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High resolution land surface fluxes from satellite data (HOLAPS v1.0): evaluation and uncertainty assessment

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Abstract

Surface water and energy fluxes are essential components of the Earth system. Surface latent heat fluxes provide major energy input to the atmosphere. Despite the importance of these fluxes, state-of-the-art datasets of surface energy and water fluxes largely differ. The present paper introduces a new framework for the estimation of surface energy and water fluxes at the land surface, which allows for temporally and spatially high resolved flux estimates at the global scale (HOLAPS). The framework maximizes the usage of existing long-term satellite data records and ensures internally consistent estimates of the surface radiation and water fluxes. The manuscript introduces the technical details of the developed framework and provides results of a 10 comprehensive sensitivity and evaluation study. Overall the results indicate very good agreement with in situ observations when compared against 49 FLUXNET stations worldwide. Largest uncertainties of latent heat flux and net radiation were found to result from uncertainties in the global solar radiation flux obtained from satellite data products. 15

1 Introduction

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Water and energy fluxes between the land surface and atmosphere are essential components of the Earth system. In the last years land-atmosphere fluxes have been mainly measured locally at the ecosystem scale by a network of flux tower sites within the frame of FLUXNET (Baldocchi, 2008; Baldocchi et al., 2001). However, to generate global datasets of water and energy fluxes, the use of satellite data as well as models

has become indispensable.

Different approaches exist to infer land turbulent surface fluxes by either one of the following methods (Kalma et al., 2008; Wang and Dickinson, 2012): (1) simulations by

²⁵ an off-line land surface model (Roads and Betts, 2000); (2) empirical statistical models, like e.g. obtained by machine learning techniques or neural networks (Jung et al.,



2011); (3) surface energy balance models forced either by satellite remote sensing or re-analysis data (Fisher et al., 2008; Su, 2002); (4) spatial variability of surface parameters as proxies for evapotranspiration (Peng et al., 2013; Peng and Loew, 2014; Roerink et al., 2000).

The Global Energy and Water Cycle Experiment (GEWEX) LandFlux initiative aims for the analysis of existing global land surface flux products as well as the generation of new datasets of land surface fluxes. A comparison of existing global latent heat flux datasets from either land surface models, re-analysis, or satellite estimates was conducted within the GEWEX LandFlux-EVAL initiative (Jiménez et al., 2011; Mueller et al., 2011) and a synergy dataset has been generated which provides latent heat flux et mentious and a set of a constitution of 1° (Mueller et al., 2010)

at monthly timescale and a spatial resolution of 1° (Mueller et al., 2013).

However, large discrepancies remain in the existing data products. The global mean latent heat flux over land was diagnosed as $45 \pm 5 \text{ W m}^{-2}$ with a spread as large as 20 W m^{-2} and substantial regional and seasonal differences (Jiménez et al., 2011).

- These discrepancies might be either related to the different methods applied to estimate the surface fluxes as well as due to different ancillary datasets used. The currently existing datasets have spatial resolutions between 0.25 and 2.5° and are focused on daily to monthly timescales (Miralles et al., 2011; Mu et al., 2007; Vinukollu et al., 2011). Novel long-term satellite data records as well as increasing computing capacities al-
- low, for the first time, to generate global and spatially (< 10 km) and temporally (< 3 h) high resolved estimates of surface fluxes. The ESA WACMOS-ET project has recently investigated the accuracy of four different algorithms for the estimation of surface evaporation at the local as well as global scale. They found accuracies between 40.8 and 80.5 W m⁻² for 3-hourly values comparing against data from 24 eddy covariance towers
 (Michel et al., 2015; Miralles et al., 2015).

The present paper introduces a novel framework for the generation of global high resolution land surface fluxes from satellite data. The High resolution Land Atmosphere surface Parameters from Space (HOLAPS) framework makes use of meteorological drivers coming exclusively from globally available satellite and re-analysis datasets and



is based on a state-of-the-art land surface scheme. HOLAPS allows for the estimation of surface energy and water fluxes at high temporal (< 1h) and spatial (~ 5 km) resolutions. The required drivers for HOLAPS comprise satellite data at different processing levels as well as re-analysis data for a limited number of variables.

- The objectives of the present study are mainly twofold. First, we introduce and validate the surface fluxes from the novel HOLAPS framework at global scales. Second, we perform a thorough uncertainty assessment of the impact of different forcing datasets on the accuracy of surface flux estimates. The latter is motivated by the question how much uncertainty is introduced when using globally available satellite information as a driver for land surface models compared to local data. The HOLAPS results are vali-
- dated using tower based eddy-covariance measurements for a wide range of ecosystems and climates.

We first briefly introduce the HOLAPS concept and framework in Sect. 2. The datasets and methods are introduced in Sects. 3 and 4 respectively. Results and conclusions summarize the study.

2 Model

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The High resOlution Land Atmosphere Parameters from Space (HOLAPS v1.0) framework is used for the estimation of global surface water and energy fluxes. It is based on a state of the art land surface model and was in particular designed to maximize the usage of satellite data as drivers as well as to ensure internal consistency of the different energy and water fluxes. HOLAPS is used for the estimation of global surface

- different energy and water fluxes. HOLAPS is used for the estimation of global surface fluxes at high spatial and temporal resolutions. Figure 1 gives an example of HOLAPS long-term mean latent heat flux estimates for the global scale with a spatial resolution of 5 km.
- Figure 2 shows the general surface state and fluxes simulated by HOLAPS. The all sky surface solar irradiance S^{\downarrow} W m⁻² is either obtained from remote sensing products or is calculated internally by the HOLAPS radiation module using the MAGIC



radiative transfer model (Mueller et al., 2009). The algorithm requires information on aerosol properties, surface albedo (*α*) as well as total column water vapor content (TCW) kg m⁻². Aerosol properties are taken from an aerosol climatology (Kinne et al., 2013). Total column water vapor content can be either derived from climatologies or re-analysis data. Details on the accuracy of the MAGIC radiative transfer model is provided by Posselt et al. (2012).

The land surface scheme is explicitly coupled to a 1-D mixed layer for the planetary boundary layer (PBL) which is used to calculate the surface downwelling radiation consistently with the surface heat fluxes. As the PBL temperature and height are directly linked to the surface turbulent fluxes, a combination of the surface heat fluxes with a PBL model helps to better constrain the surface heat flux estimates (Anderson et al., 2007; Margulis and Entekhabi, 2001). A mixed boundary layer model is assumed (Kim and Entekhabi, 1998; Margulis and Entekhabi, 2001; Smeda, 1979).

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The surface water fluxes comprise vegetation interception, soil moisture dynamics as
 well as evaporation and transpiration processes. The soil moisture dynamics is explicitly simulated using a discretization in different soil layers. The soil moisture information is used e.g. for the estimation of the surface resistance to evapotranspiration.

The present paper will focus exclusively on the validation of HOLAPS 1.0 results using in-situ flux tower measurements as well as the assessment of the sensitivity

of HOLAPS to forcing perturbations. An assessment of spatiotemporal dynamics estimated from HOLAPS and cross comparison against other existing global datasets like e.g. the LandFlux-EVAL dataset (Mueller et al., 2013) will be performed in a separate study.

All symbols are summarized in Appendix A. Details for the entire model formulation ²⁵ are provided in Appendix B.



3 Data

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The HOLAPS framework was in particular designed to (a) maximize the usage of globally available satellite data and (b) ensure internally consistent flux estimates. The drivers required to force HOLAPS are summarized in Table 1. These consist of satel-

⁵ lite remote sensing data products, which have been thoroughly validated and which are briefly introduced in the following. The datasets have in common that they provide (a) long-term observations of the required driver variables and (b) provide this information at comparably high temporal and spatial resolutions which is a major prerequisite. Datasets which are based on geostationary satellite measurements are therefore given preference. Static information on landcover and soil properties is required as well.

3.1 FLUXNET data

Measurements of surface turbulent fluxes are obtained from eddy-covariance towers of the FLUXNET network. These measure the exchange of carbon dioxide, water vapor and energy between terrestrial ecosystems and the atmosphere (Baldocchi, 2003). Standard meteorological measurements as well as soil moisture are collected at many stations. The most comprehensive compilation of these flux tower measurements is available from the "La Thuile 2007" database (Papale et al., 2012).

A subset of FLUXNET stations was used for the analysis in the present study. Stations were selected where (a) all variables required to run the HOLAPS model (Table 1) were available, (b) the station provided data for the years 2003 to 2005 with limited data gaps (> 80 % coverage).

The stations used in the present study are depicted in Fig. 3. A major number of stations are located in Europe and North America, and only a few stations are located in other regions. Table C1 lists all stations (N = 49) that fulfilled the above described criteria and provides detailed information about data availability and relevant references for each station. The total number of measurement years which is used for the present



eddy covariance measurements can be as high as 20 to 30% on average (e.g. Wilson et al., 2002). The reason for this energy balance closure problem is still not fully understood and subject of ongoing research (e.g. Ingwersen et al., 2015). Several ap-

policies. For the present study we only use data from stations, which provide their data

Eddy covariance measurements are subject to uncertainties from various sources.

A common problem is that the eddy-covariance measurements typically do not allow to close the surface energy balance ($R_N - G - H - LE = 0$). The energy imbalance for

under a "Free Fair Use" license (http://www.fluxdata.org).

proaches have been developed to empirically correct for the energy closure (Foken
 et al., 2011; Ingwersen et al., 2015; Twine et al., 2000; Wilson et al., 2002). A simple energy balance correction is applied in this study following the approach as described in Twine et al. (2000). Further uncertainties in the FLUXNET data occur under stable conditions. As the eddy covariance method requires turbulent conditions (Berbigier et al., 2001).

3.2 Large scale forcing data

In the following we will briefly summarize the different forcing datasets used within HO-LAPS. Only dataset available at global scale are used and their details are summarized in Table 1.

3.2.1 Radiation data

²⁰ The surface solar radiation flux (S^{\downarrow}) is either prescribed from existing satellite data products or can be calculated internally within the HOLAPS framework (cf. Appendix B2.2). In both cases a maximum consistency between the shortwave and longwave radiation fluxes is ensured as the same ancillary data (TCW, cloud fractional coverage) is used. This explicit internal consistency of the radiation flux estimates is unique to the HOLAPS framework.



As the surface solar radiation is a major input to the surface energy balance, it is expected that uncertainties in radiation data will also affect the accuracy of the derived water and energy fluxes.

Different approaches to estimate S^{\downarrow} are therefore analyzed in the present study. The following radiation datasets are used:

- *FLUXNET*: The radiation data measured at each FLUXNET station is used as a reference as these local measurements are expected to provide the most accurate surface solar radiation estimates for the FLUXNET locations. They capture also local changes in S^{\downarrow} at high temporal frequencies (e.g. cloud shadowing) and might also be affected by local effects like topographic conditions.

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- CM SAF-SIS: The EUMETSAT Climate Monitoring Satellite Application Facility (CM-SAF) has specialized in the generation of long-term climate data records from satellite. As part of their suite of radiation data products (www.cmsaf.eu), the CM SAF provides solar incoming surface radiation (SIS) data at hourly timescales and with a spatial resolution of 0.03° (Posselt et al., 2012) for all sky conditions. The CM SAF-SIS is based on data from the series of METEOSAT satellites. It therefore provides only a limited area coverage (see Fig. 3).
- GRIDSAT: The Gridded Satellite dataset (GRIDSAT) (Knapp et al., 2011) provides a long-term (January 1980 to present) record of top-of-atmosphere (TOA) radiances in the visible and thermal spectral domains. It is based on the International Satellite Cloud Climate Project (ISCCP) (Knapp, 2008; Rossow and Schiffer, 1991) and provides data every 3-h on an equal angular grid with a resolution of ~ 0.07°.

These TOA radiances in the visible channels are used to estimate a cloud effective albedo (CAL) (Posselt et al., 2012) which is then used subsequently for the calculation of S^{\downarrow} and cloud cover fraction (cf. Sect. B2.2).



3.2.2 Precipitation data

Satellite precipitation datasets are produced from satellite only or combined satellite and ground based measurements at a variety of spatial (0.25 to 2°) and temporal (3-hourly to monthly) resolutions at the global scale. Ground based precipitation estimates

- ⁵ like e.g. from ground based rain radars provide even higher temporal and spatial resolution, but are available only for limited areas. A comprehensive review and intercomparison of existing satellite based precipitation products and their application is provided by Kidd et al. (2012) and Kucera et al. (2013)
- The TRMM Multisatellite Precipitation Analysis (TMPA) product (3B42 v7) is used for the present study (Huffman et al., 2007). It combines microwave sounding and infrared observations and compensates product biases using rain gauge information on monthly timescales. TMPA provides 3-hourly precipitation information at a spatial resolution of 0.25°. It is available since 1998 until present and covers the geographical extent of 50° N to 50° S.
- The high temporal frequency of the measurements is a major advantage for flux estimates and the main reason why TMPA is currently used within HOLAPS. The spatial extent of TMPA however currently limits the application of HOLAPS to that same extent $(\pm 50^{\circ} \text{ latitude})$.

3.2.3 Vegetation data

Leaf area index (LAI) data products from the Moderate Resolution Spectroradiometer (MODIS) instruments (Justice et al., 2002) are used in the present study. We use an enhanced product from Beijing Normal University¹ (Yuan et al., 2011) which provides enhanced temporal and spatial consistency of the MODIS LAI fields by post-processing the original MOD15A2 products (Myneni et al., 2002). This results in much more con-



¹http://globalchange.bnu.edu.cn/research/lai

sistent LAI fields than in the original product which contains abrupt changes in the time series.

Surface albedo information is obtained from the ESA GlobAlbedo project (Muller et al., 2012; Potts et al., 2013).

Both, LAI data and surface albedo are available every 8-days. As both variables are varying slowly in time, they are linearly interpolated to the model timestep.

3.2.4 Re-analysis data

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A limited number of additional fields (temperature, wind speed, total column water vapor path, pressure) are required from global re-analysis as these variables are not available from remote sensing data at the required temporal and spatial scales. The ERA-interim re-analysis (Dee et al., 2011) fields are used for that purpose which provide 6-hourly data on a regular global grid with 512 times 256 grid points, which corresponds to a spatial sampling of ~ 0.7° . The re-analysis fields are remapped to the flux tower locations using bilinear interpolation.

15 3.2.5 Landcover data

Global landcover information is available with a spatial resolution of 300 m from the ESA Climate Change Initiative landcover project (Bontemps et al., 2012; Defourny et al., 2014). The land cover information is used for the spatial discretization of land cover dependent parameters in HOLAPS like e.g. roughness length or surface resistance parameters. These are summarized in Table B1.

However for the present study, no global landcover dataset is used as the experiments conducted are only performed on the point scale. The landcover type is known for each FLUXNET station and is therefore used in the present study.



3.2.6 Soil data

Information on soil properties is obtained from the Harmonized World Soil Database (HWSD) (FAO, 2012). Currently the HWSD is the only globally available soil information. The HWSD is based on soil mapping units with varying sizes. Thus no fixed resolution can be given, but the map is gridded with a spatial spacing of 30 arcsec. The information on soil texture (sand, clay content) is used to derive soil hydrological properties using pedo-transfer functions (Cosby et al., 1984; Lee, 2005; Rawls and

Brakensiek, 1985).

As the HWSD is a global dataset, the local soil properties might differ from the one of the used mapping units. Further uncertainties are introduced by the applied pedotransfer functions (e.g. Wösten et al., 2001).

4 Methods

4.1 Experimental setup

To quantify the accuracy of HOLAPS and the uncertainties related to the usage of
 satellite data as drivers we conduct a series of sensitivity experiments. Using the different datasets introduced in Sect. 3.2, we aim to investigate the uncertainty introduced by replacing a locally measured forcing with satellite based drivers. First a control simulation (CTRL) is conducted which is based exclusively on local measurements from FLUXNET only. This allows to quantify HOLAPS accuracies without additional uncertainties from the driver variables. Thus, the CTRL simulation is considered as the baseline accuracy of the current HOLAPS framework. For each site multiple years are

used for the simulations (see Table 2). Results are then compared against reference measurements from FLUXNET and the accuracy of the simulations is quantified using various skill scores (cf. Sect. 4.2.1).



Further experiments are conducted by replacing individual drivers (e.g. radiation, precipitation) with data from either satellite observations or re-analysis. This allows to quantify the additional uncertainty introduced by the usage of this particular data product. The different experiment names allow to identify the variable that was replaced ⁵ by satellite/re-analysis data (e.g. experiment T_a = air temperature was replaced).

However, as the different datasets introduced in Sect. 3.2 cover different spatial domains (cf. Fig. 3) we generated subsets of stations representing the following different spatial domains:

- Global (G): global coverage using the maximum number of FLUXNET stations available

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- $-\pm 50^{\circ}$ (50): as the precipitation data currently used is available only between 50° S and 50° N, we use this spatial domain to analyze the sensitivity to changes in the precipitation forcing.
- Meteosat disc (M): The analysis of the impact of satellite surface radiation datasets on HOLAPS results is investigated for the Meteosat spatial domain, as long-term radiation datasets are only available from the CM SAF for Meteosat so far.
- A few FLUXNET stations are located within the Meteosat disc, but within latitudes of 50° S to 50° N. For these stations we conducted additional simulations (M_50).
- ²⁰ Control simulations are conducted for all of these different spatial domains. As a consequence a total of four different control simulations with different number of stations are conducted. All the other experiments were also performed for these different spatial subsets where applicable. The differences between the same experiment type, at different spatial domains provides additional information on the variability of the error metrics as a function of the number of FLUXNET stations used. Table 2 summarizes all experiments conducted and the number of stations and simulation years.



4.2 Analysis

We compare the net radiation and latent heat flux of HOLAPS with the corresponding reference data from FLUXNET at hourly, daily and monthly timescales using standard statistical skill scores. The variance of the difference between the model simulations

and FLUXNET data is a function of (a) the uncertainties of the HOLAPS model itself, (b) the sensitivity of the HOLAPS model to uncertainties in the forcing data as well as (c) uncertainties in the FLUXNET reference data. Uncertainties in the FLUXNET measurements might also result from varying temporal and spatial footprints of the flux tower measurements (Chen et al., 2011).

10 4.2.1 Statistical metrics

The mean squared difference E^2 between in situ observations (*x*) and model results (*y*) is given as

$$E^{2} = \frac{1}{N} \sum_{i}^{N} (x_{i} - y_{i})^{2} = \bar{E}^{2} + {E'}^{2} = \text{RMSD}^{2}$$

with the bias $\overline{E} = \overline{x} - \overline{y}$. The overbar indicates temporal averaging. The root mean square difference (RMSD) is defined as the square root of Eq. (1). For the calculation of the centered root mean square difference (cRMSD), the bias is removed in advance. It is then defined as

$$E' = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [(x_i - \bar{x}) - (y_i - \bar{y})]^2} = \text{cRMSD}$$

which is related to the Pearson correlation coefficient (r) as (Taylor, 2001)

$$_{^{20}} E'^2 = \sigma_x^2 + \sigma_y^2 - 2\,\sigma_x\sigma_y r$$

(1)

(2)

(3)

The above defined metrics (r, cRMSD, RMSD, bias) are calculated for each FLUXNET station over the entire analysis period. We then normalize each metric by the corresponding metric obtained from the control experiment to obtain relative deviations of the error skill scores of an experiment and the same score from the CTRL simulation for the same station.

4.3 Temporal aggregation and data gaps

The comparison between FLUXNET and HOLAPS is performed on hourly, daily and monthly timescales and the above metrics are calculated for these different aggregation periods respectively.

- ¹⁰ As the FLUXNET measurements also contain data gaps these might introduce sampling biases. A traceable approach is therefore required to derive the temporally aggregated reference. A daily mean is therefore only calculated if at least 16 h (= 2/3) of valid data was available from the FLUXNET measurements on that particular day. Given half hourly data, this requires that at least 32 valid data samples are available
- from the eddy-covariance dataset. Once daily mean fluxes have been calculated these are used to estimate monthly mean statistics. A monthly mean is calculated if at least 2/3 of the days of a month contained valid values. This approach was chosen as the data gaps might introduce biases for daily and monthly values and it was found that the calculated error statistics could be largely influenced by a few dates with insufficient reference data. The chosen approach therefore provides a traceable procedure
- to provide reference data for different temporal resolutions.

5 Results

The HOLAPS validation results are summarized in the following. We hereby focus on the accuracy of the surface energy and water fluxes estimated by HOLAPS and evalu-



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ate the surface net radiation (R_N) , solar radiation (R_G) as well as the surface latent heat flux (LE) for all experiments.

5.1 Evaluation of surface net radiation (R_N)

The estimated surface net radiation from all 49 stations is compared against the corresponding measurements from FLUXNET in Fig. 4 for the CTRL experiment and all FLUXNET stations. Overall, HOLAPS provides very accurate estimates of $R_{\rm N}$ at hourly as well as daily timescales. The correlation between reference data and HOLAPS is r = 0.96 (0.91) for hourly (daily) data. All correlations are significant (p < 0.05). The corresponding RMSD is 54.4 (27.2) W m⁻² for hourly (daily) data.

- However, as these statistics are based on the entire data record from all FLUXNET 10 stations, the accuracy of HOLAPS net radiation is also validated for each of the stations individually. Statistics for the RMSD, cRMSD as well as correlation are summarized in Fig. 5 for all experiments introduced in Sect. 4.1 for hourly timescales. The corresponding error statistics for daily and monthly fluxes are summarized in the Appendix D.
- Comparable accuracies are obtained for all CTRL simulations, which are based on a 15 different number of stations (varying spatial coverage). Using satellite and re-analysis data as drivers for temperature, precipitation or wind speed the net radiation accuracies show only minor changes. Larger sensitivity of HOLAPS is observed when replacing the local surface solar radiation with satellite based surface radiation data (METEOSAT,
- GRIDSAT experiments). The RMSD for surface net radiation ranges between 100 and 20 120 Wm^{-2} for the majority of the stations compared to 30 to 60 Wm^{-2} for the other experiments, which corresponds to a significant increase in uncertainty.

While the correlation coefficients for the different CTRL simulations are very high (r >0.95), the correlation coefficients for the experiments using METEOSAT or GRIDSAT

radiation are lower, still amounting to r > 0.8 for most cases. Only minor differences can 25 be observed between the RMSD and cRMSD, which indicates that the hourly estimates of $R_{\rm N}$ have only a small bias.



The accuracy of the daily and monthly net surface radiation show a similar picture like the hourly values (see Figs. D1 and D2). The RMSD for the daily fluxes ranges between 18 and 61 W m⁻² for the majority of the results and correlations are typically larger than r = 0.95. In the cases where satellite data is used as radiation driver the RMSD also increases and the correlation coefficient reduces. However, for monthly mean fluxes (Figure D2) the discrepancy between CTRL simulations and the METEOSAT and GRIDSAT experiments reduces.

5.2 Evaluation of surface solar radiation flux (S^{\downarrow})

As shown before, major uncertainties in the surface net radiation flux are introduced by using satellite radiation products within HOLAPS. The accuracy of the radiation data itself is therefore investigated in the following at the FLUXNET stations. Figure 6 shows the RMSD and cRMSD for hourly surface global radiation fluxes. For the CTRL simulations, the deviations are close to zero as these experiments are based on the same radiation data like is used as reference. Minor deviations still occur in these cases

as the FLUXNET measurements are not available at exactly the same time steps as HOLAPS simulations. As HOLAPS interpolates the driver data to equal time steps, small interpolation differences might occur which result in non-zero RMSD values.

The RMSD of the satellite radiation data (METEOSAT, GRIDSAT) ranges between 140 and 155 W m⁻² at hourly timescales. This is partly related to a negative bias between the FLUXNET radiation data and the satellite radiation data. Thus the deviations

in the radiation data have by far the strongest effect on the surface net radiation flux and are also likely to affect the surface latent heat flux estimates, which will be analysed subsequently.

5.3 Evaluation of latent heat flux (LE)

²⁵ The overall relationship between HOLAPS latent heat flux estimates and FLUXNET measurements is illustrated in Fig. 7. The RMSD is 53, 35 and 30 W m^{-2} for the hourly,



daily and monthly flux estimates for the CTRL_G simulations. The correlation coefficient ranges between r = 0.86 for hourly data to r = 0.78 for daily and monthly data.

Error statistics for all experiments is provided in Fig. 8. The increased uncertainty in the surface solar radiation and thus R_N has a direct effect on the accuracy of the latent

⁵ heat flux estimates. Correlation coefficients are smallest for the experiments that use satellite surface solar radiation data. However, the correlations are still high with r > 0.7for most of the stations and experiments. The RMSD for the CTRL simulations ranges between 37 and 58 W m⁻² for the majority of the cases. Largest RMSD is observed for the METEOSAT and GRIDSAT experiments. However, results from the experiments when replacing the air temperature and wind speed with re-analysis data show that this introduces also uncertainties in the latent heat flux estimates. The RMSD ranges between 40 and 62 W m⁻² for these experiments. Corresponding results for daily and

5.4 Summary of HOLAPS accuracies

monthly timescales are provided in Figs. D3 and D4.

- ¹⁵ So far we have summarized the overall accuracies of HOLAPS for the different experiments. As the HOLAPS framework is designed to be used at the global scale with a maximum of satellite and re-analysis data as drivers, we summarize in the following the accuracy of the HOLAPS results for the GRIDSAT_G experiment which corresponds to the case where only satellite and re-analysis drivers are used for HOLAPS flux es-²⁰ timates. Results are compared against the accuracy of the CTRL_G experiment that
- uses exclusively FLUXNET station data and the same stations. The overall accuracies at hourly, daily and monthly timescales for these two experiments are summarized in Table 3.

On monthly timescales, the results for the latent heat flux of the CTRL simulations and GRIDSAT based estimates are rather comparable. The correlation is r = 0.75 and r = 0.78 and RMSD are 30.1 and 30.2 W m⁻² for the GRIDSAT_G and CTRL_G experiments respectively. However at the hourly and daily timescales the RMSD can be 20–



30 % larger for the GRIDSAT_G experiment than for the CTRL_G experiment, which is likely to be a result of the uncertainties of the surface shortwave radiation fluxes.

The accuracy of the two surface solar radiation dataset was estimated for the stations that were located within the Meteosat footprint. The RMSD and correlations for S^{\downarrow} are summarized in Table 3 as well. For the METEOSAT experiment, the hourly (daily, monthly) RMSD for the surface solar radiation flux is 142.0 (71.7, 15.5) W m⁻² while it is 134.3 (70.2, 32.3) W m⁻² for GRIDSAT respectively.

6 Discussion

The HOLAPS framework provides estimates of surface net radiation and latent heat flux at accuracies which are comparable to those obtained in other studies. It was found that the major source of uncertainty is the surface solar radiation data used as a forcing. When using tower only measurements (CTRL), the RMSD of HOLAPS latent heat flux is 53.0 (35.1) W m⁻² for hourly (daily) fluxes. Michel et al. (2015) evaluated the performance of four different algorithms to estimate the surface latent heat flux, within the WACHMOS-ET project, using either tower based forcings or satellite data. As this is probably one of the most comprehensive studies existing, we compare our results against results from that study. The RMSD for the algorithms investigated in this study ranges between 40.8 and 88.5 W m⁻² when comparing their results at 3-hourly timestep and using tower data as a driver. At daily timescales, the RMSD obtained for the same four algorithms ranged between 22.7 and 52.2 W m⁻². Correla-

- tions were found to range between 0.58 and 0.77 (0.43 and 0.61) for 3-hourly (daily) values. For HOLAPS we have provided the accuracy measures when using all data samples (all stations + all years) at once. These were provided in Table 3. The HO-LAPS hourly (daily) RMSD is 53.0 (35.1) W m⁻² with correlations of r = 0.86 (r = 0.78).
- However these values are not exactly comparable with the study of Michel et al. (2015) as a) the HOLAPS statistic is based on hourly values instead of 3-hourly values for the WACHMOS-ET project. Further, the information provided by Michel et al. (2015) is



given as the mean value from results of all investigated stations. Thus, instead of calculating the RMSD for all data samples, these authors calculated first the error statistics and then provided the mean skill score. When following a similar approach for the 49 stations investigated in the present study, the mean RMSD of HOLAPS corre-

⁵ sponds to 47.6 (30.7) W m⁻² with mean correlations of r = 0.89 (0.84) for hourly (daily) timescales. Thus following a similar approach like (Michel et al., 2015) the results of the present study are very similar to those of WACHMOS-ET.

Similar differences are also obtained when using satellite data as driver for the latent heat flux estimates. The RMSD obtained for 3-hourly (daily) estimates by Michel et al.

- ¹⁰ (2015) ranges between 47.6 and 88.5 (24.5 and 59.0) W m⁻² while HOLAPS hourly (daily) RMSD is 65.2 (39.5) W m⁻² with correlations of r = 0.76 (r = 0.65), while Michel et al. (2015) found correlations 0.47 < r < 0.67 (0.35 < r < 0.62) for 3-hourly (daily) comparisons respectively. Overall, HOLAPS seems to provide improved correlations which might be due to the enhanced temporal resolution of HOLAPS. It needs to be empha-¹⁵ sized however, that results of the present study are not fully comparable with Michel et al. (2015), due to the different temporal sampling, and the different number of stations
 - al. (2015), due to the different temporal sampling, and the different number of stations investigated (N = 49 in this study instead of N = 24).

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Overall, a small bias was observed, for both the simulations with flux-tower and satellite forcings (see Table 3). While the CTRL and GRIDSAT experiments differ on hourly and daily timescales, the RMSD for the monthly results is very similar. This indicates that the uncertainties due to the large scale forcing are minimized at longer timescales. Replacing station precipitation data with the TMPA large scale satellite forcing as well as using ERA-interim for temperature and wind speed has minor effect on the accuracy of the results obtained. By far the largest uncertainties are introduced when using satel-

²⁵ lite based surface solar radiation data, whereas similar accuracies are obtained using either the METEOSAT or GRIDSAT data. The accuracy for the surface solar radiation flux from METEOSAT was found to have an RMSD of 142.0 (71.7) W m⁻² for hourly (daily) timescales using the FLUXNET stations located within the Meteosat footprint (N = 19). This is somewhat contradictory to the accuracies of the METEOSAT product



reported by Müller et al. (2015) where the daily RMSD of the product is reported to be 17.9 W m^{-2} . Thus, further investigations are required to investigate the results obtained in this study. As a further improvement of the surface solar radiation flux is expected to improve the latent heat flux estimates, a further thorough investigation of the impact of different surface solar radiation dataset will be performed in a future study.

7 Conclusions

This study has introduced a new framework for the estimation of high resolution land surface water and energy fluxes, HOLAPS. The framework was developed to maximize the usage of existing satellite data records and to allow for the generation of temporal and spatial high resolved and consistent global water and energy fluxes. This first 10 study analyzed the accuracy of HOLAPS using data from 49 eddy covariance towers. A sensitivity analysis was performed to investigate the tradeoff in using satellite data as drivers instead of locally measured tower based data. The accuracy of the HO-LAPS surface fluxes was found to be comparable or even better than results obtained in other studies. The hourly (daily) RMSD for the surface net radiation flux was 54.4 (27.2) 15 W m⁻² with correlations of r=0.96 (r = 0.91) when using tower data as drivers for HO-LAPS. For the latent heat flux, the obtained RMSD was 53.0 (35.1) W m⁻² with r = 0.86(r = 0.78). Using satellite and re-analysis data as only drivers, the RMSD and correlations were found to be 68.9 W m⁻² and r = 0.75 (42.1, r = 0.63) for the latent heat flux. Largest uncertainties resulted from the uncertainties of the surface solar radiation flux. 20 However, on monthly timescales, these uncertainties were minimized which indicates

However, on monthly timescales, these uncertainties were minimized which indicates that comparable accuracies can be obtained when using satellite based drivers instead of local in-situ data.

A first dataset for HOLAPS is planned to be released to the scientific community after a thorough validation and cross comparison against other datasets like e.g. the LandFlux-Eval (Mueller et al., 2013) data. Further improvements of the HOLAPS framework will comprise the assimilation of land surface temperature data to constrain the



surface latent heat flux estimates as well as the usage of new satellite observations like e.g. provided by the new SENTINEL series of satellites.

Appendix A: Acronyms

Acronyms used throughout the text are summarized in Table A1.

5 Appendix B: Detailed HOLAPS model description

The different components of the HOLAPS framework and its land surface model are described in detail in the following sections. The variable definitions used and their units are summarized in Table A1.

B1 HOLAPS runtime environment

The general workflow of the HOLAPS runtime environment is illustrated in Fig. B1. After specifying the model setup by the user, the HOLAPS main controller checks the availability of all required data and then launches subprocesses to run the model. Required forcing data is read for each time step and interpolated in space and time if required. Surface water and energy fluxes are calculated for each timestep. Results are then written to netCDF files and additional statistics are calculated if required.

B2 HOLAPS sub-modules

The different sub-modules used within HOLAPS are described in the following.

B2.1 Surface energy balance

The surface energy balance is given as:

$$R_{\rm N} - \rm LE - H - G = 0$$



(B1)

 $R_{\rm N}$ is estimated from the shortwave and longwave radiation fluxes as:

 $R_{\rm N} = (1 - \alpha)S^{\downarrow} + \varepsilon L^{\downarrow} - \varepsilon \sigma T_{\rm s}^4$

B2.2 Radiation module

Shortwave solar surface radiation fluxes

⁵ The shortwave clear sky solar radiation flux (S_{clear}^{\downarrow}) is estimated using the MAGIC radiative transfer model (Mueller et al., 2009). The shortwave surface downwelling solar flux (S^{\downarrow}) for all sky conditions is then obtained from the clear-sky downwelling solar flux and the clear sky index *k* as (Posselt et al., 2012)

 $S^{\downarrow} = k(CAL)S^{\downarrow}_{clear}$

The clear sky index is related to CAL through the following relationship (Hammer et

al., 2003)

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$$k = \begin{cases} 1.2 & \text{CAL} \le -0.2 \\ 1 - \text{CAL} & -0.2 < \text{CAL} \le 0.8 \\ a + b \cdot \text{CAL} + c \cdot \text{CAL}^2 & 0.8 < \text{CAL} \le 1.1 \\ 0.05 & \text{CAL} > 1.1 \end{cases}$$

where a = 2.0667, b = -3.667, c = 1.6667.

Longwave surface radiation fluxes

¹⁵ The longwave surface downwelling radiation flux (L^{\downarrow}) depends on the near surface moisture and temperature profile as well as the cloud coverage. The clear sky longwave downwelling radiation flux L_{slab}^{\downarrow} is calculated using the PBL model (Margulis and Entekhabi, 2001). L_{slab}^{\downarrow} is then corrected for cloud coverage as (Brubaker and Entekhabi, 1995):

²⁰
$$L_{\downarrow} = L_{\text{slab}}^{\downarrow}(1+0.17c^2)$$

(B2)

(B3)

(B4)

(B5)

B2.3 Soil module

The surface temperature T_s [K] is obtained by a revised force restore approach (Ren and Xue, 2004) as:

$$\frac{\partial T_s}{\partial t} = C_G \left(R_N - LE - H \right) - \omega \left(T_s - T_d - \pi d \gamma_s \right) - AB'' \sin[\omega t + a'']$$
(B6)

⁵ where A [K] is the diurnal temperature amplitude of T_s , $C_G = 2(\Gamma\sqrt{86400\pi})^{-1}$

 $\mathrm{K} \,\mathrm{m}^2 \,\mathrm{J}^{-1}$ is the thermal inertia coefficient and Γ is the thermal inertia which is estimated as function of soil moisture conditions (Murray and Verhoef, 2007).

The parameters B'' and a'' in Eq. (B6) are set to $a'' = 0.45\pi$ and B'' = 0.158 (Ren and Xue, 2004). The prognostic equation for the deep soil layer temperature T_d is

$$\frac{\partial T_{d}}{\partial t} = -\frac{1}{\tau} (T_{d} - T_{s} + \gamma_{s} \pi d)$$
(B7)

where *d* is the soil temperature damping scale depth with typical values in the order of $d = 0.15 \,\mathrm{m}$. The lapse rate between the mean surface and deep-layer temperature $\gamma_{\rm s}$ K m⁻¹ is estimated from the differences between $T_{\rm s}$ and $T_{\rm d}$ and $\tau = 86\,400\,\mathrm{s}$ is the time period, one day in our case.

15 B2.4 Water balance module

The surface water balance is defined as

$$P - \frac{\partial I}{\partial t} - Q - \mathsf{ET} - \frac{\partial W}{\partial t} = 0$$

The soil moisture dynamics is calculated using a multilayer soil scheme, discretized into 5 layers. The soil layers have a thickness of dz = [0.05, 0.1, 0.25, 0.6, 1.0] m. Soil



(B8)

moisture fluxes between the different soil layers are simulated by solving numerically the Richards equation (Richards, 1931):

$$\frac{\partial m_{\rm v}}{\partial t} = \frac{\partial}{\partial z} \left[\mathcal{K}(m_{\rm v}) \left(\frac{\partial \psi}{\partial z} + 1 \right) \right]$$

The water interception by the canopy is estimated by (Valente et al., 1997)

where $ET_I = \lambda^{-1} LE_i$ is the transpiration from the canopy interception storage and *D* is the through fall and drainage of water from the canopy layer to the soil.

B2.5 Turbulent flux module

For a vegetated patch with fractional vegetation coverage f_c the surface latent heat flux is calculated as the weighted sum of the evaporation from soil (LE_S), the transpiration from the canopy (LE_c) as well as evaporation from water intercepted by the canopy layer (LE_i) as

 $LE = (1 - f_{c})LE_{S} + f_{c} [(1 - w_{I})LE_{c} + w_{I}LE_{I}])$

where $w_I = (I/I_{max})^b$ is a weighting factor dependent on the current canopy interception storage *I*, the potential maximum interception storage $I_{max}(\Lambda)$ (von Hoyningen-Huene, 1981) and an empirical parameter b = 0.5 (Chen and Dudhia, 2001). The vegetation cover fraction f_c is obtained from leaf area index (Λ) as (Norman et al., 1995):

 $f_{\rm c} = 1 - e^{-0.5\Lambda}$

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which assumes a random leaf distribution with spherical leaf angle distribution. The different latent heat flux components in Eq. (14) are then estimated using the Priestley-



(B9)

(B10)

(B11)

(B12)

Taylor approach as:

$$LE_{s} = \phi \alpha_{p} R_{N,S} \frac{\Delta}{\Delta + \gamma}$$
$$LE_{c} = \phi \alpha_{p} R_{N,c} \frac{\Delta}{\Delta + \gamma}$$
$$LE_{i} = \alpha_{p} R_{N,c} \frac{\Delta}{\Delta + \gamma}$$

⁵ where $\alpha_{pt} = 1.26$ is the Priestley-Taylor parameter for equilibrium evapotranspiration and Δ , γ are the slope of the water vapor saturation curve and psychrometer constant (Pa K⁻¹) respectively. The inhibition function $0 \le [\phi] \le 1$ describes the reduction of LE due to limiting factors like radiation, temperature and soil moisture. The soil net radiation is estimated as (Norman et al., 1995):

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$$R_{\rm N,S} = R_{\rm N} e^{0.9 \ln(1-f_{\rm c})}$$

and the canopy net radiation is then calculated as

$$R_{\rm N,C} = R_{\rm N} - R_{\rm N,S} \tag{B15}$$

The sensible heat flux is estimated as:

$$H = \rho c_{\rho} (T_{\rm s} - T_{\rm a}) / r_{\rm a} \tag{B16}$$

where the aerodynamic surface resistance r_a (sm⁻¹) is calculated as:

$$r_{\rm a} = \left[\left(\log \frac{z - d}{z_{0,\rm m}} - \Psi_{\rm m} \right) \left(\log \frac{z - d}{z_{0,\rm h}} - \Psi_{\rm h} \right) \right] \left[k^2 u_z \right]^{-1} \tag{B17}$$

where $k \approx 0.41$ is the von Karman constant. The stability correction functions $\Psi_{m,h}$ are calculated after (Paulson, 1970) using the Richardson number *Ri* as an indicator for atmospheric stability. The roughness lengths for momentum and heat ($z_{0,m}$, $z_{0,h}$) are parameterized for each landcover type (Table B1).

(B13)

(B14)

Surface inhibition functions

The canopy inhibition function $0 \le \varphi_c \le 1$ is defined as (Chen and Dudhia, 2001)

$$\phi = \frac{1 + \Delta R_r^{-1}}{1 + C_h R_c + \Delta R_r^{-1}}$$

where R_r is a function of surface air temperature and pressure, C_h is the surface exs change coefficient for heat and moisture and R_c is the canopy resistance, given as

$$R_{\rm c} = \frac{r_{\rm min}}{\Lambda f_{S\downarrow} f_{T_a} f_{\rm m_v}} \tag{B19}$$

$$f_{S^{\downarrow}} = \frac{r_{\min}r_{\max}^{-1} + ff}{1 + ff}$$

$$f_{T_{a}} = 1 - 0.0016(298 - T_{a} - 273.15)^{2}$$

$$f_{m_{v}} = \frac{\ln \frac{w_{0}w_{f}}{w_{0} + (w_{f} - w_{0})\exp(-\mu\Theta)}}{\ln w_{f}}$$

with $ff = \frac{1.1S_{\parallel}}{\Lambda r_{rad}}$, where r_{rad} is a radiation specific parameter (W m⁻²) and r_{min} and r_{max} are the minimum and maximum canopy resistance (s m⁻¹), which are all landcover specific parameters (Table B1). The relative degree of soil saturation is given by Θ and $w_0 = 1$, $w_f = 800$, $\mu = 12$ are empirical parameters (Anderson et al., 2007). f_{T_a} and $f_{S^{\downarrow}}$ are based on (Chen and Dudhia, 2001).

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(B18)

(B20)

B2.6 Planetary boundary layer module

The prognostic equations of the PBL model are given by (Kim and Entekhabi, 1998; Smeda, 1979)

$$\frac{\partial z}{\partial t} = \frac{2(G_* - D_1 - \delta D_2)\theta_{\rm m}}{gz\delta_{\theta_{\rm m}}} + \frac{H_{\rm v}}{\rho c_\rho \delta_{\theta_{\rm m}}}$$
(B21)

$${}_{5} \rho c_{\rho} z \frac{\mathrm{d} \theta}{\mathrm{d} t} = H - H_{\mathrm{top}} - R$$

with

10

 $R = a(\theta_{\rm m} - \theta_{\rm s})$

with the proportionality constant $a = 10^{-5}$ (s⁻¹) (Smeda, 1979). Alternative approaches to simulate the radiative cooling have been proposed (Kim and Entekhabi, 1998; Margulis and Entekhabi, 2001). The relationship between PBL air temperature (*T*) and θ is given by

$$\theta = T \left(P_0 P^{-1} \right)^{R/c_p} \tag{B24}$$

with $R/c_p \approx 0.286$ for air. The details of the model formulations are based on Smeda (1979) and are given as follows:

$$G_* = u_*^2$$

$$D_1 = u_*^2 u(1 - e^{-\zeta z})$$

$$D_2 = 0.4 \left(\frac{gz}{\theta_m} \frac{H_v}{\rho c_p}\right)$$

$$H_v = H + 0.61 \theta_m c_p ET \approx H + 0.07 LE$$

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with $\delta = 0$ in stable conditions and $\delta = 1$ in unstable conditions. We set $\zeta = 0.01$ to ensure a realistic collapse of the PBL (Kim and Entekhabi, 1998).

During daytime, the growth of the PBL is determined by the second term on the right side in Eq. (33). During the transition between unstable and stable conditions, the PBL collapses because of turbulence dissipation. The PBL height during this transition phase is given as (Smeda, 1979)

$$z = -\frac{2(G_* - D_1)\rho c_\rho \theta_{\rm m}}{H_{\rm v}g}$$

10

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when assuming that $H_{top} = 0$. Equation (32) is applied in this transition phase until

$$\left|\frac{\mathrm{d}z}{\mathrm{d}t} - \frac{H_{\mathrm{v}}}{\rho c_{\rho} \delta_{\theta_{\mathrm{m}}}}\right| \leq 0.05 \frac{H_{\mathrm{v}}}{\rho c_{\rho} \delta_{\theta_{\mathrm{m}}}}$$

The mixed layer is capped by an inversion with inversion strength $\delta_{\theta_m}[K]$ which determines the entrainment of overlying dry air from the free atmosphere as (McNaughton and Spriggs, 1986)

$$H_{\rm top} = -\rho c_{\rho} \delta_{\theta_{\rm m}} \frac{\mathrm{d}z}{\mathrm{d}t} \tag{B31}$$

Dry air entrainment causes the inversion strength itself to change according to

¹⁵
$$\frac{\mathrm{d}\delta_{\theta_{\mathrm{m}}}}{\mathrm{d}t} = \gamma_{\theta_{\mathrm{m}}}\frac{\mathrm{d}z}{\mathrm{d}t} - \frac{\mathrm{d}\theta}{\mathrm{d}t}$$
 (B32)

where $\gamma_{\theta m}$ (K m⁻¹) is the potential temperature lapse rate above the PBL and is assumed to be constant.

B3 Model parameterization

The landcover specific model parameters are summarized in the following table. They are based on the publications of Chen and Dudhia (2001) and Hagemann (2002).

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Appendix C: Fluxnet stations

Table C1 lists all FLUXNET stations (N = 49) that are used in this study.

Appendix D: Ancillary HOLAPS evaluation results

Error statistic for HOLAPS daily and monthly LE and R_N .

5 Code availability

land surface parameters.

Code for this paper is available from the corresponding author on request. A publication of the HOLAPS code in a public repository is envisaged as part of later releases.

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²⁰ The article processing charges for this open-access publication were covered by the Max Planck Society.



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A. Loew et al.





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Overview of ualasets used as universitor HOLAPS.								
Variable	Dataset	Spatial resolution	Temporal resolution	Reference				
Precipitation	TMPA v7	0.25°	3-h	Huffman et al. (2007)				
Surface solar radiation flux	METEOSAT SARAH SIS	2.5 km	hourly	Müller et al. (2015)				
TOA reflectance	GRIDSAT	8 km	3-h	Knapp et al. (2011)				
Temperature	ERA-interim	T255 (~ 80 km)	6-h	Dee et al. (2011)				
Wind speed	ERA-interim	T255 (~ 80 km)	6-h	Dee et al. (2011)				
Total column water vapor	ERA-interim	T255 (~ 80 km)	6-h	Dee et al. (2011)				
Soil texture	HWSD	NA	Static	FAO (2012)				
Surface albedo	Globalbedo	1 km	8 days	Muller et al. (2012)				
Leaf area index	MODIS Beijing Normal University	1 km	8 days	Yuan et al. (2011)				

Table 1. Overview of datasets used as drivers for HOLAPS.

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Table 2. List of performed model experiments. Includes the number of stations and station years as well as the data source: F = FLUXNET data; S = satellite data for precipitation and radiation; additional data from satellite for albedo and LAI, and from ECMWF reanalyses for temperature, total column water vapor, and wind speed.

Coverage	verage Experiment Number of		Pre	cipitation	Rac	Radiation		Temperature		Wind speed	
		stations	years	F	S	F	S	F	S	F	S
Global	CTRL_G	49	103	х		х		х		х	
Metosat disk	CTRL_M	19	37	х		х		x		x	
	METEOSAT_M	19	37	х			х	х		х	
	GRIDSAT_M	19	37	х			х	х		х	
Global	GRIDSAT_G	49	103	x			x	x		x	
±50°	CTRL_50	31	63	х		х		х		х	
	GRIDSAT_50	31	63	х			х	х		х	
	Tmpa_50	31	63		х	х		х		х	
	Ta_50	31	63	х		х			х	х	
	Wind_50	31	63	х		х		х			x
Metosat disk & ±50°	CTRL_M_50	10	17	х		x		x		х	
	METEOSAT_M_50	10	17		х		х		х		х
	GRIDSAT_M_50	10	17		х		х		х		х



Discussion Pa	GM 8, 10783–1	DD 0841, 2015
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Table 3. Overall HOLAPS accuracies for R_N , LE and S^{\downarrow} at hourly (h), daily (d) and monthly (m) timescales for the CTRL, GRIDSAT and METEOSAT experiments.

Variable	Experiment	$RMSD (W m^{-2})$			cRM	SD (Wr	m ⁻²)	R		
Variable	Experiment	Н	D	М	Н	D	М	Н	D	М
R _N	CTRL_G	54.4	27.2	23.0	54.3	26.9	22.6	0.96	0.91	0.91
	GRIDSAT_G	111.8	50.5	29.5	110.6	47.6	23.6	0.86	0.68	0.90
LE	CTRL_G	53.0	35.1	30.2	51.3	32.1	26.4	0.86	0.78	0.78
	GRIDSAT_G	68.9	42.1	30.1	68.3	40.8	28.1	0.75	0.63	0.75
R _G	METEOSAT_M	142.0	71.7	15.5	141.8	71.2	12.9	0.83	0.73	0.99
	GRIDSAT_M	134.3	70.2	32.3	131.6	64.8	16.6	0.86	0.74	0.98

Table A1. Acronyms used throughout the text.

$\begin{tabular}{ c c c c c } \hline C_{\rho} & Heat capacity of dry air & [J kg^{-1} K^{-1}] \\ \hline \rho & Density of dry air & [kgm^{-3}] \\ \hline \Delta & Slope of water vapor saturation curve & [PaK^{-1}] \\ \hline \gamma & Psychrometer constant & [PaK^{-1}] \\ \hline \gamma & Stefan-Boltzmann constant & [PaK^{-1}] \\ \hline \sigma = 5.670373 \times 10^{-8} & Stefan-Boltzmann constant & [Wm^{-2}K^{-1}] \\ \hline t & Time & [s] \\ \hline g = 9.80665 & Gravity acceleration & [ms^{-2}] \\ \hline T_a & Air temperature (2m) & [K] \\ \hline P & Precipitation rate & [ms^{-1}] \\ \hline Q & Runoff (fast, slow, percolation) & [ms^{-1}] \\ ET & Evapotranspiration flux & [ms^{-1}] \\ \hline \lambda & Latent heat vaporization & [J kg^{-1}] \\ \hline Radiation module & & \\ \hline CAL & Effective cloud albedo [0,, 1] & [-] \\ \hline Radiation module & & \\ \hline CAL & Effective cloud albedo [0,, 1] & [-] \\ \hline Radiation module & & \\ \hline CAL & Effective cloud albedo [0,, 1] & [-] \\ \hline Runoff (ast, slow, percolation) & [M m^{-2}] \\ \hline Radiation module & & \\ \hline DAL & Cloud cover fraction [0,, 1] & [-] \\ \hline Rh_N, R_{N,S} R_{N,C} & Surface net radiation, soil/canopy net radiation & W m^{-2} \\ \hline S^{1}_{abb} & Longwave downwelling flux, clear-sky downwelling flux & W m^{-2} \\ \hline PBL module & & \\ \hline H_{v_p} & Virtual heat flux & W m^{-2} \\ \hline PBL module & & \\ \hline H_{v_p} & Entrainment flux & W m^{-2} \\ \hline A_{a_m} & Boundary layer potential temperature & [K] \\ \hline A_{m_m} & Boundary layer potential temperature & [K] \\ \hline A_{m_m} & Boundary layer potential temperature & [K] \\ \hline A_{m} & W & Nondary layer potential temperature & [K] \\ \hline A_{m} & W & W & W & [-] \\ \hline CW & Total column parameter & [-] \\ \hline CW & Total column parameter & [-] \\ \hline CW & Total column parameter & [-] \\ \hline CW & Total column parameter & [-] \\ \hline CW & Total column parameter & [-] \\ \hline CW & Total column parameter & [-] \\ \hline CW & Total column parameter & [-] \\ \hline CW & Total column parameter & [-] \\ \hline CW & Total column parameter & [-] \\ \hline CW & Total column parameter & [$	symbol	variable	unit
$ \begin{array}{ccccc} \hline C_{\rho} & & \mbox{Heat capacity of dry air} & & \mbox{[Jkg^{-1}K^{-1}]} \\ \hline \rho & & \mbox{Density of dry air} & & \mbox{[kgm^{-3}]} \\ \hline \Delta & & \mbox{Slope of water vapor saturation curve} & & \mbox{[PaK^{-1}]} \\ \hline \gamma & & \mbox{Psychrometer constant} & & \mbox{[PaK^{-1}]} \\ \hline \gamma & & \mbox{Psychrometer constant} & & \mbox{[PaK^{-1}]} \\ \hline \gamma & & \mbox{Psychrometer constant} & & \mbox{[PaK^{-1}]} \\ \hline \gamma & & \mbox{Psychrometer constant} & & \mbox{[PaK^{-1}]} \\ \hline \gamma & & \mbox{Leaf area index} & & \mbox{[m^2 m^{-2}^2]} \\ \hline \varepsilon & & \mbox{surface emissivity} & & \mbox{[-1]} \\ \hline \sigma & = 5.670373 \times 10^{-8} & \mbox{Stefan-Boltzmann constant} & & \mbox{[Wm^{-2}K^{-1}]} \\ \hline t & & \mbox{Time} & & \mbox{[s]} \\ \hline \sigma & = 5.670373 \times 10^{-8} & \mbox{Stefan-Boltzmann constant} & & \mbox{[Wm^{-2}K^{-1}]} \\ \hline t & & \mbox{Time} & & \mbox{[s]} \\ \hline \sigma & = 5.670373 \times 10^{-8} & \mbox{Stefan-Boltzmann constant} & & \mbox{[Wm^{-2}K^{-1}]} \\ \hline t & & \mbox{Time} & & \mbox{[s]} \\ \hline \sigma & = 5.670373 \times 10^{-8} & \mbox{Stefan-Boltzmann constant} & & \mbox{[Wm^{-2}K^{-1}]} \\ \hline t & & \mbox{Time} & & \mbox{[s]} \\ \hline \sigma & = 5.670373 \times 10^{-8} & \mbox{Stefan-Boltzmann constant} & & \mbox{[Wm^{-2}K^{-1}]} \\ \hline t & & \mbox{Time} & & \mbox{[S]} \\ \hline \rho & & \mbox{Precipitation rate} & & \mbox{[ms^{-1}]} \\ \hline Q & & \mbox{Ruoff (fast, slow, percolation)} & & \mbox{[ms^{-1}]} \\ \hline P & & \mbox{Precipitation flux} & & \mbox{[ms^{-1}]} \\ \hline Radiation module & & & \mbox{[CAL} & & \mbox{Effective cloud albedo} [0, \dots, 1] & & \mbox{[-1]} \\ \hline Rakiation module & & & \mbox{[msatc]} & [msatc$	General variables		
$ \begin{array}{cccc} \rho & \mbox{Density of dry air} & \mbox{[kg m^{-3}]} \\ \Delta & \mbox{Slope of water vapor saturation curve} & \mbox{[Pa K^{-1}]} \\ \gamma & \mbox{Psychrometer constant} & \mbox{[Pa K^{-1}]} \\ \gamma & \mbox{Psychrometer constant} & \mbox{[Pa K^{-1}]} \\ \gamma & \mbox{Leaf area index} & \mbox{[m^2 m^{-2}]} \\ \varepsilon & \mbox{surface emissivity} & \mbox{[-]} \\ \varepsilon & \mbox{surface frame on the stand surface emissivity} \\ \varepsilon & \mbox{surface learning} & \mbox{surface learning} \\ \varepsilon & \mbox{surface learning} & \mbox{surface learning} \\ \varepsilon & \mbox{surface albedo} & \mbox{[m s^{-1}]} \\ \varepsilon & \mbox{surface albedo} & \mbox{[m s^{-1}]} \\ \varepsilon & \mbox{clad cover fraction [0,, 1]} & \mbox{[m s^{-1}]} \\ \varepsilon & \mbox{clad clad cover fraction [0,, 1]} & \mbox{[-]} \\ R_{\rm N} R_{\rm NS} R_{\rm NC} & \mbox{Surface net radiation, soil/canopy net radiation} & \mbox{Wm}^{-2} \\ \varepsilon^{\rm Suface} & \mbox{clause downwelling flux, clear-sky longwave downwelling flux} & \mbox{Wm}^{-2} \\ \varepsilon^{\rm L} L_{\rm L}^{\rm learning} & \mbox{Longwave downwelling flux, clear-sky longwave downwelling flux} & \mbox{Wm}^{-2} \\ \hline PBL module & & & \\ \hline H_{\nu} & \mbox{Virtual heat flux} & \mbox{Vm}^{-2} \\ H_{\rm lop} & \mbox{Entrainment flux} & \mbox{Vm}^{-2} \\ \delta_{\theta_m} & \mbox{Boundary layer potential temperature} & \mbox{K} \\ \hline \delta_{\theta_m} & \mbox{Boundary layer potential temperature} & \mbox{K} \\ \hline \delta_{0} & \mbox{Nm} & \mbox{Nm} & \mbox{Nm}^{-2} \\ \varepsilon & \mbox{Longwave long surface not suffict potential temperature} & \mbox{K} \\ \hline \delta_{0} & \mbox{Nm} & \mbox{Nm}^{-2} \\ \varepsilon & \mbox{Longwave layer inversion strength} & \mbox{K} \\ \delta_{0} & \mbox{Nm}^{-2} \\ \varepsilon & \mbox{Longwave land potential temperature} & \mbox{L} $	Cp	Heat capacity of dry air	$[J kg^{-1} K^{-1}]$
$\begin{array}{llllllllllllllllllllllllllllllllllll$	ρ	Density of dry air	[kg m ⁻³]
$ \begin{array}{ccccc} & & & & & & & & & & & & & & & & &$	Δ	Slope of water vapor saturation curve	[Pa K ⁻¹]
$\begin{array}{cccc} a_{\text{pt}} = 1.26 & \text{Priestley Taylor parameter} & [-] & [m^2 \text{m}^{-2}] \\ & & \text{Index} & [m^2 \text{m}^{-2}] \\ & & \text{surface emissivity} & [-] & [m^2 \text{m}^{-2}] \\ & & & \text{surface emissivity} & [-] & [W \text{m}^{-2} \text{K}^{-1}] \\ & & & \text{for an obstant} & [W \text{m}^{-2} \text{K}^{-1}] \\ & & & \text{for an obstant} & [W \text{m}^{-2} \text{K}^{-1}] \\ & & & \text{for an obstant} & [M \text{m}^{-2} \text{K}^{-1}] \\ & & & \text{for an obstant} & [M \text{m}^{-2} \text{K}^{-1}] \\ & & & \text{for an obstant} & [M \text{m}^{-2} \text{K}^{-1}] \\ & & & \text{g} = 9.80665 & \text{Gravity acceleration} & [m \text{s}^{-2}] \\ & & & \text{for an obstant} & [M \text{m}^{-2} \text{K}] \\ & & & \text{for an obstant} & [M \text{surface albedo} & [M \text{surface albedo} & [M \text{surface albedo} & [M \text{surface albedo} & [-1] \\ & & & \text{Surface albedo} & [-1] \\ & & & \text{Surface albedo} & [-1] \\ & & & \text{Gluad cover fraction} [0, \dots, 1] & [-1] \\ & & & \text{Radiation module} & [N \text{surface albedo} & [M \text{surface albedo} & [-1] \\ & & & & \text{Surface albedo} & [-1] \\ & & & \text{Clear sky index [0, \dots, 1]} & [-1] \\ & & & & \text{Russ} \text{R}_{N,S} R_{N,C} \\ & & & & \text{Surface net radiation, soil/canopy net radiation} & W \text{m}^{-2} \\ & & & & & \text{Clear sky index [0, \dots, 1]} & [-1] \\ & & & & & & \text{Russ} \text{K} & \text{Clear sky index [0, \dots, 1]} & [-1] \\ & & & & & & & \text{Russ} \text{K} & \text{Clear sky index [0, \dots, 1]} & [-1] \\ & & & & & & & & \text{Russ} \text{R}^{-2} \\ \end{array} \right$	γ	Psychrometer constant	[Pa K ⁻¹]
$ \begin{array}{ccccc} \Lambda & & \mbox{Leaf area index} & [m^2 m^{-2}] \\ s & \mbox{surface emissivity} & [-] \\ s & \mbox{surface emissivity} & [K] \\ \hline r & \mbox{surface emissivity} & [K] \\ \hline r & \mbox{surface emissivity} & [K] \\ \hline r & \mbox{Precipitation rate} & [m s^{-2}] \\ R & \mbox{Precipitation rate} & [m s^{-1}] \\ Q & \mbox{Runoff (fast, slow, percolation)} & [m s^{-1}] \\ \hline R & \mbox{Latent heat vaporization flux} & [m s^{-1}] \\ \hline \lambda & \mbox{Latent heat vaporization} & [J kg^{-1}] \\ \hline \hline Radiation module & & & & & & & & \\ \hline CAL & \mbox{Effective cloud albedo [0, \dots, 1]} & [-] \\ a & \mbox{Surface albedo} & & & & & & & & & \\ c & \mbox{Cloud cover fraction [0, \dots, 1]} & [-] \\ R_{N}, R_{N,S}R_{N,C} & \mbox{Surface net radiation, soil/canopy net radiation} & W m^{-2} \\ S^{1}S^{1}_{plear} & \mbox{Shortwave downwelling flux, clear-sky downwelling flux} & W m^{-2} \\ \hline PBL module & & & & & \\ \hline H_{v} & \mbox{Virtual heat flux} & W m^{-2} \\ \hline PBL module & & & & & & & \\ \hline H_{v} & \mbox{Virtual heat flux} & W m^{-2} \\ \hline R_{m} & \mbox{Boundary layer potential temperature} & & & & & \\ \hline K_{v} & \mbox{von Karman constant (≈ 0.41)} & & & & & \\ \hline f = & & & & & & \\ \hline f = & & & & & & \\ \hline f = & & & & & & & \\ \hline f = & & & & & & & \\ \hline f = & & & & & & & & \\ \hline f = & & & & & & & & \\ \hline f = & & & & & & & & \\ \hline f = & & & & & & & \\ \hline f = & & & & & & & \\ \hline f = & & & & & & & \\ \hline f = & & & & & & & \\ \hline f = & & & & & & & \\ \hline f = & & & & & & & \\ \hline f = & & & & & & \\ \hline f = & & & & & & \\ \hline f = & & & & & & \\ \hline f = & & & & & \\ \hline f = & & & & & \\ \hline f = & & & & & \\ \hline f = & & & & & \\ \hline f = & & & \\ \hline f = & & & & \\ \hline f = & & & \\ \hline f$	$\alpha_{\rm pt} = 1.26$	Priestley Taylor parameter	[]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Λ	Leaf area index	$[m^2 m^{-2}]$
σ = 5.670373 × 10 ⁻⁸ Stefan-Boltzmann constant[W m ⁻² K ⁻¹]tTime[s]g = 9.80665Gravity acceleration[m s ⁻²]T _a Air temperature (2 m)[K]PPrecipitation rate[m s ⁻¹]QRunoff (fast, slow, percolation)[m s ⁻¹]TEvapotranspiration flux[m s ⁻¹]λLatent heat vaporization[J kg ⁻¹]Radiation module[-][-]CALEffective cloud albedo [0,, 1][-]aSurface albedo[-]cCloud cover fraction [0,, 1][-]aSurface net radiation, soil/canopy net radiationW m ⁻² slabLongwave downwelling flux, clear-sky downwelling fluxW m ⁻² ℓ ¹ L _{slab} Longwave downwelling flux, clear-sky longwave downwelling fluxW m ⁻² PBL moduleH _v Virtual heat fluxW m ⁻² H _v Virtual heat fluxW m ⁻² Kθ _m Boundary layer potential temperature[K]θ _m Boundary layer potential temperature[K]kvon Karman constant (≈ 0.41)[-]ζ = 0.01Dissipitation parameter[-]	ε	surface emissivity	[-]
tTime[s] $g = 9.80665$ Gravity acceleration $[ms^{-2}]$ T_a Air temperature (2m) $[K]$ P Precipitation rate $[ms^{-1}]$ Q Runoff (fast, slow, percolation) $[ms^{-1}]$ Q Runoff (fast, slow, percolation) $[ms^{-1}]$ ETEvapotranspiration flux $[ms^{-1}]$ λ Latent heat vaporization $[J kg^{-1}]$ Radiation moduleCALEffective cloud albedo $[0, \dots, 1]$ $[-]$ c Cloud cover fraction $[0, \dots, 1]$ $[-]$ $realCloud cover fraction [0, \dots, 1][-]fClear sky index [0, \dots, 1][-]kClear sky index [0, \dots, 1]<$	$\sigma = 5.670373 \times 10^{-8}$	Stefan-Boltzmann constant	$[W m^{-2} K^{-1}]$
$\begin{array}{ccccc} g = 9.80665 & \operatorname{Gravity} \operatorname{acceleration} & [m \mathrm{s}^{-2}] \\ T_a & \operatorname{Air} \operatorname{temperature} (2 \mathrm{m}) & [K] \\ P & \operatorname{Precipitation} \operatorname{rate} & [m \mathrm{s}^{-1}] \\ Q & \operatorname{Runoff} (\operatorname{fast, slow, percolation}) & [m \mathrm{s}^{-1}] \\ ET & \operatorname{Evapotranspiration} \operatorname{flux} & [m \mathrm{s}^{-1}] \\ \lambda & \operatorname{Latent} \operatorname{heat} \operatorname{vaporization} & [J \mathrm{kg}^{-1}] \\ \hline \begin{array}{c} \operatorname{Radiation} \operatorname{module} & & \\ \hline \begin{array}{c} \operatorname{CAL} & \operatorname{Effective} \operatorname{cloud} \operatorname{albedo} [0, \ldots, 1] & [-] \\ a & \operatorname{Surface} \operatorname{albedo} & [-] \\ c & \operatorname{Cloud} \operatorname{cover} \operatorname{fraction} [0, \ldots, 1] & [-] \\ R_{\mathrm{N}}, R_{\mathrm{N}, \mathrm{S}} R_{\mathrm{N}, \mathrm{C}} & \operatorname{Surface} \operatorname{net} \operatorname{radiation}, \operatorname{soil/canopy} \operatorname{net} \operatorname{radiation} & \mathrm{W} \mathrm{m}^{-2} \\ L^{1} L_{\mathrm{slab}}^{\mathrm{plear}} & \operatorname{Shortwave} \operatorname{downwelling} \operatorname{flux}, \mathrm{clear-sky} \operatorname{downwelling} \operatorname{flux} & \mathrm{W} \mathrm{m}^{-2} \\ k & \operatorname{Clear} \operatorname{sky} \operatorname{index} [0 \dots 1] & [-] \\ \mathrm{TCW} & \operatorname{Total} \operatorname{column} \operatorname{water} \operatorname{vapor content} & \mathrm{kg} \mathrm{m}^{-2} \\ \hline \begin{array}{c} \mathrm{PBL} \mathrm{module} \\ \end{array} \\ \hline \begin{array}{c} H_{\mathrm{v}} & \mathrm{Virtual} \operatorname{heat} \operatorname{flux} & \mathrm{W} \mathrm{m}^{-2} \\ \mathrm{H}_{\mathrm{top}} & \operatorname{Entrainment} \operatorname{flux} & \mathrm{W} \mathrm{m}^{-2} \\ R_{\mathrm{m}} & \mathrm{Boundary} \operatorname{layer} \operatorname{potential} \operatorname{temperature} & [\mathrm{K}] \\ \theta_{\mathrm{m}} & \mathrm{Boundary} \operatorname{layer} \operatorname{potential} \operatorname{temperature} & [\mathrm{K}] \\ k & \mathrm{von} \mathrm{Karman} \operatorname{constant} (\approx 0.41) & [-] \\ \zeta = 0.01 & \mathrm{Dissipitation} \operatorname{parameter} \end{array} \right$	t	Time	[s]
$ \begin{array}{cccc} T_{a} & \text{Air temperature (2 m)} & [K] \\ P & \text{Precipitation rate} & [m s^{-1}] \\ Q & \text{Runoff (fast, slow, percolation)} & [m s^{-1}] \\ \hline P & \text{Evapotranspiration flux} & [m s^{-1}] \\ \hline P & \text{Evapotranspiration flux} & [m s^{-1}] \\ \hline P & \text{Evapotranspiration flux} & [m s^{-1}] \\ \hline P & \text{Evapotranspiration flux} & [J kg^{-1}] \\ \hline \lambda & \text{Latent heat vaporization} & [J kg^{-1}] \\ \hline \hline Radiation module & & & & & \\ \hline CAL & \text{Effective cloud albedo } [0, \dots, 1] & [-] \\ a & \text{Surface albedo} & [-] \\ c & \text{Cloud cover fraction } [0, \dots, 1] & [-] \\ R_{N}, R_{N,S} R_{N,C} & \text{Surface net radiation, soil/canopy net radiation} & W m^{-2} \\ S^{1}S_{1}^{L} & \text{Shortwave downwelling flux, clear-sky downwelling flux} & W m^{-2} \\ S^{1}S_{1}^{L} & \text{Longwave downwelling flux, clear-sky longwave downwelling flux} & W m^{-2} \\ k & \text{Clear sky index } [0 \dots 1] & [-] \\ TCW & Total column water vapor content & kg m^{-2} \\ \hline PBL module & & & \\ \hline H_{v} & \text{Virtual heat flux} & W m^{-2} \\ \hline H_{top} & \text{Entrainment flux} & W m^{-2} \\ \hline R_{m} & \text{Boundary layer potential temperature} & [K] \\ \theta_{m} & \text{Boundary layer potential temperature} & [K] \\ k & von Karman constant (\approx 0.41) & [-] \\ \zeta = 0.01 & \text{Dissipitation parameter} & [-] \\ \hline \end{array}$	g = 9.80665	Gravity acceleration	[m s ⁻²]
PPrecipitation rate $[m s^{-1}]$ QRunoff (fast, slow, percolation) $[m s^{-1}]$ ETEvapotranspiration flux $[m s^{-1}]$ λ Latent heat vaporization $[J kg^{-1}]$ Radiation module $[M s^{-1}]$ Radiation moduleCALEffective cloud albedo $[0,, 1]$ a Surface albedo $[-]$ c Cloud cover fraction $[0,, 1]$ $[-]$ $R_N, R_{N,S} R_{N,C}$ Surface net radiation, soil/canopy net radiation $W m^{-2}$ $S^{1}S_{plear}$ Shortwave downwelling flux, clear-sky downwelling flux $W m^{-2}$ $L^{1}L_{slab}^{1}$ Longwave downwelling flux, clear-sky longwave downwelling flux $W m^{-2}$ R_N Clear sky index $[0 \dots 1]$ $[-]$ TCWTotal column water vapor contentkg m^{-2}PBL module H_v Virtual heat flux $W m^{-2}$ A_{g_m} Mixed layer inversion strength $[K]$ θ_m Boundary layer potential temperature $[K]$ k von Karman constant (≈ 0.41) $[-]$ ζ = 0.01Dissipitation parameter $[-]$	T _a	Air temperature (2 m)	[K]
$ \begin{array}{ccccc} Q & \operatorname{Runoff} (\operatorname{fast, slow, percolation}) & [\operatorname{ms}^{-1}] \\ \operatorname{ET} & \operatorname{Evapotranspiration flux} & [\operatorname{ms}^{-1}] \\ \lambda & \operatorname{Latent heat vaporization} & [J \mathrm{kg}^{-1}] \\ \hline \\ \begin{array}{ccccccccccccccccccccccccccccccccccc$	Ρ	Precipitation rate	[m s ⁻¹]
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Q	Runoff (fast, slow, percolation)	[m s ⁻¹]
$\begin{array}{c c c c c c c c c } \hline \lambda & \ Latent heat vaporization & \ [J kg^{-1}] \\ \hline \hline Radiation module & & \ \hline \\ \hline Radiation module & & \ \hline \\ \hline CAL & \ Effective cloud albedo [0, \dots, 1] & [-] \\ a & \ Surface albedo & [-] \\ c & \ Cloud cover fraction [0, \dots, 1] & [-] \\ \hline R_{N}, R_{N,S}R_{N,C} & \ Surface net radiation, soil/canopy net radiation & W m^{-2} \\ S^{1}S^{1}_{S_{slab}} & \ Shortwave downwelling flux, clear-sky downwelling flux & W m^{-2} \\ L^{1}L^{1}_{slab} & \ Longwave downwelling flux, clear-sky longwave downwelling flux & W m^{-2} \\ k & \ Clear sky index [0 \dots 1] & [-] \\ \hline TCW & \ Total column water vapor content & kg m^{-2} \\ \hline \hline PBL module & & \\ \hline H_v & Virtual heat flux & W m^{-2} \\ \hline A_{top} & \ Entrainment flux & W m^{-2} \\ \delta_{\theta_m} & Mixed layer inversion strength & [K] \\ \theta_m & \ Boundary layer potential temperature & [K] \\ k & von Karman constant (\approx 0.41) & [-] \\ \zeta = 0.01 & \ Dissipitation parameter & [-] \\ \hline \end{array}$	ET	Evapotranspiration flux	[m s ⁻¹]
$\begin{array}{c c c c c c c c } \hline Radiation module & & & & \\ \hline CAL & Effective cloud albedo [0, \dots, 1] & [-] & & \\ a & Surface albedo & [-] & \\ c & Cloud cover fraction [0, \dots, 1] & [-] & \\ \hline R_N, R_{N,S}R_{N,C} & Surface net radiation, soil/canopy net radiation & Wm^{-2} & \\ S^{1}S_{c}^{1}er & Shortwave downwelling flux, clear-sky downwelling flux & Wm^{-2} & \\ L^{1}L_{siab}^{1} & Longwave downwelling flux, clear-sky longwave downwelling flux & Wm^{-2} & \\ \hline R_V & Clear sky index [0 \dots 1] & [-] & \\ \hline TCW & Total column water vapor content & kgm^{-2} & \\ \hline PBL module & & & \\ \hline H_v & Virtual heat flux & Wm^{-2} & \\ \hline H_{top} & Entrainment flux & Wm^{-2} & \\ \hline \theta_m & Boundary layer potential temperature & [K] & \\ \hline k & von Karman constant (\approx 0.41) & [-] & \\ \hline \zeta = 0.01 & Dissipitation parameter & [-] & \\ \hline \end{array}$	λ	Latent heat vaporization	$[J kg^{-1}]$
$ \begin{array}{c c} CAL & Effective cloud albedo [0, \dots, 1] & [-] \\ a & Surface albedo & [-] \\ c & Cloud cover fraction [0, \dots, 1] & [-] \\ R_{N}, R_{N,S} R_{N,C} & Surface net radiation, soil/canopy net radiation & Wm^{-2} \\ S^{1} S^{1}_{plear} & Shortwave downwelling flux, clear-sky downwelling flux & Wm^{-2} \\ L^{1} L^{1}_{slab} & Longwave downwelling flux, clear-sky longwave downwelling flux & Wm^{-2} \\ k & Clear sky index [0 \dots 1] & [-] \\ TCW & Total column water vapor content & kgm^{-2} \\ \hline PBL module & & \\ \hline H_{v} & Virtual heat flux & Wm^{-2} \\ H_{top} & Entrainment flux & Wm^{-2} \\ \delta_{\theta_{m}} & Mixed layer inversion strength & [K] \\ \theta_{m} & Boundary layer potential temperature & [K] \\ k & von Karman constant (\approx 0.41) & [-] \\ \zeta = 0.01 & Dissipitation parameter & [-] \\ \end{array} $	Radiation module		
aSurface albedo[-]cCloud cover fraction $[0,, 1]$ [-] $R_{\rm N}, R_{\rm N,S}R_{\rm N,C}$ Surface net radiation, soil/canopy net radiationWm ⁻² $S^{1}S_{\rm plear}^{\rm lear}$ Shortwave downwelling flux, clear-sky downwelling fluxWm ⁻² $L^{1}L_{\rm slab}^{\rm lab}$ Longwave downwelling flux, clear-sky longwave downwelling fluxWm ⁻² k Clear sky index $[0 \dots 1]$ [-]TCWTotal column water vapor contentkg m ⁻² PBL module $H_{\rm v}$ Virtual heat fluxWm ⁻² $d_{\rm gm}$ Mixed layer inversion strength[K] $\theta_{\rm m}$ Boundary layer potential temperature[K]kvon Karman constant (≈ 0.41)[-] ζ = 0.01Dissipitation parameter[-]	CAL	Effective cloud albedo [0,, 1]	[-]
$\begin{array}{ccc} c & \text{Cloud cover fraction } [0, \ldots, 1] & [-] \\ R_{\text{N}}, R_{\text{N,S}} R_{\text{N,C}} & \text{Surface net radiation, soil/canopy net radiation} & \text{Wm}^{-2} \\ S^{1} S^{1}_{plear} & \text{Shortwave downwelling flux, clear-sky downwelling flux} & \text{Wm}^{-2} \\ L^{1} L^{1}_{\text{slab}} & \text{Longwave downwelling flux, clear-sky longwave downwelling flux} & \text{Wm}^{-2} \\ k & \text{Clear sky index } [0 \dots 1] & [-] \\ \text{TCW} & \text{Total column water vapor content} & \text{kg m}^{-2} \\ \hline \hline \\ \hline \\ H_{\text{v}} & \text{Virtual heat flux} & \text{Wm}^{-2} \\ H_{\text{top}} & \text{Entrainment flux} & \text{Wm}^{-2} \\ \delta_{\theta_{\text{m}}} & \text{Mixed layer inversion strength} & [K] \\ \theta_{\text{m}} & \text{Boundary layer potential temperature} & [K] \\ k & \text{von Karman constant} (\approx 0.41) & [-] \\ \zeta = 0.01 & \text{Dissipitation parameter} & [-] \\ \hline \end{array}$	а	Surface albedo	[-]
$\begin{array}{cccc} R_{\rm N}, R_{\rm N,S} R_{\rm N,C} & {\rm Surface \ net \ radiation, \ soil/canopy \ net \ radiation} & {\rm W\ m}^{-2} \\ S^{\rm I} S^{\rm I}_{\rm plear} & {\rm Shortwave \ downwelling \ flux, \ clear-sky \ downwelling \ flux} & {\rm W\ m}^{-2} \\ L^{\rm I} L^{\rm I}_{\rm slab} & {\rm Longwave \ downwelling \ flux, \ clear-sky \ longwave \ downwelling \ flux} & {\rm W\ m}^{-2} \\ \hline R_{\rm K} & {\rm Clear \ sky \ index \ [0 \ \dots 1]} & [-] \\ {\rm TCW} & {\rm Total \ column \ water \ vapor \ content}} & {\rm kg\ m}^{-2} \\ \hline \hline \\ \hline \hline \\ $	С	Cloud cover fraction [0,, 1]	[-]
$\begin{array}{cccc} S^{1}S_{l}^{1} & & \text{Shortwave downwelling flux, clear-sky downwelling flux} & W \text{m}^{-2} \\ L^{1}L_{slab}^{1} & & \text{Longwave downwelling flux, clear-sky longwave downwelling flux} & W \text{m}^{-2} \\ \hline L^{1}L_{slab}^{1} & & \text{Clear sky index [01]} & & [-] \\ \hline TCW & & \text{Total column water vapor content} & & \text{kg m}^{-2} \\ \hline \hline PBL \text{module} & & & \\ \hline H_{v} & & \text{Virtual heat flux} & W \text{m}^{-2} \\ \hline H_{top} & & \text{Entrainment flux} & W \text{m}^{-2} \\ \hline \partial_{\theta_{m}} & & \text{Mixed layer inversion strength} & & [K] \\ \hline \theta_{m} & & \text{Boundary layer potential temperature} & & [K] \\ \hline k & & & \text{von Karman constant} (\approx 0.41) & & [-] \\ \hline \zeta = 0.01 & & \text{Dissipitation parameter} & & [-] \\ \hline \end{array}$	$R_{\rm N}, R_{\rm N,S}R_{\rm N,C}$	Surface net radiation, soil/canopy net radiation	$W m^{-2}$
$\begin{array}{cccc} L^{1}L_{slab}^{1} & & \mbox{Longwave downwelling flux, clear-sky longwave downwelling flux} & W m^{-2} & \\ \hline K & & \mbox{Clear sky index [01]} & [-] & \\ \hline TCW & Total column water vapor content & kg m^{-2} & \\ \hline PBL module & & & \\ \hline H_v & Virtual heat flux & W m^{-2} & \\ \hline H_{top} & & \mbox{Entrainment flux} & W m^{-2} & \\ \hline \partial_{\theta_m} & & \mbox{Mixed layer inversion strength} & [K] & \\ \hline \theta_m & & \mbox{Boundary layer potential temperature} & [K] & \\ k & von Karman constant (\approx 0.41) & [-] & \\ \hline \zeta = 0.01 & & \mbox{Dissipitation parameter} & [-] & \\ \hline \end{array}$	$S^{\downarrow}S^{\downarrow}_{clear}$	Shortwave downwelling flux, clear-sky downwelling flux	$W m^{-2}$
kClear sky index $[0 \dots 1]$ $[-]$ TCWTotal column water vapor contentkg m^{-2}PBL module H_v Virtual heat fluxW m^{-2} H_{top} Entrainment fluxW m^{-2} δ_{θ_m} Mixed layer inversion strength[K] θ_m Boundary layer potential temperature[K]kvon Karman constant (≈ 0.41)[-] $\zeta = 0.01$ Dissipitation parameter[-]	$L^{\downarrow}L^{\uparrow}_{slab}$	Longwave downwelling flux, clear-sky longwave downwelling flux	W m ⁻²
TCWTotal column water vapor contentkg m^{-2}PBL module H_v Virtual heat fluxW m^{-2} H_{top} Entrainment fluxW m^{-2} δ_{θ_m} Mixed layer inversion strength[K] θ_m Boundary layer potential temperature[K]kvon Karman constant (≈ 0.41)[-] ζ = 0.01Dissipitation parameter[-]	k	Clear sky index [0 1]	[]
PBL module H_v Virtual heat flux Wm^{-2} H_{top} Entrainment flux Wm^{-2} θ_m Mixed layer inversion strength[K] θ_m Boundary layer potential temperature[K] k von Karman constant (≈ 0.41)[-] ζ = 0.01Dissipitation parameter[-]	TCW	Total column water vapor content	kg m ⁻²
$ \begin{array}{ccc} H_{\rm v} & {\rm Virtual\ heat\ flux} & {\rm W\ m}^{-2} \\ H_{\rm top} & {\rm Entrainment\ flux} & {\rm W\ m}^{-2} \\ \delta_{\theta_{\rm m}} & {\rm Mixed\ layer\ inversion\ strength} & [K] \\ \theta_{\rm m} & {\rm Boundary\ layer\ potential\ temperature} & [K] \\ k & {\rm von\ Karman\ constant\ (\approx 0.41)} & [-] \\ \zeta = 0.01 & {\rm Dissipitation\ parameter} & [-] \end{array} $	PBL module		
H_{top} Entrainment flux $W m^{-2}$ δ_{θ_m} Mixed layer inversion strength[K] θ_m Boundary layer potential temperature[K] k von Karman constant (≈ 0.41)[-] $\zeta = 0.01$ Dissipitation parameter[-]	H _v	Virtual heat flux	$W m^{-2}$
$ \begin{array}{ll} \delta_{\theta_m} & \text{Mixed layer inversion strength} & [K] \\ \theta_m & \text{Boundary layer potential temperature} & [K] \\ k & \text{von Karman constant} (\approx 0.41) & [-] \\ \zeta = 0.01 & \text{Dissipitation parameter} & [-] \end{array} $	H _{top}	Entrainment flux	$W m^{-2}$
$\theta_m^{}$ Boundary layer potential temperature[K]kvon Karman constant (≈ 0.41)[-] $\zeta = 0.01$ Dissipitation parameter[-]	$\delta_{ heta_{ extsf{m}}}$	Mixed layer inversion strength	[K]
kvon Karman constant (≈ 0.41)[-] $\zeta = 0.01$ Dissipitation parameter[-]	θ_{m}	Boundary layer potential temperature	[K]
$\zeta = 0.01$ Dissipitation parameter [-]	k	von Karman constant (≈ 0.41)	[-]
	$\zeta = 0.01$	Dissipitation parameter	[-]



Table A1. Continued.

symbol	variable	unit
Turbulent flux mod	dule	
и	Wind speed	[m s ⁻¹]
LE, LE _i , LE _s LE _c	Latent heat flux, subscripts indicate: interception, soil, canopy	$W m^{-2}$
ET	Evapotranspiration	[m s ⁻¹]
ET _i	Evapotranspiration from canopy interception storage	[m s ⁻¹]
h	Vegetation height	[m]
Н	Sensible heat flux	$W m^{-2}$
G	Soil heat flux	$W m^{-2}$
И.	Friction velocity	[m s ⁻¹]
f _c	Vegetation cover fraction	[-]
r _a	Aerodynamic surface resistance	[sm ⁻¹]
$\Psi_{m,h}$	Stability correction functions	
R_i	Richardson number	[-]
$Z_{0,m}Z_{0,h}$	Noughness lengths for momentum and heat	[m]
φ		[-] [cm ⁻¹]
n _r P	Capopy resistance	[SIII] [cm ⁻¹]
h _c	Padiation atraca factor	[SIII]
⁷ rad	maulation siless lactor	$[vv_{11}]$
/ min / max	Potential temperature lance rate	[Sili] [Km ⁻¹]
Υ _{θm} z	Vegetation height	[m]
Water flux and soi	il module	[]
		[mo]
r, r _{max}	Thermal inertial exefficient	[II]
C _G	Thermal inertial coefficient	$[K \Pi J]$
d = 1.5 m	Soil tomporature domping scale depth	
u = 1.511	Soil temperature lanse rate	[///] [Km ⁻¹]
rs D	Throughfall and drainage of water from the capony layer to the soil	$[me^{-1}]$
D T	Surface temperature	[///3]
T _d	Deep soil temperature	[K]
Z	Vertical coordinate (e.g. boundary layer height, soil depth)	[m]
m,	Volumetric soil moisture	[m ³ m ⁻³]
Θ [°]	Relative degree of saturation for soil moisture	[-] ·
κ	Unsaturated soil conductivity	[m s ⁻¹]
Ψ	Soil suction pressure head	[m]
W	Water storage in soil	[m]



Table B1. Land cover specific parameters.

Landcover	$\alpha_{\rm pt}$	r _{min}	r _{max}	$r_{\rm rad}$	Z _{0,m}	Z _{0,h}	Z _{veg}
Bare soil	1.26	400	5000	-	0.001	0.001	-
Cropland	1.26	40	5000	30	0.01	0.001	0.2
Deciduous broadleaf forest	0.91	100	5000	30	1.0	0.1	15
Coniferous forest	0.91	150	5000	30	1.4	0.14	15
Coniferous forest or deciduous	0.91	150	5000	30	1.2	0.14	15
Deciduous broadleaf forest and broad leaf/mixed forest	0.91	100	5000	30	1.0	0.1	15
Grassland	1.26	40	5000	100	0.01	0.001	0.2
Savanna	1.26	300	5000	100	0.01	0.001	0.4
Deciduous broadleaf forest and broad leaf/mixed forest	0.91	100	5000	30	1.0	0.1	15

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Table C1. List of FLUXNET stations investigated.

N	Station ID	Lat	Lon		Years			Coverage		Reference
				2003	2004	2005	Global	±50°	Meteosat	
1	ΔΤΝου	47 12	11 32	x	x		x	x	×	Wohlfahrt et al. (2008)
2	AUHow	-12 49	131 15	x	x	x	x	x	~	Hutlev et al. (2000)
3	AUTum	-35.66	148.15	x	x	x	x	x		Leuning et al. (2005)
4	BEBra	51.31	4.52		x	x	x		х	Gond et al. (1999)
5	BEVie	50.31	6.00			x	x		x	Aubinet et al. (2001)
6	CAMan	55.88	-98.48	х			X			Dunn et al. (2007)
7	CAMer	45.41	-75.52	х	х		х	х		Lafleur (2003)
8	CANS1	55.88	-98.48	х	Х		Х			Gouldon et al. (2006)
9	CANS2	55.91	-98.52	х	х	х	х			Gouldon et al. (2006)
10	CANS3	55.91	-98.38		Х	х	х			Gouldon et al. (2006)
11	CANS4	55.91	-98.38	х			х			Gouldon et al. (2006)
12	CANS5	55.86	-98.49	х	Х	х	Х			Gouldon et al. (2006)
13	CANS6	55.92	-98.96	х	Х	х	х			Gouldon et al. (2006)
14	CANS7	56.64	-99.95	х	Х		х			Gouldon et al. (2006)
15	CAQcu	49.27	-74.04	х	х	х	Х	х		
16	CASF3	54.09	-106.01	х	х	х	Х			Mkhabela et al. (2009)
17	CHOe1	47.29	7.73	х			х	х	х	Ammann et al. (2007)
18	CZBK1	49.50	18.54			х	х	х	х	
19	DEGri	50.95	13.51			X	X		x	Gilmanov et al. (2007)
20	DEHai	51.08	10.45	х	X	X	X		X	Knohl et al. (2003)
21	DEMeh	51.28	10.66		X	X	X		X	Scherer-Lorenzen et al. (2007)
22	DETha	50.96	13.57	X	X	X	X		x	
23	DEWet	50.45	11.46	X	X	X	X	~	X	Rebmann et al. (2010)
24	FRHes	48.67	7.06	X	x	x	X	X	X	Granier et al. (2000)
25	FRLD	44.72	-0.77	~	v	v	÷	Ŷ	÷	Allerd at al. (2001)
20	FRPue	43.74	3.00	v	÷	÷	÷	÷	÷	Allard et al. (2008)
27	ITCoz	40.09	10.00	^	÷	÷	÷	÷	Ŷ	Corbulater at al. (2007)
20	ITEp2	41.71	11 02		Ŷ	^	Ŷ	Ŷ	Ŷ	Tedeschi et al. (2006)
29	ITSPo	42.39	10.292	×	^		Ŷ	Ŷ	Ŷ	Chiosi et al. (2005)
21	NI Ca1	51 07	10.20	Ŷ	Y	×	Ŷ	~	Ŷ	Boliaars and Bosyold (1997)
32	NLLoo	52 17	5 74	Ŷ	^	Ŷ	Ŷ		×	Dolman et al. (2002)
33	LISARM	36.61	_97.49	Ŷ	x	Ŷ	Ŷ	x	~	Eischer et al. (2002)
34	USAud	31 59	-110 51	~	Ŷ	Ŷ	Ŷ	Ŷ		Tang et al. (2011, 2008)
35	USBkg	44.35	-96.84		x	x	x	x		Zhang et al. (2008)
36	USB01	40.01	-88.29	x	x	x	x	x		Mevers (2004)
37	USEPe	48.31	-105.10	x	~	x	x	x		Gilmanov et al. (2005). Zhang et al. (2008).
38	USGoo	34.25	-89.87	~	х	~	x	x		chimanor of an (2000), Enang of an (2000)
39	USHo1	45.20	-68.74	х	x		x	x		Hollinger et al. (2004)
40	USHo2	45.21	-68.75	x	x		x	x		Hollinger et al. (2004)
41	USLos	46.08	-89.98	X	X	х	X	X		·······g•··•··(=•••·)
42	USMOz	38.74	-92.20			х	х	х		Gu et al. (2007, 2006)
43	USNe1	41.17	-96.48	х	х		х	х		Verma et al. (2005)
44	USNe2	41.16	-96.47	х	х		х	х		Verma et al. (2005)
45	USNe3	41.18	-96.44	х	х		х	х		Verma et al. (2005)
46	USOho	41.55	-83.84		х	х	х	х		
47	USSP2	29.76	-82.24	х	х		х	х		Clark et al. (2004)
48	USTon	38.43	-120.97	х		х	х	х		Baldocchi et al. (2004)
49	USWCr	45.81	-90.08	х		х	х	Х		Cook et al. (2004)



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Figure 1. Temporal mean (2001–2005) latent heat flux estimated from HOLAPS for 50° S to 50° N





Figure 2. HOLAPS estimated fluxes and modules.





Figure 3. Distribution of FLUXNET stations used in this study. Light green corresponds to latitudes between 50° N and 50° S which corresponds to the coverage of the TMPA precipitation data (see text). Stations in red cannot be used when forced with TMPA data. Light orange indicates approximate coverage of Meteosat data.





Figure 4. Comparison of surface net radiation flux (R_N) between FLUXNET measurements and HOLAPS estimates for **(a)** hourly and **(b)** daily timescales. Colors indicate the frequency of occurrence of values (data density).





Figure 5. Boxplots of validation statistics for surface net radiation (R_N) for hourly data and all experiments investigated: (a) RMSD, (b) cRMSD, (c) correlation coefficient. The box corresponds to the inner-quartile range of the data and the red line indicates the median value. Numbers indicate number of model years for each experiment.





Figure 6. Boxplots of (a) RMSD and (b) cRMSD for hourly surface solar radiation flux (Rg).

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Figure 7. Comparison of HOLAPS latent heat flux for (a) hourly and (b) daily timescale for the CTRL experiment using results from all stations and years. Units in $W m^{-2}$





Figure 8. Boxplots of (a) RMSD, (b) cRMSD and (c) correlation coefficient for HOLAPS hourly latent heat flux







Figure B1. HOLAPS runtime environment.



Figure D1. Similar error statistic for R_N like Fig. 4 but for daily timescales: (a) RMSD, (b) cRMSD, (c) correlation coefficient.





Figure D2. Similar error statistic for R_N like Fig. 4 but for monthly timescales: (a) RMSD, (b) cRMSD, (c) correlation coefficient





Figure D3. Similar error statistic for LE like in Fig. 8 but for daily values: (a) RMSD, (b) cRMSD, (c) correlation coefficient.





Figure D4. Similar error statistic for LE like in Fig. 8 but for monthly values: (a) RMSD, (b) cRMSD, (c) correlation coefficient.

