Atmospheric Research 174–175 (2016) 151–159

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Modeling of mean radiant temperature based on comparison of airborne remote sensing data with surface measured data

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ARTICLE INFO

Article history:
Received 31 July 2015
Received in revised form 22 December 2015
Accepted 5 January 2016
Available online 19 January 2016

Keywords:
Mean radiant temperature
LIDAR
Thermal comfort
Urban surfaces
Microscale modeling

ABSTRACT

Assessment of outdoor thermal comfort is becoming increasingly important due to the urban heat island effect, which strongly affects the urban thermal environment. The mean radiant temperature (Tmrt) quantifies the effect of the radiation environment on humans, but it can only be estimated based on influencing parameters and factors. Knowledge of Tmrt is important for quantifying the heat load on human beings, especially during heat waves. This study estimates Tmrt using several methods, which are based on climatic data from a traditional weather station, microscale ground surface measurements, land surface temperature (LST) and light detection and ranging (LIDAR) data measured using airborne devices. Analytical results reveal that the best means of estimating Tmrt combines information about LST and surface elevation information with meteorological data from the closest weather station. The application in this method can eliminate the inconvenience of executing a wide range ground surface measurement, the insufficient resolution of satellite data and the incomplete data of current urban built environments. This method can be used to map a whole city to identify hot spots, and can be contributed to understanding human biometeorological conditions quickly and accurately.

1. Introduction

1.1. Remote sensing application on urban thermal environment

Previous research on remote sensing in urban thermal environments has commonly involved the use of data captured by thermal infrared imager to determine LST and air temperature (Ta), which are utilized to analyze the severity of the urban heat island effect (Dozier, 1981; Lo et al., 1997). The detection of land use and land cover are also used to calculate such indices as the Normalized Difference Vegetation Index (NDVI) and the percentage impervious surface area (ISA), which are highly related to the thermal environment (Zhang et al., 2008; Sun & Kafatos, 2007).

Matzarakis et al. (2008) used a high-resolution thermal imager to identify the highest and lowest LST in one day in Freiburg. Their data include not only surface temperature, but also information related to surface radiation; they finally incorporate point information to produce a map of thermal comfort conditions based on the thermal index of Tmrt. Their result shows that, on account of building density and green area, regions that are farther from downtown have a lower Tmrt, because the lower sky view factor in downtown areas indicates great shelter, so LST drops more slowly than in rural areas during cooling. For example, in Guilin city, (Liang et al., 2012), the LST and NDVI were calculated using the Landsat Thematic Mapper (TM), with the purpose of elucidating the correlation between LST and NDVI. The highest mean NDVI was observed in the forest and the lowest NDVI was found in water, whereas the highest LST was found in construction areas and the lowest in the forest, revealing that the relationship between NDVI and LST is significantly negative. In Minnesota, Yuan and Bauer (2007) compared the ISA and NDVI indicators with LST in an urban area, using TM and enhanced thematic mapper plus (ETM+) data. They found that the ISA is strongly linearly related with LST in all four seasons, and the relationship between NDVI and LST is weaker. A comparison of these two indicators can support research into urban heat islands, based on remotely sensed data.

The need for infrastructure from extreme conditions and modifications to existing conditions caused by changes in landforms have motivated the development of LIDAR as a novel remote sensing technology to gather data about the land surface. It has been widely used in observing large areas of land, recording topographical information (Bowen & Waltermire, 2002; Shan & Sampath, 2005). LIDAR has become a very important and valuable remote sensing observation technology in recent years due to its very high resolution.

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http://dx.doi.org/10.1016/j.atmosres.2016.01.004
0169-8095/

This study uses LIDAR point cloud data directly to create a Digital Surface Model (DSM) map of the study area. The resolution of the DSM map that is based on data from LIDAR can reach 0.5–2 m, which is better than the resolution of 30–40 m achieved using satellites. Moreover, building heights, building areas, vegetation and planimetric features can be obtained by LIDAR. This study analyzes the impact of the sky view factor (SVF) and the shading factor on LST to elucidate an urban thermal environment to quantify the thermal comfort of humans.

1.2. Related issues and absence of remote sensing in previous studies

Thermal infrared (TIR) imagers on satellites have previously been used to estimate the Ta from the LST (Price, 1983; Li et al., 2004; Aniello et al., 1995). However, this method is restricted by spatiotemporal factors. For example, the satellite passes through a fixed location, limiting the observable area. An LST photograph taken by such a thermal imager cannot be captured in various periods. Additionally, certain weather conditions, such as cloud cover, reduce the ability to obtain data. Therefore, the ability to verify thermal imaging data, and to use the method at different times, is limited. In contrast, LIDAR and a TIR imager can be used to make observations and obtain DSM and LST data at any time. Due to the high flexibility of airborne LIDAR and the TIR imager, obscuring clouds and weather conditions do not pose problems. LIDAR and TIR can generate useful data faster than a satellite (Vallet, 2008; Cook et al., 2013).

The resolution of images captured by a satellite is generally not high enough to analyze the thermal environment of a small area and the LST associated with different pavement materials (Neale et al., 2009).

The DSM obtained using airborne LIDAR includes the heights of objects on the ground, supporting environmental analysis (Sohn & Dowman, 2007). Information about vertical surfaces, such as those of buildings and vegetation, which may provide shade, cannot be easily retrieved from satellite images.

Shade and LST affection, such as SVF and the ratio of the height of buildings to the width of streets, clearly affect the thermal environment (Chen et al., 2012). Failure to consider such factors reduces the accuracy of estimation. This study considers the following three key issues.

1. Urban environments must be represented accurately and in their current situation, because shading significantly changes the thermal environment.
2. The resolution of satellite images is too low to support analysis of human biometeorological conditions.
3. Land surface temperatures obtained from images from a thermal imager must be calibrated using not just one equation, but separately for shaded and non-shaded areas.

1.3. Research purpose

Urban heat islands and global warming have made in temperature increases in urban areas an urgent issue (Lin et al., 2011). Since large-scale surface measurements are difficult to make, this study used the airborne remote sensing device to estimate human biometeorological conditions. For this purpose, the Tmrt index is required, as it incorporates radiation and the shading of a location. The solar radiation obviously affects temperature. Various data are considered in the calculation of the most accurate Tmrt that can be estimated from data of airborne LIDAR and TIR image. This study addresses the issues raised in Chapter 1.2 by pursuing the following three goals.

1. To confirm that high-resolution LIDAR can accurately present the current urban built environment and capture the precise SVF, and the thermal images are consistent with surface measurements thereof. The accuracy of the calculation of SVF using the DSM is verified by comparison with the SVF calculated from fish-eye photographs. The accuracy of the thermal images is confirmed by comparison with surface measurements by thermocouple.
2. To estimate human biometeorological conditions based on Tmrt, which is highly related to radiation factors, such as shading and LST. High-resolution LIDAR and thermal image data are combined. Shaded areas are identified by simulation model (SkyHelios) using LIDAR DSM data, to analyze the relationship between Tmrt and shading. Finally, the LST data from thermal image is used to increase the accuracy of Tmrt estimation.
3. To calculate Tmrt using various combinations of methods, involving airborne and surface measurements as well as data from weather stations. The best approach to assess human biometeorological conditions is thus identified. This study adopts various methods to estimate Tmrt by comparing airborne LIDAR data with surface measurement data, in order to generate a Tmrt distribution map to visualize the urban thermal environment.

2. Method

2.1. Study area

Banqiao district (25.0096703°N 121.4590989°E) located in northern Taiwan, is the major business center of New Taipei City. The population density of Banqiao is 24,027 km^2 (2015.1). Most of the terrain is flat. The lowest average monthly temperature is 15.2 °C in January. The highest average monthly temperature is 28.3 °C in July. The Banqiao district is frequently the hottest area in Taiwan, so the problem of thermal stress in Banqiao district must urgently be solved.

This study is based on an airborne photographic survey of an area with a length of 1.6 km and a width of 2.5 km in the Banqiao central business district. The area includes buildings with multiple uses, land uses and land coverage, such as train stations, MRT stations, the city hall, shopping centers, playgrounds, parks, and rivers. The high-resolution airborne remote sensing data demand extensive information calculations in the modeling process. Accordingly, the most highly developed area of Banqiao with red frame in Fig. 1 was selected for visualization and further analysis.

2.2. Airborne measurement

This study used two sets of equipment to conduct the airborne measurement survey at 08:45 AM on 2015/09/14. The first equipment was LIDAR, which is a remote sensing technology for observing surface obstacles based on the times of reflection of various lasers. The elevation and location of surface obstacles in Banqiao were clearly identified by GPS positioning. The point density of the high-resolution LIDAR Leica ALS-60 in this study is 2 points per m^2; the spatial resolution is 1 m × 1 m per pixel, and the elevation precision is 0.18 m. The DSM covers an elevation range of 227.16 m to −7.97 m in Banqiao. The laser can measure distance with high accuracy, and surface DSM can be obtained. Therefore, building heights, building areas, vegetation and surface objects can be obtained and calculated to determine the SVF and the shading simulation.

The TIR imager can be used to make land surface temperature measurements rapidly over a wide area. The imager records information, including temperature and radiation inertia, from the reflection and emission of infrared light by surface objects. A thermal sensor detects the infrared radiation from objects, and generates an electronic image, based on that information, that captures temperature differences. The resolution of the TABI-1800 Thermal Imagery TIR imager is 0.5 m × 0.5 m per pixel, and the accuracy is 0.05 °C. The range of temperatures recorded in Banqiao is from 17.80 °C to 66.64 °C. The thermal image is used to retrieve the LST and calculate Tmrt from the urban environment information.

These two technologies are combined to create an innovative method of assessing human bio-meteorological conditions in the urban environment based on DSM using the LIDAR, and LST using the TIR imager.