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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Mean Radiant Temperature (hereafter denoted as TMR).

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

(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; Kantor 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 (hereafter 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.
the GTA’s most urbanized area was used. In the United States, similar information were retrieved from the National Land Cover Database 2011 (NLCD) and openStreetMap© datasets.

As presented in the next section, computation of thermal comfort indicators has been included in the urban and land surface modelling component, and can be used in coupled or uncoupled with the atmospheric model.

2.2. Modelling of thermal comfort indicators in urban and land surface scheme

Indices and variables that include the effect of radiative fluxes on a body at the Earth’s surface are computed in the urban and land surface models in addition to traditional meteorological outputs. Computations are conducted near the surface, at about the height of a standing person which also approximately corresponds to the height of measurements (2.5-m AGL). By extension, computations are also provided over rooftops. The main reason was to allow the comparison with sensors located over the roofs in densely urbanized locations. This model development may also be helpful to assess dwellers comfort over the roofs. Current urban building designs actually tend to provide recreations areas over rooftops, in North America as well as worldwide.

2.2.1. The wet-bulb globe temperature

In this study, measurements and prediction of WBGT follow the ISO-7243 definition (Parsons, 2013) as presented below. Forecasted WBGT expressed in °C has two different formulations for sunlit (WBGT_{SUN}) or shaded (WBGT_{SHADE}) cases:

\[ \text{WBGT}_{SUN} = 0.7 T_{WB} + 0.2 T_{G_{SUN}} + 0.1 T_{A} \]
\[ \text{WBGT}_{SHADE} = 0.7 T_{WB} + 0.3 T_{G_{SHADE}} \]

where \( T_{A} \) is the dry bulb temperature or ambient temperature, \( T_{WB} \) is the wet-bulb temperature, \( T_{G_{SUN}} \) and \( T_{G_{SHADE}} \) are the globe temperatures in the sun and in the shade, respectively, all expressed in °C. Measured WBGT corresponds to Eq. (1) with \( T_{G_{SUN}} \) directly measured with the globe sensor.

Due to the complexity of modelling \( T_{G} \) and \( T_{WB} \), and thus to predict WBGT, several attempts have been made to provide a simplified formula for numerical models. In their study, Lemke and Kjellstrom (2012) conclude that the most relevant methods are those that contain the energy budget. For the sake of comparison, another formulation of WBGT (WBGT_{SIMPLE}) is also examined in this study. It is based on the index provided by the Australian Bureau of Meteorology (ABM). The expression is written as:

\[ \text{WBGT}_{SIMPLE} = 0.567 T_{A} + 0.393 e_1 + 3.94 \]

In which \( e_1 \) is the vapor pressure given by:
\[
e_1 = \frac{RH}{100} \cdot 6.105 \cdot 10^{-19} \cdot T_A^{17.27}\]
\[
e_2 = \frac{0.01 q \cdot P}{0.622 + 0.378 q}
\]
where \(RH\) is the relative humidity in %. Eq. (3) assumes moderate high radiation levels and light wind conditions. It is worth mentioning that this simplified formulation is used in several thermal stress indices intercomparison studies (Lemke and Kjellstrom, 2012; Blazejczyk et al., 2012; Oleson et al., 2015).

2.2.2. The universal thermal climate index

The UTCI index (http://utci.org) combines environmental conditions available in the numerical atmospheric model (2-m TMR, \(T_A\), vapor pressure, and 10-m wind speed) with an advanced physiographic model presented in Fiala et al. (2012). Thermal stress and strain is computed in this study for all surface types following a 6th order polynomial approximation (Bröde et al., 2012). It should be mentioned that UTCI computation has been previously included for the streets in TEB (Masson et al., 2014). It uses vapor pressure (e2, in hPa) computed as follows:

where \(q\) is the specific humidity (in kg kg\(^{-1}\)) and \(P\) the pressure (in hPa).

2.2.3. Mean radiant temperature

TMR depends on the nature, shape, materials, and position of the body studied (Fanger, 1970). TMR (here in °C) can be expressed as follows:

\[
Q_{\text{ENV}} = \varepsilon \cdot \sigma \cdot (T_M + 273.15)^4
\]

with \(Q_{\text{ENV}}\) (in W m\(^{-2}\) as is the case for all energy fluxes presented hereafter) the total radiation flux received from the environment and absorbed by the human body, \(\varepsilon\) the emissivity of the body receiving the radiation and \(\sigma\) the Stefan-Boltzmann constant (\(\sigma = 5.67 \times 10^{-8}\) W m\(^{-2}\)K\(^{-4}\)).

In outdoor conditions, \(Q_{\text{ENV}}\) is the sum of radiation fluxes absorbed by the body and originating from direct radiation flux from the sun \(Q_{\text{SUN}}\) and from scattered all-wave radiation from the sky and from surrounding surfaces \(Q_{\text{SHADE}}\). \(Q_{\text{SHADE}}\) is written as follows:

\[
Q_{\text{SHADE}} = \sum Q_k^j + \sum Q_l^j
\]

with \(Q_k\) and \(Q_l\) the terms respectively for short and longwave radiation fluxes:

\[
Q_k^j = a_k \cdot K_{\text{SUN}} \cdot F_{\text{WBGT}}^j
\]

\[
Q_l^j = a_l \cdot L_{\text{WBGT}} \cdot F_{\text{WBGT}}^j
\]

with \(K^j\) and \(L^j\) the scattered shortwave and the longwave radiation fluxes reaching the body, \(a_k\) the body shortwave absorption coefficient and \(a_l\) the body longwave absorption coefficient (usually assumed equal to the emissivity, Thorsson et al., 2007, Gaspar and Quintela, 2009, Lindberg et al., 2008), and \(j\) corresponds to the different available sources. In the current urban modelling system, radiation fluxes from the sky are provided by the atmospheric component (radiative scheme). Short and longwave fluxes from other sources (surrounding surfaces) are provided by the surface schemes, i.e., TEB for urban covers, ISBA for vegetation, and the one for water surfaces. For locations in the street, surrounding surface sources originate in the ground and the walls. For locations over the rooftops, sources originate in the roofs and the walls only and sources from the ground are neglected. Finally, over flat surfaces, contributions are from the sky and from the ground only. Eqs. (8) and (9) involve view factors \(F_{\text{WBGT}}^j\) such that the sum is unity. These computations consider urban morphology in the street and over the rooftop based on a 1.7-m tall standing person. For flat surfaces such as water, view factors are equal to half unity for both the sky and the ground. For a body exposed to direct sunlight, the irradiance received by the body reads:

\[
Q_{\text{SUN}} = a_k \cdot K_{\text{SUN}} \cdot F_{\text{WBGT}}^j = a_k \cdot \frac{K_{\text{SUN}}}{\max(0.1, \cos \theta_z)} \cdot f_p
\]

where \(F_{\text{WBGT}}^j\) is the direct view factor of the sun which is directional, \(f_p\) is the projected area factor of the body considered and \(\theta_z\) is the zenithal angle in radians (Gaspar and Quintela, 2009). Note that the total incoming solar radiation \(K_{\text{GLOBAL}}\) is the sum of the direct \(K_{\text{SUN}}\) and diffuse \(K_{\text{SHADE}}\) components provided by the atmospheric model as received by an horizontal surface. A minimum of 0.1 is prescribed for the denominator to avoid undefined calculations at sunrise and sunset.

\(f_p\) has different expressions for a standing human or for a sphere such as a globe temperature sensor. Several observational studies report that the impact of neglecting this issue might be minor as compared to other factors (Thorsson et al., 2007). Similarly, \(a_k\), \(a_l\), and \(\varepsilon\) might differ depending on the clothed human description or on the material used for the globe temperature sensor. For the sake of rigor in this study, different expressions are used for the calculation of TMR for WBGT (TMRWBGT) or UTCI (TMRUTC). To be coherent with the spherical black globe sensor characteristics (PanAm network), TMRWBGT is computed with the globe emissivity \(e_G\) such that \(e_G = a_k = a_l = 0.957\) in Eqs. (6), (8), and (9) and \(f_p\) for a sphere equal to 0.25 in Eq. (10) (Gaspar and Quintela, 2009). For TMRUTC a standard clothed standing human is considered with \(\varepsilon = a_k = 0.97\), \(a_k = 0.7\), and the projected area factor is a function of the azimuthal angle of the face (Fanger, 1970, see his Fig. 41). For a rotationally symmetric standing human body \(f_p\) in Eq. (10) is
averaged for all azimuthal angles (see UTCI document at http://www.utci.org/utci_doku.php, Mean Radiant Temperature Tmrt.doc, last access February 2017) and is expressed as follows:

\[ f_p = 0.308 \cos \left( \frac{\pi}{2} - \frac{\theta_z}{2} \right) \left[ 1 - \left( \frac{90 - \frac{180}{\pi} \theta_z}{48402} \right)^2 \right] \]  

(11)

where the cosine argument is in radians.

2.2.4. Globe temperature

Spherical globe sensors are the common observational tool to obtain the radiant heat received by a body from the environment (Parsons, 2013). TG is measured at the center of the sphere acting as a black (or gray) body. From the globe theory (Ruehn et al., 1976; Gaspar and Quintela, 2009), energy budget at thermal equilibrium at the sphere’s surface can be expressed as follows:

\[ Q_{ENV} = Q_G + Q_H \]  

(12)

with \( Q_G \) is the radiative longwave flux emitted by the sphere and \( Q_H \) is the sensible heat flux at the surface of the sphere. TG and TMR are thus related with the following equation (with TG, TMR, and \( T_A \) in °C):

\[ e_G \sigma (TG + 273.15)^4 + h_{CG}(TG - T_A) = e_G \sigma (TMR + 273.15)^4 \]  

(13)

where \( h_{CG} \) is the coefficient for convective heat transfers between the sphere and the air (in W m\(^{-2}\) K\(^{-1}\)). Different formulations of \( h_{CG} \) can be used whether free and forced convection (e.g., wind speed larger than about 0.2 m s\(^{-1}\)) is taken into account (Bernard and Pournoghami, 1999; Gaspar and Quintela, 2009; D’Ambrosio Alfano et al., 2012). In this study the ISO 7726 (1998) standard formulation was used:

\[ h_{CG} = 6.3 \frac{U^{0.6}}{D^{0.4}} \]  

(14)

where U is the wind speed at the sensor level in m s\(^{-1}\), and D is the globe sensor diameter in m (D = 0.148 m in this study).

In many studies TMR is evaluated from measured TG using Eq. (13). The reverse is done here, i.e., TG is computed from TMR following the original method presented in Appendix A and that provides an accurate analytical solution of Eq. (13). It is worth mentioning that Weatherly and Rosenbaum (2017) uses another method such as a linearization approximation. Differences between measurements of TMR obtained with the globe thermometer and from the sum of surrounding radiative components (the six-direction method) have been evaluated in several studies. For example Thorsson et al. (2007) and Lindberg et al. (2016) have found relatively good correlations between the two methods. Chen et al. (2014) have in contrast observed greater differences and pointed out possible challenges in obtaining TMR from measured TG due to the impact of turbulence. Acero and Arrizabalaga (2016) also found some large differences from ENVI-met and TMR deduced from TG measurements. Kantor et al. (2015) have provided corrective functions between the different TMR from different measurements. Interestingly, those studies also mention a period necessary for the instrument to reach equilibrium which can vary with the type of sensor.

2.2.5. Wet-bulb temperature

The experimental WBGT traditionally includes direct measurements of the natural \( T_{WB} \) (D’Ambrosio Alfano et al., 2012) which is obtained by a sensor covered with a wetted wick naturally ventilated. In practice, and as was the case for the PanAm-2015 mesonet, it is not directly measured but retrieved from other measured quantities such as ambient temperature, and relative humidity (see the instruction manual Campbell Scientific, 2012). In the GEM atmospheric model, \( T_{WB} \) is computed based on thermodynamic functions adapted to cover a large range of conditions (Stipanuk, 1973; Schlatter and Baker, 1981). It is worth mentioning that other algorithms can be found in the literature, like for example in Stull (2011) for a limited range of conditions, or in Davies-Jones (2008) as implemented in Buzan et al. (2015). D’Ambrosio Alfano et al. (2012) have investigated the possible errors introduced by the use of a computed \( T_{WB} \) instead of the directly measured \( T_{WB} \) (referred to as natural \( T_{WB} \)). Except for very low wind velocities, they found small errors (< ± 1 °C).

In summary, the sequence of heat stress indicators calculations in GEM is as follows. TMRUTCI is first determined with the energy budget for a standing clothed human. UTCI is computed with TMRUTCI, vapor pressure, and with traditional meteorological variables such as air temperature and wind speed. A second TMRWBGT is determined for a synthetic globe sensor instrument and is used to retrieve TG. In addition, the wet-bulb temperature \( (T_{WB}) \) is computed. Finally WBGT is computed from TG, \( T_{WB} \) and \( T_A \).

2.3. Data and experimental setup

2.3.1. Measurement sites

A comprehensive observational measurement network was set up in and around the GTA (Joe et al., 2018). Fig. 2 shows the sites selected in this study among all sites for the evaluation as they are equipped for measurement of the globe temperature or of radiative components. The stations are located in the vicinity of Toronto (Fig. 2). Corresponding surface characteristics in GEM’s nearest grid points are summarized in Table 1. The main characteristics of the various stations are presented in the next paragraph with a summary of the instrumentation provided in Table 2.
First, ECCC Automated Transportable Meteorological Observing System (ATMOS) ground stations were measuring the wind components at 10-m above ground level (AGL), as well as air temperature, relative humidity, globe temperature, WBGT and incoming solar radiative flux at 2.5 m AGL (Table 2). Although the sites were close to urbanized areas, their direct neighborhood was most often composed with natural surfaces and sparse vegetation. On average, 88% of vegetation is found at the corresponding model grid points (Table 1). At rooftop stations measurements were representative of more urbanized areas with low-rise buildings (with a mean building height of about 8 m). On average, these locations exhibit natural covers for slightly more than half the area (as used in the atmospheric model). But greater variability between the sites can be noticed (Table 1). For the ATMOS A6T rooftop station,
measurements were made at 5-m for the wind and 2.5 m for the other variables (Table 2). For the other stations (19 sites including venues and transect stations) the measurements were all taken at 2.5-m above roof level (ARL) with compact weather stations. Finally, the University of Ontario Institute Of Technology (UOIT) Meteorological Super Site (PUMS) was located northeast of Toronto, in a rural area close to the city of Oshawa (UOIT Campus). Of particular interest for this study are the measurements of infrared and shortwave upward and downward radiation fluxes, as well as direct and diffused short-wave radiation fluxes that were collected by the Eppley and SPN1 radiometers, respectively (Table 2, Gultepe et al., 2015). It is worth mentioning that there was no globe sensor at this location but the measured radiative terms were used to compare model simulation results at the PUMS site. All of these observations were collected at one-minute intervals during the project (averaged with 5 s samples for ATMOS stations).

2.3.2. Experimental setup
Two case studies were selected to represent different summertime weather conditions in order to analyze physical processes modeled with the thermal stress indicators and their response to distinct atmospheric forcing. For the 15 July 2015 case, clear-sky conditions were generally present over the GTA region. For the 19 July 2015 case, heat stress warnings were issued in the GTA region by ECCC and the city of Toronto, with more complex cloudy conditions. For the measurements used in this study on 15 July 2015 (respectively on 19 July 2015), maximum of sea level pressure was 999 hPa (991 hPa), temperature reached 22 °C (30 °C) and relative humidity was up to 89% (92%).

For both cases, the simulations started during nighttime at 0600 Universal Time Coordinated (UTC) corresponding to 0200 Eastern Daylight Time (EDT). Initial conditions for soil moisture and natural surface temperature were provided with the 2.5-km CaLDAS fields (used for the recent pan-Canadian 2.5-km modelling system, Carrera et al., 2015, Milbrandt et al., 2016). Urban facets temperatures were initialized to atmospheric conditions for the roof and the walls, and to soil temperature for the roads. The water surface temperature for the Great Lakes was prescribed using 2-km hourly output from a coupled ocean-atmosphere forecasting system (Durnford et al., 2018). The surface temperature of other water bodies was prescribed through the regular MSC’s analysis and remained constant during the day.

Simulation results are analyzed with 250-m grid spacing at 15-min intervals. Measurements were averaged over the same intervals.

3. Results and discussion

Thermal stress indicators were simulated with the urban modelling system based on the method presented in the previous section. On Figs. 3 to 11, results on the left (on the right) are for 15 July 2015 (or for 19 July 2015). All heat-stress indicators are presented in °C for the sake of clarity and for consistency with the literature. In Section 3.1, maps of WBGT and UTCI are displayed over the GTA to highlight their predicted spatial distribution. There is however no possibility to evaluate objectively these maps with measurements due to the lack of suitable distributed observations. Further evaluation of simulated components is conducted in Section 3.2 at measurement stations. Sensitivity of the simulated thermal stress indicators is estimated and discussed in Section 3.3.

3.1. Spatial distribution

Previous studies have shown the impact on thermal stress indicators of environmental conditions (Schreier et al., 2013) and in a lesser extent of the surface on which humans stand (Lindberg et al., 2016). Fig. 3 illustrates predicted WBGT (Fig. 3a) and UTCI (Fig. 3b) over Southern Ontario. It should first be noted that the different range of values for WBGT and UTCI is inherent to the definition of each index. Interpretation of numerical values along with their associated comfort scale is necessary for communication to the public (e.g., D’Ambrosio Alfano et al., 2014; Provençal et al., 2015). Urban areas can be identified with Fig. 2. Note that Z1D is the closest station to downtown Toronto.

The different meteorological situations observed for the two cases are reflected in the spatial distribution of the two indices. On 15 July 2015 (left panels), a clearly defined lake-breeze front remains over the city for several hours. Companion studies have shown

<table>
<thead>
<tr>
<th>Stations</th>
<th>Instrumentation</th>
<th>Variables</th>
<th>Height above surface</th>
</tr>
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<tbody>
<tr>
<td>Ground ATMOS stations</td>
<td>ECCC ATMOS</td>
<td>T, RH, P, k&lt;sup&gt;G&lt;/sup&gt;GLOBAL, precip.</td>
<td>2.5 m</td>
</tr>
<tr>
<td></td>
<td>wind</td>
<td>TG, WBGT</td>
<td>10 m</td>
</tr>
<tr>
<td></td>
<td>BLACKGLOBE-L</td>
<td>L&lt;sup&gt;SKY&lt;/sup&gt;</td>
<td>2.5 m</td>
</tr>
<tr>
<td>Rooftop stations</td>
<td>Vaisala WX520</td>
<td>T, RH, P, precip.</td>
<td>2.5 m</td>
</tr>
<tr>
<td></td>
<td>Luft WS601</td>
<td>T, q, k&lt;sup&gt;G&lt;/sup&gt;GLOBAL</td>
<td>5 m</td>
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<td></td>
<td>ECCC ATMOS</td>
<td>wind</td>
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<td></td>
<td>BLACKGLOBE-L</td>
<td>TG, WBGT</td>
<td>2.5 m</td>
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Table 2
Measurements sensors characteristics and variables collected by the data loggers.
close agreement between the prediction and observations of the lake-breeze (e.g., Dehghan et al., 2018). There is a clear correlation between large values of both indices and low-level airmass convergence. This convergence zone north of Lake Ontario and over the urban area is favorable to the occurrence of larger temperature and lower wind speed (as do sea-breeze fronts, Leroyer et al., 2014) and are thus expected to lead to larger thermal stress indices.

In general, larger values of WBGT and UTCI are found above urban areas, with considerable spatial variability associated with enhanced vertical mixing over that region. The spatial variability of WBGT is similar to that of UTCI over land, with less amplitude as mentioned above. Local differences can be large at specific locations, such as in areas north and east of GTA where WBGT is found to be more homogeneous with values as large as for GTA. More comfortable conditions are usually simulated for a thin strip of land surrounding Lake Ontario.

For the second case, 19 July 2015, larger values for both indices are predicted over the GTA and over the areas near the lake shore. Westerly wind was dominant on that day, preventing the formation of a well-defined lake-breeze front over the GTA (King et al., 2003). Many of the differences described for the previous case are also found on 19 July 2015, like for instance UTCI showing a larger range of values than WBGT.

As expected, the results shown in Fig. 3 indicate that forecasting of both WBGT and UTCI in summertime is strongly dependent on the meteorology. Evaluation of the thermal stress indicators is presented below.
3.2. Evaluation

This section provides comparisons of some predicted thermal stress indicators with measurements. Results are averaged for one or two of the three categories of measurements (Table 1). In GEM, averaging is applied over the nearest cells corresponding to the different stations. First WBGT is compared at both ground ATMOS and rooftop stations. Evaluation of its predicted primary components (TA, TWB, and TG, see Eqs. (1) and (2)) with measurements is also shown at the ground ATMOS stations for which simultaneous verification of incoming solar radiation is possible. Finally an additional evaluation of atmospheric radiative components is provided at the PUMS station.

A comparison with measurements of WBGT predicted with Eqs. (1) and (2) (sunlit and shaded) and with the Eq. (3) (simplified formulation) is presented in Fig. 4 for ground ATMOS stations (Fig. 4a) and rooftop stations (Fig. 4b). Formulations for sunlit and shaded conditions both include the effect of cloudiness on scattered radiation fluxes. Error statistics (bias, and the standard deviation error STDE) were computed following Appendix B for Eq. (1) (sunlit) because the instruments were exposed to direct sunlight. STDE time series between the different stations is displayed on Fig. 4. Table 3 reports the computed statistics for the whole, daytime and nighttime periods. The daytime period is identified with the positive sign of solar radiation (from 06:00 to 20:45 EDT). As seen in Fig. 4, larger values of WBGT were found on 19 July 2015 than on 15 July 2015 when measurements reached the second category of heat warning (between 26.6 and 29.3 °C). For the two days, predicted values in the sunlight are in general in a good agreement with measurements and feature the same diurnal cycle. STDE are generally below 1 °C for 15 July 2015, and below 2 °C for 19 July 2015 when STDEs errors are larger in late afternoon, between 15:00 and 17:00 EDT. During daytime of 15 July 2015, predicted values of WBGT in sunlit and shaded conditions are below measurements, with relatively small differences of about 1.5 °C between the two situations. An even smaller difference is found for 19 July 2015. Results averaged for the rooftop stations (Fig. 4b) are almost similar in the sun and in the shade, with substantial underestimation during the night.

For the two days examined it is found that values from the simplified WBGT (Eq. (3)) always overestimate measurements and remain larger than values from the ISO definition (Eq. (1)) by up to 8–10 °C at night for both locations over the roof and in the street. This last result is in general coherent with Willett and Sherwood (2012) who also reported this type of behavior of the simplified WBGT although they mention that underestimation could be found for conditions with high solar radiation. This could be due to the relatively large wind speed encountered in this study, considering that WBGTSIMPLE is more appropriate for light wind conditions.

Some aspects of the results presented in Fig. 4 are different to what was obtained by Ohashi et al. (2014) in Tokyo, Japan. Predicted daily maximum WBGT in the sun for two stations and for the whole summer were found above measurements by about 2.5 °C for most of summer days. Predicted values in the shade were mostly of the time slightly smaller than measurements. The authors mostly attributed these errors to an incorrect prediction of the wet-bulb temperature. Evaluation with measurements of the different terms included in the WBGT ISO formulation (Eq. (9) in the sun and in the shade in their study) was however not presented. This type of evaluation is presented below for the ground ATMOS stations which also has the benefit of having co-located measurements of incoming solar radiation.

Evaluation of predicted values for air temperature (T_A, Fig. 5a), wet-bulb temperature (T_{WB}, Fig. 5b), and globe temperature, corresponding to predicted values in the sun (T_{SUN}, Fig. 5c) and in the shade (T_{SHADE}, Fig. 5d) is displayed in Fig. 5. It is worth...
mentioning that TG was measured in non-shaded environment. Both plots (in sunny and shaded conditions) are presented in order to evaluate the effect of direct solar radiation.

The diurnal cycle for air temperature (Fig. 5a) is fairly well reproduced by GEM for the two days, with larger values on 19 July. A slight underestimation on 15 July 2015 can be seen (with a daytime bias of $-0.5\,^\circ\mathrm{C}$, Table 3). STDEs are on average $1.1\,^\circ\mathrm{C}$ for 15 July.

Fig. 5. Comparison of 2.5-m Above Ground Level predicted (red line) components of WBGT with measurements (blue line, in non-obstructed conditions) at ground ATMOS stations for 15 July 2015 (left) and for 19 July 2015 (right), for (a) Air Temperature, (b) wet-bulb temperature (Note the different scale for the two days), (c) Globe temperature measured (blue) and predicted in the sun (red), (d) globe temperature measured (blue) and predicted in the shade (red). Time series averaging and statistics are the same as in Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. Same as Fig. 5 but for incoming global solar radiation ($K^{\text{GLOBAL}}$, in W m$^{-2}$).

The diurnal cycle for air temperature (Fig. 5a) is fairly well reproduced by GEM for the two days, with larger values on 19 July. A slight underestimation on 15 July 2015 can be seen (with a daytime bias of $-0.5\,^\circ\mathrm{C}$, Table 3). STDEs are on average $1.1\,^\circ\mathrm{C}$ for 15 July.
2015 and 1.3 °C on 19 July 2015 (Table 3), although greater variability can be found on the cloudy day, in particular around 1600–1700 EDT when measurements exhibit a drop related to the cloud cover (Fig. 5a). The diurnal cycle of \( T_{WB} \) is also well reproduced by GEM, although a persistent 1 °C underestimation during daytime can be found on 15 July 2015, but can be as large 2 °C during the afternoon of 19 July. More humidity was present on 19 July which leads to \( T_{WB} \) values closer to \( T_{A} \).

For the globe temperature it can be seen on Fig. 5c that daytime predicted values are on average in very good agreement with measurements on 15 July 2015 in cloud-free conditions. STDE errors are however larger for \( T_{GSUN} \) than for \( T_{A} \) and \( T_{WB} \) with a maximum of 4 °C at 1700–1800 EDT. Predicted values are slightly overestimated during daytime on 19 July (Table 3) with a maximum of difference up to 5 °C at about 1600 EDT. STDE at this time reaches 5.5 °C. On 15 July 2015, daytime \( T_{GSHADE} \) values (Fig. 5d) are about 8–9 °C below predicted values in the sun. On 19 July 2015, predicted values in the shade are about 3–4 °C smaller than in the sun. This suggests that the effect of solar radiation is lower for that day and the effect of diffuse radiation is likely to be larger. On average for the sites, predicted values have the same variability than measurements (as seen for example on Fig. 5c). As linked with previous results, WBGT predicted and measured values differences reflect the individual errors of the three components.

Fig. 7. Comparison of the contribution of the diffuse to the global solar incoming radiation at the PUMS site predicted by GEM (red line) and measured (blue line) for 15 July 2015. Time series averaging are same as in Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. Predicted TMRs averaged for the rooftop stations, computed to retrieve WBGT (red dotted line), UTCI (blue solid line), and for an intermediate configuration (dashed purple line). See details in the text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
As the largest weighting factor applies to $T_{wb}$ (70%), underestimation of $T_{wb}$ for 15 July 2015 is responsible for the slight underestimation of WBGT during daytime, and on 19 July for the underestimation between 1730 and 2000 EDT.

These results suggest that the method used in this study provides a relatively accurate prediction of thermal stress indicators through the domain. GEM is also found to perform well for more complex cloudy conditions. Current errors on cloud cover prediction in NWP and climate models were however pointed out to be the most important challenge in the computation of TMR and UTCI (Shreier et al., 2013). The impact of the radiative fluxes predicted by the meteorological model is then addressed in the following paragraphs.

The accuracy of predicted global incoming solar radiation flux ($K_{GLOBAL}$) is assessed in Fig. 6 for the ground ATMOS stations, at the same locations that were used for results presented in Figs. 4a and 5. Mean error statistics are in Table 3. For the 15 July 2015

![Fig. 9. Predicted energy fluxes (solid lines for short-wave $Q_k$ and dash-dotted lines for longwave $Q_L$ fluxes) contributing to $Q_{env}$ (black dotted line, scale on the right side of the figures) averaged for rooftop stations model grid points, above the rooftop (a and b) and above the ground (c). (a), for $TMR_{WBGT}$, and (b) and (c), for $TMR_{UTC}$. Orange, $Q_{K_{SUN}}$, blue, $Q_{K_{SKY}}$ and $Q_{L_{SKY}}$, red, $Q_{K_{GROUND}}$ and $Q_{L_{GROUND}}$, green, $Q_{K_{WALL}}$ and $Q_{L_{WALL}}$. See Section 2.2 for details and Eqs. (6) to (10). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image)

![Fig. 10. Scatter plots of the predicted TG and $TMR_{WBGT}$ for all stations for 15 July 2015, (a), with the standard convective coefficient (Eq. (14)), and (b), the convective coefficient of Toriyama et al. (2001) used in Ohashi et al. (2014). The evolution of colors and symbols follows the diurnal cycle with a frequency of 15-min as presented at the bottom of the figures.](image)
case, the sinusoidal shape of the diurnal cycle for both measurements and prediction indicates the occurrence of a clear-sky day. Some differences can be found during the day and are related to intermittent cloud cover occurring at the different stations (not shown).

STDEs values remain below 140 W m$^{-2}$ for the entire day. More discrepancies are found on 19 July 2015 with notable underestimation during the first part of the day followed by an overestimation in the afternoon, up to +50% at 1530 EDT. This range of +50% uncertainties on solar radiation is similar to the case study chosen in Schreier et al. (2013) to test the sensitivity of TMR to possible errors in incoming solar radiation prediction. In this study, TGSUN is then overestimated by about 8 °C (Fig. 5c) whereas TGSHADE values are the same than measurements (Fig. 5d). Both forecasts and measurements indicate a complex overcast day on 19 July 2015, although GEM is not able to represent perfectly the cloud cover at the exact time and location. STDEs values reach larger values than for 15 July 2015 and reach about 250 W m$^{-2}$ for a large part of the afternoon (Fig. 6).

Alternatively, GEM’s ability to correctly forecast the scattered contribution of the global solar radiation might be questioned. The ratio $r_{scat}$ between diffuse and global solar radiation ($r_{scat} = K_{SKY}/K_{GLOBAL}$) is provided from the atmospheric model in this study. $r_{scat}$ at the PUMS is presented on Fig. 7. For the clear-sky conditions on 15 July 2015, the curve of the diurnal cycle of $r_{scat}$ follows a bowl for both the model and measurements. The curves reach a minimum of 10% at noon in GEM whereas measurements show about 13%,

**Table 3**

<table>
<thead>
<tr>
<th></th>
<th>WBGT °C</th>
<th>TA °C</th>
<th>TWB °C</th>
<th>TG °C</th>
<th>$K_{GLOBAL}$ W m$^{-2}$</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Ground ATMOS</td>
<td>Rooftop</td>
<td>Ground ATMOS</td>
<td>Ground ATMOS</td>
<td>Ground ATMOS</td>
</tr>
<tr>
<td>15 July 2015</td>
<td>Bias</td>
<td>All</td>
<td>−0.20</td>
<td>−0.40</td>
<td>−0.01</td>
</tr>
<tr>
<td></td>
<td>Night</td>
<td>0.36</td>
<td>−0.60</td>
<td>0.97</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>STDE</td>
<td>All</td>
<td>0.93</td>
<td>0.89</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>Day</td>
<td>0.83</td>
<td>0.90</td>
<td>0.79</td>
<td>0.71</td>
</tr>
<tr>
<td>19 July 2015</td>
<td>Bias</td>
<td>All</td>
<td>0.03</td>
<td>−0.80</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Night</td>
<td>0.07</td>
<td>−0.90</td>
<td>0.59</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>STDE</td>
<td>All</td>
<td>1.22</td>
<td>1.39</td>
<td>1.34</td>
</tr>
<tr>
<td></td>
<td>Day</td>
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<td>1.50</td>
<td>1.51</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>Night</td>
<td>0.90</td>
<td>1.16</td>
<td>0.98</td>
<td>0.87</td>
</tr>
</tbody>
</table>
Table 4
Radiative characteristics \((a_k, a_l, \varepsilon)\) and projected factor for direct solar radiation \((f_p)\) used for TMR and TG computation in GEM and in the literature.

<table>
<thead>
<tr>
<th></th>
<th>(a_k)</th>
<th>(a_l)</th>
<th>(\varepsilon) for TMR ((\text{Eq. (6)}))</th>
<th>(\varepsilon) for TG ((\text{Eq. (13)}))</th>
<th>(f_p) ((\text{Eq. (10)}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEM (UTCI)</td>
<td>Clothed standing human</td>
<td>0.7</td>
<td>0.97</td>
<td>0.97</td>
<td>–</td>
</tr>
<tr>
<td>GEM (WBGT)</td>
<td>Spherical globe sensor</td>
<td>0.957</td>
<td>0.957</td>
<td>0.957</td>
<td>0.957</td>
</tr>
<tr>
<td>Gaspar and Quintela (2009)</td>
<td>Spherical globe sensor</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>Ohashi et al. (2014)</td>
<td>Spherical globe sensor</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.95</td>
</tr>
</tbody>
</table>

probably because GEM slightly underestimates the cloudiness or because of the forecasted cloud optical properties. This is however smaller than the default fixed values of 20% used in several studies on radiation-based thermal stress indicators, such as in Thorsson et al. (2007) and in Provençal et al. (2015) or 30% in Weatherly and Rosenbaum (2017). Measurements display cloud occurrence around 1500–1600 EDT (with \(r_{\text{cat}}\) reaching 35%) while it is predicted around 1800–1900 EDT. In the model \(r_{\text{cat}}\) reaches 100% which suggests that the cloudiness is too opaque for that time.

3.3. Sensitivity of thermal stress indicators in clear-sky conditions

Evaluation of WBGT and its components was performed in the previous section and revealed a relatively good agreement with measurements, especially for the clear-sky case. Unfortunately, there were no specific measurements of 6 direction radiative fluxes available for this study to evaluate directly neither TMR nor UTCI. This section is however dedicated to analyze the links between the different thermal stress indicators, the two distinct TMRs, as well as TG. In addition the impact of convection at the globe sensor surface is investigated.

TMRWBGT and TMRUTCI were computed following both configurations, as summarized in Table 4. The former corresponds to a spherical globe sensor made with copper, and the latter to a standing human with standard clothing. A comparison of TMRUTCI and TMRWBGT is presented in Fig. 8 for the rooftop stations. An important sensitivity of the configuration is found on TMR, with TMRWBGT around the maximum of insulation (1300 EDT) being about 50% larger than TMRUTCI (from about 44 °C to 66 °C). Significant differences occur from sunrise to sunset, while TMRUTCI exhibits a smaller increase than TMRWBGT. It can be noted that the evolution of TMRUTCI for the ground ATMS stations has an even more pronounced flattening (not shown). An intermediate configuration is displayed, TMRINTERMEDIATE, that uses a spherical shape but with the values of absorption coefficient and emissivity used for UTCI and exhibit about 52 °C at 1300 EDT. Thus, the difference of TMRINTERMEDIATE and TMRUTCI highlights the influence of using a sphere instead of a standing person. TMRINTERMEDIATE is smaller at sunrise and sunset because the sphere has a smaller surface exposed, and is larger around the maximum of insulation (the projected factor of the human body over the ground is then at a minimum of 0.08). It can thus be noted that a seated person would need another formulation for the mean radiant temperature. TMRINTERMEDIATE and TMRWBGT difference highlights the influence of using radiative properties of the globe sensor versus a clothed human, which can be seen all daytime long with a maximum difference of 10–12 °C.

Corresponding energy budgets absorbed by a body as defined by Eq. (6) are presented in Fig. 9. Budgets corresponding respectively to TMRWBGT and TMR UTCI for the rooftop stations are shown in Fig. 9a and b. Budget associated with TMRUTCI at the same grid points but computed in the street is shown in Fig. 9c. The total energy flux \(Q_{\text{ENV}}\) is then decomposed for the different sources (Eq. (8)) for the shortwave fluxes \(Q_j\) (Eq. (9)) for the longwave fluxes \(Q_l\) and (Eq. (10)) for the direct sunlight \(Q_{\text{SUN}}\). Analysis of Fig. 9a and b reveals that \(Q_{\text{SUN}}\) has the most obvious impact on the \(Q_{\text{ENV}}\) change between the two configurations (and thus, on TMR). \(Q_{\text{SUN}}\) has a similar increase at sunrise and sunset but reaches a smaller maximum (occurring around 1300 EDT for Fig. 9a and two maximum around 0900 and 1700 EDT for Fig. 9b). For UTCI, \(Q_{\text{SUN}}\) exhibits a clear local minimum during the maximum insulation due to a smaller projected factor. For the other contributing sources, \(Q_j\) fluxes have relatively close values whereas all \(Q_l\) fluxes are slightly larger for WBG than for UTCI, while exposing similar time series. It can be noted that the contribution from the walls above the rooftop are negligible in the shortwave range and remain small and close to 10 W m\(^{-2}\) for the longwave range. In contrast, results above the ground for the same locations than rooftop measurements (Fig. 9c) highlight \(Q_{\text{WALL}}\) contribution to be about 35–40 W m\(^{-2}\) through the day and night, whereas \(Q_{\text{WALL}}\) reach about 5 W m\(^{-2}\) during daytime, which can vary between the sites and the street aspect ratio. Fig. 9b and c exhibits substantial different energy fluxes from the sky and from the surface underneath (roof or ground) although \(Q_{\text{ENV}}\) reaches similar values (600 W m\(^{-2}\)).

In summary, these results highlight the importance to consider the different behavior between TMRUTCI and TMRWBGT to predict various heat stress indicators. Such impact of the absorption coefficients is mentioned in several studies as a possible reason of the overestimation of TMR from the standard globe sensor in clear-sky conditions when compared with TMR from the six-direction method (e.g., Chen et al., 2014; Kántor et al., 2015), or with TMR from a model (e.g., Acero and Arrizabalaga, 2016). On the contrary, underestimation is found in Thorsson et al. (2007) while using a gray globe sensor with \(D = 0.138\) m which might have lower \(a_k\). In addition to the impact of the parametrization of the TMR, further paragraphs aim at assessing the method used to compute the synthetic globe temperature necessary for the WBGT prediction.

In GEM, TG is computed from TMR by resolving Eq. (7). Although the solution of the equation is found to be relatively accurate, uncertainty remains on the formulation of the convective coefficient (Eq. (8)). For example, Thorsson et al. (2007) have suggested a new formulation of \(h_{CG}\) based on a statistical regression between TMR measurements with a 38 mm gray globe thermometer and with
six radiometers. Interestingly, Ohashi et al. (2014) have used a formulation suggested by Toriyama et al. (2001) that do not depend on the globe diameter. The relationship between TG and TMR_{WBGT} are presented in Fig. 10 for the ISO hcg used in GEM (Fig. 10a) and that of Toriyama et al. (2001) (Fig. 10b), for both ground ATMOS and rooftop stations.

For the two configurations, a clear hysteresis diurnal cycle links TG and TMR as highlighted with the colors evolution, due to the non-linear processes involved in the computation. In general, TG increases as TMR increases although with varying slopes. For example, TG increases at a smaller rate than TMR after sunrise and before sunset, whereas TG increases faster than TMR during the hours of maximum insulation, and decreases more rapidly at night. Results obtained with the convective coefficient used in Ohashi et al. (2014) display a slower increase of TG. This configuration was not retained in GEM because less agreement is found with measurements (not shown). Interestingly, results (not shown) with the revised formulation of Thorsson et al. (2007) were also not as convincing.

Particular attention is paid to the period of maximum insulation (1100–1600 EDT) in Fig. 11 which represents the evolution of the departure of TG from the air temperature with the 10-m wind speed (for the ground ATMOS stations, for the rooftop stations above the rooftop and above the ground). It is found that TG-T_{A} decreases as the wind speed increases. Values are likely to reach a plateau for the minimum between 6 and 10 °C, lower over the rooftop than above the ground. Lower wind speed values were encountered above the ground in urbanized locations, because of the presence of buildings that slow down the flow. It can be noted that wind speed values encountered for that day are relatively large as compared to studies found in the literature studying thermal stress. An overestimation of the 10-m wind speed of about 1 m s\(^{-1}\) during daytime for ATMOS ground stations was found for the 15 July 2015 with values of 4-5 m s\(^{-1}\). Based on Fig. 11, it is likely that this bias has a minor effect on TG values in this study. An inaccurate wind speed forecast for lower wind speed would however have more impact on TG and WBGT forecasting.

4. Conclusions

WBGT and UTCI are widely used radiation-based thermal stress indices and have been implemented in the GEM Canadian urban modelling system. The originality of the method presented in this study is to consider a distinct TMR used for UTCI and used for TG and WBGT, to provide an analytical solution of the equation from the globe theory, and to use an integrated sub-kilometer NWP system. Conclusions of this study can be summarized as follow:

1) Although WBGT and UTCI comfort scales are very different, they both exhibit a spatial variability strongly related to mesoscale meteorological processes.

2) Evaluation with measurements from the PanAm measurement network was relatively successful and revealed the good performance of GEM Canadian urban modelling system to predict WBGT and related indicators, for both clear-sky and cloudy days. An even better agreement during clear-sky conditions was found. It is worth mentioning that it is the first time from authors’ knowledge that time series of T_{G} from a meteorological model were directly compared with measurements.

3) The computation of thermal stress indicators using in line radiative fluxes from an atmospheric model is promising and improve the representation of the diffuse component of the global incoming radiation as compared to fixed values used in the literature. Based on this study, the ratio between diffuse to global solar radiation fluxes is likely to be 10–15% for clear-sky conditions but can reach 100% in cloudy conditions. There remain however, challenges to improve the capacity of NWP, even with the small grid spacing of 250 m used in this study, of representing all clouds at the exact time and locations (Barker et al., 2017). Current advances in NWP are likely to improve atmospheric radiation fluxes reaching the surface, such as the consideration of 3-D components, the better coupling between radiative and microphysics processes (Paquin-Ricard et al., 2016), and the inclusion of processes linked to the presence of aerosols.

4) The definition chosen for TMR is of importance and can lead to critical differences in the thermal stress indices forecasting. The use of specific TMR for WBGT or UTCI cannot be neglected.

5) Due to the convective processes at the globe surface, TG and TMR differences follow a hysteric cycle that depends on the formulation used for the convective coefficient. The current ISO formulation provides the best comparison with measurements.

Future work plans include further evaluation of radiation-based thermal stress indicators in GEM with mobile measurements in GTA during 2015 summer, as well as the comparison between WBGT, UTCI and the current operational humidex. Summertime objective evaluation of traditional meteorological variables with the PanAm network will be presented in another study. Predicted spatial heterogeneity in the GTA will be assessed with satellite imagery (e.g., following the methodology used for MODIS by Leroyer et al., 2011, 2014, or by using microscale images). An important question remains about how to deliver the useful information to the users in the context of heat-related meteorological products. The use of ensemble (Pappenberger et al., 2015) instead of deterministic forecasts, or the accumulation of time spent on thermal warning categories (Lemonsu et al., 2015) are possible avenues to deliver such meteorological services.

Acknowledgments

The authors would like to thank Dave Sills, Paul Joe, John MacPhee, Joan Klassen, Dave Henderson, Melissa MacDonald, and the ECCC PanAm science project team, for the development of the measurement database and for their interest in adding WBGT and UTCI in GEM. Acknowledgments are also provided Robert Schoetter, Valéry Masson, Aude Lemonsu, and Grégoire Pigeon from the CNRM-ville team, for the useful discussions on UTCI in TEB.
Appendix A. Globe temperature derived from mean radiant temperature

In this appendix Eq. (13) (see Section 2.2.4) is expressed as a 4th order equation to compute TG:

\[(TG + 273.15)^4 + a(TG + 273.15) - b = 0\]  
(A1)

In this system, TMR, TA, εG and hCG are known and are used to define a and b coefficients, such as:

\[a = \frac{hCG}{εGσ} \]  
(A2)

\[b = (TMR + 273.15)^4 + a(TA + 273.15) \]  
(A3)

Analytical solution Eq. (A1) (Wolfram Alpha LLC, 2015) gives four solutions but one only provides TG on the same order of magnitude than air temperature. This solution is:

\[TG = I - J\]  
(A4)

The expression can be obtained with the following terms:

\[I = 0.5 \left( \frac{2a}{\sqrt{K}} - K \right)^{0.5} \]  
(A5)

\[J = \frac{\sqrt{K}}{2} \]  
(A6)

\[K = 0.381571 E - \frac{Q}{E} \]  
(A7)

\[Q = 3.4943 b \]  
(A8)

\[E = (M + 1.73205\sqrt{N + P})^{1/3} \]  
(A9)

\[M = 9 a^2 \]  
(A10)

\[N = 27 a^4 \]  
(A11)

\[P = 256 b^3 \]  
(A12)

Performance of this code has been tested during one year of daily simulations. Errors were found not to exceed 0.01 °C. It is therefore suggested to use this simple and non-iterative solution to compute a synthetic TG from TMR to compute WBGT.

Appendix B. Error statistics

Bias, root mean square error (RMSE), and standard deviation error (STDE) are the statistics to assess the predictive error of a variable in a model as compared with a set of measurements. They are computed as follows:

\[\text{bias} = \frac{1}{n} \sum_{i=1}^{n} (F_i - M_i)\]  
(B1)

\[\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (R_i - M_i)^2}\]  
(B2)

\[\text{STDE} = \sqrt{\text{RMSE}^2 - \text{bias}^2}\]  
(B3)

where Fi is the forecast value and Mi is the measurement value for each i of n measurements.

In Figs. 4 to 6, errors are computed at a given time but for different stations (n is the number of stations) and the time series of STDE is then plotted. In Table 3, errors are computed for a part or the all of a time period (n is the sum of the number of stations and the number of time considered).

References


