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 2 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 currently 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 will be produced globally at 5km resolution in mean monthly time-steps and for 13 bands from 3.6-14.3 micron 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.

1. Table of Contents

Software version identification

The current version of the software is 2.0

2. 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), while 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 involving a radiative transfer model to first 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, and calibrated data and products that are valid across multiple missions and satellite sensors. In this 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 will be 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 (Table 1)). In this document, the LSE ESDR will be described in detail including methodologies, uncertainties and all the technical aspects.

Table 1. Planned LST&E Earth System Data Records (ESDRs)

ESDR	Spatial Resolution	Coverage	Temporal Resolution	Time Period
LEO LST-ESDR	1 km	Global	Daily, 8-day and monthly	2000-2017
GEO LST-ESDR	5 km	N. and S. America	N. America-hourly, S. America-3 hourly	2000-2017
LEO LSE (CAMEL)	**5 km**	**Global**	**Monthly**	**2000-2017***

- Revised time period: 2000-2016 due to the lack of 2017 MODIS MOD11C3 Col4.1 input data

Under the MEaSUREs project, 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 et al., 2018; Borbas et al., 2018, 2019; Feltz et al. 2018a,b). The CAMEL LSE-ESDR has been further extended to hyperspectral resolution using a PC regression approach. For the emissivity ESDR products a full set of uncertainty statistics has also been provided.

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 (GEDv4). 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 3 bands in this region (bands 29, 31, 32). This results in 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 more accurately define the spectral shape 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 together 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 together 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 step 3 and 4 in more details.

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 are summarized in Table 2 and described below.

CAMEL hinge points from 3.6 till 7.6 µm

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

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 band 10.6 and 11.3 µm. CAMEL values at these hinge points were determined from the ASTER GED observations only.

CAMEL hinge point 8.6 µm

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. $\varepsilon(\nu) = [1/(w1 + w2\ )]\ [w1 \cdot \varepsilon(1, \nu) + w2 \cdot \varepsilon(2, \nu)]$, where w is a weighting factor based on an 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. ASTER band 11 (8.6 µm) gets the 90% weight for arid and semi-arid regions, while for all the other cases the UWBF hinge-point 6 (8.3 µm) is weighted by the 90%. To determine the arid, semi-arid region, the ASTER NDVI (<0.2) and ASTER 9.1 µm band (<=0.85) is used. Additionally, over the tropical rainforest region, the MODIS MOD11 emissivity suffers from cloud contamination resulting in the emissivity value at the Restrahen band to be low. To avoid this artifact over that region (+-20 degree latitude band where ASTER NDVI is larger than 0.7 and UWBF emissivity at 8.6 µm is less than 0.96) the ASTER 11 (8.6 µm) is weighted by 90%.

CAMEL hinge point 8.3 and 9.3 µm

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 location of these inflection points were maintained, but the UWBF emissivities are improved by replacing the interpolated inflection points 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 1).

CAMEL hinge point 10. 8 µm

The CAMEL emissivity at the 10.8 µm hinge point has been determined as the linear combination of the ASTER band 10.6 µm and 11.3 µm emissivity.

CAMEL hinge points 12.1 and 14.3 µm

The UWBF at 12.1 and 14.3 µm has been adjusted by the difference between the UWBF 12.1 µm and ASTER 11.3 µm emissivity to be consistent with the 10.6-11.3 µm region (mostly ASTER based observation) and to improve the spectral shape in this longwave spectral region.

Table 2: Determination of the CAMEL hinge points

CAMEL Hinge Points	Method
3.6 µm	= $UWBF_{3.6}$
4.3 µm	= $UWBF_{4.3}$
5.0 µm	= $UWBF_{5.0}$
5.8 µm	= $UWBF_{5.8}$
7.6 µm	= $UWBF_{7.6}$
8.3 µm	= Adjusted $ASTER_{8.3}$ by $CAMEL_{8.6}$ - $ASTER_{8.6}$
8.6 µm	=Weighted combination of $UWBF_{8.3}$ and $ASTER_{8.6}$
9.1 µm	= Adjusted $ASTER_{9.1}$ by $CAMEL_{8.6}$ - $ASTER_{8.6}$
10.6 µm	= $ASTER_{10.6}$
10.8 µm	= linear interpolation between $ASTER_{10.6}$ and $ASTER_{11.3}$
11.3 µm	= $ASTER_{11.3}$
12.1 µm	= Adjusted $UWBF_{12.1}$ based on $UWBF_{12.1}$ – $ASTER_{11.3}$
14.3 µm	= Adjusted $UWBF_{14.3}$ based on $UWBF_{12.1}$ – $ASTER_{11.3}$

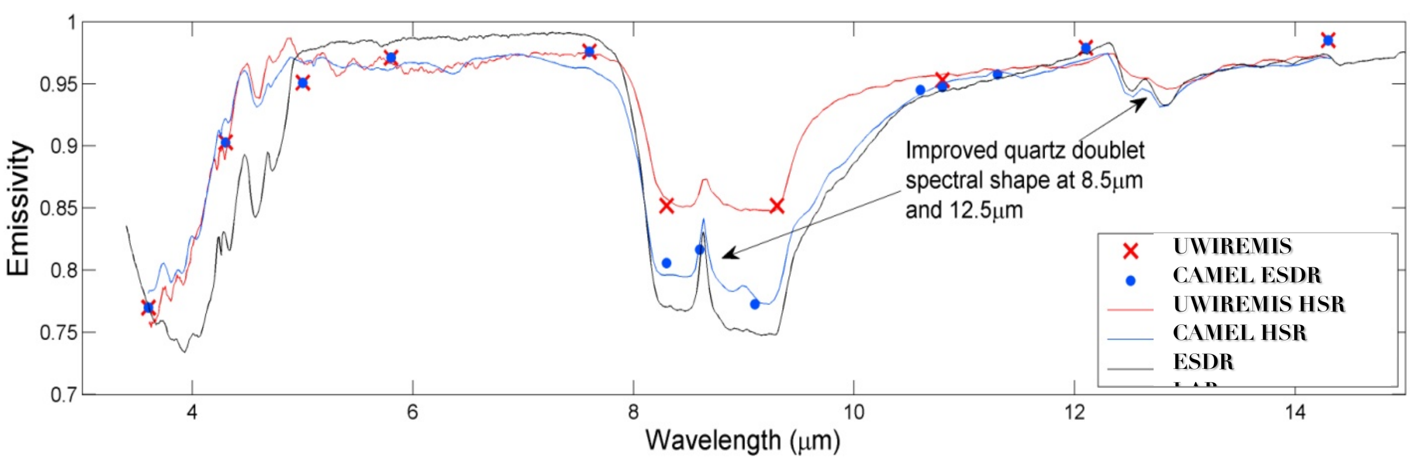

Figure 1: The advantages of combining the ASTER GED and MODIS UW Baseline Fit databases are evident here showing emissivity spectra over the Namib Desert, Namibia. UWBF v4.1 emissivity for Jan 2004 (crosses) and hyperspectral fit (red line), the CAMEL 13 hinge-point emissivity (blue dots) and hyperspectral 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 micron, and 12-13 microns.

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 to the UWIREMIS-HSR Algorithm (*Borbas and Ruston (2010)* and *Borbas et al (2014))*. The UWIREMIS-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 three sets of selected laboratory measurements in CAMEL V001 and five sets of laboratory measurements in V002 (chosen to represent various surface types) and regressed to the CAMEL 13 hinge-points as follows:

$$\vec{\mathbf{e}} = \vec{\mathbf{c}}\mathbf{U}$$

where $\vec{\mathbf{e}}$ is the CAMEL emissivity on 13 hinge points, $\vec{\mathbf{c}}$ 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 ($\vec{\mathbf{c}}$), 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 V002 HSR algorithm from the UWIREMIS 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 3.

Table 3: Determination of the number of PCs and the version number of laboratory datasets for each pixel in CAMEL V002.

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 $CAMEL_{9.1}$ <=0.85 & snow fraction =0	8 (general)	9
Carbonate test no, but $CAMEL_{9.1}$ <=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 & $CAMEL_{3.6} < 0.9$*

Note that CAMEL V002 makes use of two more laboratory datasets than does V001—V001 does not include lab version 9 or 11. The addition of these lab datasets was made in V002 to more accurately characterize partially snowy scenes. In the previous V001 if any pixel had a greater than 0.5 snow fraction, then the snow/ice only laboratory dataset was used to determine the HSR emissivity, thereby providing a false, completely snow scene spectra. In V002, however, the inclusion of lab version 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 1 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 UWIREMIS HSR fit (UWIREMIS_hyper). Biases and RMS errors were reduced by 3% and 4% respectively by using the unified LSE-ESDR instead of the original UWIREMIS product.

5. MEaSUREs CAMEL Emissivity Uncertainty determination

The product uncertainty is estimated by a total emissivity uncertainty that comprises 3 independent components of variability—a 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 4.

Table 4: 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 difference between the ASTER and UWBF products are 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 are shown in Table 5. Channel 10, at 10.8 micron, uses a linear interpolation between the ASTER channels 4 and 5. Where no ASTER data is available in the shortwave region for CAMEL channel 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 microns 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 3 uncertainty components (though are not provided to users due to file size restraints). Spatial and temporal uncertainties values are flagged unphysical if they are located 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 is any of the 3 components are flagged as being unphysical.

Table 5: Method of calculating CAMEL algorithm uncertainty

	CAMEL	UWBF	ASTER	CAMEL COMBINING METHOD	ALGORITHM UNCERTAINTY METHOD
1	3.6	Y	-	BF1	Abs(BF1*[(BF6 - ASTER2)/BF6])/√3
2	4.3	Y	-	BF2	Abs(BF2*[(BF6 - ASTER2)/BF6])/ √3
3	5.0	Y	-	BF3	Abs(0.01)/ √3
4	5.8	Y	-	BF4	Abs(0.01)/ √3
5	7.6	Y	-	BF5	0 (Minimal variation)
6	8.3	Y	Y	ASTER 1 + (CAMEL7(BF6, ASTER 2) – ASTER 2)	Abs(BF6 – ASTER1)/√3
7	8.6	S	Y	WeightedMean(BF6, ASTER 2)	Abs(BF6 – ASTER2)/√3
8	9.1	S	Y	ASTER 3 + (CAMEL7(BF6, ASTER 2) – ASTER 2)	Abs(BF6 – ASTER3)/√3
9	10.6	-	Y	ASTER 4 & BF8	Abs(BF8 – ASTER4)/√3
10	10.8	Y	-	LinearInterpol(ASTER 4, ASTER 5) & BF8	Abs(BF8 – [(ASTER4*5 + ASTER5*2)/7])/ √3
11	11.3	-	Y	ASTER5 & BF8	Abs(BF8 – ASTER5)/√3
12	12.1	Y	-	BF9 but if ASTER5 > BF9, BF9+ diff(BF9, ASTER 5)*s	Abs(BF9 – ASTER5)/√3
13	14.3	Y	-	BF10 but if ASTER 5 > BF9, BF9+ diff(BF9, ASTER 5)*s	Abs(BF10 – ASTER5)/√3

6.MEaSUREs CAMEL data product files

The V002 CAMEL emissivity, uncertainty and PCA coefficients have been processed for the time period of 2000-2016. 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=v02r01, which is equivalent of the NASA LP DAAC version V002.*

a. MEaSUREs CAMEL Emissivity Product File

The CAMEL emissivity is provided in monthly netcdf files with contents (see Table 1) and filename specification as:

Filename: CAMEL_emis_YYYYMM_VXXX.nc
    YYYY = year
    MM = month
    XXX = version number
Size: ~55 MB per file
    Total size: ~ 11GB
    Number of files: 194
    Missing files between 2000-2016: Jan-March/Aug 2000, June/July 2001, March 2002, December 2003, July 2010, February 2016
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 6: The MEaSUREs CAMEL emissivity variables

Name	Type	Dims	Scale Factor	Fill Value	Valid Range	Description
latitude	float16	latitude,	na	na	[-90 90]	**Latitude**, degrees North at grid-box center
longitude	float16	latitude,	na	na	[-180 180]	**Longitude**, degrees east at grid-box center
bfemis_qflag	int16	latitude, longitude	na	na	[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 < -8
aster_qflag	int16	latitude, longitude	na	na	[0 4]	**ASTER GED Quality Flag:** 1 = good quality ASTER-GED data 2 = sea or inland water 3 = filled value
camel_qflag	int16	latitude, longitude	na	na	[0 4]	**CAMEL Quality Flag:** 0 = sea or inland water

						1 = good quality of BF and ASTER-GED data 2 = good quality 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
aster_ndvi	int16	latitude, longitude	0.001	na	[0 1000]	**ASTER GED NDVI – vegetation fraction**
snow_fraction	int16	latitude, longitude	0.01	na	[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:** 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 microns

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 7) and filename specification as:

Filename: CAMEL_emis_uncertainty_YYYYMM_VXXX.nc
YYYY = year
MM = month
XXX = version number
Size: ~140 MB per file
Total size: ~ 27.2 GB
Number of files: 194
Missing files between 2000-2016: Jan-March/Aug 2000, June/July 2001, March 2002, December 2003, July 2010, February 2016
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 7: The MEaSUREs CAMEL emissivity uncertainty variables

Name	Type	Dims	Scale Factor	fill value	Valid Range	Description
latitude	float16	latitude,	na	na	[-90,90]	Latitude, degrees North at grid-box center
longitude	float16	longitude	na	na	[-180, 180]	Longitude, degrees east at grid-box center
wavelength	float32	spectra	na			Channel locations of CAMEL emissivity in [μm]
spatial_uncertainty	uint16	latitude, longitude,	0.001			**Spatial uncertainty of the CAMEL Emissivity database**

		spectra				
temporal_uncertainty	uint16	latitude, longitude, spectra	0.001			**Temporal uncertainty of the CAMEL Emissivity database**
algorithm_uncertainty	uint16	latitude, longitude, spectra	0.001			**Algorithm uncertainty of the CAMEL Emissivity database**
total_uncertainty	uint16	latitude, longitude, spectra	0.001			**Total uncertainty of the CAMEL Emissivity database**
total_uncertainty_quality_flag	uint8	latitude, longitude, spectra	1			**Quality flag of the CAMEL uncertainties** 0 = Sea, no CAMEL data 1 = Good quality data 2 = Unphysical uncertainty
camel_qflag	uint8	latitude, longitude	1			**CAMEL Quality Flag:** 0 = sea or inland water 1 = good quality of BF and ASTER-GED data 2 = good quality 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

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 8) and filename specification as:

Filename: CAMEL_coef_YYYYMM_VXXX.nc
YYYY = year
MM = month
XXX = version number
Size: ~130 MB per file
Total size: ~26 GB
Number of files: 194
Missing files between 2000-2016: Jan-March/Aug 2000, June/July 2001, March 2002, December 2003, July 2010, February 2016
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 8: The MEaSUREs CAMEL coefficient variables

Name	Type	Dims	Scale Factor	Fill Value	Valid Range	Description
latitude	float16	latitude	na	na	[-90 90]	**Latitude**, degrees North at grid-box center
longitude	float16	longitude	na	na	[-180 180]	**Longitude**, degrees east at grid-box center
camel_qflag	int16	latitude, longitude	na	-999	[0 4]	**CAMEL Quality Flag:** 0 = sea or inland water 1 = good quality of BF and ASTER-GED data 2 = good quality 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
snow_fraction	int16	Mask	0.01	na	[0 100]	**Snow fraction derived from MODIS MOD10**
pc_labvs	int16	Mask	na	na	[8 12]	**Version number of the Laboratory PCscores datafile**
pc_npcs	int16	Mask	na	na	[2 9]	**Number of PCs used**
pc_coefs	float16	Max_npcs, mask	na	-999	[-10 10]	**CAMEL PCA Coefficients** PCA coefficients are dependent of the version of lab PC data and 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 down 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
! 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_V002.m* Matlab subroutine which converts the land pixels into the 2 dimensional (Lat, lon) matrix is as follows:

```
for i=1:max_npcs
    clear coef
    coef=double(squeeze(pc_coefs(i,:)));
        indexlut=1;
        for j=1:Xmax
      for k=1:Ymax
            if camel.camel_qflag(k,j) > 0
            camel.coef(i,k,j) = coef(indexlut);
              if i == 1
              camel.pcnpcs(k,j) = double(pc_npcs(indexlut));
         camel.pclabvs(k,j) =double(pc_labvs(indexlut));
         camel.snowf(k,j) =double( snow_fraction(indexlut));
         end
             indexlut = indexlut + 1;
        end
      end
    end
end
```

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 2.0 (NSA LPDAAC V002/PGE v02r01) 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_V002 - contains fortran algorithm
lib - will contain the "libhsriremis_V002.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_V002_v02r01_del_10092018.tar.gz

1. 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_V002
2. edit hsriremis_EDR.inc if you run on your own data directory:
   DATA path_camel/'../data/'/
   DATA path_lab/'../coef/'/
3. make -f Makefile_lib clean
4. make -f Makefile_lib
5. 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 ./run_hsriremis_oneline.mk (compile code)
4. run ./run_hsriremis.exe
5. compare results for Namib validation site at IASI frequencies:
   sdiff Namib_iasi_emis.txt.test Namib_iasi_emis.txt

Table 9: Inputs of the CAMEL HSR Algorithm V002

Inputs	Data type	Valid range	Notes
year	Character (len=4)	[‘2000’, ’2016’]	
month	Character (len=2)	[‘01’, ’12’]	
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
Instr_wn (optional)	Real [nchs]		central wavenumber of the instrument bands in increasing order

Table 10: Outputs of the CAMEL HSR Algorithm V002

Outputs	Data type	Valid Range	Notes
hsriremis	Real (417)	[0.5, 1]	
Instr_emis (optional)	Real(nchs)	[0.5, 1]	Output only if 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
```

The codes in the CAMEL HSR package:

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.

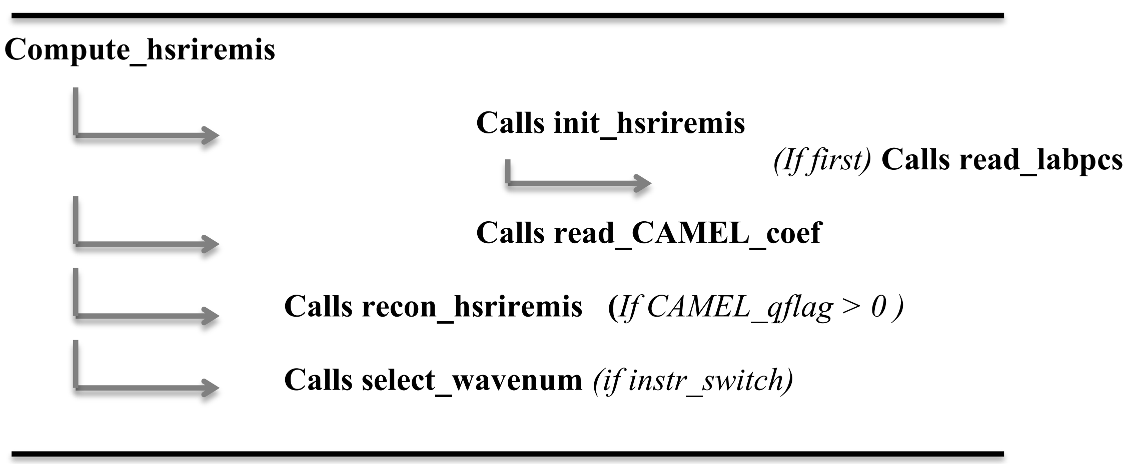

Figure 2: Structure of the MEaSUREs CAMEL HSR Algorithm

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 the version 2.0 (V002) 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.

Install the package:

File name: MEASURES_CAMEL_hsremis matlab_V002_v02r01_del_10092018.tar.gz

1. 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_V002.m
-create_HSRemis_fromCAMELemis_V002.m

<u>Test run:</u>

1. go to the mfiles directory
2. start matlab
3. run: run_MEASUREs_hsremis_test_V002.m
4. compare the resulting image and mat-file in the output directory with the *orig.png and *orig.mat file

2. References

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Appendix 1: CAMEL Product CDL Files

a. CAMEL Coefficient Product

```
netcdf CAMEL_coef_201409_V002 {
dimensions:
	latitude = 3600 ;
	longitude = 7200 ;
	max_npcs = 9 ;
	mask = 8602986 ;
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_V002.nc " ;
                :Prd_Version = "v02r01" ;
                :LP_DAAC_Version = "V002" ;
                :date_issued = "2018-10-04" ;
                :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 =
                "global_emis_inf10_monthFilled_MOD11C3.A2014244.041.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, Version 6.0  " ;
                :date_created = "2018-10-05 19:05:34Z" ;
                :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_V002 {
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_V002.nc " ;
                :Prd_Version = "v02r01" ;
                :LP_DAAC_Version = "V002" ;
                :date_issued = "2018-10-04" ;
                :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 =
                "global_emis_inf10_monthFilled_MOD11C3.A2014244.041.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, Version 6.0  " ;
                :date_created = "2018-10-05 19:05:01Z" ;
                :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_V002 {
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 Feltz 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 = "12-Oct-2018 04:47:55" ;
		:Prd_Version = "v02r01_V002" ;
		:LP_DAAC_Version = "V002" ;
		:Id = "CAMEL_emis_uncertainty_201409_V002.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_V002_v02r01_del_10092018.tar.gz package contains:

src_hsrlib_V002:

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_V002.nc

lib:

empty dir

include:

empty dir

b. Matlab version

MEASURES_CAMEL_hsremis_matlab_V002_v02r01_del_10092018.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_V002.nc
CAMEL_emis_200701_V002.nc

mfiles:

- *create_HSRemis_fromCAMELcoef_V002.m*
- *create_HSRemis_fromCAMELemis_V002.m*
- *read_CAMEL_coef_V002.m*
- *read_CAMEL_emis_V002.m*
- *run_CAMEL_hsremis_test_V002.m*

output:

- *orig:*
  - *MadisonW_CAMEL_HSRemis_200701_V002.mat*
  - *MadisonW_CAMEL_HSRemissivity_200701_V002_v02r01.png*
  - *Namib_CAMEL_HSRemis_200701_V002.mat*
  - *Namib_CAMEL_HSRemissivity_200701_V002_v02r01.png*
  - *Yemen_CAMEL_HSRemis_200701_V002.mat*
  - *Yemen_CAMEL_HSRemissivity_200701_V002_v02r01.png*