Development of the ARPS-VUC Model – a New Urbanised Version of the ARPS Meteorological Code

Abstract

This paper presents the ARPS-VUC model that has resulted from the development of the Vegetated Urban Canopy (VUC) model and its integration with the Advanced Regional Prediction System (ARPS) meteorological code. The ARPS model supports the analysis of the implications for urban meteorology at a neighbourhood scale of using vegetation as an instrument to reduce and control local heat islands and improve human comfort. This urbanised version of the ARPS model uses a drag-force approach, enabling the model to solve all meteorological fields (wind velocity, air temperature and humidity) within and above the tree canopy with a complete interaction (two-way coupling) with the momentum, heat and humidity fluxes from the canopy elements internally computed by the VUC model. The VUC model accounts for the presence of high vegetation (trees) between buildings and vegetation on building roof and wall surfaces. Trees are characterised by the spatial distribution of their frontal and horizontal area densities, whereas buildings are described by individual distributions of their frontal (walls) and horizontal (roofs) area densities. The ground surface is divided into natural surfaces (bare soil and low vegetation), pavements (roads, pavements) and buildings. An approach similar to that used in the ISBA model is implemented to model the evapotranspiration from natural soil (ground and building natural surfaces) and the transpiration of vegetation. For artificial cover (pavements, walls and roofs), an approach based on that used in the SM2-U model is implemented. Precipitation conditions, the water storage of canopy elements, anthropogenic heat fluxes and humidity fluxes from artificial surfaces without vegetation are not yet considered in the ARPS-VUC model.

Introduction

More than a half of the world's population lives in cities, and urban population numbers will continue to increase (United Nations, 2012). The urban sprawl and the attendant pollution, urban heat islands (UHIs), and health and comfort problems reported over past decades, particularly in dense urban areas, has promoted a growing interest in sustainable urban building and vegetation planning and development (Blanco *et al.*, 2009). With this development has come a rise in the popularity and introduction of green infrastructure (parks, gardens, forests and green building facades) in urban areas.

It is now well established that vegetation provides a wide range of ecosystem services, and is an important instrument of sustainable development planning strategies and greening policies to reduce and control local UHIs and improve human comfort in urban areas (Wong, 2002; Argiro and Marialena, 2003; Bowler *et al.*, 2010; Grimmond *et al.*, 2010, Mackey *et al.*, 2012). Despite the documented benefits of green infrastructure, there is still a lack of overall understanding of its implications for urban meteorology at a neighbourhood scale, that is, between the local and city scales.

With the aim of contributing to such knowledge, the VegDUD Project (Musy *et al.*, 2012) attempted to assess the role of green infrastructure, in association with built structures, on several interacting urban ecosystems, focusing on microclimate, hydrology, energy and ambience at various spatial and temporal scales. This interdisciplinary research project, funded by the French Research Agency, also

Keywords:

heat islands,
meteorological modelling,
urban areas,
vegetated canopy

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attempted to introduce urban planners and policy makers to suitable climatic policy urban vegetation and green infrastructure techniques and practices.

Understanding the impact of vegetation on urban meteorology at neighbourhood (district) and city-wide scales is difficult, as no two cities or districts are the same in size, design or climate (Kuttler, 2008). It is therefore hard to draw comparisons of the effect that green infrastructure, chiefly high vegetation and green building facades (both roofs and walls surfaces), have on microclimates, hydrology and energy. To overcome this issue, various meteorological codes and models have been developed and used to simulate meteorology in urban environments at different scales (Gill *et al*., 2008). Notwithstanding the variety of modelling tools currently available, they all use simplified one-layer modelling approaches with no information within the urban canopy (at a city to regional scale), or complex building descriptions (at a local scale), making these tools computationally too expensive to use to study the interactions between districts (at a neighbourhood scale).

In this sense, and to further verify the implications of using green infrastructure on urban meteorology at the neighbourhood scale, this paper presents the ARPS-VUC model, which resulted from the development and integration of the Vegetated Urban Canopy model (VUC) and the meteorological Advanced Regional Prediction System (ARPS) code.

Methodology

The complexity of quantifying the impact of vegetation features on urban meteorology makes the use of computational tools advantageous to study the options and configurations that exist in urban areas and to understand their influence at a range of scales. The new urbanised version of the ARPS-VUC is presented to overcome some well known constraints of existing meteorological tools in accounting for the influence of urban green infrastructure at a neighbourhood scale.

Vegetated Urban Canopy Model

The Vegetated Urban Canopy (VUC) model was developed to enable the calculation of temperature and humidity at the surface of the different canopy elements considered in the VUC (ground surfaces, buildings and green infrastructure) and to deduce the momentum, heat and humidity fluxes from the canopy using a multi-layer approach. In terms of green infrastructure, the model accounts for the presence of high vegetation between buildings (and natural ground surfaces) and vegetation on building roofs and walls (Figure 1).

In terms of ground surface, three main types of land use are considered: natural surfaces (bare soil and small vegetation, denoted by *nat*), buildings (denoted by *bat*) and pavements (roads, pavements, and other artificial ground covering surfaces, denoted by *pav*), with ground area densities (fractions) f_{nat}, f_{bat} and f_{pav} ($f_{nat} + f_{bat} + f_{pav} = 1$), respectively, made within the simulation domain.

A novelty of the VUC model is the *multi-layer* canopy spatial characterisation of high vegetation (trees, shrubs, denoted by *veg*) with vertical distributions of the frontal (A_{fveg}) and horizontal (A_{hveg}) area densities, and buildings with vertical distributions of the frontal (walls) (A_{fbat}) and horizontal (roofs) (A_{hbat}) area densities. Heat fluxes from buildings are further partitioned between walls and roofs, denoted by *wall* and *roof*, respectively, which can be also covered by natural surfaces, denoted by *natw* and *natr*, respectively. Natural ground surfaces are represented by a thin surface layer that acts as a buffer for evaporation from the surface and a root-zone layer containing available water for vegetation transpiration. This approach is similar to the ISBA model (Noilhan and Planton, 1989), except that here the root-zone layer extends under other surface types (buildings and pavements). Surface temperature (T_{snat}) is calculated by means of a force-restore type equation for the surface layer heat, which assumes that the layer is sufficiently thin to be at a uniform temperature distribution throughout its depth. The deep soil temperature (T_{soil}) is determined by a return-to-equilibrium equation towards an average temperature of all surfaces in contact with the soil (T_{snat}, T_{2pav} and T_{int}). The surface temperature evolution of high vegetation is deduced from the surface heat budget. Given the contribution of conduction, the heat flux within the plant is neglected for the moment.

Water vapour fluxes from natural surfaces (on the ground or on buildings) are determined from the sum of the water evaporation from the bare soil between vegetation and the vegetation transpiration.

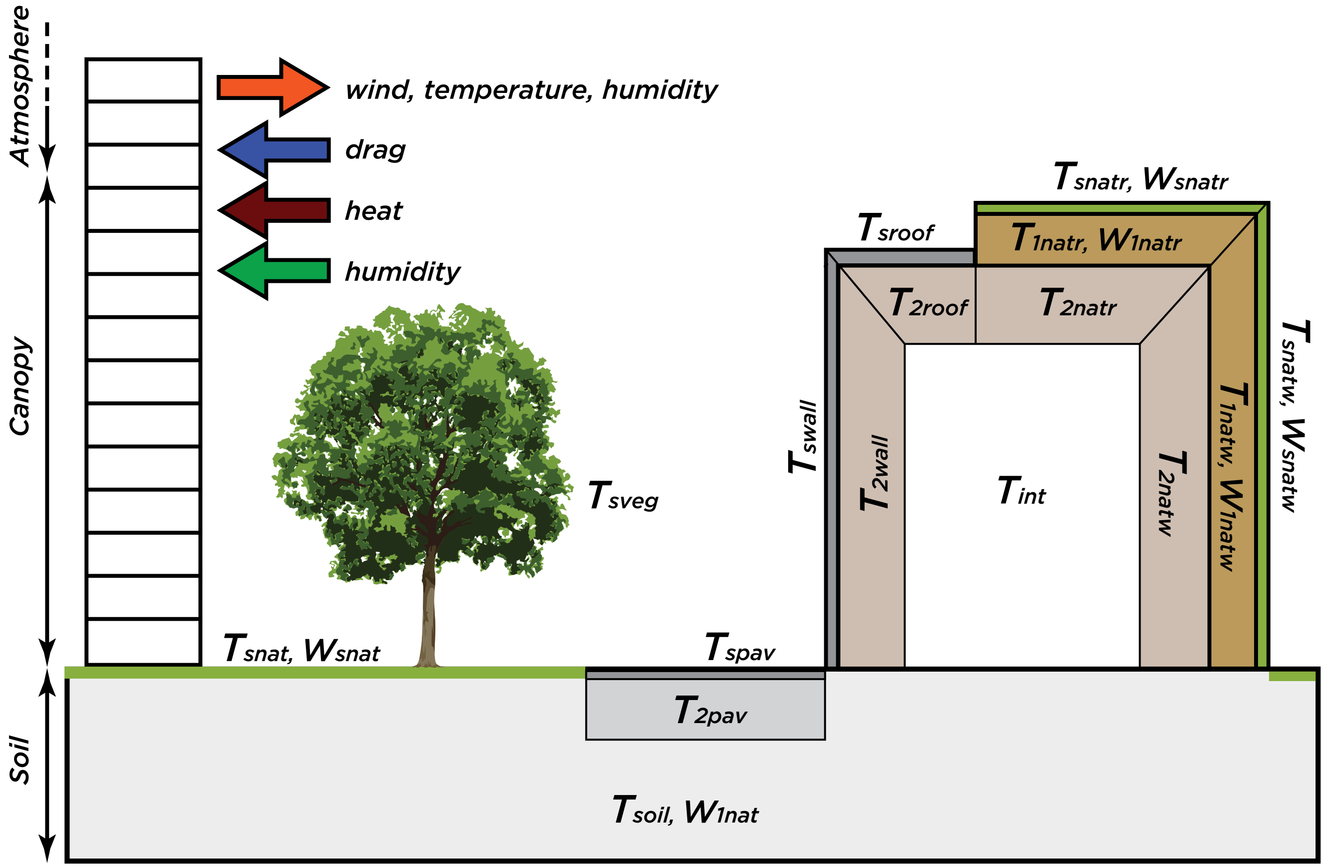

Figure 1: Schematic representation of the urban green canopy as considered in the VUC model, with an indication of the temperature (T) and humidity (W) variables associated with the canopy elements. The term *nat* refers to natural ground surfaces, *veg* to high vegetation, *pav* to pavements, *roof* to building roofs without vegetation, *wall* to building walls without vegetation, *natr* to natural surfaces on roofs, *natw* to natural surfaces on walls and *int* to building interior spaces (from Dupont *et al*., 2013).

The stomatal resistance of high vegetation is modelled following Noilhan and Planton (1989), and depends on the total leaf area index (LAI) of the vegetation, atmospheric factors (e.g., solar radiation) and available water in the soil.

Each artificial cover (pavement, building, wall and roof) is represented by two layers, as in the SM2-U model (Dupont and Mestayer, 2006). A superficial layer, denoted by as *s*, allows the model to respond quickly to the environmental forcing variations, and a second, inner layer, denoted by *2*, allows the artificial materials to store heat. Artificial cover temperatures are determined by taking into account the conduction flux between the surface and the soil layer for the pavement, or a building's air interior, and specific parameterisations of the inverse heat capacity coefficients for each canopy element (see Dupont *et al*., 2013).

When natural surfaces are present on buildings, two soil layers are added above the second building inner layers (denoted by *nart*). These two additional layers have a similar role to the two soil layers for the natural ground surface: a thin surface layer (denoted by *s*) and a root-influenced layer (denoted by *1*). The modelling approach for the natural surface temperature and evaporation of building roofs and walls is the same as that for natural ground surfaces.

The net radiation flux calculation takes into account the shadowing effects of higher canopy elements (high vegetation and buildings). It is assumed that the radiation flux exponentially decays towards the ground as a function of z (high from the ground), the canopy density (both vegetation and buildings surfaces) and time of day (Dupont *et al*., 2013). As regards shadowing effects, building wall and roof surfaces are considered differently in terms of direct solar exposure.

In this first version of the model, precipitation conditions, the water storage of canopy elements, anthropogenic heat fluxes and humidity fluxes from the pavement and non-vegetated roofs and walls are not considered. Further developments are in progress to overcome such limitations.

A detailed description of the VUC model is presented in Dupont *et al*. (2013).

ARPS-VUC model

Aiming to account for the influence of green infrastructure on meteorology at a neighbourhood scale, the VUC model was integrated into the Large-Eddy Simulation (LES) Advanced Regional Prediction System (ARPS), a regional-scale meteorological code (Xue *et al*., 2000, 2001). Recently, the ARPS model was progressively modified and adapted for forest (Dupont and Mestayer, 2006; Dupont and Brunet, 2008) and urban canopies (Maché, 2012). Within the scope of the integration of the VUC model, the model was also adapted to consider both vegetation and buildings structures within a multi-layer vegetated urban canopy (Dupont *et al*., 2013).

The novelty of this new urbanised version of the ARPS is the use of a drag-force approach to solve all meteorological fields (wind velocity, air temperature and humidity) within and above the canopy with a complete interaction (two-way coupling) between these meteorological fields and the momentum, heat and humidity fluxes of the canopy elements that are internally computed by the VUC model.

The drag force approach adds a drag force term into the momentum equations to represent the influence of a group of obstacles on the flow dynamics (Maché, 2012). To consider the influence of the canopy elements on urban meteorology, the source or sink contributions of natural and artificial surfaces and high vegetation and buildings are introduced into the momentum, air temperature and air humidity conservation equations.

A detailed description of the VUC model is presented in Dupont *et al*., (2013).

Discussion

To support the analysis of the implications for urban meteorology at a neighbourhood scale of using vegetation as an instrument to reduce and control local UHIs and improve human comfort in urban areas, the VUC model was developed and integrated into the LES meteorological ARPS model. This new vegetated urbanised version of the ARPS model (ARPS-VUC) uses a drag-force approach to solve the meteorological fields (wind velocity, air temperature and humidity) within and above the canopy with a complete interaction (two-way coupling) between these meteorological fields and the momentum, heat and humidity fluxes from the canopy elements as internally computed by the VUC model. This version accounts for the presence of high vegetation (trees) between buildings and vegetation on roofs and wall surfaces, in addition to natural, pavement and building ground coverage types. Furthermore, the model is designed to characterise both homogeneous and heterogeneous spatial (horizontal and vertical) distributions of vegetation and the morphological and aerodynamic properties of buildings to simulate real urban canopies. The recognised limitations mean that further development and tests are being conducted, in particular to account for the effect of building volume on momentum, heat and humidity turbulent diffusions, and also the effects of precipitation, anthropogenic heat fluxes and humidity fluxes from pavements.

Tests and evaluation studies are being performed that consider idealised homogeneous and heterogeneous urban canopies. The ARPS-VUC model will also be applied to a real heterogeneous urban canopy to demonstrate its capability to support the evaluation of the impact of varying green infrastructure features and designs on urban meteorology, and consequently on human comfort. Such evaluations will guide the use of vegetation as an instrument for planning strategies to reduce and control local UHIs and improve human comfort in urban areas.

Acknowledgments

This work was supported by the HPC Resources of the Institut de Développement et de Recherche pour l'Informatique Scientifique (IDRIS) under allocation 2013010132 made by GENCI, and by the Avakas cluster resources of the Mésocentre de Calcul Intensif Aquitain (MCIA) of the University of Bordeaux. The authors also thank ANR for the Post-Doc Fellowship of R. Tavares within the remit of the VegDUD project.

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