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Modelling of radiation-based thermal stress indicators for urban numerical weather prediction

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ABSTRACT

Two widely used radiation-based thermal stress indices, the Wet-Bulb Globe Temperature (WBGT) and the Universal Thermal Climate Index (UTCI), are implemented into the Canadian urbanized version of the GEM Numerical Weather Prediction (NWP) model in order to improve heat-health meteorological products in urban areas. Predictions with 250-m grid spacing over the Greater Toronto Area (GTA), Canada, reveal that spatial distribution of both WBGT and UTCI are similarly sensitive to mesoscale features such as the lake-breeze flows. Accurate prediction of WBGT and its indicators is found as evaluated with measurements during clear-sky and cloudy condition cases. In particular in clear-sky conditions the scattering index of solar radiation from the atmospheric model is found to be more realistic than fixed values. Links between intermediate important variables representing thermal load on a body, the mean radiant temperature (TMR), and a synthetic variable equivalent to the globe temperature (TG) as measured with a globe thermometer sensor are closely analyzed. Results show that the use of distinct TMR_{WBGT} and TMR_{UTCI} leads to differences of up to 50% due to a different energy partitioning and that TMR and TG are linked through a hysteresis cycle.

1. Introduction

Thermal stress indices have been issued for many years by a few operational weather centers to reflect the combined effect of temperature and other meteorological variables on human discomfort. At the Meteorological Service of Canada (MSC) the summertime Humidex (Masterson and Richardson, 1979) aims at reflecting the impact of high level of humidity on the capacity of the human's body to cool through evaporation at the skin's surface. Similarly at the United-States (US) National Weather Service (NWS) a heat index is used (Rothfusz, 1990) with a different formulae. For wintertime conditions, the wind chill equivalent temperature for North America (Osczevski and Bluestein, 2005) includes the effect of wind on discomfort. With recent advances in high-resolution Numerical Weather Prediction (NWP) forecasts (Milbrandt et al., 2016) and sub-kilometer NWP systems including urban areas (Lemonsu et al., 2009; Leroyer et al., 2014; Bélair et al., 2018), operational generation of radiation-based indices to generate alert products is now becoming possible.

Representation of thermal stress through a singular metric has been an intensive research field in the last decades. Regarding health assessment for dwellers, workers, athletes and the military, a myriad of thermal stress indices has been developed and used for many years (Buzan et al., 2015). At the present time, no real consensus has been reached (Provençal et al., 2015) while benefits and limitations of many indices and the methods to obtain them are being studied. Among such indices, the Wet-Bulb Globe Temperature

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(WBGT, Yaglou and Minard, 1957) is a labelled standard (ISO 7243, 1989, Parsons, 2013) and is widely used in health sciences as a relevant measure of summertime heat stress for several dwellers categories. D'Ambrosio Alfano et al. (2014) provided a summary of its current use. They pointed out some of its limitations mostly due to the difficulty of an accurate measurement. More recently, in 2009, the Universal Thermal Climate Index (UTCI) was created through a large project with the objective of simplifying thermal comfort communications for all weather types including wintertime (Blazejczyk et al., 2012; Jendritzky et al., 2012). These two indices take into account the radiative energy components received and absorbed by the human body through the concept of the Mean Radiant Temperature (hereafter denoted as TMR).

This temperature is a practical entity that represents the equivalent uniform temperature of a body that would lose the same radiation flux by the Stefan-Boltzmann law than the total radiation flux received from the surrounding environment (Fanger, 1970; ASHRAE Fundamentals Handbook, 2001). Experimentally, TMR can be measured by the so-called six-direction method by summing-up radiative fluxes (Thorsson et al., 2007; Kántor et al., 2014) or by use of a globe thermometer (e.g., Thorsson et al., 2007, Chen et al., 2014, Coutts et al., 2016) that can indirectly provide TMR through the measured Globe Temperature (herafter denoted as TG).

In numerical experiments, several microscale models have been including TMR such as the one dimensional RayMan model (Matzarakis et al., 2010), the 2D SOWEIG model (Lindberg et al., 2008), and the 3D ENVI-met model (Bruse and Fleer, 1998). Modelling of WBGT and UTCI in meteorological and climate models has recently been achieved in a few studies. Schreier et al. (2013) have evaluated UTCI as a post-processing of NWP models and suggest that current uncertainties in clouds simulations are the most important challenge for the quality of UTCI forecasting. Ohashi et al. (2014) have included the computation of WBGT in the Weather Research and Forecasting (WRF) model. WBGT (Weatherly and Rosenbaum, 2017) and UTCI (Lemonsu et al., 2015; Pappenberger et al., 2015) were forecasted in climate projections. While the use of such advanced thermal stress indicators is promising, there is still a need to evaluate physical processes handled by such models and to understand and improve the capability of NWP models to represent human-scale comfort.

The objectives of this study are 1) to present the radiation-based thermal comfort indicators (TMR and TG, WBGT and UTCI) that have been included into the urban Canadian modelling system, 2) to evaluate them with in-situ measurements over the Greater Toronto Area (GTA) based on data collected during the Environment and Climate Change Canada (ECCC) Panam and Para-Panam games science project (Joe et al., 2018), and 3), to investigate the physical processes predicted by GEM and their impact on heat stress indicators forecasting.

2. Materials and methods

2.1. Urban NWP system

An integrated experimental urban sub-kilometer atmospheric modelling system was set up over the GTA where the 17th Pan American and Parapan American Games were located. For more than a year, the urban NWP system produced daily 24-hour forecasts starting at 0600 UTC on grids with 10-km, 2.5-km, 1-km and 250-m grid spacing covering the GTA region. The simulation domains are represented on Fig. 1. A frequency of 15 min was used for most of outputs.

2.1.1. Limited-area atmospheric model

Forecasts were obtained with the Global Environmental Multiscale Model (GEM; Zadra et al., 2008, Girard et al., 2014), based on a specific Limited-Area Model (LAM) configuration with downscaling to 250-m grid spacing (Leroyer et al., 2014). In particular, high vertical resolution was used in the atmospheric boundary-layer. The first thermodynamic and momentum atmospheric levels are at 5 m and 10 m above the canopy level and 26 momentum levels are located below 1500 m. Condensation processes were computed following an advanced double-moment microphysics scheme (Milbrandt and Yau, 2005). The large-scale downscaling was prescribed from the operational regional deterministic prediction system (RDPS, Fillion et al., 2010) now operating at 10 km. Of particular interest in this study is the use of the radiative transfer scheme of Li and Barker (2005). The prognostic total water content is transferred directly to the radiation transfer scheme and a cloud optical depth is obtained following Li et al. (2005). Urban and land surface modelling schemes are integrated as part of the LAM model.

2.1.2. Urban and land-surface modelling

Surface physical processes over built-up areas were modeled through the single layer Town Energy Balance scheme (TEB, Masson, 2000), considering thermal and radiative street canyon properties and the influence of the canopy on the wind flow. Thermal roughness length of Kanda et al. (2007) was introduced based on work of Leroyer et al. (2010). For natural land covers, the Interactions between the Surface, Biosphere, and Atmosphere land surface model (ISBA, Noilhan and Planton, 1989; Bélair et al., 2003a, 2003b) is used. In this study, diffuse and direct solar radiation from the atmospheric model is provided to TEB and ISBA whereas former versions of the urban Canadian modelling system were only considering global radiation.

Coherent surface description over the computational domains was prescribed using Geographical Information Systems (GIS) that have continuously been developed at the Meteorological Service of Canada (MSC). In this study, orography over Canada was assigned with the Canadian Digital Elevation Data (CDED-50) and over the United States with the Shuttle Radar Topography Mission (SRTM). In Canada, vegetation attributes and water masks in and outside urban areas were provided through the Land Cover for Agricultural Regions of Canada, circa 2000 Vector geospatial dataset, compiled by Agriculture and Agri-Food Canada (AAFC). Urban surfaces characterization was provided with the CanVec geospatial dataset which is released by Natural Resources Canada and which features about 100 thematic layers including the urban fabric description. In addition, the building height and footprint database available for