NOTES AND CORRESPONDENCE

Assessment of the Urban Heat Island Effect Through the Use of Satellite Data

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ABSTRACT

A recent NASA satellite is obtaining high spatial resolution thermal infrared data at times of day appropriate for the study of the urban heat island effect. Quantitative estimates of the extent and intensity of urban surface heating are obtained by analysis of digital data acquired over the New York City–New England area. In many large cities satellite sensed temperatures are 10–15°C warmer than in surrounding rural areas. A thorough interpretation of the elevated urban surface temperature will require studies of 1) the relationship between remotely sensed surface temperatures and air temperatures, and 2) compensation for observed very localized heating due to industry and/or power plants.

1. Introduction

Interest in urban meteorology has grown rapidly in recent years, prompted by concern for the effects of air pollution on human health, federal requirements for air quality, uncertainty as to the environmental effects of energy consumption, and a general desire to improve the quality of life in urban areas. The gradual dispersion of population into suburban areas and the tendency toward movement of manufacturing and industry into sparsely populated areas makes the topic of significance to a growing fraction of the country.

For meteorological purposes the heat island effect is characterized by both direct (*in situ*) and indirect (circulation pattern) variations when compared to conditions in the surrounding countryside. The effect is directly measurable as a relative increase in air temperature within and above the city. This tendency is not universal—in some cases the air above a city may be cooler than that in surrounding rural areas. In most large cities the increase in air temperature is accompanied by elevated concentrations of CO_2, trace gases and atmospheric particulates. For very large cities these changes are observable to heights of hundreds of meters (Bornstein, 1968; McCormick and Baulch, 1962).

An indirect and more subtle meteorological effect is manifest through altered flow patterns and vertical convection in urban areas. Presumably, this modification is the result of air temperature changes associated with urbanization but the change in surface roughness produced by homes and buildings may also have an effect through modification of vertical transport mechanisms at low level. Changes in flow patterns pose possible implications for local cloudiness, for dispersion of the urban air mass and for rainfall, both in the city proper and in its surroundings (Duckworth and Sandberg, 1975; Huff and Vogel, 1978).

A major limiting factor in the study of the heat island effect has been the lack of observational data which clearly are relevant to the problem. Particularly limiting are the inability to describe quantitatively the areal extent and distribution of changes of air temperature, and the general paucity of data obtained at varying locations and under varying atmospheric conditions, including the annual cycle.

The Heat Capacity Mapping Mission [HCMM (Goddard Space Flight Center, 1978)], a small Applications Explorer satellite launched 26 April 1978, has obtained data suitable for heat island studies. The satellite acquires high-resolution thermal infrared (10.5–12.5 μm) data from an orbit especially selected to infer surface temperatures near the time of day of the diurnal maximum. Although surface temperatures estimated from a radiation measurement are not the same as air temperatures, they are potentially as useful because they provide an indication of the surface heating effect

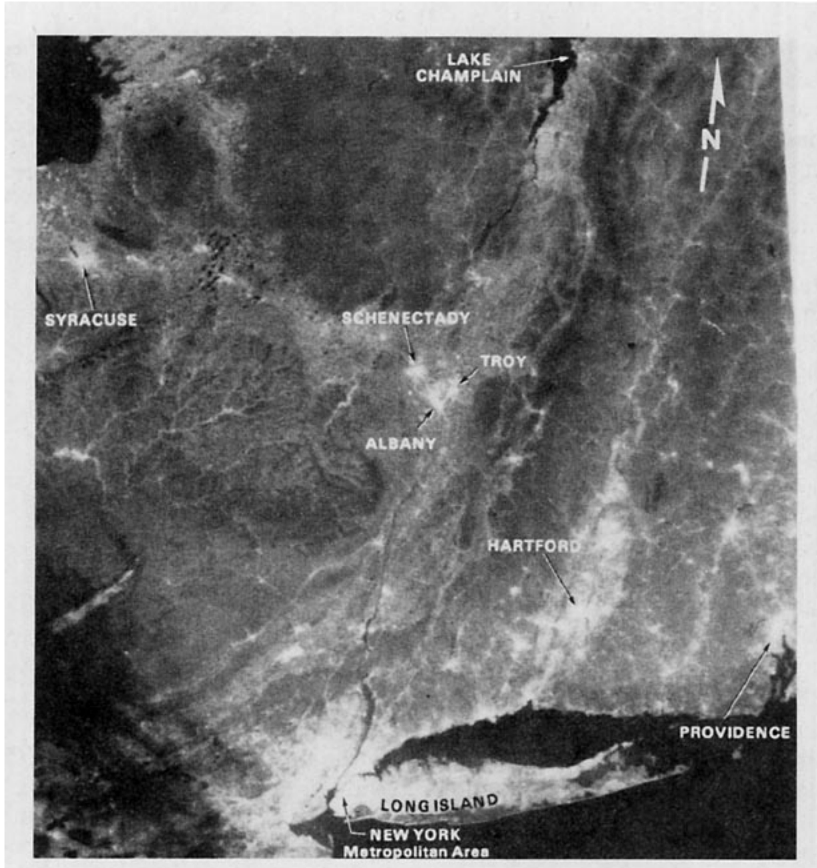

Fig. 1. Satellite overpass of the New York–New England area showing surface heating effect (light areas) in urban areas.

at the base of the atmosphere. The satellite capability is discussed in the succeeding sections.

2. Data characteristics

From an altitude of 620 km the HCMM satellite acquires visible and infrared data at a spatial resolution of 500 m. Although data transmission to ground stations is in analog form, a high-performance design has demonstrated the capability to deliver temperature data with a noise equivalent temperature of 0.4 K. (Bohse *et al.,* 1979.) The remote measurements represent an equivalent blackbody temperature as modified by absorption and reemission during passage through the intervening atmosphere, i.e., a brightness temperature given by (radiance/Stefan Boltmann constant)$^{1/4}$. Under most conditions the variation of this atmospheric correction may be neglected over small areas such as that of a city and its surroundings. The development of a relationship between surface temperatures, as obtained by remote observation, and a local air temperature (e.g., at 2 m height) is a complex problem. The relatively poor spatial resolution of early meteorological satellite data (Rao, 1972) has tended to hinder development of such a relationship. More recent studies (Carlson *et al.,* 1977; Matson, *et al.*, 1978) have utilized 1 km spatial resolution satellite data acquired during mid morning and early evening when surface temperature contrasts are relatively weak. High-resolution HCMM data should prove useful for placement of air monitoring stations in cities and for spatial interpolation between such sites.

The satellite passes over northern midlatitudes in the early afternoon and at approximately 0200 LT. A portion of an overpass at 1330 LT on 6 June 1978 is displayed in Fig. 1. Standard image products for the mission are displayed with the convention cold–black, hot–white. This is contrary to the convention used for meteorological satellite imagery and results in cold clouds being displayed as dark, or black. In Fig. 1 dark patches in the lower left and speckles in the upper left center correspond to clouds.

Man's influence on the earth's surface temperature is strikingly evident in the picture. The bright areas represent regions of significant surface heating. New York City and the entire metropolitan area stand out clearly against the darker (cooler) waters of the Atlantic Ocean. Central Park is faintly visible as a dark strip running down the center of Manhattan Island. The large cities along the Connecticut shoreline and the Hudson and Connecticut Rivers are easily recognized. Smaller cities and even roads are also apparent, as well as many features relating to surface geology and hydrological conditions.

Weather at the time of the observation was clear and brisk following passages of a weak cold front on the preceding afternoon (5 June). Through New England and eastern New York state air temperature at 1800 GMT (1300 EST) ranged from 20 to 25°C, with winds generally from the northwest at 2–5 m s^{-1} except along the coast. The air temperatures agree generally with satellite derived brightness temperatures for the rural areas in the scene. However, a detailed comparison is not feasible at this time because of the spatial variability of satellite derived temperatures, the need for a correction for atmospheric moisture and, principally, the uncertainty as to the relationship between air temperature and surface temperature.

3. Magnitude of the surface heat effect

Through analysis of the digital data represented by Fig. 1 it is possible to establish the extent and magnitude of surface heating in a number of cities compared with their surroundings. The New York metropolitan area is so large that it is difficult to establish a precise background level for comparison with values in the city center. In other cases the determination of urban–suburban–country thresholds is reasonably objective, requiring comparison with a map at a scale appropriate to the imagery, e.g., 1:1 000 000. The temperature contrast of a number of cities and towns with their surrounding rural areas is given in Table 1. The contrast is based on brightness blackbody temperature as observed by the satellite radiometer.

As one would expect, the values for temperature contrast are in rough agreement with the corresponding population figures. However, the temperature excesses in large cities are much higher than values typical of air temperatures (which is usually of the order of 2–4°C). In many cases the differences exceed 10°C. Most numerical studies (Myrup, 1969) have treated a city as a rough surface which interacts with the atmosphere in a manner similar to vegetation, rough soil, etc. The high values of surface temperature contrast suggest that a more complex description may be necessary. The highest values of temperature contrast (up to 15°C) in Table 1 are not necessarily representative of the heat island effect as specified by air temperature. Within some of the larger cities a few (1–5) isolated points indicate temperatures 2–3°C above all other values. These elevated temperatures are presumed to be associated with power plants or industrial activity. More detailed study, specifically ground truth verification of accurately mapped HCMM data, will be required in order to verify this hypothesis. It is apparent, however, that the relative importance of industry as compared to urban population need not be the same for air temperature as for remotely sensed surface temperature.

Even after discounting the effect of industry the excess of urban surface temperatures over these surrounding areas is still much greater than that of air temperatures. This effect may be due to trapping of energy within the "urban canyon" (Nunez and Oke, 1977). The vertical structure in city centers provides a potential for absorption of radiation and for heat storage at a level beneath that of strong vertical

TABLE 1. Population (1970) and observed peak temperature contrast of cities and surrounding areas.

City	Population (×1000)	Metropolitan area population (×1000)	Temperature contrast (°C)
New York, NY		7895	17.0
Hartford, CT	158	817	15.0
Schenectady, NY	78		15.0
Providence, RI	179	720	13.2
Binghamton, NY	64		12.4
Bridgeport, CT	157		12.1
Worcester, MA	177	637	11.5
New Haven, CT	138	745	11.2
Stanford, CT	109		11.2
Fitchburg, MA	43		11.2
Syracuse, NY	197	637	10.9
Waterbury, CT	108		10.9
Albany, NY	116		10.3
Troy, NY	62		10.3
Pittsfield, MA	57		9.7
Rome, NY	50		8.9
Utica, NY	91		8.0
Barre, VT	10		8.0
Montpelier, VT	8.6		6.8

TABLE 2. Area and excess radiated power from urban areas (9°C threshold).

City	Area (km^2)	Radiated power (kW)
New York City area	547	40 000
Providence	48.2	3190
Hartford	26.2	1770
Schenectady	5.3	368
Bridgeport	14.2	954
Syracuse	6.5	417
Binghamton	6.0	394
New Haven	5.8	372
Worcester	5.1	327
Albany	3.7	227
Stanford	3.2	202
Fitchburg	2.1	131
Waterbury	1.2	74
Troy	1.4	86
Pittsfield	0.7	42
Rome	0.5	27

mixing in the atmosphere. This hypothesis can be tested by comparison with appropriately taken air temperature measurements. The urban canyon effect would tend to produce air temperature maxima in regions of highest vertical relief, by inhibiting exchange of radiant energy and thermal energy with the atmosphere.

A second but less likely explanation emphasizes rooftop heating by the sun at a height above the level of standard air temperature measurements. This mechanism also implies high radiation temperatures, as observed by the satellite, but lower air temperature values near ground level. However, one would expect a strong mixing interaction to extract energy efficiently from building tops and transfer it to the atmosphere below.

For investigation of urban heating, the peak temperature is less significant than a summation (area integral) of the excess power radiated as a result of the surface temperature elevation. In Table 2 the area and integrated power are listed, where an arbitrary threshold of 9°C excess has been used to specify the urban area. (At 300 K 1 K temperature increase results in an increase in radiated power of 6 W m^{-2}). It is interesting to note that Torrance and Shum (1976) estimate the typical energy consumption rate in large cities to be in the range 20–100 W m^{-2}, which is of the order of the excess energy radiated to space in city centers due to the elevation of urban surface temperature over that of the surrounding countryside. Of course, the complete energy budget is much more complex, as most heat generated by automobiles, space heating and industry enters the environment as atmospheric warming near ground level. However, by modifying the temperature structure of the lower atmosphere this exhaust heat tends to reduce the vertical temperature gradient and hence increase the surface temperature in urban areas.

Although the mechanism for the satellite-observed large elevation of urban surface temperature is unknown, the appearance in the imagery of very small towns in New England points to the great sensitivity of remote sensing for monitoring surface temperature anomalies associated with human habitation.

5. Conclusion

The availability of high spatial resolution data in the thermal infrared opens a new avenue to the study of the urban heat island effect. Although many details must be explored for a full understanding of the significance of the satellite data, imagery such as Fig. 1 illustrates the great potential utility of the data. The more recent launch of a NOAA satellite, TIROS N, having characteristics very similar to the HCMM radiometer with 1 km spatial resolution, 1430 LT overpass at midlatitudes promises a continuing capability for study of the heat island effect.

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