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 (T_s) as one of their key inputs to derive the fluxes. Here the production of T_s -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 T_s estimates (from the instruments AATSR, MODIS, SEVIRI, AMSR-E, and SSMIS). The T_s 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 T_s 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 T_s 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 T_s estimates. Concerning the flux estimates, for those sensors with midday overpasses, a RMSD of $\sim 25\%$ are found when comparing the instantaneous latent flux (LE , or evaporation expressed as an amount of

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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 it 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.

Keywords: Land surface temperature; surface heat fluxes; terrestrial evaporation; grasslands; satellite remote sensing.

1. Introduction

Land heat fluxes govern the interactions between the Earth surface and the atmosphere [e.g., 1], are essential components of the water and energy cycles [e.g., 2], and play a key role in the climate system [e.g., 3]. 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. 4, 5, 6].

In situ measurements of land heat fluxes are operated during field experiments [e.g. 7] and by some flux tower networks [e.g 8]. 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., 9, 10] to obtain local estimates. For instance, the Food and Agriculture Organization (FAO) recommends the Penman-Monteith method to estimate crops evaporation, which

requires a number of surface meteorological inputs and relevant crop coefficients [11]. 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 [3].

If satellite surface-derived skin temperature (T_s) is available, in principle bulk transfer calculations from the aerodynamic theory of turbulent transfer can be used to produce heat fluxes [e.g., 12]. T_s is used as a proxy for the aerodynamic surface temperature (T_{as}), and the sensible heat flux (H) is derived from the difference between the skin temperature T_s and a measured air temperature (T_a), 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 T_s from satellite sensors, estimating heat fluxes from satellite-derived T_s is a common practice (see e.g. [13] for a review). However, it is not without challenges. Difficulties first arise from the fact that differences between T_s and T_a 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 T_s . In addition, the difference between T_{as} and T_s can be significant [e.g., 14], 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., 15, 16]. Still based on the bulk formulation, more elaborated models try to overcome some of these difficulties by partitioning the measured T_s 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 T_s [e.g., 17, 18], or with the dry-wet limiting conditions imposed by the surface energy balance [e.g., 19]. Other schemes use

relationships between T_s and other satellite observations, such as the vegetation index [e.g., 20, 16], and as they typically require local calibrations, there
50 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 T_s -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.info)
55 (www.globtemperature.info) aiming to provide high quality T_s data and facilitate wider use of global-scale satellite T_s in research and operational user communities. The present study serves to illustrate the potential for using satellite T_s 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
60 T_s products over a specific location, (2) to derive heat fluxes with the available T_s products, (3) to discuss the impact of T_s product selection on the derived fluxes, and (4) to highlight the difficulties of evaluating satellite T_s 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
65 enable comparisons between the satellite T_s products and derived heat fluxes with ground measurements. The T_s 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,
70 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)
75 model [19] 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
80 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. 21, 22, 23], although dif-
ficulties connected to the T_s uncertainty and the derivation of the heat transfer
coefficient have also been reported [e.g. 24, 25, 26].

85 The paper is organized as follows: first, the study site and its ground obser-
vations are presented, followed by a description of the heat flux model and the
inputs required to run the model, including the different T_s products. A com-
parison of the different T_s products and the derived heat fluxes is then made,
with a discussion about the impact of product selection in the derived fluxes.
90 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 Ri-
etholzbach in northeastern Switzerland [47.37°N, 8.99°E, 795 m asl; see 27, and
95 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 km²
and is a headwater catchment of the Thur river. The local conditions are char-
acterized 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
100 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 meteo-
105 rological and hydrological variables such as air temperature, precipitation, air
humidity, radiation, soil moisture, runoff, and ground water level. Evapotran-
spiration measurements are provided by a lysimeter and an eddy covariance

(EC) flux tower [see 28].

The installed weighing lysimeter allows the quantitative measurement of
110 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 [28]. 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
115 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 dis-
tance from the lysimeter. The tower is equipped with an ultrasonic anemometer
120 (CSAT3, Campbell Scientific Inc., USA) as well as an open-path $\text{CO}_2/\text{H}_2\text{O}$ in-
frared gas analyser (Li-7500, LI-COR Biosciences, USA). The instruments are
operated at 10 Hz and fluxes are calculated at a resolution of 30 minutes and
aggregated to hourly output.

Further measurements used in this study include precipitation P (measured
125 with Joss-Tognini type, Lambrecht, Germany), net radiation Rn (CM21 and
CG4, Kipp&Zonen, The Netherlands), ground heat flux G (HFP01, Hukseflux,
The Netherlands), air temperature Ta (Thygan, Meteolabor, Switzerland) and
wind velocity u (R. M. Young, USA). All these variables are available at 5-
minute resolution, except for G measured at hourly resolution.

130 2.2. SEBS

SEBS [19] is a one-source energy balance algorithm that is arguably one of
the most widely used energy balance approaches to derive heat fluxes. The SEBS
model calculates the sensible heat flux (H) based on the Monin and Obukhov
theory [29]:

$$\theta_0 - \theta_a = \frac{H}{ku_*\rho c_p} \left[\ln \left(\frac{z - d_0}{z_{0h}} \right) - \Gamma_h \left(\frac{z - d_0}{L} \right) + \Gamma_h \left(\frac{z_{0h}}{L} \right) \right] \quad (1)$$

$$u = \frac{u_*}{k} \left[\ln \left(\frac{z - d_0}{z_{0m}} \right) - \Gamma_m \left(\frac{z - d_0}{L} \right) + \Gamma_m \left(\frac{z_{0m}}{L} \right) \right] \quad (2)$$

$$L = -\frac{\rho c_p u_*^3 \theta_v}{kgH}, \quad (3)$$

135 where u is the wind speed, u_* is the friction velocity, k is the von Kármán constant, z is the height above the surface, d_0 is the zero plane displacement height, z_{0m} and z_{0h} are the roughness heights for momentum and heat transfer, Γ_m and Γ_h are the stability correction functions for momentum and sensible heat transfer, respectively. L refers to the Obukhov length, ρ is the air density, θ_0 is the potential land surface temperature and θ_a is the potential air temperature
140 at height z , g is the gravity acceleration and θ_v is the potential virtual air temperature at level z . Once d_0 , z_{0m} , and z_{0h} are calculated by using the model for roughness lengths described in [19], the only unknowns are H , u_* and L . This enable us to use Equations 1 to 3 to derive H . Available estimates of
145 the surface net radiation (R_n) and ground heat flux (G) can be used together with the derived H to estimate LE from the residual of the surface energy balance ($LE = R_n - H - G$). Additionally, in order to constrain H estimates, two limiting cases are considered that set upper and lower bounds for the evaporative fraction (defined here by the ratio $LE/(R_n - G)$). Under very dry conditions, LE
150 becomes zero and H is at its maximum, set by $R_n - G$. Under wet conditions, ET occurs at potential rates and therefore H is at its minimum. In this wet case, H is calculated via reverse application of the Penman–Monteith equation [9] assuming that the surface resistance is zero.

2.3. SEBS Inputs

155 2.3.1. Land Surface Temperature

The satellite T_s products considered in the study are listed in Table 1. They include two infrared instruments onboard polar satellites (AATSR and MODIS), one infrared instrument onboard a geostationary satellite (SEVIRI),

and two microwave instruments onboard polar satellites (SSMIS and AMSR-E). The AATSR T_s estimates come from the GlobTemperature harmonised dataset, reformatted from [30]. SEVIRI and MODIS estimates are extracted from the original products [31, 32]. The SSMIS and AMSR-E estimates have been processed from a data record of SSMIS [33] and AMSR-E [34] brightness temperatures following the methodology of [35] using databases of SSM/I [36] and AMSR-E [37] radiances and retrieved T_s . The AMSR-E T_s can be accessed from the GlobTemperature archive, while the SSMIS estimates are not publicly available yet but can be accessed upon request to the authors.

The spatial resolutions of the T_s estimates range from the ~ 1 km of AATSR and MODIS to the ~ 25 km of SSMIS. Temporal sampling ranges from the AATSR 3-day revisi time, one day and night overpass, to the daily 15 minutes sampling of SEVIRI. Notice that the infrared instruments cannot provide T_s estimates under cloudy conditions, and that the T_s estimates provided by the microwave instruments correspond to a depth-integrated temperature that can deviates from the infrared skin temperature on some occasions (e.g., for very dry soils where the microwave penetration depth can be of several centimeters).

Ground T_s is derived from inverting the equation relating surface temperature and the upwelling and downwelling broadband radiance measured by the station longwave radiometer. Broadband emissivity is required and it is estimated from the MODIS-based Global Infrared Land Surface Emissivity Database [38] operated by the Cooperative Institute for Meteorological Satellite Studies (CIMSS). The T_s estimates are calculated by following the approach suggested by [39] using a linear combination of narrowband emissivities at 8.5, 11, and 12 μm .

2.3.2. Surface Meteorology

Apart from T_s , SEBS also requires estimates for the surface meteorological variables Rn , G , Ta , and u . Here we use the station ground to represent as closely as possible the station conditions, but a typical larger scale application will require spatially distributed values of those parameters at adequate

Table 1: Table summarizing the T_s products. Listed are the sensor name, the satellite platform, the approximated spatial resolution, the approximated equatorial overpass local time (descending node), the product name, and the data archive.

Sensor	Platform	Spatial	Overpass	Product	Archive
AATSR	Envisat	~1 km	~10.00	GT_SSD-L2-AATSR	GlobTemperature
MODIS	Aqua	~1 km	~1.30	MYD11A1 v5	LP DAAC
	Terra		~10.30	MOD11A1 v5	
SEVIRI	MSG-2	~4 km	every 15 min	GT_SSD-L2-SEVIR	LSA SAF
AMSRE	Aqua	~15 km	~1.30	GT_SSD-L2-AMSRE	GlobTemperature
SSMIS	F16	~25 km	~7.00	LST_SSMIS_v1	Estellus *
	F17		~5.30		
	F18		~8.00		

* Not publically available.

spatial and time resolutions. While satellite-based estimates exist for Rn (al-
190 though typically at coarse spatial resolution, e.g., the Surface Radiation Budget
product [40]), G cannot be measured from space (it is approximated by some
relationships to other radiative fluxes, e.g., Equation 3 in [19]). Ta is challeng-
ing to retrieve from satellite observations (but some products exist, e.g., see an
evaluation of the AIRS Ta and near-surface humidity in [41]), and u over land
195 cannot currently be provided from satellite instruments. Alternatives are to
use products based on extrapolating the synoptic network of weather stations
to regular spatial grids (although normally at coarse spatial and temporal res-
olutions, e.g., the Climate Research Unit (CRU) monthly time series dataset
[42]), or the outputs of Numerical Weather Prediction forecasts or reanalyses
200 (with better temporal resolutions, but further away from a "purely" observa-
tional product). For this study the ~7 km hourly analysis fields of the weather

forecasting model Consortium for Small-Scale Modelling (COSMO) run by Me-
teoSwiss are used to obtain a second Ta product and a daily estimate of the
height of the planetary boundary layer (required for the calculation of the SEBS
stability correction functions).

2.3.3. Vegetation

SEBS requires the one-side Leaf Area Index (LAI) to derive a within-canopy
wind speed profile extinction coefficient as part of the calculations for the scalar
roughness lengths (Equation 7 in [19]). Here we use the MODIS product
MOD15A1 (version 5) to provide 1 km LAI over the station.

Vegetation height is also required, its is approximated by a 15 cm height
constant throughout the year (the grass at the station is regularly mowed). The
fraction of vegetation cover (FVC) is also used by SEBS to weight the contribu-
tions of the estimated soil and canopy land fractions to the scalar roughness for
heat transfer z_{0h} (see Equation 9 in [19]). In the absence of a better estimate
and given that the observation tower fetch consists of a uniformly thick layer of
grass plants, we approximate the FVC to one (i.e, we consider the contribution
of the heat fluxes coming from the grass plants much more significant than any
contribution from the soil).

2.4. Data processing

Most *in situ* data relevant to this study is available every 5 minutes, but
this excludes the heat and ground fluxes (there are available every hour). A
time miss-match can be critical for the comparison of the satellite Ts with the
station Ts at the times of the day with strong temperature gradients (e.g., at the
mid-morning AATSR and MODIS (Aqua) overpasses). Therefore, the original
5 minutes resolution has been retained (as opposed to integrating all data to
hourly resolution), with the heat fluxes re-sampled at 5 minutes resolution by
assuming a constant evaporative fraction (ratio of LE to Rn) during the hourly
interval, and the ground flux constant during the hourly interval.

230 Satellite overpasses are selected when the station location is within the satel-
 lite footprint. Given the different satellite footprint resolutions (see Table 1),
 the representativeness of the satellite footprint with respect to the station will
 depend on the sensor. Within a radius of ~ 100 m of the station tower the
 land cover is purely grassland. Away from the tower the landscape is predomi-
 235 nantly a mixture of grasslands and forest (for the ~ 3 km² research catchment
 the proportion is 73 % grasslands, 24% forest and trees, and the rest sparse
 settlements). Therefore, even at the ~ 1 km resolution of AATSR and MODIS
 the satellite footprint cannot be considered as purely grassland, and some of the
 discrepancies between the different T_s and flux estimates can be attributed to
 240 the different percentages of grassland and forest sampled by each instrument.
 Regarding the time matching between satellite overpass and ground data, given
 that the ground data is available every 5 minutes, a maximum time miss-match
 will be 2.5 minutes.

Cloud contamination (i.e., the satellite product cloud mask wrongly iden-
 245 tifies a cloudy pixel as clear-sky) can occur in the infrared T_s estimates. To
 reduce the risk of having those pixels as part of the comparisons, the ~ 5 km
 AATSR (GT_SSD-L3-AATSR) and MODIS (MOD11C1) products have also
 been inspected, and only those 1 km T_s where the corresponding 5 km T_s scene
 was mainly composed of clear pixels are kept (at least 85% of clear pixels). This
 250 strategy cannot be applied to SEVIRI (already at a resolution of ~ 5 km), but
 a much colder T_s with respect to the ground estimate (difference larger than
 15 K) has been imposed as a criterium to assure that obvious cloud contami-
 nated pixels are not included in the comparisons. The microwave T_s estimate
 do not suffer in general from cloudiness (although strong convection with heavy
 255 precipitating cells can affect the T_s retrievals).

Given the lack of specific parameterisations in SEBS to deal with negative
 evaporation (i.e., condensation, typically occurring at night) or evaporation from
 snow surfaces (i.e., sublimation), and the difficulties of the EC instruments to
 measure the fluxes in situations associated with low turbulence and precipitation
 260 conditions, the study will only consider daytime T_s , LE , and H for snow and

rain-free conditions. To detect snow a flag based on the observed shortwave
albedo is used to filter the data. Nighttime fluxes are typically small (compared
with daytime fluxes) and in principle for applications related to agriculture and
water management the daytime fluxes suffice. Nevertheless, nighttime and snow
265 fluxes can be of importance for some climatological applications [e.g. 43].

3. Results and discussion

3.1. Temperature and fluxes at the station

Equation 1 shows the large dependence of SEBS derivation of H on the dif-
ference of the potential temperatures between the surface and the overlaying
270 air, which is directly proportional to the $T_s - T_a$ difference (the same atmo-
spheric pressure measured at the station is applied to the conversion of T_s and
 T_a to potential temperatures given the 2 m observation height). Figure 1 shows
the seasonal all-sky average T_s and T_a diurnal cycles at the station (ground
measurements), compared with the same clear-sky T_s from SEVIRI and T_a
275 from COSMO (applying SEVIRI cloud mask), T_s from SEVIRI, and T_a from
COSMO. The expected seasonal changes in T_s and T_a can be observed in Fig-
ure 1. The differences between the clear-sky station and COSMO T_a are in most
cases smaller than the station and SEVIRI T_s , suggesting that it can be more
difficult to have an accurate estimate of T_s than T_a to run SEBS with gridded
280 data. For the spring and summer seasons the T_s and T_a do not have the same
absolute values (as expected), but the T_s and T_a differences are comparable,
suggesting a close evaporative fraction (i.e., similar partitioning of the surface
available energy into H and LE at both seasons).

Seasonal all-sky diurnal cycles of G , H , and LE (EC and lysimeter observa-
285 tions) from the one-hourly data record are plotted in Figure 2. The surface avail-
able energy ($Rn-G$) and the sum of LE , H are also displayed. The largest fluxes
correspond to the summer months where the available energy is the largest. The
largest evaporative fractions (estimated as the EC $LE/(H+LE)$) also occur in
the summer months and can reach values close to 0.8, indicating that the region

Figure 1: Seasonal skin temperature (T_s) and air temperature (T_a) cycles (top-left for winter, top-right for spring, bottom-left for summer, bottom-right for autumn). The data shows the station all-sky and clear-sky T_s (blue squares) and T_a (red dots), and the clear-sky SEVIRI T_s (black triangles) and COSMO T_a (green triangles). Closed symbols correspond to the all-sky measurements at the station, opened symbols correspond clear-sky measurements only (by applying SEVIRI cloud mask).

is not water limited in summer and that the available energy controls to a large extent the heat fluxes. In terms of energy closure, the averaged seasonal sum of LE and H is in most cases smaller than the observed $Rn-G$, although the difference tends to get smaller in the late afternoon hours. Overall, the average daytime closure ratio estimated at the site (i.e., the total amount of the daytime heat fluxes to the daytime available energy) amounts to 88% [28]. Regarding the agreement of the EC and lysimeter LE , for this year the largest disagreement happens in summer, where the seasonally averaged lysimeter LE can be up to 20% larger than the EC LE at midday. The agreement is closer in spring and autumn, while in winter the very low LE results in small absolute differences (but large in relative terms)[see also 28].

3.2. Satellite surface temperature time sampling and spatial resolution

The time sampling and spatial resolution required in a heat flux product depends on the application. One value per day should be enough for most agriculture and forest applications, though it may not be enough for a climatological application that requires resolving the diurnal cycle. Similar considerations

Figure 2: Seasonal cycles for the ground heat flux (G , magenta triangles), the sensible heat flux (H , cyan circles), and latent heat flux (LE , blue triangles for the lysimeter, red triangles for the EC instrument) observed at the station (top-left for winter, top-right for spring, bottom-left for summer, bottom-right for autumn). The sum of the surface heat fluxes measured by the EC instruments ($H+LE$, green squares) and the surface available energy (difference between the surface net radiation (Rn) and G , black squares) are also plotted.

apply to the required time continuity of the data record. While a few flux estimates per month may be enough as an indicator of forest health (in this case the missing data because of cloud coverage will not be critical), a climatological application may demand continuity in time (which can be provided by the "all-weather" T_s from instruments such as SSMIS). Regarding spatial resolution, this is also very much application dependent, and while the resolution of the microwave instrument AMSR-E and SSMIS (~ 15 and ~ 25 km, respectively) can be adequate for a global climatological data record, it will not be of much utility to spatially resolve evaporation for most crops. For these applications the much finer resolution of instruments such as AATSR and MODIS is more adequate. However, it should be mentioned that even their 1 km resolution can be considered too coarse for many agriculture, forestry, and land management applications, and tens of meters is a more desirable resolution [e.g. 17]. Instruments with finer resolutions in thermal infrared bands such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER, 90 m resolution) could be more relevant for those applications (e.g., see an evaluation of

Figure 3: Number of satellite daylight overpasses with an available skin temperature (T_s) estimate at site in 2010. The number is given for all overpasses (full bar) and for the overpasses without snow on the ground (black outlined bar over-plotted, indicated with text for the 11 hour data).

SEBS with ASTER imagery at [44]), although their typically very long revisiting time (16 days for ASTER) can also be a severe limitation depending on application. For even finer resolutions and coverage during overcast conditions, the use of low flying altitude Unmanned Aerial Vehicles (UAVs) equipped with thermal sensors is becoming an attractive possibility [e.g. 45].

Figure 3 illustrates the time availability of satellite T_s for the specific location of the study (after imposing the time and space matching criteria discussed in Section 2.4). The snow-free and total number of available T_s estimates is given in the figure. AATSR overpasses with usable T_s estimates are very limited in number due to the 3-days revisiting time, frequent cloudiness at the station location, and the constraint of having contiguous clear-sky pixels to minimize cloud contamination (see Section 2.4). MODIS is also affected by cloudiness, but the 1-day revisiting time and the existing 2 platforms (Aqua and Terra) result in a much larger number of T_s estimates (note that clear-sky contiguous pixels are also demanded for MODIS). Compared with the other sensors, the relative

number of MODIS T_s estimates for snow conditions is smaller, which may be an indication of the MODIS cloud-mask having difficulties to distinguish snow from cloudiness over this specific location. SEVIRI, being a geostationary instrument, provides the largest number of T_s estimates given their 15 minutes sampling. Comparing the microwave instruments with AATSR and MODIS, both SSMIS and AMSR-E have a larger number of T_s estimates per hour interval as their observations are much less affected by cloudiness. The total number of T_s estimate is larger for SSMIS than for AMSR-E due to the existence of several platforms carrying SSMIS in 2010 (F16, F17, and F18).

Concerning the time of the day, for most agriculture and forest applications one estimate per day should be enough, and the instruments AATSR, AMSR-E (one daytime overpass), MODIS (two), or SSMIS (up to three, linked to the number of orbiting satellites carrying the instrument) could provide the flux estimates. If multiple regular flux estimates per day are required, only the geostationary instrument SEVIRI can provide such sub-daily sampling. Clouds can also severely limit the time sampling for the infrared instruments. The time of the day is also of importance for the polar instruments. If only one flux estimate per day is derived, satellite estimates will be potentially more robust around midday where quantities such as the surface radiation or temperatures have larger values, typically resulting in smaller estimation errors. This can be of importance also when the instantaneous LE estimate is used to derive a daily estimate by assuming that the ratio of LE to some other reference variable (typically the available surface radiative energy) is constant during the day. In this regard MODIS (Aqua) and AMSR-E have more adequate overpass times than AATSR and SSMIS.

3.3. Satellite surface temperature cross-comparisons

A comparison of the different satellite T_s with the station T_s is presented here. Scatter plots of the satellite daytime T_s with respect to the station T_s are shown in Figure 4. Notice again the different populations used to derive the statistics, as illustrated by the number of points shown in the scatter plots. The

Figure 4: Scatter plots of satellite and observed skin temperature (T_s) at the station (from top-left to bottom-middle AATSR, MODIS, SEVIRI, AMSR-E, and SSMIS) and COSMO and observed air temperature (T_a) at the station (bottom-right). Plotted the 1:1 line (black) and the linear fit to the data (blue line). Statistics of the difference between the satellite and station T_s are given in the plot titles: square of the correlation coefficient (R^2), mean of the T_s difference (BIAS), and root mean square difference (RMSD).

three infrared instruments AATSR, MODIS, and SEVIRI, have a cold bias with respect to the station T_s , with AATSR having the smallest bias (~ 1 K, but calculated over a very small population compared with MODIS and SEVIRI).

Concerning the microwave instruments, SSMIS agrees very well with the station T_s (bias close to zero), while AMSR-E have a relatively large warm bias (~ 4 K). In terms of spatial representativeness, a clear link between satellite footprint and T_s differences is not apparent (i.e., that smaller differences are observed for the smaller satellite footprints in principle matching more closely the station surface conditions). In fact, the best agreement in terms of bias and Root Mean Square Difference (RMSD) happens for two sensors having very different resolutions (AATSR, ~ 1 km, and SSMIS, ~ 25 km).

Statistics of the T_s differences (satellite estimate and station) as a function of the time of the day are presented in Figure 5. SEVIRI is the only sensor which makes regular observations throughout the day. The RMSD is slightly smaller for hours around mid-day, compared with the mid-morning hours (even if at mid-day the absolute T_s values are larger), but the correlations at mid-day are lower than at mid-morning. This could possibly be explained by the diurnal T_s gradients at this specific location (see Figure 1): the gradients are larger at mid-morning compared with mid-day, which tends to amplify the differences

(i.e., larger RMSD) but it also helps to increase correlation values (related to the larger Ts variability). Regarding the other sensors, SSMIS is closer than SEVIRI to the station Ts for the early-morning overpasses (but SEVIRI is closer for the late-afternoon overpasses), AATSR is closer than MODIS and SEVIRI for the mid-morning overpasses, and SEVIRI is closer than MODIS and AMSR-E at mid-day. Notice also that SSMIS agrees better with the station Ts than AMSR-E (with overpasses at different times of the day), and that SSMIS and AMSR-E biases change sign with the time of the day (SSMIS colder than the station Ts in the early-morning hours, but AMSR-E and SSMIS warmer than the station Ts at mid-day).

Overall, the discrepancies found between the different sensors Ts estimates are comparable with the findings from similar satellite-ground Ts comparisons reported elsewhere [e.g. 46, 47, 48, 49]. Identifying the causes of these inter-sensor differences when compared with a common ground Ts estimate is always difficult, but in principle they should be mainly related, on the one hand, to the accuracy and representativeness of the ground longwave radiation based Ts estimates, and on the other hand, to issues related to the satellite observations, such as the impact of different viewing geometries, thermal properties of the observed scene, the use of different land surface emissivity estimates in the retrieval, calibration uncertainties of the top-of-atmosphere sensors, and the uncertainties on the parameters used in the retrieval algorithms. It should be noted that differences between the different Ts estimates are expected to be closer for the night comparisons due to the more homogeneous heating/cooling conditions of the night scenes.

3.4. Temperature derived heat fluxes

The statistics of the comparison of the SEBS heat fluxes (RMSD and square of the correlation, R^2) with station values are reported in Figure 6. SEBS heat fluxes are derived using the different satellite Ts inputs. As reference the absolute RMSD values and averaged heat fluxes (half of the hourly values) are also displayed. Figure 6 (top panel) shows that the best agreement (i.e., smaller

Figure 5: Statistics of the difference between the satellite (AATSR in red, MODIS in yellow, SEVIRI in green, AMSR-E in cyan, and SSMIS in blue) and station skin temperature (T_s) as a function of the local solar time. The top panel shows the mean of the difference (black outlined bar) and the standard deviation of the difference (over-plotted on a bar above the mean bar). The bottom panel shows the root mean square difference (RMSD, positive axis), and the square of the correlation coefficient (R^2 , negative axis).

RMSD and higher correlations) with the H measured at the station corresponds for most hours to running SEBS with the station Ts . This is expected as the station Ts is likely to be a better estimate of the the station temperature, compared with the satellite estimates. For the times of the day when H is small (i.e., early morning and late afternoon), the prediction relative errors are large (even for the fluxes derived with the *in situ* Ts , e.g., ~ 100 % RMSD at the 7-8 hour interval). Around mid-day when H is at its maximum the predictions are better (~ 50 % RMSD, $\sim 0.7 R^2$). A clear link between satellite and station Ts closeness and the station and satellite H agreement is not apparent. At the 7-11 hour intervals SSMIS compares better with the station Ts than SEVIRI, and the SSMIS-derived H correlates better with the station H and have smaller RMSD, compared with SEVIRI, but for the other intervals this relationship is not so obvious (e.g., at the 12-13 hour interval AMSR-E has the largest RMSD comparing with the station Ts , but the smaller RMSD comparing with the station H). This suggests that for this specific exercise there is not a clear relationship between Ts accuracy (judged by closeness to the station Ts) and the SEBS-derived H accuracy (judged by closeness to the station H). Different factors are likely to play a role here, including the different spatial scales of the satellite-derived H and the Eddy Covariance observations, the errors in the station Ts and H used here as reference, and how the errors in the other inputs required by SEBS impact the produced fluxes for a given Ts (e.g., as H depends on the $Ts-Ta$ difference, there may be combinations of $Ts-Ta$ that are more likely to represent the "true" temperature difference even if their Ts is not the more accurate).

Figure 6 (bottom panel) shows that the satellite-derived LE can be sometimes slightly closer to the station in terms of RMSD (compared with the LE derived with the *in situ* Ts). Notice that the hourly statistics for the different estimates are not calculated using the same number of days (see Figure 3), so small difference in RMSD and correlation could be not very representative (i.e., they can just be related to sampling different populations). The relative RMSD and correlations show a better agreement for LE than for H . This is

Figure 6: Statistics of the difference between the station Eddy Covariance (EC) sensible heat flux (H , top panel) and latent heat flux (LE , bottom panel) and the SEBS-derived estimates using skin temperature (T_s) from AATSR (red), MODIS (yellow), SEVIRI (green), AMSR-E (cyan), SSMIS (blue), and the station *in situ* T_s (magenta), as a function of the local solar time. Displayed are the root mean square difference (RMSD, positive axis), and the square of the correlation coefficient (R^2 , negative axis). Half of the EC hourly-averaged H (top) and LE (bottom) fluxes are displayed as black circles for reference.

expected given the relatively high evaporative fractions for a large part of the
 year (LE comes from the difference between the available energy and H , so the
 impact of errors in H are minimized given that H represents a small fraction
 450 of the available energy). The relative RMSD for LE at midday and early af-
 ternoon is $\sim 25\%$ for some of the satellite-derived estimates. Given some of the
 assumptions (e.g., that fluxes only come from a surface 100% cover by grass)
 and the clear miss-match between tower observation fetch and satellite sensor
 footprint in most cases, this value seems reasonable and compares well with
 455 other reported values for this type of vegetation and methodology (e.g., relative
 daytime RMSD of $\sim 20\%$ are reported over two grassland sites in [22]). It also
 compares well with the 15% to 30% relative errors typically reported when com-
 paring satellite evaporation and ground measurements over different landscapes
 [13, 3], which gives an idea of the present accuracy available to infer evaporation
 460 for agriculture and forest applications.

4. Conclusions

Surface heat fluxes are an essential variable to monitor crops and forest sta-
 tus. Their estimation by remote sensing methodologies provides the possibility
 to routinely analyze large areas, which is of importance to manage cropland
 465 and forested areas given the typically limited number of ground observations
 at most locations. This paper contributes by demonstrating the production of
 remotely sensed land surface temperature (T_s)-driven surface heat fluxes at a
 grassland site situated at the Rietholzbach Research Catchment in northeastern
 Switzerland.

470 The exercise has been conducted by running a specific heat flux method-
 ology (SEBS) driven by a number of satellite derived T_s estimates (from the
 instruments AATSR, MODIS, SEVIRI, AMSR-E, and SSMIS). The T_s esti-
 mates have been compared with a ground estimate derived from the broadband
 longwave radiometric observations at the station, and the satellite heat flux es-
 475 timates with ground measurements also operated at the station. Different to

other previous site studies, the heat fluxes are estimated from sensors operating at different resolutions (from ~ 1 to ~ 25 km), time sampling (from twice a day to half hourly), and wavelengths (infrared and microwaves), and two types of ground observations of LE (Eddy Covariance (EC) flux measurements and evaporation estimates from a lysimeter) are available to evaluate the satellite estimates.

The main conclusions of the study can be summarized as:

- Satellite T_s estimates that can be used for heat flux estimation exist at different spatial resolutions and time sampling during the day. The infrared estimates are limited in terms of temporal coverage (only clear-sky estimates), while the microwave estimates are all-sky but are limited in terms of spatial resolution (one order of magnitude coarser than the infrared estimates). Satellite overpass can also be an issue for the sensors in polar orbits (i.e., only two estimates per day), although most agriculture and forest applications do not require sub-daily time resolution. In principle sensors with overpasses at midday (e.g., MODIS and AMSR-E in Terra) are more adequate than sensors with early morning and late afternoon overpasses (e.g., SSMIS) as the typically larger fluxes at midday facilitate the flux estimation.
- The satellite T_s estimates can be compared with the station ground estimates, but the comparison suffers from spatial miss-match even for the highest infrared satellite estimates (e.g., MODIS footprint ~ 10 times larger than the footprint of the longwave radiometric observations at the station). The different nature of the observations (e.g., station broadband radiometers 2 meters above the ground versus satellite narrow-band radiometers observing at a given angle from space) also plays a role in the differences observed. Root Mean Square Differences (RMSDs) of the daytime satellite and station T_s are 2.72 (AATSR), 4.41 (MODIS), 3.59 (SEVIRI), 3.81 (AMSR-E), and 2.79 (SSMIS), but given the difficulties mentioned in the comparison it is not possible to use the agreement with

the station Ts as an absolute metric to judge satellite Ts accuracy over this specific location.

- 510 • The comparison of the satellite Ts -derived heat fluxes with the station EC is also challenging. Again, differences between the area integrated in the satellite flux measurements and the tower observations make the comparison difficult. Also, discrepancies are observed when the ground EC fluxes measured at the station are compared with some other measurements at the site (e.g., disagreements between the EC and lysimeter LE , or between the sum of the observed EC LE and H and the available energy given by $Rn-G$). This suggests that the EC fluxes, although very valuable

515 to evaluate the Ts -derived fluxes, cannot be considered as an absolute reference.
- 520 • For those sensors with midday overpasses, a RMSD of $\sim 25\%$ are found when comparing the instantaneous LE at satellite overpass with the EC observations. Larger differences with the EC observations are found for H (best RMSD values of $\sim 50\%$ at midday for some Ts estimates). The RMSD of $\sim 25\%$ compares well with the 15% to 30% relative errors typically reported when comparing satellite evaporation and ground measurements over different landscapes [13, 3], and gives an idea of the present

525 accuracy available to infer evaporation for agriculture and forest applications.
- 530 • Although in principle more accurate Ts estimates will necessarily result in more accurate heat flux estimations, a clear link between Ts and LE accuracy is not apparent for this specific comparison. This can be the result of the quality of the Ts and LE metrics used for the evaluation (closeness to the station ground estimates), but it can also be linked to SEBS accuracy not only depending on Ts but on other variables (notably Ta and Rn for this specific location where relatively constant vegetation conditions should not make a large contribution to flux changes).

535 An accurate estimation of heat fluxes from satellite T_s estimates certainly
 requires accurate T_s products. But given the sensitivity of the flux methodolo-
 gies to other input parameters [for SEBS, see e.g. 44], to fully benefit from a
 more accurate T_s an improved accuracy in some of the other parameters would
 also be required. For locations with frequent overcast conditions, the clear-sky
 540 nature of the infrared estimates can be a problem. Techniques to propagate the
 heat flux clear-sky estimates to cloudy conditions have been developed [e.g. 18],
 so infrared based estimates could made be available. However, a potentially
 more accurate estimation may be obtained by also exploiting an all-weather T_s ,
 such as the estimates provided by microwave sensors like AMSR-E. The chal-
 545 lenge here is the present lack of routine microwave T_s observations (although
 work towards making these observations is in progress [35]), and the coarse
 spatial resolution of the microwave estimates (though spatial downscaling tech-
 niques already applied with the infrared T_s [e.g. 17] could also be potentially
 used with the microwave T_s). The merging of different type of sensors should
 550 also be exploited, and GlobTemperature has already initiated work towards a
 prototype product that combines infrared and microwave polar and infrared
 geostationary T_s estimates to derive a global all-sky diurnally resolving 10-day
 composite product at 0.05° , which could be useful for some applications at those
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