Satellite multi-sensor data analysis of urban surface temperatures and landcover

B. Dousset\textsuperscript{a,b,*}, F. Gourmelon\textsuperscript{b}

\textsuperscript{a}Hawaii Institute of Geophysics and Planetology, University of Hawaii, 1680 East West Road, Honolulu, HI 96822, USA
\textsuperscript{b}Laboratoire Géomer, U.M.R 6554 C.N.R.S, I.U.E.M/U.B.O Place Copernic, 29280 Plouzané, France

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Abstract

Multiple satellite sensors are used to analyze physical processes that determine energy fluxes and their interaction at the urban surface. The study is based on summertime microclimate analyses of the Los Angeles and Paris metropolises. The method consists of deriving some parameters governing the surface heat fluxes, constructing statistics of thermal infrared images, and using a GIS to combine them with a landcover classification from SPOT-HRV multispectral images, and with data from intensive in-situ experiments. The average images reveal spatial and temporal variations of land surface temperature (LST), and distinct microclimatic patterns. The combined interpretation of the statistics images and of the landcover classification shows: (i) the effect of surface physical properties, especially in downtown business and industrial districts that display heat-islands larger than 7 °C; (ii) the temperating influence of water; (iii) the negative correlation between afternoon land surface temperature and normalized vegetation index, which confirms the cooling effect of urban parks; (iv) the correlation between variations of surface temperature and ozone concentration at diurnal and longer time scales.

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1. Introduction

The interactions of urban surfaces with the atmosphere are governed by surface heat fluxes, the distribution of which is drastically modified by urbanization. The main contributing factors are changes in the physical characteristics of the surface (albedo, thermal capacity, heat conductivity), owing to the replacement of vegetation by asphalt and concrete; the decrease of surface moisture available for evapotranspiration; changes in the radiative fluxes and in the near surface flow, owing to the complicated geometry of streets and tall buildings, and anthropogenic heat.

These physical processes are difficult to monitor solely with in-situ instruments. Satellite borne instruments can provide quantitative physical data at high spatial or temporal resolutions. Visible and near-infrared remote sensing systems have been extensively used to classify phenomena such as city growth, landuse and landcover changes, vegetation index and population statistics. However, applications to urban climatology have been fewer, owing to the complexity of the interactions of thermal infrared...
and microwave radiations with the atmosphere and urban surfaces. The use of satellite infrared remote sensing in estimating the surface physical properties and variables has been investigated for example by Carlson et al. (1981), Balling and Brazel (1988), Dousset (1989, 1991), Roth et al. (1989), Quattrochi and Ridd (1994), Owen et al. (1998), and Voogt and Oke (1998). Multi-sensor datasets, higher resolution and new processing techniques, have recently improved the accuracy of satellite thermal sensing, allowing new applications to urban climatology.

The objectives of this paper are to document the application of remote sensing by multiple satellites to derive some parameters governing urban surface fluxes, and to analyze the temporal and spatial variations of land surface temperature and their relationship to landcover. The method is based on statistics of thermal infrared images, their combination with near-infrared and visible SPOT-HRV images, and with in-situ data, using a GIS.

2. Data sites and acquisition

The sites of the experiments are the Los Angeles and Paris metropolitan areas. Los Angeles (118°W,
34°N) is located in a coastal plain bounded by mountains. A persistent elevated temperature inversion results from a large-scale subsidence and light winds associated with the semi-permanent Pacific high pressure, and traps pollutants near the surface. The Los Angeles basin is characterized by a high degree of urbanization and a low-density population of about 12 million.

Paris (2.20°E, 48.50°N) is located in a sedimentary basin on the Seine river. Its climate is moderated by the oceanic influence of the mid-latitude westerlies. Paris and its suburbs are characterized by a compact urbanization with a relatively high-density population of about 9 million.

The multi-sensor datasets used in this study include:

- for the Los Angeles basin, a multispectral image from the SPOT-1 satellite acquired in June 1986, and 85 images from the Advanced Very High Resolution Radiometer (AVHRR) on board the satellites NOAA-6 to NOAA-10, acquired in July–August 1984–1985; seven AVHRR images correspond to an intensive experiment of air flow and quality, the BASIN project, August 8–10 1984 (Wakimoto and Wurtele, 1984).

- for the Paris basin, a multispectral image from the SPOT-2 satellite acquired in March 1998, and 22 images from satellites NOAA-12 and NOAA-14 acquired at the time of an intensive experiment of air flow and atmospheric pollution, the ESQUIF project conducted in August 1998 (Menut et al., 2000).

The NOAA-AVHRR on board the NOAA satellites scans in five spectral channels centered at 0.62 μm (channel 1), 0.91 μm (channel 2), 3.74 μm (channel 3), 10.8 μm (channel 4) and 12.0 μm (channel 5). Its ground resolution varies from 1.1 × 1.1 km at nadir to 1.5 × 4.0 km at the swath edges. The NOAA satellites, launched into near-polar sun-synchronous orbits, pass in view of any point on earth twice daily. The SPOT High Resolution Visible Imagers (HRV-1 and HRV-2) have three spectral channels spanning 0.5–0.59 μm (channel 1), 0.61–0.68 μm (channel 2), and 0.79–0.89 μm (channel 3). Their ground resolution is 20 m in multispectral mode.

The flow diagram of multi-sensor data processing and merging is shown in Fig. 1. The procedure involves successive steps that are described below.

3. Derivation of some surface properties and heat fluxes parameters

Although the entire energy budget cannot be estimated solely from remotely sensed data, short wave and long wave radiative fluxes can be estimated from visible and infrared satellite images, while moisture availability is related to both vegetation index and radar cross-section. Wind speed, air temperature and specific humidity, entering the computation of the sensible and latent heat-fluxes, escape direct measurement from space. They must be either provided by independent in-situ measurements, by mesoscale numerical models, or diagnosed from the closure of the surface energy balance. Here we will focus on two parameters entering in the estimation of surface heat fluxes: land surface temperature and vegetation index, and their relationship.

A series of AVHRR images with small satellite to zenith angles were selected, to ensure ground resolutions close to 1.1 km². Using the Terascan software, the images were geometrically corrected for earth rotation and curvature, and interactively registered to common projections (Mercator for Los Angeles, Lambert for Paris). For each satellite pass, an image was produced for each channel. Land albedo, and daytime cloudiness were derived from channel 2. Pixels were flagged according to a threshold based on the histograms of cloud-free images. For daytime images, pixels were flagged as cloudy when channel 2 exceeded a threshold of 0.2 (20%), since the albedo of clouds is higher than the albedo of land. For nighttime, pixel were flagged as cloudy when the difference between infrared channels 3 and 4 exceeded a threshold of 2.5 °C in absolute value, since clouds have different optical properties and emissivity at 3.5 and 10.5 μm (Saunders and Kriebel, 1988).

Calibrated brightness temperatures were derived using the internal black body references of the satellite. Brightness temperatures differ from actual land surface temperatures (LST) due to several effects: partial absorption of blackbody radiation by water vapor in the atmosphere; surface emissivities being less than 1 and spatially and spectrally variable, especially for mineral substrates (Kahle et al., 1984; Becker, 1987; Ottle and Stoll, 1993); sub-pixel variations of surface temperature being averaged...
non-linearly through Planck’s law (Dozier, 1981; Dousset et al, 1993); urban geometry trapping radiated and incident energy in urban canyons, effectively increasing the pixel-average emissivity; non-vertical satellite viewing angles biasing towards vertical walls and hiding horizontal surfaces (Voogt and Oke, 1998).

Over the ocean (a near-perfect black body with an emissivity of 0.99), an empirical multispectral correction for water vapor is generally computed based on the differential attenuation of infrared channels 4 and 5 (McClain et al., 1985). In the Los Angeles basin, the columnar atmospheric moisture content was 8 kg/m². It did not vary significantly over the diurnal cycle and was mostly confined to the lower 400 m, below the temperature inversion. This moisture content corresponds to a brightness temperature error less than 1 °C in channel 4. In the Paris basin, the mean nighttime difference between channel 4 and channel 5 was 0.09 °C, with a standard deviation of 0.27 °C. This yields a multispectral correction less than 0.23 °C.

In both cases, the water vapor correction was negligible. Other climatological conditions, of course, would require corrections based on a full radiative transfer model and in-situ radiosondes. In the present cases, however, the uncertainties related to radiosonde data and radiative modelling would likely exceed the actual brightness temperature errors, and the corrections are not justified. Also, applying classical multispectral corrections in the presence of unknown spectral variations of emissivity would in fact degrade the estimation of surface temperatures when the water vapor correction is small (Becker, 1987).

Over the 8 to 14 μm spectral range, typical urban surfaces emissivities vary between 0.85 and 0.98. Brightness surface temperatures are thus lower than actual land surface temperatures. In channels 4 and 5, the error can be approximated by linearizing Planck’s law. At $T=20 \, ^\circ C$, the correction is 0.6 °C for each percent of emissivity below 100%. A typical pixel-average emissivity of 97% was estimated from the landcover classifications, and from values of the emissivities of various materials (Buettner and Kern, 1965). A constant correction of $+1.8 \, ^\circ C$ was therefore applied to convert channel 4 brightness temperatures to LST for the present study.

The Normalized Difference Vegetation Indices (NDVI) were obtained from the visible and near-infrared channels:

\[
\text{NDVI} = (\text{nir} - \text{vis})/(\text{nir} + \text{vis})
\]

where nir and vis are channels 2 and 1 for the AVHRR, and channels 3 and 1 for the SPOT-HRV.

4. NOAA-AVHRR image combinations and statistics

For the various times of day of the NOAA-AVHRR satellites passes (i.e. morning, afternoon, evening, night), images of average LST and of cloud frequency were constructed. Maximum and minimum LST, and amplitude of the diurnal cycle were then derived from the average images.

The images of cloud frequency over Los Angeles reveal the decreasing influence of the marine layer in forming stratus clouds with increasing distance from the coast, the presence of convective clouds near the mountains bordering the basin, and the diurnal variation of these processes.

\[\text{Fig. 2. Statistical diurnal cycle of LST in downtown Los Angeles, Santa Monica and Chino Fields, derived from NOAA-AVHRR images in July–August 1984–1985.}\]
Fig. 3. (a) Average image of Los Angeles LST, based on 15 NOAA-AVHRR thermal IR images, at 14:50 PDT in August 1985. P1, P2, P3, P4 indicate some urban parks. The temperature grey scale is labeled in °C. (b) Land cover classification of Los Angeles derived from a multispectral SPOT-HRV 1 image on June 29, 1986.
Fig. 2 displays the 1984–1985 summertime statistical diurnal cycle of LST extracted from the average images, in downtown Los Angeles, in the coastal area of Santa Monica, and in Chino Fields on the outskirts of the metropolitan area. At 04:25 PDT, the Chino Fields are cooling by unobstructed long wave radiation, while losses in Santa Monica are tempered by the oceanic influence. The heat island effect, defined as rural–urban temperature difference, is 5 °C between downtown Los Angeles and Chino Fields, and 2 °C between downtown Los Angeles and Santa Monica. At 08:30 PDT, the marine boundary layer tends to equalize LST in the basin. At 14:50 PDT, the net radiation flux is balanced mostly by the sensible heat flux in downtown Los Angeles, whereas in Chino Fields and in Santa Monica the latent heat flux plays a larger role, yielding a heat island of 9 °C between downtown Los Angeles and Chino Fields, and 7.5 °C between downtown Los Angeles and Santa Monica. At 19:40 PDT, the city reradiates the heat stored in its structures, whereas the coast and the fields are cooling more rapidly.

Fig. 3a displays the average LST image over Los Angeles at 14:50 PDT, constructed from 15 images. The LST range is 12 °C. The oceanic influence extends a few kilometers inland. LSTs increase with distance from the coast, from about 34 °C in Santa Monica to 41.6 °C in downtown Los Angeles. The LSTs of industrial and commercial areas reach 38 to 39.5 °C in Long Beach, and about 41 °C in the basin, in East Los Angeles and in Whittier. LSTs in the Santa Monica Mountains and the Puentes Hills are only 30–33 °C. The difference in LSTs between the urban parks and their surroundings appears as distinct cool islands of 3.4 °C in the Los Angeles Country Club (P1), 4.2 °C in the Wilshire Country Club (P2), 2.2 °C in the Forest Lawn Park (P3), and 5 °C in the Sepulveda Dam Recreational area (P4). The influence of topography is observed through the inverse relationship between altitude and LST.

5. SPOT-HRV landcover classification

The SPOT-HRV images were pre-processed by SPOT Image Corporation to level 1B, which includes detector radiometric equalization, bulk geometric processing to remove the earth rotation effect, resampling across-track to remove the off-nadir imaging effect and to obtain a 20-m pixel size. No atmospheric correction was performed, since only relative values are required for the multispectral landcover classification. The classification was derived differently for Los Angeles and for Paris.

The unsupervised landcover classification of Los Angeles shown in Fig. 3b is based on the bivariate distribution of SPOT HRV1 channels 1 and 3, displaying the largest variance in spectral signatures due to the high reflectance of vegetation in channel 3. The distribution was divided into six landcover classes corresponding to water, clouds and high reflectance materials, light bare soils, natural vegetation and urban parks, residential, and densely built areas.

The unsupervised landcover classification of Paris shown in Fig. 4a was derived from the three channels of the SPOT HRV-2 image. The image was classified, using the Geoimage and Arcinfo packages, into six landcover classes corresponding to water, urban densely built, suburban residential, light bare soils, densely vegetated (forest), lawns and fields. The classification was further validated using the NDVI. The GIS was used to perform a collocation, shown in Fig. 4b, of the 20-m pixels of the classified SPOT image (Fig. 4a), with the 1-km LST pixels from the NOAA-AVHRR afternoon average image (Fig. 5b). This approach facilitates the interpretation of LST, especially for pixels with mixed landcovers.

6. Spatial and temporal variability of land surface temperature and its relationship to landcover

The interpretation of microclimatic variations is provided by combining the NOAA-AVHRR statistical infrared images with classified multispectral SPOT-HRV images using the GIS.

Fig. 5a is the average NOAA-AVHRR thermal infrared image of Paris, constructed from five images collected between August 6 and 10, 1998 at 03:27 UTC. For these images taken at the end of the night, the heat island effect remains strong (7 °C) due to the different cooling rates within the rural and urban areas. The urban parks of Bois de Boulogne and Bois de Vincennes (19 °C) at the western and eastern borders of Paris, and the rural areas (16 °C) are rapidly cooled by evapotranspiration and unobstructed
Fig. 4. (a) Land cover classification of Paris derived from a SPOT-HRV 2 image on March 9, 1998. The white frame outlines the enlargement shown in (b). (b) Enlargement of the 20-m resolution landcover classification (a) of Orly, in the Paris suburbs, collocated with the 1-km resolution average afternoon image of LST (Fig. 5b). The LST values are indicated in white and the 1-km resolution grid in black.
Fig. 5. (a) Nighttime average image of Paris LST, based on five NOAA-AVHRR thermal IR images at 03:27 UTC, August 6–10, 1998. The white frame outlines the coverage of the SPOT image shown in Fig. 4a. (b) Daytime average image of Paris LST, based on five NOAA-AVHRR thermal IR images at 13:28 UTC, August 6–10, 1998.
Fig. 6. (a) Percentage of densely built class (incl. roads) at 1-km resolution, derived from the 20-m resolution landcover classification of Paris. 
(b) Joint distribution of percentage of the densely built class, with nighttime and daytime average LST images (Fig. 5a and b).
long wave radiation. Conversely, in the city (21 to 22 °C), there is little evapotranspiration, and the heat stored during the day, is now trapped by urban structures obstructing direct radiation to the sky.

Fig. 5b is the average NOAA-AVHRR thermal infrared image of Paris, constructed from five images collected between August 6 and 10, 1998, at 13:28 UTC. The temperature range is 10 °C. Highest LSTs (38 to 40 °C) are observed in the commercial/industrial areas of Ris Orangis and Orly airport to the south, Le Bourget airport to the north, and densely built suburbs such as St Denis (north). In downtown Paris, LSTs are between 35 and 37 °C. The coolest areas include urban parks in the vicinity of the Seine river. The influence of vegetation can also be seen in the suburban residential areas of detached housing such as Versailles to the west (32 to 33 °C), in the large urban parks of Bois de Vincennes and Bois de Boulogne (33 to 35 °C), and in the forests around Paris (31 to 33 °C).

7. Combination of land surface temperature, landcover and air quality

The landcover classification at 20-m resolution allows one to compute the percentage of a given class within 1-km resolution AVHRR pixels. Fig. 6a shows the percentage of the “densely built” class over Paris, and Fig. 6b displays its joint distribution with night and day average LST images (cf. Fig. 5a and b). The nighttime distribution of LST is well correlated with the increasing density of buildings from the suburbs to downtown, as seen in Fig. 5a. The daytime distribution of LST also shows a correlation with density of building, although the variance is larger, presumably due to larger fluctuations of the heat fluxes, hence of LST, under the stronger radiative forcing conditions.

Fig. 7 represents the bivariate histogram of the diurnal LST amplitude over the Paris basin between the images of August 7 at 13:28 UTC and August 8 at 03:27 UTC, versus the NDVI.
3:27 UTC, versus the NDVI. A strong negative correlation is seen, the moisture availability from vegetation allowing a larger fraction of the net radiative flux to be balanced by evapotranspiration and by the latent heat flux, thus lowering the sensible heat flux, hence LST.

Fig. 8 displays the diurnal cycle of the median LST computed over the 22 NOAA-AVHRR thermal infra-red images of the Paris basin, from August 5 to 10, and measurements of surface ozone concentration, from August 7 to 9, recorded during the ESQUIF experiment (Menut et al., 2000). The figure indicates an upward trend of the maximum and minimum LST, with a diurnal amplitude of about 22 °C, paralleled by the variations of ozone concentration.

8. Discussion and conclusion

Urban climate studies require high spatial resolution data that can only be obtained from satellites. We have illustrated the power of data fusion based on statistics of thermal infrared images at 1 km resolution, with visible and near infrared images at 20-m resolution, that better match the urban scale.

The results demonstrate the capabilities of remote sensing to derive some components of the urban energy balance, and to monitor their spatial and temporal variability. Statistics of thermal infrared images of Los Angeles reveal patterns of thermal anomalies related to surface properties and atmospheric phenomena. Statistics of thermal infrared images of Paris show the contrast between a well-defined heat island at night, and many distinct microclimates during the day influenced by surface properties. In particular, the negative correlation between LST and vegetation index, shown for Paris but also observed in Los Angeles, indicates the importance of vegetation in the partition of sensible and latent heat fluxes. Merging infrared NOAA-AVHRR images with landcover classification from SPOT-HRV2, using GIS, was a critical tool to interpret the observations, given the complexity of urban surfaces.

Future work will benefit from the higher spectral or spatial resolution of new instruments such as MERIS or ASTER, to construct maps of physical surface...
properties such as albedo and emissivity. Adding layers of information from air quality data will also advance our understanding of the interactions between urban surfaces and atmosphere.

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