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Tesis doctoral

Thermal Remote Sensing of urban areas. The case study of the Urban Heat Island of Madrid

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The urban heat island (UHI) is an example of the local weather modification which involves the process of urbanization. It is defined as the temperature difference between the urban zone and the rural surroundings. When a city expands, the natural surfaces are replaced for artificial ones, with different structural and thermal properties. As a consequence, the radiative behaviour of the area changes. The evaporation is reduced and the heating of the air in the lowest layer of the atmosphere is regulated by a surface with higher heat capacity and greater thermal admittance. Thus, heat energy is retained throughout the day and it is released slowly overnight. The three-dimensional structure of city centres also play an important role in the energy balance of the city. The basic unit of the urban structure is the urban canyon, formed by the walls of the buildings and the street. This arrangement assists the multiple reflections of radiation before being released in the highest layers of the atmosphere, favoring the warming of the air in the canopy layer (UCL, layer of the atmosphere between the average height of the buildings and the land). However, during the day, the presence of buildings shadows often makes the air temperature recorded in the city lower than the one recorded in rural areas, directly exposed to sunlight.

The UHI phenomenon has effects on energy consumption. While in cold climates it can cause a reduction in the use of heating, in warm climates, the overheating of the UHI means the rise of the energy consumption due to cooling systems used to achieve thermal comfort inside the buildings. The UHI also concerns about pollution, as warm temperatures increase photochemical harmful elements. However, the most striking effects of the UHI are those that directly affect human health, like episodes of insomnia by exposure to high night temperatures or more serious problems that can lead to death.

The UHI effect can be defined at different atmospheric levels, depending on if the air temperature is taken within the urban canopy layer or if it is in the boundary layer (UBL, layer above the canopy one). However, when using thermal remote sensing, the phenomenon is defined at surface level (surface UHI, SUHI) and it is measured as the difference between the land surface temperature (LST) of the urban and the LST of the non-urban area.

The objectives of this study are to evaluate the urban heat island effect in the city of Madrid, to select from the algorithms in the literature the one that best estimates the LSE and the LST of urban scenarios, to detect and quantify the error sources of the overall remote sensing processing chain, and to propose the conditions that a satellite must accomplish to properly monitor the heat island effect.

These goals have been solved from the analysis and exploitation of the data registered in the DESIREX campaign, which took place in Madrid from 23rd June to 6th July 2008. Different remote sensing images were acquired at high (AHS), medium (ASTER) and low (MODIS) spatial resolution. The atmosphere was characterized with atmospheric soundings and air and radiometric temperature were measured in both fixed points and mobile traverses inside the city. Moreover, spectral emissivity of different surfaces was evaluated and used to validate our LST and LSE retrieval algorithms.

Three algorithms (NDVI^{TM}, TES and TISI) have been used to retrieve the LSE from the AHS imagery. Results have been compared with *in-situ* data obtaining an error of 5.6% for the NDVI^{TM}, of 3.9% for the TES and of 3.0% for the TISI methods. Then, LSE maps have been introduced in the SW algorithm to obtain the LST of the city, which has been validated against *in-situ* measurements, obtaining an RMSE of 2.9 K for the NDVI^{TM} and of 2.0 K for the TES and TISI approaches when man-made materials are used in the validation process. According to the results, the recommended algorithm would be either the TES or the TISI method. Nevertheless, taking into account the spectral and temporal necessities of each of them, we finally recommend the TES algorithm.

Therefore, the TES method is used to retrieve LST and LSE from all the acquired AHS high resolution images. The vicarious calibration of the thermal bands of the sensor gave an RMSE of 1 K and the validation of the LST product showed an RMSE of 1.4 K for night images, when the scene is more homogeneous. From the observation of the LST maps we concluded that the urban areas present an effective anisotropy that is clearly reduced at night, when there are no directly irradiated surfaces and LSTs are more similar. The SUHI is analysed at different spatial resolutions. The results from different platforms are not directly comparable, as the different view zenith angle of each acquisition leads to the observation of different surfaces even if the same area is examined. Nevertheless the SUHI values perform similarly for all the platforms, with positive values (maximum below 5 K) during the night and near zero or even negative values during daytime. AT registered over the buildings has been used to estimate the atmospheric UHI at the UBL, while at the UCL it has been retrieved from mobile traverses inside the city. Both phenomena evolute quite similar and, when compared with the SUHI effect, we have concluded that at night the atmospheric and the surface effects match better than at midday.

Once we have processed all the AHS imagery and the SUHI has been analysed from the LST maps obtained, we studied the errors introduced in the LST and LSE products during all the processing procedure. Three different sources are proposed. First, the algorithm itself, which may not perform well for all the man-made materials found in a city. Second, the atmospheric correction performed with atmospheric soundings may not reproduce the urban atmosphere. And third, the 3D structure of the urban environment is taken into account. The influence of the roughness of the surface has been studied over the asphalt, which is the material commonly found at the bottom of the urban canyons. Therefore the three error sources over the asphalt material lead to a global error of 0.7% in LSE and of 0.5 K in LST. The error introduced by the TES algorithm is quite small and the highest influence is due to the atmospheric correction and by the urban structure itself. When the most representative urban materials are considered, only the first two error sources are considered and the overall error obtained is of 1.8% for the LSE and 1 K for the LST, the TES algorithm itself being the main source of error.

Finally, we obtained aggregated spatial resolution images from the 4 m AHS imagery. We introduced the SUHIM to evaluate the suitable spatial resolution to observe a city and we found that 50 m is the boundary resolution to differentiate the thermal performances between different areas of the city. The visit time that minimises the influence of the acquisition geometry and facilitates the relation between the heat island phenomenon at surface and at atmosphere levels is before sunrise. In addition, is at night when the thermal discomfort affects more the citizens, as it can perturb the cycle of sleep. Therefore, for an adequate observation of the UHI phenomenon, a sensor should have at least a spatial resolution of 50 m, and placed aboard a sun synchronous platform which acquires data before sunrise, with similar requirements as for NEΔT than existing sensors.