3D MODELING OF RADIATIVE TRANSFER AND ENERGY BALANCE IN URBAN CANOPIES COMBINED TO REMOTE SENSING ACQUISITIONS

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ABSTRACT

In this paper we present a study on the use of remote sensing data combined to the 3D modeling of radiative transfer (RT) and energy balance in urban canopies in the aim to improve our knowledge on anthropogenic heat fluxes in several European cities (London, Basel, Heraklion, and Toulouse). The approach is based on the forcing by the use of LandSAT8 data of a coupled radiative transfer model DART (Direct Anisotropic Radiative Transfer) (www.cesbio.ups-tlse.fr/dart) with an energy balance module. LandSAT8 visible remote sensing data is used to better parametrize the albedo of the urban canopy and thermal remote sensing data is used to enhance the anthropogenic component in the coupled model. This work is conducted in the frame of the H2020 project URBANFLUXES, which aim is to improve the efficiency of remote-sensing data usage for the determination of the anthropogenic heat fluxes in urban canopies [5].

Index Terms— 3D radiative budget, energy budget, Urban canopies, Albedo, Anthropogenic fluxes

1. INTRODUCTION

The computation of the energy budget component over urban canopies requires the availability of a radiative budget, a convective heat, a sensible heat and an anthropogenic fluxes module. This is generally assessed using bulk or contextual energy budget models like TEB [4]. But due to the complexity of the urban canopy's geometry and surface properties, a 3D radiative budget can provide more accurate and spatialized results if well configured. This approach requires extensive sources of data for geometry and surface characteristics. This is currently facilitated by the availability of 3D urban databases. Associated to remote sensing a better configured urban model can be made available for RT. Major inputs for the radiative transfer are the surface characteristics (albedo, spectral response) of the materials and their physical status (temperature, humidity). We use the DART model in combination with LandSAT8 visible data to iteratively retrieve the optical properties of the surface materials. This enables an improvement of the accuracy of the 3D RT modeling.

We also couple the DART model to an urban canyon energy budget model. The ensemble is called DARTEB. The two way coupling is done via the surface temperature. An overview of the approach in terms of inputs, outputs and coupled information is presented in Figure 1. A brief presentation of the two coupled models is also given.

2. METHODS

2.1. The DART model

We chose for this study the use of the DART (Discrete Anisotropic Radiative Transfer) model. DART is a comprehensive physically based 3D model to simulate the Earth-atmosphere radiation interaction from visible to thermal infrared wavelengths. It simulates optical signals at the entrance of imaging radiometers and LiDAR scanners on board of satellites and airplanes, as well as the 3D radiative budget, of urban and natural landscapes for any experimental configuration (atmosphere, topography,…) and instrumental specification (sensor altitude, spatial resolution, UV to thermal infrared,…). It uses innovative modeling approaches: multi-spectral discrete ordinate techniques with exact kernel, RayCarlo method, etc. Paul Sabatier University distributes free licenses to scientists. [1]

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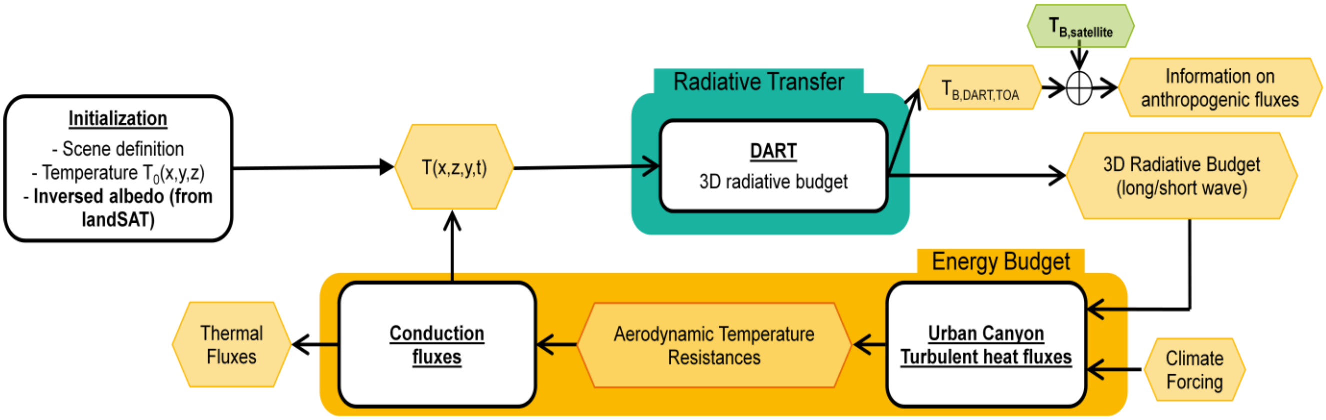

Figure 1: Summary of the operational loop in the coupling between DART and DARTEB

2.2. Urban canopy albedo

A major objective of the H2020 project is to drive parameters of urban canopies with satellite data. It is typically the case for the albedo. We present here a method using DART to drive the albedo of urban canopies [2]. DART computes the albedo $A_{DART,\Delta\lambda}$, for any hour and date, possibly with actual atmosphere data (e.g. ECMWF or Aeronet network). It is determined with the following formula:

$$A_{DART,\Delta\lambda}\left(x_{DART},y_{DART},\Omega_S,E_{S,BOA}(\Omega_S),L_{atm}(\Omega),t_{sat}\right) = \frac{\rho_{dh}E_{S,BOA}+\int\rho_{dh}(\Omega)L_{atm}(\Omega)\cos(\theta)d\Omega}{E_{S,BOA}+\int L_{atm}(\Omega)\cos(\theta)d\Omega} \quad (1)$$

with: - $A_{DART,\Delta\lambda}$: albedo computed by DART, for spectral interval $\Delta\lambda$.

- x_{DART},y_{DART}: coordinates of the point considered in the DART simulated scene
- Ω_S: solar direction
- $E_{S,BOA}$: solar irradiance at the bottom of the atmosphere
- $L_{atm}(\Omega)$: atmosphere radiance
- t_{sat}: time at satellite acquisition
- ρ_{dh}: direct-hemispheric reflectance computed by DART

DART albedo, radiance and reflectance products (ρ_{dd}, ρ_{dh}, ρ_{hd}, ρ_{hh}) are computed with optical properties as realistic as possible. For example, optical properties derived from APEX spectroradiometer data will be used for the Basel case study of the URBANFLUXES project. Obviously, optical properties cannot be exact. Hence, DART products will be calibrated with atmospherically corrected satellite data (*e.g.*, Sentinel 2), after being resampled to the satellite spatial resolution (x_{sat},y_{sat}). For example, for albedo, we get:

$$A_{\Delta\lambda}\left(x_{sat},y_{sat},\Omega_S,E_{S,BOA},L_{atm},t_{sat}\right) = K_{\Delta\lambda}(x_{sat},y_{sat},t_{sat}).A_{DART,\Delta\lambda}\left(x_{sat},y_{sat},\Omega_S,E_{S,BOA},L_{atm},t_{sat}\right) \quad (2)$$

With

$$K_{\Delta\lambda}(x_{sat},y_{sat},t_{sat}) = \frac{\rho_{dd,sat,\Delta\lambda}(x_{sat},y_{sat},\Omega_S,\Omega_V)}{\rho_{dd,DART,\Delta\lambda}(x_{sat},y_{sat},\Omega_S,\Omega_V,t_{sat})} \quad (3)$$

This approach allows the calibration of the DART products such as the urban canopy albedo for each pixel of the used satellite image. However, this method does not take into account the diversity of urban elements that can contribute to each pixel. This can infer on the angular distribution of the full radiative budget simulated by DART, and motivated the development of a more complex method, which allows a more accurate inversion of the urban optical properties. This method is quickly introduced below.

2.3. Iterative retrieval of urban optical properties

The method introduced here is an iterative calibration method that computes the actual optical properties for each type of elements in the scene per pixel or group of pixels of the satellite image. It provides the desired spatial variability in optical properties of urban elements contributing to the scene. We consider N different types of urban elements and subdivide the satellite image used for calibration in groups of MxM pixels, where each group contains more pixel than there are types of elements. Then, we compare the desired satellite radiance value and the combined contributions simulated by DART of all the elements over the groups of pixels. This leads to the solving of an equation system for the updated optical properties of the elements:

$$\sum_{n=1}^{N}\frac{\rho_{n,u}^{k+1}(x_{sat},y_{sat})}{\rho_{n,u}^{k}(x_{sat},y_{sat})}.L_{DART,\Delta\lambda,n,m}(x_{sat},y_{sat}) = L_{sat,\Delta\lambda,m}(x_{sat},y_{sat}), \forall m \in [1\ M^2] \quad (4)$$

With: - $L_{DART,\Delta\lambda,n,m}$: radiance of element n computed by DART for satellite pixel m

- $L_{sat,\Delta\lambda,m}$: satellite radiance for pixel m
- $\rho_{n,u}^{k}$: optical property of element n used in DART at iteration k, for group of pixels u
- $\rho_{n,u}^{k+1}$: optical property of element n to be used in DART at iteration k+1, for group of pixels u

We solve (4) for all the pixels groups over the satellite image and obtain the new values $\rho_{n,u}^{k+1}$ for each urban element. We apply this method for each considered spectral interval $\Delta\lambda$ and then interpolate the results to get the full spectral radiative properties of the elements. This process will be repeated iteratively in order to converge towards optical properties as realistic as needed and towards a 3D radiative budget computation with increased accuracy. The products generated by DART serve then as inputs for the DARTEB model, to produce the energy budget.

2.4. 3D COUPLED RT AND EB – DARTEB

DARTEB is a coupling between DART 3D radiative transfer model and 1D energy balance model, with coupling done through the exchange of 3D surface temperature, as can be seen in Figure 1. It simulates major energy mechanisms (heat conduction, turbulent momentum and heat fluxes, soil moisture, etc.) that contribute to the energy budget. For urban canopies, it adapts equations from the TEB urban surface scheme [4] to compute the urban fluxes, and uses the canyon and aerodynamic temperature resistances approach as in Figure 2. Each surface type (wall, soil, and roof) is discretized into layers for simulating conduction fluxes to/from the ground and building interiors.

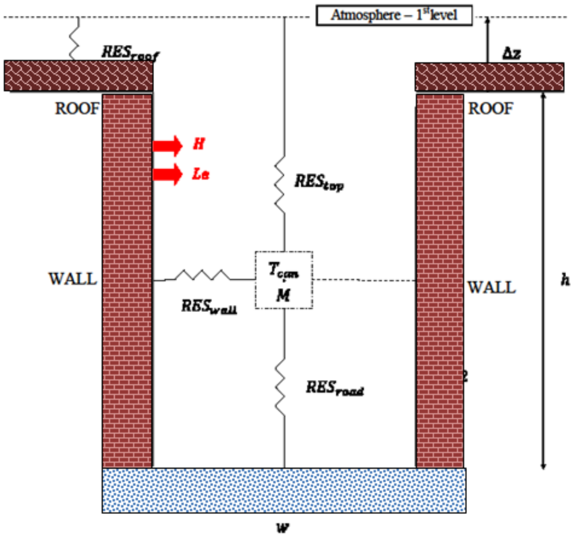

Figure 2: Representation of a urban canyon in DARTEB, used to compute the urban fluxes

The 3D radiative budget and 3D temperature are assessed with a prognostic approach. A two way coupling is done at given time steps through surface temperature. Temperature values at time t lead to the 3D TIR (Thermal Infra Red) and energy budgets at time t+1, which allows one to compute the 3D temperature distribution at time t+1, using the 3D visible and NIR radiation budget at time t+1.

Although, it uses an actual 3D radiative budget and it applies TEB equations at each point of the 3D scene, DARTEB is not a full 3D model (e.g., 1D wind profile is used instead of 3D wind distribution).

3. MATERIALS

In the frame of this study, remote sensing data is an important component of the approach. The satellite data used comes from LandSAT-8 images, as well as Sentinel-2 images upon availability and usability over the different study sites which are Basel, Heraklion, London and Toulouse. The images are atmospherically corrected with information given on the atmosphere status to ensure a proper modeling of the scenes.

Urban databases are used as well. 3D models of the cities, digital elevation models, trees characteristics serve as input for the different models in use. Those databases are made available by the different collaborators of the project for the different studied cities (ALTERRA, DLR, FORTH, GEOK, UNIBAS, UoG, UoR). The database for Toulouse was made available by the Toulouse's city hall.

We also use field datasets such as those from the CAPITOUL project and in-situ data in the different applications of this work. This data contains information on in-situ temperatures, material optical and thermal properties that are used in the different models and the validation of the approaches. This data for cities other than Toulouse is also furnished by the collaborators of the URBANFLUXES project.

4. RESULTS

The method described to derive the albedo from multi-spectral satellite data was successfully conducted on the city of Basel, one of the study sites for the URBANFLUXES project. The data used is from a LandSAT-8 image of the city taken on April 4th, 2015. The DART simulation was made using a full 3D model of the city of Basel, including trees and water, and the atmospheric information available, for all LandSAT-8 bands. Figure 3 shows a computed albedo image derived from LandSAT-8 data using this method, for the near infra-red band.

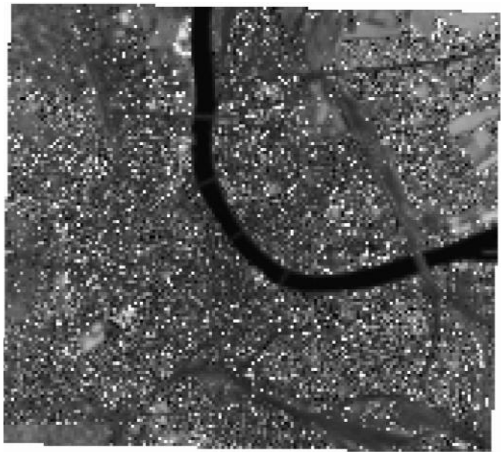

Figure 3: Albedo image derived from a LandSAT-8 image for a NIR band (864.6nm), 30m resolution

DARTEB was successfully tested in the frame of the CAPITOUL project (www.cnrm.meteo.fr/IMG/pdf/masson-capitoul.pdf) [3] of Meteo France for simulating the time evolution of the temperature of walls in a street of Toulouse (France). Figures 4 show the test site for validation (Alsace-Lorraine street, Toulouse) and some results.

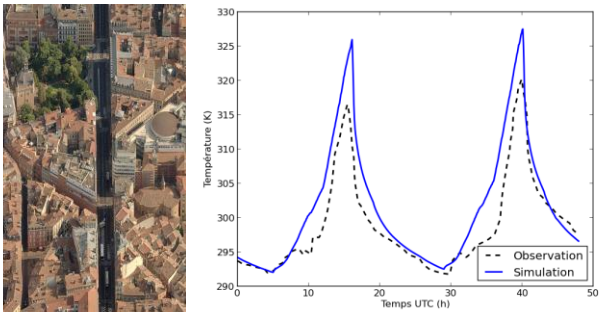

Figure 4: Photography of the *evaluation* site, Alsace-Lorraine Street, Toulouse (left). On the right is the time profile of the temperature of the west wall. Displayed are the simulated temperature (continuous line) and the measured temperature profile (dotted line)

The model was also applied to the Heraklion, Greece, site which is part of the H2020 project study sites (Figure 5).

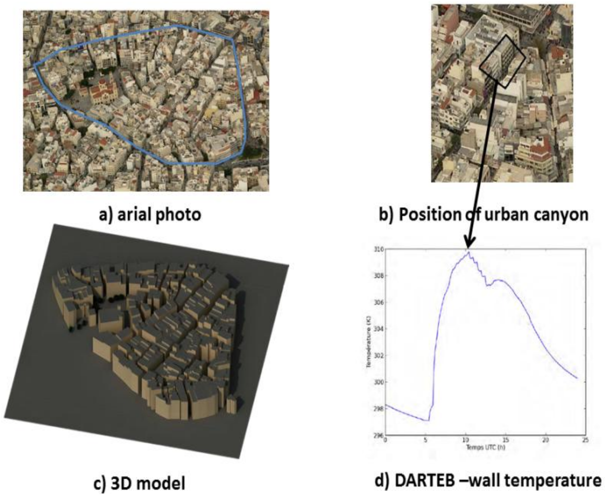

Figure 5: Application of the DARTEB model to Heraklion, Greece.

5. CONCLUSIONS

We presented here a novel approach to combine visible and infrared remote sensing data to improve energy budget estimates over urban canopies. The approach is applied over Heraklion, Basel and London (not shown here). The approach has been validated using the CAPITOUL project.

Future work will focus on the use of thermal components to improve the estimate of anthropogenic fluxes anomaly between remotely sensed thermal signature and modeled thermal signature.

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REFERENCES

[1] J.P. Gastellu-Etchegorry, T. Yin, N. Lauret et al., "Discrete Anisotropic Radiative Transfer (DART 5) for Modeling Airborne and Satellite Spectroradiometer and LIDAR Acquisitions of Natural and Urban Landscapes", *Remote Sensing*, 7:2, 1667-1701, 2015.

[2] L. Landier, A. Al Bitar et al., "Modeling parameters and remote sensing acquisition of urban canopies", *ICUC9*, Toulouse, France, (July 20-24 2015), 2015.

[3] V. Masson et al., "The canopy and aerosol particles interactions in Toulouse urban layer (CAPITOUL) experiment",*Meteorol. Atmosph. Phys.*, 94: 357-397,2007.

[4] V. Masson, "A physically-based scheme for the urban energy budget in atmospheric models", *Boundary-Layer Meteorology*, 94: 357-397, 2000.

[5] Z. Mitraka, J.P. Gastellu-Etchegorry, N. Chrysoulakis, C. Cartalis, "Third International Conference on Countermeasures to Urban Heat Island", Venice, Italy, (October 13-15 2015), 2014.