SURFACE TEMPERATURES OF THE PARIS BASIN DURING SUMMERTIME, USING SATELLITE REMOTE SENSING DATA

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ABSTRACT

The surface temperatures of the Paris basin in August 1998 were analyzed using a series of twenty two, thermal infrared images from the NOAA–AVHRR satellites, at 1km resolution; a multi-spectral image from SPOT-HRV satellite, at 20 m resolution; and in-situ data from the ESQUIF experiment. The method was based on the construction of statistical thermal infrared images, of a land cover classification image, and on their combination using a Geographic Information System. The statistical thermal infrared images revealed large spatial and temporal variations of surface temperatures. Those images displayed a significant contrast between a well-defined central heat-island at night, related to the built density and lack of vegetation, and many distinct microclimates during the day, related to surface properties. The strong negative correlation between the diurnal land surface temperature amplitude and the fractional vegetation index, confirmed the cooling effect of urban parks and suburban forests. The images combination of statistical temperatures and land cover classification improved the accuracy of data interpretation, given the urban surfaces heterogeneity.

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 objectives of this paper are to document the application of satellite remote sensing to derive some parameters governing the surface heat fluxes, and to analyze the temporal and spatial variations of land surface temperature and their relationship to land cover. 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 Geographic Information System (GIS). The site of the experiment is the Paris metropolitan area, centered at 2.20 W, 48.50 N. 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 ~9 million.

METHODS

The multi-sensor dataset comprises a multispectral image from the SPOT HRV-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 SPOT High Resolution Visible Imager HRV-2 has three spectral channels spanning 0.5-0.59 µm, 0.61-0.68 µm, and 0.79-0.89 µm. Their ground resolution is 20 m in multispectral mode. The NOAA-AVHRR on board the NOAA satellites scans in five spectral channels centered at 0.62 µm, 0.91 µm, 3.74 µm, 10.8 µm and 12.0 µm. Its ground resolution is 1.1 x 1.1 km^2 at nadir. The NOAA satellites, launched into near-polar sun-synchronous orbits, pass in view of any point on earth twice daily.

A series of AVHRR images with small satellite to zenith angles were selected, to ensure ground resolutions close to 1.1 km^2. The images were geometrically corrected for earth rotation and curvature, and interactively registered to a Lambert projection. For each satellite pass, an image was produced for each channel. Land albedo, and daytime cloudiness were derived from channel 2, and nighttime cloudiness from channels 3 and 4. Cloudy pixels were flagged according to a threshold based on the histograms of cloud-free images.

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

$$NDVI = \; (nir / vis \;) / \; (nir + vis)$$

where nir and vis are channels 2 and 1 for the AVHRR, and channels 3 and 1 for the SPOT-HRV2.

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 (1,2,3); sub-pixel variations of surface temperature being averaged non-linearly through Planck's law (4); 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 (5).

Over the ocean, an empirical multispectral correction for water vapor is generally computed based on the differential attenuation of infrared channels 4 and 5 (6). In the Paris basin, the mean nighttime difference between channel 4 and channel 5 was 0.09C with a standard deviation of 0.27 ºC, yielding a multispectral correction less than 0.23 ºC. Other climatological conditions would require corrections based on a full radiative transfer model and in-situ radiosondes. In the present case, a correction is not justified, since the uncertainties related to radiosonde data and radiative modelling would likely exceed the actual brightness temperature error.

Within the 8 µm 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 ºC, the correction is 0.6 ºC for each percent of emissivity below 100%. Typical pixel-average emissivities were estimated from the land cover classification, and from a spectral library (7). Corrections were then applied to convert channel 4 brightness temperatures to LST for the present study.

The SPOT-HRV images were pre-processed 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. The unsupervised land cover classification of Paris shown in Fig. 1a was derived from the three channels of the SPOT HRV-2 image. The image was classified, into six land cover 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, (Fig. 1b), of the 20-m pixels of the SPOT image (Fig.1a), with the 1-km LST pixels of a NOAA-AVHRR image (Fig. 2b). This approach facilitates the interpretation of LST, especially for pixels with mixed land covers.

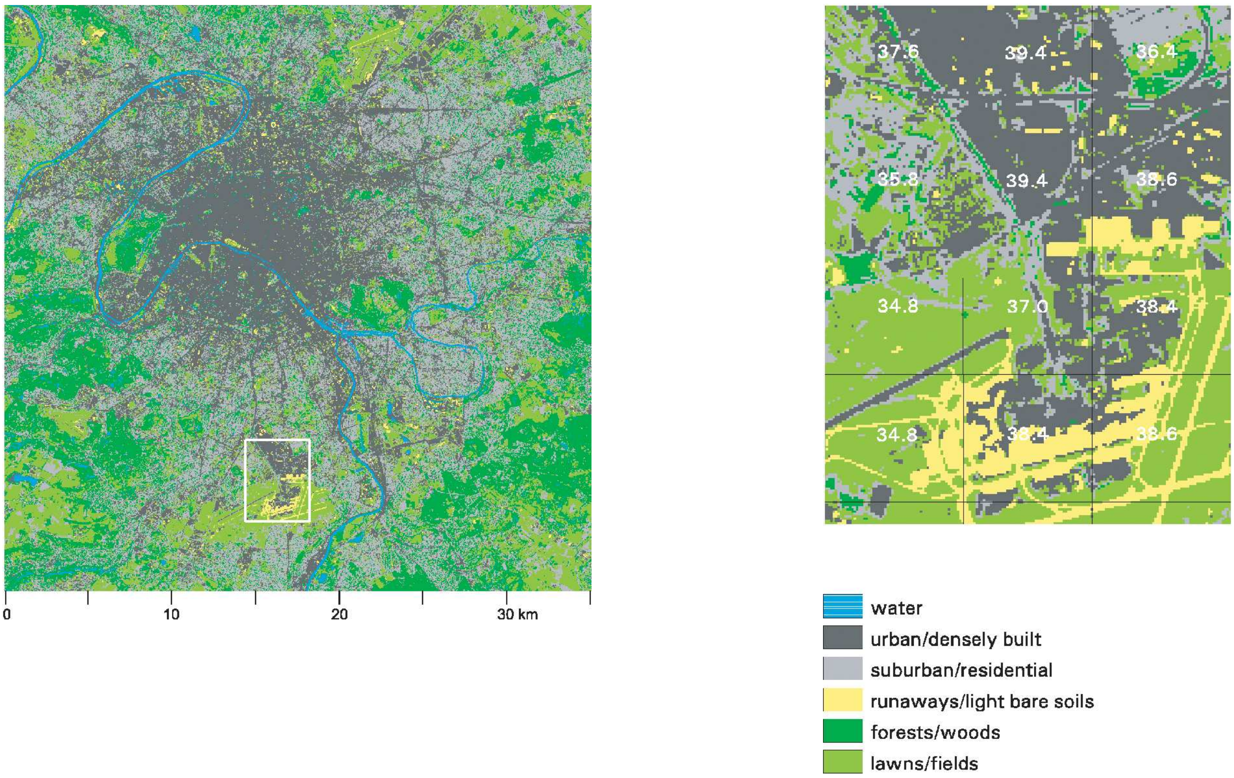

Fig.1 (a) Land cover classification of Paris from the SPOT-HRV image, (b) enlargment of the 20-m resolution land cover classification of Orly suburbs, collocated with the 1-km LST (white values) afternoon image (Fig.2b).

Fig. 2a is the average NOAA-AVHRR thermal infrared image of Paris, constructed from 5 images collected between August and 10 1998 at 03:27 UTC. For these images taken at the end of the night, the heat island effect remains strong, due to the different cooling rates within the rural and urban areas. The urban parks of Bois de Boulogne and Vincennes at the western and eastern limits of Paris, and the rural areas are rapidly cooled by evapotranspiration and unobstructed long wave radiation. Conversely, in the city (21 to 22 ºC), there is little evapotranspiration, and the heat stored during the day, is now trapped by urban structures obstructing direct radiation to the sky. Fig. 2b is the average NOAA-AVHRR thermal infrared image of Paris, constructed from 5 images collected between August 6 and 10, 1998, at 13:28 UTC. The temperature range is 10 ºC. Highest LST of 38 to 40 ºC) are observed in 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. In downtown Paris, LSTs are between 35 and 37 ºC. 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 ºC), in the large urban parks of Bois de Boulogne and Vincennes (33 to 35 ºC), and in the forests around Paris (31 to 33 ºC).

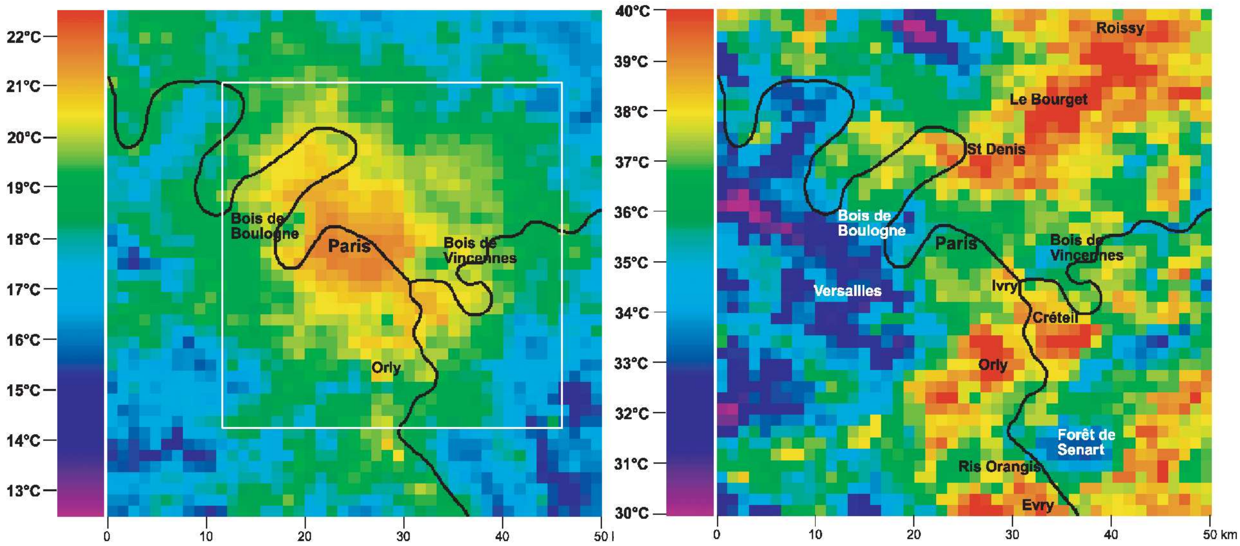

Fig.2 (a) Nighttime average image of Paris LST, based on 5 NOAA-AVHRR thermal IR images at 03:27 UTC, August 6-10, 1998. The white frame outlines the coverage of the SPOT image shown in Fig. 1a. (b) Daytime average image of Paris LST, based on five NOAA-AVHRR thermal IR images at 13:28 UTC, August 6-10, 1998.

The landcover classification at 20-m resolution allows one to compute the percentage of a given class within 1-km resolution AVHRR pixels. At nighttime, the distribution of LST is well correlated with the increasing density of buildings from the suburbs to downtown. At daytime the variance is larger, presumably due to larger fluctuations of the heat fluxes, hence of LST, under stronger radiative forcing conditions.

A significant negative correlation occurs in 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 3:27 UTC, versus the NDVI (not shown here). The moisture availability from vegetation allows 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. 3 displays the diurnal cycle of the median LST computed over the 22 NOAA-AVHRR thermal infrared 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 (8). The figure indicates an upward trend of the maximum and minimum LST, with a diurnal amplitude of 22 ºC, paralleled by the variations of ozone concentration.

Urban climatology requires high spatial resolution data that can only be obtained from satellites. The combination of statistical thermal infrared images with visible and near infrared images, that better match the urban scale, demonstrates the capabilities of remote sensing to monitor the LST spatial and temporal variability. 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, indicates the importance of vegetation in the partition of sensible and latent heat fluxes. Merging infrared NOAA-AVHRR images with land cover 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.

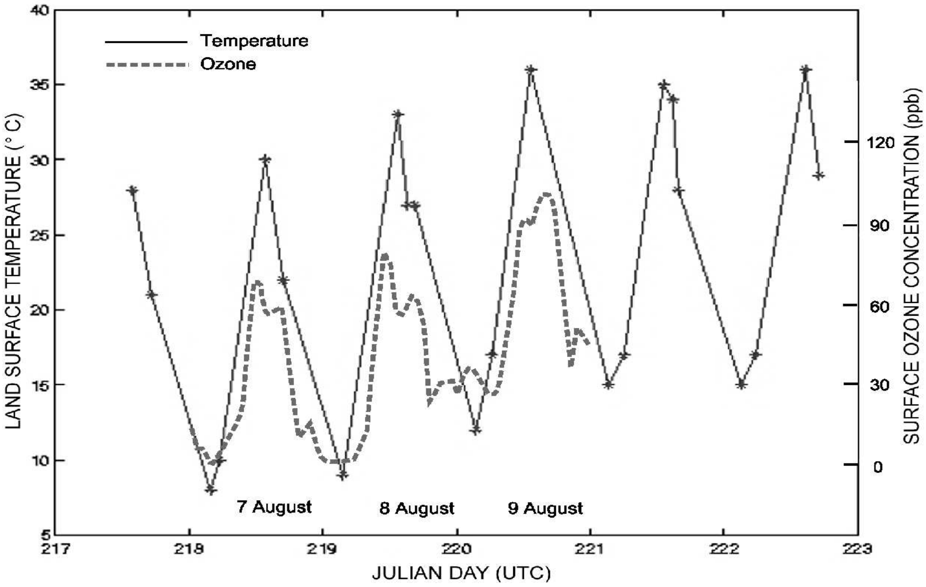

Fig. 3. Diurnal cycle of the median LST of the Paris basin from NOA-AVHRR thermal IR images, August 5 -10, 1998; and collocated surface ozone concentration from the ESQUIF experiment, August 7 - 9 1998.

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