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 Climatology Users' Guide

Technical documentation

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1. Introduction

Under the NASA MEaSUREs (Making Earth System Data Records for Use in Research Environments) project, a monthly mean unified Land Surface Emissivity (LSE) Earth System Data Record (ESDR) is being produced and maintained. This dataset combines infrared emissivity from
1) the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Emissivity Dataset (GED) v4 produced at the California Institute of Technology Jet Propulsion Laboratory (Hulley & Hook, 2009; Hulley et al. 2015, 2016), and
2) the MODIS baseline fit (BF) database produced by the University of Wisconsin (UW) Space Science and Engineering Center (SSEC) (Borbas and Seemann 2007; Seemann et al. 2008)

to leverage the spectral and spatial resolution strengths of each dataset. This combined dataset is called the Combined ASTER and MODIS Emissivity over Land (CAMEL) (Borbas et al., 2018; Feltz et al., 2018a, b). It is available as a monthly gridded product for March 2000 through December 2021, has a 0.05 degree (~5 km) spatial resolution, and has a spectral range in the thermal infrared of 3.6 to 14.3 μm. The emissivity is reported on 13 hinge-point channels with uncertainty estimates for every pixel and hinge point (as described in Feltz et al., 2018b). A high spectral resolution (HSR) product is available via a software package with laboratory dataset and principal components (PCs) inputs. The HSR emissivity product has 417 channels with the same spectral range and spatiotemporal resolution as the 13 hinge-point product. The CAMEL HSR algorithm updates the earlier UWIREMIS HSR emissivity algorithm developed for the UW SSEC MODIS baseline fit emissivity dataset (Seemann et al. 2008).

The CAMEL HSR product and its precursor, the UWIREMIS dataset, are actively used by the numerical weather prediction centers for research involving infrared satellite observations over land. An example is their integration into the Radiative Transfer for TOVS (RTTOV) model used at the European Centre for Medium-Range Weather Forecasts (ECMWF) (Borbas & Ruston, 2010; Borbas, 2014; Saunders et al., 2017; Saunders et al., 2018; Borbas & Feltz, 2019). CAMEL Version 1 was first integrated into RTTOV-12 as a module in 2016, and later on, the climatology of CAMEL Version 2 (V2) product was also released in RTTOV-13 (Loveless et al., 2020). The climatology of the CAMEL product was used to better represent the full NASA Earth Observing System satellite record. The CAMEL V2 Climatology product is only available through RTTOV or can be requested by email.

The CAMEL Version 3 (V3) Climatology is the first version made available at the LP DAAC and is based on the CAMEL V3 monthly product (also available at the LP DAAC) with similar spectral coverage and spatial resolution. The complete CAMEL V3 Climatology package consists of five components, which separately contain: 1) the 13 hinge-point emissivity, 2) the 13 hinge-point emissivity uncertainty, 3) the PC coefficients used as input to the HSR software package, 4) the climatological mean HSR spectra on a

5x5 degraded spatial scale with the diagonal of the covariance, and 5) the HSR software and associated principle component vectors. The first four components are available in netCDF file format as data products. The CAMEL V3 climatology HSR software and PCs are made available in separate tar archive files for FORTRAN and MATLAB implementations.

This document describes the CAMEL V3 Climatology product. After the Introduction section, Section 2 describes the method for computing the contents found in the Climatology netCDF files. Section 3 details the methodology for computing the climatological HSR emissivity from the coefficient climatology files. Section 4 illustrates what the CAMEL Climatology product looks like while Sections 5 and 6 details the contents of the netCDF files and HSR emissivity climatology algorithm, while Sections 5 and 6 detail the contents of the netCDF files and HSR emissivity climatology algorithm, respectively. Please refer to the CAMEL monthly product Users' Guide (Borbas et al., 2023) for details on the changes between the CAMEL Version 2 and Version 3 monthly products, as well as more details on the CAMEL methodology.

2. Method for Computing the CAMEL Climatology

The CAMEL climatology product is made available on the same 0.05-degree spatial resolution as the CAMEL monthly product and represents the mean emissivity over the years 2003 through 2021. Data from months earlier than January 2003 are available as part of the CAMEL V3 monthly product but are not included in the climatology as they are based on the Terra MODIS data, which appear to have calibration issues over those months. The climatology is reported for every calendar month and includes 1) a 13-hinge-point emissivity, 2) a 13-hinge-point emissivity uncertainty, and 3) coefficients used to compute the high spectral resolution (HSR) emissivity. Thus, the CAMEL climatology includes 36 netCDF files (12 months x 3 file types).

The 13 hinge-point emissivity and 13 hinge-point emissivity uncertainty are computed by taking an average over each available month from 2003 through 2021. The years included in climatology for a given month are specified in a global attribute of the Climatology netCDF file. A quality flag is produced for each of the 13-hinge point emissivity/coefficient products and the 13-hinge point uncertainty product. (The 13 hinge-point emissivity and coefficient product have the same quality flag.) Table 1 shows the CAMEL 13 hinge-point emissivity/coefficient quality flag values. The quality flag definitions depend on whether the set of pixels used to compute the climatology were classified as water or fill values. Table 2 shows the values of the 13 hinge-point uncertainty quality flags, which depend on whether pixels were classified as water, fill values, or as having unphysically large uncertainties assigned to them. For more details on this, the user is referred to Loveless et al. (2020).

Table 1: CAMEL 13 hinge-point Emissivity Climatology and Coefficient Climatology Quality Flag Definition. Under the Description column, "camel_qflag" refers to the CAMEL monthly product quality flag variable named "camel_qflag".

CAMEL 13 Hinge-Point Emissivity/Coefficient Climatology Quality Flag		
Value	**Basic Description**	**Definition**
0	Ocean/Sea	All pixels have camel_qflag==0
1	Best quality land	All pixels have camel_qflag==1
2	Degraded quality land	All pixels have camel_qflag==1, missing samples
3	Land with filled values	No pixels with camel_qflag==0, at least one pixel with camel_qflag>1 (filled)
4	Mixed sea and land	At least one pixel with camel_qflag==0, at least one pixel camel_qflag>0

Table 2: CAMEL 13 hinge-point Emissivity Uncertainty Climatology Quality Flag Definition. Under the Description column, "camel_qflag" refers to the CAMEL monthly product quality flag variable named "camel_qflag" and "total_uncertainty_quality_flag" refers to the CAMEL monthly product quality flag variable "total_uncertainty_quality_flag".

CAMEL 13 Hinge-Point Uncertainty Climatology Quality Flag		
Value	Basic Description	Definition
0	Ocean/Sea	All pixels have camel_qflag==0
1	Best quality land	All pixels have camel_qflag==1 & total_uncertainty_quality_flag==1
2	Degraded quality land	All pixels have camel_qflag==1, at least one pixel with total_uncertainty_quality_flag>0
3	Land with filled values	No pixels with camel_qflag==0, at least one pixel with camel_qflag>1 (filled)
4	Mixed sea and land	At least one pixel with camel_qflag==0, at least one pixel camel_qflag>0

Just like the monthly CAMEL HSR emissivity product, the CAMEL HSR emissivity climatology is provided as PC coefficients, static lab datasets, and software routines in either FORTRAN or Matlab programming language. To compute the climatology, PC coefficients, the monthly product PC coefficients, are averaged according to their unique combination of the number of PCs and the lab dataset version. Table 3 lists the unique combinations used in CAMEL V3. The total number of unique combinations is 7 and this is the theoretical upper limit on how many different PC vectors could be needed to produce the climatology for any given pixel. Due to the quite low interannual variability in vegetation and ground type, however, typically only a maximum of 2 (and sometimes 3 or 4) unique combinations of lab version and # of PCs are used for a single pixel of the climatology product. Section 4 illustrates this for an example month. Once the PC vectors are averaged according to their type, the HSR emissivity can be computed as described in the next Section.

Table 3: Unique Combinations of CAMEL lab dataset version and the number (#) of PCs that are used to create the CAMEL HSR emissivity.

Unique Combinations of Lab Version and Number of PCs							
Scene Classification	Snow/Ice	General + Carbonate + Snow/Ice	General + Carbonate	General + Snow/Ice— all types	General + Snow/Ice— bare (quartz)	General— all types	General— bare (quartz)
Lab Version #	12	11	10	9	9	8	8
# of PCs	2	5	5	7	9	7	9

## 3. Method for Computing the HSR Emissivity Climatology

For background on the high spectral resolution (HSR) emissivity methodology, the reader is referred to the CAMEL monthly product Users' Guide (Borbas et al., 2023) as well as Borbas et al. (2018). The CAMEL HSR emissivity climatology is computed via PCA regression using the same 5 distinct, static lab datasets used in the monthly CAMEL product. Climatological PC coefficients that go with these lab datasets are computed from the monthly CAMEL coefficients, as detailed in the previous section. *Figure 1* shows a basic diagram of the inputs and outputs of the CAMEL Climatology HSR Algorithm.

To compute the climatological HSR emissivity from the climatological PCs, the HSR emissivity spectra for each unique combination of lab dataset version and number of PCs (as listed in Table 3) are first computed independently and then combined via a weighted average. The weighted average defines the weights by the number of samples from each unique combination. For example, *Figure 2* shows a pixel where the given scene was characterized by two unique combinations of lab version and number of PCs over the course of the years in the month of December—lab version 12 with 2 PCs, and lab version 9 with

7 PCs. For this example, 2 sets of coefficients would be available in the climatological PC coefficient file along with their corresponding weights. The user would input these into the available Matlab or FORTRAN software routine, which would first compute the 2 independent HSR emissivity spectra as shown in *Figure 2* in color and then combine the 2 emissivity spectra via weighted averaging. The end result would be the weighted climatological emissivity, as shown in *Figure 2* as a black line.

Details of the provided Matlab and FORTRAN software packages are given in Section 6 of this Users' Guide. Sample programs to run the HSR emissivity climatology routines are also provided.
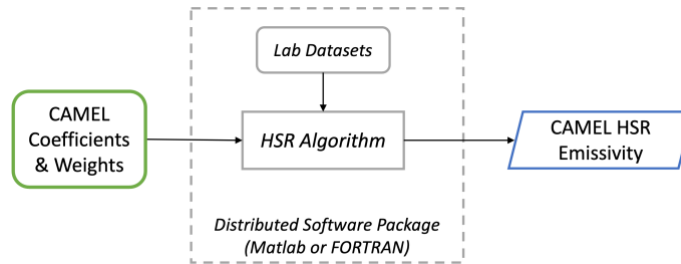
Figure 1: Diagram of the CAMEL Climatology High Spectral Resolution Emissivity Algorithm Inputs and Outputs. Inputs are coefficients and associated weights from the CAMEL Climatology netCDF product files selected by the user, as well as a set of lab datasets distributed with the software package. Output is the CAMEL HSR emissivity.
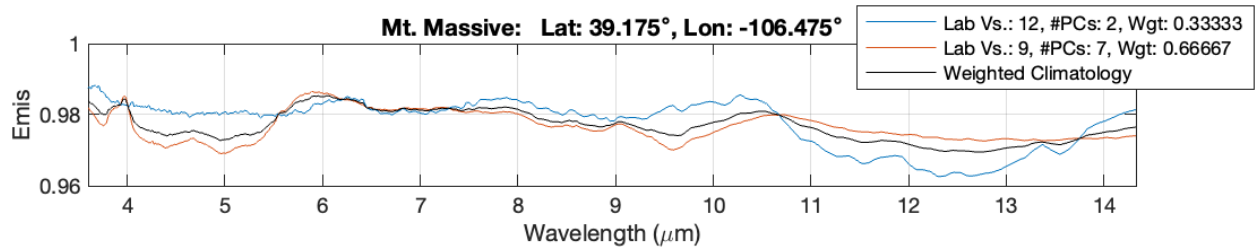

Figure 2: Illustration of the CAMEL HSR emissivity climatology computation for a site in the Colorado Rocky Mountains in December. Intermediate spectra are shown in color for the 2 lab versions and the number of PCs sets used: lab version 12/2 PCs and lab version 9/7 PCs. The final HSR climatology is shown in black and is obtained via a weighted average of the two intermediate spectra.

a) *Snow Correction*

The actual, true snow fraction is not always correctly represented by the snow fraction in the CAMEL climatology; hence the hypothetical true and climatological emissivity can be quite different, causing an inaccurate BT calculation. To minimize this issue, a snow correction has been introduced in the CAMEL climatology HSR emissivity algorithm. The snow correction is automatically applied if the input snow fraction is larger than zero. It is strongly suggested that this feature be used, especially in cases that deviate from the climatological snow situation. The snow correction process is illustrated on *Figure 3*.

Two examples of the new correction are presented in *Figure 4*. One is over the Mt. Massive, Colorado (left), and one is over the ARM SGP cart site (right). Four different snow fractions are simulated using the RTTOV Forward Model (*Saunders et al., 2018*): snow fractions 0, 0.5, 0.95, and 1. The top two panels show the calculated brightness temperatures and their differences from observations. The third panels from the top illustrate the brightness temperature differences caused by the different snow cover. The maximum differences occur between the 8-11 μm (ARM Cart site) and the 10.5 -13 μm spectral region (Mt. Massive) with the magnitude as 1K and 0.4K respectively. The bottom panels show the defined CAMEL Climatological emissivity for all four cases. For the full snow cover case, the

emissivity has been derived from the only snowy month(s) coefficients over Mt. Massive while over the ARM SGP Cart site, the RTTOV built in snow/ice spectra is used (spectrally smooth spectra) due to the lack of a fully snow-covered month in the CAMEL climatological database.
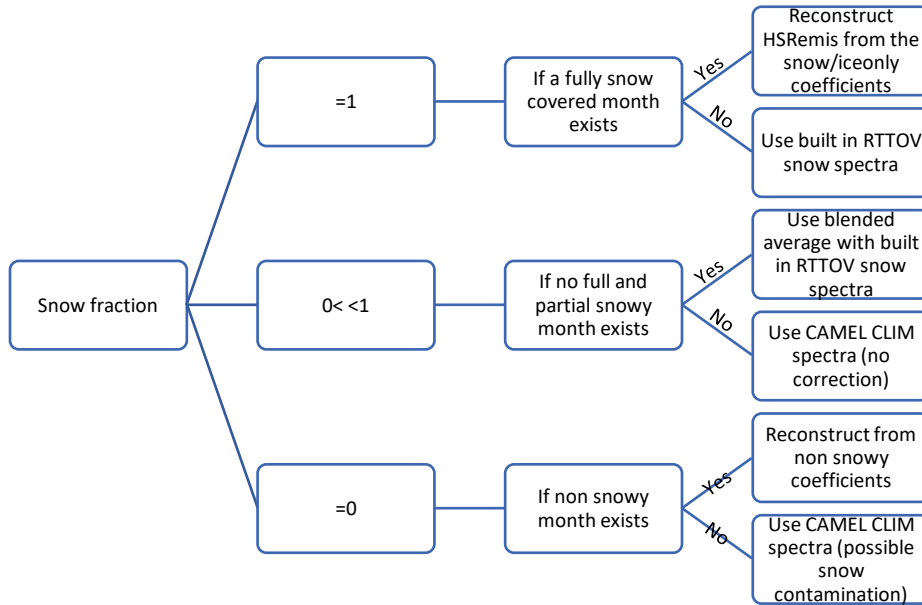
Figure 3: Flow chart of the snow correction in the CAMEL Climatology HSR Emissivity Algorithm (also seen in *Borbas and Feltz, 2019*).
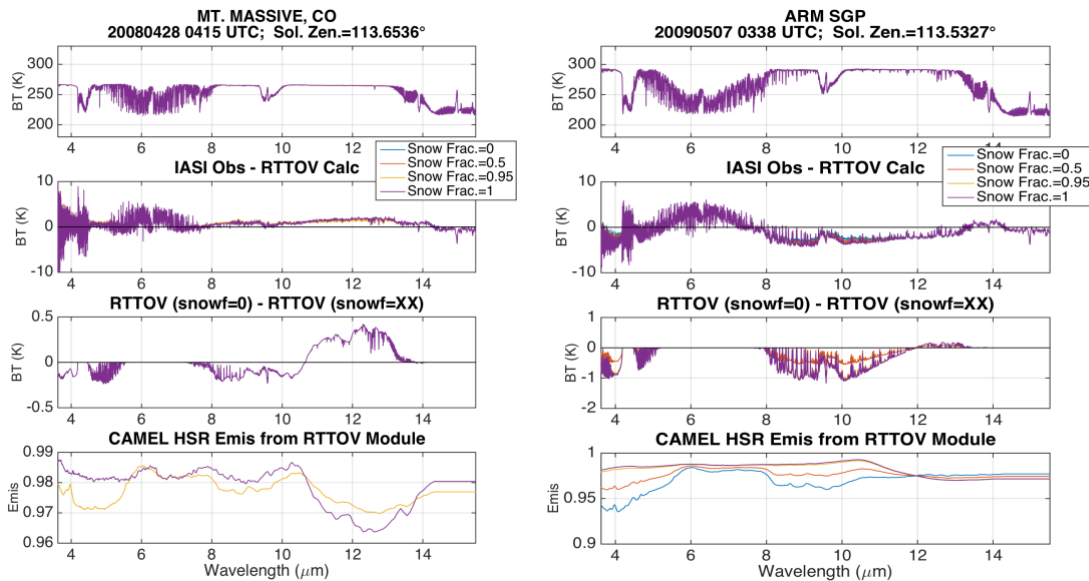
Figure 4: Snow fraction correction over (*left)* Mt Massive, Colorado, on April 28, 2008, at 3:15UTC and (*right*) over the ARM SGP Cart Site on May 7, 2009, at 03:38UTC. Four cases are simulated using RTTOV Forward Model; one when the snow-fraction is 0 (blue), 0.5 (orange), 0.95 (yellow), and 1 (purple). The top panels show the calculated brightness temperatures, the second top panels illustrate the observed minus calculated brightness temperatures, the third panel from the top shows the calculated brightness temperature differences between no snow fraction and actual snow fraction, and the bottom panels show the CAMEL climatological emissivity assigned for all four cases.

b) *Covariances*

For NWP data assimilation the inter-channel correlation of the observations is important to account for the lack of independence of the spectral observations (Desroziers et al. 2005). NWP users are anticipated to compute the observation covariance for themselves using for example the RTTOV model with the CAMEL emissivity module. However, for ease of use a spatial variance estimate of the CAMEL V3 has been created for each month on a 0.25x0.25-degree grid of 416 spectral points. The 0.25-degree resolution has been chosen to avoid memory load issues. The mean and variance of the covariance matrix from 475 points of the original 0.05-degree resolution dataset between 2003 and 2021 were calculated. No threshold for the number of observations was applied. Meanwhile, CAMEL V2 variances have been estimated between 2000 and 2016, including Terra emissivity between 2000 and 2002, resulting 425 observation points per grid cell. Besides the time cover change between V2 and V3, more significant differences are expected over the 3.6-4.0 and 8-9 µm regions. Changes over the 3.6 – 4.0 µm regions are due to the calibration update from Collection 4.1 to 6.1 of MOD11 Bands 20, 22, and 23. On the other hand, changes over the 8-9 µm Restrahen band relate to the algorithm change from the MOD11 (CAMEL V2 input) day-night algorithm to the MOD21 (CAMEL V3 input) Temperature and Emissivity Separation (TES) Method. *Figure 5* illustrates the climatological mean and standard deviation of CAMEL V2 vs. V3 at 4 µm for the month of August. The standard deviation of each spectral channel over the 5x5 spatial domain and over the multi-year record can be computed from the square root of the diagonal of the spectral covariance matrix (variance) provided in the data product. The off-diagonal elements of the covariance are not provided in CAMEL v3 due to data volume considerations but may be made available in the future in a compressed format.

The CAMEL V3 variances have been reduced, like in desert areas. However, it remains high for specific areas, like over the Sahel band, which reflects the variation of the grassland over time. The same statistics over two selected locations have been plotted in *Figure 6*. The reduced standard deviation over the 3.6-4.0 and 8-9 µm regions are apparent. The unrealistic quartz-featured dip at the 8-9 µm has been removed from the mean emissivity spectra for both vegetated and snow-covered (Park Falls in January) locations. CAMELV3 captures more physically realistic features than CAMEL V2.
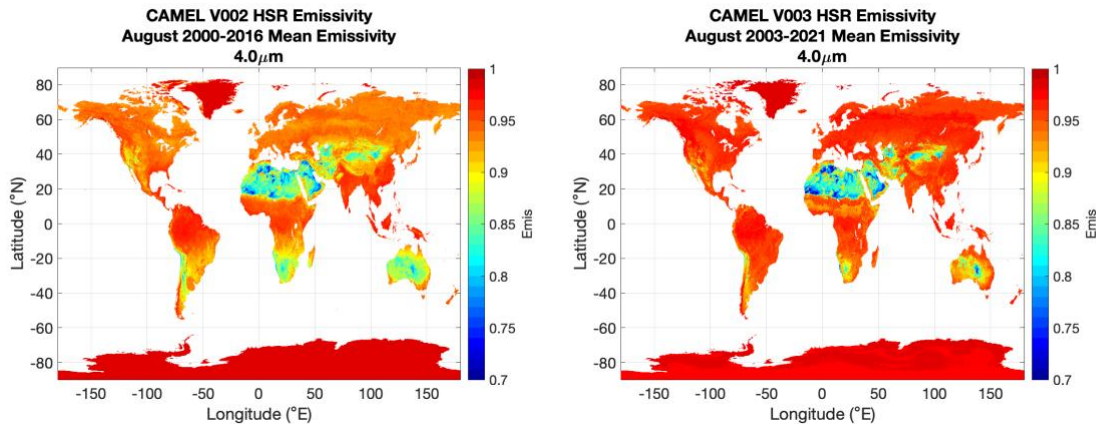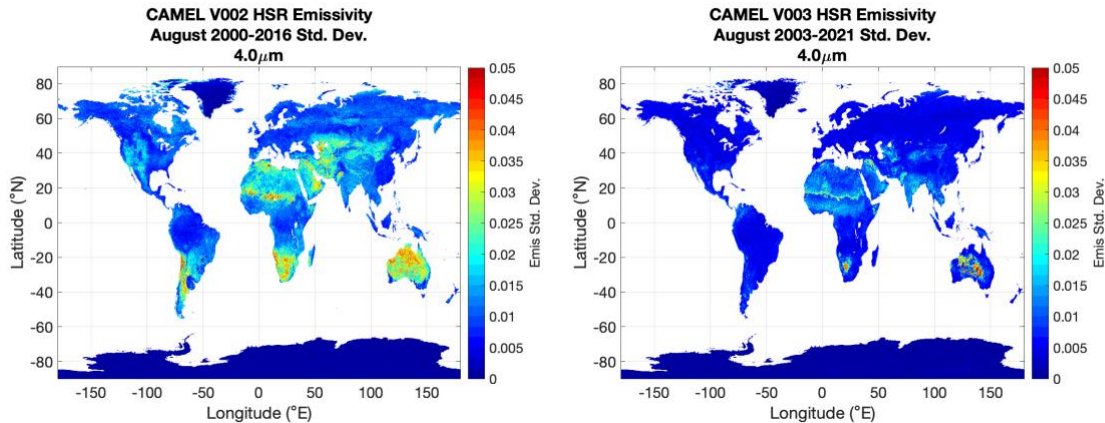
Figure 5: The mean (top) and standard deviation (bottom) of CAMEL V2 (left) vs V3 (right) emissivity at 4 μm for August. Statistics for CAMEL V2 have been calculated between 2000 and 2016 (using Terra/MODIS data for the first three years) and for CAMEL V3 between the years 2003 and 2021 (using only Aqua/MODIS emis products).
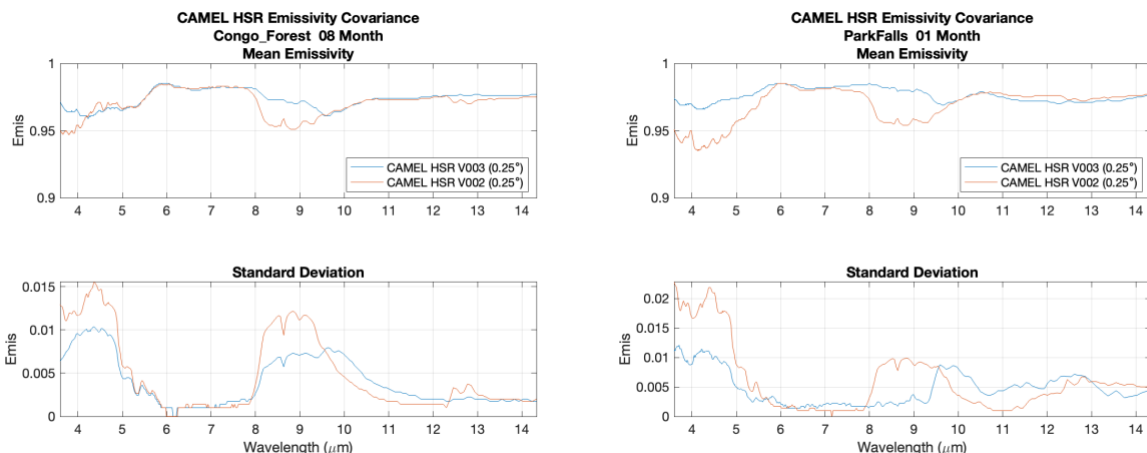
Figure 6: The mean (top) and standard deviation (bottom) of CAMEL V2 (red) vs. V3 (blue) emissivity spectra over a selected location in the Congo Forest (left) for August and over Park Falls, WI (right) for January. Statistics for CAMEL V2 have been calculated between 2000 and 2016 (using Terra/MODIS data for the first three years) and for CAMEL V3 between the years 2003 and 2021 (using only Aqua/MODIS emis products).

4. Illustration of the CAMEL V3 Climatology

This section illustrates the CAMEL Version 3 Climatology product and supports the reason for averaging the climatology over the months chosen. *Figure 7* shows a map of the January CAMEL Climatology 13 hinge-point emissivity product—both the quality flag and 8.6-micron emissivity. For the January climatology, ~67.5% of the pixels are quality flag==0 (ocean or sea). Of the non-ocean pixels, ~43.5% have quality flag==1 (best quality land), 0% have quality flag==2 (degraded quality land), ~55.9 % have quality flag==3 (land with filled values), and ~0.6% have quality flag==4 (mixed sea and land). For a pixel to be classified as a quality flag==3, at least one of the monthly emissivity estimates used to compute the climatology must be a 'filled value.' The *Figure 7* maps show that this occurs mainly around the poles and in regions with heavy cloud cover (around the equator).
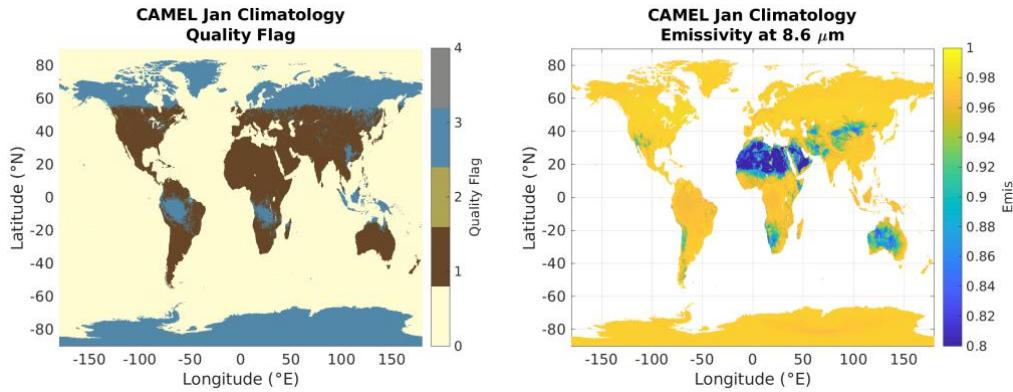
Figure 7: Maps of January CAMEL 13-Hinge Point Emissivity Climatology. (*left*) Quality flag and (*right*) Emissivity at 8.6 microns. See Table 1 for the quality flag description.

Next, *Figure 8* shows maps of the January CAMEL Climatology 13 hinge-point emissivity uncertainty product. Each uncertainty component—the algorithm, spatial, and temporal—is shown with the total uncertainty and total uncertainty quality flag for 8.6 microns. The algorithm uncertainty is characterized by differences in the ASTER and MODIS input to the CAMEL algorithm, the spatial uncertainty is a measure of the spatial variability, the temporal uncertainty is a measure of the temporal variability, and the total uncertainty is the RSS (root-sum-square) of the three components. The total uncertainty quality flag looks very similar to the 13 hinge-point/coefficient quality flag (in *Fig 7*), with the exception of the 'qflag==2' having an increased presence due to the flagging of unphysically large uncertainty values (indicating that the uncertainty assigned to the emissivity is likely to be too large).
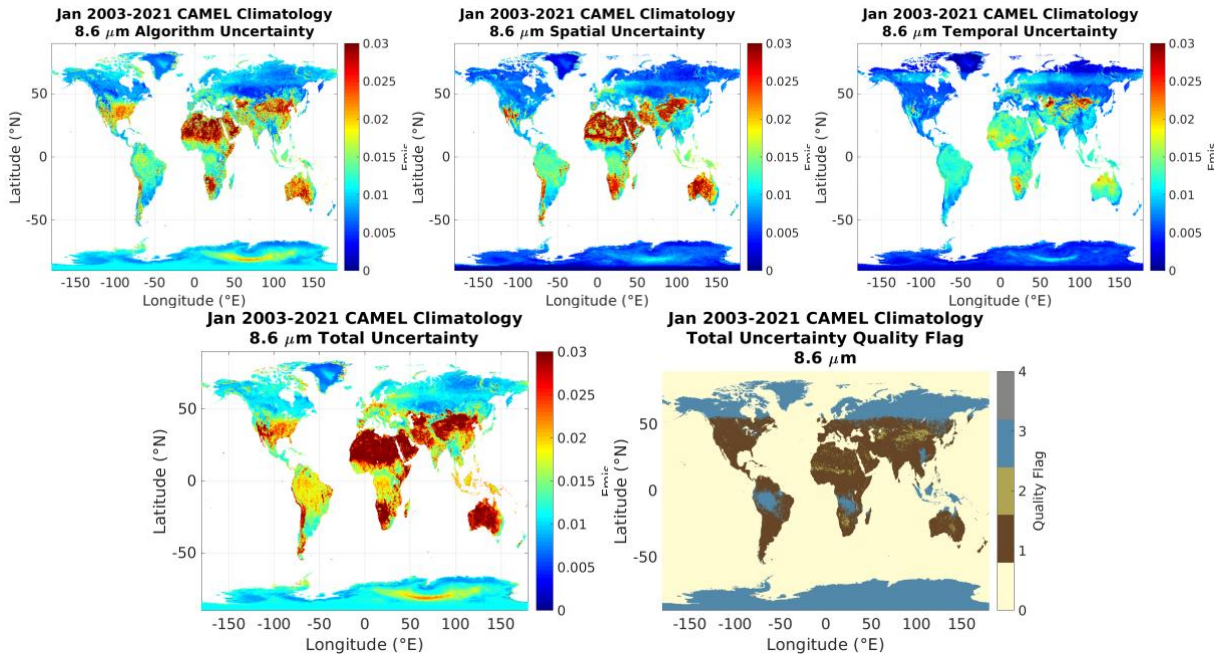
Figure 8: Maps of January CAMEL 13-Hinge Point Emissivity Uncertainty Climatology. (*top from left to right*) Algorithm uncertainty, spatial uncertainty, temporal uncertainty (*bottom from left to right*), total uncertainty and total uncertainty quality flag for the 8.6 μm channel. See *Table 2* for the quality flag description.

Figure 9 shows maps of the CAMEL coefficient climatology for January. The map of the number of unique combinations of lab version and number of PCs, or "PC sets" (*Fig 9 left*) shows the climatology can be characterized by 1 or 2 "PC sets" for the majority of pixels. Of the pixels that are non-ocean, 67.03% use 1 PC set, 26.9% use 2 PC sets, 5.82% use 3 PC sets, 0.17 % use 4 PC sets, 0.04% use 5 PC

sets, and only 2 pixels use 6 PC sets. The pixels which use 3 or more PC sets are clustered around ~40 degrees N, where variable snow cover changes the ground cover characteristics from year to year. The right panel of *Figure 9* shows a map of the number of pixels used to create the January Climatology that used the lab version 2/2 PCs combination. This combination is used to characterize snow/ice scenes, and as the maps shows, the number of samples for this combination is largest around the poles.
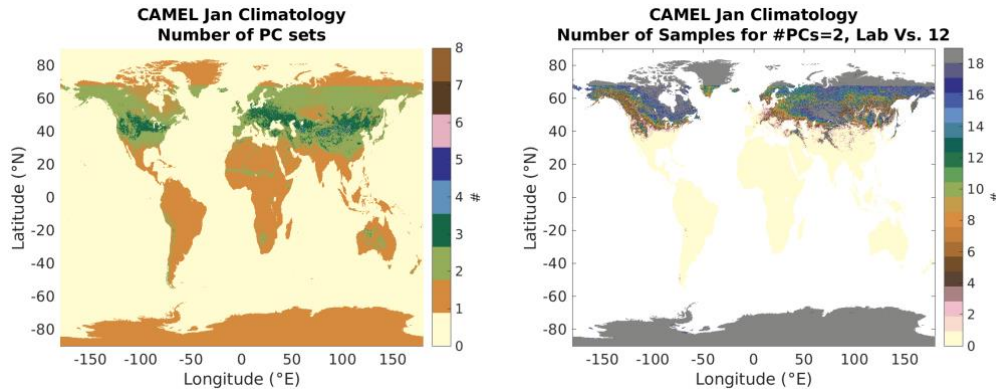
Figure 9: Maps of January CAMEL Coefficient Climatology. (*left*) Number of unique combinations of lab version & number of PCs. (*right*) Number of Samples for the combination of lab version 2 and 2 PCs.

Figure 10 shows examples of climatological HSR emissivity spectra at select case sites that have been used to validate and assess the CAMEL product. These sites include the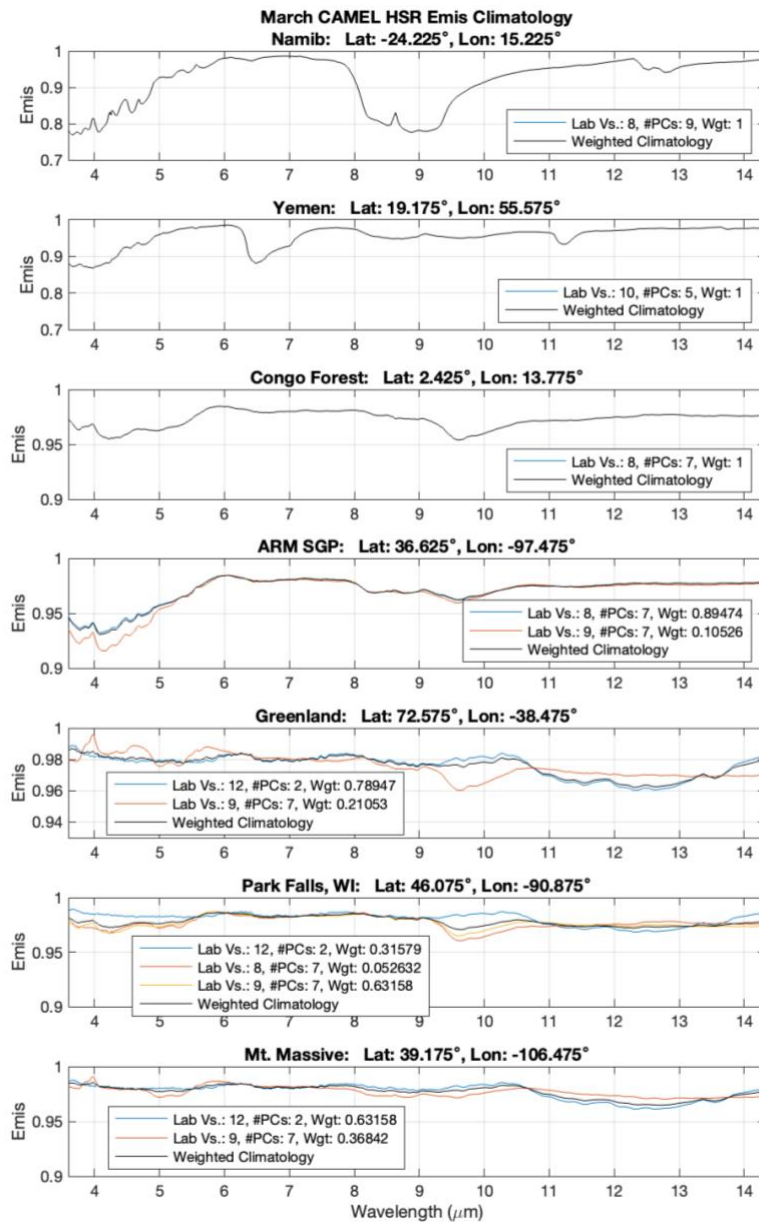 Namib Desert (quartz), Yemen (carbonate), Congo Forest, Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) (grassland/cropland), Greenland (snow/ice), Park Falls WI (evergreen forest with partial snow cover), and a Rocky Mountain site over Mt. Massive (snow/mountainous site). The Namib Desert (top panel) spectral feature around 8-9 μm is the quartz signature, while the Yemen (2nd panel from top) spectral features at ~6.5 and 11 μm are the carbonate signatures.

Figure 11 and *Figure 12* show timeseries of the CAMEL monthly emissivity product for all 13 hinge-points for two case sites—one at the Namib Desert which is a quartz dominated scene, and one in Park Falls, WI which is a site with evergreen forest which receives snow cover for part of the year. The short wavelength channels from 3.6 to 7.6 μm are based purely on the UW BF (MODIS) data, channels 8.3 through 11.3 μm are based on a combination of ASTER and UW BF (MODIS) data, and the longer wavelength channels of 12.1 and 14.3 μm are based again on UW BF (MODIS). (This is true of the entire CAMEL dataset, not just these case sites.) For more details on the current UW BF product or CAMEL combining method, the user is referred to the CAMEL V3 monthly product Users' Guide. Again, note that the CAMEL climatology does not use the complete record of the CAMEL V3 product – it only used data over the time period Jan 2003 through Dec 2021 (end of the record).

Looking at the Namib Desert case in *Figure 11*, the bottom panels show neither the lab version and # of PCs nor the snow fraction/vegetation index change with time. The 4.3, 5.0 and 5.8 μm channels have noticeable, somewhat repeatable annual variations that seem to be roughly constant with time. This is also true for the 8.3 through 11.3 μm channels—somewhat consistent annual variations are present over the CAMEL record. A slight increase over time can be seen in the 8.3, 8.6, and 9.1 μm channels and may be attributable to the artificial trend of the Aqua.MODIS Band29 Radiances due to the increasing cross-talk error over time. The CAMEL climatology emissivity would be more immune to these types of artifacts than the CAMEL monthly product. The longer wavelength channels of 12.1 and 14.3 μm show little to no variation with time.

In the *Figure 12* Park Falls, WI case site, the bottom panels highlight the changes in snow cover and vegetation fraction experienced from month to month and over the years. These changes get translated into changes in the lab version and number of PCs over time. The variable snow cover also causes variations to be present in the 12.1 and 14.3 μm channel emissivities (unlike the Namib Desert). While there is no increase in the emissivity over the record for the 8.6 to 9.1 μm channels like there were for the Namib case site, there is a decrease in emissivity after the year 2017 for the longer wavelength channels. Again, these sort of artifacts have much less of an impact on the emissivity climatology than the monthly product.

Figure 10: CAMEL Climatology HSR Emissivity Spectra for March at Selected Case Sites. (*top to bottom*) Namib Desert (quartz), Yemen (carbonate), Congo Forest, Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site (grassland/cropland), Greenland (snow/ice), Park Falls WI (snow/evergreen forest), Mt. Massive (snowy mountainous) site.
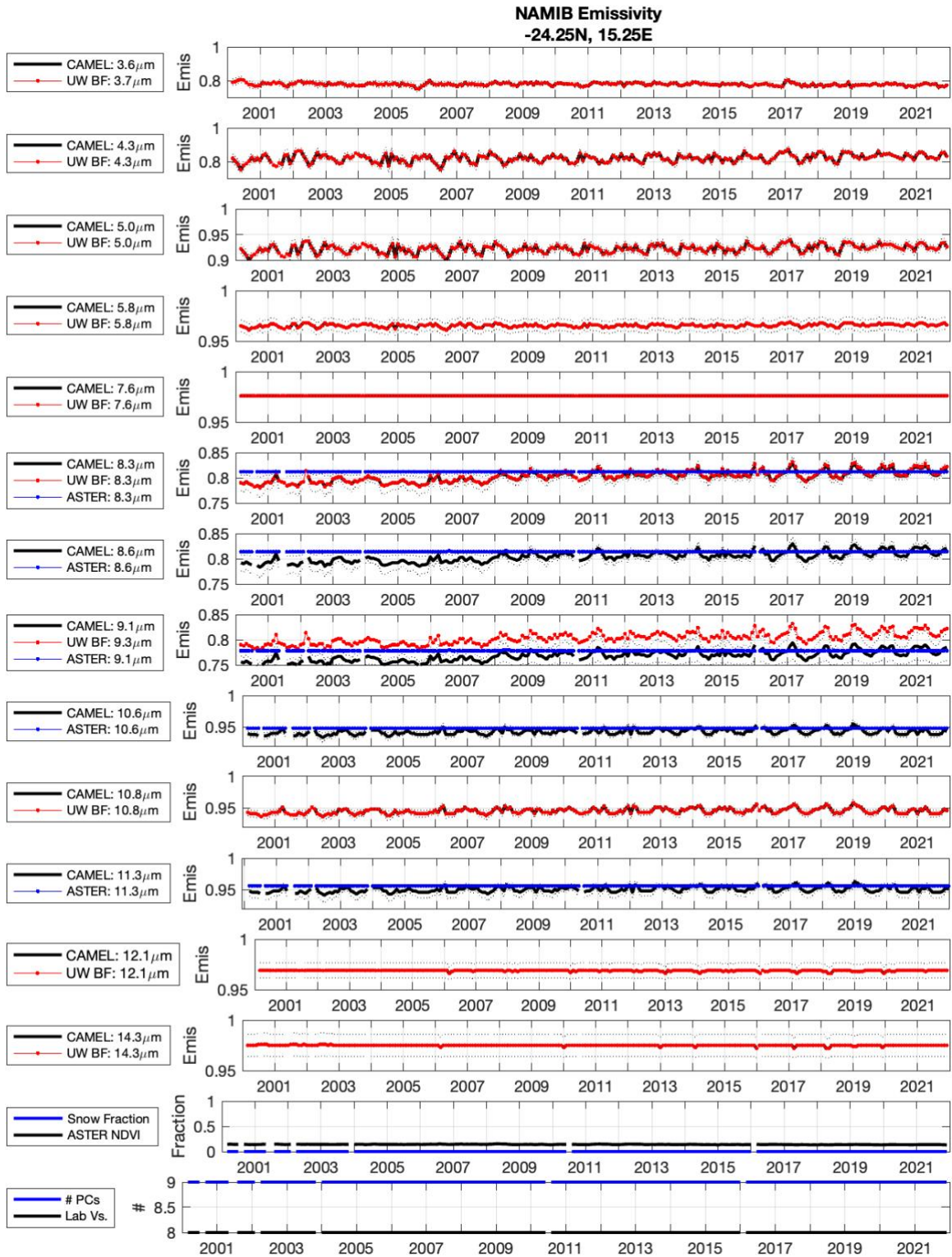
Figure 11: CAMEL monthly product emissivity timeseries at the Namib Desert (quartz) case site. CAMEL (black) is overlaid for each channel by the ASTER (blue) and UW BF (red) emissivity inputs. The bottom two rows show the snow fraction/ASTER vegetation index and the CAMEL lab version and number of PCs used to create the HSR emissivity.
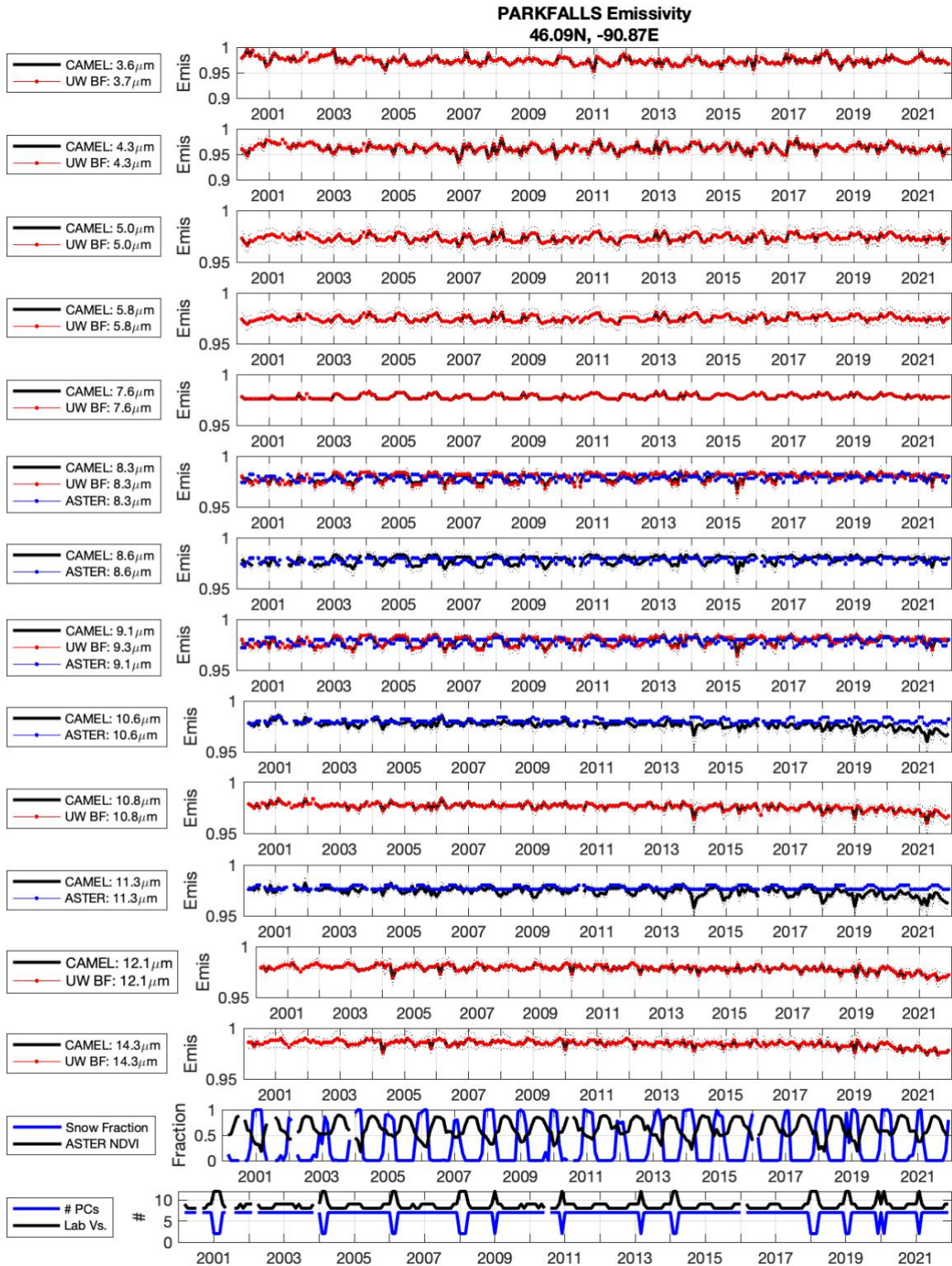
Figure 12: Same as Figure 11 except for the Park Falls, WI case site.

5. MEaSUREs CAMEL Climatology Data Product Files

The V3 CAMEL climatological emissivity, uncertainty, and PCA coefficients are available for each calendar month of the year. 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. *13 Hinge-Point Emissivity Climatology*

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

Filename: CAM5K30EMCLIM_emis_climatology_{*MM*}Month_V{*XXX*}.nc;
                         MM =month; *XXX* =version number
Size: ~45 MB per file
Number of files: 12 (One for each calendar month)
Missing files: None
Temporal Resolution: Inter-annual average over 2003 through 2021
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 climatology 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	longitude	N/A	N/A	[-180 180]	Longitude, degrees East at grid-box center
wavelength	float32	spectra	N/A	N/A	[3.6 14.3]	Wavelength of CAMEL channels in micrometers
number_samples	uint8	latitude, longitude, spectra	N/A	N/A	[0 19]	Number of samples used to calculate climatology
camel_qflag	uint8	latitude, longitude	N/A	N/A	[0 4]	CAMEL Quality Flag: 0 = sea or inland water 1 = Land, Best Quality 2 = Land, Degraded Quality 3 = Land with Filled Values 4 = Mixed Sea and Land
snow_fraction_average	uint8	latitude, longitude	0.01	N/A	[0 100]	MODIS MOD10 Snow Fraction Average
camel_emis	uint16	latitude, longitude, spectra	0.001	9999	[0 1000]	Combined ASTER MODIS Emissivity over Land Climatology

b. *13 Hinge-Point Emissivity Uncertainty Climatology*

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

Filename: CAM5K30UCCLIM _emis_uncertainty_climatology_{*MM*}Month_V{*XXX*}.nc;
$\qquad\qquad$ *MM* =month; *XXX* =version number
Size: ~140 MB per file
Number of files: 12 (One for each calendar month)
Missing files: None
Temporal Resolution: Inter-annual average over 2003 through 2021
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 4]	Quality flag of the CAMEL Total Uncertainty 0 = Sea or Inland Water 1 = Land, Best Quality 2 = Land, Degraded Quality 3 = Land with Fill Values 4 = Mixed Sea and Land

c. *Coefficient Climatology*

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

Filename: CAM5K30CFCLIM _coef_climatology_{*MM*}Month_V{*XXX*}.nc;
$\qquad\qquad\qquad$ *MM*=month; *XXX*=version number
Size: ~210 MB per file
Number of files: 12 (One for each calendar month)
Missing files: None
Temporal Resolution: Inter-annual average over 2003 through 2021
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 = 8422955 (varies by month)

Table 6: The MEaSUREs CAMEL coefficient variables

Name	Type	Dims	Scale Factor	Fill Value	Valid Range	Description
latitude	float32	latitude	1.	N/A	[-90 90]	Latitude, degrees North at grid-box center
longitude	float32	longitude	1.	N/A	[-180 180]	Longitude, degrees East at grid-box center
labvs_of_coef_set	uint8	number_of_coef_sets	1.	N/A	[8 12]	Lab Version Number of Coef Set
npcs_of_coef_set	uint8	number_of_coef_sets	1.	N/A	[2 9]	Number of PC Coefs in Coef Set
pc_coefs	float32	mask, total_number_of_coefs	1.	99.0	[-10 10]	CAMEL PCA Coefficients Climatology *Comment: PCA coefficients are different for each version of lab data and each number of PCs used. Climatological coefficients for the different sets of PCs are concatenated together in order of increasing number of PCs and then by increasing lab version number.*
pc_coef_weights	float32	mask, number_of_coef_sets	1.	N/A	[0 1]	Weights of Climatological Coefficients
pc_coef_nsamps	uint8	mask, number_of_coef_sets	1.	N/A	[0 19]	Number of samples used to calculate climatology
landflag	uint8	latitude, longitude	1.	N/A	[0 1]	Land Flag: 0=Ocean, 1=Land

To save storage and memory load space in the HSR emissivity algorithm, the values of the snow fraction, laboratory data version number, number of PCA coefficients, and PCA coefficients have been stored only over land pixels, i.e., when the CAMEL quality flag is larger than zero (landflag > 0). Instead of the dimensions being of the dimension *latitude x longitude*, the above-mentioned variables have been stored in a vector of length 8422955 (for the January climatology); however, the number of land pixels may vary by month. This method reduces the storage place and memory load to roughly a third of what is required for the original gridded formatting files.

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

```
coef_lut = -1
indexlut = 1
Do i=1,nc_dim(1)
    Do j=1,nc_dim(2)
      If (landflag(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_climatology_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* and is as follows:

```
% initiate variables on lat/long grid
coef.pc_coefs = NaN(max_npcs,nlon,nlat);
coef.pc_coef_weights = NaN(nsets,nlon,nlat);
coef.pc_coef_nsamps = NaN(nsets,nlon,nlat);

% find land indices and reshape
ind_land = find(coef.landflag > 0);
coef.pc_coefs(:,ind_land) = pc_coefs_mask;
coef.pc_coef_weights(:,ind_land) = double(pc_coef_weights_mask);
coef.pc_coef_nsamps(:,ind_land) = double(pc_coef_nsamps_mask);
```

d) *Covariances*

The Covarance matrixes of the CAMEL HSR emissivity climatology are provided in netCDF files, with contents (see *Table 7*) and filename specification as:

Filename: CAM5K30COVCLIM _hsremis_covmat_deg0.25_2003-2021_month{*MM*}_V{*XXX*}_mask.nc;
MM=month; *XXX*=version number
Size: ~80 MB per file
Number of files: 12 (One for each calendar month)
Missing files: None
Temporal Resolution: Inter-annual average over 2003 through 2021
Spatial Resolution: 0.25 degrees
Format: netCDF4
Dimensions: latitude = 720; longitude = 1440; mask = 8422955 (varies by month)

Table 7: The MEaSUREs CAMEL covariance variables

Name	Type	Dims	Scale Factor	Fill Value	Valid Range	Description
latitude	int16	Xdim [720]	0.01	N/A	[-90 90]	Latitude, degrees North at grid-box center
longitude	int16	Ydim [1440]	0.01	N/A	[-180 180]	Longitude, degrees East at grid-box center
Frequencies [1/cm]	int16	Nfreq [417]	0.1	N/A	[6980 27780]	Frequency numbers of the measurements
emis_numObs	int16	xdim, ydim	1.	N/A	[0 475]	Number of Observations
emis_mean	int16	mask, nfreq	0.001	-999.	[600 1000]	Mean of the emissivity in the grid cell over the time period
emis_diagCov	int16	mask, nfreq	1.e-06	-999.	[0 16806]	Diagonal of the covariance matrix for each grid cell over the time period

To save storage and memory load space, the values of the mean emissivity (emis_mean) and diagonal of the Covariance matrixes (emi_diagCov) have been stored only over land pixels, i.e., when the number of observations is larger than zero (emis_numObs > 0). Instead of the dimensions being of the dimension *latitude x longitude*, the above-mentioned variables have been stored in a vector of length – for example 8422955 for the month of May - however, these number may vary by month. This method reduces the storage place and memory load to roughly a third of what is required for the original gridded formatting files.

6   Description of the MEaSUREs CAMEL Climatology HSR Algorithm

The standalone version of the HSR emissivity climatology 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 climatology 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 climatology 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 – will contain the hsriremis_EDR.inc after installation
      data - includes one set of CAMEL Climatology files file for testing purpose
      test - includes a test code (run_hsriremis.f) to run the algorithm for one geographical location

Install the package:
      File name: *MEASURES_CAMEL_hsremis_lib__snowCorr_V003.tar.gz*
      unzip (gzip –d) and untar (tar –xvf)
      The complete list of the package can be found in Appendix 2.

Create the Climatology 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 Clim HSR emis library:
      1. cd test
      2. edit the library links in run_hsriremis_oneline.mk
      3. ./run_hsriremis_oneline.mk (compile 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 Climatology HSR Algorithm V003

Inputs	Data Type	Valid Range	Notes
camel_dir	character(len=400)		directory name of the CAMEL coef data
lab_dir	character(len=400)		directory name of the laboratory data
month	character(len=2)	['01' '12']	
latitude	real (4 bytes)	[-90 90]	Latitude of the location in degree
longitude	real	[-180 180]	Longitude of the location in degree
first	logical	[true false]	Switch for initialization Set TRUE for the first call and then FALSE
instr_switch	logical	[true false]	Set to TRUE for hsr emis to be calculated for a certain instrument otherwise set to FALSE
snow_flag	logical	[true false]	Set TRUE for snow correction
debug	logical	[true false]	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
snowfr	double	[0 1]	Fraction of snow cover
insr_wavenumber (optional)	double[nchs]		Central wavenumber of the instrument bands in increasing order

Table 8: Outputs of the CAMEL Climatology HSR Algorithm V003

Outputs	Data Type	Valid Range	Notes
hsremis	double(417)	[0.5 1]	
instr_emis(optional)	double(nchs)	[0.5 1]	Output only if instr_switch is set to TRUE

Usage:
call compute_clim_hsriremis(

```
                           & camel_dir,          ! in
                           & lab_dir,            ! in
                           & cmonth,             ! in
                           & lat_site,           ! in
                           & lon_site,           ! in
                           & first,              ! in
                           & instr_switch,       ! in
                           & snow_flag,          ! in
                           & debug,              ! in
                           & hsriremis,          ! out
                           & nchs,               ! in
                           & snowfr,             ! 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

24

Note to run for the whole grid (3600x7200); it is suggested to read the land flag first from the CAMEL CLIM Coeff file and then call the compute_clim_hsriemis.f subroutine for land pixels only (landflag=1).

The codes in the CAMEL HSR package:
SUBROUTINE compute_clim_hsriremis : creates library to compute high spectral resolution emissivity spectra from the MEaSUREs CAMEL Climatologicgal database

SUBROUTINE init_hsriremis (input: path of the laboratory data files): initializes variables and reads in the eigenvectors of the laboratory data (calls read_labpcs for all laboratory sets).

SUBROUTINE read_CAMEL_clim_coef_masked (name of the CAMEL coefficient file): reads the 0.05 degree resolution CAMEL clim coefficients (from the netCDF file into memory).
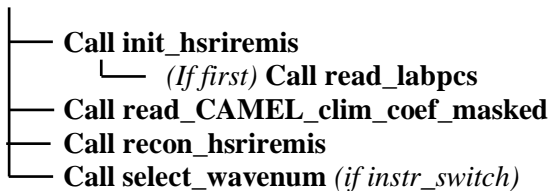
SUBROUTINE read_labpcs (path of the laboratory data, laboratory data version): read the eigenvectors and eigenvalues of the selected laboratory measurements.

SUBROUTINE recon_hsriremis (number of PCs to use, version number of laboratory set, coefficients(output), hsriremis (output), icount): creates high spectra resolution emissivities at 417 wavenumbers from the CAMEL CLIM coefficients 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 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_clim_coef_masked**
    ├── **Call recon_hsriremis**
    └── **Call select_wavenum** *(if instr_switch)*

Figure 13: Structure of the Fortran version of the CAMEL CLIM HSR Emissivity Algorithm

  b. *Matlab Version*

The Matlab package contains software to calculate the CAMEL High Spectral Resolution emissivity climatology as well as a sample program for users to understand how to run the algorithm. The software runs on version 3.0 (V003) CAMEL coefficient climatology data.

Installation:
      File name: *MEASURES_CAMEL_CLIMAT_hsremis_matlab_SnowCorr_V003.tar.gz*
      unzip (gzip -d) and untar (tar -xvf) it

Software Package Contents:
      coef - contains files of laboratory eigenvectors and eigenvalues (Matlab format)
      inputs - contains CAMEL climatological coefficient file for a test month (January)
      outputs - contains verification image and mat-file for test case

mfiles - contains the HSR emissivity climatology algorithm as well as extra readers for the 13-hinge point emissivity and uncertainty climatology netCDF files

<u>File Structure:</u>
> main code:
>> *test_CAMEL_V003_calc_climatology_hsremis.m*
>
> calls:
>> *read_CAMEL_coef_climatology_V003.m*
>>
>> *create_hsremis_from_CAMEL_coef_climatology_SnowCorr_V003.m*
>
> extra code (available for users' convenience):
>> *read_CAMEL_emis_climatology_V003.m*
>>
>> *read_CAMEL_coef_climatology_V003.m*

<u>Test run</u>:
1. go to the mfiles directory
2. start matlab
3. run: *test_CAMEL_V003_calc_climatology_hsremis.m*
4. compare the resulting image and mat-file in the output directory with the *_orig.png and *_orig.mat file

7   References

Borbas, E.E.; Seemann, S.W. (2007) Global Infrared Land Surface Emissivity: UW-Madison Baseline Fit Emissivity Database V2.0. Available online: http://cimss.ssec.wisc.edu/iremis/ (accessed on 28 Dec 2020).

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

Borbas, E., S. Hook, G. Hulley, M. Loveless, R. Knuteson. 2023a: Combined ASTER and MODIS Emissivity database over Land (CAMEL) Emissivity Monthly Global 0.05Deg V003. 2023, distributed by NASA EOSDIS Land Processes Distributed Active Archive Center, https://doi.org/10.5067/MEaSUREs/LSTE/CAM5K30EM.003.

Borbas, E.E, G. Hulley, M. Loveless, R. Knuteson, K., Cawse-Nicholson, and S. Hook, 2023b: 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, https://lpdaac.usgs.gov/documents/1612/CAMEL_V3_UG_ATBD.pdf

Feltz M., Borbas, E., Knuteson, R., Hulley G. Hook, S. J. (2018a): 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.

Feltz M., Borbas, E., Knuteson, R., Hulley G. Hook, S. J. (2018b): 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.

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.; Hook, S. (2016) AG5KMMOH: ASTER Global Emissivity Dataset, Monthly, 0.05 degree, HDF5 V041 [Dataset]; NASA EOSDIS Land Processes DAAC, USGS Earth Resources Observation and Science (EROS) Center: Souix Falls, SD, USA. Available online: https://doi.org/10.5067/Community/ASTER_GED/AG5KMMOH.041 (accessed on 28 Dec 2020).

Loveless, M., Borbas, E. E., Knuteson, R., Cawse-Nicholson, K., Hulley, G., & Hook, S. (2020). Climatology of the Combined ASTER MODIS Emissivity over Land (CAMEL) Version 2. Remote Sensing, 13(1), 111. doi:/10.3390/rs13010111.

Saunders, R.; Hocking, J.; Rundle, D.; Rayer, P.; Havemann, S.; Matricardi, M.; Geer, A.; Cristina, L.; Brunel, P.; Vidot, J. (2017) RTTOV-12 Science and Validation Report. Mission Rep.

NWPSAF-MO-TV-41, EUMETSAT Numerical Weather Prediction Satellite Applications Facility; Met Office, Exeter, UK. Available online: https://nwpsaf.eu/site/download/documentation/rtm/docs_rttov12/rttov12_svr.pdf (accessed on 28 Dec 2020).

Saunders, R.; Hocking, J.; Turner, E.; Rayer, P.; Rundle, D.; Brunel, P.; Vidot, J.; Roquet, P.; Matricardi, M.; Geer, A.; et al. (2018) An update on the RTTOV fast radiative transfer model (currently at version 12). Geosci. Model Dev. 11, 2717–2737, doi:10.5194/gmd-11-2717-2018.

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. doi:10.1175/2007JAMC1590.1.

8   Appendix 1: CAMEL Climatology Product CDL Files

a.   *13 Hinge-Point Emissivity Climatology*

```
netcdf CAMEL_emis_climatology_01Month_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. ;
                latitude:add_offset = 0. ;
                latitude:scale_factor = 1. ;
        float longitude(longitude) ;
                longitude:long_name = "Longitude; Degrees east at grid-box center" ;
                longitude:units = "degrees east" ;
                longitude:valid_range = -180., 180. ;
                longitude:add_offset = 0. ;
                longitude:scale_factor = 1. ;
        float wavelength(spectra) ;
                wavelength:long_name = "Wavelength of CAMEL channels in micrometers" ;
                wavelength:units = "microns" ;
        ubyte number_samples(latitude, longitude, spectra) ;
                number_samples:long_name = "Number of samples used to calculate climatology" ;
                number_samples:units = "none" ;
                number_samples:valid_range = 1., 19. ;
                number_samples:add_offset = 0. ;
                number_samples:scale_factor = 1. ;
        ubyte camel_qflag(latitude, longitude) ;
                camel_qflag:long_name = "Combined ASTER MODIS Emissivity over Land - Quality Flag" ;
                camel_qflag:comment = "0 = Sea or Inland Water;    1 = Land, Best Quality; 2 = Land, Degraded Quality; 3
= Land with Filled Values 4 = Mixed Sea and Land" ;
                camel_qflag:scale_factor = 1. ;
                camel_qflag:add_offset = 0. ;
                camel_qflag:valid_range = 0., 4. ;
                camel_qflag:units = "none" ;
                camel_qflag:coordinates = "latitude longitude" ;
        ubyte snow_fraction_average(latitude, longitude) ;
                snow_fraction_average:long_name = "MODIS MOD10 Snow Fraction Average" ;
                snow_fraction_average:scale_factor = 0.01 ;
                snow_fraction_average:add_offset = 0. ;
                snow_fraction_average:valid_range = 0., 100. ;
                snow_fraction_average:units = "none" ;
                snow_fraction_average:coordinates = "latitude longitude" ;
        ushort camel_emis(latitude, longitude, spectra) ;
                camel_emis:long_name = "Combined ASTER MODIS Emissivity over Land Climatology" ;
                camel_emis:scale_factor = 0.001 ;
                camel_emis:add_offset = 0. ;
                camel_emis:valid_range = 0., 1000. ;
                camel_emis:units = "none" ;
                camel_emis:coordinates = "latitude longitude spectra" ;
                camel_emis:_FillValue = 9999US ;

// global attributes:
                :title = "NASA MEASURES: Combined ASTER MODIS Emissivity over Land (CAMEL) Monthly
Climatology" ;
                :summary = "Monthly Climatology of Global Infrared Land Surface Emissivity over the years 2003 through
2021" ;
```

```
              :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 = "15-Dec-2022 16:27:53" ;
              :Prd_Version = "v03r05" ;
              :LP_DAAC_Version = "V003" ;
              :Id = "CAMEL_emis_climatology_01Month_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 = "2003-01-01 00:00:00Z" ;
              :time_coverage_end = "2021-12-31 23:59:59Z" ;
              :years_included_in_climatology = "2003  2004  2005  2006  2007  2008  2009  2010  2011  2012  2013
2014  2015  2016  2017  2018  2019  2020  2021" ;
              :month_of_climatology = "January" ;
              :numeric_month_of_climatology = "1" ;
}
```

b. 13 Hinge-Point Emissivity Uncertainty Climatology

```
netcdf CAMEL_emis_uncertainty_climatology_01Month_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:units = "none" ;
                spatial_uncertainty:scale_factor = 0.001 ;
                spatial_uncertainty:add_offset = 0. ;
                spatial_uncertainty:_FillValue = 9999US ;
        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:units = "none" ;
                temporal_uncertainty:scale_factor = 0.001 ;
                temporal_uncertainty:add_offset = 0. ;
                temporal_uncertainty:_FillValue = 9999US ;
        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:units = "none" ;
algorithm_uncertainty:scale_factor = 0.001 ;
algorithm_uncertainty:add_offset = 0. ;
algorithm_uncertainty:_FillValue = 9999US ;
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:units = "none" ;
total_uncertainty:scale_factor = 0.001 ;
total_uncertainty:add_offset = 0. ;
total_uncertainty:_FillValue = 9999US ;
ubyte total_uncertainty_quality_flag(latitude, longitude, spectra) ;
total_uncertainty_quality_flag:long_name = "Quality Flag of the CAMEL Total Uncertainty" ;
total_uncertainty_quality_flag:units = "none" ;
total_uncertainty_quality_flag:Flag_0 = "0 = Sea or Inland Water" ;
total_uncertainty_quality_flag:Flag_1 = "1 = Land, Best Quality Data" ;
total_uncertainty_quality_flag:Flag_2 = "2 = Land, Degraded Quality Data" ;
total_uncertainty_quality_flag:Flag_3 = "3 = Land with Fill Values for Emissivity" ;
total_uncertainty_quality_flag:Flag_4 = "4 = Mixed Sea and Land" ;
total_uncertainty_quality_flag:valid_range = 0., 4. ;
total_uncertainty_quality_flag:scale_factor = 1. ;
total_uncertainty_quality_flag:add_offset = 0. ;

// global attributes:
:Title = "NASA MEASUREs: Climatology of the CAMEL Emissivity Uncertainties" ;
: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 = "17-Dec-2022 01:33:40" ;
:Prd_Version = "v03r05" ;
:LP_DAAC_Version = "V003" ;
:Id = "CAMEL_emis_uncertainty_climatology_01Month_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 = "2003-01-01 00:00:00Z" ;
:time_coverage_end = "2021-12-31 23:59:59Z" ;
:years_included_in_climatology = "2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013
2014 2015 2016 2017 2018 2019 2020 2021" ;
:month_of_climatology = "January" ;
:numeric_month_of_climatology = "1" ;
}

c. *Coefficient Climatology*

netcdf CAMEL_coef_climatology_01Month_V003 {
dimensions:
latitude = 3600 ;
longitude = 7200 ;
number_of_coef_sets = 7 ;
total_number_of_coefs = 44 ;

```
            mask = 8422955 ;
variables:
        float latitude(latitude) ;
                latitude:long_name = "Latitude; Degrees north at grid-box center" ;
                latitude:units = "degrees north" ;
                latitude:valid_range = -90., 90. ;
                latitude:add_offset = 0. ;
                latitude:scale_factor = 1. ;
                latitude:coordinates = "latitude" ;
        float longitude(longitude) ;
                longitude:long_name = "Longitude; Degrees east at grid-box center" ;
                longitude:units = "degrees east" ;
                longitude:valid_range = -180., 180. ;
                longitude:add_offset = 0. ;
                longitude:scale_factor = 1. ;
                longitude:coordinates = "longitude" ;
        ubyte labvs_of_coef_set(number_of_coef_sets) ;
                labvs_of_coef_set:long_name = "Lab Version Number of Coef Set" ;
                labvs_of_coef_set:units = "none" ;
                labvs_of_coef_set:valid_range = 8., 12. ;
                labvs_of_coef_set:add_offset = 0. ;
                labvs_of_coef_set:scale_factor = 1. ;
                labvs_of_coef_set:coordinates = "number_of_coef_sets" ;
        ubyte npcs_of_coef_set(number_of_coef_sets) ;
                npcs_of_coef_set:long_name = "Number of PC Coefs in Coef Set" ;
                npcs_of_coef_set:units = "none" ;
                npcs_of_coef_set:valid_range = 2., 9. ;
                npcs_of_coef_set:add_offset = 0. ;
                npcs_of_coef_set:scale_factor = 1. ;
                npcs_of_coef_set:coordinates = "number_of_coef_sets" ;
        float pc_coefs(mask, total_number_of_coefs) ;
                pc_coefs:long_name = "CAMEL PCA Coefficients Climatology" ;
                pc_coefs:comment = "PCA coefficients are different for each version of lab data and each number of PCs
used. Climatological coefficients for the different sets of PCs are concatenated together in order of increasing number of PCs
and then by increasing lab version number." ;
                pc_coefs:units = "none" ;
                pc_coefs:scale_factor = 1. ;
                pc_coefs:add_offset = 0. ;
                pc_coefs:valid_range = -10., 10. ;
                pc_coefs:coordinates = "mask total_number_of_coefs" ;
                pc_coefs:_FillValue = 99.f ;
        float pc_coef_weights(mask, number_of_coef_sets) ;
                pc_coef_weights:long_name = "Weights of Climatological Coefficients" ;
                pc_coef_weights:units = "none" ;
                pc_coef_weights:valid_range = 0., 1. ;
                pc_coef_weights:add_offset = 0. ;
                pc_coef_weights:scale_factor = 1. ;
                pc_coef_weights:coordinates = "mask number_of_coef_sets" ;
        ubyte pc_coef_nsamps(mask, number_of_coef_sets) ;
                pc_coef_nsamps:long_name = "Number of samples used to calculate climatology" ;
                pc_coef_nsamps:units = "none" ;
                pc_coef_nsamps:valid_range = 1., 19. ;
                pc_coef_nsamps:add_offset = 0. ;
                pc_coef_nsamps:scale_factor = 1. ;
                pc_coef_nsamps:coordinates = "mask number_of_coef_sets" ;
        ubyte landflag(latitude, longitude) ;
                landflag:long_name = "Land Flag" ;
                landflag:scale_factor = 1. ;
                landflag:add_offset = 0. ;
                landflag:valid_range = 0., 1. ;
                landflag:units = "none" ;
                landflag:coordinates = "latitude longitude" ;
```

landflag:comment = "0=Ocean, 1=Land" ;

// global attributes:
:title = "NASA MEASURES: Combined ASTER MODIS Emissivity over Land (CAMEL) Monthly Coefficient Climatology" ;
:summary = "Monthly Climatology of CAMEL PCA Coefficients over the years 2003 through 2021" ;
: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 = "15-Dec-2022 16:29:55" ;
:Prd_Version = "v03r05" ;
:LP_DAAC_Version = "V003" ;
:Id = "CAMEL_coef_climatology_01Month_V003.nc" ;
:cdm_data_type = "grid" ;
:featureType = "grid" ;
: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 = "2003-01-01 00:00:00Z" ;
:time_coverage_end = "2021-12-31 23:59:59Z" ;
:years_included_in_climatology = "2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021" ;
:month_of_climatology = "January" ;
:numeric_month_of_climatology = "1" ;
}

9 Appendix 2: Contents of the CAMEL HSR Climatology Algorithm Software Package

a. *Fortran version*

MEASURES_CAMEL_hsremis_lib_snowCorr_V003.tar.gz package contains:
src_hsrlib_Vclim:
    Makefile_lib
    compute_clim_hsriremis.f
    hsriremis_EDR.inc
    init_hsriremis.f
    read_CAMEL_clim_coef.f
    read_CAMEL_clim_coef_masked.f
    read_labpcs.f
    recon_hsriremis.f
    select_wavenum.f
test:
    iasi_chans616.txt
    run_hsriremis.f
    run_hsriremis_oneline.mk
    save_results/Namib_hsriremis.txt
    save_results/Namib_iasi_emis.txt
    save_results/NorhtMadW_hsriremis.txt
    save_results/NorhtMadW_iasi_emis.txt
coef:
    pchsr_v10.2.nc
    pchsr_v11.2.nc
    pchsr_v12.2.nc
    pchsr_v8.2.nc
    pchsr_v9.2.nc
data:
    CAMEL_coef_climatology_01Month_V003.nc
lib:
    empty dir
include:
    empty dir

b. *Matlab version*

MEASURES_CAMEL_CLIMAT_hsremis_matlab_snowCorr_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

inputs:

    snow_emis_lab.txt

    V003/CAMEL_coef_climatology_01Month_V003.nc

mfiles:

    create_hsremis_from_CAMEL_coef_climatology_snowCorr_V003.m

    read_CAMEL_coef_climatology_V003.m

    read_CAMEL_emis_climatology_V003.m

    read_CAMEL_emis_uncertainty_climatology_V003.m

    test_CAMEL_V003_calc_climatology_hsremis.m

outputs:

    __test_CAMEL_V003_climatology_hsremis_ilat0887_ilon1812_orig.png

    __ test_CAMEL_V003_climatology_hsremis_ilat0887_ilon1812_orig.mat