MEaSUREs Unified and Coherent Land Surface Temperature and Emissivity (LST&E) Earth System Data Record (ESDR):

The Combined ASTER and MODIS Emissivity database over Land (CAMEL) Version 3 Algorithm Theoretical Basis Document and Users' Guide

Technical documentation

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Abstract

Land Surface Temperature and Emissivity (LST&E) data are essential for a wide variety of studies, from calculating the evapotranspiration of plant canopies to retrieving atmospheric water vapor. LST&E products are generated from data acquired by sensors in Low Earth Orbit (LEO) and by sensors in Geostationary Earth Orbit (GEO). Although these products represent the same measurement, they are produced at different spatial, spectral, and temporal resolutions using different algorithms. The different approaches used to retrieve the temperatures and emissivities result in discrepancies and inconsistencies between the different products. Over the past decade, NASA has identified the need to develop long-term, consistent, and well-calibrated data and products that are valid across multiple missions and satellite sensors. These datasets are referred to as Earth System Data Records (ESDRs) and are optimized to meet specific requirements in addressing science questions. NASA has identified LST&E data as an important ESDR, and efforts are underway to produce long time series of these data in a NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) project. This document will introduce a new land surface emissivity ESDR for the NASA MEaSUREs project – the Combined ASTER and MODIS Emissivity over Land (CAMEL). CAMEL is developed by combining the MODIS baseline-fit emissivity database (MODBF) produced at the University of Wisconsin-Madison, and the ASTER Global Emissivity Dataset (ASTER-GEDv4) produced at the Jet Propulsion Laboratory (JPL). The CAMEL ESDR has been produced globally at 5km resolution in mean monthly time steps and for 13 bands from 3.6-14.3 µm and extended to 417 bands using a Principal Component (PC) regression approach. CAMEL will benefit numerous applications, including improved atmospheric retrievals and radiative transfer simulations.

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Software version identification
The current version of the software is 3.0.

1. Introduction

Land Surface Temperature and Emissivity (LST&E) data are critical variables for studying a variety of Earth surface processes and surface-atmosphere interactions such as evapotranspiration, surface energy balance, and water vapor retrievals. LST&E have been identified as an important Earth System Data Record (ESDR) by NASA and many other international organizations (NASA Strategic Roadmap Committee #9, 2005, Global Climate Observing System (GCOS), 2003; Climate Change Science Program (CCSP), 2006, and the recently established International Surface Temperature Initiative (Willett et al. 2011).

Accurate knowledge of the LST&E at high spatial (1km) and temporal (hourly) scales is a key requirement for many energy balance models to estimate important surface biophysical variables such as evapotranspiration and plant-available soil moisture (Anderson et al. 2007b; Moran 2003). Currently, no single satellite exists that is capable of providing global LST&E products at both high spatial and temporal resolution. LST&E data are also essential for balancing the Earth's surface radiation budget. For example, an error of 0.1 in the emissivity will result in climate models having errors of up to 7 Wm-2 in their upward longwave radiation estimates –a much larger term than the surface radiative forcing (~2-3 Wm-2) due to an increase in greenhouse gases (Zhou et al. 2003). LST&E are also utilized in monitoring land-cover / land-use changes (French et al. 2008) and in atmospheric retrieval schemes (Seemann et al. 2003).

LST&E products are currently generated from sensors in Low Earth Orbit (LEO), such as the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the Terra and Aqua satellites, as well as from sensors in Geostationary Earth Orbit (GEO), such as the Geostationary Operational Environmental Satellites (GOES). Sensors in LEO orbits provide global coverage at moderate spatial resolutions (~1km) but more limited temporal coverage (twice daily). In comparison, sensors in GEO orbits provide more frequent measurements (hourly) at lower spatial resolutions (~3-4 km) over a geographically restricted area. For example, the GOES sensors produce data over North America every 15 minutes and South America every 3 hours.

LST&E products are generated with varying accuracies depending on the input data, including ancillary data such as atmospheric water vapor, as well as algorithmic approaches. For example, certain MODIS products (MOD11) use a split window algorithm applied to two or more bands in conjunction with an emissivity estimate obtained from a land classification to produce the LST. Conversely, other MODIS products (MOD21) use a physics-based approach that involves a radiative transfer model first to correct the data to a surface radiance and then use a model to extract the temperature and emissivities in the spectral bands. This physics-based approach is also used with the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Validation of these approaches has shown that they are complementary, with the split-window approach working better over heavily vegetated regions and the physics-based approach working better in semi-arid and arid regions.

NASA has recognized this general problem and identified the need to develop long-term, consistent, calibrated data and products that are valid across multiple missions and satellite sensors. In the MEaSUREs project, we address this problem for LST&E by generating a set of Earth System Data Records (ESDRs) that capitalizes on the type of observation (LEO or GEO) and retrieval type (physical-based or split-window). Three ESDRs have been produced; 1) a unified global 1 km resolution land surface temperature (LST) ESDR resampled to daily, 8-day, and monthly; 2) a unified N. and S.

America 5 km resolution LST-ESDR resampled to hourly spatial resolution for N. America and 3-hourly for S. America and 3) a unified global 5 km resolution average land surface emissivity (LSE) at monthly temporal resolution. In this document, the *LSE ESDR will be described in detail, including methodologies, uncertainties, and all the technical aspects*.

A monthly mean unified LEO LSE-ESDR at 5km has been produced by merging two current state-of-the-art emissivity databases, the UW-Madison MODIS Baseline Fit emissivity database (UWBF) (Seemann et al. 2008) and the JPL ASTER Global Emissivity Dataset (GEDv4) (Hulley and Hook 2009) and termed the Combined ASTER and MODIS Emissivity over Land (CAMEL) (Hook, 2017, 2019; Borbas et al., 2018, 2019; Feltz et al. 2018a, b). Using a PC regression approach, the CAMEL LSE-ESDR has been further extended to hyperspectral resolution. For the emissivity ESDR products, a complete set of uncertainty statistics has also been provided.

2. CAMEL V3 Updates

The input of the UWBF dataset required for producing CAMEL V2 was the MODIS MxD11C3 (Wan et al., 2021) monthly mean emissivity products, which include emissivity at 6 IR bands. The climate quality of the UWBF dataset is affected by changes in the quality of the MxD11 products over time. In 2017, the processing of the MxD11C3 Collection 4.1 and 5 (C4.1/5) product was discontinued and replaced by a new Collection 6 (C6) product with some significant differences and consequences for CAMEL. First, the C6 Band 20 and Band 29 emissivity are mistakenly identical for both Terra and Aqua MODIS, and it appears Band 29 values were copied into the Band 20 variable. Second, there is an increasing emissivity of Terra Band 29, probably due to the Band 29 crosstalk error. The copy of Band 20 and 29 issues is fixed, and the X-talk error is significantly reduced in C6.1.

During the past years, another MODIS emissivity product (MxD21, Hulley and Hook, 2021) was developed by JPL, which has high accuracy, particularly over arid regions. However, the MxD21 product includes only three bands: bands 29, 31, and 32, and not bands 20, 22, and 23 in the midwave spectral region. Since Band 20 is fixed in MxD11 C6.1 (Wan et al., 2021), *we decided to combine the MxD11 Band 20, 22, and 23 with the MxD21 Band 29, 31, and 32 in our new Version4 UWBF database hence the new CAMEL Version 3 product.*

<u>*The combination of these products allowed us to process UWBF V4 and CAMEL V3 products for the entire 2000-2021 time period.*</u> Due to calibration issues with Terra/MODIS Band 29, the Terra data were used only at the beginning of the mission, when Aqua/MODIS was not available yet (March 2000 to end of 2002). Otherwise, UWBF and CAMEL databases are based on the Aqua/MODIS for the rest of the time period.

Two significant updates of the CAMEL V3 are the new MxD21 input data in UWBF and the latest C6.1 version of MxD11 and MxD21 products with the most up-to-date calibration corrections. Furthermore, while the MxD11 products provide one monthly mean emissivity, the MxD21 product includes emissivity for both day- and nighttime. The daytime emissivity has been chosen because it is the least susceptible to soil moisture changes, and the daytime MODIS cloud mask has better quality. For CAMEL V3 processing, a quality check has also been added to MxD11 and MxD21 data. The *Mandatory Quality Assurance (QA) Flag* must be <= 1 (Good and Other quality data) to be processed. This condition filters out less than 1% of the data. Using the *Percent_land_in_grid* variable, we further filtered out coastline pixels covering more than 25% of water. This restriction filters out an additional 3% of the data.

MxD10 snow fraction is also an input of CAMEL. Some failure quality flags have occurred in C6.1 MxD10 product after 2017, mainly over the ocean; these have been fixed by filtering out the ocean pixels we do not use.

Due to the most up-to-date calibration corrections on the C6.1 MODIS data, the artificial trends in CAMEL V3 are significantly removed. The remaining trends are on a much smaller scale. For example, a drift for MYD21 Bands 31 and 32 over the Park Falls, WI, location relates to the Band 29 artificial trend in the calibration coefficient of the non-linear term (also for Band 27-30). It will be fixed in Collection 7 by freezing the coefficient change after 2012 (personal communication with Chris Moeller, science team member of MODIS MCST).

Figure 1 illustrates the time series of the CAMEL V2 and V3 emissivity for all 13 hinge points over the Southern Great Plan (SGP) ARM Cart site location in Oklahoma. As a diagnostic, we also plotted the input UWIREMIS (or UW BF) and ASTER emissivity data, the MxD10 snow fraction, ASTER NDVI, and the number of Principal Component (PC) coefficients and version of the laboratory dataset used for high spectral resolution application. Although the ASTER data helped to stabilize the strong artificial trends for bands 10.8 – 14.1 µm in Version 2, the uncertainty increased significantly. In Version 3, these trends have been minimalized with much smaller algorithm uncertainty.

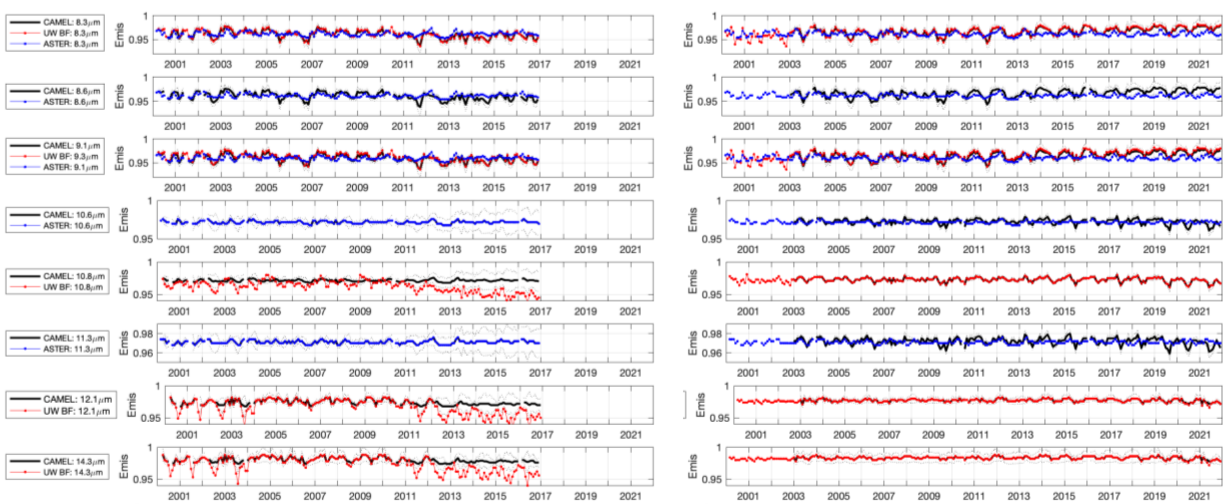

Figure 1: Timeseries of CAMEL V2 (left) and CAMEL V3 (right) 13 hinge-point emissivity (black curve) over the SGP ARM Cart site location for hinge points between 8.3 and 14.3 µm. UWBF (red) and ASTER (blue) input emissivity is also plotted.

In summary, CAMEL V3 has been processed for 2000-2021, due to the improved quality of the latest version of MODIS products and their availability. The new UWBF emissivity based on the cross-talked corrected C6.1 MODIS data shows fewer unphysical trends, which causes smaller differences between the UWBF and ASTER emissivity, especially for ~8-11 microns; hence the CAMEL V3 algorithm uncertainties are significantly reduced. In addition, CAMEL V3 has a stricter land/sea mask due to the MxD11 change from C4.1 to C6.1 and the use of the land/sea flag.

3. Emissivity Hinge-points Methodology

CAMEL has been produced by combining the UW-Madison MODIS Baseline Fit database (UWBF) and the JPL ASTER Global Emissivity Dataset (ASTER-GED v4, Hulley et al., 2015). A limitation of the

UWBF database is that emissivity in the thermal infrared region (TIR) region (8-12 µm) is not well defined because MODIS only has three bands in this region (bands 29, 31, and 32). This results in an imperfect TIR spectral shape in the two quartz doublet regions at 8.5 and 12 µm. The advantages are its moderate spatial resolution (5km), uniform temporal coverage (monthly), and emissivities, which span the entire IR region (3.6-12 µm). A disadvantage of the ASTER-GED database is that although there are more bands to define the spectral shape more accurately in the TIR region (5 bands, 8-12 µm), there are no bands in the mid-wave infrared (MIR) region around 3.8-4.1 µm, which limits its use in models and other atmospheric retrieval schemes. The advantages are its high spatial resolution (~100m) and high accuracy over arid regions. The two databases have been integrated to capitalize on the unique strengths of each product's characteristics. This involved four steps: 1) ASTER-GED v3 emissivities have been adjusted for vegetation and snow cover variations over heterogeneous regions to product ASTER-GED v4, 2) ASTER-GED v4 emissivities have been aggregated from 100m resolution to the UWBF 5km resolution, 3) the spectral emissivities have been merged to generate the CAMEL product at 13 points from 3.6-12 µm, and 4) the 13 hinge-points have been further extended to hyperspectral resolution using a PC-regression approach. We will discuss steps 3 and 4 in more detail.

The third step involves merging the spectral emissivities from the 5 ASTER bands with the 10 hinge-point bands from the UWBF database. The determination of the CAMEL emissivity by hinge points is summarized in Column 3rd of *Table 3* and described below.

<u>CAMEL hinge points from 3.6 to 7.6 µm</u>
In the ASTER band gap of the short and mid-wave IR region, the CAMEL emissivity from 3.6 to 7.6 µm has been determined by the UWBF values only, also keeping the location of the hinge points.

<u>CAMEL hinge point 8.6 µm</u>
Since the spectral response of MODIS band 29 (8.55 µm) – also UWBF 8.3 and 9.1 µm (see below) - matches closely with ASTER band 11 (8.6 µm), we used a weighting rule based on uncertainties using a 'combination of states of information' approach (e.g., Tarantola (2005)). In this approach, two pieces of information (e.g., two spectral emissivities $\varepsilon(1,\nu)$ and $\varepsilon(2,\nu)$ can be merged in a probabilistic manner by weighting each input based on its relative uncertainty, i.e., $\varepsilon(\nu) = [1/(w_1+w_2)]$ $[w_1\varepsilon(1,\nu)+w_2\varepsilon(1,\nu)]$, where w is a weighting factor based on uncertainty, σ, as follows: $w=1/\sigma$. To apply this method, we used 90% and 10% weights as the corresponding uncertainties for ASTER-GED and UWBF on a pixel-by-pixel basis. The UWBF hinge-point 6 (8.3 µm) is weighted by 90%, and ASTER band 11 (8.6 µm) gets the 10% for all the other cases, except over highly vegetated regions (like the tropical rainforest), where the MODIS emissivity suffers from cloud contamination resulting in the emissivity value at the Restrahen band being low. To determine those areas, ASTER NDVI is larger than 0.7, and UWBF emissivity at 8.6 µm is less than 0.95 are used as thresholds. To avoid this artifact, the ASTER Band 11 (8.6 µm) is weighted by 90% instead.

<u>CAMEL hinge point 8.3 and 9.3 µm</u>
The baseline-fit procedure used in generating UWBF product extends emissivity from MODIS band 29 (8.6 µm) to inflection points at 8.3 µm and 9.3 µm. The locations of these inflection points were maintained, but the emissivities were improved by replacing the UWBF values with retrieved ASTER emissivities from corresponding bands 10 (8.3 µm) and 12 (9.1 µm) and adjusting them by the emissivity difference between the new CAMEL 8.6 µm and ASTER 8.6 µm band. This significantly improved spectral shape in the Si-O stretching region (8-12 µm) (*Figure 2*).

<u>CAMEL hinge point 10. 8 µm</u>
The input of the new UWBF V4 emissivity is the more accurate MODIS MOD21 Band 31 emissivity for the 10.8 µm hinge point. Hence the CAMEL emissivity at the 10.8 µm has been determined as the UWBF value except for those vegetated regions, which were identified for the 8.6 µm and where the

MODIS emissivity suffers from cloud contamination. For those cases, the CAMEL emissivity is set to rely on the ASTER measurements only; the value is determined as the linear combination of the ASTER band 10.6 µm and 11.3 µm emissivity.

CAMEL hinge points 10.6 and 11.3 µm
The 10.6 and 11.3 µm hinge points have been added based on the additional observations from ASTER bands 10.6 and 11.3 µm. For consistency, the retrieved ASTER emissivities have been adjusted by the emissivity difference between the CAMEL at 10.8 µm and interpolated ASTER emissivity at 10.8µm; however, in the case of cloud-contaminated, vegetated areas – determined by the thresholds discussed for 8.6 µm emissivity - the retrieved ASTER emissivities without the adjustments are used.

CAMEL hinge points 12.1 and 14.3 µm
Due to the lack of ASTER bands in this spectral region, the CAMEL emissivity 12.1 and 14.3 µm have been determined by the UWBF values only, keeping the location of the hinge points.

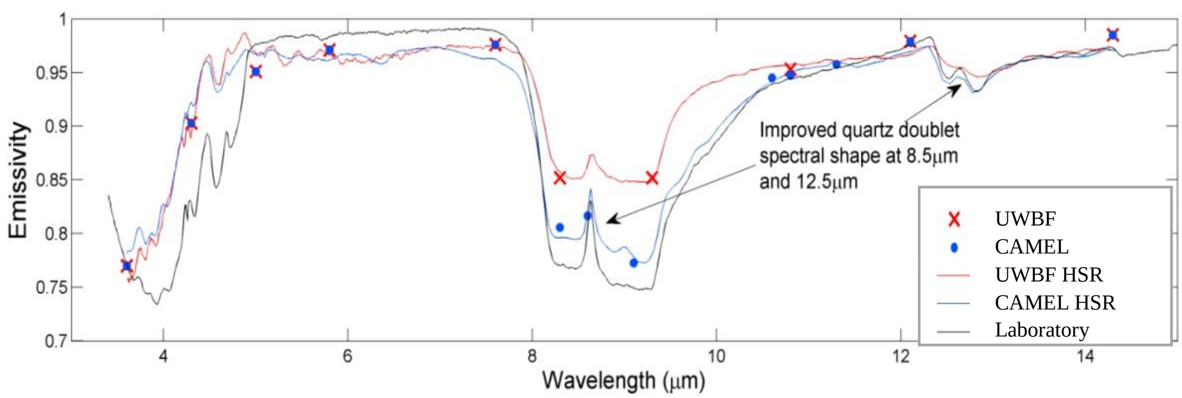

Figure 2: The advantages of combining the ASTER-GED and MODIS UW Baseline Fit databases are evident here, showing emissivity spectra over the Namib Desert, Namibia. UWBF v4.1 emissivity for Jan 2004 (crosses) and hyperspectral fit (red line), the CAMEL 13 hinge-point emissivity (blue dots) and hyperspectral fit (blue line), and lab spectra (black) of sand samples collected over the Namib Desert. Note improved spectral shape in CAMEL HSR (blue) in the quartz doublet regions from 8-10 µm and 12-13 µm.

4. High Spectral Resolution Emissivity Methodology

The MEaSUREs CAMEL database was extended to high spectral resolution (HSR) using a Principal Component (PC) regression analysis similar to the method which was developed for the UWBF-HSR Algorithm (Borbas and Ruston (2010) and Borbas et al. (2014)). The UWBF-HSR version was designed for data assimilation schemes and radiative transfer models that require accurate high spectral resolution emissivity or, as first guess emissivities in retrieval schemes of hyperspectral sounders such as AIRS, IASI, and CrIS. The PC regression approach has been adapted to generate an HSR emissivity of the CAMEL database.
The PCs (eigenvectors) were generated using the same five sets of selected laboratory measurements as for V002 (chosen to represent various surface types) and regressed to the CAMEL 13 hinge points as follows:

$$\vec{e} = \vec{c} * \boldsymbol{U}$$

where $\vec{e}$ is the CAMEL emissivity on 13 hinge points, $\vec{c}$ is the PCA coefficient vector, and **U** is the matrix of the PCs of the lab emissivity spectra on the reduced spectral resolution. After calculating the coefficients ($\vec{c}$), the high spectral resolution emissivity values are determined at the same latitude and longitude point by using the high spectral resolution PCs of the laboratory sets. There are two main updates in the CAMEL V3 HSR algorithm from the UWBF HSR algorithm:

- The number of Principal Components (PCs) now varies among 2, 5, 7, and 9, based on the surface scene type and coverage using the 3.6, 10.6, and 11.3 µm CAMEL emissivity, the ASTER NDVI, and MODIS MOD10 Snow Fraction for determination.
- Five sets of laboratory measurements have been created for the PCA regression also based on the surface scene type and coverage: general (55 spectra), general + snow/ice (59 spectra), arid (including carbonates, 82 spectra), arid + snow/ice (including carbonates, 86 spectra), and snow/ice (4 spectra).

The method for determining the number of PCs and version number of the laboratory dataset to use for each pixel is summarized in *Table 1*.

Table 1: Determination of the number of PCs and the version number of laboratory datasets for each pixel in CAMEL V3.

Tests	Version number of Laboratory dataset	Number of PCs
MOD10 snow fraction = 1.0	12 (snow/ice)	2
Carbonate test yes & snow fraction = 0	10 (general_carbonates)	5
Carbonate test yes & snow fraction > 0	11 (general_carbonates + snow/ice)	5
Carbonate test no, but CAMEL9.1 <=0.85 & snow fraction =0	8 (general)	9
Carbonate test no, but CAMEL9.1 <=0.85 & snow fraction >0	9 (general + snow/ice)	9
All the others & snow fraction = 0	8 (general)	7
All the others & snow fraction > 0	9 (general + snow/ice)	7

Carbonate test: $(CAMEL_{10.6} - CAMEL_{11.3}) > 0.009$ & *ASTER NDVI* < 0.2 & $CAMEL_{3.6} < 0.9$

The addition of lab version 9 and 11 datasets was already introduced in V2 to characterize partially snowy scenes more accurately. The inclusion of lab versions 9 and 11 enables the determination of more realistic partially snow-covered estimates by combining the snow/ice emissivity spectra and non-snowy emissivity spectra of lab datasets 12 & 8/10 in lab datasets 9/11. These lab versions are thus used when the snow fraction is between 0 and 1.0.

Figure 2 also shows an example of applying the PC regression fit to the CAMEL LSE ESDR product at 13 points over the Namib Desert, Namibia. Comparisons of the unified LSE-ESDR with lab emissivity spectra from field sand samples show very good agreement, particularly in the quartz doublet regions at 8.5 and 12.5 µm when compared with the original UWBF HSR fit. Biases and RMS errors were reduced by 3% and 4% respectively by using the unified LSE-ESDR instead of the original UWBF product.

5. MEaSUREs CAMEL Emissivity Uncertainty determination

The product uncertainty is estimated by a total emissivity uncertainty that comprises three independent components of variability—temporal, spatial, and algorithm variability. Each measure of uncertainty is provided for all 13 channels and every latitude-longitude point. A quality flag is provided for the total uncertainty, as in *Table 2*.

Table 2: Definition of CAMEL emissivity uncertainty quality flag

VALUE	DEFINITION OF 'total_uncertainty_quality_flag'
0	Sea/ no CAMEL data available
1	Good quality
2	Unphysical uncertainty

The total uncertainty is calculated from the components as a root square sum:

$$\sigma_{total} = \sqrt{\sigma_{spatial}^2 + \sigma_{temporal}^2 + \sigma_{algorithm}^2}$$

The spatial uncertainty component is calculated as the standard deviation of the surrounding 5x5 pixel emissivity, which is equivalent to a 0.25x0.25 degree latitude-longitude region. This uncertainty represents the variability of the surrounding landscape (ocean is not included) and is only provided where the CAMEL emissivity quality flag is not zero.

The temporal uncertainty is defined by the standard deviation of the 3 surrounding months (e.g. Oct. uncertainty = standard deviation (Sept., Oct., Nov.)). Even if emissivity values are not available for all 3 months as in the case of the starting or ending month of the CAMEL record, an uncertainty is still reported.

Algorithm uncertainty is estimated by the differences between the two CAMEL emissivity inputs: the ASTER-GEDv4 and UWBF products. *Table 5* below shows the CAMEL, ASTER, and UWBF channel wavelengths, the method for combing the ASTER and UWBF emissivity to create the CAMEL product, and the method for determining the CAMEL emissivity algorithm uncertainty. Because the spatial and temporal uncertainty components are estimated by a standard deviation rather than a difference, the measure of the difference between the ASTER and UWBF products is divided by the square root of 3 after an absolute value is taken. For channels 6-9 and 11-13, where ASTER and UWBF report emissivities at nearby frequencies, differences between the ASTER and UWBF emissivity are used to define the algorithm variability, as shown in *Table 3*. Channel 10, at 10.8 µm, uses a linear interpolation between the ASTER channels 4 and 5. Where no ASTER data is available in the shortwave region for CAMEL channels 1 and 2, a variability is estimated from a fractional difference from channel 7. For channels 3 and 4, it is assumed that there is a small variability which is constant across time, space, and channels, and for channel 5 at 7.6 µm, it is assumed that there is no variation.

To produce the quality flag and determine which total uncertainty values are flagged as unphysical (i.e., have a 'total_uncertainty_quality_flag'=2), unphysical uncertainties are first flagged in the three uncertainty components (though they are not provided to users due to file size restraints). Spatial and temporal uncertainties values are flagged unphysical if they are in the 99.9th percentile, while algorithm uncertainty values are determined as unphysical if the ASTER and BF differences prior to having their absolute values taken are in the 0.1st or 99.9th percentiles. Total uncertainty values are then flagged as unphysical if any of the three components are flagged as unphysical.

Table 3: Method of CAMEL and calculating its algorithm uncertainty

CAMEL Hinge points		Channel used		CAMEL Combining method	Algorithm uncertainty method
	(µm)	UWBF	ASTER		
1	3.6	Y	-	$BF_{3.6}$	$\lvert BF_{3.6}*[(BF_{8.3}-ASTER_{8.6})/BF_{8.3}] \rvert /\sqrt{3}$
2	4.3	Y	-	$BF_{4.3}$	$\lvert BF_{4.3}*[(BF_{8.3}-ASTER_{8.6})/BF_{8.3}] \rvert /\sqrt{3}$
3	5.0	Y	-	$BF_{5.0}$	$0.01 / \sqrt{3}$
4	5.8	Y	-	$BF_{5.8}$	$0.01 / \sqrt{3}$
5	7.6	Y	-	$BF_{7.6}$	0 (Minimal variation)
6	8.3	Y	Y	$ASTER_{8.3} + (CAMEL_{8.6} - ASTER_{8.6})$	$\lvert BF_{8.3}-ASTER_{8.3}\rvert / \sqrt{3}$
7	8.6	S	Y	$w*BF_{8.3} + (1-w)*ATER_{8.6}$, w=0.9 or w=0.1 **	$\lvert BF_{8.3}-ASTER_{8.6}\rvert / \sqrt{3}$
8	9.1	Y	Y	$ASTER_{9.1} +(CAMEL_{8.6} – ASTER_{8.6})$	$\lvert BF_{8.3}-ASTER_{9.1}\rvert / \sqrt{3}$
9	10.6	-	Y	$ASTER_{10.6} + (BF_{10.8}-ASTER_{int10.8})$ or $ASTER_{10.6}$ **	$\lvert BF_{10.8}-ASTER_{10.6}\rvert / \sqrt{3}$
10	10.8	Y	-	$BF_{10.8}$ $ASTER_{int10.8}$ **	$\lvert BF_{10.8} -(5*ASTER_{10.6} +2*ASTER_{11.3})/7 \rvert / \sqrt{3}$
11	11.3	-	Y	$ASTER_{11.3} + (BF_{10.8}-ASTER_{int10.8})$ or $ASTER_{11.3}$ **	$\lvert BF_{10.8}-ASTER_{11.3}\rvert / \sqrt{3}$
12	12.1	Y	-	$BF_{12.1}$	$\lvert BF_{12.1}-ASTER_{11.3}\rvert / \sqrt{3}$
13	14.3	Y	-	$BF_{14.3}$	$\lvert BF_{14.3}-ASTER_{11.3}\rvert / \sqrt{3}$

*** if ASTER NDVI > 0.7 and $BF_{8.3}$ <= 0.95*

6. MEaSUREs CAMEL data product files

The V3 CAMEL emissivity, uncertainty, and PCA coefficients have been processed for the time period of 2000-2021. This section describes the technical information of the three data files. Please, note that we track a local version in the global attributes of each file as prd_version=v03r05, which is equivalent to the NASA LP DAAC version V3.

a. *MEaSUREs CAMEL Emissivity Product File*

The CAMEL emissivity is provided in monthly NetCDF files with contents (see *Table 4*) and filename specification as:

Filename: CAMEL_emis_YYYYMM_VXXX.nc;   YYYY=year; MM=month; XXX=version number
Size: ~55 MB per file
Number of files: 255
Missing files: 2000 Jan, Feb, Aug; 2001 Jun, Jul; 2002 Mar; 2003 Dec; 2010 Jul; 2016 Feb.
Temporal Resolution: Monthly
Spatial Resolution: 0.05 degrees
Format: netcdf4 (internally compressed with deflate_value=5)
Dimensions: latitude = 3600 [-89.975, 89.975]; longitude = 7200 [-179.975, 179.975]; spectra = 13

Table 4: The MEaSUREs CAMEL emissivity variables

Name	Type	Dims	Scale Factor	Fill Value	Valid Range	Description
latitude	float32	latitude	N/A	N/A	[-90 90]	**Latitude**, degrees North at grid-box center
longitude	float32	latitude	N/A	N/A	[-180 180]	**Longitude**, degrees East at grid-box center
bfemis_qflag	int16	latitude, longitude	N/A	N/A	[0 4]	**UW Baseline Fit Emissivity Quality Flag**: 0 = no MOD11 data 1 = baseline fit method was applied 2 = averaged from the 2 adjacent months 3 = 2003 annual average 4 = average over the annual average over all emissivity with latitude < -80
aster_qflag	int16	latitude, longitude	N/A	N/A	[1 3]	**ASTER-GED Quality Flag**: 1 = good quality ASTER-GED data 2 = sea or inland water 3 = filled value
camel_qflag	int16	latitude, longitude	N/A	N/A	[0 4]	**CAMEL Quality Flag:** 0 = sea or inland water 1 = good quality of UWBF and ASTER-GED data 2 = good quality of UWBF and filled ASTER-GED data 3 = good quality of ASTER-GED data and filled UWBF data 4 = both BF and ASTER-GED data are filled values
aster_ndvi	int16	latitude, longitude	0.001	N/A	[0 1000]	**ASTER-GED NDVI – vegetation fraction**
snow_fraction	int16	latitude, longitude	0.01	N/A	[0 100]	**Snow fraction** derived from MODIS MOD10
camel_emis	int16	latitude, longitude, spectra	0.001	-999	[0 1000]	**Combined ASTER MODIS Emissivity over Land**: Global emissivity at 3.6, 4.3, 5.0, 5.8, 7.6, 8.3, 8.6, 9.1, 10.6,10.8, 11.3,12.1, 14.3 µm

b) MEaSUREs CAMEL Emissivity Uncertainty Product File

The CAMEL emissivity uncertainty is provided in monthly netcdf files congruent to the CAMEL emissivity product with contents (see *Table 5*) and filename specification as:

Filename: CAMEL_emis_uncertainty_YYYYMM_VXXX.nc;
YYYY=year; MM=month; XXX=version number
Size: ~140 MB per file
Number of files: 255
Missing files: 2000 Jan, Feb, Aug; 2001 Jun, Jul; 2002 Mar; 2003 Dec; 2010 Jul; 2016 Feb.
Temporal Resolution: Monthly
Spatial Resolution: 0.05 degrees
Format: netcdf4 (internally compressed with deflate_value=5)
Dimensions: latitude = 3600 [-89.975, 89.975]; longitude = 7200 [-179.975, 179.975]; spectra = 13

Table 5: The MEaSUREs CAMEL emissivity uncertainty variables

Name	**Type**	**Dims**	**Scale Factor**	**Fill Value**	**Valid Range**	**Description**
latitude	float32	latitude	N/A	N/A	[-90 90]	**Latitude**, degrees North at grid-box center
longitude	float32	latitude	N/A	N/A	[-180 180]	**Longitude**, degrees East at grid-box center
wavelength	float32	spectra	N/A	N/A	N/A	Wavelength of CAMEL hinge points in µm
spatial_uncertainty	uint16	Latitude, longitude, spectra	0.001	9999	[0 1000]	**Spatial uncertainty of the CAMEL Emissivity database**
temporal_uncertainty	uint16	Latitude, longitude, spectra	0.001	9999	[0 1000]	**Temporal uncertainty of the CAMEL Emissivity database**
algorithm_uncertainty	uint16	Latitude, longitude, spectra	0.001	9999	[0 1000]	**Algorithm uncertainty of the CAMEL Emissivity database**
total_uncertainty	uint16	Latitude, longitude, spectra	0.001	9999	[0 1000]	**Total uncertainty of the CAMEL Emissivity database**
total_uncertainty_quality_flag	uint8	Latitude, longitude, spectra	1.	99	[0 2]	**Quality flag of the CAMEL uncertainties** 0 = Sea, no CAMEL data 1 = Good quality data 2 = Unphysical uncertainty
camel_qflag	uint8	latitude, longitude	1.	99	[0 4]	**CAMEL Quality Flag:** 0 = sea or inland water 1 = good quality of UWBF and ASTER-GED data 2 = good quality of UWBF and filled ASTER-GED data 3 = good quality of ASTER-GED data and filled UWBF data 4 = both BF and ASTER-GED data are filled values

c) MEaSUREs Coefficient Product File

The CAMEL PCA coefficients are the inputs of CAMEL HSR Emissivity algorithm. The CAMEL PCA coefficients are provided in monthly netcdf files congruent to the CAMEL emissivity product, with contents (see *Table 6*) and filename specification as:

Filename: CAMEL_emis_coef_YYYYMM_VXXX.nc;
YYYY=year; MM=month; XXX=version number
Size: ~130 MB per file
Number of files: 255
Missing files: 2000 Jan, Feb, Aug; 2001 Jun, Jul; 2002 Mar; 2003 Dec; 2010 Jul; 2016 Feb.
Temporal Resolution: Monthly
Spatial Resolution: 0.05 degrees
Format: netcdf4 (internally compressed with deflate_value=5)
Dimensions: latitude = 3600 [-89.975, 89.975]; longitude = 7200 [-179.975, 179.975]; max_npcs=9, mask = 8685101 (varies by month)

Table 6: The MEaSUREs CAMEL coefficient variables

Name	Type	Dims	Scale Factor	Fill Value	Valid Range	Description
latitude	Float32	latitude	N/A	N/A	[-90 90]	**Latitude**, degrees North at grid-box center
longitude	Float32	latitude	N/A	N/A	[-180 180]	**Longitude**, degrees East at grid-box center
camel_qflag	int16	latitude, longitude	N/A	N/A	[0 4]	**CAMEL Quality Flag:** 0 = sea or inland water 1 = good quality of UWBF and ASTER-GED data 2 = good quality of UWBF and filled ASTER-GED data 3 = good quality of ASTER-GED data and filled UWBF data 4 = both BF and ASTER-GED data are filled values
snow_fraction	int16	mask	0.01	N/A	[0 100]	**Snow fraction** derived from MODIS MOD10
pc_labvs	int16	mask	N/A	N/A	[8 12]	**Version number** of the Laboratory PCs datafile
pc_npcs	int16	mask	N/A	N/A	[2 9]	**Number of PCs** used
pc_coefs	float32	max_npcs, mask	N/A	-999	[-10 10]	**CAMEL PCA Coefficients** PCA coefficients are dependent on the version of lab PC data and the number of PCs used.

To save storage and memory load space in the HSR emissivity algorithm, the values of the snow fraction, the version number of laboratory data, the number of PCA coefficients, and the PCA coefficients have been stored only over land pixels, i.e., when the CAMEL quality flag is larger than zero (camel_qflag > 0). Instead of the 3600x7200 dimensions, the above-mentioned variables have been stored in a vector of length 8685101 (for Jan 2007); however, the number of land pixels may vary by month. This method reduces the storage place and memory load to a third of what is required for the original gridded formatting files.

The part of the read_CAMEL_coef.f Fortran subroutine, which converts the land pixels into the 2-dimensional (Lat, lon) matrix, is as follows:

```
!-----------------------------------------------------
! Generate the look-up table into the emissivity data
!-----------------------------------------------------
coef_lut = -1
indexlut = 1
Do i=1,nc_dim(1)
     Do j=1,nc_dim(2)
         If (camel_qflag(j,i) > 0) then
              coef_lut(j,i) = indexlut
             indexlut = indexlut + 1
        End If
     End Do
End Do
! extract coef for a pixel (gridx,gridy):
If (coef_lut(gridx,gridy) > 0) Then
         coeff(:) = pcacoefs(1:npcs,coef_lut(gridx,gridy))*pca_sfac + pca_offs
End If
```

, where npcs is between 1 and 13, pca_sfac is the scale factor, and pca_offs is the offset. The part of the read_CAMEL_coef_V003.m Matlab subroutine, which converts the land pixels into the 2-dimensional (lat, lon) matrix, has been sped up by one of the CAMEL users, *Larrabee Strow* is as follows:

```
camel.coef=NaN(max_npcs,Ymax,Xmax);
camel.pcnpcs=NaN(Ymax,Xmax);
camel.snowf=NaN(Ymax,Xmax);
camel.pclabvs=NaN(Ymax,Xmax);

k = find(camel.camel_qflag > 0);
camel.coef(:,k) = pc_coefs;
camel.pcnpcs(k) = double(pc_npcs);
camel.pclabvs(k) = double(pc_labvs);
camel.snowf(k) = double(snow_fraction);
```

7. Description of the MEaSUREs CAMEL High Spectral Resolution Algorithm

The standalone version of the HSR emissivity Algorithm has been developed in MATLAB and Fortran. In this section, you can find technical details about these software packages.

a) Fortran version

This package contains software to create a Fortran library to calculate the CAMEL High Spectral Resolution emissivity, as well as a sample program for users to understand how to run the algorithm. The software runs on version 3.0 (NASA LPDAAC V003) CAMEL emissivity coefficients data. Output of the software can be (1) a 5 wavenumber resolution emissivity at 417 wavenumbers (between 698 and 2778) and/or (2) an instrument specific emissivity.

Requirements:
Software requirement: netcdf4 library (gcc)

Software package contains:
- src_hsrlib_V003 - contains fortran algorithm
- lib - will contain the "libhsriremis_V003.a" after installation
- coef - contains all the laboratory eigenvector and eigenvalues netcdf files
- include - contains the hsriremis_EDR.inc
- data - includes one CAMEL coefficient file for testing purpose
- test - includes a test code (run_hsriremis.f) to run for one geographical location

Install the package:
- File name: *MEASURES_CAMEL_hsremis_lib_V003.tar.gz*
- unzip (gzip –d) and untar (tar –xvf) it
- The complete list of the package can be found in Appendix 2.

Create the HSR emis library:
1. cd src_hsrlib_V003
2. make -f Makefile_lib clean
3. make -f Makefile_lib
4. make -f Makefile_lib install

Test code for the HSR emis library:
1. cd test
2. edit the library links in run_hsriremis_oneline.mk
3. ./run_hsriremis_oneline.mk (complie code)
4. ./run_hsriremis.exe
5. compare results for Namib at IASI frequencies:
   sdiff Namib_iasi_emis.txt.test Namib_iasi_emis.txt

Table 7: Inputs of the CAMEL HSR Algorithm V003

Inputs	Data Type	Valid Range	Notes
year	character(len=4)	['2000' '2021']	
month	character(len=2)	['01' '12']	
path_camel	character(len=300)		directory name of the CAMEL coef data
latitude	real	[-90 90]	Latitude of the location in degree
longitude	real	[-180 180]	Longitude of the location in degree
first	logical	[yes no]	Switch for initialization Set TRUE for the first call and then FALSE
instr_switch	logical	[yes no]	Set to TRUE for hsr emis to be calculated for a certain instrument otherwise set to FALSE
debug	logical	[yes no]	Set to TRUE for more outputting otherwise set to FALSE
nchs	integer		Set to zero if calculating hsr emis for a certain instrument (if instr_switch = TRUE) otherwise set to the number of channels of the instrument
insr_wavenumber (optional)	real[nchs]		Central wavenumber of the instrument bands in increasing order

Table 8: Outputs of the CAMEL HSR Algorithm V003

Outputs	Data Type	Valid Range	Notes
hsremis	real(417)	[0.5 1]	
instr_emis(optional)	Real(nchs)	[0.5 1]	Output only if number of channels (nchs) is not set to zero

Usage:

```
call compute_hsriremis(
        & cyear,          ! in
        & cmonth,         ! in
        & lat_site,       ! in
        & lon_site,       ! in
        & first,          ! in
        & instr_switch,   ! in
        & debug,          ! in
        & hsriremis,      ! out
        & nchs,           ! in
        & instr_wn,       ! in, optional
        & instr_emis)     ! out, optional
```

The wavenumber of the HSR emissivity is not output, but it can be obtained by the following:

```
Do i=1,numwave
      hsr_wavenum(i) = 698 +(i-1)*5
Enddo
```

Note to run for the whole grid (3600x7200), it is suggested to read the camel_qflag first and call the compute_hsriemis.f subroutine for land pixels only (camel_qflag > 0).

```
call read_CAMEL_coef_qflag(
      & fn_coef,          !in          character (len=300) - name of the coefficient file
```

& camel_qflag) !out int2[7200,3600] - CAMEL quality flag

<u>The codes in the CAMEL HSR package:</u>
SUBROUTINE compute_hsriremis : creates library to compute high spectral resolution emissivity spectra from the MEaSUREs CAMEL database

SUBROUTINE init_hsriremis (name of the CAMEL coefficient file): initializes variables and reads in the eigenvectors of the laboratory data (calls read_labpcs for all three laboratory sets).

SUBROUTINE read_CAMEL_coef (name of the CAMEL coefficient file): reads the 0.05 degree resolution MEaSUREs CAMEL (from the netCDF file into memory).

SUBROUTINE read_CAMEL_coef_qflag (name of the CAMEL coefficient file): reads the CAMEL quality flag from the 0.05 degree resolution MEaSUREs CAMEL Coefficient file into memory.

SUBROUTINE read_labpcs (laboratory data version): read the eigenvectors and eigenvalues of the selected laboratory measurements.

SUBROUTINE recon_hsriremis (number of PCs to use, version number of laboratory set, coefficients(output), hsriremis (output)): creates high spectra resolution emissivities at 417 wavenumbers from the MEaSUREs CAMEL emissivity database (at 13 hinge points) and laboratory measurements using principal component analyses.

SUBROUTINE select_wavenum hsremis (number of channels, instr_wavenum, instr_emis (output)): is called if instr_switch is set to TRUE. The subroutine finds the closest wavenumber from the MEaSUREs CAMEL HSR emissivity spectra for the instrument frequency and assigns the instrument emissivity by either choosing the closest spectral point value or bilinear interpolating between the two closest spectral point values.

Compute_hsriremis

- **Call init_hsriremis**
  - *(If first)* **Call read_labpcs**
- **Call read_CAMEL_coef**
- **Call recon_hsriremis** (*If CAMEL_qflag > 0*)
- **Call select_wavenum** *(if instr_switch)*

Figure 3: Structure of the MEaSUREs CAMEL HSR Algorithm

b) ***Matlab version***

The package contains software to calculate the CAMEL High Spectral Resolution emissivity as well as a sample program for users to understand how to run the algorithm. The software runs on version 3.0 (V003) CAMEL emissivity coefficients data. The HSR emissivity can be calculated using the CAMEL 13 hinge points emissivity values or the CAMEL Principal Component Analyses coefficients as input.

<u>Install the package:</u>

File name: *MEASURES_CAMEL_hsremis matlab_V003.tar.gz*
unzip (gzip -d) and untar (tar -xvf) it

<u>Software package contains:</u>

coef **-** contains files of laboratory eigenvectors and eigenvalues (Matlab format)
data **-** contains MEaSUREs emissivity and coefficients files for a test month (2007 January)
outdir **-**contains an image and a mat-file of the test case result for sanity check
mfiles **-**contains the MEaSUREs HSR algorithm

<u>file structure:</u>

main code: run*_MEASUREs_hsremis_test_V002.m*
calls: -*read_CAMEL_coef_V002.m*
-*read_CAMEL_emis_V002.m*
-*create_HSRemis_fromCAMELcoef_V003.m or*
-*create_HSRemis_fromCAMELemis_V003.m*

<u>Test run</u>:

1. go to the mfiles directory
2. start matlab
3. run: *run_MEASUREs_hsremis_test_V003.m*
4. compare the resulting image and mat-file in the output directory with the *orig.png and *orig.mat file

References

Anderson, M.C., Norman, J.M., Mecikalski, J.R., Otkin, J.A., & Kustas, W.P. (2007). A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 2. Surface moisture climatology. *Journal of Geophysical Research-Atmospheres*, **112**.

Borbas, E. E., and B. C. Ruston (2010), The RTTOV UWiremis IR land surface emissivity module, Mission Report NWPSAF-MO-VS-042, EUMETSAT Numerical Weather Prediction. *Satellite Applications Facility*, Met Office, Exeter, U.K. URL: http://research.metoffice.gov.uk/research/interproj/nwpsaf/vs_reports/nwpsaf-mo-vs-042.pdf

Borbas, E (2014): Investigation into the angular dependence of IR surface emissivity. Mission Report. EUMETSAT NWPSAF-MO-VS-050. https://nwpsaf.eu/vs_reports/nwpsaf-mo-vs-050.pdf

Borbas, E., Hulley G., Feltz M., Knuteson, R., Hook, S. J. (2018): The Combined ASTER MODIS Emissivity Over Land (CAMEL) Part 1: Methodology and High Spectral Resolution Application, *Remote Sensing*, Special Issue "Advancing Earth Surface representation via Enhanced Use of Earth Observations in Monitoring and Forecasting Applications", **10**, 643, doi:10.3390/rs10040643.

Borbas, E. & Feltz, M. (2019) Updating the CAMEL surface emissivity atlas for RTTOV. Mission Report. EUMETSAT NWPSAF-MO-VS-058, https://www.nwpsaf.eu/publications/vs_reports/nwpsaf-mo-vs-058.pdf

Feltz M., Borbas, E., Knuteson, R., Hulley G. Hook, S. J. (2018a): The Combined ASTER MODIS Emissivity Over Land (CAMEL) Part 2: Uncertainty and Validation, *Remote Sensing*, Special Issue "Advancing Earth Surface representation via Enhanced Use of Earth Observations in Monitoring and Forecasting Applications", **10**, 664, doi:10.3390/rs10050664.

Feltz M., Borbas, E., Knuteson, R., Hulley G. Hook, S. J. (2018b): The Combined ASTER MODIS Emissivity Over Land (CAMEL) Global Broadband Infrared Emissivity Product, *Remote Sensing*, Special Issue "Advancing Earth Surface representation via Enhanced Use of Earth Observations in Monitoring and Forecasting Applications", 10, 1027, doi:10.3390/rs10071027.

French, A.N., Schmugge, T.J., Ritchie, J.C., Hsu, A., Jacob, F., & Ogawa, K. (2008). Detecting land cover change at the Jornada Experimental Range, New Mexico with ASTER emissivities. *Remote Sensing of Environment*, **112**, 1730-1748.

Hook, S. (2017) *Combined ASTER and MODIS Emissivity database over Land (CAMEL) Emissivity Monthly Global 0.05Deg V001* [Data set]. NASA EOSDIS Land Processed DAAC, doi:10.5067/MEaSUREs/LSTE/CAM5K30EM.001.

Hook, S. (2019) *Combined ASTER and MODIS Emissivity database over Land (CAMEL) Emissivity Monthly Global 0.05Deg V002*. [Data set]. 2019, distributed by NASA EOSDIS Land Processes DAAC, https://doi.org/10.5067/MEaSUREs/LSTE/CAM5K30EM.002.

Hulley, G.C., & Hook, S.J. (2009). The North American ASTER Land Surface Emissivity Database (NAALSED) Version 2.0. *Remote Sensing of Environment*, 1967-1975.

Hulley, G., Hook S.J, Abbott, E., Malakar, N., Islam, T., Abrams, M., (2015), The ASTER Global Emissivity Dataset (ASTER-GED): Mapping Earth's emissivity at 100 meter spatial resolution, *Geophysical Research Letters*, **42**, doi:10.1002/2015GL065564.

Hulley, G., S. Hook. (2021) *MOD21 MODIS/Terra Land Surface Temperature/3-Band Emissivity 5-Min L2 1km V061*. [Data set]. Distributed by NASA EOSDIS Land Processes DAAC, https://doi.org/10.5067/MODIS/MOD21.061. Accessed 2023-01-23.

Moran, M.S. (2003). Thermal infrared measurement as an indicator of plant ecosystem health, in: *Thermal Remote Sensing in Land Surface Processes*, edited: Quattrochi, D. A. and Luvall, J., Taylor and Francis, 257-282.

Seemann, S.W., Li, J., Menzel, W.P., & Gumley, L.E. (2003). Operational retrieval of atmospheric temperature, moisture, and ozone from MODIS infrared radiances. *Journal of Applied Meteorology*, **42**, 1072-1091.

Seemann, S.W., Borbas, E.E., Knuteson, R.O., Stephenson, G.R., & Huang, H.L. (2008). Development of a global infrared land surface emissivity database for application to clear sky sounding retrievals from multispectral satellite radiance measurements. *Journal of Applied Meteorology and Climatology*, **47**, 108-123.

Tarantola, A., 2005. Inverse Problem Theory and Methods for Model Parameter Estimation. Society of Industrial and Applied Mathematics (SIAM), and Springer-Verlag.

Wan, Z., S. Hook, G. Hulley. (2021) *MODIS/Terra Land Surface Temperature/Emissivity 5-Min L2 Swath 1km V061*. [Data set]. Distributed by NASA EOSDIS Land Processes DAAC, https://doi.org/10.5067/MODIS/MOD11_L2.061. Accessed 2023-01-23.

Willett, K., P. Thorne and the ISTI Steering Committee, 2011. Progress Report for the International Surface Temperature Initiative. http://www.wmo.int/pages/prog/gcos/SC-XIX/IntlSurfaceTempInitiative--Willett.pdf.

Zhou, L., Dickinson, R.E., Tian, Y., Jin, M., Ogawa, K., Yu, H., & Schmugge, T. (2003). A sensitivity study of climate and energy balance simulations with use of satellite-derived emissivity data over Northern Africa and the Arabian Peninsula. *Journal of Geophysical Research-Atmospheres*, **108**, 4795.

Appendix 1: CAMEL Product CDL Files

a) CAMEL Coefficient Product

```
netcdf CAMEL_coef_201409_V003 {
dimensions:
	latitude = 3600 ;
	longitude = 7200 ;
	max_npcs = 9 ;
	mask = 8416131;
variables:
	float latitude(latitude) ;
		latitude:units = "degrees north" ;
		latitude:long_name = "Latitude; Degrees north at grid-box center" ;
		latitude:comment = "none" ;
		latitude:valid_range = -90.f, 90.f ;
		latitude:coordinates = "latitude" ;
	float longitude(longitude) ;
		longitude:units = "degrees east" ;
		longitude:long_name = "Longitude; Degrees east at grid-box center" ;
		longitude:comment = "none" ;
		longitude:valid_range = -180.f, 180.f ;
		longitude:coordinates = "longitude" ;
	short camel_qflag(latitude, longitude) ;
		camel_qflag:units = "none" ;
		camel_qflag:long_name = "Combined ASTER MODIS Emissivity over Land: Quality Flag" ;
		camel_qflag:comment = "0 = sea or inland water;1 = good quality of BF and ASTER-GED data; 2 = good
qality of BF data and filled ASTER-GED data;3 = good quality of ASTER-GED data and filled BF data ;
4 = both BF and ASTER-GED data are filled values" ;
		camel_qflag:valid_range = 0s, 4s ;
		camel_qflag:coordinates = "latitude longitude" ;
	short snow_fraction(mask) ;
		snow_fraction:units = "none" ;
		snow_fraction:long_name = "Snow fraction derived from MODIS MOD10" ;
		snow_fraction:comment = "" ;
		snow_fraction:scale_factor = 0.01f ;
		snow_fraction:valid_range = 0s, 100s ;
		snow_fraction:coordinates = "latitude longitude" ;
	short pc_labvs(mask) ;
		pc_labvs:units = "none" ;
		pc_labvs:long_name = "Version number of the Laboratory PCscores datafile" ;
		pc_labvs:comment = "None" ;
		pc_labvs:valid_range = 8s, 12s ;
		pc_labvs:coordinates = "latitude longitude" ;
	short pc_npcs(mask) ;
		pc_npcs:units = "none" ;
		pc_npcs:long_name = "NUmber of PCs used" ;
		pc_npcs:comment = "None" ;
		pc_npcs:valid_range = 2s, 9s ;
		pc_npcs:coordinates = "latitude longitude" ;
	float pc_coefs(mask, max_npcs) ;
		pc_coefs:units = "none" ;
		pc_coefs:long_name = "Combined ASTER MODIS Emissivity over Land: PCA Coefficients" ;
		pc_coefs:comment = "PCA coefficients are dependent of the version of lab PC data and number of PCs
used." ;
		pc_coefs:_FillValue = -999.f ;
		pc_coefs:valid_range = -10.f, 10.f ;
		pc_coefs:coordinates = "mask npcs" ;

// global attributes:
```

```
                    :institution = "UW-MAD/SSEC/CIMSS, Cooperative Institute for Meteorological  Satellite Studies, Space Science and Engineering Center, University of Wisconsin, Madison, http://cimss.ssec.wisc.edu/" ;
                    :creator = "Eva E. Borbas " ;
                    :contributor = "Glynn C. Hulley " ;
                    :id = "CAMEL_coef_201409_V003.nc " ;
                    :Prd_Version = "v03r05" ;
                    :LP_DAAC_Version = "V003" ;
                    :date_issued = "2022-12-12" ;
                    :cdm_data_type = "grid " ;
                    :featureType = "grid " ;
                    :spatial_resolution = "0.05 degrees " ;
                    :spectral_resolution = "3.6, 4.3, 5.0, 5.8, 7.6, 8.3, 8.6, 9.1, 10.6,10.8, 11.3, 12.1, 14.3 micrometer " ;
                    :source = "BFemis_MYD11C3.A201409.061.V41.nc,ASTER_GEDv4_A2014244.nc" ;
                    :title = "NASA MEASUREs: Combined ASTER MODIS Emissivity over Land (CAMEL) COEF ESDR " ;
                    :summary = "Monthly Mean Global IR Land Surface Emissivity; " ;
                    :license = "No restrictions on access or use" ;
                    :keywords_vocabulary = "NASA Global Change Master Directory (GCMD) Earth Science Keywords,
                    :date_created = "2022-12-12 21:57:16Z" ;
                    :geospatial_lat_min = -89.9749984741211 ;
                    :geospatial_lat_max = 89.9749984741211 ;
                    :geospatial_lat_resolution = "0.05 degree grid " ;
                    :geospatial_lat_units = "degrees north " ;
                    :geospatial_lon_min = -179.975006103516 ;
                    :geospatial_lon_max = 179.975006103516 ;
                    :geospatial_lon_resolution = "0.05 degree grid " ;
                    :geospatial_lon_units = "degrees east " ;
                    :time_coverage_start = "2014-09-01 00:00:00Z" ;
                    :time_coverage_end = "2014-10-01 00:00:00Z" ;
                    :time_coverage_duration = "P1M " ;
}
```

b) ***CAMEL Emissivity Product***

```
netcdf CAMEL_emis_201409_V003 {
dimensions:
          latitude = 3600 ;
          longitude = 7200 ;
          spectra = 13 ;
variables:
          float latitude(latitude) ;
                    latitude:units = "degrees north" ;
                    latitude:long_name = "Latitude; Degrees north at grid-box center" ;
                    latitude:comment = "none" ;
                    latitude:valid_range = -90.f, 90.f ;
                    latitude:coordinates = "latitude" ;
          float longitude(longitude) ;
                    longitude:units = "degrees east" ;
                    longitude:long_name = "Longitude; Degrees east at grid-box center" ;
                    longitude:comment = "none" ;
                    longitude:valid_range = -180.f, 180.f ;
                    longitude:coordinates = "longitude" ;
          short bfemis_qflag(latitude, longitude) ;
                    bfemis_qflag:units = "none" ;
                    bfemis_qflag:long_name = "UW Baseline Fit Emissivity Quality Flag" ;
                    bfemis_qflag:comment = "0 = no MOD11 data;1 = baseline fit method was applied;  2= averaged from the 2 adjacent months;3 = 2003 annual average ; 4 = average over the annual average over all emis with latitude<-8" ;
                    bfemis_qflag:valid_range = 0s, 4s ;
                    bfemis_qflag:coordinates = "latitude longitude" ;
          short aster_qflag(latitude, longitude) ;
                    aster_qflag:units = "none" ;
                    aster_qflag:long_name = "ASTER GED Quality Flag" ;
```

```
                aster_qflag:comment = "2 = sea or inland water; 1 = good quality ASTER-GED data;3= filled value" ;
                aster_qflag:valid_range = 0s, 4s ;
                aster_qflag:coordinates = "latitude longitude" ;
        short camel_qflag(latitude, longitude) ;
                camel_qflag:units = "none" ;
                camel_qflag:long_name = "Combined ASTER MODIS Emissivity over Land – Quality Flag" ;
                camel_qflag:comment = "0 = sea or inland water;1 = good quality of BF and ASTER-GED data; 2 = good
qality of BF data and filled ASTER-GED data;3 = good quality of ASTER-GED data and filled BF data ; 4 = both BF and
ASTER-GED data are filled values" ;
                camel_qflag:valid_range = 0s, 4s ;
                camel_qflag:coordinates = "latitude longitude" ;
        short aster_ndvi(latitude, longitude) ;
                aster_ndvi:units = "none" ;
                aster_ndvi:long_name = "ASTER GED NDVI" ;
                aster_ndvi:comment = "none" ;
                aster_ndvi:scale_factor = 0.001f ;
                aster_ndvi:valid_range = 0s, 1000s ;
                aster_ndvi:coordinates = "latitude longitude" ;
        short snow_fraction(latitude, longitude) ;
                snow_fraction:units = "none" ;
                snow_fraction:long_name = "MODIS MOD10 Snow Fraction" ;
                snow_fraction:comment = "none" ;
                snow_fraction:scale_factor = 0.01f ;
                snow_fraction:valid_range = 0s, 100s ;
                snow_fraction:coordinates = "latitude longitude" ;
        short camel_emis(latitude, longitude, spectra) ;
                camel_emis:units = "none" ;
                camel_emis:long_name = "Combined ASTER MODIS Emissivity over Land" ;
                camel_emis:comment = "Emissivity at 3.6, 4.3, 5.0, 5.8, 7.6, 8.3, 8.6, 9.1, 10.6,10.8,11.3,12.1, 14.3 micron"
                camel_emis:scale_factor = 0.001f ;
                camel_emis:_FillValue = -999s ;
                camel_emis:valid_range = 0.f, 1000.f ;
                camel_emis:coordinates = "latitude longitude spectra" ;

// global attributes:
                :institution = "UW-MAD/SSEC/CIMSS, Cooperative Institute for Meteorological Satellite  Studies, Space
Science and Engineering Center, University of Wisconsin, Madison, http://cimss.ssec.wisc.edu/" ;
                :creator = "Eva E. Borbas " ;
                :contributor = "Glynn C. Hulley " ;
                :id = "CAMEL_emis_201409_V003.nc " ;
                :Prd_Version = "v03r05" ;
                :LP_DAAC_Version = "V003" ;
                :date_issued = "2022-12-12" ;
                :cdm_data_type = "grid " ;
                :featureType = "grid " ;
                :spatial_resolution = "0.05 degrees " ;
                :spectral_resolution = "3.6, 4.3, 5.0, 5.8, 7.6, 8.3, 8.6, 9.1, 10.6,10.8, 11.3, 12.1, 14.3 micrometer " ;
                :source = "BFemis _MYD11C3.A201409.061.V041.nc,ASTER_GEDv4_A2014244.nc" ;
                :title = "NASA MEASUREs: Combined ASTER MODIS Emissivity over Land (CAMEL) ESDR " ;
                :summary = "Monthly Mean Global IR Land Surface Emissivity; " ;
                :license = "No restrictions on access or use" ;
                :keywords_vocabulary = "NASA Global Change Master Directory (GCMD) Earth  Science Keywords,
                :date_created = "2022-12-12 21:56:56Z" ;
                :geospatial_lat_min = -89.9749984741211 ;
                :geospatial_lat_max = 89.9749984741211 ;
                :geospatial_lat_resolution = "0.05 degree grid " ;
                :geospatial_lat_units = "degrees north " ;
                :geospatial_lon_min = -179.975006103516 ;
                :geospatial_lon_max = 179.975006103516 ;
                :geospatial_lon_resolution = "0.05 degree grid " ;
                :geospatial_lon_units = "degrees east " ;
                :time_coverage_start = "2014-09-01 00:00:00Z" ;
```

```
                :time_coverage_end = "2014-10-01 00:00:00Z" ;
                :time_coverage_duration = "P1M " ;
}
```

c) CAMEL Uncertainty Product

```
netcdf CAMEL_emis_uncertainty_201409_V003 {
dimensions:
        latitude = 3600 ;
        longitude = 7200 ;
        spectra = 13 ;
variables:
        float latitude(latitude) ;
                latitude:long_name = "Latitude; Degrees north at grid-box center" ;
                latitude:units = "degrees north" ;
                latitude:valid_range = -90., 90. ;
        float longitude(longitude) ;
                longitude:long_name = "Longitude; Degrees east at grid-box center" ;
                longitude:units = "degrees east" ;
                longitude:valid_range = -180., 180. ;
        float wavelength(spectra) ;
                wavelength:long_name = "Wavelength of CAMEL channels in micrometers" ;
                wavelength:units = "microns" ;
        ushort spatial_uncertainty(latitude, longitude, spectra) ;
                spatial_uncertainty:long_name = "Spatial uncertainty of the CAMEL Emissivity database" ;
                spatial_uncertainty:valid_range = 0., 1000. ;
                spatial_uncertainty:_FillValue = 9999US ;
                spatial_uncertainty:units = "none" ;
                spatial_uncertainty:scale_factor = 0.001 ;
                spatial_uncertainty:add_offset = 0. ;
        ushort temporal_uncertainty(latitude, longitude, spectra) ;
                temporal_uncertainty:long_name = "Temporal uncertainty of the CAMEL Emissivity database" ;
                temporal_uncertainty:valid_range = 0., 1000. ;
                temporal_uncertainty:_FillValue = 9999US ;
                temporal_uncertainty:units = "none" ;
                temporal_uncertainty:scale_factor = 0.001 ;
                temporal_uncertainty:add_offset = 0. ;
        ushort algorithm_uncertainty(latitude, longitude, spectra) ;
                algorithm_uncertainty:long_name = "Algorithm uncertainty of the CAMEL Emissivity database" ;
                algorithm_uncertainty:valid_range = 0., 1000. ;
                algorithm_uncertainty:_FillValue = 9999US ;
                algorithm_uncertainty:units = "none" ;
                algorithm_uncertainty:scale_factor = 0.001 ;
                algorithm_uncertainty:add_offset = 0. ;
        ushort total_uncertainty(latitude, longitude, spectra) ;
                total_uncertainty:long_name = "Total uncertainty of the CAMEL Emissivity database" ;
                total_uncertainty:valid_range = 0., 1000. ;
                total_uncertainty:_FillValue = 9999US ;
                total_uncertainty:units = "none" ;
                total_uncertainty:scale_factor = 0.001 ;
                total_uncertainty:add_offset = 0. ;
        ubyte total_uncertainty_quality_flag(latitude, longitude, spectra) ;
                total_uncertainty_quality_flag:long_name = "Quality flag of the CAMEL uncertainties" ;
                total_uncertainty_quality_flag:Flag_0 = "0 = Sea, no CAMEL data" ;
                total_uncertainty_quality_flag:Flag_1 = "1 = Good quality data" ;
                total_uncertainty_quality_flag:Flag_2 = "2 = Unphysical uncertainty" ;
                total_uncertainty_quality_flag:valid_range = 0., 2. ;
                total_uncertainty_quality_flag:_FillValue = 99UB ;
                total_uncertainty_quality_flag:units = "none" ;
                total_uncertainty_quality_flag:scale_factor = 1. ;
                total_uncertainty_quality_flag:add_offset = 0. ;
        ubyte camel_qflag(latitude, longitude) ;
```

```
                camel_qflag:long_name = "Combined ASTER MODIS Emissivity over Land – Quality  Flag" ;
                camel_qflag:Flag_0 = "0 = sea or inland water" ;
                camel_qflag:Flag_1 = "1 = good quality of BF and ASTER-GED data" ;
                camel_qflag:Flag_2 = "2 = good quality of BF data and filled ASTER-GED data" ;
                camel_qflag:Flag_3 = "3 = good quality of ASTER-GED data and filled BF data" ;
                camel_qflag:Flag_4 = "4 = both BF and ASTER-GED data are filled values" ;
                camel_qflag:valid_range = 0., 4. ;
                camel_qflag:_FillValue = 99UB ;
                camel_qflag:units = "none" ;
                camel_qflag:scale_factor = 1. ;
                camel_qflag:add_offset = 0. ;

// global attributes:
                :Title = "NASA MEASUREs:Emissivity Uncertainties of the CAMEL database" ;
                :Created_by = "Eva Borbas and Michelle Loveless UW/CIMSS/SSEC" ;
                :Institution = "UW-MAD/SSEC/CIMSS, Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin, Madison, http://cimss.ssec.wisc.edu/" ;
                :Creation_date = "16-Dec-2022 01:49:46" ;
                :Prd_Version = "v03r05_V003" ;
                :LP_DAAC_Version = "V003" ;
                :Id = "CAMEL_emis_uncertainty_201409_V003.nc" ;
                :cdm_data_type = "grid" ;
                :featureType = "grid" ;
                :spectral_resolution = "3.6, 4.3, 5.0, 5.8, 7.6, 8.3, 8.6, 9.1, 10.6,10.8, 11.3, 12.1, 14.3 micrometer" ;
                :spatial_resolution = "0.05 degrees" ;
                :geospatial_lat_min = "-89.975" ;
                :geospatial_lat_max = "89.975" ;
                :geospatial_lat_resolution = "0.05 degree grid" ;
                :geospatial_lat_units = "degrees north" ;
                :geospatial_lon_min = "-179.975" ;
                :geospatial_lon_max = "179.975" ;
                :geospatial_lon_resolution = "0.05 degree grid" ;
                :geospatial_lon_units = "degrees east" ;
                :time_coverage_start = "2014-09-01 00:00:00Z" ;
                :time_coverage_end = "2014-10-01 00:00:00Z" ;
}
```

Appendix 2: Contents of the CAMEL HSR algorithm Software package

a) ***Fortran version***

MEASURES_CAMEL_hsremis_lib_V003.tar.gz package contains:

src_hsrlib_V003:
Makefile_lib
compute_hsriremis.f
hsriremis_EDR.inc
init_hsriremis.f
read_CAMEL_coef.f
read_CAMEL_coef_qflag.f
read_labpcs.f
recon_hsriremis.f

test:
iasi_chans616.txt
Namib_hsriremis.txt.test
Namib_iasi_emis.txt.test
run_hsriremis.f
run_hsriremis_oneline.mk

coef:
pchsr_v10.2.nc
pchsr_v11.2.nc
pchsr_v12.2.nc
pchsr_v8.2.nc
pchsr_v9.2.nc

data:
CAMEL_coef_200701_V003.nc

lib:
empty dir

include:
empty dir

b) ***Matlab version***

MEASURES_CAMEL_hsremis_matlab_V003.tar.gz package contains:

coef:
pchsr_v10.2.mat
pchsr_v11.2.mat
pchsr_v12.2.mat
pchsr_v8.2.mat
pchsr_v9.2.mat
pcmodast_v10.2.mat
pcmodast_v11.2.mat
pcmodast_v12.2.mat
pcmodast_v8.2.mat
pcmodast_v9.2.mat

data:
CAMEL_coef_200701_V003.nc
CAMEL_emis_200701_V003.nc

mfiles:

create_HSRemis_fromCAMELcoef_V003.m
create_HSRemis_fromCAMELemis_V003.m
read_CAMEL_coef_V003.m
read_CAMEL_emis_V003.m
run_CAMEL_hsremis_test_V003.m

output:

orig:

MadisonW_CAMEL_HSRemis_200701_V003.mat
MadisonW_CAMEL_HSRemissivity_200701_V003.png
Namib_CAMEL_HSRemis_200701_V003.mat
Namib_CAMEL_HSRemissivity_200701_V003.png
Yemen_CAMEL_HSRemis_200701_V003.mat
Yemen_CAMEL_HSRemissivity_200701_V003.png