

VALIDATION OF LAND SURFACE TEMPERATURE PRODUCTS WITH 5 YEARS OF PERMANENT IN-SITU MEASUREMENTS IN 4 DIFFERENT CLIMATE REGIONS

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Abstract

Land Surface Temperature (LST) is operationally retrieved from measurements of several space-borne sensors, e.g. the LST product derived by Land Surface Analysis – Satellite Application Facility (LSA-SAF) for the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on-board Meteosat Second Generation (MSG) and the LST product derived for the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS-Terra by the MODIS Land Team. The relative accuracy of an LST product can be assessed by cross-validating between products obtained with different LST retrieval algorithms and / or for different sensors. Alternatively, so-called 'radiance based validation' can be employed, which is not a validation method in a strict sense but a comparison of satellite-retrieved LST with results from radiative transfer models and requires precise knowledge of surface and atmospheric conditions. Ultimately, 'ground truth' measurements are needed for validating satellite LST products. Therefore, the LST product derived by LSA-SAF is validated with independent in-situ measurements ('temperature based validation') at four permanent stations located in different climate regions. However, temperature based validation is largely complicated by the spatial scale mismatch between satellite sensors and ground based sensors: areas observed by ground radiometers usually cover about 10 m², whereas satellite measurements in the thermal infrared typically cover between 1 km² and 100 km². The characterization of the surface is particularly critical for all validation approaches, as in-situ measurements revealed that current land surface emissivity (LSE) products over arid regions can be wrong by more than 3%. LSEs of the dominant surface cover types at Gobabeb (Namibia) and at Dahra (Senegal) were obtained from in-situ and laboratory measurements. Both validation sites have quite large fractions of bare ground and are, therefore, particularly prone to be misrepresented in satellite-retrieved LSEs. Accurate estimations of in-situ LSE are essential to validate satellite LST&E products and to limit the uncertainty of ground-based LST observations. The monitoring capability of the validation stations is demonstrated with 5 years of LST derived operationally by LSA-SAF from MSG/SEVIRI data.

INTRODUCTION

LST is an important quantity for the energy and water exchange between the earth's surface and the atmosphere and, therefore, an important parameter of many environmental models. LST derived operationally from SEVIRI by LSA-SAF has a target accuracy of better than $\pm 2^\circ\text{C}$. Karlsruhe Institute of Technology (KIT) operates four permanent validation stations for LST retrieved from thermal infrared (TIR) satellite measurements. The stations are operated within the framework of LSA-SAF and their main objective is to validate LST derived from SEVIRI onboard MSG. As discussed in (Trigo, 2008a) and (Yu, 2008), ground measurements have their own issues, including the following: 1) the low number and discontinuity of high-quality data sets, 2) the lack of global representativeness, and 3) the up-scaling of LST "point" measurements to satellite pixel size. In order to reliably validate LST derived from MSG/SEVIRI, the small spots observed by in-situ radiometers (order of 10 m²) need to be representative for satellite pixels the size of about 5x5 km². Therefore, KIT's permanent LST validation stations were set up in carefully selected, large homogeneous areas (*Figure 1*): Evora (Portugal), Dahra (Senegal), Gobabeb (Namibia) and Kalahari Farms RMZ & Heimat (Namibia).

KIT Validation Stations

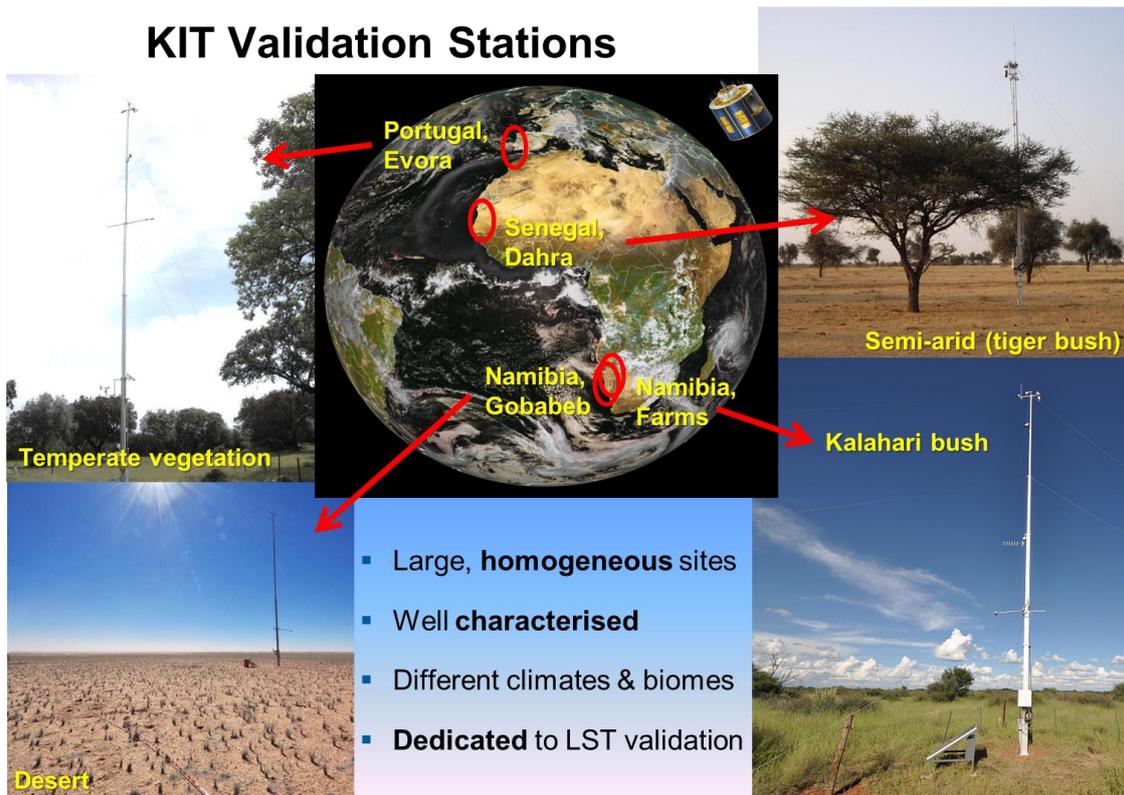


Figure 1: Locations of KIT's stations on the MSG/SEVIRI earth disk and the respective land covers.

IN-SITU DATA AND DATA PROCESSING

The validation stations' core instrument is the chopped "KT-15.85 IIP" IR-radiometer from Heitronics GmbH, Germany. During a CEOS inter-calibration campaign in 2009 performed with precision blackbodies and over the sea surface, the KT15.85 IIP was shown to have an absolute accuracy of $\pm 0.3\text{K}$ over a temperature range of 5°C to 60°C (Theocharous et al., 2010). The stability of the Heitronics radiometer was tested in a long-term parallel run with the self-calibrating radiometer "RotRad" from CSIRO, which was continuously calibrated with 2 blackbodies (Kabsch et al., 2008). The parallel run at the Evora site started in April 2005; a year later the agreement between the instruments was still excellent (correlation 0.99).

At each station a set of radiometers measures the radiance leaving the relevant surface end-members as well as down-welling "sky" radiance between $9.6\ \mu\text{m}$ and $11.5\ \mu\text{m}$. In-situ LST is determined from the combination of these radiometric measurements and land surface emissivity (LSE) (Göttsche et al., 2013). LSE is nearly constant at Gobabeb (a hyper-arid site), but due to vegetation dynamics and changing soil moisture LSE at the other sites varies significantly. Therefore, only for Gobabeb LSE is set to a constant value obtained from in-situ measurements with the emissivity box method (Rubio et al., 1997; Göttsche and Hulley, 2012), which was also shown to be in very good agreement with the corresponding emissivity retrieved from data of the ASTER sensor on-board EOS-Terra. The LSE during the dry season at Dahra was determined with in-situ & laboratory measurements (Xu et al., 2013). However, due to the strong seasonal change of land cover at Dahra, the LSE values derived operationally by LSA-SAF are used (Trigo et al., 2008b; Freitas et al., 2010). The land cover fractions of the relevant end-members at the validation sites were determined from high resolution satellite data (Rasmussen et al., 2011; Bork-Unkelbach, 2012).

Since the four LST validation stations were set up at different dates, the available data records vary accordingly: Gobabeb - Jul 2008 to present, Evora-1: Apr 2005 to Aug 2007, Evora-2/3 - Mar 2008 to present, RMZ farm (Kalahari) - Apr 2009 to Feb 2011, Farm Heimat (Kalahari) - Mar 2011 to present,

and Dahra since Feb. 2009. Except for Dahra there are only relatively minor data gaps. The stations' high sampling rate allows the matching of in-situ LST to SEVIRI acquisition times to within one minute: during "good" months, i.e. with few clouds and a clear atmosphere, there are about two thousand match-ups between SAF LST and in-situ LST per station for the about 2900 possible SEVIRI measurements per month. In contrast, during wet seasons there may be only several hundred match-ups and increased data scatter due to undetected clouds.

DAHRA, SENEGAL

Dahra LST validation station (15°24'N, 15°25'W) is located in a hot, semiarid climate (Sahel). The land cover at Dahra is tiger bush with a tree crown cover of about 4% (Rasmussen et al., 2011). Bush and trees are oriented along ancient dunes, causing stripes of high vegetation – hence the name "tiger bush". The region exhibits a strong natural seasonality due to pronounced rainy and dry seasons: grass is usually desiccated with progressively larger fractions of bare soil between November and April, while the sparse trees stay green all year. During the wet season the grass grows high (about 1m) and dense and the entire site is covered by vegetation. In terms of atmospheric correction the situation at Dahra is highly challenging: the low elevation of 40 m asl results in long atmospheric paths and the atmospheric water vapour load varies strongly over the year. Furthermore, occasional outbreaks of Sahara dust complicate cloud detection. In-situ LST is derived from measurements of two separate radiometers observing a patch of grass and a tree crown. Figure 2 shows the monthly bias & rmse between in-situ LST and LSA-SAF LST as well as the number of match-ups over nearly four years.

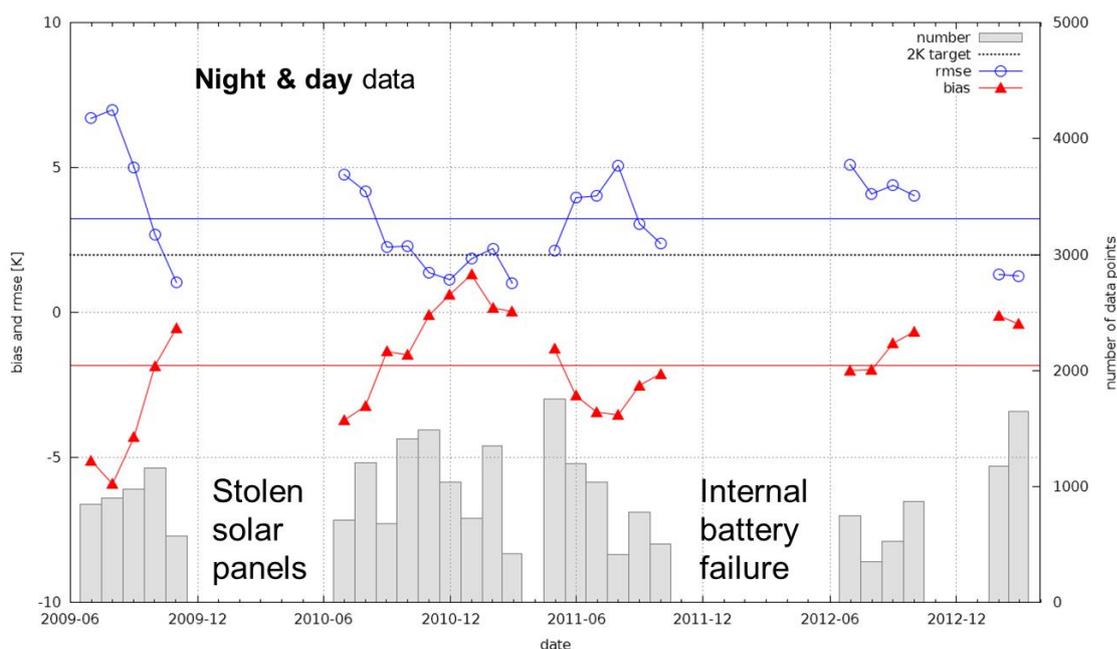


Figure 2: Analysis of LSA-SAF LST and in-situ LST for Dahra, Senegal. Monthly bias (red triangles), root mean square error (rmse, blue circles) and their respective mean values (solid horizontal lines) relate to the left y-axis; the number of match-ups between in-situ LST and LSA-SAF LST (grey bars) relate to the right y-axis. From about November to May (most of the dry season) the LST algorithm meets its target accuracy of 2 K (indicated by the dotted line).

For the entire valid data between July 2009 and March 2013 (Figure 2) the average bias is -1.8 K and average rmse is 3.2 K. However, during the dry season LSA-SAF LST agrees significantly better with in-situ LST than during the rainy season. This is demonstrated in Figure 3: in March (dry) 2013 the bias is -0.4 K and rmse is 1.3 K (right), whereas for August (rainy) 2012 the bias is 2.0 K and rmse is 4.1 K (left). Reasons for the poor performance during the rainy season may be attributed to localised rain events, e.g. the higher LSA SAF LST in Figure 3 (red circles above the 1:1 line, left plot): these could be due to rain fall at the location of the station, whereas large areas within the corresponding SEVIRI pixel remained dry. The observed larger data scatter during the wet season compared to the dry season (Figure 2 and Figure 3) is probably mainly due to undetected sub-pixel clouds in the

SEVIRI data. Due to the strong seasonality of the vegetation from full cover during the rainy season to practically bare soil during the dry season, LSE over the site varies considerably: for March 2013 (Figure 3, right) the mean LSA-SAF LSE at Dahra is 0.968, which was also the value used to calculate the corresponding in-situ LST shown in the plot. This value is about 2% higher than the in-situ emissivity determined for SEVIRI ch10.8 for dry soil (0.945).

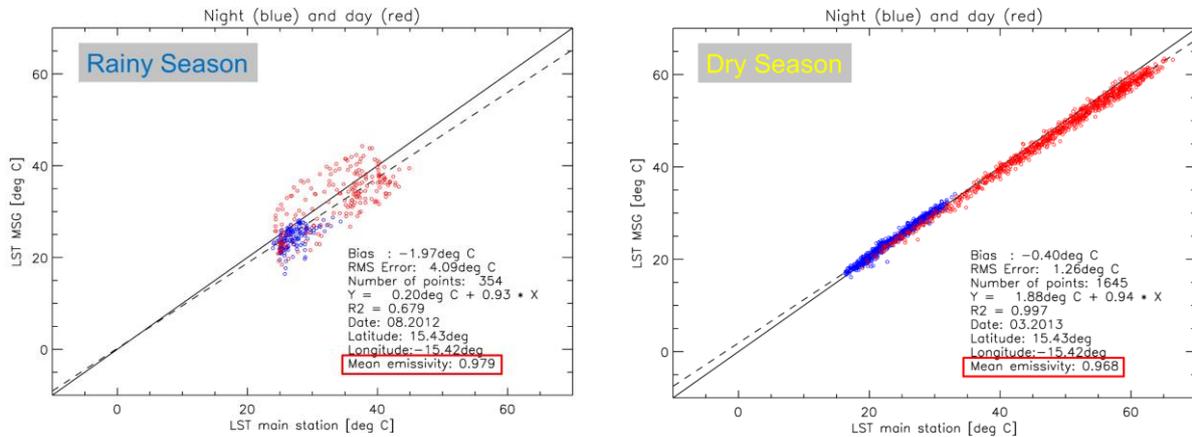


Figure 3: LSA-SAF LST vs. in-situ LST for Dahra, Senegal. For August 2012 (rainy season, left) there are 354 match-ups and rmse exceeds 4°C. For March 2013 (dry season, right) there are 1645 match-ups and rmse is only 1.26 °C, which is well within LSA-SAF's target accuracy of 2°C.

A comparison of LSA-SAF LSE with the corresponding 'CIMSS baseline fit emissivity' showed differences of similar magnitude and insufficient seasonal variation of LSA-SAF LSE (Xu et al., 2013). The mean LSA-SAF LSE of 0.979 determined for August 2012 (Figure 3, left), when vegetation cover was high, is realistic and in agreement with typical literature values. Dahra is the most challenging of KIT's validation sites in terms of local conditions. However, the station provides valuable in-situ measurements from a sub-tropical climate and during the dry season the LSA-SAF algorithm meets its target accuracy of 2K.

GOBABEB, NAMIBIA

Gobabeb LST validation station is located on the large and highly homogeneous gravel-plains of the Namib desert at 405 m asl. The station's instruments are mounted at several heights of Gobabeb's 30m high wind profiling tower (23°33'S, 15°03'E) and the ground-observing KT-15 radiometers are at 25 m height, facing downwards under a view angle of 30° in northern direction. This set-up combined with a full view angle of 8.5° of the radiometer results in a field of view (FOV) of about 13 m². Towards the south of Gobabeb station the Kuiseb River separates the gravel plains from large sand dunes and, thus, forms a natural boundary. The gravel plains are a vast and flat area covering about 10000 km² consisting mainly of coarse gravel and sand, which is sparsely covered by desiccated grass (Göttsche and Hulley, 2012). On a time scale of years the surface cover is almost constant. Thus the gravel plains are a highly homogeneous area in space and time, which makes them an ideal LST validation site. Nevertheless, for reliable product validation the effect of the small scale variation of surface materials (e.g. dry grass, rock outcrops) and topography needs to be fully characterised. Using measurements along a 40 km track covering about 8000 m², Göttsche et al. (2013) showed that station LST is representative for the validation area of about 1000 km². The results show a high level of homogeneity and a stable relationship between station LST and LST obtained for the gravel plain with small biases between -0.1°C and 0.8°C (Bork-Unkelbach, 2012). Figure 4 (right plot) shows a comparison between Gobabeb station LST, LST obtained along a track as well as the corresponding LSA-SAF LST: the match between station LST and LSA-SAF LST is near perfect, whereas the 'mobile LST' shows some variation around station LST (differences up to 3 K). This is mainly due to variations of surface cover and small scale topography effects along the track.

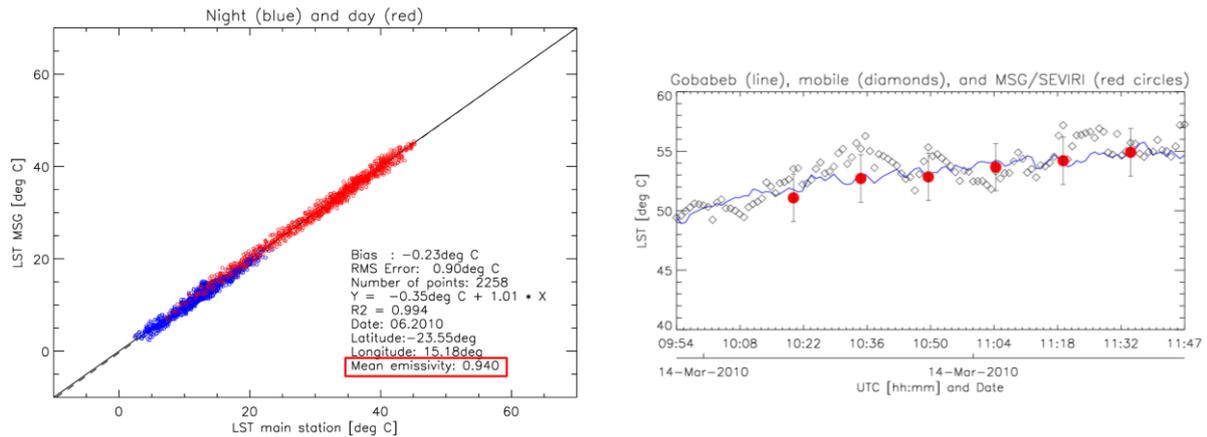


Figure 4, left: LSA-SAF LST vs. in-situ LST for Gobabeb, Namibia. In June 2010 (winter, southern hemisphere) the rmse of the LSA-SAF LST is less than 1K and the bias is -0.23 K while the temperature range exceeds 40 K. **Right:** Using the same in-situ LSE of 0.940 (left) for the determination of the 'mobile LST' (40km track across the gravel plains) shows the excellent agreement with station LST and verifies its representativeness for the validation area.

Considering that the shown LST values exceed 50°C (Figure 4, right), these spatial variations are relatively small and the temporal averages of the three LST time series are close to each other, which demonstrates the site's high degree of surface homogeneity. Figure 5 shows a 5 year time series of monthly bias and rmse for LSA-SAF LST minus in-situ LST for a pixel located to the North-east of the station on the gravel plains. Additionally, the number of available data match-ups is given. The mean bias of the time series is -0.1 K and the mean rmse is 1.5 K. However, there is also a slow variation of the monthly bias by about ±1K which appears to be partly seasonal. Increased errors and reduced number of available data match-ups are observed during Namibia's small (October/November) and big rainy seasons (January/February): in 2011 the big rainy season was exceptionally "wet" and cloudy even in the desert and resulted in a low number of match-ups (see Figure 5); the corresponding low data quality caused LSA-SAF LST to miss its target accuracy of 2 K (dotted line). Otherwise the agreement between LSA-SAF LST and in-situ LST is excellent and rmse lies between 1.0 K and 1.5 K.

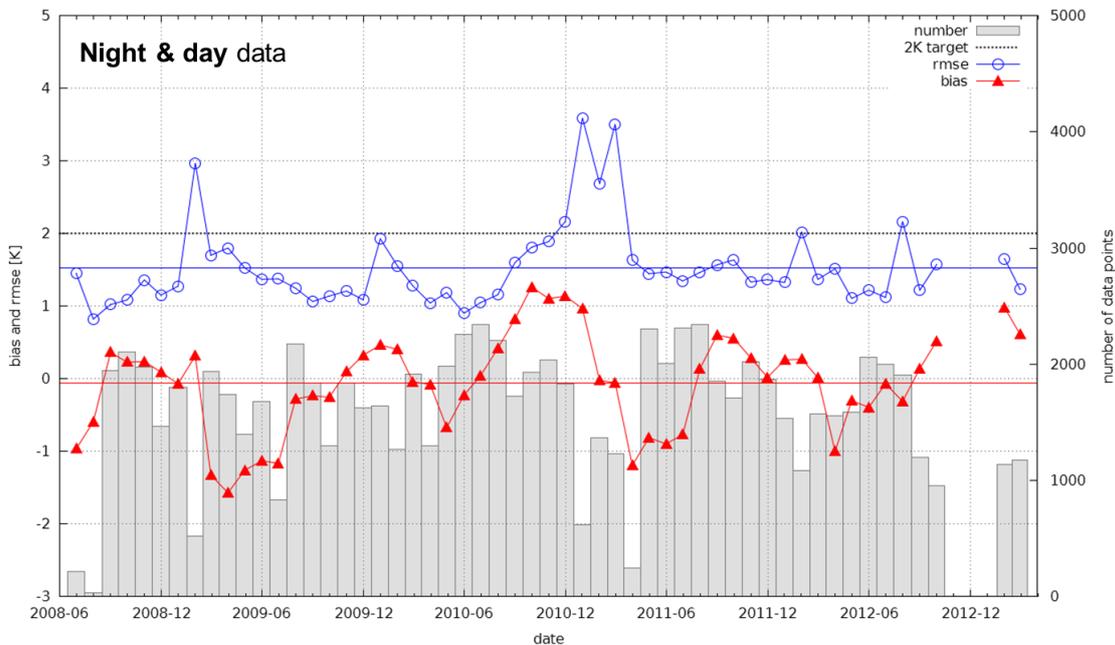


Figure 5: Analysis of LSA-SAF LST and in-situ LST for Gobabeb, Namibia. Monthly bias (red triangles) and root mean square error (rmse, blue circles) and their respective mean values (solid horizontal lines) relate to the left y-axis; the number of match-ups between in-situ LST and LSA-SAF LST (grey bars) relate to the right y-axis. Errors are increased between Jan and Mar 2011 due to an exceptional rainy season with few matchups and cloud detection problems.

CONCLUSIONS

The four stations operated by KIT are the only long term (> 5 years) LST validation stations in the field of view of the METEOSAT satellites. The stations represent different climates and surface covers and are located in flat, homogeneous terrains at the scale of several MSG-SEVIRI pixels. Land cover fractions at the validation sites were determined from high resolution satellite data (Rasmussen et al., 2011; Bork-Unkelbach, 2012) while LSE at Gobabeb and at Dahra were obtained from in-situ and laboratory measurements (Göttsche and Hulley, 2012).

Analyses of several years of in-situ LST and LSA-SAF LST showed that the absolute value of the mean and the monthly bias between the two data sets is generally less than 1 K for all stations when excluding rainy seasons with few matchups. The root mean square error was less than 1.5 K for the three African stations and it was below 1.6 K for Evora station in Portugal. There are frequently undetected clouds during Winter & Spring and local rainy seasons. During dry seasons, in-situ LST and LSA-SAF LST generally agree well with each other and the validation results demonstrate the excellent quality of this operational LST product. The validation of LST products retrieved from sensors on-board of polar orbiters (AATSR, IASI, MODIS, and VIIRS) is investigated and the products are inter-compared with LSA-SAF LST. Furthermore, in Spring 2013 a field campaign was performed at Gobabeb, which investigated LST anisotropy with goniometric in-situ measurements (Verestek, 2013). The results of this campaign are currently analysed and will add further credibility to the in-situ data.

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