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Evaluation of a microclimate model for predicting the thermal behavior of different ground surfaces

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A B S T R A C T

The microclimate model ENVI-met Version 4 was evaluated with field data in terms of the thermal behavior of different types of ground surface. A field experiment was conducted in a real construction project in Guangzhou, South China, from 29 August to 2 September in 2010. The surface types of concrete, tile, asphalt and grass were investigated. The comparison between observation and prediction was performed for both sub- and above-surface variables, including soil temperature at different depths, soil heat flux at the surface, surface temperature, and air temperature and humidity at different heights. The results show that the ENVI-met model is capable of reasonably modelling the diurnal thermal behavior of different ground surfaces and their effects on local air temperature and humidity. The comparison of spatial distributions of air temperature and humidity shows that the hotter/drier and cooler/wetter spots predicted by ENVI-met were generally consistent with the observations. The quantitative evaluation shows that the ENVI-met model is capable of predicting the microclimate in terms of different variables with good accuracy.

1. Introduction

Numerical simulation, a technique well suited to dealing with the complexities and non-linearities of urban climate system, has been widely used in urban climate study and continues to grow in popularity. However, an indispensable step in the development of an urban climate model is to evaluate its performance with field data, especially using independent field data for both outputs and process variables under various urban configurations and weather conditions. This paper investigated a three-dimensional microclimate model ENVI-met [1], which was designed to simulate the surface-plant-air interaction in urban environment with a typical spatial resolution of a few meters and a timestep between 1 and 5 s. The model, based on computational fluid dynamics (CFD) and thermodynamics, is able to simulate flow around and between buildings, exchange processes of heat and vapor at the ground surface and at walls, exchange of energy and mass between vegetation and its surroundings, bioclimatology, and particle dispersion.

ENVI-met has been employed by many researchers to study the effects of different urban design options on outdoor thermal environment (e. g [2–4]), as well as on air quality (e. g [5,6]). On the other hand, some studies have attempted to assess the performance of ENVI-met by comparing simulation results with field experimental data. Samaali et al. [7] evaluated the radiation flux calculation in ENVI-met with two validated models as well as the measurements from a soybean field experimentation. They indicated that ENVI-met simulated the long-wave radiative transfer in the vegetation canopy reasonably; however, the weakness of some hypotheses such as the non-attenuation of short-wave diffuse radiation within the vegetation was revealed. Chow et al. [8] compared the ENVI-met outputs to the observed temperature data acquired from a bicycle traverse in a hot-arid city. They showed that ENVI-met is capable of simulating both spatial and temporal temperature data with reasonable accuracy, although the model also shows relatively larger systematic errors. Krüger et al. [5] reported that, at 2.1 m above ground within the street canyon, the wind speeds predicted by ENVI-met were consistent with field data for input wind speeds below 2 m/s, but tends to overestimate wind speeds for input wind speed over 2 m/s. By comparing the air temperature derived from the local meteorological stations in a desert city with the modeled data, Chow and Brazel [9] concluded that ENVI-met tends to underestimate daytime air temperature but overestimate nighttime air temperature. Ng et al. [10] estimated ENVI-met by focusing on the air temperature in a hot-humid city.

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They showed that the correlation coefficients (R^2) between observations and predictions ranged from 0.63 to 0.77.

These studies showed that the ENVI-met model is capable of modeling outdoor thermal environment for different climate patterns with acceptable accuracy. However, only a few of variables were considered in these studies, and most attempts just focused on air temperature. There was no investigation to assess ENVI-met with field data involving more comprehensive variables, as well as spatial distribution of microclimate. In addition, the older versions of ENVI-met (V 3.0/3.1) were investigated in these previous studies. In this study, the new version of ENVI-met model (V 4.0) was evaluated. Significant modifications have been made in ENVI-met 4.0 compared to the versions prior to 4.0, and one of the most remarkable improvements is the new function called "full forcing". This new function allows users to employ the measured meteorological data to force the model during the simulation (further explanation is given in section 2), while only relatively "simple" weather profiles can be used in the previous versions of ENVI-met, such as constant wind velocity and idealized profiles for air temperature and solar radiation. It was expected that ENVI-met 4.0 can show better performance than the previous versions of ENVI-met.

This paper is a first step in evaluating the new ENVI-met program (V 4.0) with field measurements. We focused on a key aspect of urban climate system that is the diurnal thermal behavior of different ground surfaces. A field experiment was conducted in Guangzhou, South China, from 29 August to 2 September in 2010. Three types of pavements (tile, concrete, and asphalt) and a lawn were selected as the studied objects. Both sub- and above-surface variables were measured in this field experiment, including meteorological data, soil temperature at different depths, surface temperature, soil heat flux, and near-ground air temperature and humidity. A brief introduction of ENVI-met is given in section 2. Section 3 describes the field experiment and the numerical simulation. The results and conclusion are presented in section 4 and 5, respectively.

2. The ENVI-met model

The ENVI-met model is composed of four main systems: soil, vegetation, atmosphere and building. The soil from the surface to 2 m depth is divided into 14 layers with the vertical spacings from 1 cm near the surface to 50 cm in the deep layers. Different soil profiles and patches of surfaces can be modeled by allocating various natural soils or artificial materials for each grid cell. For natural soils, the heat and water vapor transfers are taken into account while merely heat transfer is considered for sealed materials. The ground surface temperature is calculated from the net radiative fluxes, the turbulent fluxes of heat and vapor and the heat conduction into the ground at the surface. Note that the albedo of natural soil is determined by the model itself, as a function of solar incident angle and water content of top soil layer.

A new 3D vegetation model has been implemented in ENVI-met 4.0, which is different from the 1D vegetation model used in previous ENVI-met models. The 3D vegetation model makes it possible to describe different trees with varied shapes and spatial distribution of the leaves. Each vegetation grid cell has its own energy and mass budget. For shading calculation, vegetation is treated as a turbid medium and the attenuation coefficient is the function of the optical path of the solar beam through the canopy and leaf area density (LAD). However, the attenuation of the diffuse radiation by vegetation is not yet taken into account. The non-hydrostatic incompressible Navier–Stokes equations and the standard E-ε model are used in the atmospheric system to prognosticate flow field and turbulence. A series of source and sink terms has been incorporated into these prognostic equations to describe the heat, vapor and momentum exchanges of the vegetation with atmosphere. The building model has been dramatically improved in ENVI-met 4.0. For example, the new model can take into account the heat inertia of wall and roof, which was totally neglected in prior versions of ENVI-met. Further details about this model are given in [1,11,12].

The main input parameters for an ENVI-met simulation include meteorological data, initial soil wetness and temperature profiles, structures and properties of ground surfaces, vegetation and buildings. As mentioned in section 1, the new function "full forcing" available in ENVI-met 4.0 can simulate various meteorological conditions by forcing the model with a user-specified weather profile by the hour or sub-hour. The customizable meteorological variables include incoming direct and diffuse solar radiations, downward long-wave radiation, background concentration of particle/gas, as well as 1D vertical profiles of atmospheric parameters (such as air temperature, specific humidity, wind speed and direction). These 1D meteorological profiles (from the ground surface to 2500 m height) are used as the lateral and top inflow boundaries of the main model (3D). Usually, the atmosphere profile information is obtained from radiosonde observation. However, if there is a lack of such information, the observed data from meteorological station at ground-level can be interpolated temporally and spatially to the full 1D profile. The methods of interpolation are illustrated as follows: the assumption of neutral stratification of atmosphere is used for air temperature profile (constant potential temperature for all levels); simple logarithmic interpolation is applied for the vertical wind profile calculation; wind direction is kept constant at all levels; the humidity profile of atmosphere is interpolated linearly, according to the observed data at ground level and the input specific humidity at 2500 m above ground.

3. Methods

3.1. Field experiment

3.1.1. Study area

A field measurement was carried out in metropolitan Guangzhou, located in south China (23° 09′ N, 113° 20′ E). Guangzhou has a population of more than 12 million and endures a hot-humid subtropic climate. The statistic data of Chinese Typical Year Weather [13] show that June to September are the hottest months of the year, with daily average temperatures ranging from 27.5 to 29 °C, daily maximum temperatures ranging from 34.4 to 35.9 °C, and a daily average relative humidity of around 80%. The study area is located in Guangzhou University Town, which is on a large river island in the south of Guangzhou. The terrain of the island is flat, with an average elevation of 16 m. Guangzhou University Town has a high greening rate of over 50%, and most of the buildings on the island are not more than 8 stories. A meteorological station has been installed in the center of the island by Guangzhou Meteorological Bureau, about 1 km away from the experimental site.

With the aim of investigating the thermal behavior of different ground surfaces, the field experiment was carried out in cooperation with a real construction project implemented by the local planning department. Fig. 1 shows the layout of the project and the surrounding environments. The field within black dashed polylines is the newly constructed area, which was originally covered with lush weeds. As seen from Fig. 1, the project consists of a square and a parking place. The square was designed to be a concrete base with ceramic tile surface. For the parking place, the part of parking is paved with grass pavers while the driveway is covered with compacted sand. Two concrete access roads are located on the both sides of the parking place. The environment of the site is open and