LINKS BETWEEN SATELLITE THERMAL IMAGERY AND BUILDING ENERGY USE

ABSTRACT

This paper describes an exploration of the utility of satellite thermal imagery in estimating energy consumption in buildings. Thermal infrared imagery in the waveband 8 μm - 12μm measures radiative emissions from objects that are proportional to that object's temperature to the fourth power and the object's emissivity (a measure of how effective an emitter of radiation it is). Thermal imagery provides insight to energy flow out of objects, a property that is of possible use in estimating energy use in buildings. An evaluation of intermediary variables was also undertaken to determine which of them improve the accuracy of energy consumption estimates from thermal imagery. The intermediary variables were chosen to account for the contribution of solar radiation to surface temperature. Primary data sets employed included LANDSAT satellite thermal infrared imagery and ZIP code aggregate annual building electricity use, reported separately for residential, commercial, and industrial uses. An area consisting of five ZIP codes in and around Ann Arbor, Michigan was selected as a case study area for this work. This temperate climate site was examined in the summer cooling season, with the intention of including the winter heating season in future work.

INTRODUCTION

Remotely sensed thermal image data records radiant energy in the 8-14μm wavelength band that is a function of the surface temperature and emissivity of materials in view of the sensor, as seen in Equation 1, where radiant energy is measured in Watts per square meter (Lillesand and Kiefer 1987). Emissivity is a property that explains the effectiveness of a material in emitting radiation; shiny reflective materials have low emissivity and dull dark materials tend to have high emissivity. Most building roof materials have high emissivities (≈ 0.9), as do most natural materials, such as vegetation, water, and soil.

$$\text{radiant energy} = \varepsilon \, \sigma \, T^4 \tag{1}$$

where
ε = emissivity
σ = Stefan-Boltzmann constant
T = temperature (°K)

Are thermal image data applicable to the problem of measuring building energy use? Aerial thermal imagery has been used to study the relationship between land cover and urban heat island properties in several cities (Quattrochi et al. 1998; Lo et al. 1997; Nichol 1996; Quattrochi et al. 1994). Stone and Rogers used aerial thermal imagery to explore the links between urban form and the urban heat island in Atlanta (Stone and Rogers 2001). By highlighting unusually warm building roofs, aerial thermal sensors have given some utility companies an idea of which homeowners might want to increase the amount of insulation in their roofs and reduce their energy use (Imwalle 1996). This was a cold-climate application of thermal image data, though a similar argument can be made for hot climates where one would be identifying unusually cool roofs. The contribution of heat from energy consumption (i.e. combustion) to the thermal conditions in built up areas has also been a topic of study (Harrison et al. 1984). Hand-held calibrated thermal sensors have been employed to characterize heat flow out of buildings by measuring the temperature of elements on building facades (windows, wall assemblies, etc.) over a period of time (Hoyano

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et al. 1999). Thermal sensors have a clear history of utility in studies concerned with land cover and energy use. Indeed, all of the studies that are concerned with urban heat islands are motivated by the cost of (electric) energy used to cool buildings in these areas when, in fact, a much greater amount of energy is used to heat buildings in colder climates. Attention should ideally be paid to energy use due to both heating and cooling requirements.

But satellite thermal sensors are working under a handicap. Not only are they of coarser resolution than hand-held or aerial sensors, but they must deal with a much greater thickness of atmosphere and its attendant complications (clouds, dust, aerosols, etc.). Thermal radiance measured by satellite sensors is a function of incoming solar radiation (insolation), surface characteristics (emissivity and roughness - related to buildings, hardscape, and vegetation), and energy consumption, all modified by path radiance, absorption, and scattering (Lillesand and Kiefer 1987). Insolation data are available and surface characteristics can be measured from aerial photos, leaving only energy use as an unknown, provided we assume that path effects are relatively constant. In areas where energy use *is* known, an opportunity to explore the relationship between thermal radiance measured at a satellite sensor and energy use is available.

The purpose of this investigation was the examination of the utility of satellite thermal imagery in estimating energy consumption in buildings. More specifically, this project focused on evaluating intermediary variables (population, % tree canopy, etc.) to determine which of them might improve the accuracy of energy consumption estimates from thermal imagery while accounting for the contribution of solar radiation to surface temperature. The main tasks required for this work were 1) the collection and combining (to the smallest possible homogeneous geographic unit) of the appropriate data sets and 2) the development of a relationship between thermal image data and energy use for the different areas of a test case area in Washtenaw County, Michigan centered on the city of Ann Arbor.

The relationship between thermal data and energy use would ideally be examined separately for both summer and winter cases to determine whether the same relationship held in both seasons and whether the same set of intermediary variables is pertinent. Natural gas use is much lower in summer than in winter since it is used for cooking and heating water in summer, but not for its largest winter end use, space heating. Given the lower anthropogenic heat output and higher solar radiation input in the summer, this summer case is somewhat more challenging than the winter one for investigating the links between thermal radiation and energy consumption, as the portion of the radiation sensed at the satellite attributable to energy use is a smaller fraction of the total.

METHODS

This project relied heavily on geographic information systems (GIS) as a way to organize and combine the necessary spatial data sets. Besides the obvious thermal imagery and energy use data required in a project such as this, GIS data layers for several US Census geographic units (i.e. blocks, block groups, and tracts) were also employed.

Data

Thermal Imagery. A LANDSAT ETM+ scene collected on July 15, 1999 covering southeast Michigan was selected for use. This date was chosen since it was during the time period for which energy consumption data were available. A subset of this scene slightly larger than Washtenaw County was extracted from the larger image. The high gain thermal band (band 6.2 with a spatial resolution of 60 meters) was the only band used in the investigation and no image processing was performed on the data. A winter scene with acceptable cloud cover for the winters of 1998 or 1999 could not be found, unfortunately limiting analysis to the summer case for this project.

Energy Consumption Data. Since winter thermal imagery was unavailable, the energy use data was limited to electricity. Electricity consumption data for the entire year of 1999 was provided by the local electrical utility company for four ZIP codes in the Ann Arbor area (48103, 48104, 48105, and 48108). Energy data were aggregated by ZIP code due to customer privacy concerns and simply because it was easy for the utility company since ZIP code was already part of their billing and record-keeping system. These data were separated within each ZIP code into residential, industrial, and commercial categories. The number of meters/sites in each category was also provided for each ZIP code. The most recent available data for ZIP code 48109 (The University of Michigan) were collected for the months March 1998 through February 1999 from the Central Utilities portion of the Plant Operations Department website (http://www.plantops.umich.edu/utilities/Utilities/CentralPowerPlant/).

Census and Other Data Sets. The State of Michigan's Department of Natural Resources maintains a spatial data archive accessible through the main DNR web site at http://www.dnr.state.mi.us/. Washtenaw County files from this archive that were examined included:

- TIGER-95 (ArcInfo shapefile, 1:100,000) - US Census data
- MIRIS base maps (1:24,000) - 1978 Michigan land use data
- USGS 1983 LULC (1:250,000) - land use data
- digital orthophoto quarter quadrangles (DOQQ)

Attention was focused first on the TIGER-95 Census files, as the MIRIS land use data were old, the USGS land cover was at poorer and less useful resolution, and the DOQQ's included only the western half of Ann Arbor. Given the relatively flat topography in the study area, a digital elevation model was not used as a primary data source for this investigation.

Data processing

Several operations on the original data were necessary before the actual analysis could begin. The TIGER-95 files downloaded from the MI DNR archive were in the Michigan GeoRef projection (GRS80 spheroid). In order for these data layers to accurately overlay on the satellite thermal imagery, these shapefiles were individually reprojected into UTM zone 17N (WGS84 spheroid). The reprojected shapefiles were then converted into ArcInfo coverages to enable further analysis. These coverages included separate layers for blocks, block groups, tracts, ZIP codes, streets, rivers and streams, airports, and a number of other feature types.

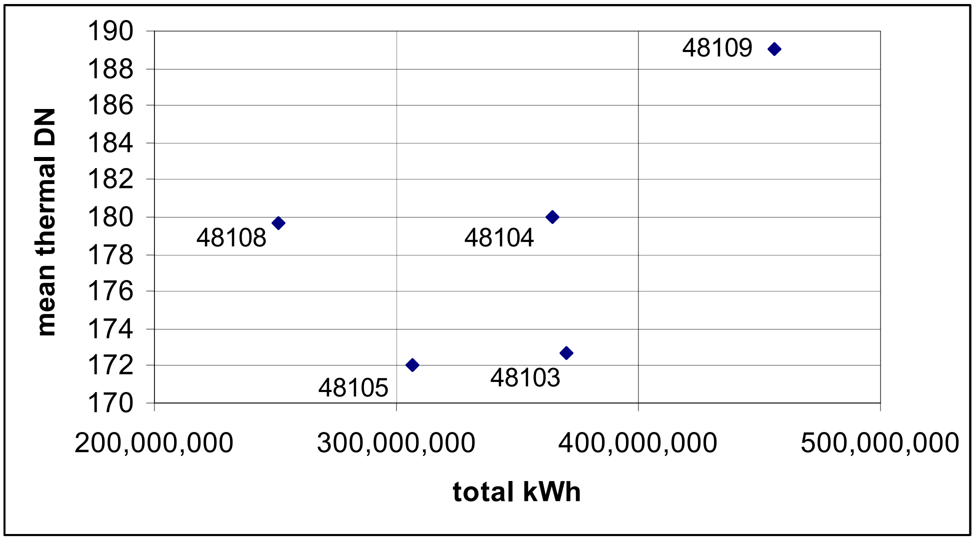
To get the electricity consumption data into the GIS, seven new fields were added to the ZIP code layer's polygon attribute table in ArcInfo: 3 fields for energy use by category (residential, commercial, industrial), 3 fields for the number of meters/sites by category, and a total energy use field calculated as the sum of the 3 energy use categories in each ZIP code. The ZIP code layer then had these seven new attributes for the five ZIP codes for which energy data were available.

In order to extract data from the thermal imagery to compare with the electricity data, the coverage layers containing ZIP code, tract, block group, and block polygons were opened at the same time as the raster LANDSAT thermal image. The maximum, minimum, range, mean, and standard deviation of the thermal image data were calculated for every polygon in each polygon layer. This calculation operates on one polygon layer at a time, calculating the descriptive statistics listed above for each polygon and then appending these statistics to each record in the polygon attribute table.

Results

The rationale taken in this analysis was that it was an exploratory investigation and would begin from the simplest starting point and would include more complex methods only as they were needed. The first step in the analysis was thus the simplest. All electricity used in each ZIP code was totaled and plotted against the mean data value from the thermal image, Figure 1.

FIGURE 1.
Total electricity consumption (residential, commercial, and industrial) and mean thermal image data value for five ZIP codes around Ann Arbor, MI.



There are two notable points to be made about this plot. First, the mean values from the thermal image are quite close together and second, there is a trend towards higher means for ZIP codes with higher electricity use. This trend is encouraging though not completely convincing with only five points, as the small number of points makes any pattern difficult to extract. The relative compression of the thermal image data suggests that a re-scaling of these data might be helpful (i.e. histogram equalization), though all analyses reported here use the original unscaled thermal image. The problem with histogram equalization is that it is an image-dependent transformation and, as such, makes it difficult to apply any results generically to different images.

The second step taken in the analysis was conversion of the ZIP code electricity data to a more appropriate spatial unit. Since ZIP codes aren't a standard Census geographic unit, a method of translating the energy use data from ZIP codes to tracts, block groups, and blocks was devised to continue the analysis. The most straightforward method relies on the assumption that blocks do not cross actual ZIP code boundaries. The differences between actual ZIP code areas and the area covered by a collection of census blocks approximating a ZIP code were taken, as a first estimate, to be negligible. ZIP code is actually listed as a census blocks attribute in the TIGER files, which it would not be if blocks crossed a ZIP code boundary, so this assumption seems reasonable. Population was summed for the collection of blocks contained in a ZIP code area and then energy use in that ZIP code was calculated on a per capita basis, effectively making electricity use a block attribute. A plot of block-level electricity use against the mean data value from the thermal image indicated no obvious relationship between residential electricity consumption and mean thermal image data value, so a more complicated analysis will be necessary.

This method of scaling energy data from ZIP codes to blocks is valid but the per capita energy estimates can only be scaled to larger geographic units within the ZIP codes for which energy data were originally available. This means that scaled up energy estimates for block groups and tracts will only be accurate if they contain exclusively blocks from the original energy data ZIP code areas. Since blocks outside these areas would have no energy use attribute, including them in block groups and tracts (and any other larger geographic unit) would bias total energy estimates incorrectly downward. This is a limitation here due to the small number of ZIP codes for which energy data were available, but it would not be a problem if a more geographically complete energy data set were collected.

Another possibility for estimating energy use in larger geographic units would be to take the total electricity use and divide it by the total population in those ZIP codes to calculate an average per capita electricity use that could then be applied in areas where the population was known but electricity use was not. This estimation technique is not helpful in developing a relationship between energy use and thermal imagery however, and so it was not pursued further.

Both of the methods discussed above for changing the spatial basis of electricity data, being based on population, ignore the significant amount of electricity used in commercial and industrial areas that also contributes to the thermal radiation recorded in thermal imagery. In Ann Arbor, the industrial category includes all of the academic buildings at the University of Michigan, which have no resident population but consume a large amount of electricity. All of these difficulties argue for a different approach than the ones described above.

An examination of the thermal data may provide some guidance. Table 1 contains thermal image statistics for all ZIP codes in Washtenaw County, as well as area and population calculated from block data.

TABLE 1
Thermal image statistics and ZIP code statistics for the ZIP codes in Washtenaw County, MI.

			Thermal image statistics				
ZIP code	**Area (M^2)**	**Pop.**	**Max**	**Min**	**Range**	**Mean**	**Std Dev**
48103	162238768	41263	222	144	79	172.685	7.837
48104	23702046	47564	220	157	64	179.986	9.307
48105	134854734	28543	213	156	58	172.000	7.641
48106			181	167	15	171.900	4.818
48108	51202708	17948	223	156	68	179.638	9.028
48109	375681	0	220	170	51	189.050	9.193
48118	206821519	9504	226	139	88	170.159	7.429
48130	162855532	8276	216	135	82	171.457	7.292
48137	36094769	1312	203	155	49	167.328	7.052
48158	266780411	6163	223	148	76	170.101	6.770
48160	99916865	8220	223	156	68	171.592	7.713
48167	30043907	1525	211	159	53	172.422	7.921
48170	46320884	1771	200	160	41	173.023	6.388
48176	193593463	13356	223	150	74	172.922	8.038
48178	42930160	1637	204	158	47	170.200	6.206
48189	56397887	5812	219	155	65	169.850	7.459
48191	46027583	2574	202	160	43	169.673	5.839
48197	103059832	46790	228	116	113	176.383	9.499
48198	87990760	39534	232	117	116	175.788	9.944
49236	37988097	454	203	156	48	171.047	6.572
49240	42016516	612	198	158	41	169.966	6.724
49285	8693631	150	204	158	47	173.504	8.745

49287	11269	0	171	164	8	166.600	2.319

These data show that, although area and population vary quite widely, the range of thermal data values is quite small, as was hinted at in Figure 1. As mentioned previously, a re-scaling of the thermal data and/or some other image processing might be helpful with this difficulty, though such processing would only be useful if it were not data dependent. Also, stratifying the analysis by land cover type might be one way to include the zero population commercial and industrial areas in the analysis. Dividing up ZIP codes by land cover type would enable a better assignment of electricity use to spatial units. This method is reliant on access to land cover data contemporaneous with other data and of appropriate spatial resolution. Since such land cover data were not available for this investigation, this method was not explored.

The last of the initial investigations looked at the four ZIP codes for which electricity use data were available. Table 2 contains residential electricity use data for the four ZIP codes around Ann Arbor, on both a per capita basis and a per household basis.

TABLE 2.
Annual residential electricity consumption by ZIP code, per capita and per household.

ZIP code	Pop	kWh/cap	# HUS	kWh/HUS
48103	41263	4112	17937	9459
48104	47564	2023	16577	5805
48105	28543	3415	12263	7948
48108	17948	3889	7494	9314

The differences in electricity use by ZIP code illustrated in Table 2 suggest a further examination of house age and size, and other possible explanatory variables. None of these variables are available at the ZIP code level, though they could perhaps be generated from the block level data.

CONCLUSIONS

This paper describes preliminary investigations into the links between satellite thermal imagery and building energy consumption using Ann Arbor, Michigan as a test site. Energy consumption data were only available aggregated to the ZIP code level, so the analysis was constrained to five data points representing a relatively large geographic area. Total energy consumption in a ZIP code shows a weak positive correlation with thermal image data. Thermal image processing to expand the range of data would be useful, but only if it is not image dependent. Calculating block-level energy consumption from the ZIP aggregate data produced no relationship to block-level thermal image data, possibly since the simple apportioning of energy to population doesn’t capture the actual variety of energy use patterns.

An important factor to be considered is the large effect solar radiation has on the upwelling thermal radiation recorded in thermal imagery. This is logically considered as part of the land cover data mentioned above, as it involves the measurement of such quantities as percent tree canopy cover and percent impervious surface. These quantities don't specifically measure incoming solar radiation, but are proxies for how the surface responds to and stores solar input. Measurement of these quantities requires aerial photography or DOQQ's. The DOQQ's aren't readily available, though aerial photography is available in an unrectified, ungeoreferenced form. Use of either of these image sources requires a significant commitment of time and money to get data useful for this type of investigation. This analysis indicates that incorporation of land cover data is necessary in further work on the links between satellite thermal imagery and building energy consumption.

Finally, the limiting of the analysis to a summer case is a problem. Locating an acceptable winter thermal image and collecting natural gas consumption data are both nontrivial but critical steps. In Ann

Arbor's climate, much more energy is expended on heating in the winter than in cooling in the summer. Thermal emissions in winter are expected to be more tightly linked to energy use, both because of this and to the much weaker solar input.

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