configuration of CAPs

During inversions, temperature was positively correlated with elevation, the lowest points of the valley being the coldest. Temperature could deviate by more than 25 K between the lowest stations and the ones mostly above the cold pool (Fig. 4). The spatial configuration (shape and structure) of the CAP remains quite similar whenever an inversion forms, irrespective of its intensity (Fig. 4). Noteworthy during the study period, the coldest temperature was not recorded at the MeteoSwiss station of La Brevine, where the coldest temperature has been recorded in January 1987 (-41.8°C), but at two of the temperature loggers established for this study. At these two loggers, the lowest temperatures recorded were -30.5 and -32.1°C on 29 December 2014, whereas the MeteoSwiss station at La Brevine recorded -29.6°C at the same time. One of these temperature data loggers was situated at the lowest point of the valley bottom, and the other was situated significantly higher but in another concave area where another pool of cold air forms.

3.5. Are the frequency and intensity of CAPs changing under ongoing climate change?

Although mean temperature has increased by 0.41 K decade\(^{-1}\) over the period 1965-2014 in Switzerland (based on the monthly homogenized series by MeteoSwiss, data not shown), the frequency of extreme freezing events has significantly increased at the bottom of the La Brevine valley (Fig. 5). Temperatures below -20°C occurred about 13 times a year, -25°C was reached about 5 times a year and -30°C was reached about 1.6 times a year, with high interannual variability but no significant trends over the last 5 decades (Fig. 5).
Interestingly, the frequencies of the events below –20, –25 and –30°C are significantly correlated to the North Atlantic Oscillation index (NAO) (Table 3). The lower the NAO index the higher the frequency of low temperature extremes.
4. Discussion and conclusions

Readings from 46 temperature loggers in the La Brevine valley permitted us to identify spatial and temporal patterns of CAP formation in this valley. Our study showed that CAPs formed under various temperature conditions, with temperature values recorded at the top of the valley ranging from –10 to 9.9°C at the moment of maximum inversion. We showed that significant inversions occurred during 48% of the winter nights 2014–2015, and among all the detected inversions lasting at least 3 hours, 29% had an intensity exceeding 10 K and 18% exceeded 15 K. The frequency and intensity of these inversions was 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 forests covering all surrounding slopes, strong sheltering effects led to high rates of radiative cooling without air mixing from aloft. Finally, in spite of the general increase in mean winter temperature due to climate change observed throughout Switzerland, 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 index, showing the strong dependence of CAPs to atmospheric pressure rather than to 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 (Daly et al., 2010).

Although temperature inversions have been shown to occur under dry conditions (Whiteman et al., 2007), here we found rather high values of relative humidity during strong inversions. However, relative humidity values in this case have to be considered with caution, because the air humidity measurements were provided by a meteorological station situated in the valley bottom. Thus, the air humidity data originate from an air mass which has just gone through a strong and quick cooling process, increasing the relative air humidity of an air mass that may have previously been dry. Particularly in winter, with temperature ranging mostly between -10 and +10 °C at the start of the cooling process, relative humidity rises fast in an air mass cooled by 10 or 20 K.

The cooling was recorded at mostly the same time 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, thus avoiding the possibility of cold air drainage from higher surrounding slopes. Consistent with this hypothesis, no abrupt decreases in temperature were observed in the upper part of the valley slopes during temperature inversion. 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 the evergreen conifer species Picea abies cover all the slopes of the valley, and may have enhanced the sheltering effect by reducing the wind speed and consequently the vertical mixing, as has been previously reported for other sites.
Radiative cooling rates are highly dependent on the sky-view factor as outgoing longwave radiation loss increases 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 relatively high cooling rates from the beginning of the inversion to its time of maximum intensity; cooling rates averaged 0.8 K h\(^{-1}\) with numerous inversions exceeding 2 K h\(^{-1}\) and several ranging up to 4.4 K h\(^{-1}\). This result is typical for a narrow valley with strong sheltering effect 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). During all the study period (DJF), a thick snow pack covered the valley bottom, which we suspect to have enhanced CAPs formation compared to other seasons, when herbaceous vegetation covers the ground, decreasing surface albedo. Further investigations would be necessary to characterize the seasonal variation and intensity of CAPs during an entire year.

The lack of connection between the temperature measured outside of the valley and the intensity of the inversion stands in contradiction to the expectation that very cold conditions should allow 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, they 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 bottom of the valley 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 outside the valley 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.

4.2. Climate change has not affected the frequency and intensity of extreme events in the La Brevine valley

Local but intense CAPs that lead to extreme freezing events in narrow valleys, such as those presented in this study, have substantial impacts on vegetation (Blennow and Lindkvist, 2000), in particular by affecting species phenology and ultimately plant fitness, especially if they occur in late spring when vegetation is more sensitive to frost (Vitasse et al., 2014). Very few studies have investigated 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 20th century and particularly since the 1970s in Switzerland as a result of the ongoing climate warming (Rebetez and Reinhard, 2008), no trends of warming during winter were observed in La Brevine, either in minimum temperature or in the frequency of extreme freezing events. The frequencies of temperatures below –20, –25 or –30°C showed no significant trends
since the 1960s but were correlated with the NAO index calculated in winter, corroborating their strong dependence on the atmospheric pressure conditions. Positive NAO index has 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 is 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.

These extreme low temperatures for the region result from strong CAPs frequently occurring in the valley and dominating the general warming signal. We therefore confirm that in such narrow valleys, CAPs are decoupled from the free atmosphere temperature and escape from the regional trend of warming predicted by general circulation models (GCMs). This result has implications in agroforestry because a general increase in mean temperature is likely to release the dormancy of woody species earlier in late winter/early spring, leading to earlier dehardening of plant tissue (Vitasse et al., 2014) at a time when strong inversions due to CAPs can still occur.

Acknowledgements

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Table 1 Number of significant normal (i.e., negative) lapse rates, significant inversions (i.e., positive lapse rates) and non-significant lapse rates detected for the winter days 2014-2015 along with their mean values.

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<th>Number</th>
<th>fraction (%)</th>
<th>Mean lapse rate (K 100 m$^{-1}$)</th>
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<tr>
<td>Normal lapse rate (lapse rate &lt; 0)</td>
<td>26</td>
<td>29</td>
<td>-0.58</td>
</tr>
<tr>
<td>Inversions (lapse rate &gt; 0)</td>
<td>43</td>
<td>48</td>
<td>+4.93</td>
</tr>
<tr>
<td>Non-significant lapse rate</td>
<td>21</td>
<td>23</td>
<td>+0.12</td>
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Normal lapse rates and inversions were determined by using linear regressions between temperature values recorded across the 46 loggers and elevation at the time when temperature was recorded as the coldest at the bottom logger.
Table 2 Number, duration and intensity of all temperature inversions observed during winter 2014-2015 in the La Brevine valley, along with the associated minimum temperature recorded at the bottom logger and the cooling rate between the beginning of the inversion and its maximum intensity.

<table>
<thead>
<tr>
<th>Inversion intensity [K]</th>
<th>Number [%]</th>
<th>Duration [h]</th>
<th>Minimum temperature at the bottom logger [°C]</th>
<th>Mean cooling rate [K h(^{-1})]</th>
<th>Maximum cooling rate [K h(^{-1})]</th>
</tr>
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<tbody>
<tr>
<td>0-5</td>
<td>38</td>
<td>6.8</td>
<td>-11.7</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>5–10</td>
<td>12</td>
<td>12.7</td>
<td>-13.7</td>
<td>1.2</td>
<td>2.6</td>
</tr>
<tr>
<td>10–15</td>
<td>8</td>
<td>19.6</td>
<td>-19.1</td>
<td>1.4</td>
<td>4.4</td>
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<tr>
<td>15–20</td>
<td>6</td>
<td>37.9</td>
<td>-22.7</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>&gt; 20</td>
<td>6</td>
<td>38.9</td>
<td>-30.5</td>
<td>1.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Sum/mean</td>
<td>70</td>
<td>14.7</td>
<td>-6.9</td>
<td>0.8</td>
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We selected only inversions longer than 3 hours. The intensity of the inversion was computed as the deviation between the temperature value measured at the bottom logger and the expected value using the top logger as reference and a lapse rate of \(-0.58\) K 100 m\(^{-1}\) (cf. Fig. 2).
Table 3 Pearson coefficient correlations between the annual frequency of extreme freezing events below various thresholds recorded at the bottom of the La Brevine valley and the NAO index during the period 1959–2014.

<table>
<thead>
<tr>
<th>Threshold [°C]</th>
<th>r</th>
<th>P value</th>
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<tbody>
<tr>
<td>&lt; –20</td>
<td>-0.47</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>&lt; –25</td>
<td>-0.49</td>
<td>&lt;0.001</td>
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<tr>
<td>&lt; –30</td>
<td>-0.36</td>
<td>=0.004</td>
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Figure captions

**Fig. 1** Map of the La Brevine valley with location of the data loggers and MeteoSwiss weather stations.

**Fig. 2** Methodology applied to determine the intensity of the inversion.

As an example to illustrate the method, we used a temperature of 0°C at the top logger and -2.8°C at the bottom logger, which corresponds to the mean lapse rate found during inversions (+4.93 K.100 m⁻¹).

**Fig. 3** Correlations between daily maximum inversion intensity and various climatic parameters.

a, Wind speed; b, Atmospheric pressure; c, Relative air humidity; d, Relative sunshine duration; e, Temperature at the top logger. Triangles represent significant normal lapse rates, circles indicate significant inversions and squares indicate non-significant lapse rates. Except for temperature at the top logger, all parameters were extracted from the MeteoSwiss weather station located at the bottom of the valley.

**Fig. 4** Spatial distribution of temperatures for weak, moderate and strong temperature inversions during winter 2014-2015. Black dots represent the 46 temperature loggers.

**Fig. 5** Annual frequency of extreme freezing events recorded at the bottom of the valley during the period 1959–2014.

Solid line, frequency of temperatures below –20°C; dashed line, frequency of temperatures below –25°C; dotted line, frequency of temperatures below –30°C. 5-year moving windows from 1959 to 2014.
Figure 1
Figure 3

-a: Wind speed [km/h] vs Temperature inversion [K] with R² = 0.16, P < 0.001
-b: Atmospheric pressure [hPa] vs Temperature inversion [K] with R² = 0.1, P = 0.001
-c: Relative air humidity [%] vs Temperature inversion [K] with R² = 0.08, P = 0.005
-d: Relative sunshine duration 9–10 am [%] vs Temperature inversion [K] with R² = 0.35, P < 0.001
-e: Temperature at the top logger [°C] vs Normal lapse rates, Significant inversion, Non significant lapse rates

Legend:
- △ Normal lapse rates
- ○ Significant inversion
- □ Non significant lapse rates
Figure 5
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\[ R^2 = 0.16 \quad P < 0.001 \]

\[ R^2 = 0.1 \quad P = 0.001 \]

\[ R^2 = 0.08 \quad P = 0.005 \]

\[ R^2 = 0.35 \quad P < 0.001 \]

\[ R^2 = 0.03 \quad P = 0.064 \]

213x221mm (96 x 96 DPI)
The graph shows the frequency of events versus year, with different lines indicating different temperature thresholds:

- **Events < -20°C** where $R^2 = -0.01$ and $P = 0.58$
- **Events < -25°C** where $R^2 = 0.01$ and $P = 0.441$
- **Events < -30°C**

The graph indicates a decrease in frequency over time for all temperature thresholds.