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Heat flux, urban properties, and regional weather

P.A. Makar[a,*], S. Gravel[b], V. Chirkov[c], K.B. Strawbridge[d], F. Froude[d], J. Arnold[a], J. Brook[a]

[a]*Air Quality Research Branch, Meteorological Service of Canada, Environment Canada, 4905 Dufferin Street, Toronto, Ontario, Canada M3 H 5T4*

[b]*Meteorological Research Branch, Meteorological Service of Canada, Environment Canada, 4905 Dufferin Street, Toronto, Ontario, Canada M3 H 5T4*

[c]*Transition to New Technologies Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria*

[d]*Air Quality Research Branch, Meteorological Service of Canada, Environment Canada, Centre For Atmospheric Research Experiments, 6248 Eighth Line, Egbert, Ontario, Canada L0L 1N0*

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Abstract

The flux of heat from human activities such as commercial energy use, renewable source combustion, and the human metabolism has been incorporated into a variable resolution global weather forecast model, along with improved urban surface roughness and radiative properties. Sensitivity studies of these changes were used to show that the addition of anthropogenic heat improves the accuracy of surface air temperature forecasts. The addition of urban surface radiative properties has a secondary effect on the forecast temperature, and the addition of urban surface roughness changes has a minimal effect. Comparisons between observed and forecast boundary layer heights suggest that this parameter is poorly predicted by the model employed here, but that the impact of anthropogenic heating is likely to be a substantial increase in PBL heights over urban regions. Decreased atmospheric stability is also evidenced by comparisons of the diffusion constants for heat and moisture between the original and modified models, which show increases from a factor of 2 to a factor of 16 near the surface, depending on the size of the city. An examination of the effects of spatial averaging on heat flux suggests that significant sub-gridscale anthropogenic heating effects may occur, and implies that the results of the current simulations represent lower bounds. The simulations suggest that anthropogenic heat flux has a large local impact, with important implications for simulations of air-quality and radiative balance on regional and global scales.

Keywords: Heat island; Boundary layer; Air pollution; Climate change

1. Introduction

Urban heat islands have been studied on the local scale since the beginning of the industrial age, with the observation of temperature differences between urban London and the surrounding rural area in 1818 (Howard, 1818). In the latter part of the 20th century, detailed observational studies in cities such as New York (Bornstein, 1968), Calgary (Nkemdirim, 1976), Vancouver (Oke, 1976), Montreal (Oke and East, 1971) and other urban regions in North

*Corresponding author.
E-mail address: paul.maker@ec.gc.ca (P.A. Makar).

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America and Europe (Oke, 1973), showed that urban to rural temperature enhancements of 4–7 °C were common. Two-dimensional (Estoque and Bhumralkar, 1970; Bornstein, 1975) and more recently three-dimensional (Kimera and Takahashi, 1991; Saitoh and Fukuda, 1985; Saitoh et al., 1996) numerical simulations have been performed to simulate heat islands on domains the size of the urban centres themselves. The most sophisticated of these solve the full set of governing equations for the non-hydrostatic atmosphere, and have been shown to simulate the heating associated with a given city to a high degree of accuracy (Saitoh et al., 1996).

The potential impact of the anthropogenic heat flux on global climate has recently been discussed and summarized in a seminal paper by Crutzen (2004). Crutzen (2004) showed that the total amount of energy released by human activity is relatively small compared to the solar energy intercepted by the earth, but the human energy emissions are concentrated in the relatively small percentage of the earth's surface making up urban areas. The potential impact of the flux of anthropogenic heat on local climatology in human-populated areas may therefore be large. In addition, model simulations of climate change associated with greenhouse gas emissions usually include scaling factors for those emissions in response to expected increases in population, these increases in population will also have associated increases in the flux of anthropogenic heat, which may have a significant influence on predicted temperatures in urban regions. The effect of the flux of anthropogenic heat is therefore of interest on both synoptic and climatological time scales.

Operational weather forecast models (e.g., Côté et al., 1998) employ detailed parameterizations for surface exchange processes (Belair et al., 2003), but have traditionally neglected sources of anthropogenic heat and urban impacts, on account of their poorly resolved scales and the computational constraints associated with the application of high-spatial-resolution models over regional or global domains. In more recent years, increases in computational power have allowed these models to improve their resolution to the extent that individual cities and individual portions of the large metropolises housing the bulk of the world's population may be resolved.

Land surface schemes are used to describe the exchanges of heat, moisture and momentum between different land use types and the atmosphere in weather forecast models (Belair et al., 2003). These surface exchange parameterizations describe the time-dependent surface and mean surface temperatures as functions of the net solar radiation, sensible heat flux, latent heat flux, surface thermal coefficient, and the melting and freezing fluxes of snow and soil water. The alterations to this "natural" radiative balance and meteorology resulting from urban areas may thus be addressed through the incorporation of thermal properties of urban surfaces into these parameterizations. Past implementations of surface exchange parameterizations in operational weather forecast models have not included the flux of anthropogenic heat as an additional term in the radiative balance equations. They have been limited to describing the natural radiative balance resulting from the absorption or re-emission of naturally occurring net solar, sensible and latent heat from urban surfaces. More sophisticated approaches for urban surface have recently been put forward (cf Masson, 2000; Best, 2005) and may provide improved estimates of urban radiative effects.

We have incorporated high-resolution estimates of the flux of anthropogenic heat, urban surface roughness, and urban-urban surface properties into the land surface scheme of an operational variable resolution global weather forecast model. We then use comparisons between the original and revised model and measurements to assess the likely effect of the flux of anthropogenic heat on forecasts of local and regional weather, climate change, and atmospheric pollution.

2. Methodology

2.1. The weather forecast model

The weather forecasts were performed using the current regional version of the operational global environmental multiscale model (GEM, the weather forecasting model operated by the Canadian Meteorological Centre). The horizontal domain of the regional version of GEM makes use of a rotated latitude–longitude coordinate system with a variable spatial resolution. The highest resolution "core" of this version of GEM occurs over North America, with a constant grid spacing of 0.1375° in rotated latitude and longitude coordinates, and a gradually decreasing resolution outside of North America for the rest of the global domain. GEM