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Comparative analysis of urban reflectance and surface temperature

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Abstract

Urban environmental conditions are strongly dependent on the biophysical properties and radiant thermal field of the land cover elements in the urban mosaic. Observations of urban reflectance and surface temperature provide valuable constraints on the physical properties that are determinants of mass and energy fluxes in the urban environment. Consistencies in the covariation of surface temperature with reflectance properties can be parameterized to represent characteristics of the surface energy flux associated with different land covers and physical conditions. Linear mixture models can accurately represent Landsat ETM+ reflectances as fractions of generic spectral endmembers that correspond to land surface materials with distinct physical properties. Modeling heterogeneous land cover as mixtures of rock and/or soil Substrate, Vegetation and non-reflective Dark surface (SVD) generic endmembers makes it possible to quantify the dependence of aggregate surface temperature on the relative abundance of each physical component of the land cover, thereby distinguishing the effects of vegetation abundance, soil exposure, albedo and shadowing. Comparing these covariations in a wide variety of urban settings and physical environments provides a more robust indication of the global variability in these parameter spaces than could be inferred from a single study area. A comparative analysis of 24 urban areas and their non-urban peripheries illustrates the variability in the urban thermal fields and its dependence on biophysical land surface components. Contrary to expectation, moderate resolution intra-urban variations in surface temperature are generally as large as regional surface heat island signatures in these urban areas. Many of the non-temperate urban areas did not have surface heat island signatures at all. However, the multivariate distributions of surface temperature and generic endmember fractions reveal consistent patterns of thermal fraction covariation resulting from land cover characteristics. The Thermal-Vegetation (TV) fraction space illustrates the considerable variability in the well-known inverse correlation between surface temperature and vegetation fraction at moderate (<100 m) spatial resolutions. The Thermal-Substrate (TS) fraction space reveals energetic thresholds where competing effects of albedo, illumination and soil moisture determine the covariation of maximum and minimum temperature with illuminated substrate fraction. The dark surface endmember fraction represents a fundamental ambiguity in the radiance signal because it can correspond to either absorptive (e.g. low albedo asphalt), transmissive (e.g. deep clear water) or shadowed (e.g. tree canopy shadow) surfaces. However, in areas where dark surface composition can be inferred from spatial context, the different responses of these surfaces may still allow them to be distinguished in the thermal fraction space.

Keywords: Urban; Landsat; Reflectance; Thermal; Temperature; Heat island; Spectral mixture analysis

1. Introduction

The urban climate is of interest for at least three reasons. (1) It has a direct impact on approximately half of the world's population. (2) Its dynamics are, to some extent, predictable. (3) It may be possible to influence it, for better or worse, with specific land use patterns. Regional mesoscale dynamics are known to be influenced by land cover differences between urban areas and the hinterlands on their peripheries (e.g. Avissar, 1996; Avissar & Verstraete, 1990; Bornstein & Lin, 2000). Understanding and predicting these dynamics requires an understanding of the spatial and temporal variations of the surface energy balance and physical properties. This, in turn, requires synoptic observations of surface conditions and estimates of energy fluxes from remotely sensed measurements.

Urban reflectance properties are strong determinants of environmental conditions in the urban environment. Surface reflectance is a first order determinant of energy flux but reflectance is also influenced by factors such as moisture availability and temperature. The relationship between surface temperature and reflectance provides information about both the surface properties (e.g. composition, emissivity) as well as

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processes (e.g. evapotranspiration, latent and sensible heat flux) that are key determinants of surface energy balance. For this reason, considerable effort has been devoted to understanding the factors that influence the relationship between surface temperature and optical reflectance. To date, most effort has been focused on using estimates of vegetation cover to constrain evapotranspiration (e.g. Carlson & Buffum, 1989; Carlson et al., 1995, 1981, 1990; Gillies & Carlson, 1995; Gillies et al., 1997; Goward et al., 1985, 2002; Price, 1982, 1984, 1990), and emissivity (Kahle et al., 1980; van de Griende & Owe, 1993; Valor & Caselles, 1996). The covariation of surface temperature with albedo is also used to constrain surface energy balance (e.g. Menenti, 1993; Roerink et al., 2000; Menenti et al., 1989). The recognition that albedo and vegetation cover impact surface energy flux has lead to a variety of methods to extract synoptic surface parameters from remotely sensed imagery (see Dash et al., 2002 for a recent review). However, methods that rely on vegetation indices (e.g. NDVI) as proxies for surface properties must contend with a nonlinear dependence on areal vegetation fraction (Asrar et al., 1985; Elmore et al., 2000; Small, 2001) and the fact that difference indices are not associative (Price, 1990). It has also been shown that vegetation indices are influenced by underlying soil reflectance (Huete, 1986; Huete et al., 1985).

In addition to albedo and vegetation cover, surface energy fluxes are also strongly influenced by soil properties and surface roughness. Roughness affects both advective cooling and shadowing while soil properties influence moisture availability and emissivity. Moreover, soil reflectance is known to change with moisture content thereby changing the energy partition between latent and sensible heat flux. In order to decouple the effects of vegetation cover, soil properties (e.g. albedo, emissivity), surface conditions (e.g. moisture content) and surface illumination on synoptic thermal imagery, it is necessary to incorporate more information from the coincident surface reflectance measurements. One obvious option would be to combine the vegetation cover and albedo approaches referred to above but vegetation indices and albedo are not independent. Linear transformations of multispectral imagery (e.g. Jackson, 1983; Kauth & Thomas, 1976) contain more information than vegetation indices and provide greater separation of vegetation and soil reflectance but the resulting greenness and wetness bands are still not generally independent. There is, however, another option. Linear mixture models provide an alternative approach that can deconvolve the competing influences of vegetation cover, substrate properties (both pervious and impervious) and surface shadowing on both aggregate reflectance and surface temperature measurements. Recent analyses of diverse global collections of Landsat ETM+ imagery suggest the existence of a global mixing space in which >90% of multispectral image variance can be described as linear mixtures of three independent spectral endmembers (Small, 2004, 2005). These analyses reveal a consistency in spectral mixing processes in a wide variety of both developed and undeveloped landscapes. A simple three endmember mixture model can resolve ETM+ spectra into estimates of areal fractions of rock and soil substrate, vegetation and dark surface components with RMS errors less than 0.04 reflectance units in >95% of 30,000,000 spectra (Small, 2004). Additional endmembers can be added to accommodate important characteristics of specific mixing spaces. Rock and soil Substrate, Vegetation, and non-reflective Dark surfaces represent three fundamental physical components of a wide variety of landscapes and they have distinct influences on surface energy flux. Understanding how these components simultaneously influence surface temperatures at moderate (30 m) spatial scales could resolve some ambiguities in our current understanding of surface energy fluxes in urban areas and their non-urban hinterlands.

The objective of this analysis is to investigate the relationship between optical reflectance properties and surface energy balance in a diverse range of urban settings and non-urban peripheries. The approach is to quantify the relationship between surface temperature and biophysical land surface fractions (SVD = Substrate, Vegetation and Dark surface) at moderate spatial scales for a wide variety of developed and undeveloped landscapes and to determine which characteristics of the reflectance and surface temperature covariation are consistent across the range of different environments. A three endmember linear mixture model is inverted with a single suite of generic global endmembers to yield directly comparable estimates of vegetation, substrate and dark surface fractions for 24,000,000 Landsat ETM+ spectra in 24 diverse urban settings and their rural peripheries. The covariation of surface temperature with substrate, vegetation and shadow fractions in these thermal fraction spaces is determined by physical properties such as moisture content, surface roughness and emissivity. While most studies to date have focused on individual study sites, a comparative analysis of these thermal fraction spaces under a range of environmental conditions for different landcover mosaics can highlight consistencies in the relationship between surface temperature and different biophysical components of the landscape. It is not feasible to field validate such a diverse collection of study sites (without generous funding) but the spatial resolution of the ETM+ sensor makes it possible to infer many of the land cover types from spatial context within the image. The strategy is to use a wide variety of urban settings, landscapes and environmental conditions to quantify consistencies in the relationship between reflectance properties and surface temperature.

2. The spectral mixture model

Simple linear mixture models can be used to quantify reflectance properties on the basis of fundamental biophysical components of the land surface. Spectral Mixture Analysis (SMA) provides a methodology whereby an observed radiance is modeled as a linear mixture of spectrally pure endmember radiances. Linear mixture models are based on the observation that, in many situations, radiances from surfaces with different endmember reflectances mix linearly in proportion to area within the IFOV (Johnson et al., 1983; Singer, 1981; Singer & McCord, 1979). This observation has made possible the development of a systematic methodology for spectral mixture analysis (Adams et al., 1993; 1986; Gillespie et al., 1990; Sabol