



The importance of topography in the formation of cold-air pooling in urban spaces. The example of the city of Coimbra (Portugal)

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Abstract

The aim of this paper is to analyze the existence of cold-air pools on anticyclonic nights in a narrow urban valley where three hospital units and a road with intense traffic are located and where the slopes associated with proximity to a medium-size mountain introduce different factors from that observed in other valleys where this phenomenon forms on cold, calm nights. On these nights, it is observed that cold-air pools develop in the valley just after sunset, in opposition to the ridge that dominates the valley (thermal belts), and it is found that their formation, development, and disappearance after the first hours of the day is a daily phenomenon. Using fixed data loggers and portable data loggers on the surface and at altitude coupled to a UAV (drone), it was possible to calculate the variation of the air temperature (as well as to locate the inversion layer) in different sectors defined along the valley. The finding of temperature oscillation along the longitudinal profile and at altitude, reflects a double source of feeding: in-situ irradiation, and the air draining down the slopes of the massif.

1 Introduction

In recent decades, the debate on the impact of urban space on the modification of the local climate, with repercussions on bioclimatic comfort, air quality and energy consumption, has significantly advanced the understanding of the bases of urban climate. These, in turn, are increasingly seen as a multidisciplinary area that nowadays encompasses a broad scientific knowledge spectrum (Oke 2006; Oke et al. 2017).

The perspective of planning the urban and peri-urban (or suburban) spaces of a territory must take into account an entire holistic and integrated process. This must be addressed by balancing the different climatic, topographic and land-use variables of this territory; with the interaction between the different spatial mosaics in place. The sustainable city, which is the goal, must be seen as a human settlement built

by a society aware of its role as a transforming agent of spaces, the relationship between which should be evidenced through a synergistic action between ecological prudence, energy efficiency and socio-spatial equity (Romero 2007; Farr 2013; Kazantseva et al. 2021).

At the top and on the urban microclimate scale, the consensus seems to be that these elements are influenced by factors such as construction density, urban morphology, topography, soil waterproofing, vegetation and the proximity to bodies of water. These factors that are responsible not only for thermal and hygrometric spatial contrasts, but also have direct effects on wind fields (Oke et al. 2017). This is undoubtedly one of the preponderant factors in medium-sized cities where the urban settlement is set in a rugged topography.

The analysis of the literature on the subject shows that most papers and work on urban climate are slanted towards the existence or dynamics of “heat islands” in urban spaces, (e.g. Oke et al. 2017). However, taking into account the morphological aspects that characterize the settlements of some Portuguese cities, as well as their growth in recent decades, there is another aspect that should be understood as having significant importance in the urbanism of some of these cities: cool-air pooling. References on this phenomenon call for an enticing reflection in the context of its application to urbanism and urban design, when the urban climate is seen as one of the focuses of the work carried out in the context

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of resilience to climate change in urban space (Alcoforado et al. 2005). There is an evident difference in the representativeness of works on cold-air pooling and those on “urban heat islands”: the former are not very abundant and have been fundamentally carried out in rural spaces or suburban sectors (Price et al. 2011; Vosper et al. 2013; Clements et al. 2003; Sachsen et al. 2013; Burns & Chemel 2014); Hughes et al. 2015; Jemmett-Smith et al. 2018), while the latter are numerous and span all latitudes (Oke et al. 2017; Peres et al. 2018; Chieppa et al. 2018; Dian et al. 2020)¹.

Cold-air pooling is a particular phenomenon in the stable boundary layer (SBL), associated with anticyclonic nights of strong atmospheric stability, and although it has already been analyzed at length, the mechanisms behind its formation are not fully understood (Bodine et al. 2009; see Vosper et al. 2013). It is evidenced by the existence of warmer air at a higher altitude, creating a situation of thermal inversion, primarily caused by the cooling of the surface (Yoshino 1984; Lopes 1995). This inversion of the thermal gradient takes on a more complex nature in urban spaces, since it will prevent the polluted air of anthropogenic origin from dispersing at altitude, leading to an accumulation of pollutants in these sectors and the resulting public health problems associated with them (Sheridan et al. 2013; Jammatt-Smith et al. 2018).

In extreme circumstances, such as those occurring in tectonic openings with downstream strangulation, the temperature difference between the valley bottom and the top thermal belts may be as high as ten degrees (Ganho 1998; White-man et al. 2001; Clements et al. 2003; Zängl 2005; Marques et al. 2008). In the Portuguese case, the analysis of the cold-air pooling phenomenon seems to show a dichotomy between the case of the Lisbon region, where the focus was on predominantly rural spaces (Alcoforado et al. 1993; Lopes 2003), and Coimbra, where a valley that was once a peri-urban sector became an inner urban space (Ganho 1998; Marques et al. 2008). Still, morphological constraints were the fundamental factor in both territories. In both territories, the fundamental factor is related to morphological constraints. As we know, the identification of cold air paths for large areas is a difficult process. Given its spatial dimension, it is hard to cover large areas in a city (Grunwald et al. 2020; Grunwald & Weber 2021) and in Coimbra we are working in a valley within the urban perimeter, which makes this research very interesting (Vosper & Brown 2008; Vosper et al. 2013).

The mechanisms for understanding the formation of cold-air pooling have long been discussed, although katabatic or drainage flows are referred to as their main cause (Bodine et al. 2009). However, it is not clear how important their role is in the thermal balance in the lower sector of a valley (Vosper et al. 2013). Still, double-feeding is usually mentioned in-situ irradiation and the feeding of cold air that drains down the slopes. According to those authors, drainage flows occur when the radiation heat loss of the slope brings cold air into the surface layer, causing the cooling of the temperatures below. The resulting horizontal buoyancy gradient drives a flow in the downward direction, transporting air towards the bottom of the valley (Vosper et al. 2013).

In fact, Goldreich’s article (1981), using the concept of “urban-topographic climatology”, highlights the necessary interrelationship between topography and urban climate, as well as the occurrence of thermal inversions on anticyclonic nights. The formation of cold-air pooling in valley bottoms or topographically depressed areas has been closely linked to the topography that influences the cold air drainage processes that occur along the slopes (Yoshino 1984; Bodine et al. 2009; Oke et al. 2017) and the fluctuating thickness of these pools is due to the fluctuation of the thickness of these pools is due to the greater or lesser intensification of drainage and soil roughness (Yoshino 1984; Lopes 1995).

The understanding of areas prone to cold-air pooling in urban spaces, along with the recognition of their importance in urban planning in this situation, makes it possible to identify the areas of greatest bioclimatic discomfort, when there are cold waves, as well as those conducive to the formation of frost, ice, and fog (Yoshino 1984: 239). This fact was also found in the city under study (Pinto et al. 2008; Santos 2022) where, consequently, there are consequently sectors with a potential for a greater retention of pollutants.

Thus, and still in a peri-urban context, in 1998, Nuno Ganho identified the existence of intensification of atmospheric stability that characterizes anticyclonic nights in the region and the cold-air pooling in the northern valleys of the city of Coimbra on anticyclonic nights. Coimbra is a medium-size Portuguese city (with around 100.000 inhabitants) located on the coast of central Portugal and its territory is morphologically marked by sharp contrasts in the landscape (Fig. 1). To the east there is a low-mountain sector — the “Maciço Marginal de Coimbra” — with altitudes slightly above 500 m, formed by metasediments and with significant slopes (>25°). In turn, the central and western sectors and consist of of a large alluvial plain, surrounded by limestone, marl and sandstone sectors that dominate these alluvial sectors, with altitudes not exceeding 12 meters (Rebelo 1999; Cordeiro 2021). The boundary between these two units is very rigid, as evidenced by the strong tectonic control. Also of structural genesis, we highlight the rigidity of the

¹ Moreover, their relative importance can be seen through the approach of Oke et al. (2017: 343), in which the reference of “pooling of cool air” appears associated with the factor “topography”, in the chapter of “Geographical Controls”, while the “urban heat islands” are dealt with in a chapter of their own, a fact that seems to show their relative importance in the context of urban climatology.

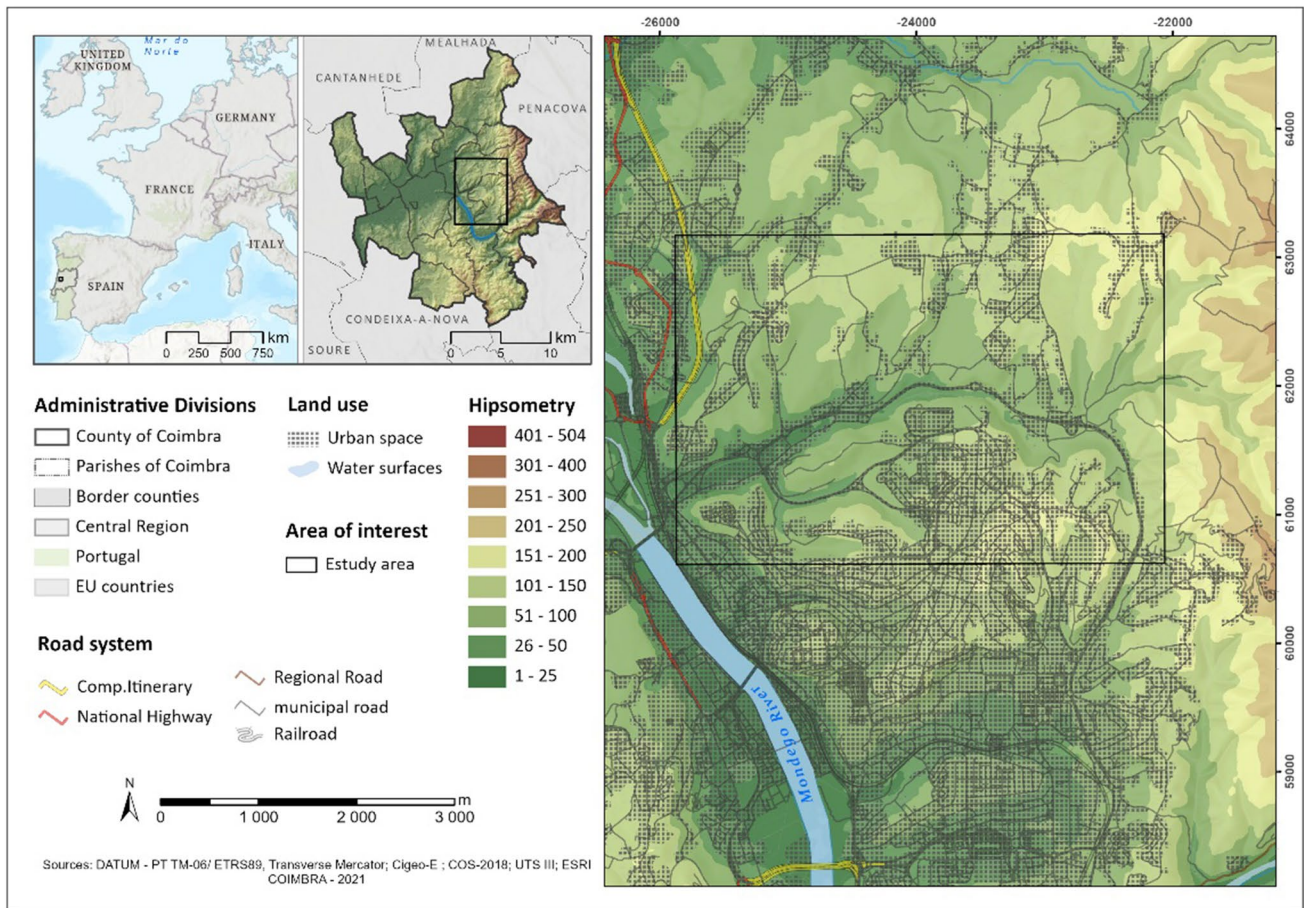


Fig. 1 Geographical setting of the study area- on the Iberian Peninsula; in the Central Portugal; in the municipality of Coimbra

contours of the valleys of the right bank of the Mondego River, namely that which is the object of the study: the Valley of Coselhas (E-W). This stream runs through a narrow valley with thalweg altitudes between 12 and 122 m and presents in some sectors small tectonic control openings in some sectors. Its top is dominated by 100m (downstream) and 160m (upstream) plateaus — the ridges — which have been densely urbanized since the mid-last century (Cordeiro 2021), and where the “urban heat island” form is significantly developed significant development (Ganho 1998).

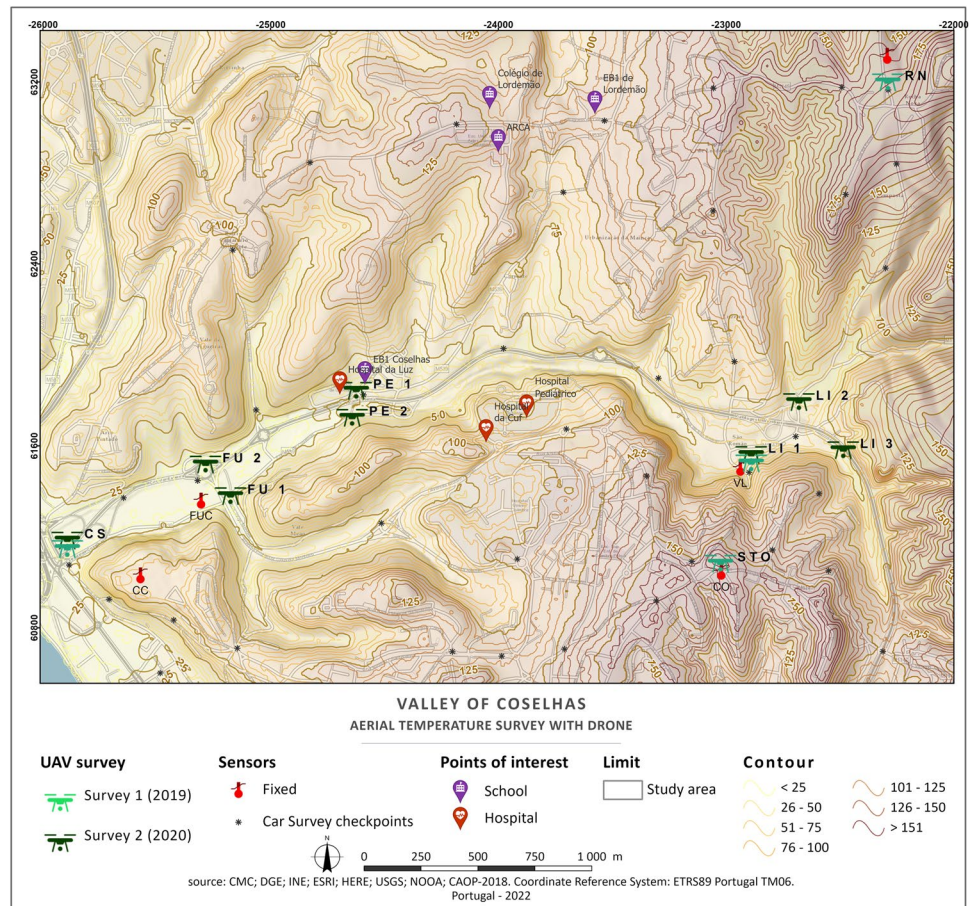
Thus, it is in this very particular morphological context of a mid-sized city in central-coastal Portugal, where three large health units and two schools were built in the last decade, that this valley becomes an interesting laboratory of analysis; in the framework of the research on resilience to climate change in the urban space. The present analysis aims to carry out a first attempt at a three-dimensional understanding of the cold-air pooling in an urban valley (and its relationship with the urban expansion experienced in the meantime), by obtaining real values through the integration of different methodologies.

2 Objectives and methodologies

The need for responses in the context of urban planning in the expectant sectors of an average city, as well as the search for preliminary and exploratory data for the development of a broader project on adaptations to urban climate change, has encourage the exploration of for different paths in the monitoring and analysis of one of the least explored climatology phenomena in the urban space (Alcoforado et al. 2009; Grimmond et al. 2010; Reis and Lopes 2019).

The main objective of this paper thus, the main objective is to try to understand the changes in the cold air mass at altitude occurring at night in a narrow valley in the urban space of Coimbra, with measurements being made in the early hours of the day. At the same time, we tried to delimit the altitude of the inversion layer and its oscillation; in terms of thickness and shape in the different sectors of this valley, particularly its relationship with the location of different health facilities and schools built in the meantime. Cold air lakes were identified at altitude and at the surface, especially at a small-scale level in a valley with steep slopes and where the dynamics of the cold air flow contribute to a dependence

Fig. 2 Location of fixed probes and drone descent locations in both campaigns



of cold air along the valley. The winter campaigns of 2020 and 2021 sought not only to identify the thickness of the cold air lakes, but also the spatialization of the thermal belt of the flattened levels that dominate and delimit the valley, drawing heavily on pre-existing knowledge from previous campaigns (Ganho, 1998; Marques et al. 2008).

The methodology used was to reinforce the differentiated approaches used previously. Thus, fixed sensors were used for data collection (Tinytag Plus 2 - TGP-4500) — both at the bottom of the valley and at the levels that dominate it, creating two axes perpendicular to the stream (Fig. 2): two at the bottom of the valley — at the confluence with the Mondego River Valley at 17 m of altitude (FUC), and in the sector upstream from the narrows of the Linhares valley, which lies at an altitude of 60 m altitude (Valley of Linhares - VL). The mobile sensors were used both on the surface and at altitude. The methodology used for sensor readings performed by driving on different nights of the coldest period of the year (for a maximum of 90 min, stopping two minutes before recording at each point in Fig. 2) was purposely the same as in previous campaigns (Marques et al. 2008).

The methodologies associated with the use of the drone and the temperature sensor (Tinytag Plus 2 - TGP-4020) are presented as alternative and central elements in this

approach. It involves actual second-by-second temperature recordings, creating vertical profiles at altitude with continuous descent (at a speed of 1 m/s). The sensor is positioned 10 m below the drone, so as to avoid interference from the rotor vortex. The lift of the drone and sensor was carried out at a distance of more than 10 m from the point of descent and with a two-minute stop at the top, so that all sensor elements are stabilized and record the values more accurately. The response rate of all the temperature sensors used is $\pm 0.01^\circ\text{C}/^\circ\text{C}$ with a reading resolution of at least 0.02°C , allowing us to rely on the values and the calibration ability were made. For this analysis we were able to use the drone to calculate the wind through the drone at different altitude intervals. Thus, wind is calculated using the angle and the speed of the aircraft at each point of the flight (Wind Algorithm: v2.2 from AIRDATA).

Between the routes to each place where the temperature profiles were taken with the drone, a quick trip had to be made so as not to waste time in the data collection period. In total, the routes did not exceed 1h in total between the first and the last temperature collection. The same methodologies was applied to car routes.

Five fixed data loggers (Tinytag Plus 2 - TGP-4500, with the same response rate, $\pm 0.01^\circ\text{C}/^\circ\text{C}$) were positioned

in different morphological settings of the valley, with sequential temperature time recording (Fig. 2): two at the bottom of the valley – at the confluence with the Mondego River Valley at 17 m of altitude (FUC) and in the sector upstream from the narrows of the Linhares valley, which lies at an altitude of 60 m (Valley of Linhares - VL). Three sensors were also installed in sectors of ridges: one to the north (Rocha Nova - RCN, at an altitude of 170 m), and the other two at the levels that overlook the valley from the south (Olivais Graveyard - CO) at 162 m, (a similar elevation to the one of the one installed on the north bank) and CC, which is at 80 m (closer to the Mondego Valley). This distribution took into account the sun exposure and potential ventilation identified in the 2008 campaign for the different locations of this sector of the territory were taken into account. The places where the descents with the drone were carried out (some of these close to fixed sensors) - LI 1 (Linhares), CS1 (Casa do Sal) and RN (Rocha Nova) present different nuances in stage of analysis of results. This is very much in accordance with the objectives sought: dispersion through the valley bottom and ridges in the 1st campaign — February 2019 — and a concentration only on the thalweg (and nearby sectors) in the 2020 campaign. The latter presented itself in the moments before the slopes of the valley were exposed to the sun. Thus, it is possible to quickly make different thermal profiles, for each chosen period of the first moments of the day, mid-morning and the theoretically warmer period of the day to identify any changes in the vertical structure of the friction layer on certain days and in different parts of the city. It is also possible to ascertain and to measure the thickness of the surface/layer of inversion during the morning, in addition to the identification of the thickness of the cold air pool in the different sectors of the valley.

Regarding the spatialization of surface temperatures, the construction of cartograms, we follow an existing model; in which the correlations between the horizontal location and temperature data are considered the main source for the geostatistical analyses (collected or obtained via car or pedestrian routes) in this study. Initially, a Kriging calculation was used based on the theory of the variable regionalized variogram in order to estimate data values in three dimensions. In general terms, this calculation estimates the magnitude and spatial scale of the input data. In other words, the number of records, the size and the layout are the main data sources for processing, in that accuracy depends on the number of comparisons between the data (Oliver and Webster 1990; 316). The basis for linear models is simple or ordinary kriging (Gribov and Krivoruchko 2020; 62) and its development is mainly linked to the grouping of local estimation methods, including

simple or ordinary kriging, co-kriging, universal kriging and disjunctive kriging, based on the regionalized theory of estimates (Oliver and Webster 1990, 317). Although there are a number of processing techniques associated with the use of kriging, we will use simple kriging in this study. Second (Gribov and Krivoruchko 2020: 2) this method for geostatistical interpolation merges geostatistical models with estimated values; in Euclidean distance metrics for projected data. This method was chosen for the geostatistical interpolation of points because it has the ability to assume input values, coordinates and temperature (x , y and t), with characteristics similar to the data produced for the study.

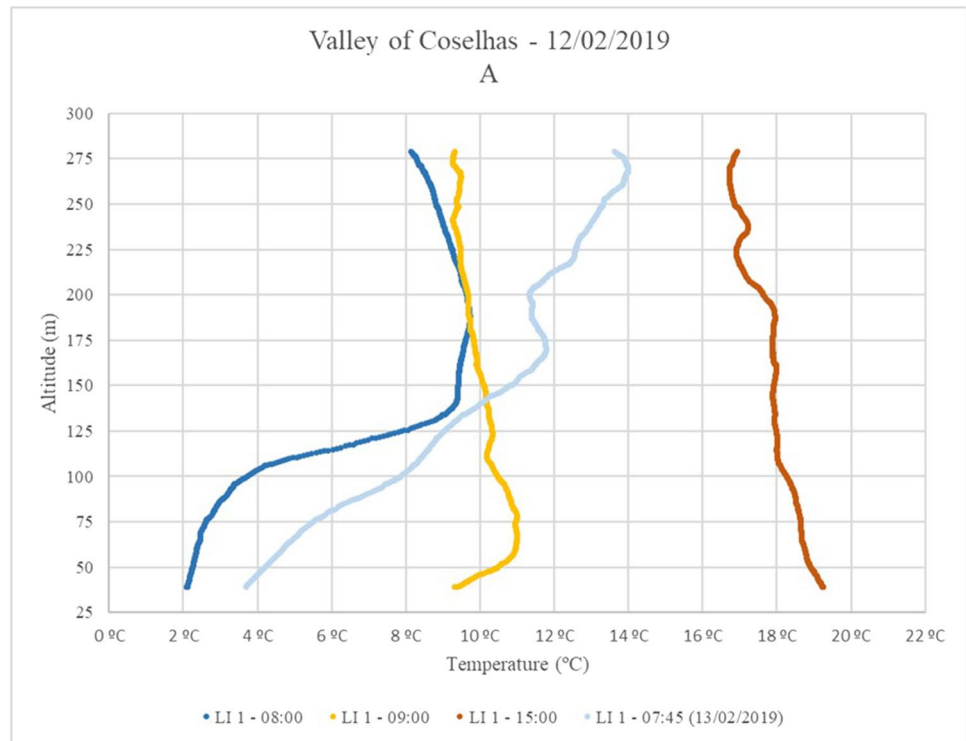
3 Cold-air pooling in the urban and peri-urban context of the city of Coimbra: data analysis

The existence of three important hospitals and health units (and the possibility of building a fourth unit), combined with the urban growth observed in the last decade; and the previous knowledge of the existence of the cold-air pooling in this predominantly east-west valley made us choose a different approach from those used previously. The recording of temperatures in a sequential profile of 200 m of the stable boundary layer was carried out through descents made with the support of a drone with a coupled sensor. This enabled the mapping enabled the making of several temperature profiles in a 60-/70-min period (between 8 and 9 surveys) and made it possible to repeat the process throughout the day and on different days of the year. Based on these profiles, the aim is to produce a three-dimensional visualization offering new perspectives of analysis.

In addition to this new perspective, the approaches were maintained using the routes made by car, as well as the installation of 5 fixed data loggers, in different topographic and land-use contexts², which record temperature and humidity throughout the year. After collecting the data using the different aforementioned methodologies, the intended preliminary approach looks at different aspects: (a) changes in the cold air mass throughout the day; (b) temperature changes in accordance with topographic positioning; (c) the three-dimensional context of cool-air pooling in the topography and its importance in the perspective of urban design in these areas of the city.

² There is, at the present time, a network of 14 data loggers distributed throughout the city, and by the end of 2020, the number of environmental measurement stations (climate and pollution) is expected to double.

Fig. 3 Evolution of cold-air pooling throughout the day (February 12–13, 2019 – local time)



3.1 Changes in the cold air mass throughout the day

The existence of cold-air pooling in this valley with particular urban characteristics has long been known about (Ganho 1998). It forms in the moments after sunset and is fed during the night, as shown by Yoshino (1984)³. As mentioned, one of the objectives of this paper is to observe the changes in cold-air pooling and the inversion layer in the first moments of transition between the night and post sunrise. Therefore, in addition to the data from the fixed loggers, the drone was lowered at 7 a.m. and again at 8 a.m. (the first hours of the day), and made further descents at 3 p.m. The goal was to note the decrease in thickness and disappearance of the layer during the day, as well as the development of the whole process throughout the following night (Fig. 3).

Although somewhat differentiated in terms of gradient, the profiles of the early hours of February 12–13, 2019 make it possible to see that cold-air pooling at 0700 LT was about 100 m thick at LI 1 on both days. However, cold-air pooling at 0800 LT was already 70 m thick, as its position in relation to the inversion layer was observed at practically the same

altitude of the surrounding ridges—STO and RN (Fig. 3). The difference in the profiles appears to show that, on February 12, the temperature is slightly lower on the surface than at the same time on the next day (5.55°) and there was a more significant gradient next to the surface (colder air). On February 13, the profile shows a gradual warming for the inversion layer, although it is located at virtually the same altitude – 120 m. One hour later — at 0830 LT — and already with radiation received in the slope with southern exposure, there is a significant decrease in the thickness of the cold-air pooling, which is only about 30 m thick. At 1500 LT, the profile reflects a total absence of cold air near the surface, with a thermal gradient that is assumed to be close to what is expected.

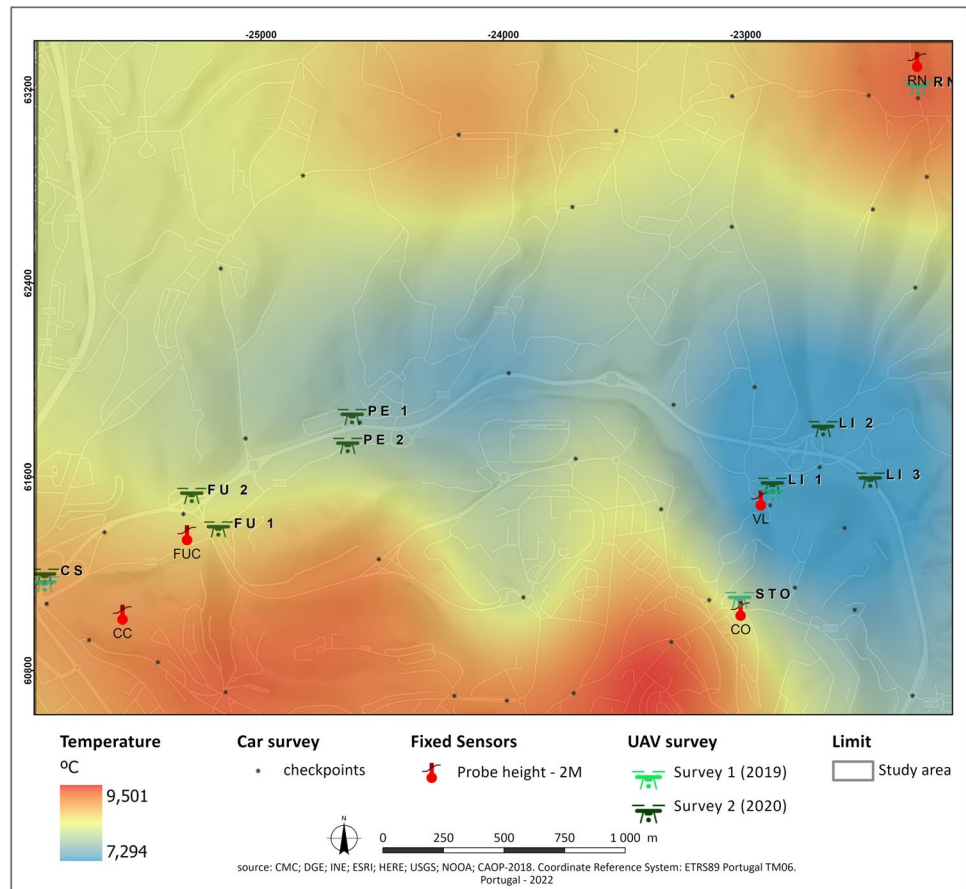
3.2 Temperature variability as a function of topographic positioning — the thermal belts of the ridges

Following the work carried out in 1998 and 2008, the existence of colder thermal belts was again observed in the flattened levels that dominate the valley, in contrast to the accumulation of cold air from the bottom of the valley, in the line referred to by Yoshino (1984: 239; see Lopes 1995) and Vosper et al. (2013).

The confirmation of the existence of these thermal belts is related to the understanding that has always been sought in terms of the bioclimatic comfort of the ridges, which was empirically present in the genesis of Coimbra's own

³ After sunset, the thermal inversion near the surface begins to be observed, not only because the radioactive balance of the surface is negative—the absence of solar radiation and irradiation losses of large infrared wavelengths—but fundamentally being fed by the drainage of heavier cold air throughout the night along the slopes and which, according to Lopes (1995), presents itself as intermittent.

Fig. 4 Thermal belt surrounding the cold-air pool of Coselhas (data obtained on 12/12/2019, 2200 LT)



urban growth in the late nineteenth century and the first half of the twentieth century. This was evidenced by the development of residential areas on the plateaus dominating small tributaries of the Mondego that flow through the city (Cordeiro 2021). From the point of view of urban design, the response to the bioclimatic comfort that these spaces offered for urban expansion (in terms of ventilation and radiation), made these ridges privileged spaces for the development of residential areas for the middle and upper social classes. In fact, the thermal belts observed along these levels are visible not only from the statistical parameters of the time series; but also from the cartograms associated with the conducted car-routes and vertical profiles. In this particular case, the profiles of the thermal gradient of the ridges are quite different from those of the valley bottom, with differences as large as 8°C at the coldest hours of the day (Fig. 4 and Fig. 5).

There also substantial differences between the valley bottom and the plateaus on anticyclonic nights — nearly 10°C (on December 12, 2007) between points STO and LI 1 — a difference of 104 m in altitude and a time-distance by car of under 3 min (see Fig. 2). Regarding the ridges, both morning and afternoon profiles show the expected regularity of the thermal gradient.

This context is reinforced by the analysis of Fig. 2 which demonstrates the existence of thermal variations in the 3 places where the fixed sensors are located (a transverse axis in the valley). In this case, we will analyze the absolute minimum, mean and maximum values recorded daily (24h) during February 2019, coinciding with one of the temperature surveys obtained with the drone. The fixed sensors were programmed to record temperatures every hour, so they also recorded the temperature amplitude i.e., the maximum and minimum values, during this interval (1h). Hence, the graph was formatted so that we could organize the data in this interval and compare the different locations of all temperatures. This was done by averaging all the included temperature values, the values at the exact time recorded by the sensor and those recorded during the 1h interval, as well as all maximum and minimum values during this period.

When analyzing the values of the sensors located on the highest points of the hill, at Olivais (CO) and Rocha Nova (RN), we find that, when compared to FUC, the cold air accumulation oscillates less in terms of the average minimum temperatures between Q1 and Q3.

In summary, and in general, the temperature values in the FUC show greater variation, with a tendency to accumulate cold air that is represented by predominantly cooler

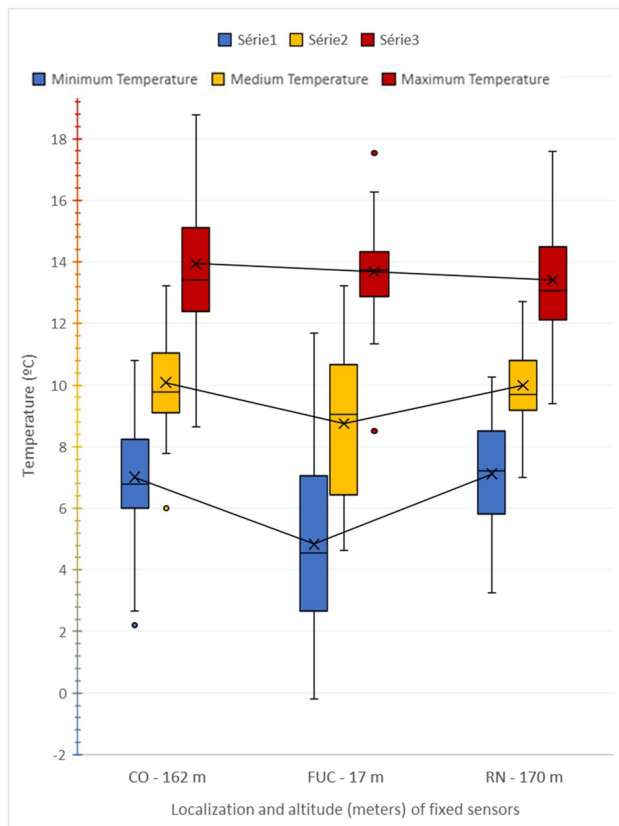


Fig. 5 Cross-valley transects between our 3 fixed sensors

locations. By contrast, in CO and RN, we note that temperatures are also homogeneous but tend to be higher than those of the first sensor (based on average and maximum temperature values).

3.3 Vertical structure of cold-air pooling on winter nights

The analysis of the profiles collected in the early morning hours of 19 February 2020, a campaign focused entirely on the valley bottom, clearly shows the existence of cold-air pooling and a sizeable layer of inversion throughout the valley (Fig. 6). The objective was to delimit the inversion layer, and measure the thickness of the cold-air pocket in the different sectors of the valley. Eight drone descents were made in the thalweg of the stream, both longitudinally and transversely, according to the following 4 axes — CS, FU, PE, and LI. This created a network offering a significant amount of data that will be further associated with the observed results of fixed probes of the valley and ridges, as well as with the information wind information collected in 7 levels spaced 30 m vertically. And like the previous campaign in the proximity of the open valley of the main river, the analysis of the profiles again shows that the CS reflects a slightly

higher temperature throughout the descent in relation to the others. Its profile reflects a more attenuated gradient and it is only in the 30 m near the surface that a breeze (blowing under 5 km/h from a southern direction) denounces the lake of cold air (Fig. 7)⁴. The temperature in the longitudinal direction of the valley is always lower moving from downstream to upstream, showing that the intensity of the cold-air pooling assumes a greater importance in the valley openings closer to the Marginal Massif — the largest accumulation of cold air is here probably associated here with the flows from the slopes — LI 1 and LI 2, with a slight breeze (between 0 and 4 km/h), from the eastern quadrants that is, towards the slope of the river. When analyzing the different profiles we should bear in mind that, in this campaign, data was collected at the beginning of the day — at first hour after sunrise. Although the data collection sites were all close to the thalweg of the valley, two of them were located at the base of the slope with southern exposure, receiving direct solar radiation at that hour. Thus, the PE 2 and FU 2 profiles present a warming next to the ground since the artificial ground cover heating much faster. This produces a slight change in the profiles, with the existence of a pocket of warmer air at about 10 m. The colder air mass remains over this air to be heated, but with its thickness is less significant than at PE 1 and FU 1.

In an analysis of the sector presenting the greatest thickness of the cold-air pooling — Linhares (LI 1; LI 2; and LI 3) — it is observed that this last profile, due in great part to the higher altitude (69 m) and associated with the valley morphology itself, is placed closer to the lower limit of the inversion layer. Therefore, it presents a smaller value for the thickness of cold air. In the case of LI 3 the breeze is observed up to 60 m, while above this altitude the winds already reflect the dynamics outside the shelter of the tight valley. Conversely, LI 1 and LI 2 reflect relatively close profiles (100 m apart) and present a more continuous gradient in the sector with greater northern exposure. Finally, the profile next to the slope with southern exposure shows a more abrupt rise in temperature up to 110 m, already reflecting the existence of slightly stronger winds (about 18 km/h). It is also observed the values approach each other that at the top of the profiles, ending at 190 m because they present identical temperatures. The inversion layer is very clear and

⁴ We mention here the particularity of the CS profile (located at the confluence of the river with the open valley of the Mondego River) presenting a profile with a gradient somewhat different from the profiles of the narrower sectors of the valley upstream, showing a lower influence of cold drainage air from the Marginal Massif. However, the inversion layer is at the same level as the other sites under analysis and the temperature increase at 160 m is most likely due to the existence of fog formed at night on the water plane associated with the Mondego River.

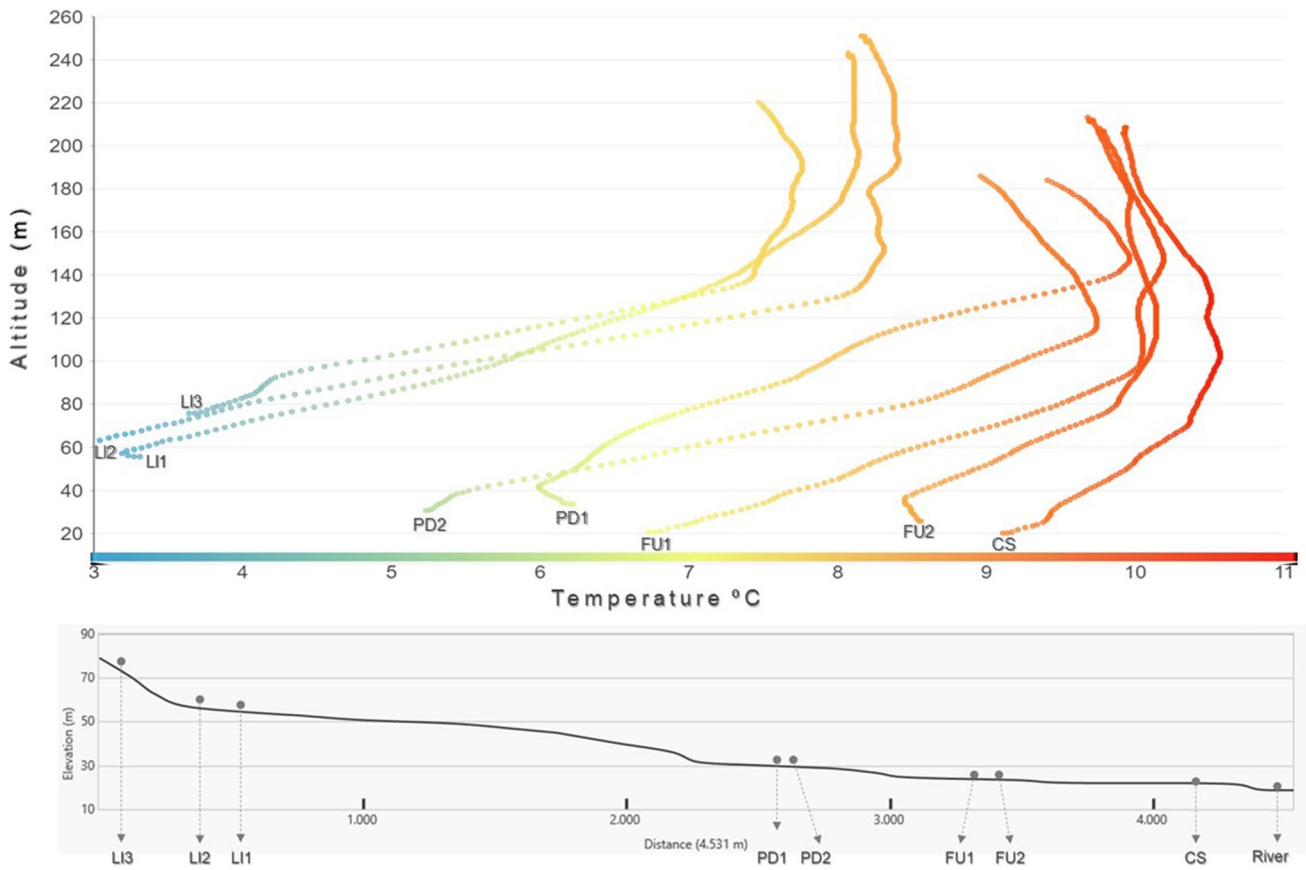


Fig. 6 Thermal profiles associated with the cold-air pool of Coselhas (19 February 2020)

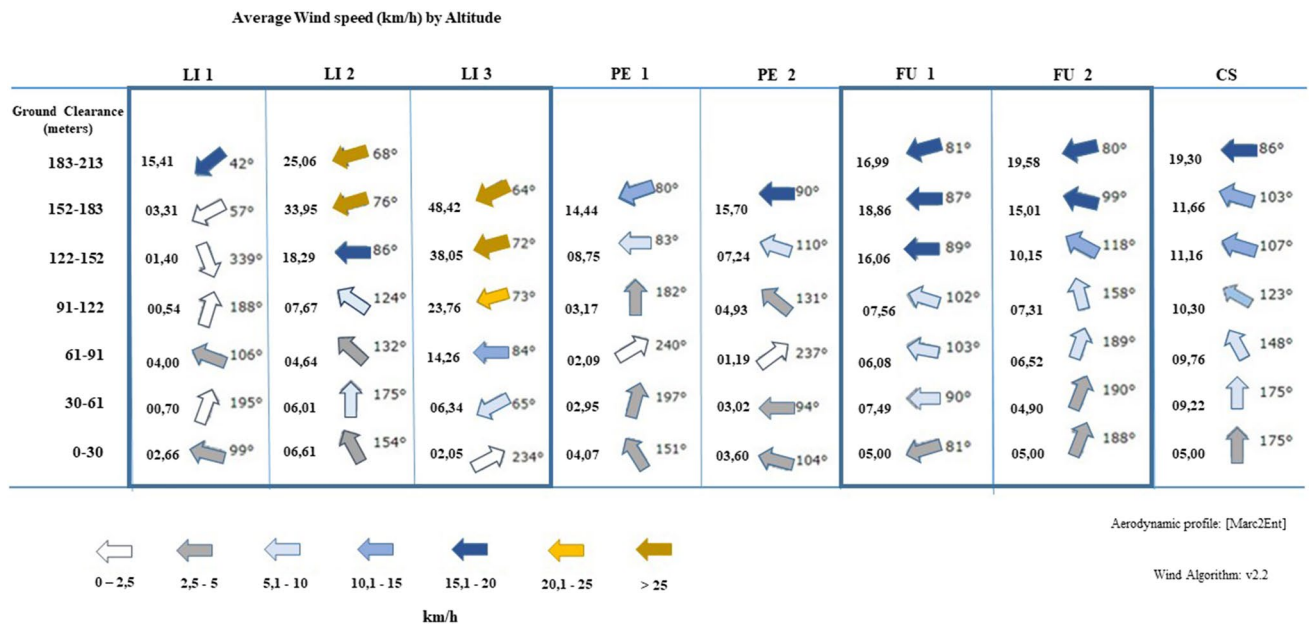


Fig. 7 Synthesis of wind directions and speed in thermal profiles associated with the cold-air pool of Coselhas

shows an identical altitudinal behaviour, except for what was expected from the first profile, due to accumulation in the tectonic “alveolus”, and the second profile, LI 3, due to its elevated position similar to that observed in semi-closed depressions (Haiden et al. 2011; Kiefer & Zhong 2011; Whiteman et al. 2010).

Slight breezes (between 0 and 4 km/h) are observed in these alveoli, and even along the innermost sectors of the tight valley. These very clearly reflect the existence of the stable cold air lake near the surface (and even in the lower 120 m), which is dominated by the ridges of the valley and in which global speed values are clearly superior and the wind assumes an East orientation, reflecting the winds associated with the general dynamics (Fig. 7).

It is also observed that the slight breezes recorded in the profiles closer to the valley axis — LI 1, PE 2 and FU 1 — present an East orientation, which seems to show the dynamics of cold and heavier air coming from the Marginal Massif.

4 Discussion of results

The understanding of the existence of cold-air pooling in small narrow valleys that delimit different sectors of the urban space of a mid-sized Portuguese city — Coimbra — becomes of special interest when new and collective investments are evaluated. This was a decisive factor for undertaking a new work on the cold-air pooling identified in 1998, by Nuno Ganho.

Since the late nineteenth century, morphological complexity has introduced particularities in the context of urbanism and urban design itself, with regard to urban climatology and the energy efficiency of buildings. Thus, noting the significant urban growth of Coimbra, particularly in its northern sector, it was decided to undertake a new based methodologies associated with fixed registers, car routes and a drone (through the use of data loggers). The campaign was based on four fundamental premises: (i) the introduction of a real three-dimensional analysis, with continuous data collection from a drone descent, enabling prompt mapping of sequential thermal profiles of sequential profiles thermal and the observation of wind dynamics; (ii) a better understanding, throughout the day and in particularly in the early morning, of the vertical structure of the stable boundary layer in a narrow valley with a predominantly east-west orientation; (iii) the role played by the morphology of the valley and its surrounding ridges in the accumulation of cold air just after sunset; (iv) the importance of urban climatology in the urban design of a sector of the city where various collective facilities — hospitals and schools — have been built and for which energy efficiency in the context of resilience to climate change in the urban space ought to merit particular attention.⁵

The initial approach was identical to the one used for more than two and a half decades by Ganho (1998), although the new tools with the new tools enabled a better visualization of the surface of the cold air lake and the thermal belt observed in the ridges that surround the valley under study. However, the primary objective of this paper was to use a methodology based on the vertical collection of temperature data of the friction layer, to try to interpret the three-dimensional grouping of cold air. This approach was supported by profiles from different valley sectors that present specific basic morphological contexts: significant slopes and the talweg itself (even near the alluvial plain of the main river); openings of tectonic genesis leading to the accumulation of cold air, and the east-west orientation.

The campaigns carried out seem to show that (1) as mentioned in the thematic bibliography, the cold air lake forms daily after sunset, fading in the morning, disappearing in the early afternoon and developing again after the disappearance of the sun's rays; (2) as the thermal profiles approach the top of the valley (LI 1; LI 2 and LI 3), the temperatures are lower (when compared with those of the open valley by the Mondego river - CS), and it is also observed that that those carried out upstream (particularly in the tectonic socket) are three-dimensionally lighter; (3) the cold air layer is thicker upstream, near the marginal massif and especially in the sectors closer to the southern slope (sheltered from the first sun rays of the day), coinciding also with the absence of wind (or the presence of slight breezes); (4) the inversion layer extends for several meters in some sectors of the valley; (5) immediately after the first sun rays, when direct solar radiation is already observed, “a small cushion” air develops on the southern exposure slope on the southern exposure slope develop of about 10 m of warmer air. The mass of cold air that had formed during the night was again observed, although with an understandable reduction in thickness (PD 1 and FU 2); (6) From the data collected by both fixed and mobile probes mobile probes, it appears that the ridges (flattened levels) that dominate these valleys with cold air masses have significantly higher temperatures (even reaching differences of 10°C).

In this context, following a set of data collection campaigns (2019 and 2020) and an altitude approach with temperature and wind records, the existence of cold air lakes

⁵ For example, in the air conditioning of public, private and residential buildings, the need for double glazing for air conditioning, the need for more recent technologies that are used in countries with more specific needs to face situations of intense cold, but also in the equation of new arboreal spaces so that the demand for thermal amplitudes is more attenuated both in the warmer period, but especially in the cold winter days.

was unequivocally demonstrated, both at the surface and at altitude. In the latter case, these lakes are found in narrow valleys along the small mountain, where there are quite significant slopes

Observing the lower temperatures at the surface and the increase in temperature up to an altitude of 100 m, in the downstream sector (CS) and 140 upstream (LI 1 and LI 2), this greater thickness reflects the existence of cold air accumulation wells accumulating at the bottom of the valleys in the steepest relief to the east. Their origin (either by the result of cooled air flows provided by topography and gravity or by radiative cooling) is reflected in this greater thickness. In these about 100 ms of air thickness, wind speed — 0 to 10 km/h — has little significance — and directions are somewhat erratic, while at altitudes above the ridges —120–140 m—the winds blow mostly from the East with speeds above 15 km/h (sometimes even above 25 km/h).

5 Concluding remarks

Within a framework of the holistic view that physical supports in urbanism should assume, the topoclimatological approach to spatial planning and urban design, takes on particular importance in its relationship with the topography. This is one of the central points of a broader project that focuses on the analysis of the adaptation and resilience to urban climate change. It is also in line with the objectives of the UN Development Agenda, particularly when the assumption of sustainability is considered in a territory where health facilities have been built and rapid urban growth has been a reality in the last decade. The political authorities of the municipality (largely due to ignorance of the phenomenon) have not expressed any concerns about the issue of energy efficiency and the influence of pollution on residents and users of public facilities operating in this area.

The existence of the cold-air pooling in urban and peri-urban valleys in a medium-sized city in central Portugal has long been acknowledged (Ganho 1998; Marques et al. 2008). It has a surface origin, with these “cold air pockets” probably being generated by radiative cooling or as the result of cooled air flows provided by topography and gravity, and accumulating at the bottom of valleys.

In essence, this paper attempts to perceive the structure of one of these areas of cold-air pooling with the support of the latest available technologies— e.g., drone; data loggers; modelling—looking for their three-dimensional visualization with a degree of detail that is thought to be even more consistent. This effort made it possible to observe differences in the thickness of these pools, the adaptation of the inversion layer to the influence of the surface morphology itself, the disappearance of these pools throughout the morning, and the differences between the slopes with exposure to

the south and north, as well as between the different sectors of the valley.

The existence of school and health facilities, a road with a significant volume of traffic in the morning, and a significant and growing residential area that has been developing in this valley explains why the interference of pollution in human health may be more important when the cold air lake is more intense and the inversion layer is at lower altitudes. In this context, and bearing in mind that topoclimatic conditions will hardly change, the entire planning process will become decisive, reinforcing the need to rethink traffic and the very expansion and typology of the buildings in this valley that has been integrated into the urban boundary of Coimbra.

Resilience to climate change in the urban space is a goal currently included in the relationship between urbanism and topography-climate associated with the United Nations 2030 Agenda for Sustainable Development and the European Union’s Sustainable Cities Agenda. Thus, this paper seeks to act as an initial local reflection on the subject in cities with a Mediterranean influence and, in this particular case, this particular case, in urban sectors with a rugged morphology. The different objectives related to climate and sustainable development underline this finding; and should be viewed as a starting point for a differentiated approach to the importance of the cold-air pooling in urban (and peri-urban) valleys, in terms of energy efficiency and the quality of life of citizens. This is especially relevant especially when there is an important development of public facilities and residential areas in these same sectors of the territories.

Code availability Not applicable.

Author contribution The author AR had a major development in the part of writing, the Introduction, Discussion of Results and Concluding Remarks and linked the various topics that were addressed throughout the article. The author AO had a determining role in the part of data collection, in the article’s global writing mainly in the Objectives and Methodologies and in the analysis and writing of the data obtained, as well as the creation of figures and graphs. The author DD carried out data collection, processing and mainly cartographic elaboration, data analysis and some work of Writing. All authors read and approved the final manuscript.

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Data availability The authors confirm that the data supporting this study are available within the article that we are trying to submit and all supplementary materials, data, and information were collected by us. All data generated or analyzed during this study are included in this published article and data sharing is currently still subject to approval after the publication of the paper.

Declarations

Ethics approval/declarations Not applicable. If necessary, this authors accept the approval/ethical declaration, consent to participate and consent for publication.

Consent to participate All authors consent to participate and approved the final manuscript.

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