4.3 MESOSCALE SIMULATIONS OF THE URBAN ENVIRONMENT OF WASHINGTON, DC: COMPARISON OF COAMPS SIMULATIONS TO DCNET OBSERVATIONS AND SENSITIVITY OF PLUME TRANSPORT TO AN URBAN CANOPY PARAMETERIZATION

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1. Introduction

Though the horizontal grid resolution of operational mesoscale numerical models has significantly increased in recent years, to values on the order of kilometers, the resolution is still not sufficient to explicitly account for the effects of the urban environment. Thus, these mesoscale models often employ an area-averaged parameterization to account for sub-grid scale building effects. One such model, the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS^{TM})* developed by the Naval Research Laboratory (NRL), is used to simulate the urban environment of the Washington, DC metropolitan area.

COAMPS is a complete three-dimensional mesoscale prediction system that has been used for operational mesoscale forecasting since 1996. It consists of atmospheric and ocean data assimilation with data quality control, analysis, initialization, and a nonhydrostatic atmospheric forecast model with an imbedded aerosol/passive tracer model. Because the urban infrastructure can have a tremendous impact on surface and atmospheric dynamic and thermodynamic structure, an urban canopy parameterization (UCP) has been implemented recently into COAMPS. This parameterization accounts for effects due to building drag, turbulent production, radiation balance, and anthropogenic and rooftop heating, and makes use of an additional equation for the rooftop surface energy balance.

Simulations with COAMPS at 1-km horizontal resolution are compared to observations from the National Oceanic and Atmospheric Administration (NOAA) DCNet. DCNet is a new local weather network consisting of eight towers with mean and turbulence sensors mounted mainly on buildings throughout the Washington, DC metropolitan area. Simulations with variations in the model specification of land-use characterization and urban morphology are also conducted to assess the sensitivity of model simulations to changes in the lower boundary condition.

The impact of the urban canopy layer on mesoscale plume transport, as well as its development and evolution, is also examined using COAMPS simulations with the imbedded passive tracer model. Model tracer releases occurring both within and above the urban canopy are compared to assess the impact of the urban canopy on transport of the plume.

*(COAMPS^{TM} is a trademark of the Naval Research Laboratory)

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2. Mesoscale model

Numerical simulations were performed using COAMPS (see model description at NRL Web site: http://www.nrlmry.navy.mil/~coamps/coamps), coupled to the NOAH land surface model, but without coupling to the ocean model. Experiments were conducted with and without the urban canopy parameterization. The UCP is that of Chin et al. (2000), extending the work of Brown and Williams (1998) and Yamada (1982). The UCP accounts for additional drag due to urban effects by modifying the u-, v-, and w-momentum equations:

$$\frac{\partial u}{\partial t} = \ldots - f_{urb} C_d a(z) u |u| \quad (1)$$

where f_{urb} is the fraction of the horizontal model grid covered by buildings, C_d is the urban canopy drag coefficient, and a(z) is the building surface area density profile. The UCP accounts for increased turbulent production by modifying the turbulent kinetic energy (TKE) equation:

$$\frac{\partial (TKE)}{\partial t} = \ldots + f_{urb} C_d a(z)(|u|^3 + |v|^3 + |w|^3) \quad (2)$$

The thermodynamic urban effects are included in the potential temperature (θ) equation:

$$\frac{\partial \theta}{\partial t} = \ldots + \frac{1}{\pi \rho c_p}\{(1 - f_{urb})\frac{\partial R_N}{\partial z} + f_{urb}\frac{\partial q_{urb}}{\partial z} + (1 + \frac{1}{B})^{-1}[(f_{urb} - f_{roof})\frac{\partial R_{Nc}}{\partial z} + f_{roof} b(z)\frac{\Delta q_{roof}}{C_{roof}}]\} \quad (3)$$

where f_{roof} is the horizontal model grid fraction covered by roof, R_N and R_{Nc} are net downward radiative fluxes outside the urban canopy and between the buildings, respectively, π is the perturbation exner function, ρ is air density, c_p is specific heat of dry air, C_{roof} is the roof heat capacity, q_{urb} is the anthropogenic heat flux, B is the Bowen ratio, b(z) is the roof fraction weighting function, and Δq_{roof} is the roof heat flux change computed as:

$$\Delta q_{roof} = R_{SW}^{\downarrow}(1 - \alpha) + \varepsilon (R_{LW}^{\downarrow} - \sigma T_{roof}^4) - \rho c_p C_{Droof} |V| (T_{roof} - T) \quad (4)$$

where R_{SW} and R_{LW} are downward shortwave and longwave radiative fluxes at the roof surface, α is the roof albedo, ε is the roof emissivity, C_{Droof} is the roof drag coefficient, V is the wind velocity, T is the ambient air temperature and T_{roof} is the roof temperature determined by the roof surface energy equation.

Urban effects are assumed to impact the surface energy budget only through the attenuation of net total radiative flux reaching the surface R_{NG}:

$$R_{NG} = (1 - f_{urb})(R_{SW}^{net\downarrow} - R_{LW}^{net\uparrow})_G + f_{cnyn}[R_{Nc}(0)]_G \qquad (5)$$

where subscript G refers to the ground surface and f_{cnyn} is the between building horizontal grid fraction (note: $f_{urb}=f_{roof} + f_{cnyn}$).

Figure 1 shows the model configuration for the COAMPS simulations. The model was configured with four nested grids of 27-, 9-, 3-, and 1-km horizontal resolution, each with 85x85x44 grid points in the x-, y-, and z-directions, respectively for nests 1, 2, and 3, and 61x61x44 grid points for nest 4. The lowest model vertical level is at 2-m and there are 13 levels below 600 m. The UCP is employed only on nest 4.

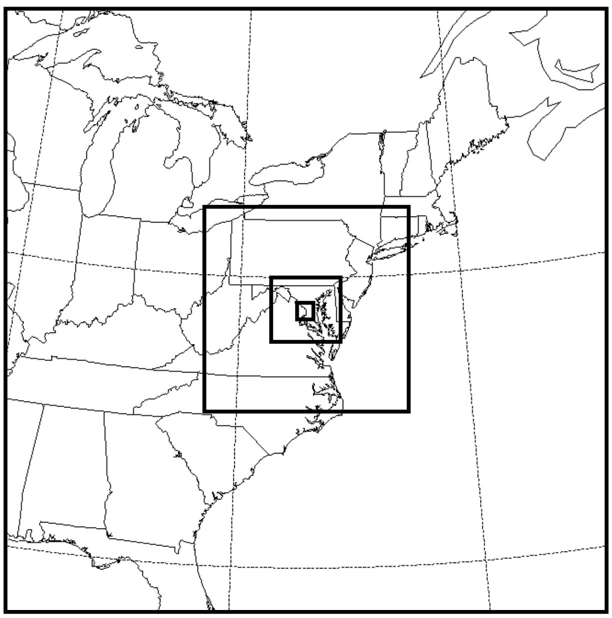


Figure 1. COAMPS nested grid configuration (27-, 9-, 3-, and 1-km).

3. DCNet and COAMPS aerosol model description

A NOAA Air Resources Lab (ARL) demonstration project called DCNet has recently been implemented in the metropolitan Washington, D.C. area. The current network consists of eight 10-m towers mounted on top of buildings throughout the metro area to obtain data of the "skimming" flow located just above the urban building canopy. Figure 2 shows the location of the seven towers on the COAMPS 1-km nest 4 used in this study.

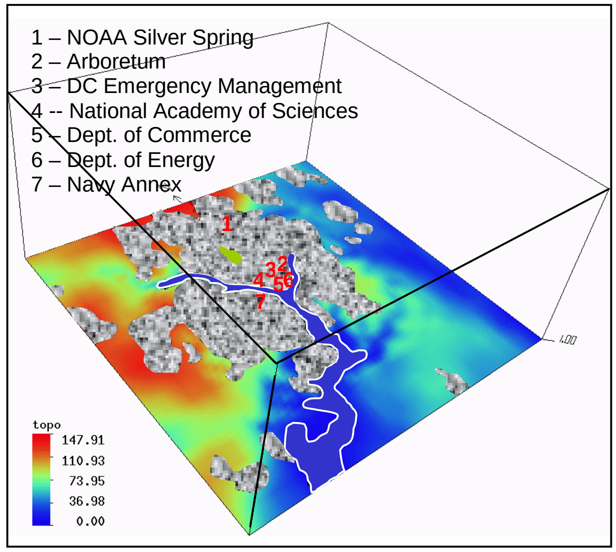


Figure 2. COAMPS nest 4 (1-km) domain viewed from the southwest. DCNet tower locations are given by numbers. Urban areas are denoted by gray stippling and model topography (m) is in color.

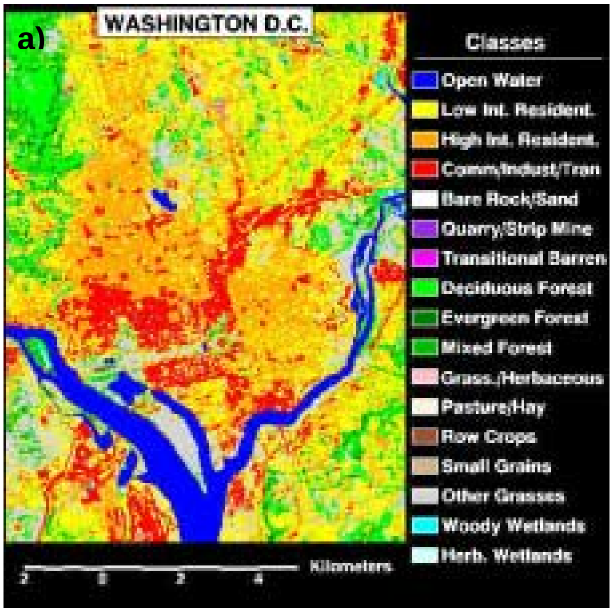
The main goal of DCNet "is to refine our understanding of how hazardous trace gases and particles are dispersed across the kind of area where people work and live." To that end, COAMPS simulations with the imbedded aerosol model were performed with the passive tracer option (Liu et al. 2002). The tightly coupled, or imbedded, aerosol model is run within COAMPS using the dynamical and thermodynamical values as produced by the model and can provide forecasts of either dust aerosol or passive scalar using two-way grid interaction between aerosols. The 3-D transport of passive tracer for this simulations uses a 5^{th} order Bott's advection scheme.

4. Numerical simulations

COAMPS simulations were conducted for the period 12 UTC 13 July – 12 UTC 14 July 2003. The 24-h cold start COAMPS forecast was performed at 12 UTC 13 July in which global 1-degree fields from the Navy Operational Global Atmospheric Prediction System (NOGAPS) were interpolated to the COAMPS grids. An MVOI analysis was then made using the NOGAPS interpolated data blended with available observations (but not including DCNet data). This time period was chosen purely to demonstrate the capability of the model, with no regard to specific synoptic or mesoscale weather conditions.

Two sets of COAMPS experiments were first conducted to assess the impact of the UCP on the simulations. The control experiment was conducted using COAMPS without the UCP. The second experiment (Urban) was exactly the same as the control except the UCP was used on nest 4 only.

The characterization of urban areas for nest 4 uses currently available urban databases and satellite imagery to delineate between 3 classifications: i) commercial, industrial, transportation (CIT), ii) high intensity residential (HIR), and iii) low intensity residential (LIR). Figure 3 shows satellite imagery used in COAMPS urban characterization along with the resultant model classifications.



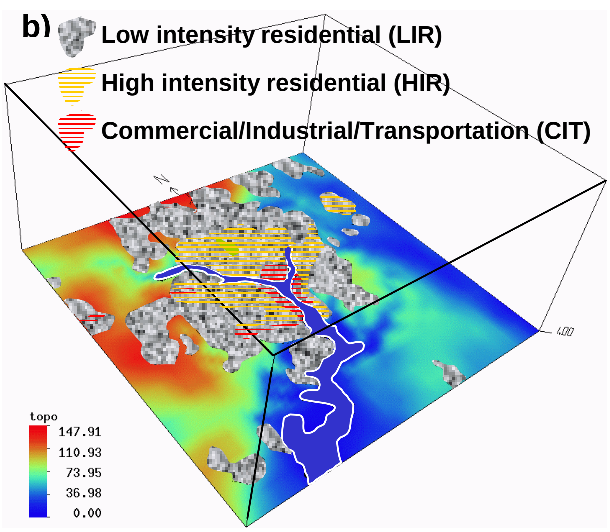


Figure 3. a) Satellite image showing land-use classifications for the Washington, D.C. area, and b) COAMPS nest 4 urban classifications, similar to Figure 2.

5. Results

A comparison of the COAMPS 24-h forecasts without the UCP (Control) and with the UCP (Urban) to observations from the DCNet observation site atop the Dept. of Commerce Building is given in Figure 4.

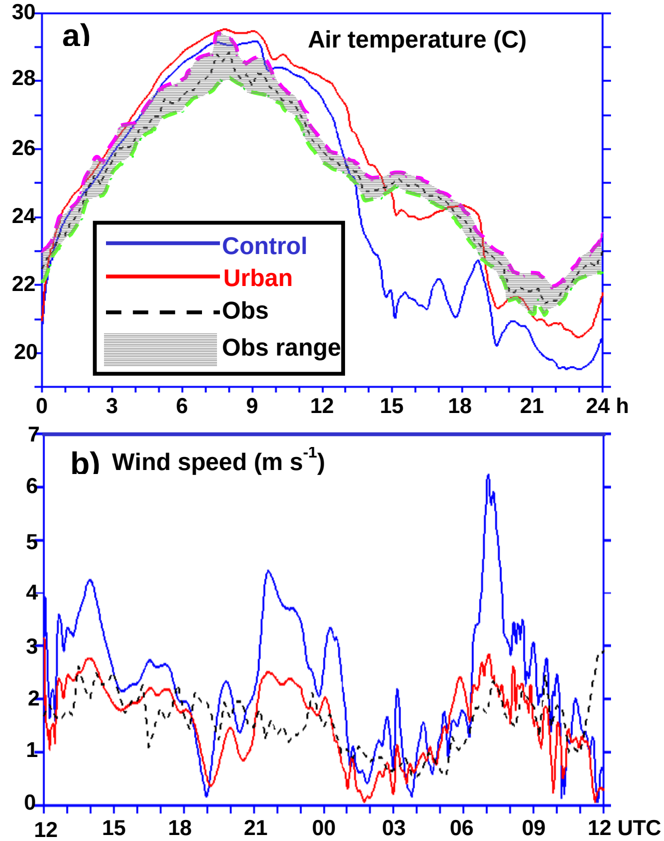


Figure 4. COAMPS 1-km (nest 4) forecasts at 31-m elevation and DCNet Dept. of Commerce roof-top observations from 12 UTC 13 July to 12 UTC 14 July 2003 of a) air temperature (deg C), and b) wind speed (m s^{-1}).

Results from this site are typical of the entire, more commercial region in the city center of Washington. The largest impact from the UCP on air temperature generally occurs in the nighttime hours (03-07 UTC). The Urban simulation is as much as 2.5 deg C warmer than Control during this period, as the UCP accurately accounts for the urban heat island effect prominent in the observations. Air temperature differences between Control and Urban are small (< 0.4 deg C) from the morning to late-afternoon (12-22 UTC). The reduction in wind speed due to the urban canopy is also evident in the Urban simulation throughout the 24-h period (Fig. 4b). Winds for Control can be as much as 3 m s^{-1} too strong during the evening hours.

Figure 5 shows a time-height cross-section of passive-tracer concentration and atmospheric stability for a continuous release at 2-m elevation at the Dept. of Energy site. The cross-section shows similar low-level stability during the daytime (12-22 UTC) for Control and Urban, but the development of a deeper stable layer (up to ~200m) for Control at night. Thus, the UCP provides more turbulent mixing over a deeper layer at night.

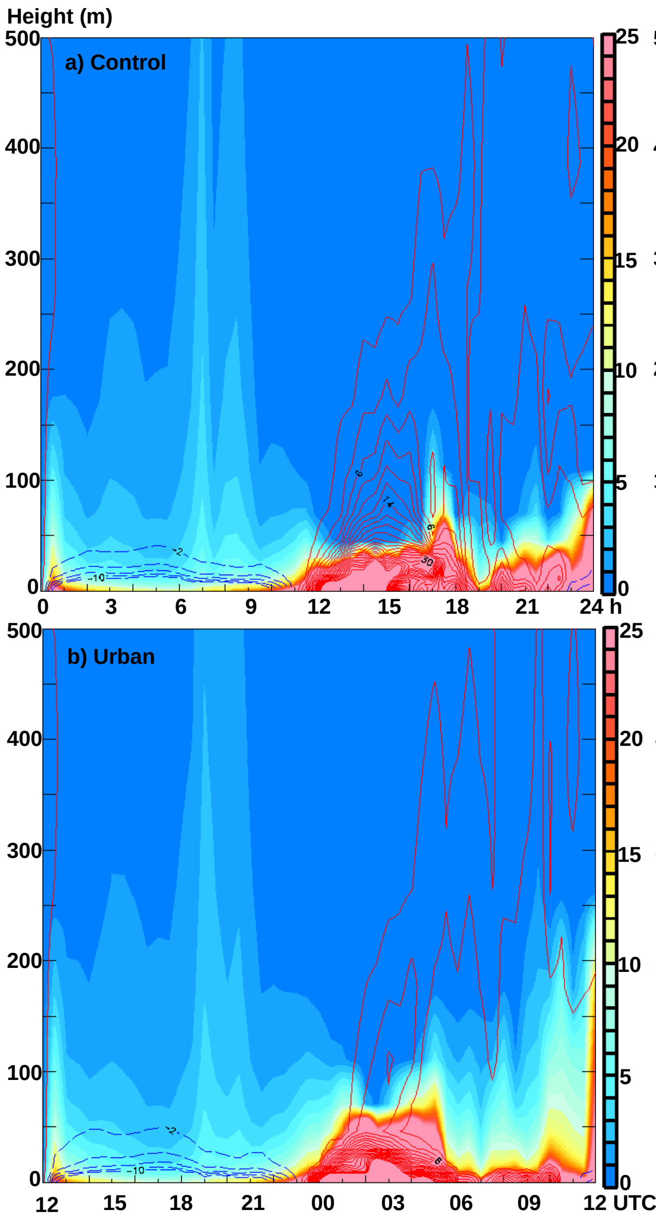


Figure 5. COAMPS 24-h time-height cross-section of passive-scalar concentration (mg m^{-3}) (color) for a 2-m release height, and Brunt-Vaisala frequency (contour: red = stable, blue=unstable) valid from 12 UTC 13 July to 12 UTC 14 July 2003 at the DCNet Dept. of Energy site for a) Control simulation, and b) Urban simulation.

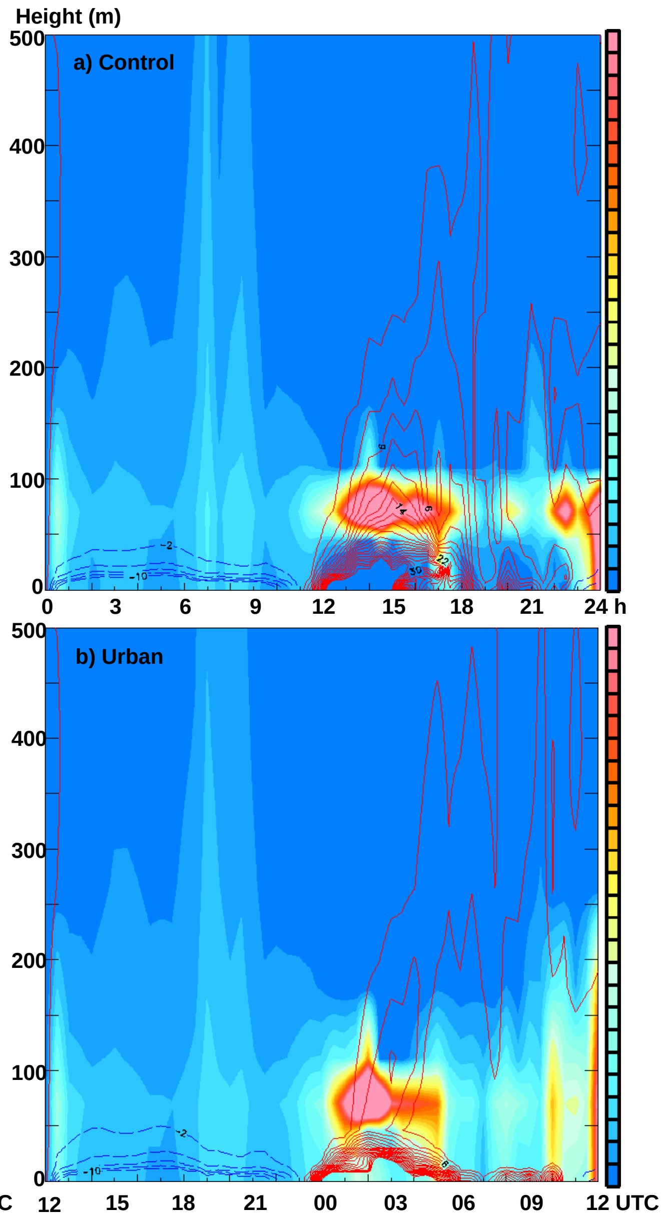


Figure 6. Same as Figure 5, except for passive tracer release is at 70-m instead of 2-m.

Subsequently, there are larger concentrations in lowest ~50m for Control versus larger concentrations over a deeper layer (~200m) for Urban at night.

For a release above the height of the urban canopy (70-m), the distribution of passive tracer concentration is much different than at 2-m within the canopy. Figure 6 shows the concentration and stability similar to Figure 5 but for a 70-m release. Concentrations in the stronger stable layer for Control generally do not mix down to the surface at night, as compared to Urban. Subsequently, concentrations in the elevated less-stable layer for Urban mix down to the surface and result in larger surface concentrations at night. Thus, the UCP can have a tremendous impact on transport of materials released both within and above the urban canopy. Horizontal footprints of surface dosage (Figure not shown) differ significantly from Control to Urban, depending on the atmospheric stability, the amount of mixing, and turbulence generated in the urban canopy layer.

Sensitivity experiments to the Urban simulation were conducted to examine the impact of variations in urban morphology and urban classifications on COAMPS forecasts. Figure 7 shows the 24-h COAMPS forecast

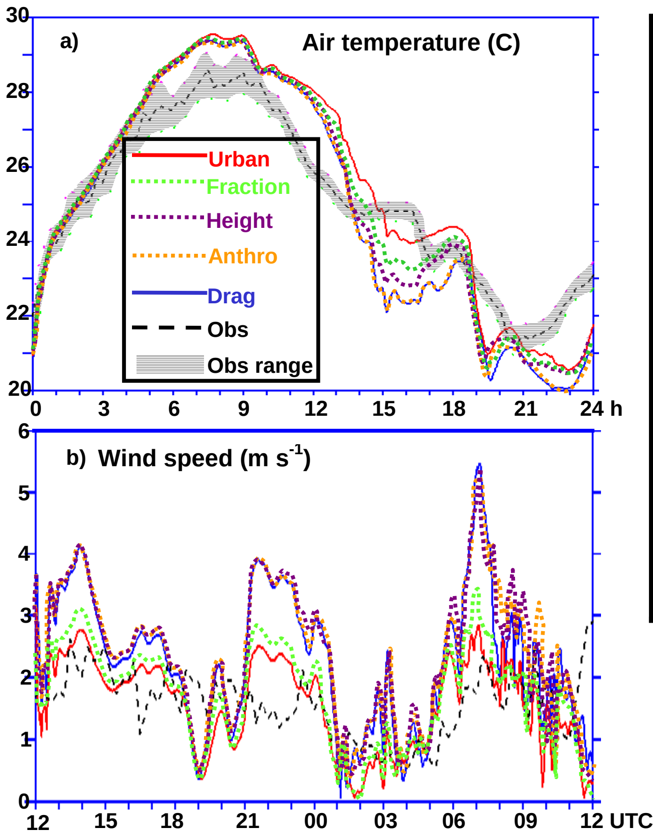


Figure 7. COAMPS 1-km (nest 4) sensitivity forecasts with the UCP at 31-m elevation and DCNet Dept. of Commerce roof-top observations from 12 UTC 13 July to 12 UTC 14 July 2003 of a) air temperature (deg C), and b) wind speed (m s^{-1}).

of air temperature and wind speed for the DCNet Dept. of Commerce site similar to Figure 4, but for sensitivity experiments to the original Urban experiment discussed above.

Table 1 gives the urban parameters for the Urban experiment for the 3 classifications, as well as sensitivity experiments shown in Figure 7. The "Fraction" experiment is the same as Urban except the urban fraction (f_{urb}) and roof fraction (f_{roof}) for both commercial/industrial/transportation (CIT) and high intensity (HIR) residential classifications are reduced to be the same as low intensity residential (LIR). The "Height" experiment is the same as "Fraction" except the height of the urban canopy (h_{urb}) for the CIT classification has been reduced to that of HIR and LIR. The "Anthrop" experiment is the same as "Height" except the anthropogenic heating (q_{urb}) has been reduced for CIT to that of HIR and LIR. The "Drag" experiment is the same as "Anthrop" except the urban drag coefficient (C_d) for CIT is the same as HIR and LIR. The net effect of these changes in urban parameters is to sequentially evaluate the difference between the CIT classification down to LIR. Thus, the "Drag" experiment is simply a LIR horizontally homogeneous urban region.

Class	Exp.	f_{urb}	f_{roof}	h_{urb} (m)	q_{urb} (W m^{-2})	C_d
Comm Indust Trans	Urban	0.9	0.4	32	50	0.025
	Fraction	0.5	0.2	32	50	0.025
	Height	0.5	0.2	12	50	0.025
	Anthrop	0.5	0.2	12	20	0.025
	Drag	0.5	0.2	12	20	0.012
High intens. Res.	Urban	0.7	0.3	12	20	0.012
	Fraction	0.5	0.2	12	20	0.012
	Height	0.5	0.2	12	20	0.012
	Anthrop	0.5	0.2	12	20	0.012
	Drag	0.5	0.2	12	20	0.012
Low intens. Res.	Urban	0.5	0.2	12	20	0.012
	Fraction	0.5	0.2	12	20	0.012
	Height	0.5	0.2	12	20	0.012
	Anthrop	0.5	0.2	12	20	0.012
	Drag	0.5	0.2	12	20	0.012

Table 1. Urban parameters for COAMPS sensitivity experiments.

A comparison of experiments in Figure 7 shows that a reduction in urban and roof fractions (Fraction) has the largest impact on air temperature, while a reduction in building height (Height) has the largest impact on wind speed. Reductions in anthropogenic heating and drag coefficient have lesser impacts on temperature and wind speed.

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6. References

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