MODIS 4 μm Radiance in Global Megacities Depends on Seasonality, Land Cover, and View Zenith Angle

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***Abstract*— We explored variation in 4 μm radiance in and nearby eight global megacities using MODIS band 23 calibrated radiance. We found the linkage between MIR radiance seasonality and seasonal pattern of insolation, especially stronger/ pronounced at higher latitude than at tropics zones. The meteorological parameter - precipitation was identified as an impact factor of MIR radiance attenuation. Similarity of MIR radiance from desert, bare soil areas, or areas with a little of crop cover to MIR radiance from urban areas makes the distinction of cover using only MIR information even impossible during the time when insolation is the highest. Also, the seasonal variations of MIR radiance are being affected by the heterogeneity of cover as different types of building and construction materials, and urban green spaces. Conceivably, additional data and MIR radiance with higher spatial resolution improve and refine/detail information about MIR radiance behavior for further investigation.**

I. INTRODUCTION

The middle infrared (MIR) electromagnetic radiation spans 3-5 μm, a window of relatively high atmospheric transparency. MIR is a mixing zone of solar and terrestrial radiation. Using MIR for urban remote sensing has been proposed as a means to overcome anthropogenic haze and smoke [1-2]. However, there are few studies outside of the USA. Here we show initial results characterizing sources of variation in 4 μm radiance during 2010 at eight global megacities. We confirm the dependence of MIR radiance on view zenith angle (VZA) in diverse environments [2]. Interactions of insolation seasonality and land cover dynamics point to limitations of MIR for urban monitoring in settings where the soil background radiance persistently high or where the rainy season coincides with near-peak insolation.

II. DATA SET

A. *Remote Sensing Data*

Data were Aqua MODIS band 23 (4.02-4.08 μm) from the Level 1B calibrated radiance dataset distributed through the Level 1 and Atmospheric Archive and Distribution System (LAADS): http://ladsweb.nascom.nasa.gov/. Nominal spatial resolution of these near daily data is 1km.

B. *Areas of Interest*

We selected eight megacities: Beijing, Cairo, Istanbul, Mexico, Moscow, Nairobi, Delhi, and São Paulo (Table I).

III. METHODOLOGY

For each megacity the daily radiance data (MYD021KM) for 2010 were sorted into one of four view zenith angle (VZA) classes (0-15°, 15-30°, 30-45°, 45-60°) as time series data where each band was a monthly maximum value composite. We used the IGBP land cover scheme in the MODIS land cover product to select multiple quasi-homogeneous areas of about 5x5 pixels (~25 km^2) for each megacity. Sampled land covers included urban/built-up (as proxy for impervious surface), forest and arable (for vegetation), desert or savanna (for natural areas), open water (for control), and we included a mixed class for Delhi: arable area mixed with natural vegetation. Multiple samples from each representative land cover were chosen and averaged by cover class. Samples from urban areas were located in every city center with samples taken from the built-up core. However, depending on the shape and a compactness of the city and the building density, the samples differed in shape and size. To assess the seasonality of 4 μm radiance as a function of VZAs, average values were calculated from by city, land cover class, and month.

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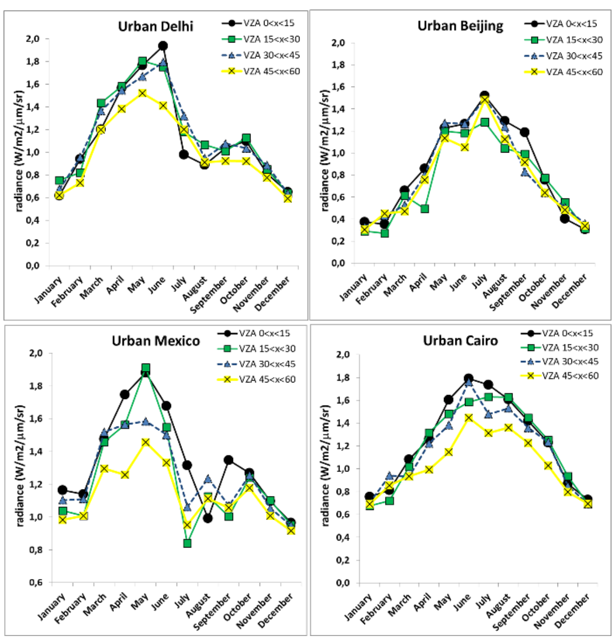
TABLE I

City, Country	Latitude	Longitude
Beijing, China	39°54' 50" N	116° 23' 30" E
Cairo, Egypt	30° 03' 24" N	31° 13' 34" E
Istanbul, Turkey	41° 00' 19" N	28° 58' 38" E
Mexico City, Mexico	19° 03' N	99° 22' W
Moscow, Russia	55° 45' 8" N	37° 36' 56" E
Nairobi, Kenya	1° 17' S	36° 49' E
Delhi, India	28° 36' 50" N	77° 12' 32"E
São Paulo, Brazil	23° 32' S	46° 37' W

IV. RESULTS

Seasonal patterns of MIR radiance from urban land cover varied by latitude (Fig. 1). In the northern hemisphere MIR radiance was very low at the beginning and end of the year, and no significant difference between VZA classes was evident then. Images during the December-February were noisy. High amplitude unimodal patterns were observed at higher latitude sites in the northern hemisphere (Beijing, Cairo, Istanbul, and Moscow). In contrast, attenuated seasonal amplitudes were in the southern hemisphere (Nairobi, São Paulo). Mexico City and Delhi show strong bimodal patterns where the first, stronger peaks occur April-May, followed by an abrupt decrease and emergence of second, smaller but distinct modes occur September-October.



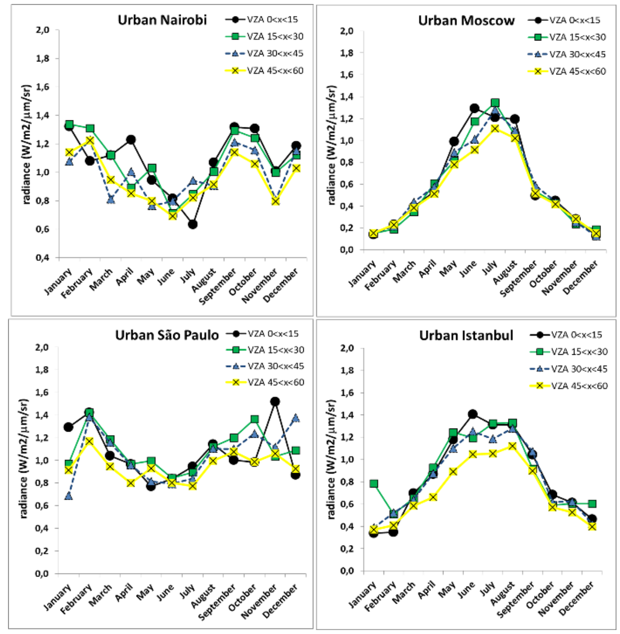


Fig. 1. Average MIR radiances by VZA class for representative urban land cover in for each megacity.

As 2010 progressed, radiance values among VZA classes diverged and differences in land covers emerged. During the summer season, when insolation was greatest, the differences among VZA classes were most apparent. Values of MIR radiance based on VZA could be divided into two groups, $0<x\leq30^{o}$ and $30<x\leq60^{o}$, with the former exhibiting generally higher amplitudes.

We used weather information (http://www.tutiempo.net/en) to check on sudden changes in mean values. Delhi was a good example of seasonal modulation of MIR by weather, where the arrival of the monsoon sharply reduces radiance (Fig. 2). A similar pattern was found in Mexico City, annual precipitation peaks in July-August (Fig. 1).

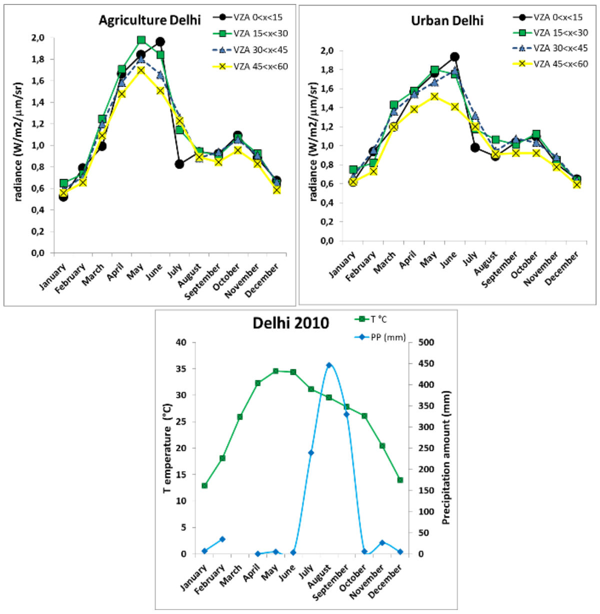


Fig. 2. The average MIR radiances for agriculture urban (top left) and urban (top right) classes for Delhi in 2010, and average monthly temperature and precipitation for Delhi in 2010 (bottom). Monsoon rains in June reduces MIR radiance sharply.

Urban areas generally exhibited the highest values of MIR radiance during the summer time (depending on hemisphere) when insolation was highest. Variations in urban samples were more evident, for instance, in the tropics than higher latitudes, but the differences were subtle (Fig. 3).

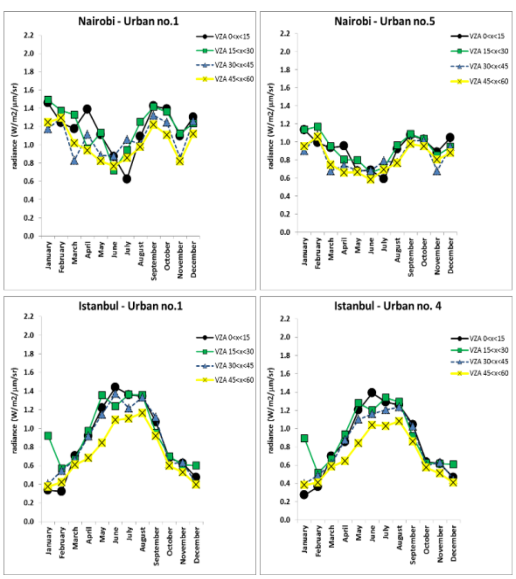


Fig. 3. Samples of average MIR radiance for urban class from Nairobi (top) and Istanbul (bottom).

MIR radiance from desert, bare soil areas, or areas with a little of crop cover looked similar at certain times of the year to MIR radiance from urban cover making it difficult to distinguish cover using MIR alone (Fig. 4).

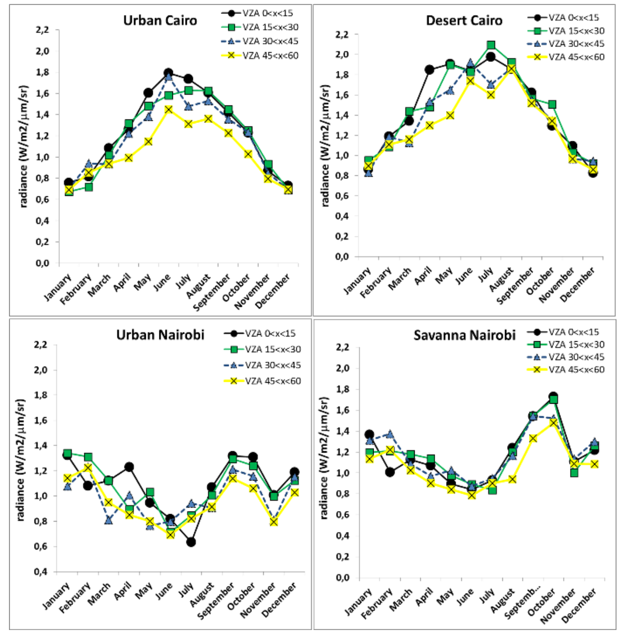


Fig. 4. Average seasonal MIR radiance by VZA for urban and desert classes for Cairo (two at left) and for urban and savanna classes for Nairobi (two at right).

To explore seasonal patterns of MIR radiance across the eight megacities, we fitted a convex quadratic (CxQ) model of monthly MIR radiance as a function of accumulated monthly MIR radiance. The CxQ approach was first developed for land surface phenology to link time series of vegetation indices to thermal time calculated as accumulated growing degree-days [4][6]. The approach has been extended to model the daily growing degree-day increments as a function of accumulated growing degree-days [3][5]. Here we extend the CxQ model the monthly MIR data; it yields two metrics calculated from the fitted parameter coefficients: the modeled peak radiance and the accumulated radiance to peak. Coefficients of determination ranged widely with the southern megacities fitting poorly (0.22 and 0.25 for Nairobi and São Paulo, respectively) and the northern megacities fitting well (0.83-0.97). The exception was Delhi (r^2=0.59) where the monsoon effect truncated the descending arm of the parabola (*cf*. Fig. 2) For the six megacities in northern hemisphere there is a strong linear relationship (r^2=0.93) between these two metrics, but not for the two southern megacities (Fig. 5).

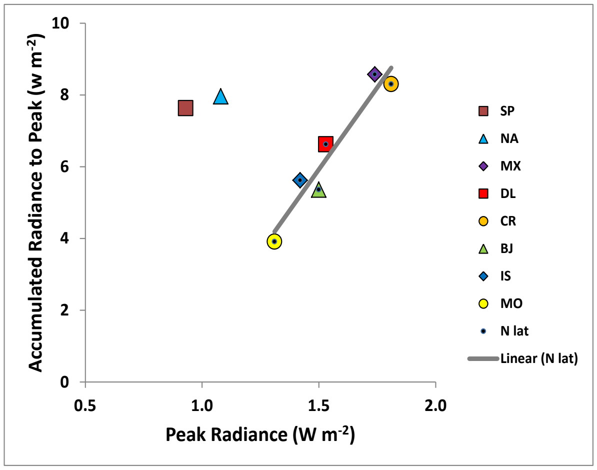


Fig. 5. Relationship between modeled monthly peak MIR radiance and accumulated monthly MIR radiance for the eight megacities and the linear relationship (r^2=0.93) among the six northern megacities. SP=São Paulo; NA=Nairobi; MX=Mexico City; DL=Delhi; CR=Cairo; BJ=Beijing; IS=Istanbul; MO=Moscow.

Viewing the accumulated radiance to peak in terms of latitude, a strong parabolic pattern (r^2=0.84) emerges but one that would need additional megacities in the southern hemisphere to confirm (Fig. 6).

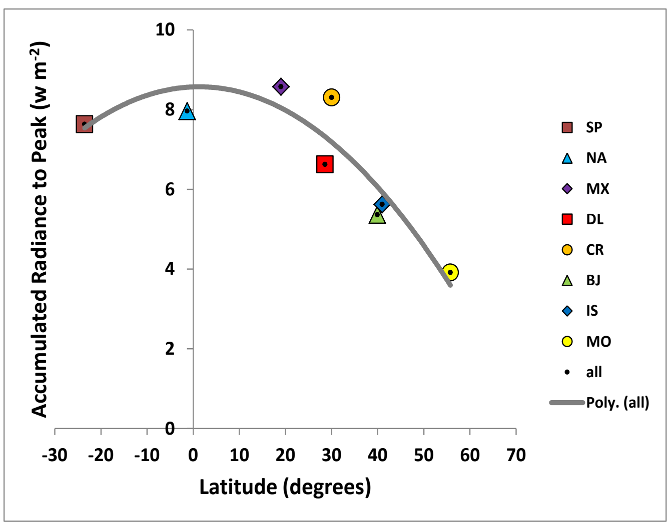


Fig. 6. Latitudinal pattern of accumulated MIR radiance to peak (r^2=0.84). Legend as in Fig. 5.

V. DISCUSSION

MIR brightness is high for impervious surfaces, dried vegetation, and dry soils; while MIR radiance is low for open water, snow and ice, and dense vegetation [1]. Although there can be substantial variation within these classes, particularly mixed classes, it is difficult to distinguish due to the relatively coarse 1 km spatial resolution of the MODIS MIR bands. Earlier work using airborne sensors with multispectral MIR capability showed the advantages in urban settings of the MIR over thermal bands [1]. Use of the MODIS band 23 has been shown to respond strongly to impervious surface area in typical urban areas found in the USA's northern tier, albeit with seasonal sensitivity and dependence on VZA [2]. By examining MIR dynamics in representative megacities, we also found strong seasonality in MIR radiance linked to seasonal pattern of insolation; however, the seasonal amplitude was stronger outside of the tropics. Moreover, we identified seasonal precipitation as a significant source attenuating MIR radiance.

Finally, in addition to VZA and land cover, we speculate that the seasonal variations of MIR radiance in urbanized areas are influenced by the specific characteristics of built environments, including the various emissivities of soils, building and paving materials, spatial arrangements that affect skyview, and urban vegetation cover fraction and phenology. However, the spatial heterogeneity of such factors is high relative to the spatial resolution of MODIS and other spaceborne sensors measuring in the MIR region [1]. Future work will explore blending Terra and Aqua ascending and descending acquisitions and the synergistic use of the MIR with higher spatial resolution visible-near infrared sensors.

Acknowledgments

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