

# **Simulating microscale climate interactions in complex terrain with a high-resolution numerical model: A case study for the Sydney CBD Area (Model Description)**

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## **ABSTRACT**

The lower part of the atmosphere where we live is directly influenced by local exchange processes which can develop an individual local climate, different to the expected average conditions. Especially in urban areas the great variety of different surfaces and sheltering obstacles produces a pattern of distinct microclimate systems. To simulate these local systems, microscale numerical models with special extensions for typical artificial urban boundaries are needed. The basic concept and the main equations of the three-dimensional non-hydrostatic model ENVI-met [1,2] are presented in this paper. The model was used to simulate the local climate inside the Sydney CBD Area. Due to the complexity, the simulation results are only presented on the poster or can be seen on the ENVI-met website [3].

## **INTRODUCTION**

Analyzing the interactions between the environment and the atmosphere on local scale is much more complicated than looking at the same system on a regional scale. The multitude of different surface materials and sheltering objects produce a very distinct pattern of different climate conditions, especially within the building structures such as street canyons or backyards.

This paper presents the microscale model ENVI-met [1,2] which is able to simulate the interactions between different urban surfaces, vegetation and the atmosphere. ENVI-met allows to analyze the effects of small scale changes in urban design (e.g. trees, backyard greening, new building constellations) on microclimate under different mesoscale conditions.

The model is used to study the interactions between environment and the atmosphere in the CBD of Sydney, Australia. The Sydney CBD Area, including the harbor districts and the Botanical Gardens, build a system of very different urban elements forming the local climate by interacting in a complex way. Very tall buildings in the main CBD create a strong modification of the atmospheric boundary up to a height of more than three hundred meters. This area of high roughness is surrounded by the Botanical Gardens with grass and occasional trees as well as by the Pacific Ocean. Both systems have a moderate daily surface temperature amplitude, high transpiration rate and reduced wind friction offering good ventilation properties.

Because of their complexity, the results cannot be show in an suitable form in this paper. They are presented on the accompanying poster on the ICUC/ICB Conference and can be downloaded from the ENVI-met Website [3]. At this location, you can also download the software package which is Freeware. You are welcome to use it for your own needs.

## **MODEL DESCRIPTION**

Only the basic equations from the physical model are presented here. The complete model system includes a number of additional moduls such as biometeorological or particle dispersion models, not used in this study.

### a) Mean Air Flow

The basic concept to describe three-dimensional turbulent flow is given by the non-hydrostatic incompressible Navier-Stokes equations in the *Boussinesq*-approximated form (1a – c) and the Continuity equation (2):

$$\frac{\partial u}{\partial t} + u_i \frac{\partial u}{\partial x_i} = -\frac{\partial p'}{\partial x} + K_m \left( \frac{\partial^2 u}{\partial x_i^2} \right) + f(v - v_g) - S_u \quad (1 a)$$

$$\frac{\partial v}{\partial t} + u_i \frac{\partial v}{\partial x_i} = -\frac{\partial p'}{\partial y} + K_m \left( \frac{\partial^2 v}{\partial x_i^2} \right) - f(u - u_g) - S_v \quad (1 b)$$

$$\frac{\partial w}{\partial t} + u_i \frac{\partial w}{\partial x_i} = -\frac{\partial p'}{\partial z} + K_m \left( \frac{\partial^2 w}{\partial x_i^2} \right) + g \frac{\theta(z)}{\theta_{ref}(z)} - S_w \quad \text{with } u_i=(u,v,w), x_i=(x,y,z) \text{ for } i=1,2,3 \quad (1 c)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (2)$$

Here,  $f (=10^4 \text{ sec}^{-1})$  is the Coriolis parameter,  $p'$  is the local pressure perturbation and  $\theta$  the potential temperature at level  $z$ . The reference temperature  $\theta_{ref}$  should represent average mesoscale conditions and is provided by a one-dimensional model running parallel to the main model. The local source/sink terms  $S_u$ ,  $S_v$  and  $S_w$  describe the loss of wind speed due to drag forces at vegetation elements. This effect can be parameterized with

$$S_{u(i)} = \frac{\overline{\partial p'}}{\partial x_i} = c_{d,f} \text{LAD}(z) \cdot W \cdot u_i \quad (3)$$

where  $W=(u^2+v^2+w^2)^{0.5}$  is the mean wind speed at height  $z$  and  $\text{LAD}(z)$  is the leaf area density [ $\text{m}^2 \text{m}^{-3}$ ] of the plant in that height [4,5]. The mechanical drag coefficient at plant elements  $c_{d,f}$  is set to 0.2.

### b) Temperature and Humidity

The distribution of temperature ( $\theta$ ) and specific humidity ( $q$ ) inside the atmosphere is given by the combined advection-diffusion equation with internal source/sinks :

$$\frac{\partial \theta}{\partial t} + u_i \frac{\partial \theta}{\partial x_i} = K_h \left( \frac{\partial^2 \theta}{\partial x_i^2} \right) + Q_h \quad (4)$$

$$\frac{\partial q}{\partial t} + u_i \frac{\partial q}{\partial x_i} = K_q \left( \frac{\partial^2 q}{\partial x_i^2} \right) + Q_q \quad (5)$$

Similar to the momentum equations,  $Q_h$  and  $Q_q$  are used to link heat and vapor exchange at the plant surface with the atmospheric model. The quantity of  $Q_h$  and  $Q_q$  is provided by the vegetation model described later on.

### c) Turbulence and Exchange Processes

ENVI-met can use the 1<sup>st</sup> order mixing length approach [6] as well as an 1.5 order closure model (E- $\epsilon$  Model) based on the work of Mellor and Yamada [7]. For this study, the more accurate 1.5 order closure was selected which adds two more equations for local turbulence (E) and its dissipation rate ( $\epsilon$ ) to the model:

$$\frac{\partial E}{\partial t} + u_i \frac{\partial E}{\partial x_i} = K_E \left( \frac{\partial^2 E}{\partial x_i^2} \right) + \text{Pr} - \text{Th} + Q_E - \epsilon \quad (6)$$

$$\frac{\partial \epsilon}{\partial t} + u_i \frac{\partial \epsilon}{\partial x_i} = K_\epsilon \left( \frac{\partial^2 \epsilon}{\partial x_i^2} \right) + c_1 \frac{\epsilon}{E} \text{Pr} - c_3 \frac{\epsilon}{E} \text{Th} - c_2 \frac{\epsilon^2}{E} + Q_\epsilon \quad (7)$$

The influence of mechanical shearing (Pr) and thermal forces (Th) is given by

$$\text{Pr} = K_m \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \quad \text{and} \quad \text{Th} = \frac{g}{\theta_{\text{ref}}(z)} K_h \frac{\partial \theta}{\partial z}$$

To calibrate the  $\epsilon$ -equation standard values  $c_1=1.44$   $c_2=1.92$  and  $c_3=1.44$  given by Launder and Spalding [8] have been used. Additional turbulence production as well as the accelerated cascade of turbulence energy from large to small scales near to plant foliage elements can be calculated as [4,9]:

$$Q_E = c_{d,f} \text{LAD}(z) \cdot W^3 - 4c_{d,f} \text{LAD}(z) \cdot |W| \cdot E \quad (8)$$

$$Q_\epsilon = 1.5c_{d,f} \text{LAD}(z) \cdot W^3 - 6c_{d,f} \text{LAD}(z) \cdot |W| \cdot \epsilon \quad (9)$$

From the calculated E- $\epsilon$  field the turbulent exchange coefficients are calculated assuming local turbulence isotropy using the relationships

$$K_m = K_h = K_q = c_\mu \frac{E^2}{\epsilon}; \quad K_E = \frac{K_m}{\sigma_E}; \quad K_\epsilon = \frac{K_m}{\sigma_\epsilon} \quad (10)$$

with  $c_\mu=0.09$ ,  $\sigma_E=1$  and  $\sigma_\epsilon=1.3$ . To simulate boundary layer flows under different thermal stratification, additional scaling functions given by Sievers *et al.* [10] and Businger *et al.* [11] are needed to adjust the exchange coefficients.

#### d) Radiative Fluxes

The modification of the radiative energy fluxes is the major factor in urban environments causing differences in local climate. Therefore a accurate representation of the radiative fluxes is essential in urban climate models. A complex ray-tracing algorithm [12] is used in ENVI-met to estimate the modification of the different radiative fluxes at each grid point of the model. The results are stored as reduction coefficients ( $\sigma_{...}$ ) ranging from 1 for undisturbed fluxes to 0 for a total absorption. Five reduction coefficients are used for the different radiative fluxes:

- $\sigma_{\text{sw,dir}}(z) = \exp(-F \cdot \text{LAI}^*(z))$
- $\sigma_{\text{sw,dif}}(z) = \exp(-F \cdot \text{LAI}(z, z_p))$
- $\sigma_{\text{lw}}^\downarrow(z, z_p) = \exp(-F \cdot \text{LAI}(z, z_p))$
- $\sigma_{\text{lw}}^\uparrow(0, z) = \exp(-F \cdot \text{LAI}(0, z))$
- $\sigma_{\text{svf}}(z) = 1/360 \sum_{\pi=0}^{360} \cos \lambda(\pi)$

Coefficients (a)-(d) describe the influence of vegetation on (a) direct and (b) diffuse shortwave radiation and on the (c) downward and (d) upward flux of longwave radiation. LAI is the one-dimensional vertical leaf area index of the plant from level  $z$  to the top of the plant at  $z_p$  or the ground  $z=0$ :

$$\text{LAI}(z, z + \Delta z) = \int_z^{z+\Delta z} \text{LAD}(z') dz' \quad (12)$$

For the direct component the three-dimensional index  $\text{LAI}^*$  is calculated with respect to the angle of incidence from the incoming sun rays. If a building is found to lie between the point of interest and the sun,  $\sigma_{\text{sw,dir}}$  is set to zero immediately (=shaded).

Coefficient (e) describes the local sky obstruction by buildings („*Sky-View-Factor*“) and ranges from 1 (free sky) to 0 (no sky visible).  $\lambda$  is the maximum shielding angle found by the ray-tracing module in direction  $\pi$ .

With given coefficients, the local radiative fluxes can be calculated for each grid point inside the model domain. The shortwave radiation in height  $z$  is given by

$$R_{sw}(z) = \sigma_{sw,dir}(z)R_{sw,dir}^0 + \sigma_{sw,dif}(z)\sigma_{svf}(z)R_{sw,dif}^0 + (1 - \sigma_{svf}(z))R_{sw,dir}^0 \cdot \bar{a} \quad (13)$$

Here,  $R_{sw,dir}^0$  and  $R_{sw,dif}^0$  are the direct and diffuse components at the model top. The additional last term considers reflection of shortwave radiation from the environment with  $\bar{a}$  being the average wall albedo.

In case of the longwave radiation it is assumed that shielding vegetation layers will absorb parts of the radiative flux and replace it with their own longwave radiation. Depending on the temperature and distribution of vegetation the resulting longwave fluxes can be higher or lower than in unshielded areas. The influence of surrounding buildings is taken into account by adding additional fluxes weighted with the sky-view-factor. Using the concept of reduction coefficients, the downward and upward fluxes at level  $z$  are:

$$R_{lw}^{\downarrow}(z) = \sigma_{lw}^{\downarrow}(z, z_p)R_{lw}^{\downarrow,0} + (1 - \sigma_{lw}^{\downarrow}(0, z))\epsilon_f \sigma_B \bar{T}_{f+}^4 + (1 - \sigma_{svf}(z))\epsilon_w \sigma_B \bar{T}_w^4 \quad (14)$$

$$R_{lw}^{\uparrow}(z) = \sigma_{lw}^{\uparrow}(0, z)\epsilon_s \sigma_B T_0^4 (1 - \sigma_{lw}^{\uparrow}(0, z))\epsilon_f \sigma_B \bar{T}_{f-}^4 \quad (15)$$

Here  $\bar{T}_{f+}$  and  $\bar{T}_{f-}$  are the average foliage temperature of the overlying and underlying vegetation layer,  $T_0$  is the surface temperature and  $\bar{T}_w$  the average wall temperature of walls 'seen' from the grid point. The emissivities of the foliage, the ground surface and of the walls are  $\epsilon_f$ ,  $\epsilon_s$  and  $\epsilon_w$ ,  $\sigma_B$  is the Stefan-Bolzman constant.

## THE SOIL MODEL

Very different soils and surface materials can be found in the urban environment. To allow an accurate simulation, individual thermodynamic and hydraulic properties can be selected for each grid cell of the soil model. The transfer of heat ( $T$ ) and volumetric moisture content ( $\eta$ ) are calculated in the one-dimensional form for a vertical soil column:

$$\frac{\partial T}{\partial t} = \kappa_s \frac{\partial^2 T}{\partial z^2} + Q_h \quad (16)$$

$$\frac{\partial \eta}{\partial t} = D_\eta \frac{\partial^2 \eta}{\partial z^2} + \frac{\partial K_\eta}{\partial z} - S_\eta(z) \quad (17)$$

The thermal diffusivity  $\kappa_s$  is a function of soil moisture  $\eta$  for natural soils [13] and a given constant for artificial material. To allow water bodies to be treated similar to soils, an additional internal heat source  $Q_h$  was added in (16) in order to simulate the absorption of shortwave radiation inside the water body. This simple formulation does not allow a turbulent mixing inside the ocean and is more suitable for water pools or lakes.

For natural soils, the hydraulic conductivity  $K_\eta$  and diffusivity  $D_\eta$  are calculated using the formulae given by Clapp and Hornberger [14]. No water transport is possible in or through sealed soil layers.

The water loss inside the soil due to uptake by plant roots is included by the sink term  $S_\eta$  in (17) provided by the vegetation model.

## THE VEGETATION MODEL

Vegetation is treated as a one-dimensional column with height  $z_p$  with a given normalized leaf area density (LAD) and root area density (RAD) profile. This scheme is universal and can be used for small plants like grass or crop as well as for huge trees.

The interactions between the plant leaves and the surrounding air can be expressed in terms of direct heat flux ( $J_{f,h}$ ), evaporation flux ( $J_{f,evap}$ ) and transpiration flux ( $J_{f,trans}$ ):

$$\begin{aligned}
J_{f,h} &= 1.1r_a^{-1}(T_f - T_a) \\
J_{f, \text{evap}} &= r_a^{-1}\Delta q\delta_c f_w + r_a^{-1}(1 - \delta_c)\Delta q \\
J_{f, \text{trans}} &= \delta_c(r_a + r_s)^{-1}(1 - f_w)\Delta q
\end{aligned} \tag{18 a,b,c}$$

$T_a$  and  $q_a$  are the temperature and the specific humidity of the surrounding air,  $T_f$  is the foliage temperature and  $q_*$  the saturation value of  $q$  at the leaf surface.  $\Delta q$  is the vapor saturation deficit with  $\Delta q = q_*(T_a) - q_a$ . The transfer coefficient for sensible  $r_a$  heat is calculated with respect to leaf geometry and local wind speed [15].

The vapor exchange is controlled by stomatal resistance  $r_s$  which takes into account plant type, water availability, radiation input and water content inside the root zone [16].

$\delta_c$  is set to 1 if evaporation and transpiration can occur ( $\Delta q \geq 0$ ), otherwise  $\delta_c$  is 0 and only condensation is possible.

Assuming that only wet parts of the vegetation can evaporate (18b) and, on the other side, only dry parts will transpire (18c), the fraction of wet leaves inside one grid box is needed. This can be calculated as

$$f_w = \left( W_{\text{dew}} / W_{\text{dew,max}} \right)^{2/3} \tag{19}$$

where  $W_{\text{dew}}$  is the actual amount of dew on the leave surfaces and  $W_{\text{dew,max}}$  is the maximum possible value ( $0.2 \text{ kgm}^{-2}$ ) [16]. The foliage temperature  $T_f$  is calculated from the actual energy balance with neglecting internal energy storage inside the leaf.

The vegetation model is coupled with the main atmospheric model using the source/sink terms

$$Q_h(z) = \text{LAD}(z)J_{f,h} \tag{20}$$

$$Q_q(z) = \text{LAD}(z)(J_{f, \text{evapo}} + J_{f, \text{trans}}) \tag{21}$$

For the soil model, the water sink term  $S_\eta$  is obtained by distributing the total amount of transpired water over the root layer using the given root area density as weighting factor [17].

## GROUND SURFACE AND BUILDING WALLS

The temperature of the ground and wall surfaces are obtained by solving their energy balance equations. For the ground surface,  $T_0$  can be calculated from

$$0 = R_{\text{sw,net}} + R_{\text{lw,net}} - c_p \rho J_h^0 - \rho L \cdot J_q^0 - G \tag{22}$$

where  $R_{\text{sw,net}}$  and  $R_{\text{lw,net}}$  are the net shortwave and longwave radiation absorbed by the surface and  $G$  is the heat flux from/ into the deeper soil. For wall surfaces,  $G$  is replaced by the heat transmission through the walls which is a function of the difference between indoor and outdoor temperature and of the insulation of the wall.

To calculate latent heat flux, the surface humidity  $q_0$  has to be calculated parallel to the surface temperature  $T_0$ .

It depends on the soil moisture content at level  $z=-1$ , the air humidity  $q_a$  and the saturation value  $q_*$  using the  $\beta$ -approach from Deardorff [16]:

$$\begin{aligned}
q_0 &= \beta q_*(T_0) + (1 - \beta)q(z=1) \\
\beta &= \min(1, \eta(z=-1)/\eta_{fc})
\end{aligned} \tag{23}$$

where  $\eta_{fc}$  is the field capacity of the soil at level -1. For wall surfaces,  $q_0$  is always equal to  $q_a$  and for water surfaces  $q_0$  is always equal to  $q_*$ . The turbulent fluxes of momentum, heat and vapor between the surfaces and the surrounding air are calculated using the similarity law from Monin and Obhukov.

## MODEL IMPLEMENTATION

The equations are solved on a three-dimensional rectangular grid with variable spacing in x-, y- and z-direction. The alternating direction implicit (ADI) method was used to solve the advection-diffusion equations. Dependencies with the pressure field were removed from the Navier-Stokes equations and an explicit correction method (SOR) is used to correct the obtained auxiliary flow field into a mass-conserving flow field.

The model calculates transient forward in time with a maximum time step of 10 sec. Explicitly linked parameters such as the surface temperatures or plant parameters are updated after given time intervals.

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