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Challenges to quantitative applications of Landsat observations for the urban thermal environment

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A B S T R A C T

Since the launch of its first satellite in 1972, the Landsat program has operated continuously for more than forty years. A large data archive collected by the Landsat program significantly benefits both the academic community and society. Thermal imagery from Landsat sensors, provided with relatively high spatial resolution, is suitable for monitoring urban thermal environment. Growing use of Landsat data in monitoring urban thermal environment is demonstrated by increasing publications on this subject, especially over the last decade. Urban thermal environment is usually delineated by land surface temperature (LST). However, the quantitative and accurate estimation of LST from Landsat data is still a challenge, especially for urban areas. This paper will discuss the main challenges for urban LST retrieval, including urban surface emissivity, atmospheric correction, radiometric calibration, and validation. In addition, we will discuss general challenges confronting the continuity of quantitative applications of Landsat observations. These challenges arise mainly from the scan line corrector failure of the Landsat 7 ETM+ and channel differences among sensors. Based on these investigations, the concerns are to: (1) show general users the limitation and possible uncertainty of the retrieved urban LST from the single thermal channel of Landsat sensors; (2) emphasize efforts which should be done for the quantitative applications of Landsat data; and (3) understand the potential challenges for the continuity of Landsat observation (*i.e.*, thermal infrared) for global change monitoring, while several climate data record programs being in progress.

Contents

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Introduction

The Landsat program, jointly operated by the National Aeronautics and Space Administration (NASA) and the U. S. Geological Survey (USGS), has been collecting space-based imagery with moderate spatial resolution of the Earth's surface since the launch of its first satellite in 1972. This series of land-observing satellites has created a historical archive that is unmatched in quality, spatial coverage, and length. Landsat 8, launched on 11 February 2013, is the newest satellite in the Landsat program. Furthermore, NASA and USGS have started work on Landsat 9, which is planned to be launched in 2023. Landsat 9 will extend the Landsat program to half a century (NASA, 2015a). Furthermore, the Landsat program will potentially be sustained operationally further by Landsat 10 (Loveland and Dwyer, 2012).

The spatial resolution of Landsat observation is important. On the one hand it is coarse enough for continuous global coverage, and on the other hand it is detailed enough to characterize human-scale processes. With the use of Landsat observations, it is possible to investigate human interactions with the environment in a global scale (NASA, 2015b). At present, the data collected for over more than forty years by the Landsat program provide a unique database for global change research. The continuity characterized with consecutive, temporally overlapping observations and cross-sensor calibration, makes Landsat observation an important asset for climate studies (Trenberth et al., 2013). Furthermore, thanks to the free data policy (Woodcock et al., 2008; Loveland and Dwyer, 2012) the Landsat data have been adopted in a wide range of studies and applications. Accordingly, the Landsat program has significantly benefited both the academic community and societal applications such as the management of water, land, forest, wildlife, and natural hazards. The annual economic benefits in 2011 obtained from the Landsat imageries were estimated to be $2.19 billion, although this estimate may be conservative (Loomis et al., 2015).

So far, the thermal images acquired by Landsat sensors, including the Thematic Mapper (TM) on-board Landsat 4/5, the Enhanced Thematic Mapper Plus (ETM+) on-board Landsat 7, and the Thermal Infrared Sensor (TIRS) on-board Landsat 8, have high spatial resolution (Table 1) for monitoring urban thermal environment (Sobrino et al., 2012; Xiao et al., 2007), especially when compared with the coarser-resolution thermal images collected by AVHRR (or Advanced Very High Resolution Radiometer) and MODIS (or MODerate Resolution Imaging Spectroradiometer). Landsat 4 was operated over 10 years from 1982 to 1993. Landsat 5 successfully collected data from its launch in 1984 until the communication system failures in November 2011, and finally went out of commission in June 2013 (USGS, 2013b). Landsat 7, launched in April 1999, has acquired observations for more than 17 years so far. Actually, a thermal channel was firstly embedded in Landsat 3 MSS; however, its poor performance and few data-acquisition make application of its data impossible (Arvidson et al., 2013). Compared with its predecessors, Landsat 8 has two separate push-brooms scanners, including the Operational Land Imager (OLI) and the TIRS. Specifically, the OLI has two additional channels provided with narrower bandwidths (*i.e.*, Band 1 and Band 9), while the TIRS has two thermal channels in the range of 10.0–13.0 μm (Table 1). Relative spectral responses (RSRs) for the channels are shown in Figs. 1 and 2. The two new bands of Landsat 8 OLI are not shown in Fig. 1. Effective wavelengths for thermal channels given in Fig. 2 are 11.154 μm (Landsat 4 TM), 11.457 μm (Landsat 5 TM), 11.269 μm (Landsat 7 ETM+), 10.904 μm (Landsat 8 TIRS1), and 12.003 μm (Landsat 8 TIRS2). The effective wavelengths are obtained through a "Trapezoid"

Table 1 – General information about the Landsat sensors.

	Landsat 4/5 TM	Landsat 7 ETM+	Landsat 8 OLI/TIRS
Visible (μm)	0.45–0.52 (30 m)	0.45–0.52 (30 m)	0.45–0.51 (30 m)
	0.52–0.60 (30 m)	0.52–0.60 (30 m)	0.53–0.59 (30 m)
	0.63–0.69 (30 m)	0.63–0.69 (30 m)	0.64–0.67 (30 m)
Near infrared	0.76–0.90 (30 m)	0.77–0.90 (30 m)	0.85–0.88 (30 m)
Short-wave infrared	1.55–1.75 (30 m)	1.55–1.75 (30 m)	1.57–1.65 (30 m)
	2.08–2.35 (30 m)	2.09–2.35 (30 m)	2.11–2.29 (30 m)
Panchromatic		0.52–0.90 (15 m)	0.50–0.68 (15 m)
Thermal infrared	10.40–12.50 (120 m [a])	10.40–12.50 (60 m [b])	10.60–11.19 (100 m [c])
			11.50–12.51 (100 m)
[Band 1]			0.43–0.45 (30 m)
[Band 9]			1.36–1.38 (30 m)

[] Compared with its predecessors, Landsat 8 has two new bands, including a band (Band 1, 0.43–0.45 μm) useful for coastal and aerosol studies and a band (Band 9, 1.36–1.39 μm) useful for cirrus cloud detection. Values in parentheses in Table 1 are spatial resolutions of the specific thermal images. The resolution for ETM+ and OLI panchromatic bands of is 15 m, and the spatial resolution for other spectral bands located within visible, near infrared, and short-wave infrared regions is 30 m. Information in Table 1 is obtained from http://landsat.usgs.gov/band _designations_landsat_satellites.php.

[a] TM thermal band was originally acquired at 120 m resolution. But, products processed before February 25, 2010 are resampled to 60 m pixels, while products processed after February 25, 2010 are resampled to 30 m pixels.

[b] ETM+ thermal band is acquired at 60 m resolution. Products processed after February 25, 2010 are resampled to 30 m pixels.

[c] TIRS thermal bands are acquired at 100 m resolution, but are resampled to 30 m in delivered data product.

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