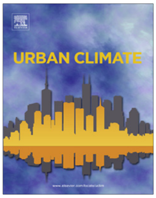
Urban Climate 10 (2014) 19–34

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim



A new perspective of urban–rural differences: The impact of soil water advection

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ARTICLE INFO

Article history:
Received 27 May 2014
Revised 5 August 2014
Accepted 27 August 2014

Keywords:
Advection–diffusion
Land surface temperature
Phase lag
Soil water flux
Surface energy balance
Urban heat island

ABSTRACT

Urban-rural contrast is central to many urban environmental problems, a prominent example being the urban heat island effect. To ameliorate urban thermal stress, extensive research work has been focused on the mitigation of critical environmental temperatures, while the timing of excessive heating was largely overlooked. Advection of soil water flux plays a critical role in determining the soil thermal field, which in turn modulates surface energy fluxes and land–atmosphere interactions. In this paper, we formulate the wave phase differences between soil temperatures and soil heat fluxes due to soil water advection based on harmonic function method. It has been found that phase lags, viz. hysteresis effects, exist among all land surface energy budgets and the land surface temperature. More generally, the difference of phase and time evolution of the land surface temperature and the ground heat flux is also manifested in annual cycles. In the context of urban–rural differences, the temporal difference in peak surface temperatures and peak turbulent fluxes has profound implication to human thermal comfort and building energy efficiency.

1. Introduction

Urbanization is a now a global phenomenon which leads to critical issues that challenge environmental sustainability. Today, urban areas are home to more than half of the world's population, with a

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http://dx.doi.org/10.1016/j.uclim.2014.08.004

projected urban population of 6.3 billion (68% total global population) in 2050 (UN, 2012). The concentration of population in urban areas has positively affected the economic growth, spurring entrepreneurship, inventions, and business innovation (Bettencourt et al., 2007). On the other hand, rapid urbanization rates in the last few decades are associated with substantial modifications of land use and land cover, involving the transformation of natural landscapes into the built environment. The resulted urban–rural difference gives rise to numerous environmental challenges, for example, the well-known urban heat island (UHI) effect. UHI is characterized by the excessive atmospheric temperature over built terrains as compared to their rural surroundings (Oke, 1982; Taha, 1997). The main contributors of UHI include albedo (solar reflectivity), lack of moisture and evaporative cooling, anthropogenic heat emission, and thermal storage in engineered materials (e.g. concrete and asphalt) used in cities. Up to date, however, most UHI investigations have been devoted to the study of excessive atmospheric temperature in the urban atmospheric boundary layer (ABL), while research efforts on surface and subsurface UHI are still scarce (Chow et al., 2012). In addition, research on the UHI mitigation have been exclusively focused on the reduction of the urban environmental temperature, especially the 2 m air temperature, using strategies such as cool and/or green roofs (e.g. Sailor, 2008; Akbari et al., 2012; Yang and Wang, 2014). While the magnitude of temperature is a main (and probably the most important) measure of the UHI effect, little research work has been focused on the timing of the excessive (especially peak) urban temperatures and heat fluxes.

Both factors, the lack of characterization of subsurface UHI and the temporal evolution of land surface temperature (LST) and heat fluxes, point to the pressing need of more study on the subsurface dynamics of the coupled heat and soil water transport. The two major players governing the wave phase evolution of temperatures and heat fluxes at the land surface and the induced hysteresis effect are the thermal inertia and the soil water content (Grimmond and Oke, 1999; Gao et al., 2010; Sun et al., 2013b). In particular, soil water movement regulates both the magnitude and the time evolution of the LST that contains important signature of partitioning of the incoming solar energy and regulates the surface energy balance (Wang and Bras, 2011; Bateni and Entekhabi, 2012). Thus the subsurface signals subsequently manifest themselves in thermodynamic and aerodynamic conditions in urban canopies and ABL via land–atmosphere interactions.

The subsurface soil heat transfer consists of two major dynamic processes: the molecular diffusion (conduction) and the vertical transport concomitant with soil moisture (advection). Explicit solutions of prognostic equations for subsurface heat transfer, practically, were not included in land–atmosphere interactions until 1970s. Some early predictive models parameterized the ground soil flux as a constant fraction of the sensible heat flux (Kasahara and Washington, 1971) or the net radiative flux (Nickerson and Smiley, 1975), from which the LST was deduced. In these early models, the details of soil thermal fields are ignored and the evolution of LST is solely governed by meteorological forcing in the ABL. Corby et al. (1972) proposed a parameterization including subsurface soil storage, by assuming soils are lumped thermal masses with uniform temperatures. This led to the development of a family of the so-called force-restore methods as prognostic equations for predicting the LST, first derived by Bhumralkar (1975) and improved later by other researchers (Deardorff, 1978; Arya, 2001; Gao et al., 2008). In force-restore methods, the heat diffusion process is simplified and represented as a first order ordinary differential equation (ODE), such that numerical quadrature techniques can be directly applied to obtain solutions of the ODE. Hence solutions of force-restore equations, at best, converge to numerical solutions of the second order heat diffusion equation.

Alternatively, a number of numerical models for predicting soil thermal fields have been developed in past decades, based on solutions of the more realistic heat diffusion (second order partial differential) equation, where a soil layer is usually treated as semi-infinite one-dimensional (1D) domain for simplicity. Kernel solutions of these numerical procedures are analytical or semi-analytical in nature, and are numerically more accurate as compared to force-restore methods (Wang and Bras, 1999). Hitherto most of these analytically-based methods for soil heat transfer were focused on the heat diffusion process, while the advection part of the subsurface heat transfer is largely ignored (Wang, 2012). The focus on heat diffusion is valid for urban environments with relatively large fraction of impervious surfaces in most applications and phase evolutions of LST or surface heat fluxes are not of particular concern. The vertical advection of heat concomitant with soil water flux, on the other hand, plays an important role in the coupled soil heat and water transport processes by modifying,