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Applying multiple land surface temperature products to derive heat fluxes over a grassland site

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ABSTRACT

Land heat fluxes are essential components of the water and energy cycle and important variables in the management of agronomy and forestry resources. The estimation of the heat fluxes can be done with a number of methodologies, with some of them having the land surface temperature (*Ts*) as one of their key inputs to derive the fluxes. Here the production of *Ts*-driven surface heat fluxes over a grassland site in Switzerland is demonstrated by running a specific heat flux methodology (SEBS) fed by a number of satellite *Ts* estimates (from the instruments AATSR, MODIS, SEVIRI, AMSR-E, and SSMIS). The *Ts* estimates are compared with an *in situ* estimate derived from radiometric observations at the station, and the satellite latent heat flux (*LE*) estimates with the station Eddy Covariance (EC) measurements. The satellite *Ts* products include estimates at different spatial resolutions (from ~1 to ~25 km) and time samplings (from 2 overpasses per day to 1/2 hourly observations). Root Mean Square Differences (RMSDs) between the daytime satellite and station *Ts* are 2.72 (AATSR), 4.41 (MODIS), 3.59 (SEVIRI), 3.81 (AMSR-E), and 2.79 (SSMIS), but given the different time samplings and spatial resolutions its is difficult to be conclusive about the accuracy of the *Ts* estimates. Concerning the flux estimates, for those sensors with midday overpasses, a RMSD of ~25% are found when comparing the instantaneous latent flux (*LE*, or evaporation expressed as an amount of water) at satellite overpass with the EC observations, which compares well with the accuracy reported elsewhere for similar landscapes. Given that both *Ts* and *LE* are evaluated at the station, a link between *Ts* and *LE* accuracy is investigated, but its is not apparent for this specific comparison. This could be related to SEBS accuracy also depending on other variables, apart from *Ts*, but also to the representativeness of the metrics used for the evaluation given the spatial miss-matches existing between the satellite estimates and station observations. Discrepancies were observed between the EC fluxes, the measured surface available energy, and the evaporation estimates from a lysimeter also present at the station, illustrating also the difficulties of the ground observations to provide accurate heat fluxes for satellite evaluation.

1. Introduction

Land heat fluxes govern the interactions between the Earth surface and the atmosphere (e.g., Betts, 2009), are essential components of the water and energy cycles (e.g., Sorooshian et al., 2005), and play a key role in the climate system (e.g., Wang and Dickinson, 2012). The latent heat flux is also an important variable in the management of agronomy, forestry, and hydrological resources and evaporation estimates (the heat flux expressed as an amount of water) at different spatial scales, from individual plants for managing irrigation to basin scales to evaluate water resources, are required in many applications (e.g. Dunn and Mackay, 1995; Le Maitre and Versfeld, 1997; Gowda et al., 2008).

In situ measurements of land heat fluxes are operated during field experiments (e.g. Pauwels et al., 2008) and by some flux tower networks (e.g Baldocchi et al., 2001). Being point measurements and requiring special equipment, they cannot be applied for routine measurements covering large areas. Therefore, more readily available observations are combined with well known flux formulations (e.g., Monteith, 1965; Priestley and Taylor, 1972) to obtain local estimates. For instance, the Food and Agriculture Organization (FAO) recommends the Penman-Monteith method to estimate crops evaporation,

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which requires a number of surface meteorological inputs and relevant crop coefficients (Allen et al., 1998). Satellite remote sensing could be used for routine estimates at different time and spatial scales, but the challenge here is that fluxes do not have a direct signature that can be remotely detected, so again satellite observations related to surface temperature, soil moisture, or vegetation need to be combined to infer the fluxes. An overview of different methodologies for *LE* estimation can be found in Wang and Dickinson (2012).

If satellite surface-derived skin temperature (*Ts*) is available, in principle bulk transfer calculations from the aerodynamic theory of turbulent transfer can be used to produce heat fluxes (e.g., Tarpley, 1994). *Ts* is used as a proxy for the aerodynamic surface temperature (*Tas*), and the sensible heat flux (*H*) is derived from the difference between the skin temperature *Ts* and a measured air temperature (*Ta*), scaled by a transfer coefficient characterizing the transport of heat and depending on site-specific data, such as surface roughness and wind speed. The latent heat flux (*LE*) can then be estimated from an energy balance model, assuming the surface radiation and the ground flux are known.

Given the routine availability of *Ts* from satellite sensors, estimating heat fluxes from satellite-derived *Ts* is a common practice (see e.g. Kalma et al., 2008 for a review). However, it is not without challenges. Difficulties first arise from the fact that differences between *Ts* and *Ta* are rather limited for many environmental conditions and the accuracy of each measurement (often of the same order of their difference) can have a detrimental effect on the estimated *Ts*. In addition, the difference between *Tas* and *Ts* can be significant (e.g., Kustas and Humes, 1997), as well as the difference between the soil and the vegetation temperatures with only one integrated temperature being estimated from the satellite instrument (e.g., Kustas and Norman, 2000; Nishida, 2003). Still based on the bulk formulation, more elaborated models try to overcome some of these difficulties by partitioning the measured *Ts* into its soil and canopy components, and by exploiting the relationship between soil moisture and thermal inertia. For instance, formulations have been derived to constrain the heat fluxes with the diurnal gradient of *Ts* (e.g., Norman et al. (2003); Anderson et al. (2007), or with the dry-wet limiting conditions imposed by the surface energy balance (e.g., Su, 2002). Other schemes use relationships between *Ts* and other satellite observations, such as the vegetation index (e.g., Carlson et al., 1995; Nishida, 2003), and as they typically require local calibrations, there are better suited for field scale applications (e.g., for irrigation management) rather than for relatively large scales (e.g. to derive basin integrated estimates).

Here we demonstrate the production of *Ts*-driven surface heat fluxes over a grassland site in Switzerland. The European Space Agency (ESA) is currently running the GlobTemperature Data User Element (DUE) project (www.globtemperature.infoaiming to provide high quality *Ts* data and facilitate wider use of global-scale satellite *Ts* in research and operational user communities. The present study serves to illustrate the potential for using satellite *Ts* to derive land heat fluxes from an end user point of view. In that regard, the main objectives of the study are: (1) to select and cross-compare a range of *Ts* products over a specific location, (2) to derive heat fluxes with the available *Ts* products, (3) to discuss the impact of *Ts* product selection on the derived fluxes, and (4) to highlight the difficulties of evaluating satellite *Ts* and heat fluxes. The location selected for the exercise is a grassland site situated at the Rietholzbach Research Catchment in Switzerland, where *in situ* observations enable comparisons between the satellite *Ts* products and derived heat fluxes with ground measurements. The *Ts* products include datasets from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard the geostationary satellite Meteosat Second Generation (MSG)-2, the Advanced Along-Track Scanning Radiometer (AATSR) onboard ESA EnviSAT polar-orbiting satellite, the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites, the Special Sensor Microwave Imager/Sounder (SSMIS) onboard the United States Air Force Defense Meteorological Satellite Program (DMSP) satellites, and the Advanced Microwave Scanning Radiometer - Earth observing system (AMSR-E) on board the Aqua satellite. Finally, concerning the heat flux methodology, the Surface Energy Balance System (SEBS) model (Su, 2002) will be applied. SEBS is an energy balance model based on a detailed parameterization of *H* at the surface, with *LE* derived from the surface energy balance once *H* is estimated. It is a one-source model, i.e., bulk fluxes are derived without partitioning the soil and canopy contributions, but this is not judged as a severe limitation given the vegetation coverage of the selected location. In the past, SEBS has proven to estimate realistic evaporation rates at a variety of scales, ranging from local to regional (e.g. Jia et al., 2003; Su et al., 2007; McCabe and Wood, 2006), although difficulties connected to the *Ts* uncertainty and the derivation of the heat transfer coefficient have also been reported (e.g. Lu et al., 2012; Wang et al., 2013; Ershadi et al., 2014).

The paper is organized as follows: first, the study site and its ground observations are presented, followed by a description of the heat flux model and the inputs required to run the model, including the different *Ts* products. A comparison of the different *Ts* products and the derived heat fluxes is then made, with a discussion about the impact of product selection in the derived fluxes. Finally, the main conclusions of the study are summarized.

2. Methods and data

2.1. Site description

The study is conducted at the hydrometeorological research catchment Rietholzbach in northeastern Switzerland (47.37°N, 8.99°E, 795 m asl; see Seneviratne et al., 2012, and www.iac.ethz.ch/url/rietholzbach for an overview of the site). The pre-alpine catchment (elevation range: 682–950 m asl) drains an area of 3.31 km^2 and is a headwater catchment of the Thur river. The local conditions are characterized by a temperate humid climate with mean air temperature of 7.0 °C and a mean annual precipitation amount of 1447 mm. The land use in the catchment consists of a mixture of grasslands and forest (73% grasslands, 24% forest and trees, the rest sparse settlements).

The measurements considered in this article are conducted at the research site “Büel”, which is located in the upper part of the Rietholzbach catchment within a grassland area. The on-going measurements include standard meteorological and hydrological variables such as air temperature, precipitation, air humidity, radiation, soil moisture, runoff, and ground water level. Evapotranspiration measurements are provided by a lysimeter and an eddy covariance (EC) flux tower (see Hirschi et al., 2016).

The installed weighing lysimeter allows the quantitative measurement of water mass changes within a soil column using three load cells. In combination with the measurement of precipitation and lysimeter seepage (both measured using tipping buckets), actual evapotranspiration is estimated on an hourly time scale (Hirschi et al., 2016). The lysimeter at “Büel” has a radius of 1 m and a total depth of 2.5 m including a gravel filter layer at the bottom. The surface is covered by grass and maintained in agreement with the surrounding grassland area (with a specified cutting scheme and fertilization).

The EC measurements (i.e., sensible and latent heat fluxes, *H* and *LE*) used here are conducted 2 m above ground at a flux tower located in ~10 m distance from the lysimeter. The tower is equipped with an ultrasonic anemometer (CSAT3, Campbell Scientific Inc., USA) as well as an open-path CO_2/H_2O infrared gas analyser (Li-7500, LI-COR Biosciences, USA). The instruments are operated at 10 Hz and fluxes are calculated at a resolution of 30 min and aggregated to hourly output.

Further measurements used in this study include precipitation *P* (measured with Joss-Tognini type, Lambrecht, Germany), net radiation