THE EFFECT OF STABILITY ON ESTIMATED 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. Moisture availability is determined by site surface cover only in super-stable conditions and in the absence of wind. In other weather conditions, the effect of stability on advection from more distant source areas is weak.

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

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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:

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

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

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:

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

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.

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:

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

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 relation 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, 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 incorporates the Obukhov stability length,, L, which cannot be calculated only from data available from typical weather stations operated by the meteorological service. CAT uses empirical stability relations 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. α is calculated from equation (5), which is adapted from Grimmond and Oke (2002) by adding weighting factors to account for variations in source area at different stability conditions.

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

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 m) 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 equal to unity. The values of the numerical coefficients in (5) (0.2 and 0.65) are the average of those obtained for the vegetated and irrigated surface fractions in their study. Successful implementation of these correlations will provide an independent test of their accuracy.

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 area was assigned accordingly from one of 16 source areas corresponding to 22.5° pie-shaped sectors centred on the site. Each sector was further divided into concentric rings, at distances of 100-500 m from the site and 500-1000 m away (Figure 2). The area immediately adjacent to the site, up to a distance of 100 m, 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 images using other sensors), and might change during the course of the observation period. 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 and moisture content at the canyon site, 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

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

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}.

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

Initial results from Gothenburg are 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. The quality of the predictions is illustrated in Figure 3, which 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 May 2004 (for which full moisture data are available). Values of the stability weighting factors for different atmospheric conditions were assigned so as to minimize the error in predicted air temperature for this period, as indicated by the Williamson Degree of Confirmation. The same values were then used to test the model for several other month-long periods..

The value of α calculated using (5) varied for the two sites with the changing synoptic, stability and land cover conditions (Figure 4). For north-easterly to south-easterly winds, moisture availability was low, reflecting the urban character of the source area, irrespective of stability. For south-westerly to north-westerly winds, values for α are substantially higher, as the source area comprises extensive areas of water. The average value of α calculated for the month of May 2004 was 0.34 at the reference site compared with 0.43 at the street canyon, in spite of the latter having practically far fewer local sources of moisture. The difference is attributed to advection from the river (as illustrated by Figure 2).

The effect of atmospheric stability on the source areas for moisture is dichotomous: In super-stable conditions, with no wind, moisture availability is determined primarily by the properties of the area immediately adjacent to each of the measurement locations. In all other conditions, the local site characteristics have a very small effect, and moisture availability must
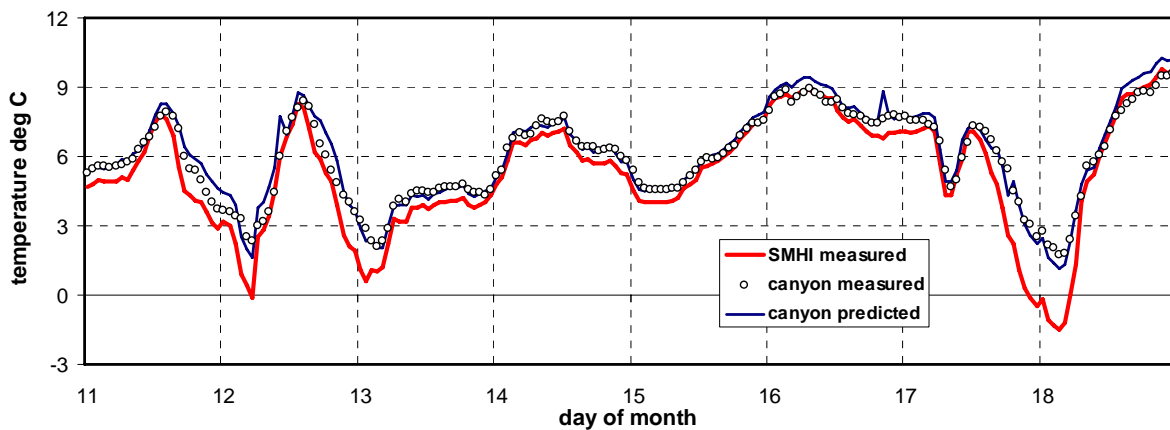

Figure 3. Time series showing measured air temperature at the SMHI station (reference site) and predicted and measured temperature at the street canyon site.
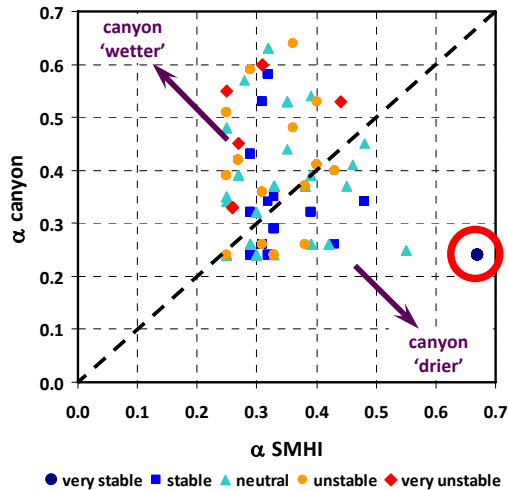
Figure 4. Hourly moisture availability (calculated from equation 5) at two sites by stability conditions, with the respective source areas. The circled dot at bottom right represents perfectly calm weather, in which there is no advection and moisture availability depends only upon site properties. Data for May 2004.

Figure 5. Except for perfectly still conditions, differences between the sites in moisture availability (α, as calculated by Equation 5 and represented by different shades of blue), appear to have little (direct) correlation with atmospheric stability; wind direction is the primary factor controlling moisture availability. Data for May 2004.

be calculated based on the surface cover of the upwind source area. However, as shown in Figure 5, differences in surface cover between the inner and outer rings in any given sector are not sufficient to determine a clear effect of stability on the moisture availability for the particular sites in Gothenburg (other than for the super-stable state).

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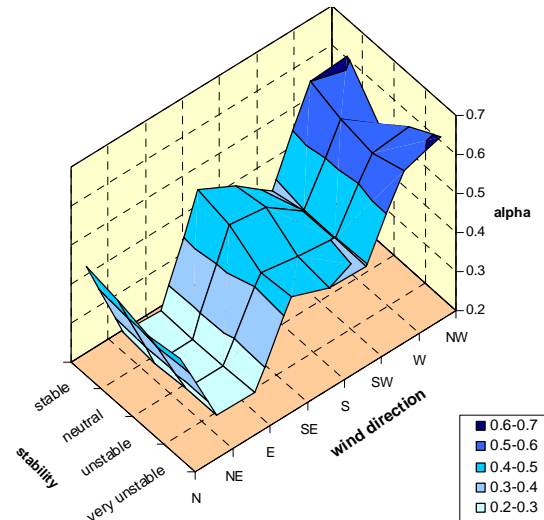
2) It provides a demonstration of the capabilities of CAT using experimental data obtained independently in Gothenburg, in climate conditions and physical surroundings that are quite different to those in Adelaide on which it was first tested in the original formulation of the model.

The revised CAT model still needs some work. In particular, although predictions of air temperature are good, those for air moisture content, although an improvement over non-urbanized data, are still less useful. Model performance at present is not sufficiently sensitive to establish with certainty the values of the stability coefficients for the moisture source areas used in Equation 5.

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