INCORPORATING SPATIAL AND TEMPORAL VARIATIONS OF ADVECTED MOISTURE IN THE CANYON AIR TEMPERATURE (CAT) MODEL

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Abstract

CAT (Canyon Air Temperature) is a parametric model that predicts site-specific air temperature in an urban street canyon for extended periods on the basis of data from a reference station in the region. A method is described for incorporating spatial and temporal variations in advected moisture, allowing application of the model with no prior knowledge of moisture availability in the area. The revised model is tested against data from field experiments in Gothenburg and Adelaide, in all seasons and in a variety of atmospheric conditions.

Key words: canyon model, advection, moisture availability

1. INTRODUCTION

The Canyon Air Temperature (CAT) model (Erell & Williamson, 2006) was designed to predict site-specific air temperature in an urban street canyon for extended periods on the basis of data from a reference station exposed to the same meso-scale weather, typically located at a nearby airport or in a semi-rural location outside of the city centre. Each site is described by means of its geometry (height of buildings, if any, and width of street); the albedo and thermal properties of the surfaces; moisture availability; and anthropogenic heat. Time-series of meteorological parameters measured at standard weather stations (including solar radiation), typically at hourly intervals, serve as descriptors of the constantly evolving meso-scale weather. By calculating site-specific modifications to air temperature resulting from the surface energy balance at each of the two sites, the model can predict the evolution of air temperature at one of them based on measured meteorological parameters in the other, in diverse weather conditions and for extended periods.

The first version of the CAT model was tested for a street canyon site in Adelaide, Australia, using fixed values for moisture availability based on monthly precipitation and on the surface cover characteristics of the immediate vicinity of the two sites. These were deemed sufficient to account for seasonal variations – and the model gave satisfactory predictions of air temperature.

However, such a simplified method lacks the capacity for universal application. In particular, it is unable to account for short-term variations in moisture availability, such as might be found in a location with frequent but irregular rainfall or where surface properties in the vicinity are highly heterogeneous. The purpose of this paper is to demonstrate a systematic way of assigning a value for the moisture availability that may be applied anywhere with no prior knowledge of local conditions, other than that obtained through standard meteorological records or from publicly available surface cover data.

2. THE CAT MODEL

2.1. Conceptual basis

At any location, the canopy level air temperature may be described in terms of a meso-scale "base" temperature overlaid by a local transformation that is caused by the unique properties of the site. The temperature for an urban site and for a meteorological station may thus be expressed as follows:

$$T_a(t)_{urb} = T_b(t) + \Delta T(t)_{urb} \tag{1}$$

$$T_a(t)_{met} = T_b(t) + \Delta T\ (t)_{met} \tag{2}$$

where T_a refers to air temperature at a given location, T_b the meso-scale base temperature, and ΔT is the local transformation. The subscripts '$_{urb}$' and '$_{met}$' refer to urban and meteorological (reference) locations, respectively. All elements are time-dependent. If one assumes that the meso-scale temperature at a certain elevation above the city is uniform and independent of location, then combining the above expressions yields:

$$T_a(t)_{urb} = T_a(t)_{met} + (\Delta T(t)_{urb} - \Delta T(t)_{met}) \tag{3}$$

To obtain the local transformation (ΔT), a complete energy balance must be calculated for both the urban site and the meteorological (reference) site, taking into account differences in net radiant flux, latent heat, thermal storage and anthropogenic heat. If there is substantial heterogeneity in surface cover near either of the sites – the effect of advection cannot be neglected.

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2.2 Sensible heat flux

In the energy balance calculation for each of the two sites, sensible heat flux is parameterized for each canyon surface from the net radiant balance (Q^*) and the storage flux (ΔQ_s) using the expression proposed by De Bruin and Holtslag, (1982), in the revised form given by Grimmond & Oke (2002) for urban conditions:

$$Q_H = \frac{(1-\alpha)+(\gamma/s)}{1+(\gamma/s)}(Q^* - \Delta Q_s) - \beta \quad (4)$$

where s is the slope of the saturation vapour pressure-versus-temperature curve; γ is the psychrometric constant; and α and β are empirical parameters. α depends on the soil moisture status, and accounts for the strong correlation of Q_H and Q_E with Q^*-ΔQ_S, whereas β accounts for the uncorrelated portion.

2.3 Assigning time-varying values for α in varying atmospheric stability conditions

The parameterisation above requires two empirical constants (α and β). Values for these constants depend upon the availability of moisture at the surface, which affects the parcelling of available energy into sensible and latent heat. Empirical data from several cities shows that α may vary between 0.19 (in dry Mexico City) to 0.71 (in more humid Chicago), averaging about 0.45, whereas the value for β in urban sites was found to be in the range –0.3 to 8.4, with an average of about 3 (Grimmond & Oke, 2002). A relationship between α and land cover in the source area for advected moisture was proposed on the basis of back-calculated experimental data, showing a correlation between α and the percentage of land covered, respectively, by vegetation *Fv* ($\alpha = 0.686\,F_v + 0.189$) or by irrigated plants *Fir* ($\alpha = 0.610\,F_{ir} + 0.222$). The present study assigned a time-dependent value for α based on these correlations but calculated from the fraction of the upwind surface area that is covered by vegetation and by water.

Atmospheric stability affects the distance moisture is likely to be transported to the site from potential source areas. The effect of atmospheric stability on the turbulent source areas may be assessed according to Schmid and Oke (1990). However, this approach has two limitations within the present context: From the theoretical standpoint, one should note that their model is restricted to unstable conditions (L<0). From a practical standpoint, L cannot be calculated only from data available from typical weather stations operated by the meteorological service. CAT uses empirical stability relationships that are based on the difference between air temperature at screen height (which is given as input) and the sol-air temperature of the surface at the reference site as an approximation of the real surface temperature (Erell and Williamson, 2006).

It is not practical to generate separate surface cover maps for source areas contributing to the site in all possible stability conditions. The approach adopted here is to assign different weights to predetermined fixed source areas, according to stability: nearby areas are assumed to have a greater effect in stable conditions. α is then calculated from the following expression, which is adapted from the empirical correlations reported in Grimmond and Oke (2002) by adding weighting factors to account for variations in source area at different stability conditions. The values of the numerical coefficients in Equation 5 (0.2 and 0.65) are the average of those obtained for the vegetated and irrigated surface fractions in G&O. Successful implementation of these correlations will provide an independent test of their accuracy.

$$\alpha = 0.2 + 0.65 * [s_{100} * (F_{w100} + F_{v100}) + s_{500} * (F_{w500} + F_{v500}) + s_{1000} * (F_{w1000} + F_{v1000})] \quad (5)$$

F_w and F_v are the surface fraction of each source area covered by water bodies and vegetation, respectively. The subscripts 100, 500 and 1000 refer to the maximum distance from the site (in meters) covered by each of these areas. s_{100}, s_{500} and s_{1000} are weighting factors that assign the relative contribution of the source areas in each sector according to atmospheric stability. Their sum is always equal to unity. The values of the stability weighting factors for different atmospheric conditions were obtained by optimizing model performance for one month, and were then left fixed for the rest of the analysis.

3. EXPERIMENTAL EVALUATION

The revised CAT model was evaluated using meteorological data obtained from two sites in Gothenburg, Sweden, for a period of over one year. Data for an urban street canyon (Eliasson et al, 2006) – see Figure 1a - were the object of the simulation, which used data from a station run by the Swedish Meteorological and Hydrological Institute (SMHI) located about 2 kms east of the canyon (Figure 1b) as input for the model.

Average wind direction was calculated on an hourly basis, and a fetch sector was assigned accordingly from one of 16 source areas corresponding to 22.5-degree pie-shaped sectors centered on the site. Each sector was further divided into concentric rings, at distances of 100-500 meters from the site and 500-1000 meters away (Figure 2). The area immediately adjacent to the site, up to a distance of 100 meters, is considered as a separate source area, independent of wind direction.

The database of surface cover is prepared using aerial photographs (Google Earth), in which the proportion of each sector covered by vegetation and water is estimated visually. No attempt is made to distinguish between irrigated or non-irrigated vegetation: this information cannot be obtained from these photographs (although it might be available from satellite photos using other sensors), and might change during the course of the experiment. Since irrigation is not common in Sweden, this was not expected to have an effect on the results.

4. RESULTS

The quality of the model was assessed by comparing the predicted air temperature, provided at hourly intervals, with measured data. Simple tests of correlation are inappropriate as a measure of goodness of fit, since there is a high degree of auto-correlation between the variables. The primary metric used was the Williamson degree of confirmation (Williamson, 1995): It gives a value of '0' if the predicted value is not a better indicator of the measured value than a trivial estimate (in this case, T_{met}), a value of 1 for perfect prediction and negative values if the predicted value is a worse estimate of T_{canyon} than T_{met}.

Initial results from Gothenburg were promising: The Williamson degree of confirmation obtained for separate month-long periods spanning an entire year was in the range of 0.3-0.5, indicating a substantial improvement on the use of raw data from the weather station. Figure 3 compares simulated canyon temperature with measured data for the canyon and for the SMHI station over a period of 8 consecutive days during November 2003.

Variations in the value of α, as an indicator of moisture availability, were analyzed for the month of November, a total of 720 hours. The average value of α calculated for the two sites was nearly identical – 0.40 at the reference site compared with 0.38 at the street canyon, in spite of the radically different site characteristics (as illustrated by Figure 1). However, the value of α also exhibited substantial variations, reflecting the different source areas. Table 1 shows values for α at the canyon site, calculated from Equation 5. Mean values for 8 wind directions are presented (although the CAT code actually uses a finer

Figure 1. Goteborg canyon site (top) and SMHI weather station (bottom).

Table 1. Variation of moisture availability coefficient α at the urban canyon site with wind direction and atmospheric stability, calculated from Equation 5.

	stability					freq.
wind dir.	very stable	stable	neutral	unstable	very unstable	hours
N	-	0.37	0.41	0.46	-	38
NE	-	0.24	0.25	0.24	-	59
E	-	0.25	0.25	0.25	-	128
SE	-	0.31	0.42	0.46	-	156
S	-	0.37	0.39	0.42	0.55	166
SW	-	0.32	0.39	0.38	0.30	80
W	-	0.46	0.52	0.57	0.64	48
NW	-	0.55	0.50	0.56	0.53	31
freq.	14	91	114	494	7	

Note: In very stable conditions, wind speed was '0', and was not assigned a direction.

Figure 2. Land surface cover in source areas for moisture at the canvon site.

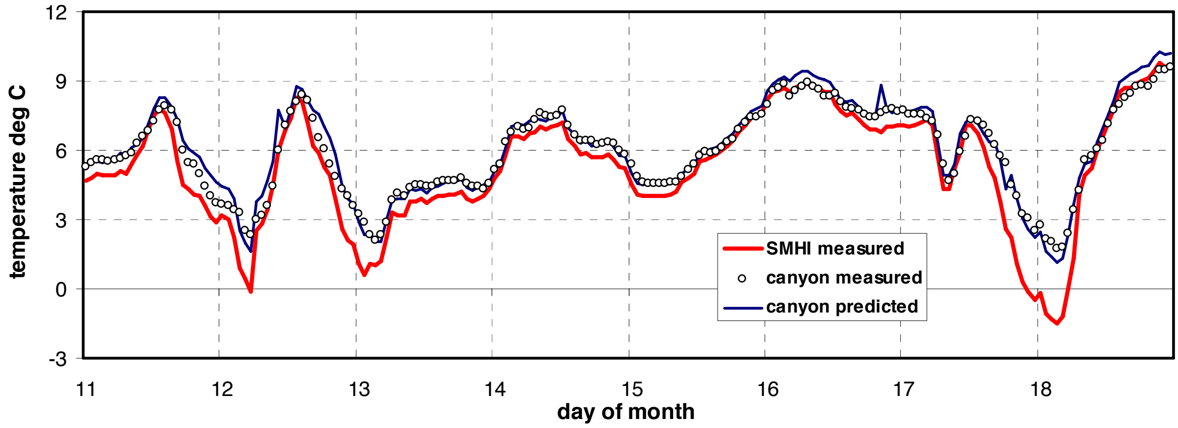

Figure 3. Time series showing measured air temperature at the SMHI station (used as a reference) and predicted and measured temperature at the street canyon site.

spatial grid based on 16 sectors), binned according to atmospheric stability. For north-easterly to south-easterly winds, moisture availability is low, reflecting the urban character of the source area, irrespective of stability. For southwesterly to northwesterly winds, values for α are substantially higher – and tend to increase with instability, as the source area comprises extensive areas of water. In highly stable conditions, possible only when wind speed was extremely low, α=0.27 .

5. DISCUSSION AND CONCLUSIONS

Site-specific climate knowledge is essential for the development of a building design that responds to the local environment, for accurate design of HVAC systems and for the development of efficient control strategies. The CAT model was developed as a tool to generate such data from measured records at a standard weather station. Evaluation of the model using Gothenburg data demonstrated that accurate modeling of air temperature at any given location also requires a means of establishing the the concurrent time-varying moisture. The methodology described here provides two contributions to the state of the art:

1) It provides independent empirical support for the parameterization of the moisture availability coefficient α proposed by Grimmond and Oke (2002).

2) It provides a demonstration of the capabilities of CAT using experimental data obtained independently in Gothenburg, in climate conditions and physical surroundings that are quite different to those in Adelaide on which it was first tested in the original formulation of the model.

The revised CAT model still needs some work. In particular, the stability coefficients for the moisture source areas (Equation 5) have been fixed arbitrarily, and the sensitivity of the model to their values needs to be assessed.

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