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Uncertainty assessment of surface net radiation derived from Landsat images

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ABSTRACT

The net radiation flux available at the Earth's surface drives evapotranspiration, photosynthesis and other physical and biological processes. The only cost-effective way to capture its spatial and temporal variability at regional and global scales is remote sensing. However, the accuracy of net radiation derived from remote sensing data has been evaluated up to now over a limited number of *in situ* measurements and ecosystems. This study aims at evaluating estimates and uncertainties on net radiation derived from Landsat-7 images depending on reliability of the input surface variables albedo, emissivity and surface temperature. The later includes the reliability of remote sensing information (spectral reflectances and top of canopy brightness temperature) and shortwave and longwave incoming radiations.

Primary information describing the surface is derived from remote sensing observations. Surface albedo is estimated from spectral reflectances using a narrow-to-broadband conversion method. Land surface temperature is retrieved from top of canopy brightness temperature by accounting for land surface emissivity and reflection of atmospheric radiation; and emissivity is estimated using a relationship with a vegetation index and a spectral database of soil and plant canopy properties in the study area. The net radiation uncertainty is assessed using comparison with ground measurements over the Crau–Camargue and lower Rhone valley regions in France. We found Root Mean Square Errors between retrievals and field measurements of 0.25–0.33 (14–19%) for albedo, ~1.7 K for surface temperature and ~20 $W \cdot m^{-2}$ (5%) for net radiation. Results show a substantial underestimation of Landsat-7 albedo (up to 0.024), particularly for estimates retrieved using the middle infrared, which could be due to different sources: the calibration of field sensors, the correction of radiometric signals from Landsat-7 or the differences in spectral bands with the sensors for which the models where originally derived, or the atmospheric corrections. We report a global uncertainty in net radiation of 40–100 $W \cdot m^{-2}$ equally distributed over the shortwave and longwave radiation, which varies spatially and temporally depending on the land use and the time of year. *In situ* measurements of incoming shortwave and longwave radiation contribute the most to uncertainty in net radiation (10–40 $W \cdot m^{-2}$ and 20–30 $W \cdot m^{-2}$, respectively), followed by uncertainties in albedo (<25 $W \cdot m^{-2}$) and surface temperature (~8 $W \cdot m^{-2}$). For the latter, the main factors were the uncertainties in top of canopy reflectances (<10 $W \cdot m^{-2}$) and brightness temperature (5–7 $W \cdot m^{-2}$). The generalization of these results to other sensors and study regions could be considered, except for the emissivity if prior knowledge on its characterization is not available.

1. Introduction

Accurate characterization of the land surface energy balance is fundamental in climate studies for understanding the partitioning of energy and water at the Earth surface. It is also required at finer scales for evapotranspiration monitoring in irrigation management and water resources planning. Net radiation is the main driver of surface energy

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balance and evapotranspiration. It expresses the balance of radiative energy at the Earth surface and thus the available energy for exchanges of sensible and latent heat fluxes between the surface and the atmosphere. Net radiation (Rn) depends on several land surface parameters and variables, including surface albedo (α), surface emissivity (ε) and surface temperature (Ts) which are changing in space and time under the influences of the type of land use, water availability and incoming radiation. At the instantaneous scale, net radiation can be expressed as:

$$Rn = (1-\alpha)R_{SW}{}^{\downarrow} + \varepsilon\left(R_{LW}{}^{\downarrow} - \sigma\,\mathrm{Ts}^4\right) \quad (1)$$

where σ is the Stefan-Boltzmann constant, $R_{SW}{}^{\downarrow}$ the solar irradiance (or incoming shortwave irradiance), and $R_{LW}{}^{\downarrow}$ the atmospheric irradiance (or incoming longwave irradiance).

Remote sensing is the only methodology which makes it possible to assess the spatial distribution of land surface variables at regional scale in a cost-effective way. The main sensors which were available in the last decades for assessing energy balance at a relatively fine spatial resolution (~100 m) and on an operational basis were Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) on board of the Landsat satellites 5 and 7. As these sensors were in flight for long periods of time (Landsat 5 for almost 29 years and Landsat 7 for 14 years), they may be used to assess the impact of evolution in land use and climate on net radiation and surface energy balance. The scientific community has recognized the potential interest of the follow-up of Landsat missions (see Anderson, Allen, Morse, and Kustas, 2012). The development of new satellite systems with improved performances, in particular in the thermal infrared bands, either in terms of radiometric resolution and accuracy, spatial resolution and revisiting time are also undergoing, for instance HyspIRI (Abrams & Hook, 2013), MISTIGRI (Lagouarde et al., 2013) or THIRSTY (Crebassol, Lagouarde, & Hook, 2014). In parallel, there is an increased interest in the development of standardized remote sensing products that facilitate the use of remote sensing data for the various user communities. This is already well developed for low resolution sensors with products such as surface temperature, surface spectral reflectances, albedo, or Leaf Area Index (*e.g.*, for Moderate-Resolution Imaging Spectroradiometer (MODIS), SPOT-VEGETATION or PROBA-V sensors). The use of these products has made it possible strong progresses in global water and carbon cycle studies and monitoring the impact of recent climate evolutions over land (*e.g.*, Ciais et al. (2005); Tang et al. (2014); Xia et al. (2014)). The development of similar products for Earth Observation satellites at higher resolution is in project with the supply of new services for distributing ready-to-use information to the user community. Evidence of this is a data center dedicated to land surfaces named THEIA which has started to operate in 2014 in France (Hagolle, Huc, Villa Pascual, & Dedieu, 2015; WWW1). It is a French national inter-agency organization designed to foster the use of images coming from the space observation of land surfaces. Within the Land Data Centre, the French Space Agency CNES set up a production center named MUSCATE (WWW2) which aims to provide operational products derived from time series of images acquired by Landsat, SPOT and Formosat-2 and later by the future satellites Sentinel-2 and Venμs (L'Helguen et al. (2014); Leroy et al. (2014); Hagolle et al. (2015)). Concerning Landsat, the data presently available consist in Top Of Canopy (TOC) spectral reflectances, together with a cloud mask, and Top Of Atmosphere (TOA) brightness temperatures. Work is undergoing for the production of TOC brightness temperature and surface temperature (Rivalland, Boulet, Mira, Brut, & Olioso, 2014).

The main advantages of using land surface products result from *1*) the availability of information that can be used in applications without requiring a strong expertise in the preprocessing of remote sensing images (*e.g.*, georeferencing, atmospheric corrections and retrieval of biophysical variables), *2*) the standardization of data processing and data quality management, *3*) the improvement in data documentation and metadata, and *4*) the community use of the data which enhances feedback on their quality and use. It is important that the definition of land surface products takes into account the user needs in order to provide higher level of requirement definition and feedbacks.

The accuracy of surface net radiation information derived from remote sensing data has been evaluated, in particular in the frame of evapotranspiration estimation and mapping. Root Mean Square Errors (*RMSE*) between remote sensing retrievals and field data were found typically in a 20 to 80 $\mathrm{W \cdot m^{-2}}$ range (*e.g.*, Jacob, Olioso, Gu, Su, and Seguin (2002a); Merlin et al. (2014); Tang et al. (2011); Wang, Liang, and He (2014)). However, these analyses compared remote estimates to a limited number of *in situ* measurements over specific ecosystems. Few studies have dealt with the impact of uncertainties in the derivation of the surface variables required to map surface net radiation products and associated uncertainties (*e.g.*, Bhattacharya, Mallick, Patel, and Parihar (2010); Cheng, Liang, Yao, and Zhang (2013); Mattar et al. (2014); Tang et al. (2011)). The performance of the algorithms used to estimate variables in order to derive net radiation, such as albedo, surface temperature and emissivity needs to be evaluated.

The objective of this study is to assess the uncertainties in surface net radiation estimates due to uncertainties in the derivation of surface albedo, surface emissivity and surface temperature from pre-operational remote sensing products, as well as uncertainties in atmospheric information and incoming radiations. We focused on the derivation of albedo, emissivity and surface temperature from Landsat-7 products provided by the THEIA Land Data Centre. The analysis was performed over the lower Rhône Valley region, South Eastern France, where a dense network of ground stations measuring surface energy balance components and meteorological variables was set up on various surfaces for several years. The methodology and data are presented in Section 2. Results are presented in Section 3 and discussed in Section 4, respectively.

2. Materials and methods

2.1. Background and definitions

Surface albedo is a dimensionless characteristic of the soil–plant canopy system which represents the fraction of solar energy reflected by the surface. It is expressed as the ratio of the radiant energy scattered upward by a surface in all directions, compared to that received from all directions, integrated over the wavelengths of the solar spectrum (Pinty & Verstraete, 1992). Sellers et al. (1995) suggested that an absolute accuracy of 0.02 is required for climate modeling. The latter corresponds to a typical accuracy on monthly averaged reflected solar irradiance at the satellite overpass of 10 $\mathrm{W \cdot m^{-2}}$. It is expected that the estimation of albedo from multispectral remote sensing can reach these requirements. When considering instantaneous flux, a simple calculation shows that an absolute accuracy of 0.02 (roughly equivalent to 10% error in albedo for agricultural landscape) corresponds to a relative accuracy on net radiation of around 5%. As shown in Jacob et al. (2002a) in the context of mapping evapotranspiration, this accuracy may result in an absolute error of 20 $\mathrm{W \cdot m^{-2}}$ in net radiation (*RMSE* established over 16 days with remote sensing acquisition over 6 months and 3 to 5 ground measurements of net radiation).

The most classical approach to derive albedo from multispectral remote sensing is the Narrow-To-Broadband (NTB) conversion method (*e.g.*, Brest and Goward (1987); Ranson, Irons, and Daughtry (1991); Weiss et al. (1999); Liang (2000); Jacob, Olioso, Weiss, Baret, and Hautecoeur (2002b); Jacob, Weiss, Olioso, and French (2002c)). This method considers that it is possible to integrate the surface reflectance obtained in the spectral bands provided by visible – near infrared – middle infrared sensors through a linear combination to represent the whole solar domain.