



A new perspective to assess the urban heat island through remotely sensed atmospheric profiles



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ABSTRACT

The detection of urban heat island (UHI) is generally conducted from ground observations of air temperature and remote sensing of land surface temperature (LST). Satellite remotely sensed LST has many merits, such as global coverage and consistent periodicity, which overcomes the weaknesses of ground observations related to the footprint, site distributions, and costs. For human related studies and urban climatology, air temperatures are equally important. This study explores the potential to estimate the near-surface air and dew-point temperatures from the MODIS 07 atmospheric profile product (MOD07_L2) to capture the UHI dynamics at 5 km resolution. Four mega-cities in North America: Phoenix, Houston, Chicago, and Toronto, are evaluated during 2003–2013 summers. The comparison between the MODIS near-surface temperature and the ground observations suggests an accuracy of 3–7 K RMSE for different cities and times of day. For air temperature, the Aqua overpass has better agreements, and nighttime has higher accuracy than daytime in most cases. In general, very dry (Phoenix) and very moist (Houston) climate conditions increase the variability of the MODIS temperature accuracy. This study also develops an urban heat island curve (UHIC) to represent UHI intensity by integrating the urban surface heterogeneity in a curve, showing the relationship between air temperature and urban fraction. UHIC provides a new way to quantify UHI city by city, which emphasizes the temperature gradients, consequently decreasing the impact of data biases.

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1. Introduction

Urban heat island (UHI) is a phenomenon where the urban area is warmer than its ambient rural area. The progressive modification of surface covers and structures as well as other human activities cause UHI. With a growing trend of urban populations, a threat to human health is posed due to the increased temperatures (Kalkstein & Greene, 1997; Patz, Campbell-Lendrum, Holloway, & Foley, 2005) and air pollution (Mage et al., 1996; Taha, 1997) in urban environments, which has created wide public concern, especially under global climate changes. To solve these problems requires intensive investigations of UHI at multiple scales.

UHI studies are well documented across time and space by using various measuring techniques and temperatures as summarized by Voogt and Oke (2003). Two distinct classes of UHI are often defined: atmospheric UHI is assessed through in-situ and vehicle mounted sensors measuring air temperatures in the urban canopy layer (UCL) (Oke, 1976) and through ground-based, airborne and tower mounted sensors for the urban boundary layer (UBL) (Barlow et al., 2011; Grimmond, 2006; Roth, 2000; Voogt & Oke, 2003); the second class is surface UHI (SUHI) and is based on the use of thermal remotely sensed data (Voogt & Oke,

2003). Traditionally, the atmospheric UHI magnitude is defined/estimated by comparing air temperature in urban and rural sites (Grimmond, 2006). However, measurements for atmospheric UHI at urban sites face substantial challenges. Oke (2008) addressed the detailed siting and exposure requirements for measurements. Stewart (2011) pointed out that about a half of 190 observational UHI studies have not sufficiently controlled for the essential effects of weather, relief or time to quantify UHI intensity. Moreover, the limited footprint of a ground-based measurement makes it difficult to capture a comprehensive distribution of temperature over highly heterogeneous urban areas. To solve these problems, usually a well-designed network of stations is required. Perhaps, an easy and straightforward approach would be to use a consistent gridded dataset of observations, such as those from satellite remote sensing.

SUHI research is thriving after land surface temperature (LST) data became available (Gallo, Tarpley, McNab, & Karl, 1995; Voogt & Oke, 2003). Moreover, the global coverage, temporally consistent LSTs from satellite observations provide a way to estimate air temperature distributions, but the relationship of LST and air temperature remains empirical (Voogt & Oke, 2003). To link the LST and air temperature, many factors must be considered, such as the surface properties, atmospheric conditions and solar angles (Kim & Han, 2013; Vancutsem, Ceccato, Dinku, & Connor, 2010). Therefore, it becomes difficult to get a simple and consistent estimation for a large area. The air temperature directly retrieved from satellite remote sensing probably has more potential for universal

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applications of UHI and human health related research, which avoids the scaling issues and the problems associated with the different essential physical factors impacting those two types of temperatures.

The atmospheric temperature and moisture profiles are important descriptors of the urban environment. Kidd, Levizzani, and Bauer (2009) summarized the progress of satellite-based atmospheric observations and discussed the applications of retrieved atmospheric parameters for improving weather forecasting, extending weather systems' monitoring ability, and understanding climate change. Sounding sensors are typically designed with horizontal resolutions from tens to hundreds of kilometers. For application over the urban area, the coarse spatial resolutions may fail to capture the surface heterogeneity over the urban area.

Temperature and moisture information retrieved from MODIS at 5 km horizontal resolution can bridge gaps in an atmospheric UHI study that requires observations with relatively high spatial and temporal resolution. These global-coverage data are not only used for atmospheric effect corrections of other MODIS products, such as sea/land surface temperature (SST/LST), but also for capturing the atmospheric features of column water vapor and ozone (Seemann, Borbas, Li, Menzel, & Gumley, 2006; Borbas et al., 2011). However, the applications of MODIS atmospheric profiles are only discussed in a few studies outside the MODIS product groups, such as the MODIS-based estimation of net radiation (Bisht & Bras, 2010; Bisht, Venturini, Islam, & Jiang, 2005; Wang & Liang, 2009) and potential evapotranspiration (Kim & Hogue, 2008). These studies directly estimated the surface temperature and moisture from MODIS profiles without quantifying the accuracy. The error propagation from the MODIS product may explain part of the errors in their estimations.

Moreover, the spatial distribution of temperature does not solve UHI quantification problems as a result of unclear urban–rural division at the current stage (Stewart, 2011). Schwarz, Lautenbach, and Seppelt (2011) concluded that different SUHI indicators have weak correlations, and emphasized the critical role of choosing indicators to quantify SUHI effects. It becomes very difficult to conduct an intercomparison among the UHI studies in the literature due to the unstandardized indicators. Consequently, a better way to quantify UHI magnitude is required considering the surface heterogeneity and ambiguous urban/rural boundaries.

The purpose of this study is to provide an innovative analysis for using MODIS retrieved near-surface air temperature to investigate the UHI. This study first assessed the accuracy of the near-surface air and dew-point temperatures from MODIS 07 atmosphere profiles over four mega-cities in North America by using long-term ground observations. Both day and night overpasses of Terra and Aqua were investigated due to the potential applications to address diurnal UHI effects. Moreover, according to the strengths of MODIS air temperature, we developed a city-dependent UHI curve as a function of urban fraction, which is able to integrate the spatially heterogeneous physical properties and long-term variations of temperature to quantify UHI intensity.

2. Study area and data

2.1. Study area

Four mega cities in North America are selected for this research: Phoenix, Houston, Chicago and Toronto. Fig. 1 shows the domains and 2012 land cover distributions of the four cities. According to NOAA's national coastal population report, about 39% of the U.S. population lived in coastal areas in 2010 (NOAA National Ocean Service, 2013), so three cities located near/on the shoreline were chosen. Chicago and Toronto, with similar geographic location and prevailing weather conditions, are featured as the humid continental climate with warm/hot and humid summers. Although, the higher latitude and location near the Great Lakes may help decrease the energy consumption for air conditioning, the population growth and climate change may put these cities under the exposure of a higher heat vulnerability. Houston is located in the humid subtropical climate zone, known for hot and very humid

summers. Phoenix is under a subtropical desert climate with extremely hot and clear summers. It is important to include cities with very clear and very cloudy summers to extend the understanding of the performance of the MODIS data.

2.2. Satellite data

The MODIS atmospheric profile product (MOD07_L2 for Terra and MYD07_L2 for Aqua, hereafter MOD07_L2 for MODIS 07 product) for 5-minute Level-2 Collection-6 was processed from 2003 to 2013 in June–July–August (JJA) for both daytime and nighttime overpasses. The median local standard time of each satellite overpass for four cities ranges from 10:30–11:05 (Terra-Day), 21:15–22:15 (Terra-Night), 12:25–13:20 (Aqua-Day), and 1:35–2:10 (Aqua-Night). MOD07_L2 product consists of temperature and moisture profiles (20 pressure levels: 5, 10, 20, 30, 50, 70, 100, 150, 200, 250, 300, 400, 500, 620, 700, 780, 850, 920, 950, and 1000 hPa), total-ozone burden, atmospheric water vapor and other atmospheric information under clear skies at 5 km horizontal resolution.

The MOD07_L2 temperature and moisture sounding data are retrieved from MODIS multispectral thermal radiation measurements. The MODIS retrieval algorithms (Seemann et al., 2006) are adjusted from the TIROS (Television Infrared Observation Satellite) Operational Vertical Sounder (TOVS) algorithms (Reale, 2002) and Geostationary Operational Environmental Satellite (GOES) Atmospheric Sounder algorithms (Menzel & Purdom, 1996), which are based on a statistical regression retrieval (Seemann, Li, Menzel, & Gumley, 2003). Further details regarding the retrieval algorithm and MOD07_L2 Collection 6 quality can be found in the product algorithm theoretical basis document (Borbas et al., 2011). In general, MODIS has a limited ability to capture the fine-scale vertical structure compared to the high spectral resolution sounding sensors (e.g. Atmospheric Infrared Sounder (AIRS) (Aumann et al., 2003)), but it provides higher horizontal resolution of temperature and moisture distributions. This is useful to help understand the urban climate by capturing the urban surface heterogeneity globally for a long-term perspective.

However, the MODIS atmosphere product could not avoid some issues which is related to the nature of remote sensing techniques. For example, the view angle impacts the land surface temperature in the MODIS products (Hu, Brunzell, Monaghan, Barlage, & Wilhelm, 2014) even when the retrieval algorithm considers the view angle influences. Moreover, thermal anisotropy widely exists in the urban surface. These issues will not be addressed in this study, but need to be considered for studies where higher accuracy is required.

To estimate the near-surface air temperature, the digital elevation model (DEM) from U.S. Geological Survey (USGS)'s National Elevation Dataset (NED) was used instead of the surface elevation (SE) layer from the MOD07_L2 product. The SE varies temporally, which is estimated from the surface pressure. To match the spatial resolution of the MOD07_L2 product, the DEM is upscaled from the original 30 m to 5 km by averaging. The mean differences between DEM and SE over the area with less terrain variations (where most of the cities are located) are small, while the mountainous areas result in larger gaps up to 100–200 m.

The yearly MODIS land cover product (MCD12Q1) at 500 m resolution from 2003 to 2012 was used for discrimination of urban and rural pixels in UHI analysis. The 2012 land cover information was used for 2013 due to the unavailability of 2013 land cover data.

2.3. Ground observations

The Integrated Surface Global Hourly observations from the National Climatic Data Center (NCDC) (<http://www.ncdc.noaa.gov/cdo-web/datasets>) were used for validation. Ground observations were filtered based on the following criteria: 1) observational data passed all the quality control checks, 2) the ground observation time was within ± 1 h of satellite overpass, and 3) the observation sites were within

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