SATELLITE MONITORING OF SUMMERTIME HEAT WAVES IN THE PARIS METROPOLITAN AREA

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Abstract

Warming trends increase the incidence, intensity and duration of heat waves, as predicted by climate models for the 21st century. Heat waves are especially deadly in cities owing to surface properties, anthropogenic heat and pollutants. Following the extreme heat wave of August 2003, a summertime satellite monitoring has been developed for the Paris region. Satellite thermal IR images are used to observe the diurnal amplitudes of surface temperatures and their spatial distribution, to estimate the associated heat stress, and to improve the health alert system. The data of August 2003 indicates large surface temperature gradients and variable daytime / nighttime urban heat islands patterns. The heat wave is associated with high nighttime temperature compared to normal summers. Temperature thresholds and areas most vulnerable to heat stress were delineated. The data was then applied to a case study of persons over 65 age living at home, to analyze the spatial variability of heat stress factors. A website displaying satellite IR images in near real time is being tested to inform the local public and authorities on extreme surface temperatures and associated impacts in the Paris region.

Keywords: urban surface temperature, heat waves, heat stress, satellite remote sensing.

1. INTRODUCTION

According to climate model for the 21st century, summer warming trends might increase the incidence, intensity and duration of heat waves, particularly in western and central Europe, the Mediterranean regions, and the western and southern regions of the United States, (Meehl and Tebaldi, 2004; Shar et al., 2004). Heat waves are especially deadly in cities due to the alteration of their surfaces, a decrease of surface moisture available for evapotranspiration, changes in radiative fluxes and near surface flow, and production of anthropogenic heat and pollutants. At night, while temperature may drop in rural areas, cities release the heat stored in the buildings, inducing a lack of relief and increasing the risk of heat stress and mortality for the more vulnerable population (the elderly, infants and people with chronic diseases). In summer 2003, the western Europe experienced a heat wave of exceptional strength and duration, with a death toll exceeding 70 000 (Robine et al., 2008). In August, the Paris metropolitan area encountered nine consecutive days with temperature reaching 38°C in daytime and increasing from 20°C to 25°C in nighttime at the peak of the heat wave, resulting in a 4,867 excess mortality (Fig.1).

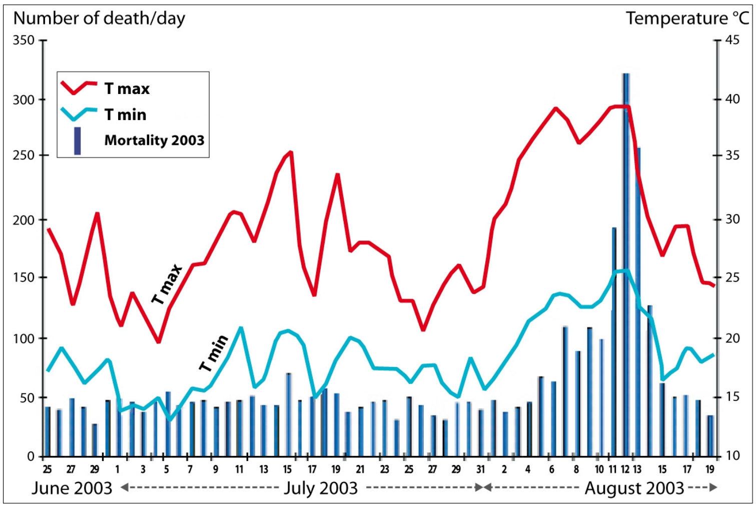

Fig.1: Surface air temperature from an urban park, and mortality during the summer of 2003 in the Paris region. (*source IVS 2003*)

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Estimates of urban heat stress and vulnerability requires observations at high spatial resolution, which are best obtained from satellites thermal infrared imagery. Applications have shown the relationship between sprawling conurbations, complex heat islands patterns and horizontal temperature gradient (Dousset and Gourmelon 2003). Previous analysis of surface temperature variability in the Paris basin during the 2003 heat wave, have indicated that early satellite observation might have contributed to issue appropriate warning (Dousset et al., 2007).

The objectives of this research were: firstly, to monitor and analyze the diurnal gradient of radiant surface temperature during a summertime heat wave episode in the Paris metropolitan area; secondly, to estimate the associated heat stress and to contribute to adaptation strategies; and thirdly to improve the urban heat and health alert systems.

2. DATA SET AND PROCESSING

During the August 2003 heat wave, only two high resolution satellite images, one Landsat TM (August 9) and one Terra-Aster (August 10), were available and the twice daily passes from MODIS were insufficient to resolve the diurnal cycle. The simultaneous activity of three NOAA satellites did provide a repeat of up to six images per twenty-four hours. Eighty four NOAA-AVHRR images were selected, with small satellite viewing angles to ensure ground resolution close to 1.1 km and to minimize directional effects. The images were geometrically corrected for earth rotation and curvature, and interactively registered to a Lambert projection. The AVHRR scans in five spectral channels centered at 0.62µm, 0.91µm, 3.74µm,10.8µm and 12.µm. Land albedo and daytime cloudiness were derived from channel 2, and nighttime cloudiness from the difference of channels 3 and 4. Cloudy pixels were flagged according to a threshold based on the histograms of cloud free images. Vegetation Indices (NDVI) were computed from channels 1 and 2. The differential atmospheric attenuation of infrared channels 4 and 5 yielded to a negligible water vapor correction, but directional effects were compensated. The objectives being to study the temporal variations of surfaces temperatures, emissivity corrections were neglected, being time independent. Composite Images of surface temperature were constructed from 50 NOAA-AVHRR images, at the various time of the satellites passes (i.e., morning, afternoon, evening, night) during the 9-day heat wave episode.

Surface characteristics and properties were extracted from a SPOT-4 High Resolution Visible multispectral image acquired on July 13, 2003, three weeks before the heat wave. The processing of the SPOT image comprised detector radiometric equalization, geometric processing and resampling across-track to a uniform 20 m pixel size. An unsupervised land cover classification was derived and validated using the NDVI to interpret the thermal data.

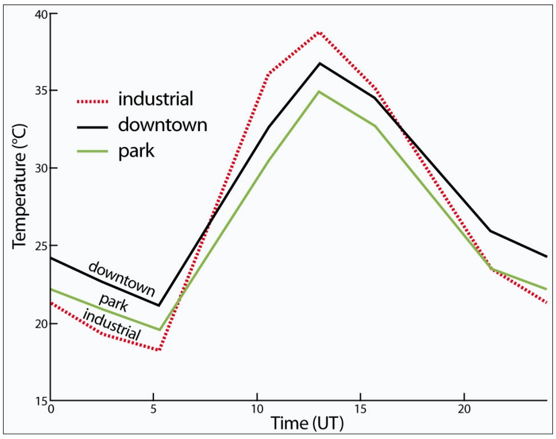
The health data consisted of a case study of 482 people aged 65 and over, living at home in the Paris region, from August 8 to 13, 2003. The study included 241 deceased cases and 241 control cases (Vandentorren et al., 2006). Thermal indices were extracted from 61 NOAA-AVHRR images at the 482 geocoded addresses from August 1 to 13, a total of 29 402 indices.

3. RESULTS

The satellite observations indicate large surface temperature gradients and contrasted daytime/ nighttime heat island patterns. At nighttime a significant heat island develops in downtown Paris, due to built density and lack of evapotranspiration. At daytime multiple thermal anomalies scatters over industrial suburbs, attributable to low thermal inertia and unobstructed fields of view.

Figure 2 represents the mean diurnal cycle of surface temperature over the heat wave, consructed from the composite images. It demonstrates the different rate of radiant cooling and heating between downtown Paris, the suburban and rural areas, enhanced by the stable atmosphere and low wind which characterized the heat wave episode. A near constant difference of ~1.5°C to 2.2°C occurs between downtown and the park. Differences happen of -3°C at night, and 3.5°C at noon between downtown and the industrial site, and of 4.5 °C at noon between the latter and the park. The 26°C highest nighttime temperature occured in downtown Paris. The relatively small temperature amplitude, in reference to normal summers, confirms the impact of high minimum temperatures on the heat wave process and the lack of night-time relief and subsequent heat stress and mortality.

Figure 3 displays the distribution of the 482 geocoded addresses over the Paris region. The thermal indices correspond to the surface temperature of each pixel that includes an address. Different indicators of temperature exposure were constructed based on minimum and maximum surface temperatures, covering a 7-day interval from the date of deceased. Those indicators were integrated into a conditional logistic model adjusted for factors such as age, sex, socio-economic conditions and behaviour (Breslow and Day, 1980).



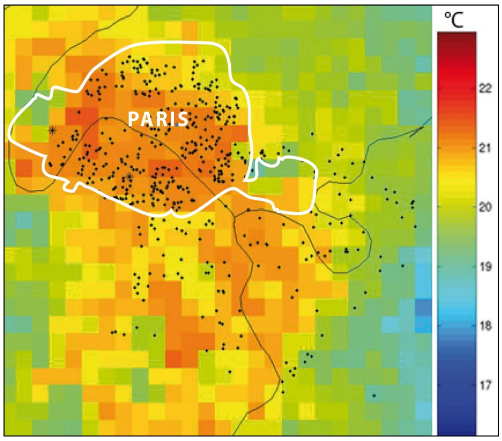
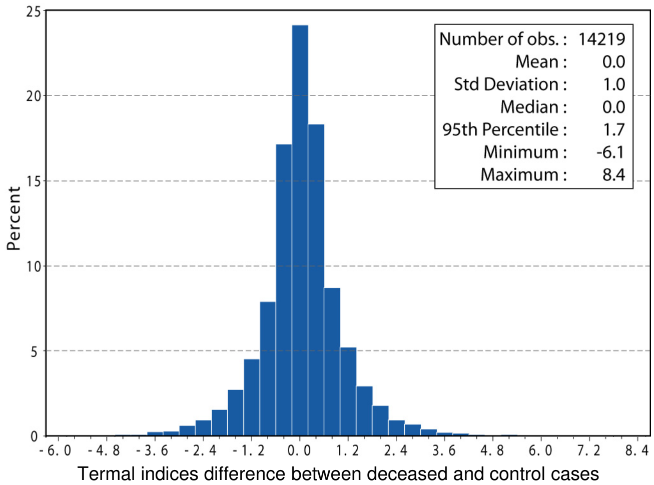


Fig. 2: Mean diurnal cycles of land surface temperature, at an industrial site, in downtown Paris, and in an urban park, constructed from 50 NOAA-AVHRR images (August 4 -13, 2003).

Fig. 3: Spatial distribution of the 482 geocoded addresses in the Paris region, over a nighttime NOAA-AVHRR image (August 2003).

Figure 4 is the distribution of the differences between the deceased and control cases, calculated from 14 219 thermal indices, that were extracted from 61satellite images between August 1 and 13. The differences are small and mostly comprised between 1 and -1. The health results from the linear regression analysis were statistically significant for minimum temperatures. The best result concerns the mean minimum temperature in the 7-day interval before the date of decease including the latter. The odds ratios associated with 0.5 difference in surface temperature between the deceased and the control cases was 2.22 (a confidence limits of 95% = -1.03-4.81).



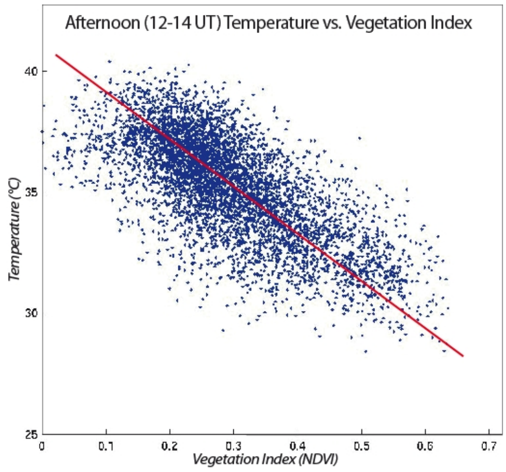


Fig. 4: Distribution of the thermal indices difference between deceased and associated control cases, from 61 NOAA-AVHRR images (August 1-13, 2003).

Fig. 5: Bivariate histogramme of the afternoon surface temperature versus the NDVI, in the Paris region.

A previous deceased and control cases study has been conducted on the 2003 heat wave to estimate the mortality determinants in Paris (Vandentorren et. al., 2006). The study used a LANDSAT-5 TM image of August 9 at 10:17 TU. The corresponding NOAA-AVHRR image of August 9 at 11:20 TU is consistent with the heat island pattern in the LANDSAT image. Higher temperature values in the AVHRR image are attributable to a sensing time nearer from solar noon. Although the 120 m resolution of the LANDSAT image is more appropriate to urban scale, the NOAA satellites offered a ~4 to 6-hour repeat cycle unachievable with the16-day repeat cycle of LANDSAT.

During the spring of 2003, both a strong incident radiation and a large precipitation deficit progressively reduced the moisture content of the soil. The vegetation index of August 2003 was thus lower than normal summers. Nevertheless, Figure 5 indicates a negative correlation between the afternoon surface temperature and the NDVI with a slope of 2°C per NDVI unit.

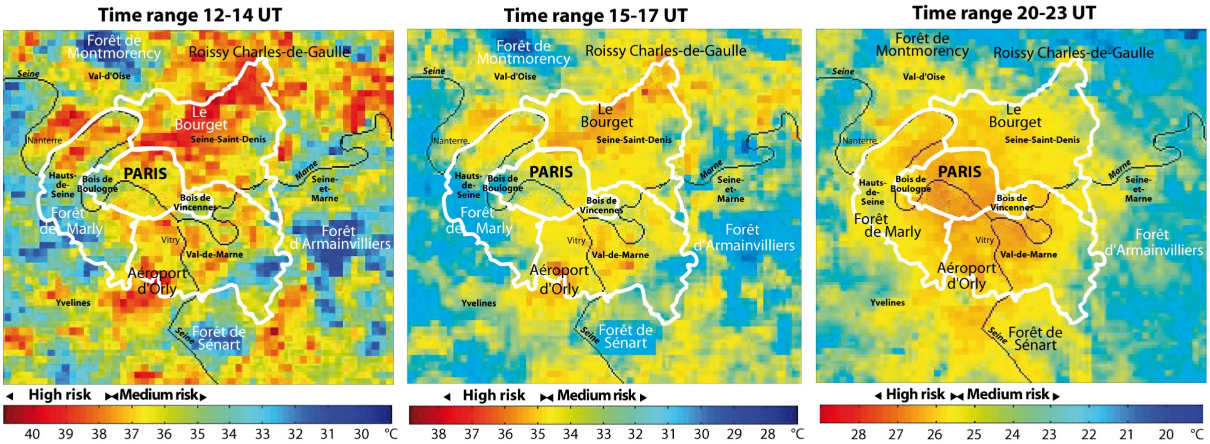


Fig. 6: Maps of temperature thresholds delineating the areas vulnerable to heat stress in August 2003.

Figure 6 shows three maps of temperature thresholds and areas vulnerable to heat stress, delineated from the NOAA-AVHRR time series images. Using the land cover classification from the SPOT-4 image and the Paris geographic database, those maps impart the displacement of heat stress and level of risk according to the occurrence and intensity of heat islands and thermal anomalies, surfaces properties (especially the albedo), water and vegetation, and building and population density.

4. SUMMARY

The combined analysis of satellites thermal images and public health data of the Paris region, during the summer of 2003, confirms the importance of high minimum temperatures in the heat wave process and the subsequent heat stress and mortality. A summertime satellite surveillance system is being developed to monitor heat waves over the Paris Metropolitan area, and to inform the local public and authorities on extreme surface temperatures and potential heat stress. The use of satellite thermal remote sensing over cities is yet a trade-off between accuracy and efficiency. However, it should improve the current health alert systems, contribute to adaptation strategies and reduce the societal impacts of climate change.

Acknowledgements

This work is funded by the Maif Foundation. The NOAA-AVHRR images were provided by Elena Mauri from the Istituto Nazionale di Oceanografica e di Geofisica Sperimentale in Trieste. The Paris geographic database was produced by the Atelier Parisien d'Urbanisme. The heath data was obtained from the Institut de Veille Sanitaire.

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