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Spatiotemporal estimation of air temperature patterns at the street level using high resolution satellite imagery

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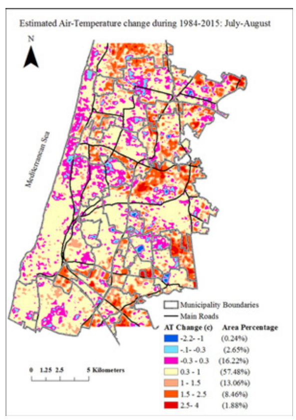
HIGHLIGHTS

- We predicted Air-Temperature at high spatial resolution (30 m).
- The model showed good performance ($R^2 = 0.9$, RMSE = 1.5°C).
- Highest residuals stem from a site error measurements.
- Air-Temperature increased over the last 30 years.

GRAPHICAL ABSTRACT



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ABSTRACT

Although meteorological monitoring stations provide accurate measurements of Air Temperature (AT), their spatial coverage within a given region is limited and thus is often insufficient for exposure and epidemiological studies. In many applications, satellite imagery measures energy flux, which is spatially continuous, and calculates Brightness Temperature (BT) that used as an input parameter. Although both quantities (AT-BT) are physically related, the correlation between them is not straightforward, and varies daily due to parameters such as meteorological conditions, surface moisture, land use, satellite-surface geometry and others. In this paper we first investigate the relationship between AT and BT as measured by 39 meteorological stations in Israel during 1984–2015. Thereafter, we apply mixed regression models with daily random slopes to calibrate Landsat BT data with monitored AT measurements for the period 1984–2015. Results show that AT can be predicted with high accuracy by using BT with high spatial resolution. The model shows relatively high accuracy estimation of AT ($R^2 = 0.92$, RMSE = 1.58 °C, slope = 0.90). Incorporating meteorological parameters into the model generates better accuracy ($R^2 = 0.935$) than the AT-BT model ($R^2 = 0.92$). Furthermore, based on the relatively high model accuracy, we investigated the spatial patterns of AT within the study domain. In the latter we focused on July–August, as these two months are characterized by relativity stable synoptic conditions in the study area. In addition, a

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temporal change in AT during the last 30 years was estimated and verified using available meteorological stations and two additional remote sensing platforms. Finally, the impact of different land coverage on AT were estimated, as an example of future application of the presented approach.

1. Introduction

The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) stated that between 1880 and 2012 the global surface air temperature has risen approximately by 0.85 °C (IPCC, 2013). Kuglitsch et al. (2010) indicated that over the entire Eastern Mediterranean region, hot summer daytime and nighttime Air Temperature (AT) have steadily increased by 0.38 ± 0.04 °C/decade and 0.30 ± 0.02 °C/decade, respectively, since the 1960s. According to the Israel Climate Change Information Center (ICCIC) climate report, there has been a decadal increase in average annual temperature, an increase in the duration and intensity of heat waves, and a reduction in the average precipitation quantity (ICCIC, 2012).

Growing evidence has linked elevated summertime AT with increased daily mortality (Basu and Samet, 2002; Brauer and Hystad, 2014; Medina-Ramón and Schwartz, 2007; Xu et al., 2012; Zanobetti and Schwartz, 2008; Zhang et al., 2015; Peretz et al. 2011). Importantly, these effects vary spatially and temporally across the city (Laaidi et al., 2012; Lee et al., 2014; White-Newsome et al., 2013). Therefore, it is of high importance to estimate AT with high spatial resolution in regions that suffer from hot summers, and where the increase in AT has been observed over the past decades. Unfortunately, this estimation is not possible using ground monitoring meteorological stations, due to their sparse locations.

Satellite imagery provides spatially continuous observations of radiance, yielding estimations of the energy emitted from surfaces in the Thermal Infra-Red (TIR) portion of the spectrum on a pixel based. The radiation is then translated to Brightness Temperature (BT) or Land Surface Temperature (LST, corrected for the disturbance of the atmosphere and/or surface emissivity). Although AT and BT are physically related, the correlation between them is not straightforward, and it varies daily due to meteorological and seasonal conditions, moisture of the surface, land use, urban geometry, surface reflectance and satellite-surface geometry (Benali et al., 2012; Kloog et al., 2012; Kloog et al., 2014; Shi et al., 2016).

There are several methods commonly used to quantify and model the AT-BT relation. Zakšek and Schroedter-Homscheidt (2009) reviewed and divided them into three groups: 1) the temperature-vegetation index approach (TVX) (e.g., Czajkowski et al., 2000; Prihodko and Goward, 1997; Stisen et al., 2007; Vancutsem et al., 2010; Zhu et al., 2013). This approach is based on the hypothesis that the biomass of vegetation expressed by vegetation indices, mainly through the normalized differential vegetation index (NDVI), is linearly and negatively correlated with the LST (Zakšek and Schroedter-Homscheidt, 2009). 2) Energy-balance approaches, (e.g., Pape and Löffler, 2004; Sun et al., 2005; Zakšek and Schroedter-Homscheidt, 2009). These approaches emerged from a physical point of view. They are based on the equation that the incoming net radiation flux together with anthropogenic heat flux equals the sum of the soil heat flux, sensible flux and latent heat flux (Sun et al., 2005; Zakšek and Schroedter-Homscheidt, 2009). 3) statistical approaches, (e.g., Benali et al., 2012; Fu et al., 2011; Kloog et al., 2012, 2014; Schwarz et al., 2012; Shi et al., 2016; Widyasamratri et al., 2013). This study focus on a statistical approach.

Statistical methods are usually based on regression models between BT/LST and AT and combined with another land use/meteorological parameters. Ben-Dor and Saaroni (1997) measured both AT (by mobile traverses equipped with thermistors) and LST (using thermal video radiometer mounted on a helicopter) at night, during stable winter conditions in the city of Tel-Aviv. Those authors found that coefficient of determination (R^2) between AT and LST ranged between 0.51 and 0.88 using relatively small dataset. Several studies quantified the similarity between LST patterns and AT using different statistical approaches and for different land-covers using satellite and airborne imagery (e.g. Benali et al., 2012; Fu et al., 2011; Schwarz et al., 2012). Widyasamratri et al. (2013) utilized high spatial resolution of Landsat (30 m) to estimate AT in Jakarta, Indonesia and obtained $R^2 = 0.77$ and AT differences between observed and estimated AT ranging from -2 to $+9$ °C. Benali et al. (2012) tried to estimate Tmax (maximum temperature), Tmin (minimum temperature) and Tavg (average temperature) for a 10 year period based on LST data obtained from MODIS and auxiliary data (such as elevation, distance to coast or freshwater bodies) using a statistical approach. The model efficiency was between 0.87 and 0.94 with an RMSE (root-mean-square error) of 1.33–1.83 °C. Recent studies by Kloog et al. (2012, 2014); Shi et al. (2016) applied a mixed-effects model approach to assess AT pattern with LST from 1 km MODIS in the eastern coast of the USA with R^2 up to 0.97 and RMSE of 1.38 °C. Recently, Pelta et al. (2016) analyzed spatial and temporal profiles of AT within the city of Tel-Aviv for 14 Landsat images during 1989–2014 using a mixed-effects model approach with $R^2 = 0.81$.

1.1. Problem definition - the need for high spatial resolution

The majority of previous studies used coarse spatial resolution of at least 1 km pixel size, which is more suitable for a national or regional scale, and it is rather inadequate for the street-level urban analyses. Fig. 1 illustrates this premise by showing the difference between MODIS LST (Terra and Aqua) 1 km pixel size (Fig. 1a, c) and Landsat BT 30 m pixel size (Fig. 1b). It refers to the city of Tel-Aviv and applies for the same day in July 2015. A dashed square refers to the size of one MODIS pixel. It shows the variability and contribution of different surfaces we can capture in the same area using high spatial resolution found in Landsat.

Furthermore, one may argue that AT does not commonly change every 30 m, and that 1 km area represents the AT at the urban area fairly well. However, as Potchter et al. (2006), Saito et al. (1990), Sani (1990) and others showed, AT in adjacent areas in urban environments can fluctuate by a few degress Celsius (e.g. in the vicinity of parks and neighborhoods).

1.2. Study goals

Given the above issues, we aim to: 1) develop mixed regression models with daily random slopes to correlate Landsat BT data with monitored AT measurements using 188 images for the period 1984–2015. As an independent validation, the results were compared using long-term AT measurements during July–August. In addition, we also compared BT temporal change using other available satellite data sources: MODerate-resolution Imaging Spectroradiometer (MODIS) and Atmospheric Infrared Sounder (AIRS); 2) using the model results, we examined the temporal change in AT over the course of 30 years and the impact of different land cover types at a pixel level.

2. Study area

The selected area for this study is the Tel-Aviv metropolitan area, known as Gush-Dan (Fig. 1, left), which includes the city of Tel-Aviv and the adjacent cities. Gush-Dan is the largest urban and most populated area in Israel. It is located at the eastern shoreline of the