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Tree model with drag, transpiration, shading and deposition: Identification of cooling regimes and large-eddy simulation

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Trees play an important role in the urban heat island effect and urban air quality due to their impact on the transfer of radiation, momentum, heat, moisture and pollution. However, the effects of trees are hard to quantify due to their complex interactions with urban surfaces and the turbulent atmosphere overhead.

We present a complete tree model for large-eddy simulations (LES) that represents the effects of trees on drag, transpiration, shading and deposition at resolutions of O(1 m, 0.1 s) whilst minimising the number of model parameters. The tree model avoids the necessity to resolve the leaf temperature via a derivation of the Penman-Monteith equation and distinguishes between cooling via transpiration and shading. The latent heat flux is further broken down into radiative and advective components in order to better understand the mechanism behind transpirational cooling (e.g. the 'oasis' effect).

The new tree model is investigated analytically to provide insight into tree cooling regimes, and is applied to field studies to contextualise the analysis. The combined cooling effect of trees due to transpiration and shading processes can be reduced to a four-dimensional parameter space. The net tree cooling (NTC) and tree cooling ratio (TCR) parameters are defined to enable a systematic categorisation of the thermal effect of a tree into five regimes: net heating, net reduction (shading dominated), net reduction (transpiration dominated), net cooling (shading dominated) and net cooling (transpiration dominated). Existing parameterisations for tree cooling are reviewed, illustrating their limitations and highlighting the need for complete models to determine tree cooling.

The tree model is implemented into the LES model uDALES. The drag and canopy energy balance models are validated, and results are presented for domains that are 1) fully covered by trees; 2) partially covered by trees; and 3) have a single line of trees. These simulations provide physical insight into the effect of trees on the microclimate and provide evaluation data for future studies.