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Potential for passive cooling of buildings by night-time ventilation in present and future climates in Europe

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ABSTRACT: Given the general shift in recent decades towards a lower heating and higher cooling demand for buildings in many European countries, passive cooling by night-time ventilation has come to be seen as a promising option, particularly in the moderate or cold climates of Central, Eastern and Northern Europe. The basic concept involves cooling the building structure overnight in order to provide a heat sink that is available during the occupancy period. In this study, the potential for the passive cooling of buildings by night-time ventilation is evaluated by analysing climatic data, irrespective of any building-specific parameters. An approach for calculating degree-hours based on a variable building temperature — within a standardized range of thermal comfort — is presented and applied to climatic data from 259 stations throughout Europe. The results show a very high potential for night-time ventilative cooling over the whole of Northern Europe and a still significant potential in Central, Eastern and even some regions of Southern Europe. However, given the inherent stochastic properties of weather patterns, series of warmer nights can occur at some locations, where passive cooling by night-time ventilation alone might not suffice to guarantee thermal comfort. It should also be remembered that climatic cooling potential is likely to have fallen appreciably by the end of the 21st century due to climate warming.

Keywords: Passive Cooling; Night-time Ventilation; Climate Change; Climatic Cooling Potential

1. INTRODUCTION

In Europe, commercial buildings in particular have experienced an uptrend in cooling demand over the last few decades. An increase in internal loads coupled with higher solar gains — especially in modern, highly glazed buildings — has fed the demand for air-conditioning systems, even in moderate and cold climates such as in Central or Northern Europe. Additionally, increased comfort expectations in summertime and the gradual warming of our climate are pushing up the cooling demand. While the heating requirement can be effectively reduced by installing thermal insulation, cooling plays a more significant role in the overall energy demand of buildings.

Particularly in moderate climates, such as in Switzerland, Germany or the UK, and cold climates such as in Scandinavia, with relatively low night-time temperatures even in summer, passive cooling of buildings by night-time ventilation appears to hold considerable potential. The basic concept involves cooling the building structure overnight in order to provide a heat sink that is available during occupancy periods [1]-[4]. Such a strategy could guarantee the daytime thermal comfort of building occupants without mechanical cooling or, at least, with a lower daytime cooling energy requirement.

However, this concept is highly dependent on climatic conditions, as a sufficiently high temperature difference between ambient air and the building structure is needed during the night to achieve efficient convective cooling of the building mass.

The purpose of this study is to evaluate the climatic potential for the passive cooling of buildings by night-time ventilation in present and future climates in Europe.

2. METHOD

A method was developed, verified and applied which is basically suitable for all building types, regardless of building-specific parameters. This was achieved by basing the approach solely on a building temperature variable within a temperature band given by summertime thermal comfort.

2.1 Definition of the 'Climatic Cooling Potential'

Degree-days or degree-hours methods are often used to characterise a climate's impact on the thermal behaviour of a building. In this study, the climatic potential for ventilative cooling, *CCP*, is defined as the sum of degree-hours for the difference between building and external air temperature (Fig. 1). In the numerical analysis, it was assumed that night-time ventilation starts at $h_i = 19h$ and ends at $h_f = 7h$. As a certain temperature difference is needed for effective convection, night ventilation is only applied if the difference between building temperature, T_b and external temperature, T_e is greater than $\Delta T_{crit} = 3K$.

2.2 Building temperature

As heat gains and night-time ventilation are not simultaneous, energy storage is an integral part of the concept. In the case of sensible energy storage, this is associated with a variable temperature of the building structure. This aspect is included in the model by defining building temperature as a sine oscillation around *24.5°C* with an amplitude of *2.5 K*. The maximum building temperature occurs at the initial time of night ventilation, h_i, and, given a ventilation time of 12 hours, the minimum building temperature occurs at the final time, h_f (Fig. 1). The temperature range $T_b = 24.5°C \pm 2.5°C$ is equivalent to that recommended for thermal comfort in offices [5] [6]. The exact definition of CCP and building temperature can be found in [7].

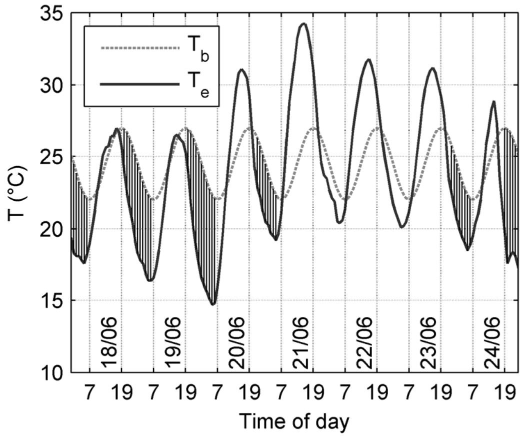

Figure 1: Shaded areas illustrate graphically the Climatic Cooling Potential during one week in summer 2003 for Zurich SMA (ANETZ data).

2.3 Climatic data

Hourly air temperature data are needed to analyse the climatic potential for the passive cooling of buildings by night-time ventilation using the presented approach. For Switzerland, the National Weather Service (MeteoSwiss) provides high-quality long time series of measured hourly temperature data. In addition to air temperature *2 m* above ground level, the automatic measurement network (ANETZ) measures a range of meteorological parameters.

The commercial database Meteonorm [8] provides semi-synthetic meteorological data for 7400 stations around the world. Hourly air temperature data are generated on the basis of measured long-term monthly mean values (mainly 1961-1990). For analysis of the climatic cooling potential in Europe, data were selected from 259 meteorological stations at densely populated locations.

2.4 Practical Significance of CCP

The following example should give an idea of the practical significance of the calculated degree-hours. This simple calculation should be seen only as a rough analysis. It is not intended to replace a detailed simulation for a specific building at a given location by means of a building energy simulation code.

The thermal capacity of the building mass is assumed to be sufficiently high so as not to limit the heat storage process. If the building is in the same state after one cycle, the heat which charges the building structure, Q_{charge}, during the occupancy period, t_{occ}, is equal to the heat released through night ventilation, $Q_{release}$. The mean heat flux during the storage process, $\dot{q}$, per room area, *A*, can then be calculated as follows:

$$\dot{q} = \frac{Q_{charge}}{At_{occ}} = \frac{Q_{release}}{At_{occ}} = \frac{\dot{m}c_p}{At_{occ}} CCP \qquad (1)$$

The effective mass flow rate, $\dot{m}$, is written as $\dot{m} = AHR\eta\rho$, where *H* is the room height, *R* the air change rate and η a temperature efficiency, defined as $\eta = (T_{out} - T_e)/(T_b - T_e)$, that takes account of the fact that the temperature of the outflowing air, T_{out}, is lower than the building temperature, T_b. The density and specific heat of the air are taken as $\rho = 1.2\, kg/m^3$ and $c_p = 1000\, J/(kg\, K)$.

Assuming a room height of $H = 2.5\, m$, a constant effective air change rate of $R\eta = 6\, h^{-1}$, and an occupancy time of $t_{occ} = 8\, h$, the heat flux, $\dot{q}$, absorbed per degree-hour of the cooling potential *CCP*, can be calculated as:

$$\frac{\dot{q}}{CCP} = \frac{2.5\, m \cdot 6h^{-1} \cdot 1.2 \frac{kg}{m^3} \cdot 1000 \frac{J}{kg\, K}}{8 \cdot 3600\, s} = 0.625 \frac{W/m^2}{K\, h} \qquad (2)$$

The solar and internal gains of an office space can vary substantially depending on the local climate, orientation and total solar energy transmittance of the façade, building geometry and type of building. Assuming e.g. internal heat gains of $20\, W/m^2$ and solar gains of $30\, W/m^2$ — with both values referring to the time period of *8 h* — a climatic cooling potential of about *80 K h* per day is needed to discharge the stored heat.

3. VERIFICATION OF THE METHOD

To verify the applicability of the presented method, the climatic cooling potential was calculated on the basis of measured hourly temperature data for Zurich SMA. ANETZ data downloaded from the National Weather Service (MeteoSwiss) data centre were employed. The data for 2003, which witnessed exceptionally high temperatures in July and August, were used [9].

3.1 Building temperature

Figure 1 shows the building temperature as defined in section 2.2, the measured external air temperature at Zurich SMA and the resulting climatic cooling potential (shaded area) for one week in June. In most cases, the theoretical building temperature appears reasonable in that it correlates quite well with the outdoor temperature. However, in the two nights between June 21st to 23rd, the building temperature drops to the same level, even without night ventilation, which is physically implausible. A cooling potential might exist during the later hours of the night-time period where the building temperature remains at a constant level. While a more 'realistic', building temperature could obviously be obtained using a building energy simulation code, the associated drawback of having to define numerous building parameters would entail a loss of generality.

3.2 Sensitivity of *CCP*

The sensitivity of *CCP* to different parameters was examined. Especially for nights with a high cooling potential, *CCP* was not found to be very sensitive to either the building temperature amplitude, ΔT_b, or the critical temperature difference, ΔT_{crit}. A slightly higher sensitivity was found in respect of the selected ventilation period, where a shift of $\pm 1h$ results in a variation of maximum $\pm 10Kh$ in *CCP* [7].

3.3 Cooling potential in different time intervals

For the comparison of different climates, the cooling potential can be averaged over a certain time period. It must, however, be remembered that nightly values exhibit wide fluctuations within a bandwidth of up to *200 K h* within a few days; weekly mean values still vary by about *50-100 K h* within a month. For example, although August 2003 witnessed a whole week without any notable potential for night cooling, the monthly mean value still exceeded *50 K h*. This warrants close attention, especially given that low night cooling potential is associated with a high cooling demand.

Not only does cooling potential per night differ within a month, the monthly mean values also vary over the years. The standard deviation, minimum and maximum of monthly mean values were computed for all calendar months for the period 1981-2002. Figure 2 also shows the impact of the exceptionally hot summer of 2003 [9] on the climatic potential for night cooling; mean values for June and August lie far below all the data from the previous 22 years. This might help to estimate the impact of a warmer climate on night cooling potential.

3.4 Applicability of semi-synthetic climatic data

The hourly temperature data provided by the meteorological database Meteonorm [8] are semi-synthetic values generated from monthly mean values. The applicability of Meteonorm data for calculating cooling potential was verified for two locations, Zurich SMA and Copenhagen Vaerlose [7].

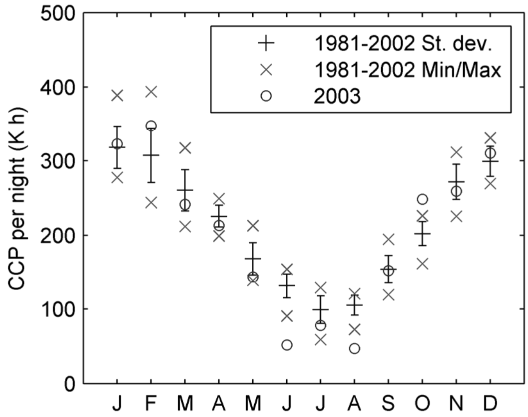

Figure 2: Mean value and standard deviation, minimum and maximum of monthly mean *CCP* for Zurich SMA 1981-2002 and monthly mean *CCP* for 2003 (ANETZ data).

4. RESULTS

To give a general picture of the climatic potential for night-time cooling in Europe, the July mean values for *CCP* were plotted on a map (Fig. 3). As expected, a clear gradation from north to south emerges. Even in the hottest month of the year, Northern Europe (including the British Isles) exhibits a very high cooling potential of *120* to *180 K h*. In Central and Eastern Europe, but also in the northern parts of Portugal, Spain, Greece and Turkey, the cooling potential is still *60* to *140 K h*.

Cumulative frequency distributions allow a more detailed analysis of cooling potential by showing the number of nights per year when cooling potential exceeds a certain value. Two cumulative frequency charts for 20 different locations showing the climatic *potential* for night-time cooling in maritime and continental climates are presented in the Appendix.

A usable potential during the colder periods can be observed at locations for which Figure 3 indicates only very low potential. For example, in Lisbon, where the July mean value is about *40-60 K h*, there are more than 200 nights per year with over *100 K h*. On the other hand, some 15 nights per year offer no cooling potential at all.

The cumulative frequency charts also illustrate the difference between continental and maritime climates. While the lines for maritime climates are flatter, the curves for continental climates cover a wider range of *CCP* and display a steadier gradient.

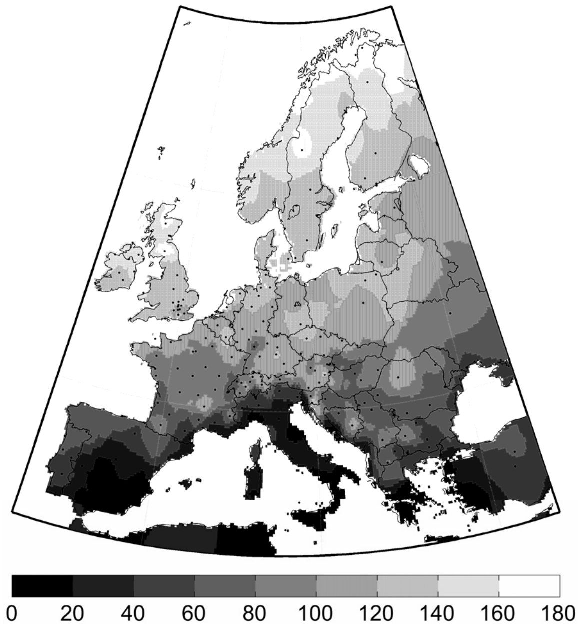

Figure 3: Map of mean Climatic Cooling Potential (K h / night) in July based on Meteonorm data [8].

5. OUTLOOK

As significant gradual global warming in consequence of increasing greenhouse gas concentrations is expected to occur within the service life of buildings constructed at the present time, the impact of rising temperatures on the potential of passive cooling by night-time ventilation warrants investigation. The temperatures observed during the exceptionally hot summer of 2003 could well serve as a preview of a typical summer at the end of this century [9]. The monthly mean *CCP* values in Zurich for June and August of that year are about *50 K h*, compared to *100 – 150 K h* in the years before. Given the wide variation in nightly values and the fact that warm nights are associated with a high daily cooling demand, this shift may cause periods of high thermal discomfort in buildings designed for cooling by night-time ventilation in present-day climatic conditions. It is clear that a more detailed analysis is needed of the night cooling potential in a warmer climate and, accordingly, the presented method will also be applied to climate projections for the end of this century.

The PRUDENCE project [10] provides climatic data for the period 2070-2100. These data were obtained by using Regional Climate Models (RCMs) for downscaling the results of Atmosphere Ocean General Circulation Models (AOGCMs) to a finer grid over Europe. Figure 4 shows the shift in the mean daily minimum temperatures in June to August, modelled by the Danish Meteorological Institute (DMI) and based on a HadAM3H A2 AOGCM simulation run. The trend is particularly marked in Southern Europe, totalling *5* to *6.5 K* for central Spain. A similarly pronounced shift emerges in the Baltic Sea region. In Northern, Central and Eastern Europe too, the shift in summer mean daily minimum temperature simulated by this model still reaches *2.5* to *5 K*. However, future climate simulation models — forcing scenarios, AOGCMs and RCMs — are subject to a high level of uncertainty, and a detailed analysis of data from different models plus related effect on cooling potential is needed.

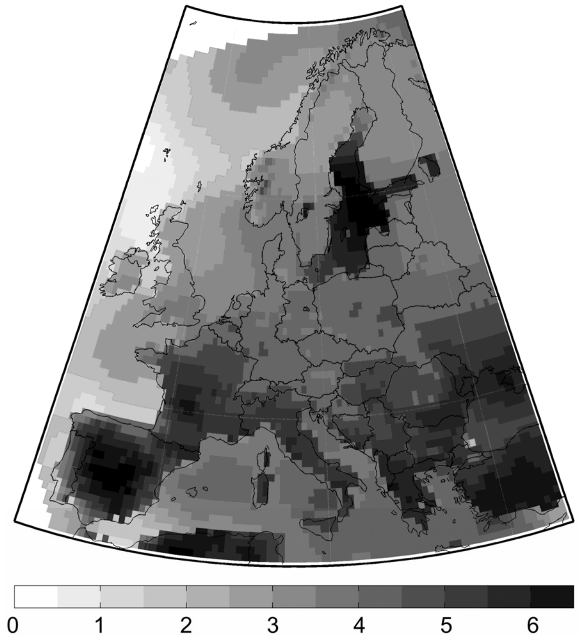

Figure 4: Map of shift in mean daily minimum temperature in June to August, modelled by DMI [10].

6. DISCUSSION

Under current climatic conditions, the whole of Northern Europe (including the British Isles) exhibits a mean *CCP* per night in July of roughly *120* to *180 K h*. Even allowing for variations in nightly values around the monthly mean value, this region appears to hold sufficient cooling potential to assure thermal comfort throughout the year in most cases.

Central, Eastern and some regions of Southern Europe offer a mean monthly *CCP* of *60* to *140 K h*. In these regions, cooling by night-time ventilation is a promising technique for most applications. Still, it must be remembered that nightly values can fall far below the monthly mean and that very low cooling potential may be experienced on a few nights per year. In the wake of climate change, the incidence of higher temperatures with high cooling demand and low night cooling potential is very likely to increase. The acceptability of the resulting discomfort needs to be examined for each specific case.

In regions such as southern Spain, Italy and Greece with mean *CCP* per night for July of less than *60 K h*, night-time ventilation alone might not suffice the whole year round. Other passive cooling techniques, such as radiant or evaporative cooling, might therefore prove useful for buildings requiring a high level of thermal comfort. Hybrid systems should be considered wherever passive systems cannot provide the required cooling duty. For example, even in air-conditioned buildings, night-time ventilation could service to cut the energy demand for the mechanical cooling system.

Some buildings, mainly commercial facilities with high internal and/or solar loads, need to be cooled even if the outdoor temperature is well below the thermal comfort limit. Thus, especially in the warmer climates of Southern Europe, cooling may also be required during spring and autumn, and even, for some buildings, in winter. Hybrid systems incorporating night-time ventilative cooling can be used in such cases to reduce the energy demand of air-conditioned buildings. Night-time ventilation would be exploited whenever the outside air temperature is significantly below the building temperature, with mechanical cooling serving as a backup to safeguard thermal comfort.

The information provided by cumulative frequency charts might be of particular interest for design engineers seeking to estimate the potential for cooling by night-time ventilation.

7. CONCLUSIONS

In this study, a method was developed to compute the climatic potential for the passive cooling of buildings by night-time ventilation. This method is based on a variable building temperature, which is intrinsic to this passive cooling concept. The building temperature varies within a range of thermal comfort as specified in international standards and is defined independently of any building-specific parameters. The robustness of the degree-hours approach was tested and the impact of the assumed building temperature function and the threshold value for the temperature difference between building and external air investigated. This method was employed for a systematic analysis of European climate with regard to passive cooling by night-time ventilation using 259 stations.

Considerable potential for the passive cooling of buildings by night-time ventilation was shown to exist throughout Northern Europe (including the British Isles), where the technique seems generally applicable. Climatic cooling potential is still significant in Central, Eastern and even in some regions of Southern Europe, though, given the inherent stochastic properties of weather patterns, series of warmer nights can occur at some locations, where passive cooling by night-time ventilation might not suffice to guarantee thermal comfort. If short periods of lower thermal comfort are not acceptable, additional cooling systems would be required. Climatic cooling potential is limited in regions such as southern Spain, Italy and Greece. Nevertheless, the passive cooling of buildings by night-time ventilation might be useful for hybrid systems.

The presented method provides a valuable aid in assessing the cooling potential offered by a particular climate and could be of greatest assistance during the initial design phase of a building at a given location. It must, however, be stressed that a more thorough analysis of the summertime transient thermal behaviour of a building needs to be based on a building energy simulation that factors in all building-specific parameters such as time-dependent internal and solar gains, active building thermal mass, thermal insulation of building envelope, along with air flow rates and patterns. The latter may even require a computational fluid dynamics analysis given that room geometry, window type and positioning may significantly affect the air flow rate and, hence, the cooling effect.

For a better understanding of the long-term potential of this technology, the impact of future gradual climate warming on cooling potential needs closer investigation. Also required is a more fundamental grasp of air exchange and the resulting cooling effect, backed by improved modelling algorithms in building energy simulation codes.

ACKNOWLEDGEMENTS

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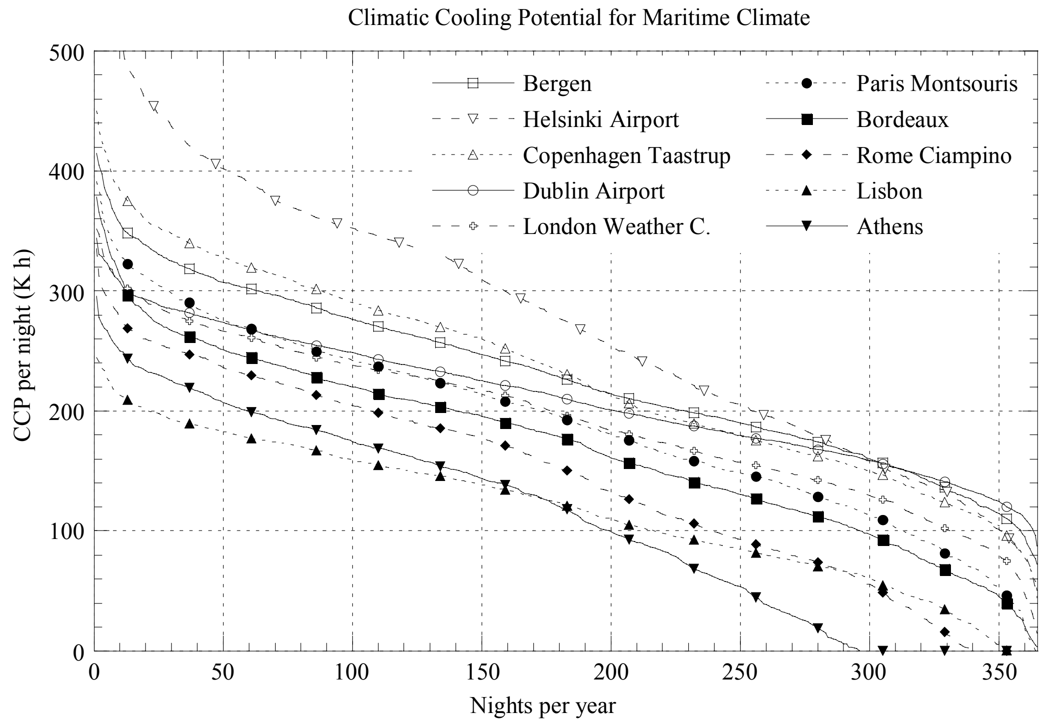
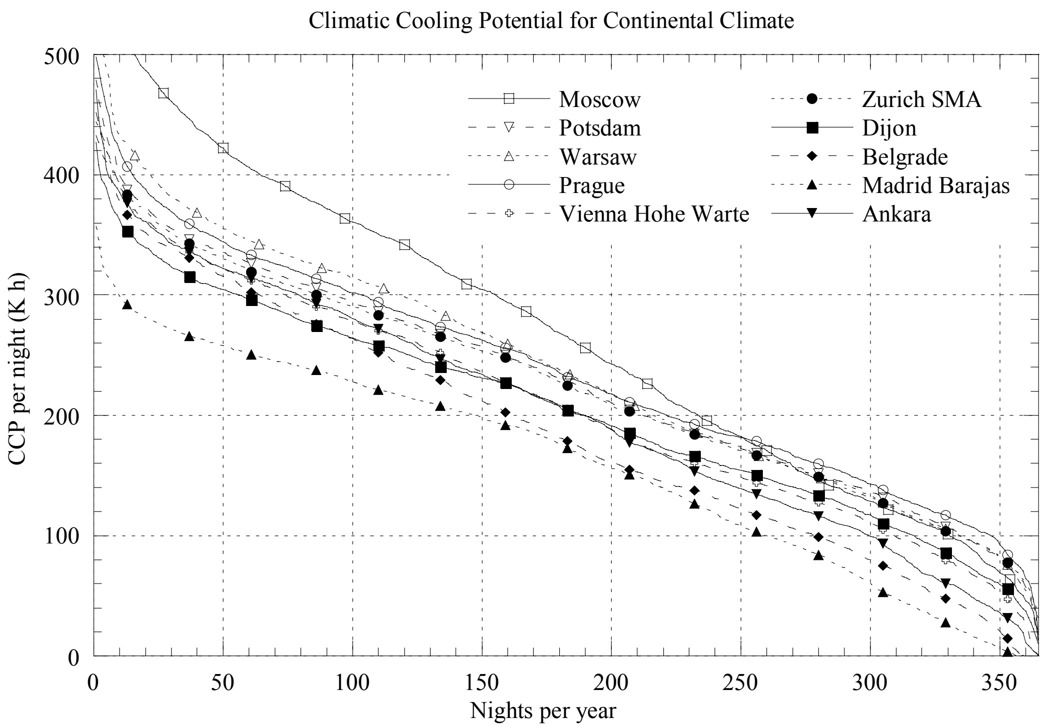
APPENDIX


Climatic Cooling Potential for Maritime Climate
CCP per night (K h)
Nights per year
Bergen
Helsinki Airport
Copenhagen Taastrup
Dublin Airport
London Weather C.
Paris Montsouris
Bordeaux
Rome Ciampino
Lisbon
Athens
0
100
200
300
400
500
0
50
100
150
200
250
300
350


Climatic Cooling Potential for Continental Climate
CCP per night (K h)
Nights per year
Moscow
Potsdam
Warsaw
Prague
Vienna Hohe Warte
Zurich SMA
Dijon
Belgrade
Madrid Barajas
Ankara
0
100
200
300
400
500
0
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