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# POTENTIAL OF NIGHT VENTILATIVE COOLING STRATEGIES IN OFFICE BUILDINGS IN SPAIN. COMFORT ANALYSIS

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## ABSTRACT

Night ventilation has been applied successfully to many passively-cooled or low-energy office buildings. This paper analyses the thermal comfort achievable in office buildings in Spain according to European standard EN 15251:2007. Furthermore, the comfort level is evaluated using the Degree Hours (DH) criteria and the maximum indoor temperature. Considering the high interest of architects and engineers in the evaluation of optimal comfort condition as a function of building typology (8 typologies), glazing ratio (30% and 60%) and climate (12 different Climate Zones), a total of 192 different study cases are simulated. For every case, an optimal air change per hour (ACH) that can range from 1 to 50 ACH is then determined. The research shows that passive night ventilation should be considered as an effective strategy for all Spanish Climates to reduce cooling demand in buildings with high daily internal gains (i.e. offices buildings), improving comfort conditions and flattening peak temperatures.

## KEYWORDS

Night Ventilation, Offices, Comfort, Building Typology, Climate Zones

## 1 INTRODUCTION

Europe is dealing with a radical change in trying to improve the energy efficiency of buildings. The construction of buildings with low, almost zero, energy consumption is one of the most ambitious objectives set out in the DIRECTIVE 2010/31/UE. Because of this, the targets set in the earlier Directive 2002/91/EC and in its transposition in Spain through the Technical Building Regulation got outdated. The case of Spain has some peculiarities that need to be mentioned to understand properly the seriousness of the current situation. While the rest of states of the European Union were concentrating their efforts on defining new effective strategies to reduce their energy consumption, the late entry into force[1] of the Spanish Technical Code- *CTE* (March 2006) was, in contradiction, accompanied by a frenzied construction activity in Spain.

According to the number of construction permits registered in the Spanish Architect Association in 2006, 181702 construction permits (113041 of them new buildings) were registered. This figure has dramatically decreased ever since, in 2012 a total of 24.285 permits were counted, this decrease has been undoubtedly influenced by the gravity of the economical crisis in Spain (Table 1).

[1] *CTE* is the transposition of the Directive 2002/91/EC, EPBD: Energy Performance of Building Directive.

Table 1: Construction permits registered in Spain between 2000 -2012 (Ministerio de Fomento 2012).

| Year | Total construction permits | New buildings | Refurbishment | New offices |
|---|---|---|---|---|
| 2000 | 143902 | 89889 | 23240 | 496 |
| 2001 | 140618 | 82803 | 25952 | 521 |
| 2002 | 136544 | 82569 | 24977 | 621 |
| 2003 | 152785 | 94476 | 26793 | 583 |
| 2004 | 166437 | 102121 | 29335 | 537 |
| 2005 | 179257 | 107577 | 33183 | 585 |
| **2006** | **181702** | **113041** | **32051** | **577** |
| 2007 | 151730 | 86357 | 35610 | 625 |
| 2008 | 108332 | 50959 | 34679 | 418 |
| 2009 | 89108 | 31600 | 36947 | 426 |
| 2010 | 89788 | 29715 | 39653 | 365 |
| 2011 | 76339 | 24285 | 34209 | 229 |
| 2012 | 60670 | 18289 | 27504 | 139 |

Thus, when new strategies are to define, it is important to consider that almost all the existing buildings in Spain do not comply the minimum requirements established by the *CTE*, which means that in the near future, a great amount of recently constructed buildings should be refurbish to fulfil the new European requirements. Moreover, the recently entry into force of the energy labelling for existing buildings will highlight, even more, the necessity to act on them.

In 2007 the United Nations presented a report before the Bali Climate Change Conference (2007) exposing that Spain was at the head unfulfilling the Kyoto Protocol considering that the $CO_2$ emissions increased to 53% between 1990-2005, when a limit of 15% was defined.

A recently published report (European Environment Agency 2013) assesses that Europe is on track to fulfil the 2020 targets. However, in the case of Spain the report exposes that the registered decrease in energy consumption is due to the economic crisis more than due to the implementation of energy efficiency policies. Furthermore, it highlights that the policy package is not ambitious, lacks long-term view and will not be sufficient to bring 2020 emissions below their respective 2020 target.

On the other hand, the use of air conditioning in the building sector is increasing rapidly. In almost the 46% of the houses in the Organisation for Economic Co-operation and Development (OECD) it has been rising by 7% each year. It is reasonable to think that in the case of office buildings this figure is even higher.

Since 1990, the energy consumption in office buildings has increased by 300%. Office buildings are responsible for the 50% of the energy consumption in the building the sector and 8.6% of the total energy consumption in Spain (IDAE 2011). The 26.2% of the energy consumption in office buildings is due to air conditioning and it is expected to increase considering the proliferation of squanderer glass buildings in the last decade, since concepts related to modernity, technology and transparency are playing a predominant role in their design.

The environmental impact associated to the intensive use of air conditioning in terms of $CO_2$ emissions will have achieved the value of 18.1 Mt in Europe by 2020, far from the figure 0.516 Mt registered in 1990 (Adnot 1999). This disproportioned increase in $CO_2$ levels does not reflect the international compromise adopted with the Kyoto protocol that established a reduction of 5% in $CO_2$ and CFC emissions, habitual in air condition systems.

Intensive use of air conditioning is the result of many processes (Santamouris 2007), in particular:

- adoption of an universal style of buildings that does not consider climatic issues and results in increasing energy demands during the summer period;
- increase of ambient temperature, particularly in the urban environment, owing the heat island phenomenon, which exacerbates cooling demand in buildings;
- changes in comfort culture, consumer behaviour and expectations;
- improving of living standards and increased affluence of consumers;
- increase in buildings' internal loads.

A significant number of studies are focusing on the energy efficiency and applicability of night ventilation cooling in office buildings under various climatic conditions. In (Blondeau et al 1997) is shown a reduction of diurnal variation from 1.5 to 2°C, resulting in a significant comfort improvement for the occupants. In addition, (Givoni 1991, 1996) argues that the night ventilation techniques are efficient particularly for arid regions where day time ventilation is insufficient to ensure thermal comfort. Moreover, a study conducted in the hot humid climate of Israel argues that it is possible to achieve a reduction of 3-6ºC in a heavy structured building without operating an air conditioning unit (Shaviv et al 2001).

The role of intensive night cooling in the warm Mediterranean climates is also analysed in (Becker et al 2002) (Artmann et al 2006). In buildings with large internal loads, intensive night ventilation enables the lowest internal mass temperature and the lowest power loads throughout the whole working day. The peak power load is reduced by 13%.

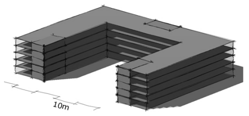
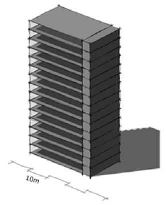
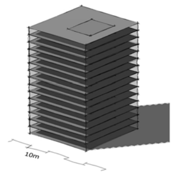
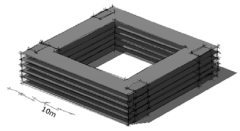
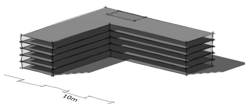
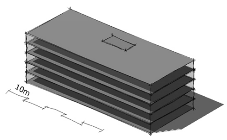
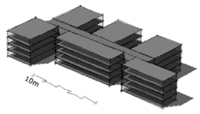
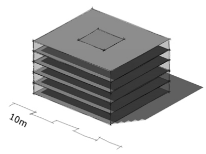
Because of all these reasons, counteracting the environmental and energy impact of air conditioning is one of the main objectives in the near future. Passive cooling is presented as an effective strategy for the case of Spain in order to achieve the Kyoto Agreement, reducing the energy demand of office buildings and providing an adequate thermal comfort (Santamouris et al 2010) (Santamouris et al 2013).

## 2 OBJECTIVE

This work continues the research line started by the project "Energy Efficiency of Ventilated Active Façades applied to office buildings in Spain". The project was financed by the Spanish National Plan for Research and finished on 2009. Its main objective was to determine the energy saving achievable (reduction of cooling demand) by the use of a Ventilated Active Façade - VAF. For the analysis 192 study cases were considered. The study cases represented the 8 most common typologies of offices in Spain, the typical glazed surface in façades (30% and 60%) and 12 Spanish climate zones (Table 2). The software used in the study was LIDER.

The simulation results demonstrated that the achievable energy saving is very dependent on the building typology, the glazed surface and the climate zone (Salmeron et al 2007). Furthermore, the work stated that using the VAF technology the cooling demand of office buildings could be reduced averagely into a 20%, and even up to a 40% in many cases (Irulegi et al 2011), (Irulegi et al 2012).

Table 2: Description of the 8 most common typologies of office buildings in Spain. The number in the nomenclature of each building represents the percentage of glazed facade (30% and 60%).

| **U Typology**<br>(U30 / U60) | **Tower with commu-nication core in façade**<br>(TF30 / TF60) | **Tower with central communication core**<br>(TC30 / TC60) | **Ring typology**<br>(O30 / O60) |
|---|---|---|---|
|  |  |  |  |
| **L-Typology**<br>(L30 / L60) | **Linear Typology**<br>(LI30 / LI60) | **Disperse Typology**<br>(D30 / D60) | **Compact typology**<br>(CP30 / CP60) |
|  |  |  |  |

The present work evaluates a different strategy to reduce the cooling demand of office buildings in Spain. Night ventilation is particularly suited to office buildings because these are usually not occupied during the night.

Many studies evaluate the benefits of night ventilation (Kolokotroni et al 2006), (Kolokotroni et al 2010), (Santamouris 2007). Some researches state that the peak temperature inside office buildings can be reduced between 0ºC and 2.6ºC for cross ventilated buildings and between 0.2ºC and 3.5ºC in single-sided ventilation buildings (Geros et al 1999). Other studies show that for day and night ventilation of 4 ACH, internal temperature is reduced about 1ºC and 1.5ºC in UK (Kolokotroni et al 1998).

Based on it, this article studies the impact of applying passive night ventilation in the Spanish climate and the thermal comfort achievable, according to European standard EN 15251:2007.

Specifically, the comfort level is evaluated using the Degree Hours (DH) criteria and the maximum indoor temperature. For the DH criteria, four base temperatures are considered: 25ºC and the three categories for acceptable ranges of operative temperature around the adaptive comfort temperature established in the standard for free running buildings.

The Category III corresponds to a moderate expectation of the occupants, the Category II corresponds to a mid-expectation, the Category I is related to a high level of expectation.

Considering the significant influence of the air flow (air changes per hour - ACH) in the efficacy of night ventilation, a wide range of them is considered. The air changes per hour range from 1 to 50, while the operating period goes from 02:00 to 08:00 hours (coolest outdoor temperature).

The results of the research show, for every typology, glazed surface in façade and climate zone, an optimal night ventilation pattern to achieve the highest level of comfort.

As an example of the results, in Almeria, a city in the south of Spain characterized by hot summers with average daily temperature of 26ºC, in the case of a Linear Typology with 30% glazed façade, the best comfort result is achieved by a night ventilation period of 6 hours, from 02 to 08 solar time, and 10 ACH. In comparison with the Base Case (1 ACH) the DH are reduced from near to 90% for the case of Category III to 68% for Category I, that means a very significant improve of the comfort level. The peak temperatures are reduced near to 2ºC.

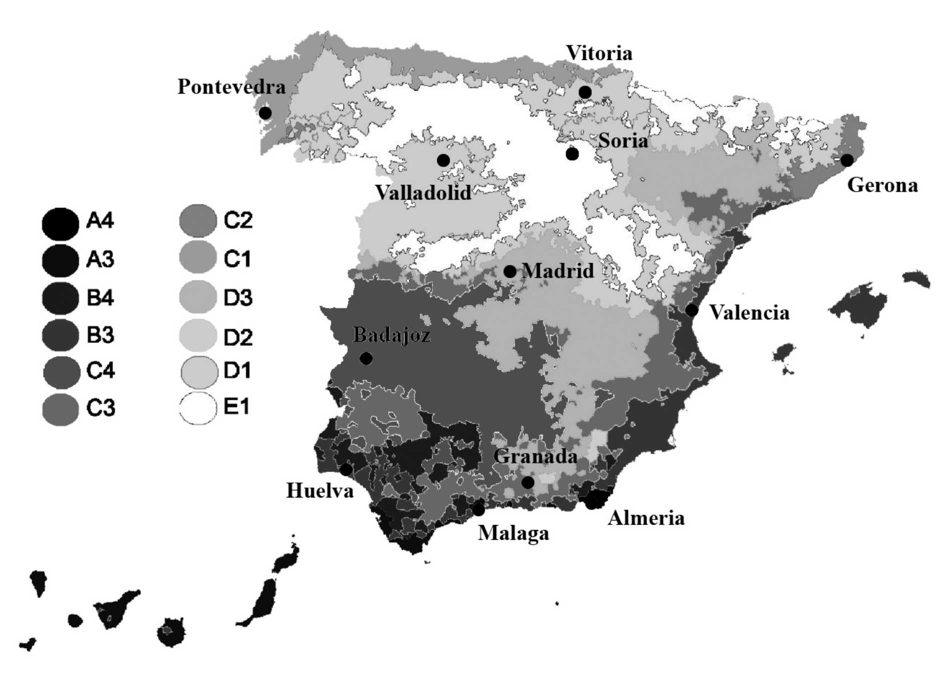
A detailed study is as well conducted for other cities representing different climate zones: Granada (Zone C3), Valladolid (Zone D2) and Soria (Zone E1).

The research shows that passive night ventilation should be considered as an effective strategy **in all the climate zones** to reduce cooling demand in buildings with high daily internal gains (i.e. offices buildings), improving comfort conditions and flattening peak temperatures. In addition, the optimal ventilation flow is in general **below 10ACH**, further increases in air ventilation flow produce marginal improves in the comfort variables.

## 3 SIMULATIONS

In order to analyse the influence of night ventilation on the comfort of office building occupants in Spanish climates, a sample of 16 buildings representing the most common building typologies in Spain (8 different typologies and 30% and 60% of glazed surface in façade) is considered. The buildings are simulated in a free-floating mode in 12 cities representing the 12 climate zones defined in the Spanish Technical Code -CTE. The results of the simulations cover a wide range of possible combinations providing very useful information to architects and designers.

Table 3: Climate Zones in CTE and representative cities.




| Zone | City |
|---|---|
| A4 | Almeria |
| C4 | Badajoz |
| C2 | Gerona |
| C3 | Granada |
| B4 | Huelva |
| D3 | Madrid |
| A3 | Malaga |
| C1 | Pontevedra |
| E1 | Soria |
| D2 | Valladolid |
| B3 | Valencia |
| D1 | Vitoria |

The simulation program used is LIDER, the official software used for regulation purposes in Spain (Ministerio de Vivienda de España 2009). LIDER uses a dynamic and multizone detailed simulation model to perform simulation in free floating mode and calculations of heating and cooling needs of buildings. The calculation engine of LIDER, is the evolution of the simulation software “S3PAS” which was developed in the University Seville. S3PAS was validated with the Building Energy Simulation Test (BESTest), (Lomas et al 1997) performed an experimental validation of several dynamic thermal simulation programs proving an excellent agreement between the results predicted by S3PAS and the measured data.

The Table 3 shows the 12 different Spanish Climate Zones and their representative cities considered for this study. The denomination of the Climate Zone is given by a letter and a number. The letter represents the winter climate severity, where “A” is the less severe zone, thus, the case with less heating demand. The letter “E” is the climate with most severe winter. The number represents the summer climate severity, where the number “1” is the climate with less cooling demand and the number “4” is the climate with highest cooling demand.

## 3.1 Definition of buildings

The main constructive characteristics of the 16 study cases are described in the Table 4. The denomination and model of each case is depicted in Table 2.

Table 4: Main construction and geometrical characteristics of the 16 buildings.

| **Building nomenclature** | **Floors** | **Construction surface** | **Total Façade Surface** | **Façade surface facing South** | **Total glazed surface** | **Glazed surface facing South** | **Shape Factor: S/V** |
|---|---|---|---|---|---|---|---|
| CP30 | B+4 | 6480$m^2$ | 3240 $m^2$ | 810 $m^2$ | 972 $m^2$ | 243 $m^2$ | 0.2 $m^{-1}$ |
| CP60 | B+4 | 6480$m^2$ | 3240 $m^2$ | 810 $m^2$ | 1944 $m^2$ | 486 $m^2$ | 0.2 $m^{-1}$ |
| DS30 | B+3 | 12240$m^2$ | 8262 $m^2$ | 1620 $m^2$ | 2478,6 $m^2$ | 486 $m^2$ | 0.242 $m^{-1}$ |
| DS60 | B+3 | 12240$m^2$ | 8262 $m^2$ | 1620 $m^2$ | 4957,2 $m^2$ | 972 $m^2$ | 0.242 $m^{-1}$ |
| L30 | B+4 | 4680 $m^2$ | 4050 $m^2$ | 945 $m^2$ | 1215 $m^2$ | 283,5 $m^2$ | 0.281 $m^{-1}$ |
| L60 | B+4 | 4680 $m^2$ | 4050 $m^2$ | 945 $m^2$ | 2430 $m^2$ | 567 $m^2$ | 0.281 $m^{-1}$ |
| LI30 | B+4 | 7200 $m^2$ | 3780 $m^2$ | 1350 $m^2$ | 1134 $m^2$ | 405 $m^2$ | 0.205 $m^{-1}$ |
| LI60 | B+4 | 7200 $m^2$ | 3780 $m^2$ | 1350 $m^2$ | 2268 $m^2$ | 810 $m^2$ | 0.205 $m^{-1}$ |
| O30 | B+4 | 12960 $m^2$ | 9720 $m^2$ | 1620 $m^2$ | 2916 $m^2$ | 486 $m^2$ | 0.200 $m^{-1}$ |
| O60 | B+4 | 12960 $m^2$ | 9720 $m^2$ | 1620 $m^2$ | 5832 $m^2$ | 972 $m^2$ | 0.200 $m^{-1}$ |
| TC30 | B+14 | 18900 $m^2$ | 9720 $m^2$ | 2835 $m^2$ | 2916 $m^2$ | 850,5 $m^2$ | 0.145 $m^{-1}$ |
| TC60 | B+14 | 18900 $m^2$ | 9720 $m^2$ | 2835 $m^2$ | 5832 $m^2$ | 1701 $m^2$ | 0.145 $m^{-1}$ |
| TF30 | B+14 | 9720 $m^2$ | 7290 $m^2$ | 2430 $m^2$ | 2187$m^2$ | 729 $m^2$ | 0.196 $m^{-1}$ |
| TF60 | B+14 | 9720 $m^2$ | 7290 $m^2$ | 2430 $m^2$ | 4374 $m^2$ | 1458 $m^2$ | 0.196 $m^{-1}$ |
| U30 | B+4 | 7920 $m^2$ | 6480 $m^2$ | 1350 $m^2$ | 1944 $m^2$ | 405 $m^2$ | 0.270 $m^{-1}$ |
| U60 | B+4 | 7920 $m^2$ | 6480 $m^2$ | 1350 $m^2$ | 3888 $m^2$ | 810 $m^2$ | 0.270 $m^{-1}$ |

Following this geometrical parameters, all the buildings are modelled using the software LIDER. The configuration of the façade in every case is adapted to the severity of the climate zone, to comply-with the minimum requirements of energy demand established in CTE. The impact produced by the variation of the thermal inertia, is not studied in this work.

## 3.2 Description of simulations

The method followed for simulating all the buildings in every climate zone is described below:

a) Firstly, a Base Building is defined in order to have a comparison pattern that permits to evaluate the benefits of applying night ventilation. The Base Building consists of a building with 1 ACH, a daily constant value. 1 ACH is the typical ventilation flow for office buildings according to the Spanish Regulation about Salubrity – HS3. There are 16 Base Buildings in each of the 12 climate zones, 192 Base Buildings in total.

b) For every building, simulations with different night ventilation flows are then conducted, considering the following ACH: 2, 4, 6, 8, 10, 13, 16, 20, 25, 30, 40 and 50. Night Ventilation is applied during 6 hours (from 02:00 am to 08:00 am), coinciding with the lowest exterior temperatures.

c) The occupancy schedule is set from 07:00 to 15:00 and from 17:00 to 20:00 during the week and from 07:00 to 15:00 on Saturdays. Internal loads in this period are:

-People: 10 $W/m^2$
-Lighting: 7.5 $W/m^2$
-Appliances: 7.5 $W/m^2$

The results obtained are an hourly register of air temperature for every space of the building and for the whole year. For evaluating the benefits obtained by applying night ventilation in every case, the following variables are considered:

a) Weighing factor, (wf). It is used the definition given in the Standard EN 15251:2007, Annex F, Method B "Degree hours criteria". With it, long term thermal comfort conditions are evaluated. Wf consists of an *hourly cumulative calculation of the difference between the operative temperature registered for one space and the acceptable maximum temperature*. In the A.2 section of the former Standard, three different Categories of expectation and a specific limit of operative temperature are defined. Category III (moderate expectation of the occupants), Category II (normal expectation of the occupants), Category I (high expectation of the occupants). These limits are calculated using an adaptive comfort method, so that do not correspond to a fix limit, but change with the time and the exterior temperature of every location. In this study, apart from the given three temperature limits, the limit of 25ºC is as well considered, as it represents the usual upper value for non-adaptive thermal comfort analysis.

b) Maximum interior temperature. This variable permits to evaluate, in a quite direct way, the effect of night ventilation since it is expected that interior temperature will reduce when ventilation flow increases. However, the inconvenience is that, for every space in a building, a different maximum temperature is registered. For this reason, the average maximum temperature is calculated for every room and then a weighted average value is obtained for the whole building, where the weight of every room is proportional to its surface area.

## 4 RESULTS

The results obtained for each variable are shown separately in the following two sections. In the first one it is studied the influence of night ventilation on the Degree Hours, while in the other one it is shown the effect on the interior maximum air temperature. General conclusions of the work are completed with a detailed analysis of the cities of Almeria (Climate Zone A4), Granada (Climate Zone C3), Valladolid (Climate Zone D2) and Soria (Climate Zone E1).

### 4.1. Weighing factor

As mentioned before, due to the wide range of building typologies and climate zones considered in this study, for the evaluation of the variation of the weighing factor, the "degree hour variation" (∇wf) will be used.

The ∇wf variable is defined as the ratio between the weighing factor of the building with different ventilation flows (case_study) and the Base Building (1ACH).

$$\nabla wf = \frac{wf_{case\_study}}{wf_{base\_building}} \quad (1)$$

Although the variation is proportionally similar in warm and cool climates, the absolute value is different, resulting lower in the coolest ones. Relating this fact with the values of the variation shown for the limits of Category II and I, thanks to night ventilation in the coolest climates it is possible to stay within comfort limits in almost the whole day

The Figure 1 shows that in warm climate zones, the ∇wf value is higher than in cool climates, that indicates that the reduction of the DH is lower in warmer climates than in the cooler ones. The reason for it is that the night-time temperature in cool climates is usually lower and the daytime temperature is not very distanced from the comfort limit.

In addition, for the ∇wf variation based on the limits of Category II and I, (Figure 1, b, c) the reduction of DH is similar in the climate zones with a climatic severity for summer of 4, 3 and 2, resulting remarkable that the same occurs for all the climates zones with limit of 25ºC (Figure 1, d).

a)Mean values of ∇wf for Limit of Category III
b) Mean values of ∇wf for Limit of Category II
c) Mean values of ∇wf for Limit of Category I
d) Mean values of ∇wf for Limit of 25ºC

Figure 1. Degree Hours variation respect to Base Building (∇wf), for all the climatic zones.

Furthermore, as it is observed in the graphics (Figure 1), there is not a perfectly homogeneous trend. For example, in Figure 1, a, the ∇wf variation in zones C3 and D3 is higher than in the adjacent zones (B3 and C2). This breaks the descending trend in the graph.

This is due to the location of the cities: Granada (Zone C3) and Madrid (Zone D3) have an inland location while Malaga (Zone A3), Valencia (Zone B3) and Gerona (Zone C2) are located in the coast (or near it) where the influence of the Mediterranean see produces different night temperature patterns.

A similar remark, but for different reasons, can be made for climate zones C1, D1 and E1. In these cases, it is observed that the variation between night and day temperatures is lower in Pontevedra (Zone C1) and Soria (Zone E1) than in Vitoria (Zone D1). This causes, as a general trend, lower values of ∇wf variation in D1 zone than in E1 or C1 zones.

In addition, the data in the Figure 1 are ordered according to their summer severity (from the hottest summer A4 to the mildest summer E1). As it is expect, it is possible to define a global downtrend that relates summer severity and effect of night ventilation.

The results show that:

- Considering the comfort limits established for Category II and I, the proportional improvement of the comfort is almost the same in the warm and moderate climates. In the coolest climates, it is possible to achieve the comfort in a greater number of hours.

- If the limit is 25ºC, for all the climate zones, the interior temperatures are located in a distance from the comfort that is proportionally very similar in all the cases.

### 4.1.1. Almeria (Climate Zone A4)

The city of Almeria is situated in the South of Spain (36.85ºN, 2.38ºW, Elevation: 21m) with an annual mean temperature of 18.5ºC (Figure 2). Its climate is characterized by having hot dry summers and mild dry winters. In summer, the mean temperature is 26ºC (in a typical summer day this value can range from 18ºC to 35ºC). The day / night temperature variation suggests that the use of night ventilation for cooling purposes in Almeria could be beneficial.

Furthermore, it has to be highlighted that from June to October the daily highest temperature exceeds typically 25ºC. Furthermore, it is quite common to record this value from March to November. This fact suggests that the use of night ventilation in Almeria can be beneficial in a larger period of time.

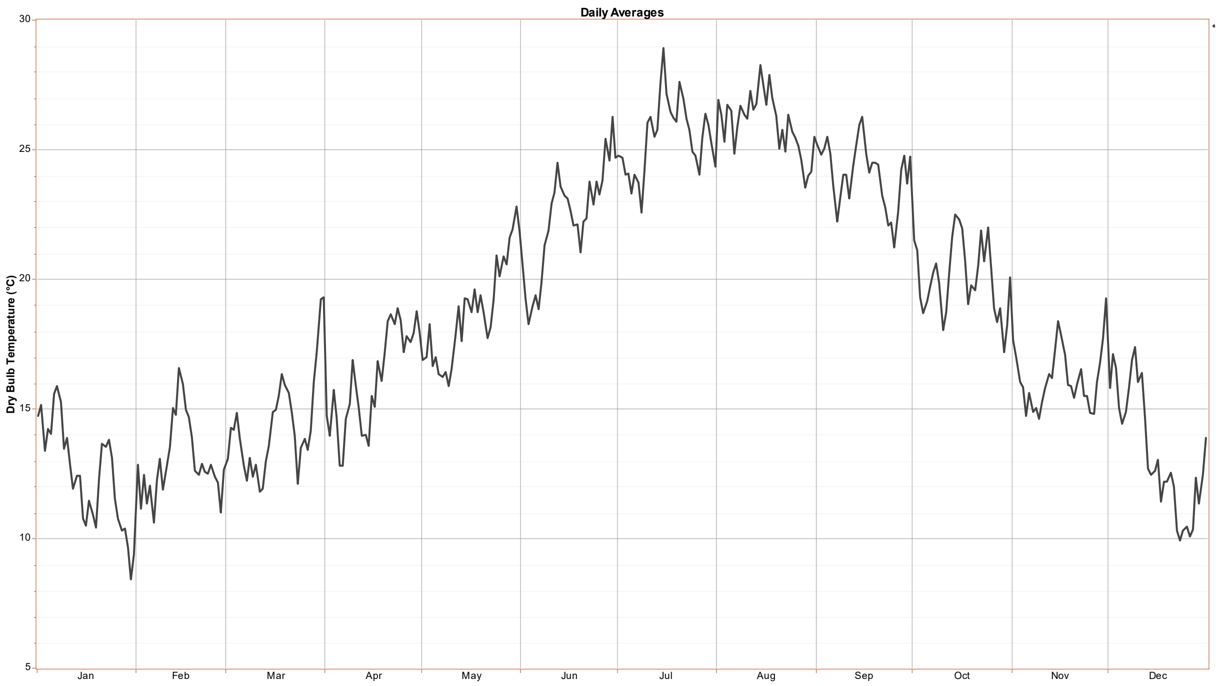
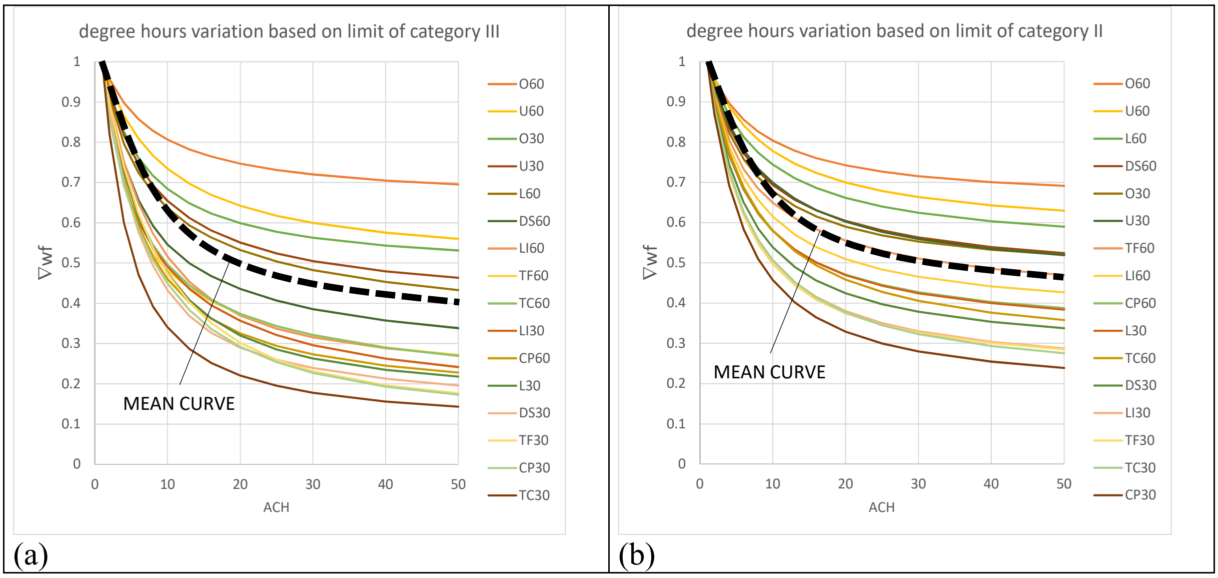



Figure 2. Daily Dry Bulb Temperature Average in Almeria.

In the graphs, the former defined Categories III, II and I and the limit of 25ºC are studied. Each line represents the deviation of ∇wf for every building respect to its Base Building as the ventilation flow increases.

When the variation of ∇wf is *zero*, it means that the interior temperature is within the comfort boundaries.



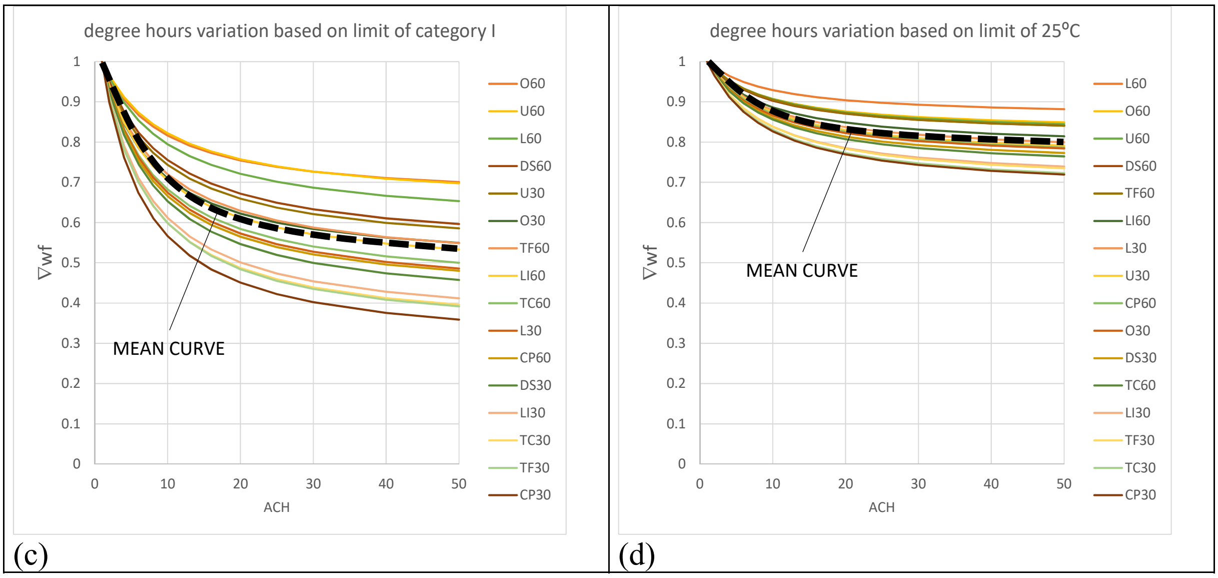



Figure 3 Degree Hours based on the limit of Category III (a), Category II (b), Category I (c) and limit of 25ºC (d) in Climate Zone A4.

Analysing the dispersion[2] of the ∇wf value in Almeria, it is observed that in the case of Category III (Figure 3a), the dispersion is very high and depends primarily on the building typology[3] (the variation ranges from 0.70 to 0.15 for 50ACH where the mean value is 0.4). In addition, the dispersion is lower when the expectation of the occupants rises (Category II, Category I and Limit of 25ºC). In general, the lower the shape factor (TC, TF and CP) the lower is the ∇wf value. Buildings with 30% of glazed surface present a lower ∇wf value.

In the limit of Category II (Figure 3b), the dispersion is slightly lower than in the former case, although the ∇wf values remain high. In the cases of Category I (Figure 3c) and limit of 25ºC (Figure 3d) the dispersion is minor and the influence of the building typology is not so evident.

As it is observed, in most of the study cases and comfort Categories, the highest reduction of the ∇wf value is registered for a night ventilation rate below 10ACH and increasing this rate produces only marginal benefices.

### 3.1.1. Granada (Climate Zone C3)

The city of Granada is situated in the South of Spain (37.18ºN, 3.78ºW, Elevation: 559m) with an annual mean temperature of 15.0ºC (Figure 4). Its climate is characterized by having hot dry summers and cold- dry winters. In summer, the mean temperature is 22.5ºC (in a typical summer day this value can range from 12ºC to 37ºC). The day / night temperature variation suggests that the use of night ventilation for cooling purposes in Granada could be beneficial.

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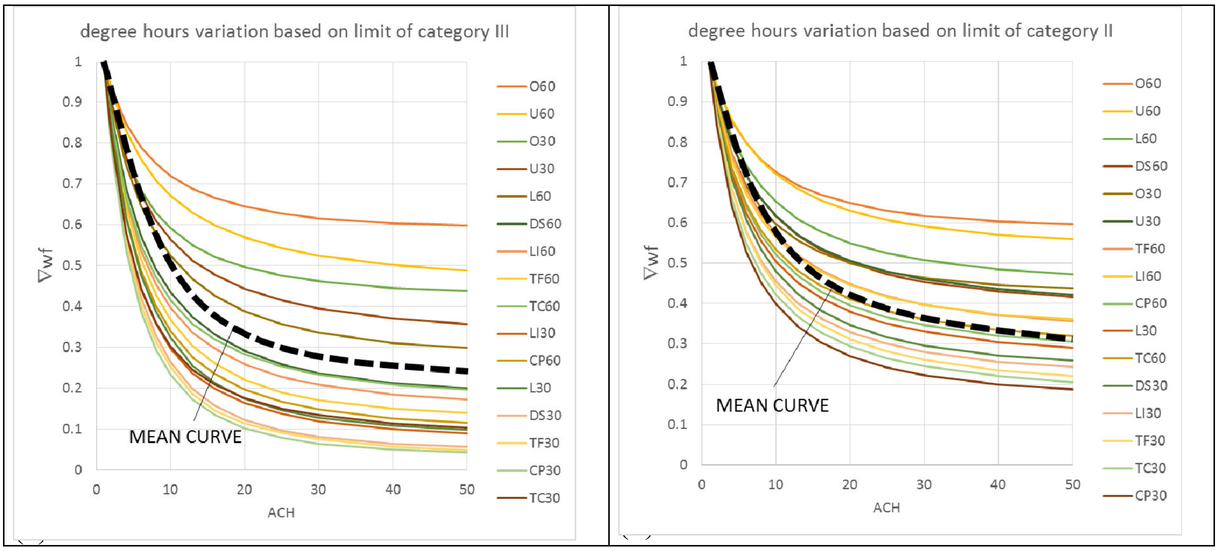
[2] The dispersion of the ∇wf value is defined as the difference between the cases with highest and lowest variations of the ∇wf value.

[3] It has to be highlighted that the influence of the building typology on ∇wf is very significant, but a detailed study of it exceeds the scope of the present article.


Figure 4. Daily Dry Bulb Temperature Average in Granada.

The following graphs show the deviation of ∇wf for every building respect to its Base Building as the ventilation flow increases in Granada.



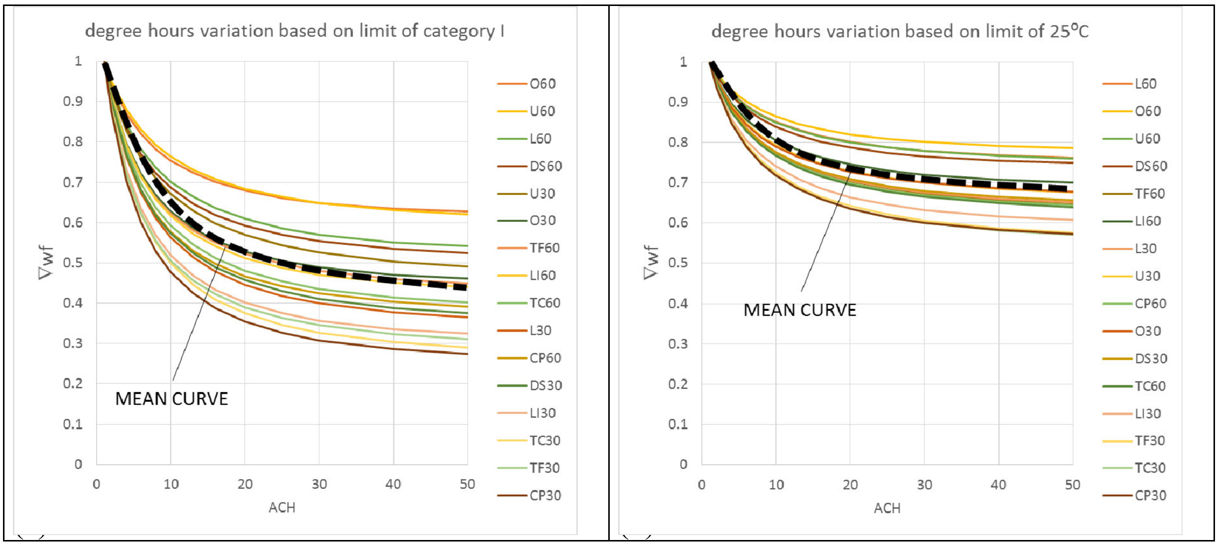



Figure 5. Degree Hours based on the limit of Category III (a), Category II (b), Category I (c) and limit of 25ºC (d) in Climate Zone C3.

Analysing the dispersion of the ∇wf value in Granada, it is observed that in the case of Category III (Figure 5a) the dispersion is even higher than in the case of Almeria (Zone A4) and depends primarily on the building typology (the variation ranges from 0.5 to 0.05 for 50ACH where the mean value is 0.25). In addition, the dispersion is lower when the expectation of the occupants rises (Category II, Category I and Limit of 25ºC). In general, the lower the shape factor (TC, TF and CP) the lower is the ∇wf value. Buildings with 30% of glazed surface present a lower ∇wf value.

In the limit of Category II (Figure 5b), the dispersion is slightly lower than in the former case although the ∇wf values remain high. In the cases of Category I (Figure 5c) and limit of 25ºC (Figure 5d) the dispersion is minor although the influence of the building typology remains significant.

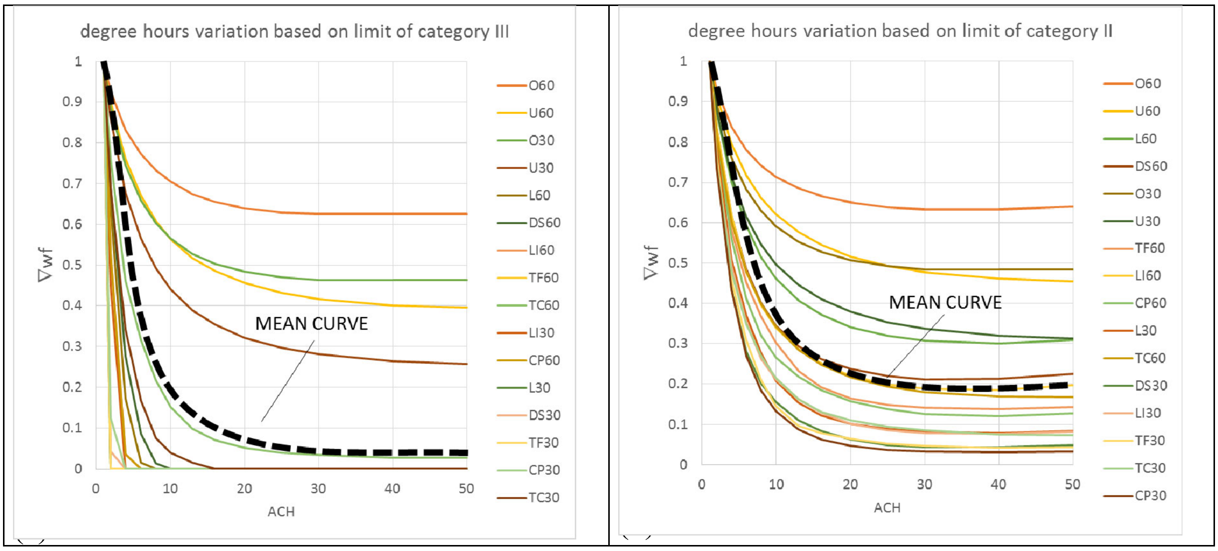
As it happens in the case of Almeria (zone A4), in most of the study cases and comfort Categories, the highest reduction of the ∇wf value is registered for a night ventilation rate below 10ACH and increasing this rate produces only marginal benefeces.

### 3.1.2. Valladolid (Climate Zone D2)

The city of Granada is situated in the North of Spain (41.65ºN, 4.77ºW, Elevation: 735m) with an annual mean temperature of 12.0ºC (Figure 6). Its climate is characterized by having mild summers and cold winters. On summer, the mean temperature is 19.5ºC (in a typical summer day this value can range from 13ºC to 32ºC). The day / night temperature variation suggests that the use of night ventilation for cooling purposes in Valladolid could be beneficial.


Figure 6. Daily Dry Bulb Temperature Average in Valladolid.

The deviation of ∇wf for the buildings in Valladolid is shown in the following graphs.



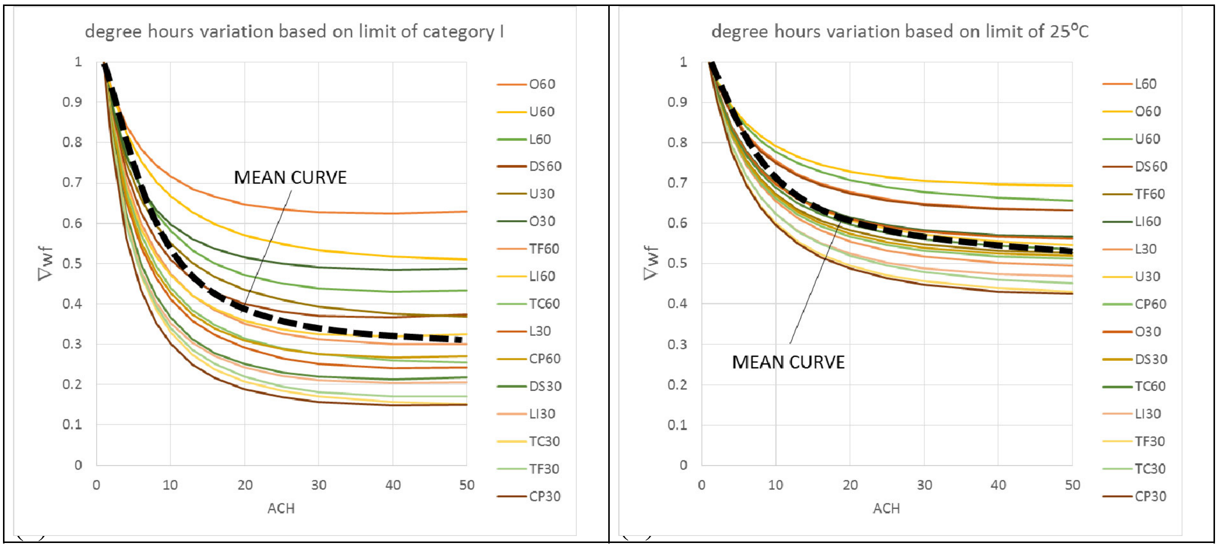



Figure 7. Degree Hours based on the limit of Category III (a), Category II (b), Category I (c) and limit of 25ºC (d) in Climate Zone D2.

Analysing the dispersion of the ∇wf value in Valladolid, it is observed that in the case of Category III (Figure 7a) the dispersion is even higher than in the former cases of Almeria (zone A4) and Granada (Zone C3) and depends primarily on the building typology (the variation ranges from 0.65 to 0.00 for 50ACH where the mean value is 0.4). In addition, the dispersion is lower when the expectation of the occupants rises (Category II, Category I and Limit of 25ºC). As it occurs in the former climate zones, the lower the shape factor (TC, TF and CP) the lower is the ∇wf value and the cases of buildings with 30% of glazed surface present a lower ∇wf value.

In the limit of Category II (Figure 7b), the dispersion is slightly lower than in the former case although the ∇wf values remain high. In the cases of Category I (Figure 7c) and limit of 25ºC (Figure 7d) the dispersion is minor although the influence of the building typology remains significant.

Furthermore, in most of the study cases and comfort Categories, the highest reduction of the ∇wf value is registered for a night ventilation rate below 10ACH and increasing this rate produces only marginal benefices.

It has to be highlighted that for the comfort limit of Category III, several buildings reach the zero value at a relatively low night ventilation rates (less than 10ACH). This fact indicates that the indoor temperature is within the comfort range in the 100% of the hours.

Moreover, the average curve reaches a value near to zero.

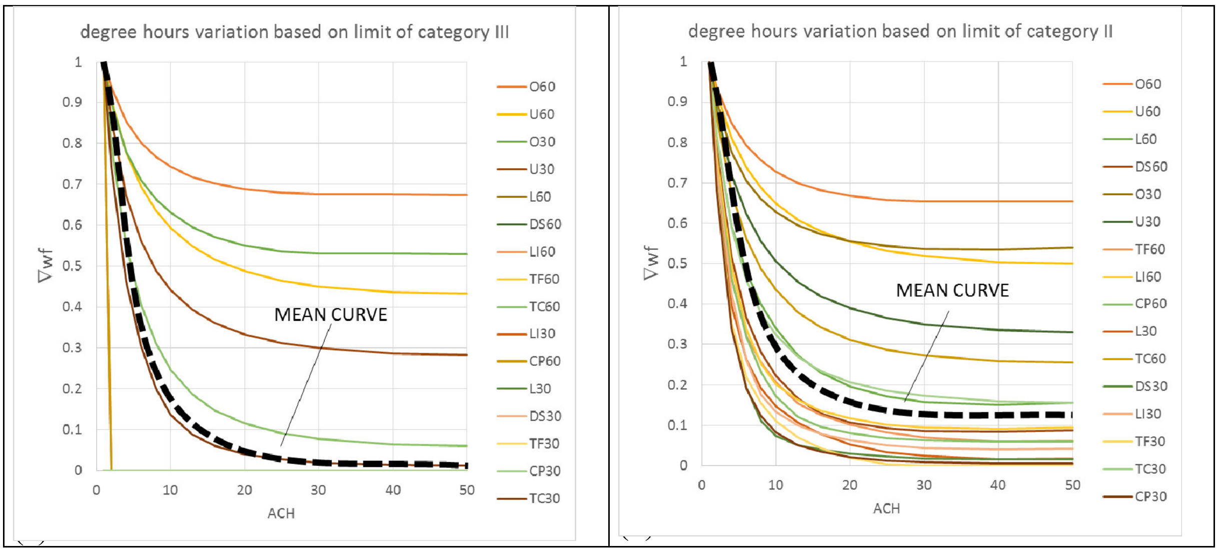
### 3.1.3. Soria (Climate Zone E1)

The city of Soria is situated in the North of Spain (41.77ºN, 2.48ºW, Elevation: 82m) with an annual mean temperature of 11.0ºC. (Figure 8). Its climate is characterized by having mild summers and cold winters. On summer, the mean temperature is 17.5ºC (in a typical summer day this value can range from 8ºC to 27ºC). The day / night temperature variation suggests that the use of night ventilation for cooling purposes in Soria could be beneficial.

Furthermore, it has to be highlighted that from July to September the daily highest temperature exceeds typically 25ºC. Furthermore, it is quite common to record this value from June to September.


Figure 8. Monthly Statistics for Dry Bulb Temperature in Soria.

As in previous localities, the deviation of ∇wf for the buildings in Soria is shown in the following graphs.



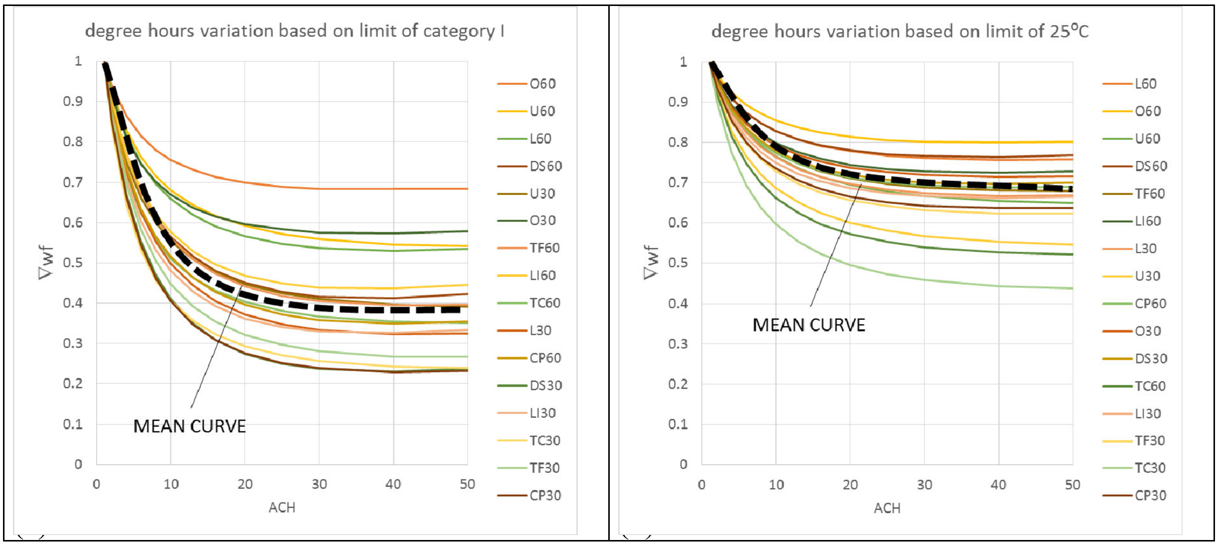



Figure 9. Degree Hours based on the limit of Category III (a), Category II (b), Category I (c) and limit of 25ºC (d) in Climate Zone E1.

Analysing the dispersion of the ∇wf value in Soria, it is observed that in the case of Category III (Figure 9a) the dispersion is similar to the former case of Valladolid (zone D2) and depends primarily on the building typology (the variation ranges from 0.68 to 0.00 for 50ACH although the mean value is 0.00). This was not expected because Soria has a milder summer than Valladolid. However, a further analysis revealed the reasons of the little variation between these two localities:

- Day and night temperature variation in Soria is lower than in Valladolid
- The limits of the adaptive comfort are different in each case, presenting lower values in Soria than in Valladolid;
- In Valladolid the "cold" storage for the buildings are near to the maximum, making impossible a higher storage.

#### 4.1.2. Discussion about the variation of weighing factor

The research shows that the use of night ventilation is beneficial to improve comfort conditions in office buildings of Spain and this occurs for the all the locations and climate zones. In general, the deviation of ∇wf for the buildings falls down significantly when ventilation flow increases till 10ACH and further increases provide marginal improvements.

When ∇wf equals zero, the comfort conditions are achieved in 100% of the hours.

In most of the buildings located in climate zones with mild summers (Zone D2 and E1) it is possible to achieve comfort conditions (according to Category III) in 100% of the time by applying night ventilation.

Moreover, in the city of Valladolid (Climate Zone D2), a night ventilation flow of 10ACH is enough to reach a zero value of ∇wf.

In the case of Soria (Climate Zone E1) the ventilation flow to achieve comfort conditions is even lower: 5ACH.

In addition, in most of the buildings located in climate zones with hot summers (Zone A4, Zone C3) it is possible to achieve comfort conditions (according to Category III) in approximately 65% and 50% of the time by applying night ventilation.

## 4.2. Effect on maximum temperature

The Table 5 shows the influence of night ventilation in the maximum indoor temperature for every building, climate zone and ventilation flow respect to its Base Building (1 ACH). The temperature difference is represented by ∇Tmax. In the Table, for every climate zone the "coldest case" corresponds to the building with the lowest maximum temperature. "The hottest case" to the building with the higher maximum temperature and the "Mean" corresponds to the average value for all the buildings.

Table 5: Variation of the peak temperature (∇Tmax) for the coldest, hottest and mean building, for every climate zone and ventilation flow. The temperature difference is respect to its Base Building (1 ACH).

| Climate Zone | | 1 ACH | | | 10 ACH | | | 20 ACH | | | 50 ACH | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Coldest case | Mean | Hottest case | Coldest case | Mean | Hottest case | Coldest case | Mean | Hottest case | Coldest case | Mean | Hottest case |
| **A3** | Tmax | 28.6 | 30.2 | 31.3 | 28.5 | 29.1 | 30.9 | 28.4 | 29.0 | 30.7 | 28.3 | 28.9 | 30.6 |
| | ∇Tmax | | | | -0.1 | -0.3 | -0.4 | -0.2 | -0.4 | -0.6 | -0.3 | -0.5 | -0.8 |
| **A4** | Tmax | 29.3 | 31.1 | 31.9 | 29.2 | 29.8 | 31.5 | 29.1 | 29.7 | 31.4 | 29.0 | 29.5 | 31.2 |
| | ∇Tmax | | | | -0.1 | -0.3 | -0.4 | -0.2 | -0.4 | -0.6 | -0.3 | -0.5 | -0.8 |
| **B3** | Tmax | 27.9 | 28.6 | 30.5 | 27.7 | 28.3 | 30.0 | 27.6 | 28.2 | 29.9 | 27.5 | 28.1 | 29.7 |
| | ∇Tmax | | | | -0.2 | -0.3 | -0.5 | -0.2 | -0.4 | -0.6 | -0.3 | -0.5 | -0.8 |
| **B4** | Tmax | 29.3 | 30.0 | 32.1 | 29.1 | 29.7 | 31.6 | 29.0 | 29.6 | 31.4 | 28.9 | 29.5 | 31.2 |
| | ∇Tmax | | | | -0.2 | -0.3 | -0.5 | -0.2 | -0.4 | -0.7 | -0.3 | -0.6 | -0.9 |
| **C1** | Tmax | 24.3 | 25.1 | 27.2 | 24.3 | 25.0 | 26.7 | 24.3 | 24.9 | 26.6 | 24.3 | 24.9 | 26.4 |
| | ∇Tmax | | | | 0.0 | -0.1 | -0.5 | 0.0 | -0.2 | -0.8 | 0.0 | -0.2 | -1.0 |
| **C2** | Tmax | 26.4 | 27.2 | 29.0 | 26.4 | 26.8 | 28.4 | 26.2 | 26.7 | 28.2 | 26.0 | 26.6 | 28.1 |
| | ∇Tmax | | | | 0.0 | -0.4 | -0.6 | 0.0 | -0.5 | -0.8 | 0.0 | -0.6 | -1.0 |
| **C3** | Tmax | 28.7 | 29.6 | 31.8 | 28.4 | 29.1 | 31.0 | 28.2 | 28.9 | 30.8 | 27.9 | 28.7 | 30.5 |
| | ∇Tmax | | | | -0.3 | -0.5 | -0.8 | -0.4 | -0.7 | -1.1 | -0.6 | -1.0 | -1.4 |
| **C4** | Tmax | 29.5 | 30.5 | 32.6 | 29.2 | 30.0 | 31.9 | 29.1 | 29.8 | 31.6 | 28.8 | 29.6 | 31.4 |
| | ∇Tmax | | | | -0.3 | -0.5 | -0.7 | -0.4 | -0.7 | -1.0 | -0.6 | -0.9 | -1.3 |
| **D1** | Tmax | 22.9 | 23.7 | 25.6 | 22.9 | 23.6 | 25.1 | 22.9 | 23.5 | 24.9 | 22.9 | 23.5 | 24.8 |
| | ∇Tmax | | | | 0.0 | -0.1 | -0.5 | 0.0 | -0.1 | -0.8 | 0.0 | -0.2 | -1.0 |
| **D2** | Tmax | 26.0 | 26.9 | 29.3 | 25.7 | 26.4 | 28.5 | 25.5 | 26.2 | 28.3 | 25.2 | 26.0 | 28.1 |
| | ∇Tmax | | | | -0.3 | -0.5 | -0.8 | -0.5 | -0.8 | -1.1 | -0.6 | -1.0 | -1.4 |
| **D3** | Tmax | 28.0 | 29.0 | 31.3 | 27.7 | 28.5 | 30.6 | 27.5 | 28.3 | 30.4 | 27.4 | 28.1 | 30.2 |
| | ∇Tmax | | | | -0.3 | -0.5 | -0.7 | -0.4 | -0.6 | -0.9 | -0.5 | -0.8 | -1.2 |
| **E1** | Tmax | 24.6 | 25.5 | 28.0 | 24.6 | 25.3 | 27.2 | 24.6 | 25.2 | 27.0 | 24.6 | 25.1 | 26.8 |
| | ∇Tmax | | | | 0.0 | -0.2 | -0.8 | 0.0 | -0.3 | -1.1 | 0.0 | -0.3 | -1.3 |

In general, the temperature variation (∇Tmax) is relatively little. The value decreases when the ventilation flow increases, with an asymptotically trend. For some buildings the peak temperature reduction continues increasing for high ventilation flows, when in other cases, the reduction is almost marginal. The difference between the minimum and maximum values for every case moves around 0.5ºC. Moreover, the results achievable by increasing the ventilation

flow or changing the climate zone are similar. That confirms, once again, that the building typology is more significant than the absolute increase of ventilation flow when night ventilation is applied.
To better illustrate the effect of night ventilation on maximum indoor temperature, four examples, corresponding to each of the four summer climate zones existing in Spain, are shown below

### 4.2.1. Effect on maximum temperature in Almeria (Climate Zone A4)

It is observed that in all the cases, the maximum indoor temperature decreases by increasing the ACH and it is limited to an asymptotic value. The maximum indoor temperature varies considerably depending on the building typology and the glazed surface in façade and ranges from 0.25ºC to 0.8ºC at 50 ACH. This decrease is low in comparison with the results reported by Geros et al. and Kolokotroni et al. The discussion about these results is done in paragraph 4.2.5.

As it occurs with the ∇wf value, the lower the shape factor (TC, TF and CP), the higher the reduction of the maximum indoor temperature. In addition, the lower the glazed surface in façade, the higher the reduction of the maximum indoor temperature.

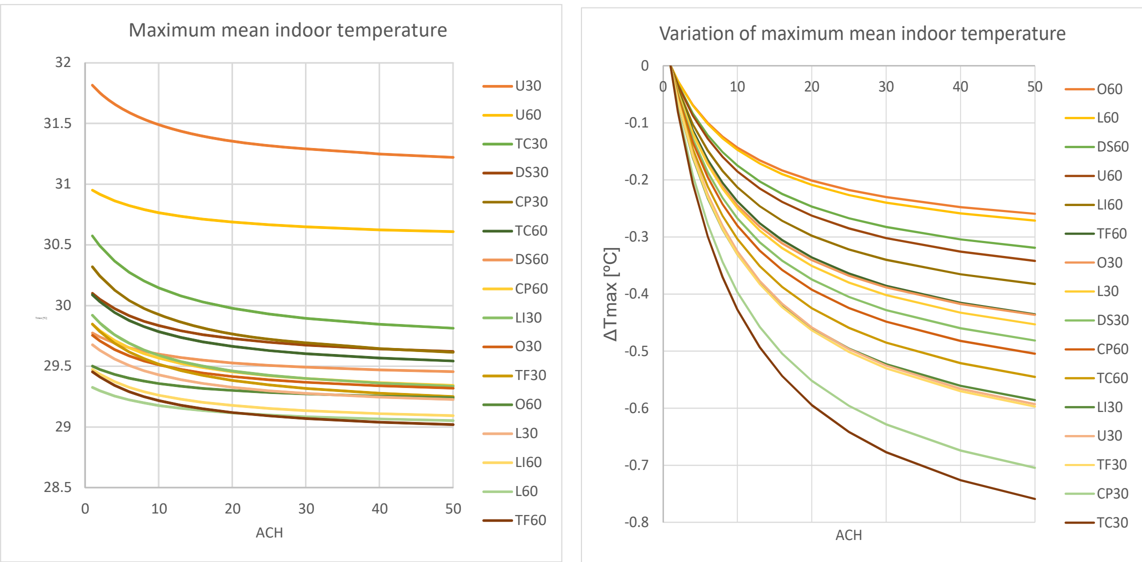



Figure 10. Maximum mean indoor temperature for all the buildings situated in Almeria, Climate Zone A4 and Variation of the maximum mean indoor temperature for all the buildings situated in Climate Zone A4.

### 4.2.2. Effect on maximum temperature in Granada (Climate zone C3)

The case of Granada presents similarities with Almeria (zone A4). In all the cases the maximum indoor temperature decreases by increasing the ACH and it is limited to an asymptotic value (Figure 11). The maximum indoor temperature varies considerably depending on the building typology and the glazed surface in façade and ranges from 0.6ºC to 1.4ºC at 50 ACH.

As it occurs with the ∇wf value in Granada, the lower the shape factor (TC, TF and CP), the higher the reduction of the maximum indoor temperature. In addition, the lower the glazed surface in façade, the higher the reduction of the maximum indoor temperature.

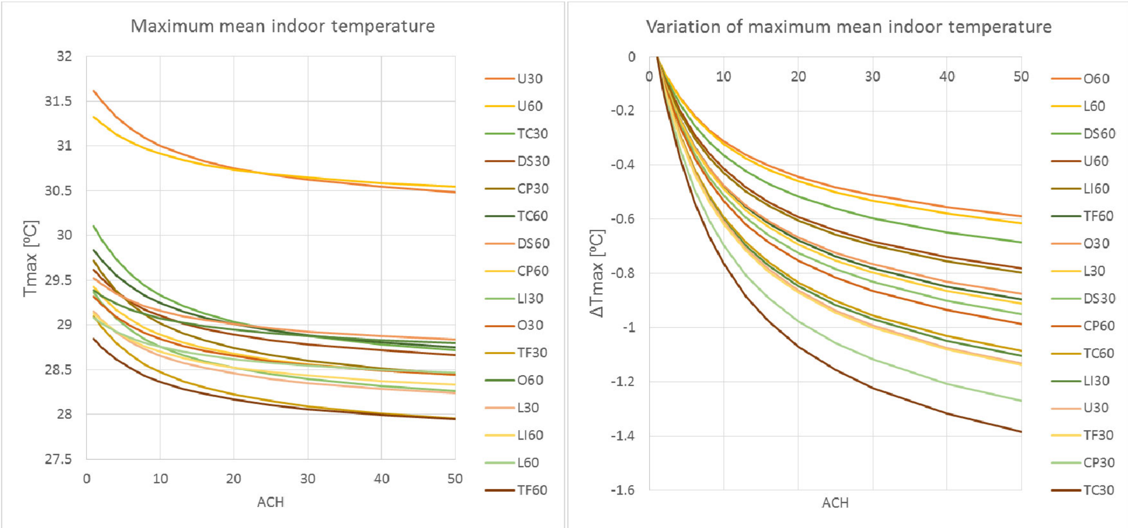



Figure 11. Maximum mean indoor temperature for all the buildings situated in Granada, Climate Zone C3 and Variation of the maximum mean indoor temperature for all the buildings situated in Climate Zone C3.

### 4.2.3. Effect on maximum temperature in Valladolid (Climate Zone D2)

The results of the mean maximum temperature in Valladolid (Figure 12) show a similar pattern to than the precedent two zones.The variation of the maximum mean indoor temperature is similar to the reduction observed for Granada. This was an unexpected result because the summer of Valladolid is smoother than the summer of Granada. The reason of this behaviour is explained by the fact that the peak temperatures of the buildings in Valladolid are lower than those in Granada, as can be observed in figures 11a and 12a. This lower temperature in Valladolid produces a decrease in the potential of temperature reduction.

The case of Valladolid presents similarities with Almeria (zone A4) and Granada (zone C·). It is observed that in all the cases the maximum indoor temperature decreases by increasing the ACH and it is limited to an asymptotic value (Figure 12). The maximum indoor temperature varies considerably depending on the building typology and the glazed surface in façade, ranging from 0.6ºC to 1.4ºC at 50 ACH. It has to be highlighted that the indoor temperature variation in Granada and in Valladolid are similar, although the summers in Valladolid are milder.

The reason of this behaviour is due to the lower peak temperatures of the buildings in Valladolid (Figures 11a and 12a) that produces a decrease in the potential of temperature reduction.

As it occurs with the ∇wf value in Valladolid, the lower the shape factor (TC, TF and CP), the higher the reduction of the maximum indoor temperature. Moreover, the lower the glazed surface in façade, the higher the reduction of the maximum indoor temperature.

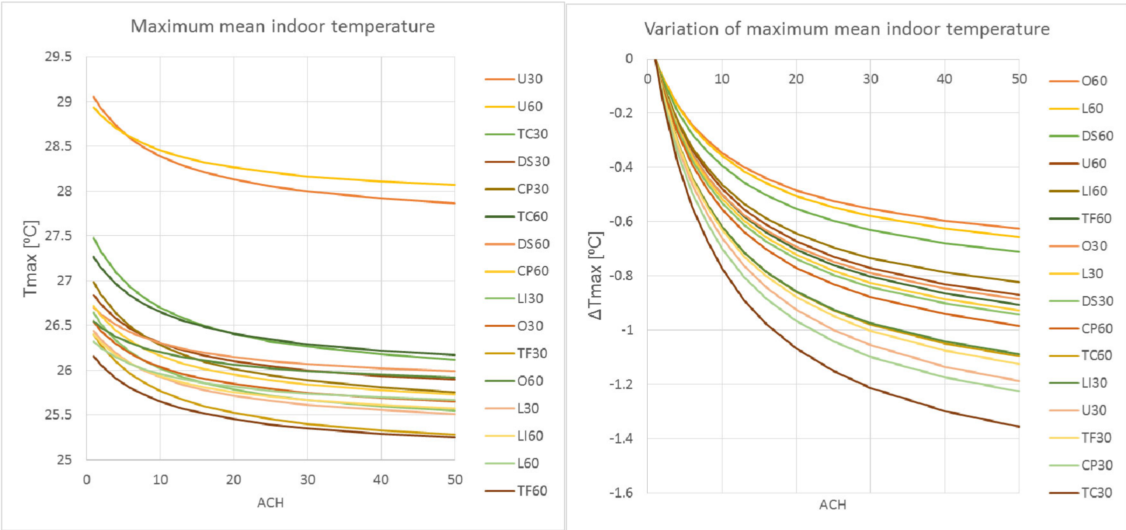



Figure 12. Maximum mean indoor temperature for all the buildings situated in Valladolid, Climate Zone D2 and Variation of the maximum mean indoor temperature for all the buildings situated in Climate Zone D2.

### 4.2.4. Effect on maximum temperature in Soria (Climate Zone E1)

The results of the mean maximum temperature in Soria (Figure 13) present a different pattern in comparison with the former climate zones. The influence of the building typology is evident and two groups of buildings are detected. The first group consists of 4 buildings that present a similar mean maximum temperature reduction than in the former cities. Contrary to this, the second group of buildings do not present a significant fall in their peak temperature.

The biggest difference between the two groups is the peak temperature at 1ACH. The buildings of the first group have a peak temperature higher than 25.5ºC at 1ACH. This group shows an appreciable temperature reduction by increasing the night ventilation airflow rate. However, the peak temperature of the second group of buildings is lower than 25.5ºC at 1ACH and remains practically constant by incrementing the night ventilation airflow rate.

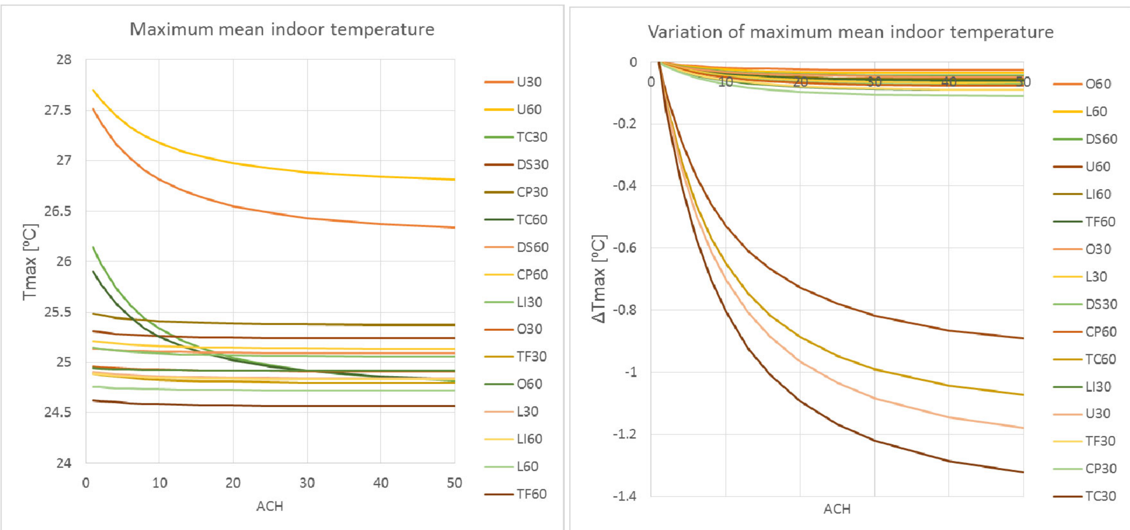



Figure 13. Maximum mean indoor temperature for all the buildings situated in Soria, Climate Zone E1 and Variation of the maximum mean indoor temperature for all the buildings situated in Climate Zone E1.

### 4.2.5. Discussion about the effect on maximum temperature

It is observed that the maximum indoor temperature in all the locations and climate zones of Spain is lower when night ventilation is applied. The temperature decrease depends on the outdoor temperature, ventilation flow, glazed surface in façade and building typology. In general a reduction that ranges from 0.1ºC to 0.8ºC is achievable by applying 10 ACH. This value is relatively low in comparison with the range of results reported by Geros et al (from 0ºC to 3.5ºC) and Kolokotroni (from 1ºC to 1.5ºC) at comparable flow rates of night ventilation.

One of the reasons for that could be the procedure followed to calculate the peak temperature. In this article, the peak temperatures represent the mean peak value of the building. This method presents the advantage that the mean value shows more precisely what happens in the whole building although a peak reduction in a particular specific spaces might be hidden.

Furthermore, the building materials and construction systems defined in the study cases follow the Spanish Regulation and present low thermal inertia reducing the "cold storage" potential of the buildings.

## 5 CONCLUSIONS

Night ventilation is an operative strategy to improve comfort conditions in the users of office buildings in Spain. Depending on the level of request (expressed by Categories I, II, III and 25ºC limit) and the climate zone, it is possible to maintain comfort conditions in 100% of the working occupation period, making not necessary the use of air conditioning. Some studies suggest (Geros et al 1999), (Kolokotroni et al 1998), (Kolokotroni et al 2007) that peak temperature can be reduced up to 3.5ºC. The results of this paper show that in the case of Spain, the achievable reduction is approximately 1ºC. It has to be pointed that this variations are the mean of the maximum temperatures and not the maximum absolute. In addition, different construction materials were not considered in this work, where the influence of thermal inertia could help to reduce peak temperatures.

As expected, in the coldest locations of Spain, the deviation of ∇wf for the buildings falls down significantly when ACH increases. This value can even reach the zero value, what means that comfort conditions are achieved in 100% of the hours. Furthermore, the typical night ventilation flow for all the buildings that reach the comfort is lower than 10ACH and even lower in some of the cases.

It is observed that with mild summers, the variation of maximum temperature in buildings is higher, but this trend is not always continuous as shown for the climate Zone E1.

Furthermore, the results show that the building typology is an important factor for evaluating night ventilation as *effective or significant* to improve comfort conditions. Two main variables in buildings are identified as relevant for optimal and effective night ventilation: low glazed surfaces in façade and a low shape factor (compact buildings).

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