

# MICROCLIMATE MODIFICATION: CALCULATING THE EFFECT OF TREES ON AIR TEMPERATURE

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## ABSTRACT

This study is a part of a masters thesis by the author, in which a methodology has been developed to quantify cooling of air due to trees at the scale of a house or a residential neighborhood. The cooling effect on ambient air is associated with the phenomenon of evapotranspiration, and dispersion of moisture into the atmosphere. In this pilot study a model has been proposed for calculating evapotranspiration rate and moisture dispersion pattern around trees. Temperature distribution is then calculated and demonstrated by solving sample study cases.

## 1. INTRODUCTION

Cooling of air temperature due to the effect of trees has been well documented in the past through various studies. A tree can be regarded as a natural “evaporative cooler” using up to 100 gallons of water a day (Kramer and Kozlowski, 1960). This rate of evapotranspiration translates into a cooling potential of 230,000 kcal/day. This cooling effect, observed in a study by Geiger, is the primary cause of 5 deg C differences in net peak noontime temperatures observed between forests and open terrain, and a 3 deg C difference found in noontime air temperatures over irrigated millet fields as compared to bare ground (Geiger, 1957). Temperature measurements in suburban areas recorded similar but smaller variations in daytime peaks of 2 deg C to 3 deg C between neighborhoods under mature tree canopies and newer areas with no trees (McGinn, 1982).

The release of moisture into the atmosphere through the stomata of leaves is caused due to the evaporation of water at the stomata into the air, thus causing cooling of the air.

The problem of quantifying this cooling of air, lies in the difficulty of understanding the pattern of dispersion of moisture into the atmospheric boundary layer, due to the action of turbulence. In this study, a model is presented to calculate evapotranspiration rate from a species of tree and to determine its dispersion in the air. Following this a method of quantifying the decrease in air temperature is proposed and demonstrated using study cases.

## 2. PREVIOUS STUDIES

A study from Lawrence Berkeley Laboratory by J. Huang, H. Akhbari, H. Taha and A.H. Rosenfeld titled “The Potential of Vegetation in Reducing Summer Cooling Loads in Residential Buildings” (Huang, et al., 1987) describes a model to estimate the cooling of air temperature due to trees at the scale of a city. Using an equation for calculating potential evapotranspiration, the quantity of moisture being released by trees in a city is computed. A ‘mixing height’ is then determined, which becomes the basis of estimating a volume of air above the city into which moisture released from the trees is assumed to be mixed uniformly due to turbulence. It is assumed that the effect of the additional evapotranspiration is adiabatic and results in lowered dry bulb temperatures, increased humidity ratios, but no change in wet bulb temperature. The resulting humidity and dry bulb temp are hence calculated.

## 3. NEW APPROACH

Some of the limitations of the study by Huang et al., are identified below:

(a) It is assumed that the air over the city is well mixed with no differences in potential temperatures and humidity ratios (i.e., the only temperature differences are due to adiabatic lapse rate)

(b) The cooling effect of evapotranspiration from an increased number of trees is uniform throughout the urban microclimate.

(c) The model cannot be of use to calculate cooling localized in a neighborhood, as the concept of mixing height and the model described for it will no longer be applicable. The authors recognize this limitation of their work by stating that "... cooling can be localized at the neighborhood level, the correct solution of these local effects requires a three dimensional urban climate model."

(d) The use of potential evapotranspiration compromises on accuracy as it only predicts the maximum evapotranspiration possible assuming ample supply of water and favorable conditions. Trees in the city considered may not experience these conditions.

To counter the above-mentioned limitations, and to develop a model for predicting microclimate modification at the scale of a house or a neighborhood, a new approach was adopted for this study.

### 3.1 Estimating Evapotranspiration

All plants transpire water at a rate relative to their species, availability of water at the site, and other climatic factors such as wind-speed, access to solar radiation, humidity and temperature of the air. In this study, to determine the amount of evapotranspiration as a function of time and ambient conditions, an empirical model is employed.

Evapotranspiration for a particular crop or species of tree ( $ET_C$ ) is determined by multiplying a crop coefficient ( $K_C$ ) by the reference evapotranspiration ( $ET_O$ ).

$$ET_C = K_C ET_O$$

For a single tree, the volumetric rate of evapotranspiration ( $V_{ET}$ ) is obtained by multiplying the crown area ( $A_C$ ) by the evapotranspiration rate of the tree ( $ET_C$ ). (Akbari et al., 1992)

$$V_{ET} = ET_C A_C = K_C ET_O A_C$$

To estimate reference evapotranspiration ( $ET_O$ ) for any given climatic condition, the 'ASCE and FAO Penman Monteith' method has been chosen for this study and is described below. This equation has been formulated using the reference ET computation guidelines and procedures

that were recommended in ASCE (American Society of Civil Engineers) Manuals and Reports on Engineering Practice No. 70. "Evapotranspiration and Irrigation Water Requirements" edited by Jensen, et.al (1990). and has been quoted here from the REF-ET Reference Manual 2000, edited by Dr. Richard G. Allen, University of Idaho.

$$ET_o = \left( \frac{\Delta(R_n - G) + K_{time} \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left( 1 + \frac{r_s}{r_a} \right)} \right) / \lambda$$

where

$ET_o$	is the reference evapotranspiration, (mm d <sup>-1</sup> or mm h <sup>-1</sup> )
$R_n$	is the net radiation, (MJ m <sup>-2</sup> d <sup>-1</sup> or MJm <sup>-2</sup> h <sup>-1</sup> )
$G$	is the soil heat flux, (MJm <sup>-2</sup> d <sup>-1</sup> or MJm <sup>-2</sup> h <sup>-1</sup> )
$(e_s - e_a)$	represents the vapour pressure deficit of the air, (kPa)
$e_s$	is saturation vapour pressure of the air, (kPa)
$e_a$	is the actual vapour pressure of the air, (kPa)
$\rho_a$	is the mean air density at constant air pressure, (kg m <sup>-3</sup> )
$c_p$	is the specific heat of the air, (MJ kg <sup>-1</sup> °C <sup>-1</sup> )
$\Delta$	is the slope of the saturation vapour press temp relationship, (kPa °C <sup>-1</sup> )
$\gamma$	is the Psychrometric constant, (kPa °C <sup>-1</sup> )
$r_s$	is the (bulk) surface resistance, (s m <sup>-1</sup> )
$r_a$	is the aerodynamic resistance, (s m <sup>-1</sup> )
$\lambda$	is latent heat of vaporization, (MJ kg <sup>-1</sup> )
$K_{time}$	is a units conversion, equal to 86,400 s d <sup>-1</sup> for ET in mm d <sup>-1</sup> and equals 3600 s h <sup>-1</sup> for ET in mm h <sup>-1</sup>

### 3.2 Estimating Moisture Dispersion

To be able to quantify cooling from the moisture released by trees in the neighborhood, it is important to understand the dispersion pattern of the moisture in the neighborhood and the advection of moisture in the windward direction

From the point of view of dispersion, the case of moisture being released by a tree, is similar to that of any other source, say an industrial plant, releasing a gas from its stack. Since water vapour behaves as a perfect gas, this analogy implies that equations used to describe pollution dispersion can be used to trace the concentration profile of water vapor from a tree.

Dispersion of moisture can be calculated using a simple gaussian dispersion model described below as referenced from Oke (1978).

$$\chi_{(x,y,z,H)} = \frac{X}{\pi\sigma_y\sigma_z\bar{u}} \exp\left[-\frac{y^2}{2\sigma_y^2}\right] \times \left[ \exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right) \right]$$

where

- $\chi$  concentration of pollution at any point in a plume (kg/m<sup>3</sup>, more reasonably – g/m<sup>3</sup>)
- $X$  rate of emission from the source (kg/s)
- $\sigma_y, \sigma_z$  horizontal and vertical standard deviations of the pollutant distribution in the y and z directions (m)
- $\bar{u}$  mean horizontal wind speed through the depth of the plume (m/s)
- $H$  height of tree from base of trunk to center of foliage (m)

A tree can be assumed to be a stack projection, of Height  $H$ , which releases vapour at a steady rate  $X$ , calculated by using the model for evapotranspiration described earlier.

Dispersion studies performed using the above described dispersion model show the characteristic bell-shaped concentration profile of concentration, at the ground level, downwind from the source as seen in Fig. 1.

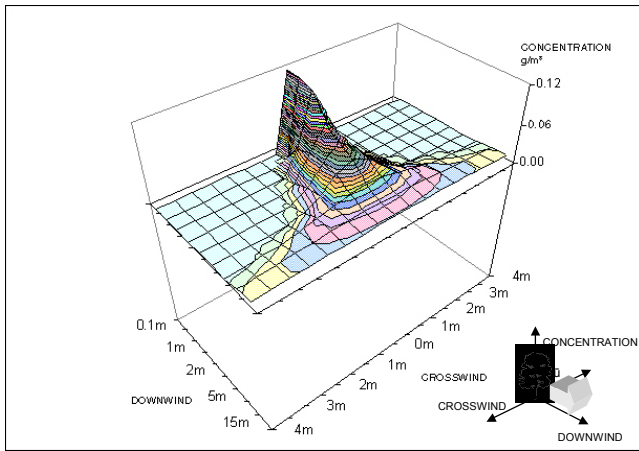


Fig. 1: 3D plot of concentration profile of water vapour downwind from a single tree plotted using the gaussian plume dispersion model.

The base conditions for the graph in Fig. 1 are: Emission rate of source  $X$  (g/s) = 0.8, Wind speed  $\bar{u}$  (m/s) = 1, Tree Height = 4, Height of observation plane  $z$  (m) = 0.

### 3.3 Calculating Air Temperature in a Residential Neighborhood with Trees

Study cases were developed to demonstrate the methodology developed to estimate cooling due to evapotranspiration.

The study cases consists of - a hypothetical design of a neighborhood composed of about 144 residential units of approximately 1000 sq.ft., each with an individual plot of 5600 sq.ft. House type A is a house with no trees and House type B, a house with six trees planted in its back and front yards.

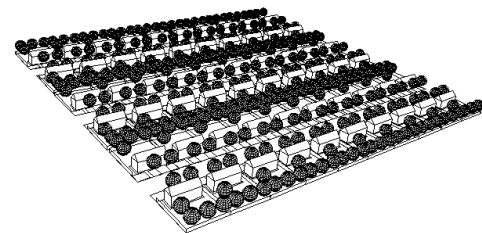
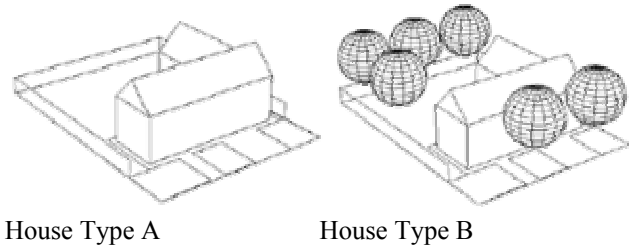


Fig 2: Study Cases. House types and neighborhood comprising of all Type B Houses.

Using the equations described in sections 3.1 and 3.2, rate of evapotranspiration, and moisture dispersion from a single tree can be determined. The same method is now applied to an array of six trees in the case of a single house (House type B) using a worksheet developed in Microsoft® Excel. Evapotranspiration rate for each tree is different as they are each exposed to slightly different environmental conditions.

Fig. 3 shows one such contour plot of moisture concentration around a single house with six trees (House type B). Wind direction is from top of the image. Wind speed = 1m/s, atmospheric stability rating = B, Tree Kc value = 0.65, Height of building = 4m.

To quantify the decrease in temperature, it is first required that total moisture content in a volume of air around the house (control volume) be calculated. This is done by creating moisture contours as in Fig. 3, for a plane of observation at every meter of height starting from the ground level ( $i=0$ ) to the top of the control volume ( $i=h_{cv}$ , where  $h_{cv}$  is the height of the control volume), shown schematically in Fig. 4.

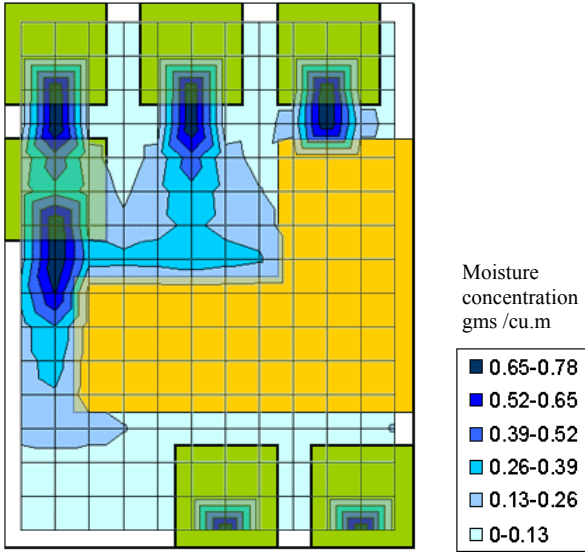


Fig. 3: Contour plot of moisture concentration around house type B.

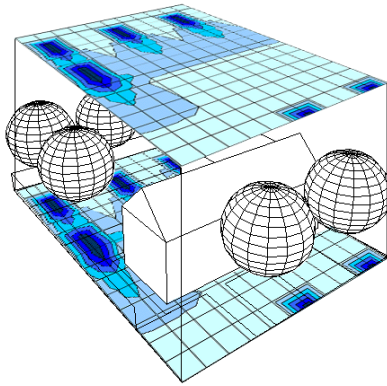


Fig. 4: A control volume with moisture concentration at two planes of observation: At the base  $i=0$  and top  $i=h_{cv}$

A summation of these values is done to obtain the moisture content of the control volume in gms or lbs of moisture.

$$m_{total} = \sum_{i=1}^{i=10} m_i$$

Since this process of evapotranspiration involves evaporation of water at the stomata of leaves, it is assumed to be adiabatic, in other words, due to the addition of moisture into the air, the wet bulb temperature remains the same, only the humidity increases and the dry bulb temperature decreases. Using a psychometric chart, this cooling can now be quantified in the same way as evaporative cooling.

#### 4. STUDY CASE CALCULATIONS AND RESULTS

For the study cases described earlier, calculations were done for 1st June 12:00pm using the TMY2 weather file of Phoenix, Arizona. A tree of radius 1.5 m has been considered with a  $K_C$  value of 0.8. The calculations result in an emission rate of 6.27 g/sec from one tree. Other values for other trees in the neighborhood are also computed. This value is then used in the Microsoft® Excel worksheet to obtain a dispersion pattern and moisture content in a control volume. Fig. 5 and Fig. 6 show two different moisture concentration profiles at ground level for a house type B. In the first case the houses around it are type A and in the second case they are type B.

**Temperature decrease**  
= 1.07 deg F

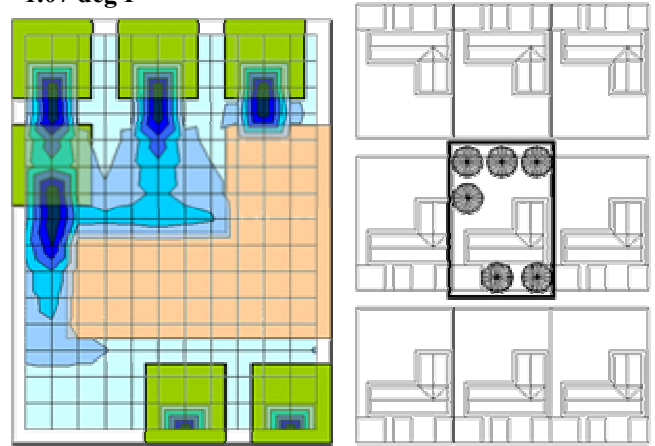


Fig. 5: Moisture dispersion in a study case for a type B house with trees, surrounded by type A houses without trees.

The dry bulb temperature depression is then calculated using a psychometric chart. It is found that the temperature decreases by 1.07 deg F in the first case, and by 1.34 deg F for the second case. The effect of advection of moisture from trees from other type B houses causes the greater temperature decreases in the second case.

The Microsoft® Excel workbook provides a flexibility to change inputs and create many variation of the sample cases solved here. Variables that can be changed include position of trees and houses, evapotranspiration rate, wind speed, atmospheric stability conditions and tree and building heights.

Temperature decrease  
= 1.34 deg F

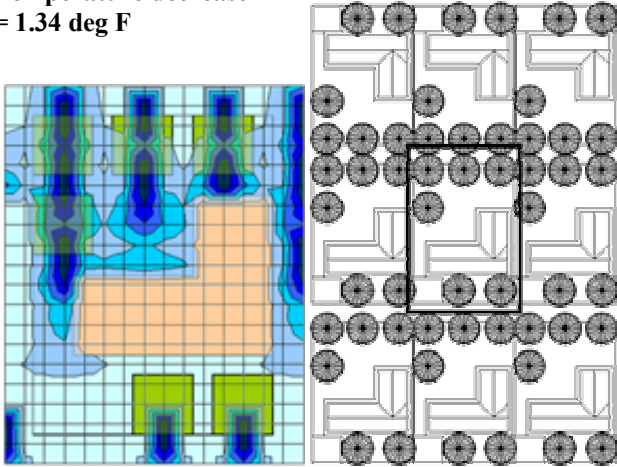


Fig. 6: Moisture dispersion in a study case with a type B house with trees surrounded by other type B houses.

## 5. ACKNOWLEDGMENTS

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