**Intra-urban nocturnal cooling rates: model development and evaluation**

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dated: 15 June 2015

1. Introduction

The urban heat island (UHI) and the intra-urban heat island (IUHI) are mainly nocturnal phenomena that develop through differences in cooling between urban and rural sites or between intra-urban sites of various types (Eliasson 1994; Runnalls and Oke 2000). These differences are a result of site characteristics such as building density, surface material, amount of vegetation and presence of anthropogenic heat (Oke 1987). It has been observed that nocturnal cooling progresses in two distinct phases (phase 1: site-dependent cooling around sunset, and phase 2: site-independent cooling from about one or two hours after sunset until sunrise) (Oke and Maxwell 1975; Upmanis et al. 1998; Holmer et al. 2007; Holmer et al. 2013). In this study, the temporal development of nocturnal cooling was investigated especially focusing on the two phases using observational data from Gothenburg, Sweden (Onomura et al. 2015). Based on the data analysis, a NOcturnal Cooling RAte Model (NOCRAM) was analytically developed to simulate nocturnal air temperature at urban sites using standard meteorological variables and sky view factor of the site. The model is evaluated with other datasets in the city and further applied to one built-up site with complex urban geometry in London UK.

2. Model development

2.1 Model structure

A conceptual profile of nocturnal cooling rates typical for open sites under ideal (clear and calm) conditions is shown in figure 1. The temporal development of cooling rates is partitioned into three parts, phase 1A, 1B and 2, which are drawn by red, blue and green thick lines. As a basic profile, the cooling rate curve is firstly created in the model. Initial cooling rate (CR1) of phase 1A is calculated using observed air temperature. Phase 1A and 1B are modelled with cosine functions using CR1, most intensive cooling rate (CRpeak) in phase 1 and initial cooling rate (CR2) of phase 2. The angles applied to the two phases range from 0 to π and π to 2π, respectively. Phase 2 is modelled with a linear function using CR2 under the assumption that cooling ends at sunrise. The profile is modified every time step by estimating the impact of the temporal changes in wind speed (ΔCRw(t)) on cooling rates (grey thin line in Figure 1). Cooling rates (CR) in the three phases are calculated as follows:

\[
\text{Phase 1A: } CR = (CR_1\cdot CR_{peak})/(\cos(f(t-t_1))-1)/2 + CR_1 + \Delta CR_w(t) \quad \text{when } t_1 \leq t < t_{peak} \\
\text{Phase 1B: } CR = (CR_2\cdot CR_{peak})/(\cos(f(t-t_{peak}))-1)/2 + CR_{peak} + \Delta CR_w(t) \quad \text{when } t_{peak} \leq t < t_2 \\
\text{Phase 2: } CR = (t_{end} - t)/(t_{end} - t_2)\cdot CR_2 + \Delta CR_w(t) \quad \text{when } t_2 \leq t < t_{end}
\]

where function f converts time into radian, \(t_1\) and \(t_2\) are the onset of phase 1A and 2, \(t_{peak}\) is the timing of the most intensive cooling and \(t_{end}\) is the end of phase 2. \(CR_{peak}\), \(CR_2\) and \(\Delta CR_w(t)\) as well as \(t_1\), \(t_2\), \(t_{peak}\) and \(t_{end}\) have to be determined to simulate a nocturnal cooling rate profile. The procedure for determining these variables is based on the data analysis in Onomura et al. (2015) and summarized in 2.2 – 2.5. Note that the current version of the model does not take into account the impacts of anthropogenic heat, latent heat (e.g. from vegetation and precipitation) and synoptic weather changes (e.g. cold fronts) on cooling rates.
The relationship is shown in figure 2b for $\text{CRIF}$ from 0 to 1.
The influence of SVF on \( CR_{\text{peak}} \) is handled by introducing the Sky View Impact Factor (SVIF), which is the ratio of \( CR_{\text{peak}} \) at a built-up site to an open site. The value of SVIF decreases with higher SVF under a certain condition of CI and \( U \). In the same way as figure 2b, the trend line for clear and calm condition was derived from the data analysis and assigned the average \( \text{CRIF} = 0.72 \). Under cloudy condition (average \( \text{CRIF} = 0.20 \)) SVIF was found to have little impact on \( CR_{\text{peak}} \), so SVIF was set to 0.99, which was treated as a threshold value below which SVIF does not change with SVF. Assuming that the relationship between SVIF and SVF scales linearly with CRIF, SVIF can be then expressed as:

\[
SVIF = CR_{\text{peak, built-up}} / CR_{\text{peak, open}} = 0.99 + b \cdot (1 - SVF)
\]

where \( b = -0.88 \cdot (\text{CRIF} - 0.2) / (1 - 0.2) \), which is shown graphically in figure 2c. Using SVIF, \( CR_{\text{peak}} \) is finally expressed as:

\[
CR_{\text{peak}} = [-0.2 - 0.083 \cdot \text{CRIF} \cdot (T_{\text{max}} + 13)] \cdot \text{SVIF}
\]

2.4 Determination of initial cooling rate in phase 2 (\( CR_2 \))

The magnitude of \( CR_2 \) was found to increase with lower hourly average wind speed at \( t_2 (U_2) \) under a certain condition of CI. The line trend under clear condition is derived from the data analysis and assigned the average CI = 0.96. It was also found that under cloudy condition (average CI = 0.57) \( CR_2 \) changes little with \( U_2 \). The line of CI = 0.57 is used to determine the minimum magnitude of \( CR_2 \). Assuming that the relationship between \( CR_2 \) and \( U_2 \) scales linearly with CI and that when \( U_2 \geq 2 \text{ m s}^{-1} \), \( CR_2 \) follows the line of CI = 0.57, \( CR_2 \) is expressed as:

\[
CR_2 = CR_{2\text{, min}} + (CR_{2\text{, clear}} - CR_{2\text{, min}}) \cdot (CI - 0.57) / (1 - 0.57)
\]

where \( CR_{2\text{, clear}} = -1.6 + 0.67 \cdot U_2 \) and \( CR_{2\text{, min}} = -0.34 + 0.03 \cdot U_2 \). The relationship is shown in figure 2d for CI from 0.57 to 1.

2.5 Modelling the impact of wind change

Cooling rates are affected by changes in weather, particularly wind and cloudiness. The effects of wind speed changes are considered in the model but cloudiness changes are not since cloud data are often not available during night. Every time step, the wind impact is estimated as a function of the third root of the difference between wind speed at the time step and average wind speed of the phase (\( \bar{U}_{\text{phase1A}}, \bar{U}_{\text{phase1B}} \) and \( \bar{U}_{\text{phase2}} \)). The use of the third root was determined by the sensitivity test, which showed that the impact of small wind speed changes on cooling rates is reasonably estimated using the third root rather than other formulas. The transition of atmospheric stability from unstable to stable is found to occur around \( t_{\text{peak}} \). It is suggested that higher wind speed brings colder air from above the canopy layer and enhances cooling rates in phase 1A, whereas it brings warmer air from above and diminishes cooling rates in phase 1B and 2. In addition, weak wind promotes mixing the air down to the ground (Acevedo and Fitzjarrald 2003). Therefore, higher wind speed than the average wind speed increases the magnitude of cooling rates during phase 1A, whereas it decreases during phase 1B and 2. The case of lower wind speed than the average wind speed is the other way around. Furthermore, the magnitude of the wind impact on cooling rates should decrease under cloudier condition due to weaker stratification of the atmosphere. Therefore, the Wind Impact Factor (WIF) is introduced to adjust the impact depending on CI. WIF is set to 0.35, 0.15 and 0.1 under clear (CI \( \geq 0.9 \)), semi-cloudy (0.75 \( \leq CI < 0.9 \)) and cloudy (CI \( < 0.75 \)) conditions, respectively. Finally, the variation of cooling rate caused by the wind speed change at time \( t (\Delta CR_{\text{w}}(t)) \) is estimated as

\[
\Delta CR_{\text{w}}(t) = \begin{cases} 
-WIF \cdot (U(t) - \bar{U}_{\text{phaseX}})^{1/3}, & \text{if } X = 1A \\
+WIF \cdot (U(t) - \bar{U}_{\text{phaseX}})^{1/3}, & \text{if } X = 1B \text{ or } 2
\end{cases}
\]
3. Model evaluation

3.1 Study site and data

An open site (SVF = 0.92) and a built-up site (SVF = 0.40) in Gothenburg Sweden and one built-up site (SVF = 0.46) in London UK were chosen for model evaluation. The former two sites are located in the city centre with most buildings having three to six stories and being almost regularly arranged. The site in London is located at the Barbican Estate, which has very complex urban settings and a large variation in building height. The sites mentioned were not used for the model parameterisation. Meteorological input data are taken from nearby reference meteorological stations (LUMA; Onomura et al. 2015). The SVF representing each site was taken to be the average SVF within a 25 m radius, calculated using digital surface models of buildings and vegetation as described in Lindberg and Grimmond (2010) and using the ArcMap 10.1 software.

3.2 Model performance

The mean profiles of modelled and observed cooling rates and air temperature for the three sites for the three CI classes are shown in figure 3. The model simulates cooling rates well for all the sites. From the profiles of the open site (first column), it is clearly seen that the model successfully estimates the magnitude of cooling rates decreasing with lower CI. Also the two phases in cooling are modelled as less distinct under cloudier condition. In comparison with a built-up site in Gothenburg (second column), the model is successful to reduce the magnitude of cooling rates in phase 1 with lower SVF under all the cloud conditions. For the built-up site in London, cooling rates are modelled with the performance as good as Gothenburg. This suggests that the model is able to simulate cooling rates at built-up sites with complex urban geometry using only SVF. For CI ≥ 0.9, standard deviations are large. This is due to a small number of the samplings, but also because of the large variation of wind speed probably related to the complex geometry. Using the modelled cooling rates, nocturnal air temperature is estimated with high accuracy (R² ≥ 0.80 and RMSE ≤ 1.61).
5. Conclusion

The NOcturnal Cooling RAte Model (NOCRAM) was analytically developed specifically to represent the process of nocturnal cooling progressing in two distinct phases, as well as to represent the relationships between cooling rates and sky-clearness, wind speed, maximum daily air temperature and sky view factor. The model requires commonly-used meteorological variables (i.e. incoming shortwave radiation, air temperature, relative air humidity, wind speed, and air pressure) as well as the geometric information (i.e. the sky view factor of the site and the geographical coordinates of reference meteorological station). The model simulates cooling rates well, capturing the characteristic development of cooling in the two phases under a wide range of wind and cloud conditions, as well as the effect of sky view factor on cooling rates. Using the modelled cooling rates, the temporal development of nocturnal air temperature is calculated with high accuracy. Due to its simplicity, the model can be easily used in climate applications, such as nocturnal human thermal comfort estimation and climate-sensitive urban planning and design.
Acknowledgment

This project is financially supported by the Swedish Research Council Formas, the Swedish Energy Agency, the Swedish Environmental Protection Agency, the Swedish National Heritage Board and the Swedish Transport Administration (214-2010-1706 and 250-2010-358). We appreciate Ms. Janina Konarska for operating the intra-urban air temperature measurement in Gothenburg during 2012 – 2014, and Mr. William Morrison and Dr. Simone Kotthaus for providing observational data from London.

References


