MONITORING AND FORECASTING OF URBAN HEAT ISLAND PHENOMENON IN TEN EUROPEAN CITIES THE UHI PROJECT

Paolo Manunta* [a], Monique Viel [a],Giulio Ceriola [a], Ioannis A. Daglis [b], Koen de Ridder [c], Theodoros Giannaros [d], Iphigenia Keramitsoglou [b], Bino Maiheu [c], Dimitrios Melas [d], Enrique Montero Herrero [e], Marino Palacios [e], Andrea Radius [f], Tania Sapage [f], Maria Tamame [e], Han Tambuyzer[g].

[a] Planetek italia Srl, Bari (Italy) (manunta@planetek.it) ;
[b] National Observatory of Athens - Institute for Space Applications and Remote Sensing – NOA-ISARS, Athens (Greece), [c] VITO, Flemish Institute for Technological Research, Mol (Belgium)
[d] Aristotle University of Thessaloniki – Laboratory of Atmospheric Physics, Thessaloniki (Greece)
[e] INDRA ESPACIO, S.A., Madrid (Spain)
[f] EDISOFT S.A , Lisbon (Portugal)
[g] EUROSENSE, Wemmel (Belgium)

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ABSTRACT:
Over the last decade, heat waves have claimed an increasing number of casualties among the elderly – particularly in southern Europe. Prolonged periods of high temperatures also put a strain on medical resources and place an additional financial cost to society as a whole. High densely built-up areas trap the heat, especially at night, causing what is called Urban Heat Islands (UHI) in which city centers can be up to 10° C warmer than surrounding rural areas. Another consequence of UHIs is that energy consumption rises with the increased use of air conditioners and refrigeration appliance. ESA has recently launched a set of activities to aid decision and policy makers in mitigating the effects of UHIs through appropriate alert systems and, in terms of reducing risk, through improved urban planning. Within this framework, ESA is funding **the Urban Heat Island Urban Thermography** (**UHI)** project under the DUE – Data User Element – program. The project started on 1st November 2008 and will last 2.5 years. The project is analyzing the UHI trends **over 10 European cities** (Athens, Bari, Brussels, Budapest, Lisbon, London, Madrid, Paris, Seville, Thessaloniki) over the last 10 years, using a multi-sensor approach. The UHI project is relying on all satellite missions that embark TIR sensors (SEVIRI, AVHRR, AATSR, MODIS, LANDSAT, ASTER) to analyze the spatial variability of the Urban Heat Islands in the metropolitan areas. Moreover, thermography mapping using airborne data have been or will be performed for Athens, Madrid and Brussels. The objectives of the project are: 1) Integration / assimilation of satellite remote sensing observations and ground weather stations data into meteorological and urban climate models, to facilitate mitigating the impact of Urban Heat Islands and to reduce the risk of a heat wave effects. 2) Study of the mission requirements for a high-resolution TIR (Thermal InfraRed) satellite Sensor. 3) Study of how TIR observations from space can support the implementation of urban energy efficiency policies embracing typical issues for Southern Europe (i.e., energy for air conditioning demand); as well as for Northern Europe (i.e. energy for domestic heating). A high challenging issue is the implementation of Air Temperature products at different scales through the use of urban modeling that would contribute to advanced research in that field.

1. INTRODUCTION

The climatic changes and the energy problems has been a growing interest for the technology of thermal remote sensing, that allows to monitor globally and continuously the important phenomena of urban surface energy budgets and urban heat island (UHI). The analysis of these phenomena is significant in **urban climatology, global environmental changes and human–environment interactions** that are very important for planning and management constructive techniques.
The urban climatology is a complex phenomenon, due to the presence of many processes that influence the thermal parameters; mainly, the man-made structures of the cities modify the evapotranspiration capacity of the terrain and the air fluxes, causing the changing of the absorption-reflectivity-emissivity processes of the solar radiation.
The thermal remote sensors can observe the Surface Urban Heat Island (SUHI), or, more specifically they 'see' the spatial patterns of upwelling thermal radiance received by the remote sensor (most often radiometric temperatures or brightness temperatures corrected only for atmospheric transmission). So, it is possible to use low- medium or high resolution multispectral sensors to examine the spatial structure of urban thermal patterns and their relation to urban surface characteristics.
The integration of the thermal remote sensing observations with ground-based measurement and of the knowledge of the urban surface morphology allows to characterize the directional effects inherent in directional radiometric temperature observations made over urban areas; moreover, the integration with urban atmosphere models improves the analysis of the study surface–air temperature relations.

1.1 Objectives

The main objectives and related goals of the UHI project, are:

1. Integration /assimilation of satellite remote sensing observations and ground weather stations data into urban meteorological and climate models, to facilitate mitigating the impact of UHI and to reduce the risk of a heat wave effects;

2. Study of the mission requirements for a high resolution TIR (Thermal Infra Red) satellite sensor;
3. Study of how TIR observations from space can support the implementation of urban energy efficiency policies embracing typical issues from Southern Europe, i.e. energy demand for air conditioning as well as from Northern Europe, i.e. energy demand for domestic heating.

The prediction and mitigation of UHI spatial and temporal variability in metropolitan areas is the ultimate goal, to which the project is designed to contribute through:

- fostering users participation and diffusion of advanced Earth Observation (EO) based technology;
- provision of scientific understanding of the factors influencing urban climate;
- establishment of operational EO-based services for monitoring and assessment;
- building the consensus needed for the definition of a dedicated Thermal Infra Red satellite mission.

The project will analyze the UHI trends over 10 European cities over the last 10 years, using a multi-sensor approach. It is planned to make the best use of all satellite missions that embark TIR sensors (SEVIRI, AVHRR, AATSR, MODIS, LANDSAT, ASTER) to analyse the spatial variability of the Urban Heat Islands in the metropolitan areas. Thermography mapping using airborne data will be performed for two cities.

This requires:

- to monitor land surface temperature and air (1.5 to 2m height) temperatures (respectively LST and AT) variability with different temporal and spatial resolutions. LST retrievals - derived from remote sensing observations – will be assimilated into urban climate models.
- to acquire and process long time series (10 years) of LST retrievals in order to study the historical trends of surface and air temperatures in the metropolitan and surrounding rural areas of the cities.
- to produce bio-climatic indicators (e.g. thermal stress indices).
- to identify in Near Real Time and forecast the location and magnitude of urban heat islands in particular during heat waves. That entails to integrate LST retrievals derived from remote sensing observations into Numerical Weather Prediction (NWP) models.
- to analyze and interpret the observed LST and air temperatures as a function of land use/land cover, surface albedo, surface emissivity, surface roughness.
- to produce thermographic maps at high and very high resolution to understand the energy efficiency of city surfaces and to monitor the impact of energy efficiency policies.

The project is funded by the European Space Agency (ESA) within the framework of the Data User Element (DUE) program. The project started in November 2008 and will last 2.5 years. Indeed, the results presented in this article are still preliminary.

1.2 The UHI users

Ten (10) cities from the Northern and Southern Europe are participating to cover different climatic conditions from continental climate to typical Mediterranean climate, namely Athens, Bari, Brussels, Budapest, Lisbon, London, Madrid, Paris, Seville, Thessaloniki.

Seventeen (17) public organizations are involved in the project as users with different institutional roles and tasks:

- Ecology and Environment institutes/ agencies: Athens, Brussels, Budapest, Paris and Seville
- Planning authority: London
- Civil Protection departments: Bari, Athens, Thessaloniki, and Lisbon
- Meteorological services and broadcasting channels: Athens and Thessaloniki.
- Urban engineering and GIS/cartography departments or agencies: Lisbon and Madrid
- Health : Lisbon

At the beginning of the project, meetings with the cities organisations involved into the project let to a further definition of the needs of each category of users *vis a vis* of the UHI products. In summary:

- **Civil Protection departments, Emergency departments, Health institutes and Meteorological services,** and broadcasting channels are particularly interested in forecast and NRT products as possible support to prevention and mitigation activities.
- **Ecology and Environment institutes/agencies** are interested with products to quantify energy efficiency, Air Temperature (AT) and Land Surface Temperature (LST) as well as risk maps of UHI.
- **Urban engineering and GIS/cartography departments or agencies** are concerned by LST and AT data and also Urban Thermography data**.**

2. METHODOLOGYAND APPROACH

In order to select the most appropriate algorithms and methodology for satellite/airborne image processing, an accurate analysis of advantage and disadvantage of the algorithms and climatology proposed in literature followed by a trade-off analysis have been achieved for each of UHI products, taking also into consideration criteria such as : 1) ancillary data needed in terms of quantity and characteristics 2) algorithms easy to translate into an operational implementation chain.

The UHI products, characterized by the satellite sensor used as well as the algorithms or models selected at the end of the trade off analysis, are summarised in the following table :

Products	Sensor/model/algorithms
LST (3-5 km)	Seviri (GSW Madeira, 2002)
AT (3-5 km)	LST (3-5km) + Surface energy balance + objective hysteresis model (test phase)
LST (1 km)	AVHRR, ASTRR, MODIS (SWT Jiménez-Muñoz and Sobrino 2008)
AT (1km)	LST (1km) + Surface energy balance + objective hysteresis model(test phase)
LST (around 100m)	• ASTER (TES Gillespie et al. 1998; Dash et al. 2002) • Landsat (Single channel Jiménez-Muñoz and Sobrino 2003 and Jiménez-Muñoz and Sobrino Nichol et al., 2009)
AT (around100 m)	LST (100m) Aerodynamic resistance model (to be tested)
LST (5-30 m)	Airborne sensor (AHS) (Hybrid method Peres et al., 2008; SWT Jiménez-Muñoz et al. (2006), Single Channel; Sobrino et al. (2008)
AT (5-30) m	LST (5-30m) + aerodynamic resistance model (to be tested)
NRT and forecast of AT (1km)	• HRES-SEB algorithm (NRT) (Homscheidt, 2008) • Model (WRF) (retrieval of AT at 2 m from satellite LST 1 km is in development)
NRT and forecast of Discomfort Index; TSI (Thermal Stress Index)	• formula introduced by Giles et al,1990. • Formula developed by Givoni (1969).
NRT of UHI maps <1km seasonal, monthly	UHI measurement with the Streukter (2003) methodology
Heat wave hazard and risk, monthly	Methodology still in development
NRT heat wave hazard and risk, daily	Methodology still in development
Thermographic mapping above 5m	Town Energy Balance model (TEB) Masson 2000
Thermographic mapping airborne	Based on the TES algorithm as per product LST at 100m.
Emissivity	• Seviri (LandSAF AL product) • Other sensors : use ASTER data and TES algorithm to extract emissivity for high resolution and low resolution data
Surface Albedo	• Seviri (LandSAF AL product) • Other sensors: application of the formulation of physics, starting from the Liang (2000) approach
Surface roughness	use of a LUT table which retrieves surface roughness from the CORINE Land Cover classes of Wieringa, J. (1993).

Table 1. UHI products

As mentioned in table 1, some of the algorithms and methodology are still in development and definition of the final methodology is expected at the beginning of next year (January 2010).

Validation of all the products is one of the central activity of the project and the validation protocol is currently in development.

Moreover, taking into account the complexity of the matter and the number of UHI products, the delivery to the users will be distributed among the 2.5 years of the project, as follows:

- 2010 (January): Athens, Lisbon, Madrid
- 2010 (June) : Brussels. Bari, Seville
- 2011 (London, Paris, Thessaloniki, Budapest).

3. PRELIMINARY RESULTS AND PRODUCTS

A first set of NRT and forecast products have been tested during 2009 summer (15 days duration) for Athens, Lisbon and Madrid The outcomes have been discussed further with the users of Athens and Lisbon.

3.1 The forecast products at 1km

The forecast products delivered are Air Temperature, Discomfort Index and UHI Intensity maps.

The core of the UHI-Forecasting System (UHI-FS) is the Weather Research and Forecasting (WRF) model, version 3.0.1. The model has been properly configured and compiled by the LAP-AUTH team in order to exploit its parallelism capabilities and enable its implementation on the computational infrastructure of HellasGrid (www.hellasgrid.gr). The implementation of the forecasting service is fully automatic and under normal conditions requires no user interaction at all.

WRF has been being “fed”, on a daily basis, with the 12-UTC cycle NCEP-GFS (U.S. National Centre for Environmental Prediction-Global Forecasting System) forecasts (~90-km spatial resolution). The ancillary data (i.e. topography, vegetation, soil and land use/cover) used for the 3 cities originated from the model’s default U.S.G.S. (U.S. Geological Survey) database

Prototype forecast products for the 3 cities of interest are presented in Figs. 1 – 3:

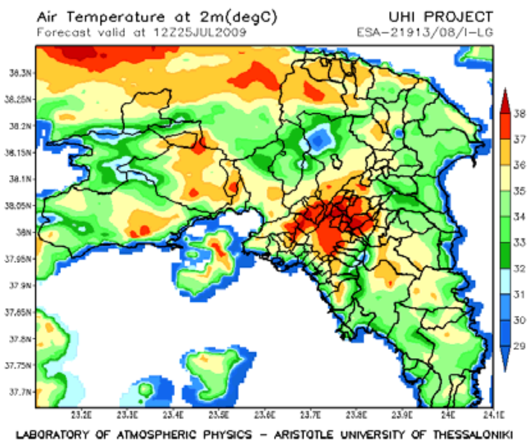

Figure 1. Air temperature at 2m
City of Athens (25 July 2009, 12-UTC)

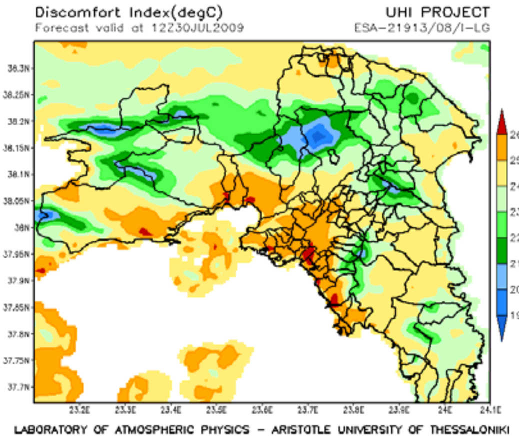

Figure 2. Discomfort Index
City of Athens (30 July 2009, 12-UTC)

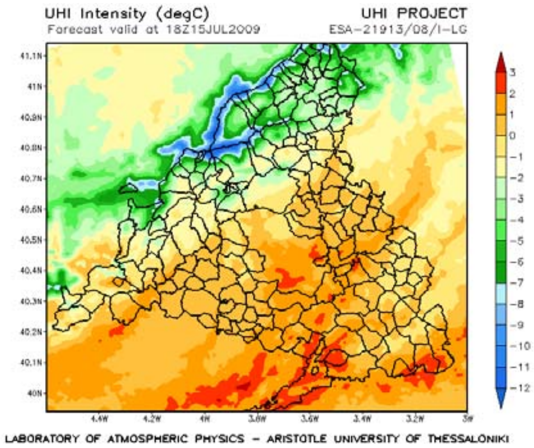

Figure 3. UHI intensity (Degree Celsius) Discomfort Index
City of Madrid (15 July 2009)

Lessons learned:

- Representation of urban structure not fully adequate: The inadequacy of the representation of urban structure was revealed, especially in the case of the city of Lisbon. The 1-km forecasts over the city were somehow problematic and quite "noisy". Therefore, in order to revise the representation of urban structure in the model, the existing source of land use data (USGS) will be substituted with updated and higher spatial resolution data (i.e. CORINE 2000).
- Model accuracy: the operational implementation of the UHI-FS during the DP revealed the capability of the model to successfully simulate the spatial characteristics, and the formation and evolution of the heat island effect over all the three (3) cities of interest. However, the comparison of the model's results with ground-based observations, wherever and whenever available, has proved that the model underestimates the magnitude of the maximum air temperature by a factor of 2-3 deg-C.

3.2 The NRT products at 1km

Figure 4 showed the NRT process chain from data acquisition to air temperature map production.

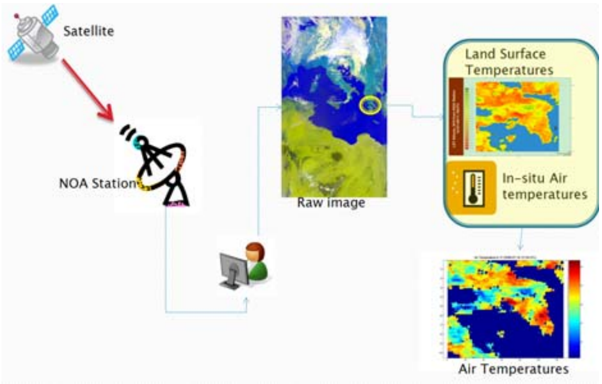

Figure 4. NRT process chain for the city of Athens

In the following schema is shown the different steps to process NRT Air Temperature starting from the selected methodology developed by the DLR and the Slovenian governmental agency in an associate study and proposed in the EUMETSAT Meteorological Satellite Conference (2008).

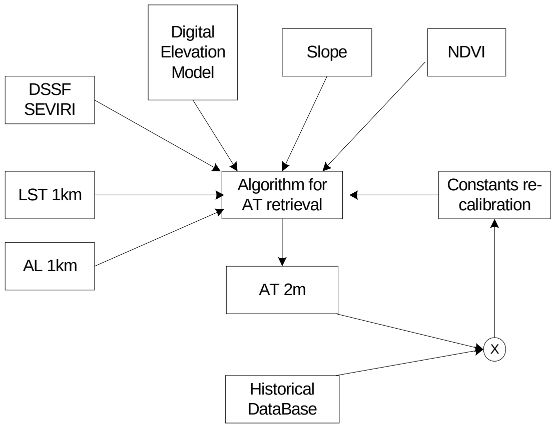

Figure 5. Scheme for AT retrieval

In the following are presented some NRT products of Air Temperature and Discomfort Index obtained for the 3 cities.

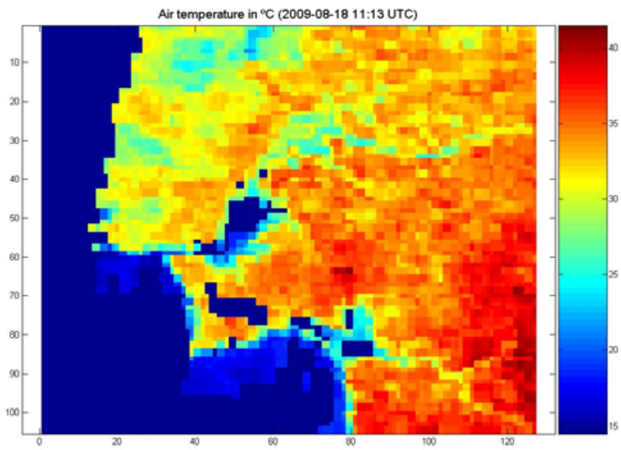

Figure 6. NRT distribution of AT (°C).
City of Lisbon (18 August 2009).

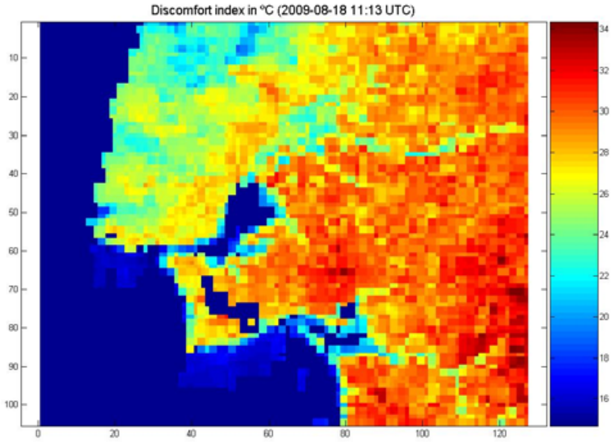

Figure 7. NRT distribution of Discomfort Index City of Lisbon (18 August 2009)

Lessons learned:

- It emerged the necessity of establishing a stable and reliable source of NRT EO data (from AATST, AVHRR and Modis archive)
- NRT products generation:
  - The registration process between the SEVIRI images and the LST maps has to be refined to remove the geo-references mismatches issue.
  - The use of data with lower resolution (from SEVIRI) introduces some error in the AT, especially in pixels in the boundary between land and ocean. Indeed, the sea pixels influence the AT estimation in the boundary land/sea. That must be taken in consideration for the calibration phase. 1 km resolution data will be used to minimize this type of imprecision.
  - Additional in situ air temperature data should be found for Madrid (2 or 4 ground stations are rather insufficient)
  - Use of AVHRR data from the NOAA-19 satellite affected the quality of the products generated for Athens. Those data – until proper calibration of the LST procedure – should not be used.

3.3 Feedbacks from the users

The NRT and forecast products were delivered to the users for their verification and comments. The feedbacks from Athens and Lisbon could be summarised as follows:

- Final products (maps) were considered appropriate in terms of text on the plot, axes titles, colour scale and clarity of the information.
- All maps should be available in the projection system specified by the municipality and GIS format (e.g GeoTIFF)
- Need to include cartographic information such as municipality boundaries and names, as well as the location of the used ground meteorological stations.
- Use a single colour scale for all products and all days either for forecast and NRT products.
- The 1 km spatial resolution is considered almost adequate, although 200-500 m would be definitely more useful for investigating variability within large municipalities.
- Need of knowing of level of confidence of each product (validation)

All the users have considered the NRT and forecast products potentially useful for::

- Integration into existing forecasting procedure (Meteorological service)
- Planning and activation of particular measures during HW events (civil protection)
- Presentation on their web site (civil protection)
- Integration into existing fire risk models (e.g. Municipality of Amaroussion, Greece)
- Notification of vulnerable citizens and activation of civil protection measures within their municipality (e.g. M. Amaroussion, Greece)

4. CONCLUSIONS

The main achievements of the UHI project after one year of activity are the following:

- Further analysis with the users of their needs in relation with their role and activities (civil protection, health, environmental protection, meteorological services) that confirm the interest and commitment of all users.
- Trade-off analysis to identify the best algorithms and models to be used to the purpose of the project
- Design of the procedures to be implemented for production of all UHI products.
- Test of the NRT and forecast procedures. The trial provided satisfactory results (test of the WRF model and forecast procedures; of the 1km-LST algorithm and relevant NRT procedures). Operational issues (data acquisition, data geo-referencing) were partially solved. Feedbacks from the users of two cities were positive and useful to identify improvement to be made as for products editing and validation.

Currently, the project is focused on the production of long time series (10 years May-September) of LST retrievals over Athens, Lisbon and Madrid from 3-5km spatial resolution to 100m spatial resolution and the preparation of the validation protocol that would be applied to validate all products before delivering to the users.

Moreover, the test of the urban modeling at low resolution to produce long time serie of Air Temperature (3-5 km and 1 km) is going on and it is expected to be ready for data production next January 2010.

5. REFERENCES

Dash, P, Gottsche, F.-M. Olesen, F.-S. and H. Fischer, 2002. Land surface temperature and emissivity estimation from passive sensor data: theory and practice–current trends. *Int. J. Remote Sens.*, 23, 2563 - 2594.

Gillespie, A., Rokugawa, S., Matsunaga, T., Cothern, J. S., Hook, S. and Kahle, A. B., 1998. A temperature and emissivity separation algorithm for advanced spaceborne thermal emission and reflection radiometer (ASTER) images. *IEEE Transactions on Geoscience and Remote Sensing*, 36, 1113–1126.

Givoni, B., 1969. Man, climate and architecture, New York, John Wiley & Sons.

Homscheidt M.S.,. Zaksek K, 2008 . Air temperature in high temporal and spatial resolution from a combination of the SEVIRI and MODIS instruments. EUMETSAT Meteorological Satellite Conference, 8-12 Sept. 2008

Jiménez-Muñoz, J. C. and Sobrino, J. A., 2008. Split-Window Coefficients for Land Surface Temperature Retrieval From Low-Resolution Thermal Infrared Sensors. *IEE Goscience and Remote Sensing Letters*, 5, No. 4, 806 – 809.

Jimenez-Munoz, J.C. Cristobal, J. Sobrino, J.A. Soria, G. Ninyerola, M. Pons, X. , 2009. Revision of the Single-Channel Algorithm for Land Surface Temperature Retrieval From Landsat Thermal-Infrared Data *IEEE Transactions on Geoscience and Remote Sensing*, vol. 47, issue 1, pp. 339-34.

Liang, S., 2000. Narrowband to broadband conversions of land surface albedo I Algorithms, *Remote Sens. Environ.*, 76, 213–238.

Madeira, C., 2002, Generalised Split-Window Algorithm for Retrieving Land-Surface Temperature from MSG/SEVIRI Data, *SAF on Land Surface Analysis Training Workshop*, Lisbon, Portugal, July 8-10.

Masson, V., 2000: A physically-based scheme for the urban energy budget in atmospheric models. Bound.-Layer Meteor., 94, 357-397.

Peres, L. F., Sobrino, J. A., Libonati, R., Jiménez-Muñoz, J. C., Dacamara, C. C. and Romaguera, M.(2008), Validation of a temperature emissivity separation hybrid method from airborne hyperspectral scanner data and ground measurements in the SEN2FLEX field campaign, *International Journal of Remote Sensing*, 29:24,7251- 7268.

Sobrino, J. A., Jiménez-Muñoz, J. C., Sòria, G., Romaguera, M., Guanter, L., Moreno, J., Plaza, A. and Martínez, P., 2008. Land Surface Emissivity Retrieval From Different VNIR and TIR Sensors. *IEEE Transactions on Geoscience and Remote Sensing*, 46, 316 - 327.

Streutker, D. R. (2003) Satellite-measured growth of the urban heat island of Houston, Texas. *Remote Sensing of Environment*, 85, pp. 282-289

Wieringa, J., 1993: Representative roughness parameters for homogenous terrain. *Boundary-Layer Meteorology*, 63, 323-363

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