

Article

Climatology of the Combined ASTER MODIS Emissivity over Land (CAMEL) Version 2

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Abstract: The Combined ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) MODIS (Moderate Resolution Imaging Spectroradiometer) Emissivity over Land (CAMEL) Version 2 (V002) has been available since March 2019 from the NASA LP DAAC (Land Processes Distributed Active Archive Center) and provides global, monthly infrared land surface emissivity and uncertainty at 0.05 degrees (~5 km) resolution. A climatology of the CAMEL V002 product is now available at the same spatial, temporal, and spectral resolution, covering the CAMEL record from 2000 to 2016. Characterization of the climatology over case sites and IGBP (International Geosphere-Biosphere Programme) land cover categories shows the climatology is a stable representation of the monthly CAMEL emissivity. Time series of the monthly CAMEL V002 product show realistic seasonal changes but also reveal subtle artifacts known to be from calibration and processing errors in the MODIS MxD11 emissivity. The use of the CAMEL V002 climatology mitigates many of these time dependent errors by providing an emissivity estimate which represents the complete 16-year record. The CAMEL V002 climatology's integration into RTTOV (Radiative Transfer for TOVS) v12 is demonstrated through the simulation of IASI (Infrared Atmospheric Sounding Interferometer) radiances. Improved stability in CAMEL Version 3 is expected in the future with the incorporation of the new MxD21 and VIIRS VNP21 emissivity products in MODIS Collection 6.1.

Keywords: emissivity; infrared; surface; land; radiation; hyperspectral; climatology; CAMEL; MODIS



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1. Introduction

Land surface emissivity is a critical variable in a multitude of Earth science studies and applications. For example, broadband emissivity [1,2] data are widely used in the land surface modeling community as a key component for accurately constraining Earth's surface energy budget. Sensitivity tests based on the National Center for Atmospheric Research Community Land Model [3] indicate that an emissivity error of 0.1 (10%) in desert areas results in current climate models having errors of up to 7 Wm^{−2} in their upward longwave radiation estimates [4,5]—a much larger term than the surface radiative forcing due to an increase in greenhouse gases (~2–3 Wm^{−2}). This makes emissivity a critical component for predicting changes in future climate scenarios. Emissivity products, in particular spectrally resolved emissivity products, are also heavily utilized by the atmospheric constituent retrieval community and numerical weather prediction operational centers, which depend on emissivity data in their forward modeling schemes to estimate Earth surface emission in the infrared domain. The University of Wisconsin uses a high spectral resolution infrared emissivity dataset (called UWIREMIS) for the Moderate Resolution Imaging Spectroradiometer (MODIS) atmospheric profile retrieval algorithm (MOD07) to reduce uncertainties in water vapor retrievals, particularly over desert regions. The UWIREMIS

dataset is also currently used as a first guess in the Atmospheric Infrared Sounder (AIRS) v6 retrieval, which reduced the errors in land surface temperature retrievals from 5 K to 2 K on average, when compared to using the more traditional National Oceanic and Atmospheric Administration (NOAA) surface regression [6]. Unknown uncertainties in the spectral emissivities used with hyperspectral sounder products over land from sounders such as AIRS and the Cross-track Infrared Sounder (CrIS) have limited the accuracy of the retrieval of other important climate variables such as atmospheric water vapor and temperature. Additionally, Yao et al. [7] showed that using fixed or unphysical spectral emissivity in AIRS retrievals could lead to errors of 4–6 K in boundary layer air temperature, and up to 20% in water vapor. Consequently, a high spectral, spatial, and temporal emissivity dataset which covers the globe is a highly desirable asset for the Earth science community.

Examples of current spectrally resolved infrared satellite-based emissivity datasets include the following: the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Emissivity Dataset (GED) produced at the California Institute of Technology Jet Propulsion Laboratory (JPL) [8], the MODIS MxD11 and MxD21 retrieved emissivity products [9–11], the MODIS baseline fit (BF) produced by the University of Wisconsin (UW) Space Science and Engineering Center (SSEC) [12,13], and Infrared Atmospheric Sounding Interferometer (IASI) emissivity datasets developed separately by Zhou et al. at the Langley Research Center [14], the Laboratoire de Météorologie Dynamique Analyse du Rayonnement Atmosphérique (ARA) group [15–17], and Huang et al. at the University of Michigan [18]. This is not an exhaustive list but includes examples of currently available global datasets.

A recent joint effort by UW SSEC and JPL to create a consistent global, high spectral, moderate spatial and temporal resolution infrared emissivity dataset is the Combined ASTER and MODIS Emissivity over Land (CAMEL) product developed as a project under the National Aeronautics and Space Administration (NASA) Making Earth System Data Records for Use in Research Environments (MEaSUREs) program [19–23]. The MEaSUREs CAMEL product combines the JPL ASTER GED v4 [24] with the UW SSEC MODIS baseline fit dataset [13] to leverage the spectral and spatial resolution strengths of each dataset. Available as a monthly gridded product for the period April 2000 through December 2016, CAMEL has a 0.05 degree (~5 km) spatial resolution and is reported on 13 hinge-point channels which cover the thermal infrared spectral range from 3.6 to 14.3 μm . Additionally, a software package, laboratory dataset, and associated principal components (PCs) are provided to enable the user to produce a 417 channel high spectral resolution (HSR) emissivity at the same spatiotemporal resolution and spectral range as the 13 hinge-point product. The CAMEL HSR algorithm is an update to the earlier UWIREMIS HSR emissivity algorithm developed for the UW SSEC MODIS baseline fit emissivity dataset [12,13]. The CAMEL HSR emissivity PC coefficients are produced via regression of HSR lab data onto the narrowband measurements from ASTER and MODIS, as described in detail in Borbas et al. 2018 [22]. An important new feature of the NASA MEaSUREs CAMEL dataset are emissivity uncertainty estimates provided for every pixel and spectral channel as described in Feltz et al. 2018 [23]. One of the significant advantages of the CAMEL HSR dataset is that it provides an estimate of the surface emissivity for the entire thermal infrared region, including channels used for sounding the atmosphere, at a spatial resolution higher than current hyperspectral infrared sounding instruments.

The CAMEL HSR product and its precursor, the UWIREMIS dataset, are actively used by the numerical weather prediction (NWP) community in research into the use of infrared satellite observations over land for weather forecasting. An example is the integration of the CAMEL HSR product into the Radiative Transfer for TOVS (RTTOV) model used at the European Centre for Medium-Range Weather Forecasts (ECMWF) [25,26]. CAMEL was first integrated into RTTOV 12 as a module where Version 1 (V001) data from the year 2007 were used as a best representation of the full CAMEL record, which ranged from 2000 to 2016 [27,28]. Subsequently, under an NWP SAF Associate Scientist mission [29], the RTTOV emissivity module was updated to use CAMEL version V002 and was significantly revised to use a

climatology of the CAMEL data rather than CAMEL data from a single year. The climatology was derived from the CAMEL V002 monthly product for the period 2000–2016, making it a better representation of the full NASA Earth Observing System satellite record. This RTTOV emissivity update was released in RTTOV version 12.3 and includes both an update to the error covariance matrix as well as a snow correction option in the emissivity module.

This paper highlights the CAMEL V002 climatology—it describes the method for computing the climatology and associated covariances, and it offers an evaluation of the climatology, demonstrating its use in RTTOV. Lastly, it provides preliminary comparisons between the CAMEL V002 climatology and the ECOSTRESS Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) emissivity. The paper is broken down as follows: Section 2 describes the data and software, Section 3 highlights changes in CAMEL from V001 to V002, Section 4 describes the methodology, Section 5 shows analyses of the climatology dataset, Section 6 demonstrates its use in RTTOV, and Section 7 compares the CAMEL and ECOSTRESS datasets.

2. Data and Software

2.1. CAMEL V002

The climatology described in this paper is based on the MEaSUREs CAMEL V002, which is available from the NASA Land Processes Distributed Active Archive Center (LP DAAC). Three separate products comprise the monthly CAMEL V002, including the 13 hinge-point emissivity [20], 13 hinge-point emissivity uncertainty [19], and PC coefficients [21]. All are available in monthly files on a 0.05 degree (~5 km) global grid for land surfaces over the years 2000–2016. To compute the HSR emissivity using the PC coefficients, users can download the laboratory datasets and either a FORTRAN or Matlab software package from the NASA archive.

All products for V002 can be found online at the links contained within the news release at <https://lpdaac.usgs.gov/news/release-nasa-measures-camel-5-km-v2-products/>. Further descriptions of the datasets can be found in Borbas et al. and Feltz et al. [22,23]. A users guide for the CAMEL dataset is available online at the following link [30]: https://lpdaac.usgs.gov/documents/219/cam5k30_v2_user_guide_atbd.pdf.

2.2. Other Data

The MODIS Land Cover Type Product (MCD12C1) supplies global maps of land cover at annual timesteps starting in the year 2001 and is provided on a $0.05^\circ \times 0.05^\circ$ grid resolution. It can be obtained from the Global Land Cover Facility online with the most recent version, version 6 available here: <https://lpdaac.usgs.gov/products/mcd12c1v006/> [31]. More information is available in Friedl et al. and Channan et al. [32,33]. There are 17 land cover types defined by the International Geosphere-Biosphere Programme (IGBP) classifications, and these are used in this paper to characterize the climatological emissivity behavior over different surface regimes.

While CAMEL ingests data from MODIS and ASTER, ECOSTRESS is another instrument onboard the International Space Station that provides emissivity estimates from space. ECOSTRESS acquires radiance in 5 channels, centered at: 8.29 μm , 8.78 μm , 9.20 μm , 10.49 μm , 12.09 μm . All 5 channels were used between August 2018 and March 2019, and band 2, 4 and 5 have been used since that time due to an anomaly on board that reduced the buffering storage capacity. The emissivity is calculated using a temperature emissivity separation algorithm described by Hulley and Hook [34], and the temperature and emissivity data are made available as a standard product [35]. Data can be downloaded from the NASA LP DAAC and have the following doi: 10.5067/ECOSTRESS/ECO2LSTE.001.

3. Changes in CAMEL V002 from V001

In March 2019, CAMEL V001 was replaced with CAMEL V002. This update improved the characterization of partially snow and ice covered scenes and included the addition of two more laboratory datasets for use in the creation of the HSR emissivity for fractional

snow/ice cover over either vegetation and/or bare soils. The CAMEL V001 HSR algorithm includes three sets of laboratory spectra—55 spectra (called version 8) for general use, 82 spectra (called version 10) for non-vegetated cases and 4 snow/ice spectra (version 12). The two additional laboratory sets in CAMEL V002 were included to represent partially snow-covered scenes and include a combined general plus snow/ice (called version 9) and a combined carbonates plus snow/ice (called version 11). The number of PC coefficients used for each new lab set was kept the same as its corresponding non-snow version. Table 1 describes these lab versions and also lists the corresponding number of PCs used for each lab dataset. Since lab dataset 8 and 9 can each use either 7 or 9 PCs (depending on the surface type), there are 7 total unique combinations of lab dataset version and number of PCs for CAMEL V002.

Table 1. Laboratory datasets of spectral emissivity used in the Combined ASTER MODIS Emissivity Over Land (CAMEL) V002.

Lab Version	Description	Number of Lab Spectra	Number of PCs	Snow Fraction
V8.3	General—bare (quartz)	55	9	=0
	General—all types		7	=0
V9.3 *	General + Snow/Ice—bare (quartz)	55 + 4	9	$0 < \dots < 1$
	General + Snow/Ice—all types		7	$0 < \dots < 1$
V10.3	General + Carbonates	82	5	=0
V11.3 *	General + Carbonates + Snow/Ice	82 + 4	5	$0 < \dots < 1$
V12.3	Snow/Ice	4	2	=1

* New to CAMEL in V002.

CAMEL V001 used only the snow/ice lab version if the snow fraction was equal to or larger than 0.5, whereas the CAMEL V002 uses the combined general + snow/ice or general + carbonates + snow/ice laboratory set for any snow fraction between 0 and 1 to better characterize the partially snow-covered scenes. The effect of this change is most evident in the transitional months between fall, winter, and spring where partial snow cover is common in middle and northern latitudes. An example described later in detail is the seasonal variation of the area surrounding Mt. Massive in Colorado, which is typically 100% snow covered in winter but has a mixture of snow and bare quartz mineral scenes or snow and vegetated scenes in other seasons.

4. CAMEL Climatology Description and Methodology

The CAMEL climatology is produced on the same 0.05° spatial resolution grid as the CAMEL monthly dataset and represents a mean emissivity for each calendar month for years 2000–2016. A quality flag is produced for the climatology and takes the following values: 0 for ocean, 1 for best quality land, 2 for degraded quality land, 3 for land with filled values, and 4 for mixed sea and land. Datasets of netcdf files for the 13 hinge-point and HSR emissivity CAMEL V002 climatology are available by request from the lead author. These files are produced for each calendar month and contain estimates of the mean emissivity. The mean 13 hinge-point emissivity and uncertainty climatology estimates are computed for each calendar month by averaging over each of the available years of the record.

Similar to the monthly CAMEL HSR emissivity product, the CAMEL HSR emissivity climatology is provided as PC coefficients, lab datasets, and software routines in either FORTRAN or Matlab. This method is used to reduce the file sizes of the product. When computing the mean climatological HSR PCs, coefficients corresponding to each unique combination of number of PCs and lab dataset version are kept separate. Table 2 lists the unique combinations of number of PCs and lab versions used in the CAMEL V002 product. Since there are seven unique combinations, a theoretical maximum of seven different PC vectors could be included for one pixel of the climatology. However, due to minimal interannual variations in land cover over a single pixel (e.g., due to vegetation or snow

cover change), typically only a maximum of 2 and sometimes 3 or 4 are used for a single pixel and calendar month over the full extent of the CAMEL record. From the averaged climatological PC vectors, corresponding CAMEL HSR emissivities can then be computed. The HSR emissivities are then averaged together using weights which are based on the number of samples of each unique combination. These weights are included in the PC climatology files. Figure 1 illustrates the process of computing the mean HSR emissivity climatology for March over a partially snow covered scene in northern Wisconsin, USA. For this particular pixel and month, only two unique combinations of number of PCs and lab version are used—lab version 12 with 2 PCs and lab version 9 with 7 PCs, having the respective weights of 0.4 and 0.6. Figure 1 shows the two intermediate HSR spectra in color which represent lab version 12 with 2 PCs and lab version 9 with 7 PCs, as well as the final HSR emissivity climatology in black, which is the weighted average of the intermediate spectra.

Table 2. Unique combinations of the CAMEL lab dataset version and number of principal components (PCs) used to construct the high spectral resolution emissivity.

Unique Combinations of Lab Version and Number of PCs							
Lab Version	12	10	11	8	8	9	9
Number of PCs	2	5	5	7	9	7	9

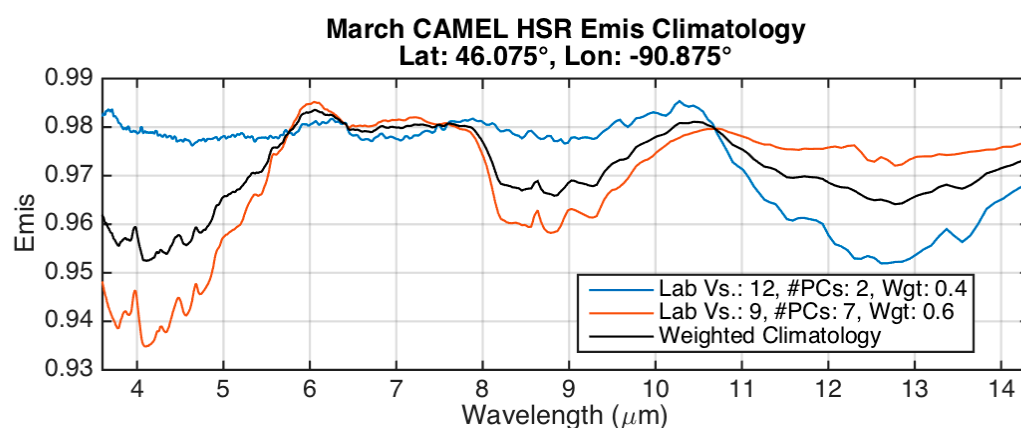


Figure 1. Illustration of the CAMEL HSR emissivity climatology computation for March over northern Wisconsin. Intermediate spectra are shown in color for the 2 lab versions and number of PCs sets used: lab version 12/2 PCs and lab version 9/7 PCs. The final HSR climatology is shown in black and is obtained via a weighted average of the two intermediate spectra.

While the above-mentioned files describe the mean estimate of CAMEL, covariances are also an important measure used to characterize the climatology. For example, covariances or the inter-channel correlation of the observations are needed for data assimilation purposes to account for the lack of independence between the spectral observations [36]. These are used in applications such as numerical weather prediction or atmospheric and land surface reanalyses. For the analyses shown in this paper, covariances are calculated using the following equations, where $\mathbf{X}$ is a matrix containing the HSR emissivities for a single calendar month over the complete CAMEL record and has the dimensions of number of months by number of channels, and where N is the number of months: ++

$$\hat{\mathbf{X}} = \mathbf{X} - \bar{\mathbf{X}} \quad (1)$$

$$\text{Cov}(\mathbf{X}) = (\hat{\mathbf{X}}^T \times \hat{\mathbf{X}})/N \quad (2)$$

It is planned to make the HSR emissivity covariance available to users via PCA compression to minimize data volume.

5. Results

5.1. Case Site Analyses

This section contains illustrations of the CAMEL V002 climatology and dataset at four selected case sites, chosen for their diverse representations of land cover type. The selected sites are: (1) the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site, which is a grassland site in Lamont, Oklahoma at middle latitudes; (2) a site in Yemen whose surface is dominated by carbonate; (3) a site in the Namib Desert which is dominated by quartz ground cover; and (4) a site in the Colorado Rocky Mountains which is characterized by fractional snow cover of basalt rock.

Figure 2 shows the monthly 13 hinge-point and HSR emissivity overlaid by the climatological mean estimates at each of the four sites, as well as the standard deviation of emissivity spectra over the years 2000–2016 for the month of April. Comparison of the 13 hinge-point and HSR emissivity spectra highlights the higher spectral resolution features that are not evident in the 13 hinge-point product; for example, the Yemen carbonate signature around 6.5 μm or the Namib quartz feature at 12.5 μm . Variations at the shorter wavelengths between 3.6 and 5 μm are likely dominated by uncorrected solar effects that are largest for the desert case sites with higher surface reflectivity, but are seen at all four sites, likely indicating that the climatology includes dry, non-vegetated and non-snow covered months for each of the four sites. Variations in general are largest at the desert sites where larger spectral contrast exists between bare soil and vegetation. The lack of prominent variation at the Namib Desert site at 8.5 μm is due to the fact that the pixel selected is located over homogeneous sand dunes and does not include any variations due to changes in vegetation phenology, or soil moisture. Variations in quartz sensitive channels are prominent at the ARM SGP grassland site around 8–10 μm and are also visible at the mountainous case site.

Figure 3 shows the corresponding HSR emissivity covariances for the same case sites and for the same April time period as in Figure 2. Just as in Figure 2, channels which vary substantially from year-to-year over the CAMEL record can be easily picked out by their larger covariances along the diagonal; for example, the shorter wavelength channels at all four case sites, the quartz region of the ARM SGP site, or the carbonate sensitive region around 7 μm at the Yemen site. Spectrally correlated channels are also now identifiable by inspection of the off diagonal elements of the covariance matrices. The Mt. Massive case site located in the Rocky Mountains contains covariations which cover broader spectral ranges than other case sites. These broader features represent changes in snow cover—for example, a stronger snow signature will decrease emissivity around 12.5 μm but increase emissivity around 3.6 to 5 μm and 8 to 10 μm as the underlying surface is covered by snow.

Time series for the same case sites are shown in Figures 4–7. The first time series in Figure 4 is for the ARM SGP site. In the top four left hand panels, the monthly CAMEL product time series is overlaid by the climatological CAMEL values for four selected channels at 3.6, 8.6, 10.8, and 12.1 μm . For this case, the monthly product looks quite similar to the climatology—i.e., there appears to be little interannual variability. The middle column shows the monthly emissivity uncertainty time series overlaid by the uncertainty climatology. For the 10.8 and 12.1 μm channels, the monthly total uncertainty increases over the years 2012 through 2016 due to an increase in the algorithm component. (Note the algorithm and total monthly uncertainties are close to equaling each other, so the black and blue lines are mostly overlaid.) This increase in the algorithm component of the emissivity uncertainty is due to an increase in the difference between the ASTER and MODIS MYD11C3 input emissivity over time. This increase in the difference between ASTER and MYD11C3 is due to processing anomalies of the MYD11C3 Col. 4.1 caused by

issues with initialization of the algorithm. Meanwhile, the total uncertainty climatology is much more stable but still has distinct seasonal variations. Explanation of the CAMEL uncertainty and its components can be found in Feltz et al. [23]. The right hand top four panels show the emissivity anomalies (i.e., the monthly minus climatological emissivity) overlaid by a best fit trend line with 95% confidence bounds. While the authors chose to compute and show these trends, they are not advertising them as physically meaningful trends—i.e., the trends are frequently affected and caused by known processing anomalies of the MODIS MYD11C3 day/night emissivity algorithm. Since emissivity processing artifacts are subsequently present in the monthly CAMEL emissivity product for some years of the data record, this further motivates the use of the CAMEL climatology, which averages out the slowly varying and spurious processing-induced artifacts. More dramatic examples of processing-induced artifacts are seen in the following case studies.

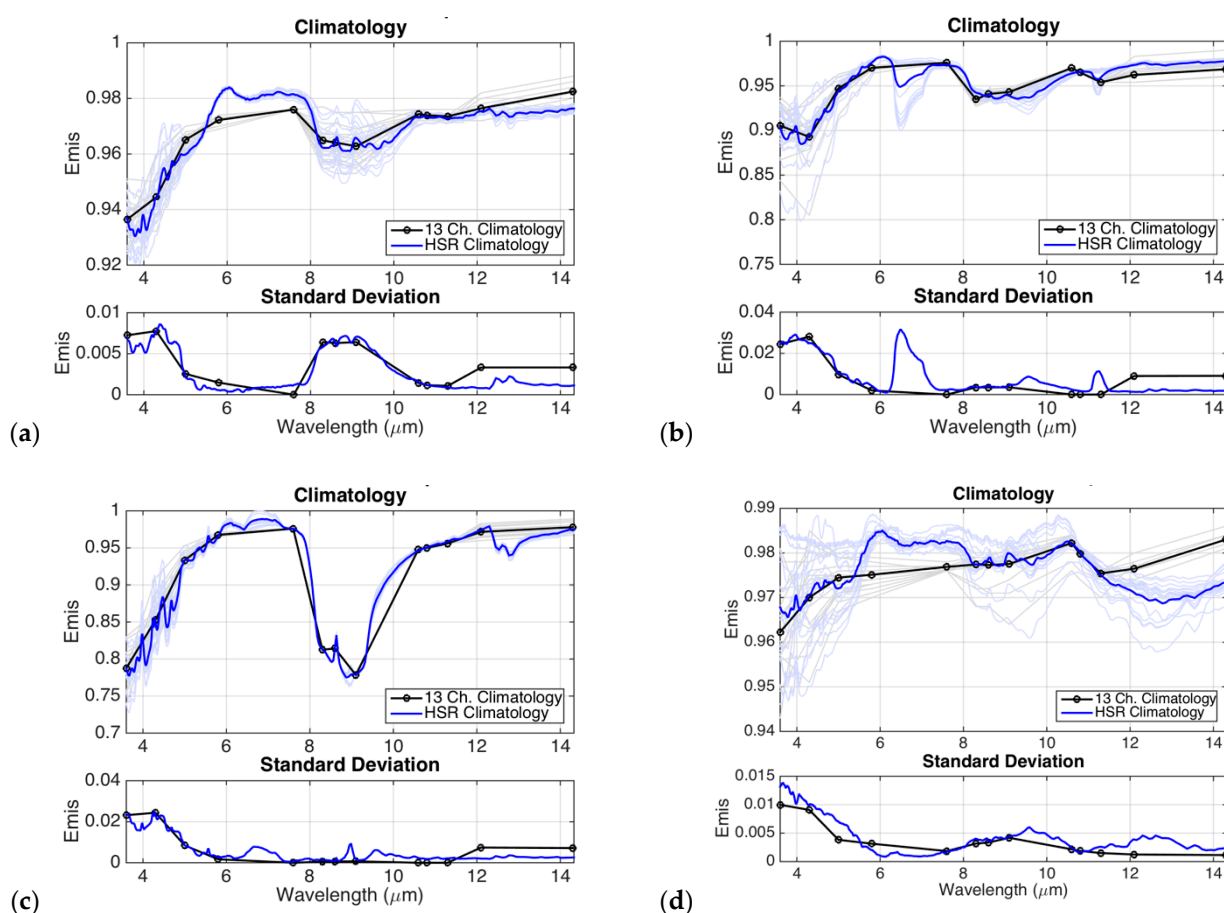


Figure 2. April 2000–2016 CAMEL 13 hinge-point monthly (grey) and climatology (black) emissivity overlaid with the HSR monthly (light blue) and climatology (blue) emissivity (top row), and standard deviation over the same years (bottom row) shown for the (a) Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP), (b) Yemen, (c) Namib, and (d) Rocky Mountain, Mt. Massive case site.

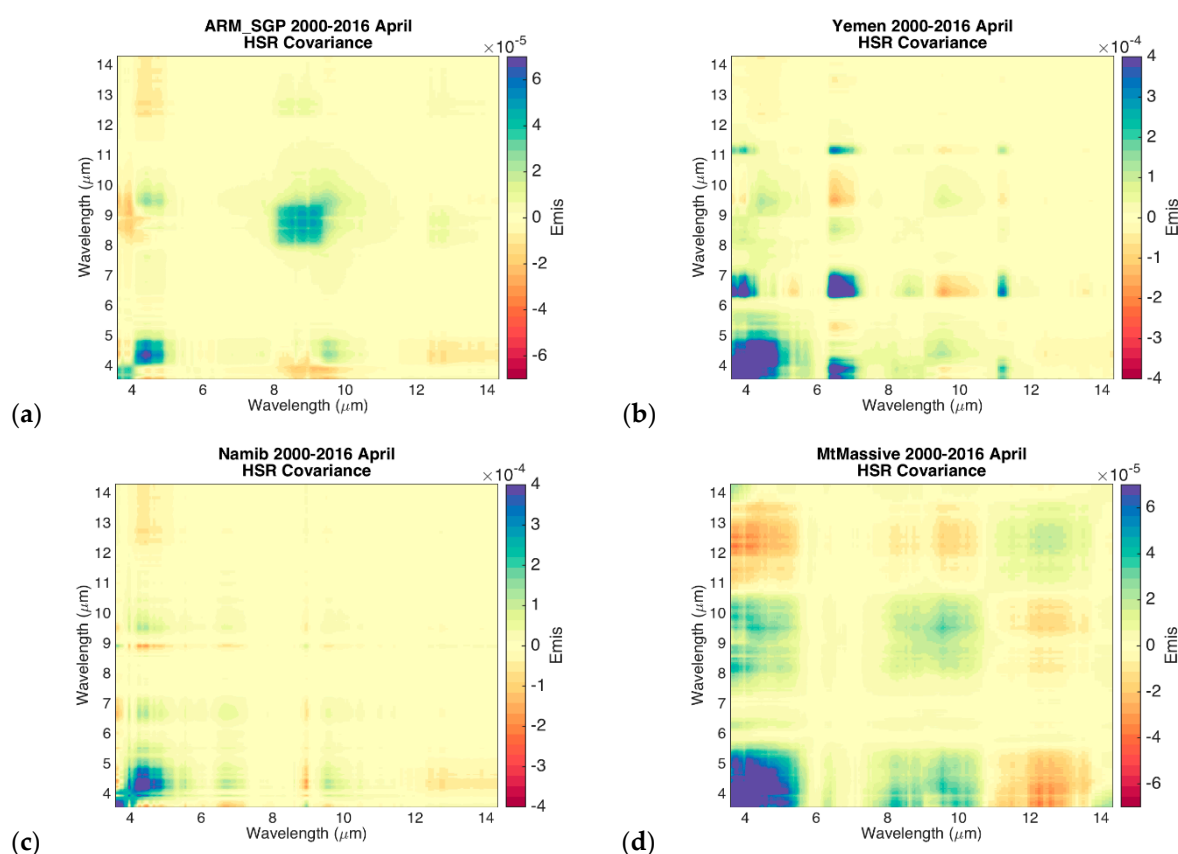


Figure 3. April 2000–2016 CAMEL HSR emissivity covariance for the (a) ARM SGP, (b) Yemen, (c) Namib, and (d) Rocky Mountain, Mt. Massive case site. Corresponding HSR emissivities are shown in Figure 2. Note the scale change for each site.

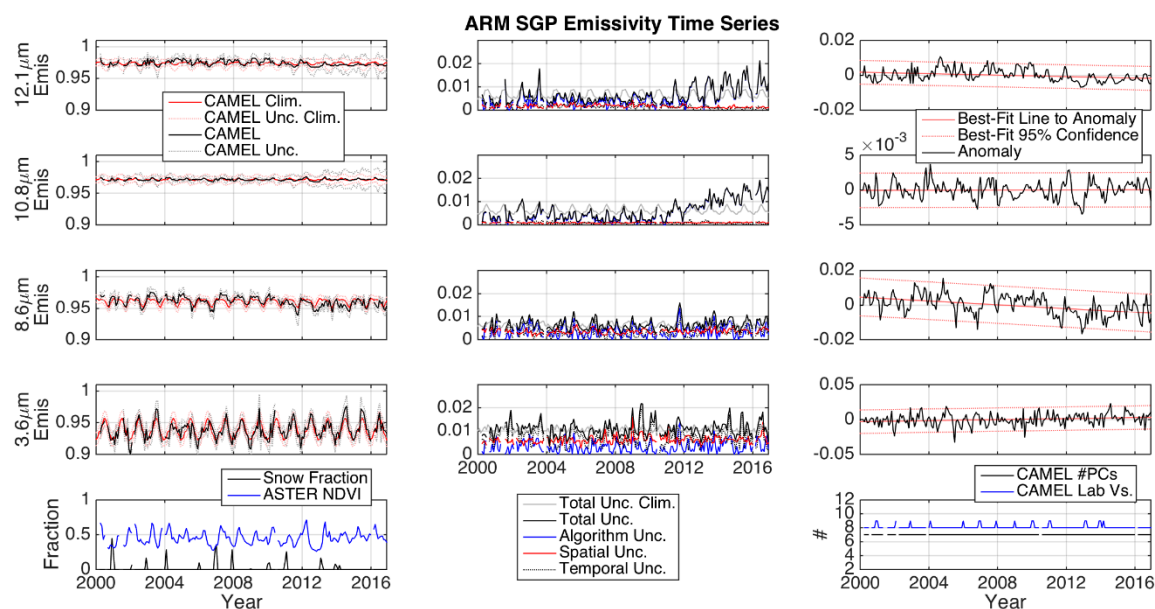


Figure 4. Time series over the ARM SGP site of the (left) CAMEL monthly and climatological emissivity, (middle) the CAMEL monthly and climatological uncertainty, and (right) the CAMEL monthly emissivity anomalies with a best fit line. Bottom row shows the (bottom, left) monthly snow fraction and NDVI and (bottom, right) lab version and number of PCs for the monthly CAMEL HSR emissivity.

Figure 5 shows the same time series plots for the Namib quartz site. Very little variation is seen from month-to-month and year-to-year in the 8.6 and 10.8 μm channels while the 12.1 μm channel monthly emissivity has a noticeable decrease in emissivity around 2009 which is also seen as a more significant trend in the right column. This discrepancy between the channels is an outcome of the CAMEL method of combining MODIS and ASTER data at different channels as described in Borbas et al. [22]. Specifically, the CAMEL 10.8 μm channel is based solely on ASTER data and the CAMEL 8.6 μm channel is based on a weighted mean of ASTER and UW BF data, where ASTER gets 90% weight in arid regions such as this Namib case site. Meanwhile, the CAMEL 12.1 μm channel is either based solely on UW BF data or is a weighted combination of ASTER and UW BF data where the weights are defined by the difference between the ASTER and UW BF emissivities. Thus, ASTER's characteristic of being more stable over time is reflected more heavily in the CAMEL 8.6 and 10.8 μm channels. The decrease in the CAMEL 12.1 μm emissivity around 2009 is due to MODIS MYD11C3 processing anomalies that occur after 2009. These anomalies are believed to be due to issues with initialization of the emissivity algorithm.

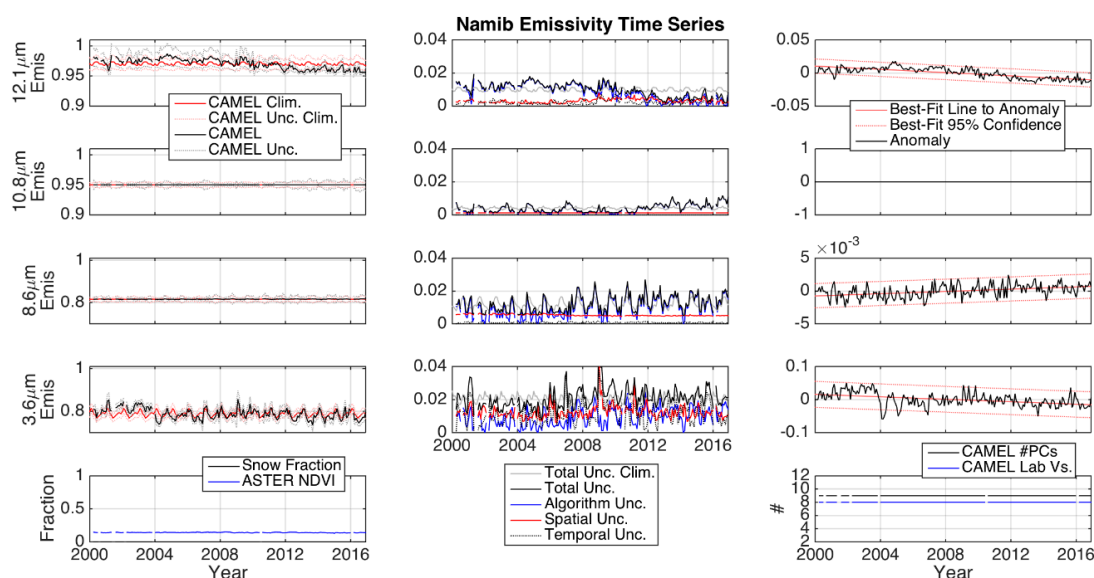


Figure 5. Same as Figure 4 except for the Namib Desert quartz site.

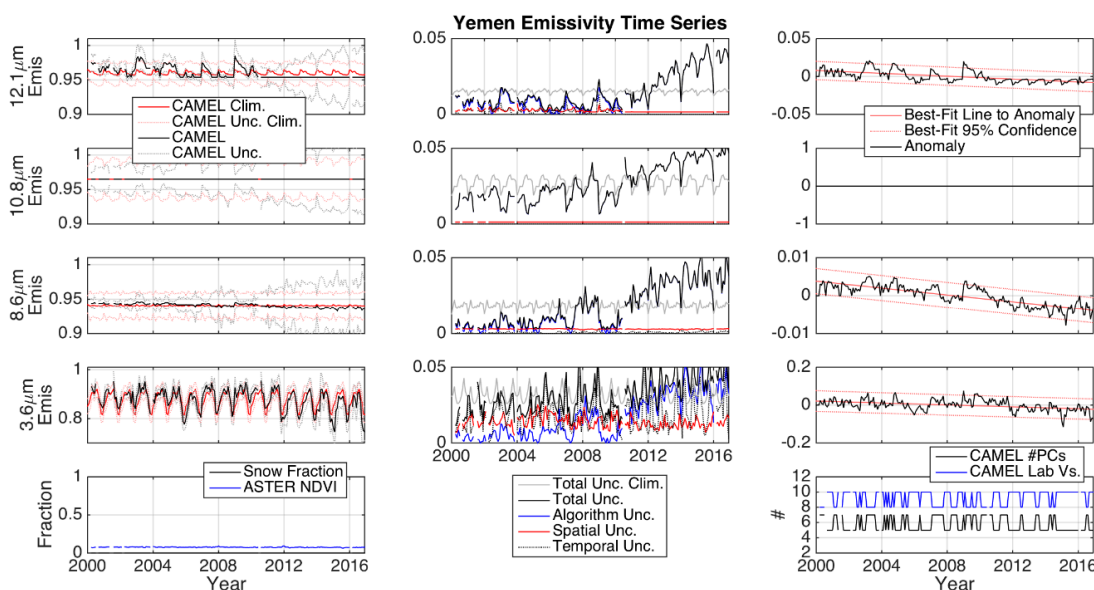


Figure 6. Same as Figure 4 except for the Yemen carbonate site.

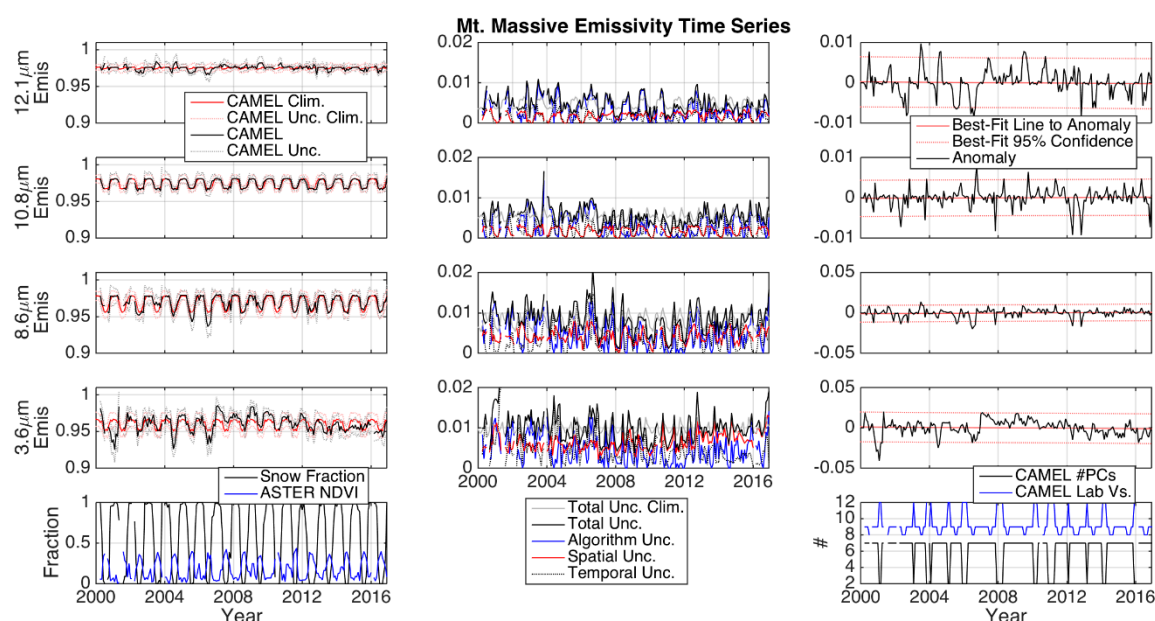


Figure 7. Same as Figure 4 except for the Mt. Massive, Colorado Rocky Mountain partially snowy, mountainous site.

As was the case for the Namib site, the Yemen monthly emissivity for the 8.6 and 10.8 μm channels also have very little temporal variation. This is shown in Figure 6. The 3.6 μm channel, however, has highly repeatable annual variations which are captured in the climatology. The 12.1 μm monthly emissivity appears to suffer from the MYD11C3 processing artifacts, based upon the sporadic temporal changes over the first 10 years of the record which are completely absent in the last 7 years of the record. This unique behavior is seen here at the Yemen site and not others due to the unique surface type present at Yemen—the surface type determines what combination of ASTER and MODIS are used to create the CAMEL emissivity. These MYD11C3 processing artifacts are also evidenced by the total monthly uncertainty that more than doubles in magnitude over the last 7 years of the record due to the algorithm component, which signals larger differences between the UW BF and ASTER emissivities around the 12 μm region. The differences between the UW BF and ASTER data dictate what weighting is used for the averaging of the ASTER and UW BF data for the CAMEL 12.1 μm channel emissivity; thus, as the difference between ASTER and UW BF changes, so do the characteristics of the CAMEL 12.1 μm emissivity. Note the 12.1 μm channel climatology overlaid in red provides more moderate values over the annual cycle.

Figure 7 shows time series results for the last case site over Mt. Massive. Fewer processing artifacts seem to be present and the total emissivity uncertainty has a more equal mix of the three components—spatial, temporal, and algorithm—than do certain channels for other sites. Large and highly repeatable changes in snow cover are present in this case and contribute to the annual variations seen in each of the four emissivity channels shown. The behavior of the emissivity timeseries for this case is greatly improved in CAMEL V002 compared to V001 due to the inclusion of fractional snow cover in a combination with bare mineral and vegetation. This leads to a much more realistic seasonal variations of the surface emission.

5.2. Analyses Stratified by IGBP Land Cover Class

This section contains similar timeseries plots as the previous case site section; however, results are now shown for the global mean emissivities of IGBP land classification categories. To obtain the monthly estimates, all CAMEL pixels classified under a single IGBP category are averaged together for that month. The IGBP category climatological values are then obtained by averaging the monthly mean IGBP values over all available years. The standard deviation of the CAMEL monthly emissivity over IGBP category is included as a time

series as a measure of how well the monthly mean IGBP emissivity estimate represents all CAMEL spectra within the IGBP category.

Figure 8 shows results for the IGBP Mixed Forest category, where the number of samples for each month is around 252,000. This category is located predominantly around the high mid-latitudes and is defined to have at least 60% tree cover with both deciduous and coniferous trees contributing to the cover in roughly equal portions. For this category, large annual variations in snow cover are seen, as well as variations in the corresponding ASTER normalized difference vegetation index (NDVI). Time series of the standard deviation of the CAMEL monthly emissivity over IGBP category (seen in left column with right hand axis) shows that the CAMEL emissivity is relatively homogeneous within the Mixed Forest category for the 10.8 and 12.1 μm channels. Seasonal changes in the standard deviation over IGBP category are seen in the 8.6 and 3.6 μm channels and show larger variations in CAMEL emissivity during the months with higher average snow fractions. The largest temporal variations in emissivity are seen in the 3.6 μm channel where the climatological emissivity varies by ~ 0.015 over the annual cycle. A caveat is added to the interpretation of this result, however, as the change in the 3.6 μm emissivity is likely not explainable by only the changes in phenology of the Mixed Forest category but could be contributed to by the remains of uncorrected solar effects. While seasonal variations are also present in the 8.6 and 10.8 μm channels, they are smaller than those seen at the Mt. Massive site where snow cover also changed dramatically over the annual cycle. This is due to the fact that the background forested ground cover emissivity is closer to the emissivity of snow than is the rocky ground cover found at Mt. Massive. Around the year 2007, a distinct change in the emissivity and uncertainty time series can be seen as a subtle discontinuity. This change in behavior is due to a change in the MOD11C3 Col. 4.1. algorithm—prior to the year 2007, the algorithm used the Col. 4 cloud mask, and after January 2007 it used the Col. 5 cloud mask. Again, the climatology averages this effect out and shows a more realistic characterization of the dataset.

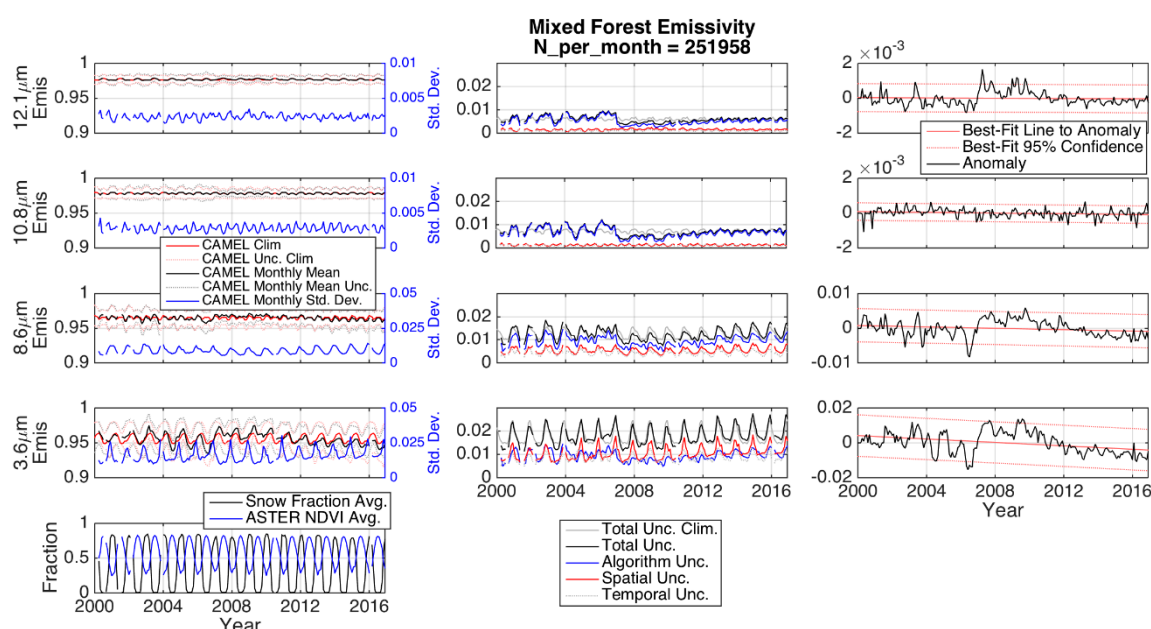


Figure 8. Time series for the IGBP Mixed Forest land classification category of CAMEL (**left**) monthly and climatological emissivity (black and red) and standard deviation of the monthly CAMEL emissivity over the IGBP category (blue), (**middle**) the CAMEL monthly and climatological uncertainty, and (**right**) the CAMEL monthly emissivity anomalies with a best fit line. Bottom row shows the (**bottom, left**) monthly snow fraction and NDVI. The number of samples per month is 251,958.

Results for the Barren and Sparse Vegetation IGBP category are shown in Figure 9. This category is dominated by the following geographic regions: the Sahara Desert, the Arabian Peninsula, Iran and surrounding regions, and the Taklamakan and Gobi Deserts north of

the Tibetan Plateau. Similar to the Mixed Forest category, the 10.8 and 12.1 μm channel monthly IGBP mean emissivity seems to represent all spectra within the category quite well—the standard deviation of the emissivity over the IGBP category is contained under ~ 0.01 for all months and years. The 8.6 and 3.6 μm channel emissivity, however, is much more variable within a given single month for the IGBP Barren and Sparse Vegetation category, with standard deviations as high as ~ 0.1 , ten times greater than at 10.8 and 12.6 μm . This is anticipated for desert scenes and is explained by the large spectral contrast that exists between the bare soil cover and vegetation. Minimal temporal variations are now seen in the quartz sensitive 8.6 μm and 10.8 μm channels. Somewhat sporadic temporal variations are seen in the 12.1 μm channel, as was seen in the Yemen case site time series. These temporal variations are likely due to undetected cloud cover over snow-free surfaces, which the 12.1 μm channel is typically sensitive to. This is supported by the fact that similar features are seen in the emissivity uncertainty, particularly the algorithm component, which imply that these sporadic variations are due to processing artifacts in the MODIS MOD11 emissivity processing. Again, the trends show decreasing emissivity over the CAMEL record but are likely induced by processing artifacts. The climatology for this case offers a more stable emissivity than the monthly product.

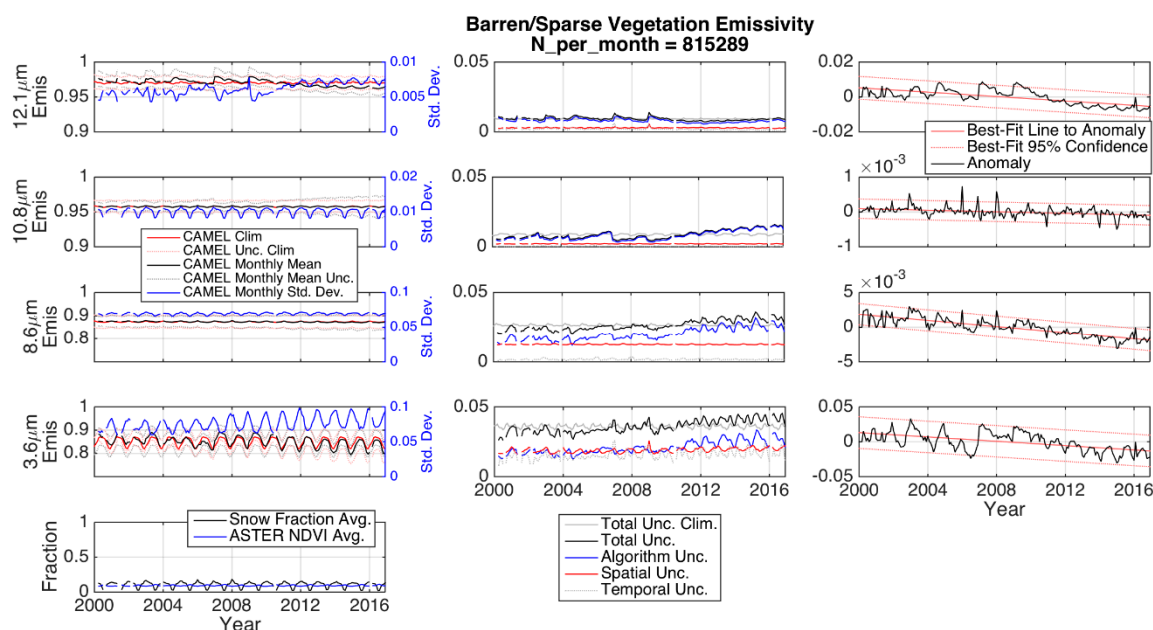


Figure 9. Same as Figure 8 except for the Barren and Sparse Vegetation IGBP category with number of samples per month equal to 815,289.

5.3. Global Temporal Emissivity Variation

Figure 10 illustrates the global emissivity interannual variability experienced over the CAMEL record using the covariance diagonal for four separate channels. This covariance was computed on a 0.25 degree grid and is currently available for use within the most recent RTTOV software package (RTTOV v12.3). Results for the 4, 8.5, 10.8 and 12 μm channel are shown for the month of April. The largest variations are seen at 4 μm over desert regions possibly due to incomplete correction of solar reflected radiation. The 8.5 μm channel shows permanent glaciers have the lowest variability over the data record while regions with seasonal snow cover or vegetation cover have the largest variability. The 10.8 and 12 μm channels experience smaller variations over the CAMEL record for the month of April, where variations are seen primarily in the high northern latitudes, likely due to the timing of the onset of snow melt in the boreal spring. The Sahel region is also highlighted

in the 10.8 and 12.0 μm maps, indicating a change in vegetation cover that is likely due to the interannual changes in precipitation.

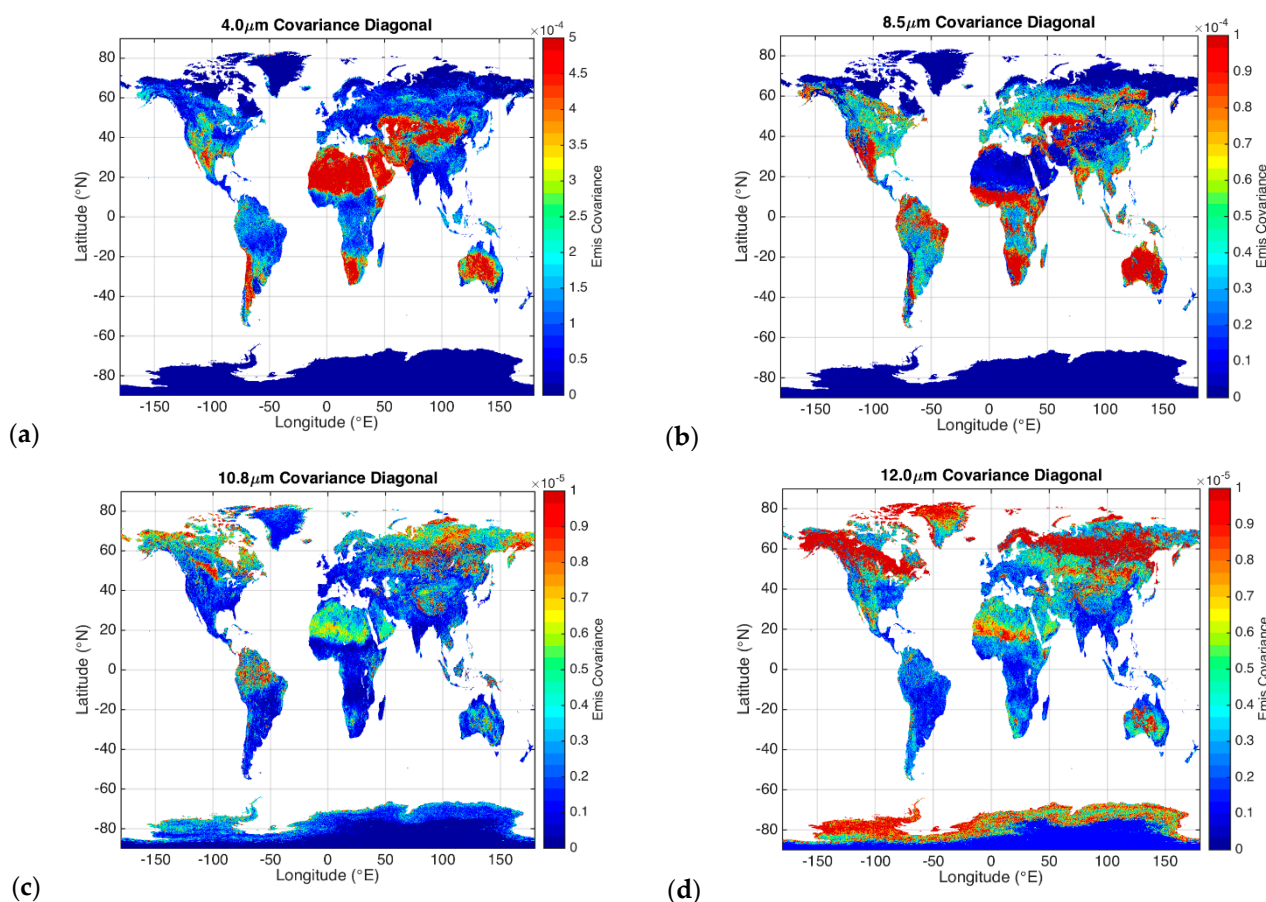


Figure 10. The diagonal of the CAMEL covariance for the month of April at (a) 4, (b) 8.5, (c) 10.8 and (d) 12 μm . The covariance diagonal is computed at 0.25 degree resolution and is available as part of the RTTOV CAMEL V002 climatology emissivity dataset. Note the color scale change between subplots.

6. Evaluation Using RTTOV Calculations and IASI Observations

This section demonstrates the use of CAMEL in the RTTOV model and offers an assessment of the CAMEL V002 climatology. The assessment is made using RTTOV calculated minus observed brightness temperatures (BTs) from the Infrared Atmospheric Sounding Interferometer (IASI), which has an accuracy of better than 0.5 K [37]. The motivation here is to use the IASI observations as a validation reference for the emissivity dataset via radiative transfer calculations. Brightness temperatures are computed with RTTOV v12 using each the CAMEL V002 climatology emissivity dataset as well as the previously used single year of CAMEL V001 2007. The single year of 2007 was chosen for the V001 emissivity dataset because the MODIS MYD11C3 processing did not have any artifacts at that time and because the year 2007 is a good representation for the CAMEL V001 dataset, which extends from 2000 to 2016. Each set of calculated BTs is compared to corresponding observed BTs from IASI, and the relative agreement of each calculation set with the observations is used as a check on the climatology's accuracy. For a more in-depth validation of the CAMEL V001 monthly product, the readers are directed to Feltz et al. [23], and for more comparisons of the RTTOV emissivity datasets, the readers are referred to Borbas et al. [29].

Since the time periods selected for evaluation here are from the years 2008 and 2009, there is no expectation that the CAMEL V002 climatology will agree better with the IASI observations than the CAMEL V001 year 2007; rather, this analysis illustrates example BT

differences from using these two different datasets. De-biased spectral variances of the RTTOV calculated minus observed IASI BTs over three different spectral regions are used to measure the CAMEL emissivity's ability to reduce the spectral brightness temperature variance caused by incorrect assumptions of surface emissivity. The de-biased spectral variance is computed by first finding the mean calculated minus observed difference over the 10.5 to 13 μm window region and then subtracting that mean value from the calculated minus observed difference spectra. For the final step, the variance of the de-biased difference over specified spectral regions are computed. Analyses are shown for selected case sites as well as globally for four case study days. In the rest of this paper, as well as in the figures, the previously used CAMEL V001 RTTOV emissivity dataset is referred to as "RTTOV2007", and the more recent RTTOV emissivity dataset based on the CAMEL V002 climatology is referred to as "RTTOVclim".

6.1. Case Sites

For the case site analyses, brightness temperatures are computed for IASI footprints located closest to the site latitude and longitude. These calculations are done using the RTTOV v12 model, which takes in as primary input the atmospheric state, skin temperature, and surface emissivity. The ERA Interim reanalysis is used to define the atmospheric state and skin temperature parameters, and the CAMEL HSR product is used to define the surface emissivity. The ERA Interim reanalysis is also used to screen for clear sky scenes, while IASI is used to define the solar zenith angle.

Figure 11 shows results for two case studies—each from the month of May 2009 over the ARM SGP grassland site. Figure 11a) shows results for a nighttime case (May 7th, 2009 at 3:38 UTC, 22:38 local time) and Figure 11b) shows results for a daytime case (May 30th, 2009 at 16:22 UTC, 9:22 local time). Observation minus calculation differences are shown in the second from top panels, where the bias offsets from 10.5 to 12 μm indicate a skin temperature error in the ERA reanalysis, which is larger in the daytime case. Differences of the two RTTOV calculations are shown for each case in the third from top panels, and the bottom panel shows associated CAMEL emissivities used in the calculations. De-biased spectral variances of the calculated minus observed difference are listed for three spectral regions and show relatively close agreement between the CAMEL V002 climatology and V001 single year of 2007. The de-biased variances for the nighttime case study are all lower than the daytime de-biased variances, likely due to a larger error in the ERA skin temperature at the time of the daytime overpass at about 09:30 am local time compared to the nighttime overpass at about 09:30 pm local time. Overall, results from the case sites illustrate changes in the RTTOV CAMEL emissivity that are within reason of realistic emissivity uncertainty estimates.

6.2. Four Case Days

This section contains IASI observation minus calculation results for four case study days, each representing a different season. Calculations done for this analysis use the ECMWF forecast as input along with the MAIA cloud mask [38] to screen for clear-sky only scenes. To summarize results, statistics are computed for the IGBP land cover categories. De-biased variances of RTTOV calculated minus observed BTs for the 10–13, 8–9, and 3.6–5 μm spectral regions are shown in Tables 3–5 below. These regions were chosen due to their different spectral behaviors. The 3.6–5 μm region has a large quartz spectral feature and includes only MODIS as input (ASTER data are not available at these wavelengths). The 8–9 μm region is the Reststrahlen band and is sensitive to quartz (non-vegetated) surfaces. The 10–13 μm region is an infrared window where surface emissivity is relatively smoothly varying with wavelength and exhibits a lower BT variability compared to the other selected spectral regions.

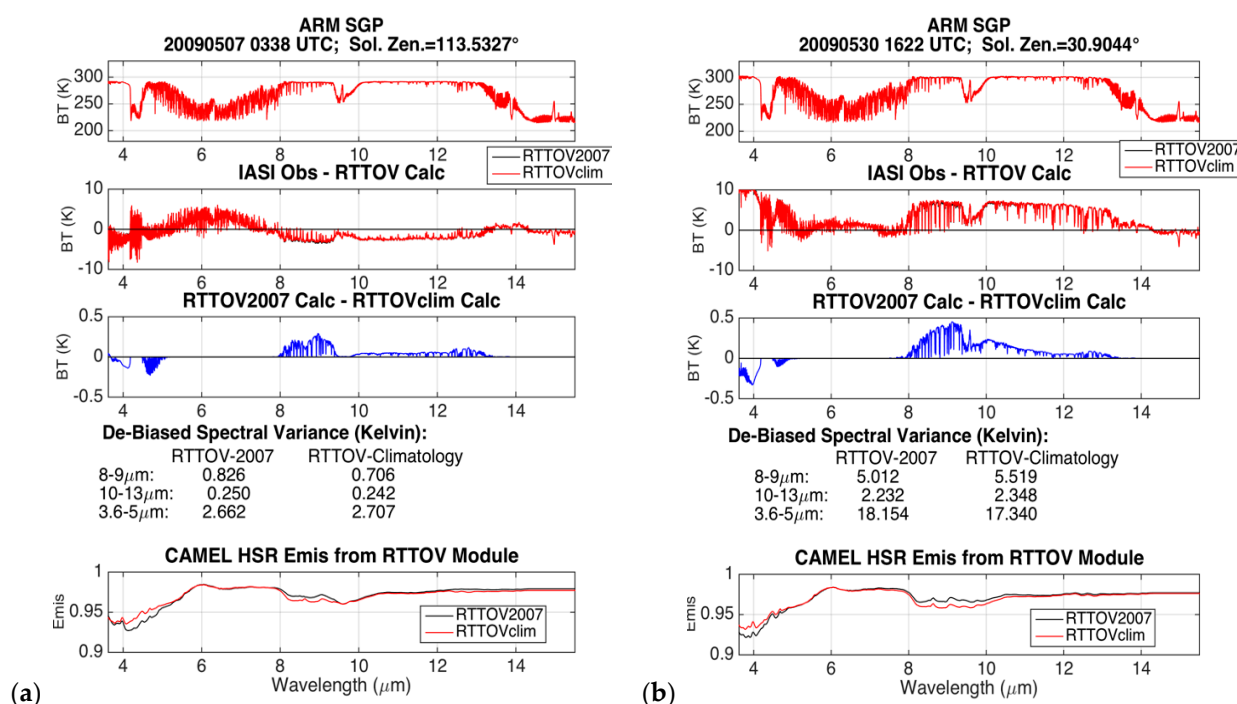


Figure 11. Comparison of IASI BTs calculated using the current RTTOV emissivity module (“RTTOV2007”) and the updated module (“RTTOVclim”) for the ARM SGP site on (a) May 7th, 2009 at 03:38 UTC and (b) on May 30th, 2009 at 16:22 UTC. Top panel shows the RTTOV calculated BTs overlaid for each emissivity module, second from top panel shows IASI observed minus calculated BT again overlaid for each emissivity module (RTTOVclim curve in red is overlaying the RTTOV2007 curve in black), third panel from top shows calculation differences, bottom panel shows the RTTOV CAMEL emissivities overlaid. The de-biased spectral variances are listed in Kelvin² for each observation minus calculation difference for three spectral regions. Solar zenith angle is noted in the top title.

Table 3. RTTOV calculated minus IASI observed 10–13 μm day+night de-biased BT variances (listed in units of Kelvin²) for four case days representing the four seasons. Results for the previous RTTOV CAMEL V001 single year of 2007 emissivity (“CAMEL 2007”) and the new CAMEL V002 climatology (“CAMEL clim”) are shown.

	CAMEL 2007	CAMEL Clim	CAMEL 2007	CAMEL Clim	CAMEL 2007	CAMEL Clim	CAMEL 2007	CAMEL Clim
	January 15th 2008		April 14th 2008		July 15th 2008		September 29th 2008	
1: Evg. Needle Forest	0.51	0.50	0.39	0.33	0.93	0.92	0.47	0.46
2: Evg. Broad Forest	0.83	0.83	0.79	0.77	0.94	0.93	0.58	0.57
3: Dcds. Needle Forest	0.46	0.42	0.53	0.57	1.30	1.30	0.25	0.24
4: Dcds. Broad Forest	0.43	0.42	0.52	0.50	0.70	0.69	0.77	0.77
5: Mixed Forest	0.37	0.32	0.33	0.27	0.94	0.93	0.46	0.45
6: Closed Shrubs	0.48	0.51	1.00	1.01	0.93	0.93	1.02	1.01
7: Open Shrubs	0.52	0.53	0.60	0.60	0.65	0.65	0.51	0.50
8: Woody Savanna	0.5	0.51	0.71	0.70	0.79	0.79	0.71	0.70
9: Savanna	0.65	0.67	0.77	0.78	0.66	0.66	0.6	0.59
10: Grassland	0.51	0.50	0.62	0.64	0.73	0.74	0.50	0.50
11: Wetland	0.35	0.36	0.23	0.24	0.76	0.76	0.46	0.45
12: Cropland	0.47	0.47	0.46	0.44	0.66	0.65	0.59	0.58
13: Urban Area	0.74	0.72	0.67	0.70	0.89	0.88	0.78	0.77
14: Crop Mosaic	0.53	0.52	0.67	0.66	0.63	0.63	0.68	0.67
15: Antarctic/Snow	0.25	0.21	0.21	0.19	0.32	0.31	0.31	0.29
16: Barren/Desert Land	0.57	0.56	0.68	0.68	0.79	0.78	0.44	0.42
18: Tundra	0.24	0.28	0.45	0.47	1.46	1.45	0.46	0.43

Table 4. Same as Table 3 except for the 8–9 μm region.

	CAMEL 2007	CAMEL Clim	CAMEL 2007	CAMEL Clim	CAMEL 2007	CAMEL Clim	CAMEL 2007	CAMEL Clim
	January 15th 2008		April 14th 2008		July 15th 2008		September 29th 2008	
1: Evg. Needle Forest	3.50	3.48	1.86	1.83	5.31	5.23	2.34	2.34
2: Evg. Broad Forest	4.99	5.01	5.22	5.18	5.94	5.94	3.03	3.04
3: Dcds. Needle Forest	2.22	2.23	5.94	5.78	9.25	9.07	1.28	1.31
4: Dcds. Broad Forest	2.20	2.23	2.19	2.25	3.28	3.16	4.13	4.15
5: Mixed Forest	1.95	1.93	1.38	1.41	5.26	5.09	2.34	2.32
6: Closed Shrubs	2.07	2.07	4.41	4.50	4.95	4.76	5.29	5.28
7: Open Shrubs	2.62	2.52	2.58	2.62	2.29	2.20	1.91	1.86
8: Woody Savanna	2.87	2.84	4.09	4.07	4.74	4.64	2.92	2.90
9: Savanna	2.89	2.84	3.68	3.69	3.87	3.76	2.12	2.01
10: Grassland	2.45	2.38	2.95	3.15	2.18	2.16	1.96	1.96
11: Wetland	1.69	1.68	1.27	1.25	3.32	3.28	2.73	2.64
12: Cropland	2.64	2.60	2.17	2.16	3.15	3.09	2.96	2.94
13: Urban Area	2.67	2.77	3.05	3.35	5.09	5.16	3.55	3.66
14: Crop Mosaic	3.22	3.17	2.98	3.02	3.58	3.46	3.44	3.40
15: Antarctic/Snow	1.28	1.28	1.16	1.17	1.54	1.56	1.80	1.83
16: Barren/Desert Land	3.02	2.96	3.03	3.00	2.79	2.75	1.90	1.86
18: Tundra	0.83	0.83	3.80	3.75	8.78	8.63	2.80	2.84

Table 5. Same as Table 3 except for the 3.6–5 μm region and only nighttime cases.

	CAMEL 2007	CAMEL Clim	CAMEL 2007	CAMEL Clim	CAMEL 2007	CAMEL Clim	CAMEL 2007	CAMEL Clim
	January 15th 2008		April 14th 2008		July 15th 2008		September 29th 2008	
1: Evg. Needle Forest	27.90	27.90	2.13	2.14	2.88	2.83	2.86	2.84
2: Evg. Broad Forest	3.68	3.66	5.41	5.34	5.32	5.27	2.28	2.23
3: Dcds. Needle Forest	187.00	186.00	15.60	15.30	5.80	5.52	2.25	2.20
4: Dcds. Broad Forest	37.10	37.00	2.39	2.41	2.59	2.48	3.50	3.47
5: Mixed Forest	82.60	82.50	1.94	1.94	3.33	3.20	2.94	2.89
6: Closed Shrubs	25.50	25.50	5.04	4.95	3.00	2.90	2.75	2.70
7: Open Shrubs	23.20	23.10	3.61	3.51	1.94	1.80	2.04	1.99
8: Woody Savanna	87.00	86.90	4.53	4.47	3.48	3.38	2.48	2.43
9: Savanna	2.85	2.88	2.89	2.81	3.32	3.20	1.66	1.59
10: Grassland	20.30	20.20	2.80	2.76	2.21	2.16	2.20	2.14
11: Wetland	92.20	92.10	15.10	15.10	3.00	2.95	2.79	2.73
12: Cropland	8.81	8.83	2.75	2.71	2.92	2.86	2.94	2.88
13: Urban Area	2.80	2.82	2.19	2.32	3.94	3.88	2.95	2.98
14: Crop Mosaic	10.90	10.90	2.71	2.69	3.22	3.13	2.76	2.69
15: Antarctic /Snow	281.00	281.00	175.00	175.00	129.00	129.00	114.00	114.00
16: Barren/Desert Land	3.71	3.55	1.70	1.56	1.91	1.79	2.08	1.95
18: Tundra	69.40	69.30	21.60	21.60	10.20	10.80	4.32	4.36

Table 3 shows de-biased BT variances for the 10–13 μm region, combined day and night for the four case days and IGBP categories. Again, results using the previous RTTOV CAMEL emissivity dataset are labeled “CAMEL 2007” and are located in the left sub-columns, and results using the new RTTOV CAMEL V002 climatology dataset are labeled “CAMEL clim” and are located in the right sub-columns. Table 3 shows that the CAMEL V002 climatology agrees well with the single year of CAMEL V001 2007.

Table 4 shows similar results for the 8–9 μm region. For all IGBP categories and each emissivity dataset, the 8–9 μm region de-biased variances are increased in comparison to the 10–13 μm region, as expected. Lastly, Table 5 shows results for the 3.6 to 5 μm region. For these results, only nighttime cases are used to avoid issues with solar contamination during the day. Again, all de-biased variances are increased in comparison to the 10–13 μm

window region results, as expected. Overall, the IGBP statistic results over the three spectral regions demonstrate that the V002 climatology is in close agreement with the CAMEL V001 single year of 2007.

7. Preliminary Comparison with ECOSTRESS

In this section, we have compared CAMEL to ECOSTRESS over three of the case sites with cloud-free ECOSTRESS acquisitions during the ECOSTRESS 5-band acquisition period. ECOSTRESS pixels and observations flagged in the accompanying quality control product have been filtered out. While the CAMEL climatology does not cover the same year as the ECOSTRESS acquisitions (2018–2019), this comparison serves as an illustration of consistency between the different instruments. A recent validation study showed that ECOSTRESS retrieved emissivities had a RMSE of 0.023 (2.3%) for all five thermal IR bands on average when compared to measured laboratory spectra of field samples [39].

Here ECOSTRESS emissivity values within a 0.05 degree block centered on the site coordinates are spatially averaged to match the CAMEL emissivity, since ECOSTRESS acquires data at a much finer 70 m resolution. For each month with multiple ECOSTRESS observations, the median ECOSTRESS emissivity value is shown in Figure 12, overlaid by the CAMEL V002 climatological emissivity and 2 sigma (95% confidence interval, or $k = 2$) uncertainty. In general, ECOSTRESS matches the CAMEL climatology well, being within the 2 sigma uncertainty, with some deviation over the Mt. Massive site, which is a heterogeneous site that may not be consistent between years.

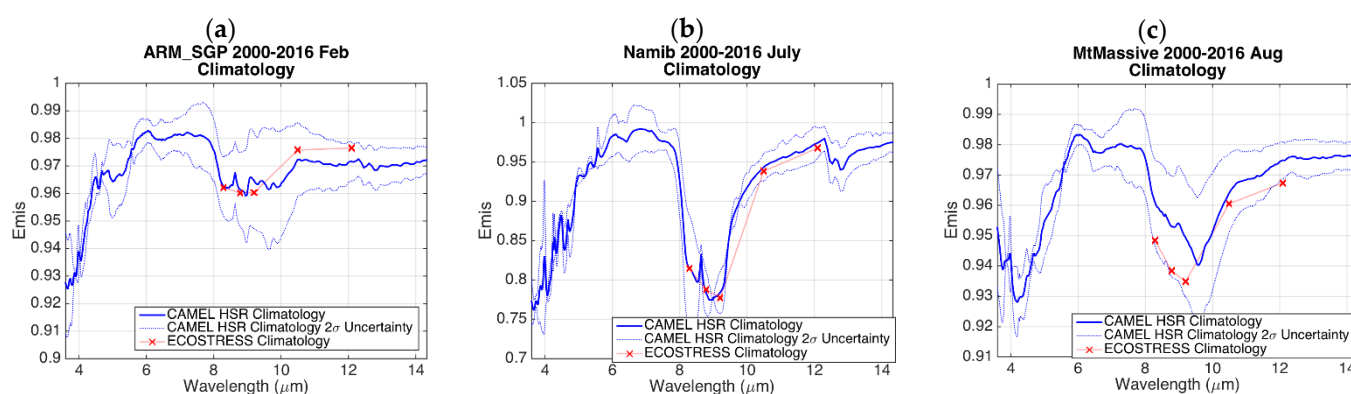


Figure 12. CAMEL HSR climatology (solid blue line) with the 2 sigma uncertainty estimate (dotted blue lines) overlaid by ECOSTRESS (red crosses) emissivity. ECOSTRESS follows the CAMEL climatology very closely over (a) ARM SGP in the month of February, and (b) the Namib site in the month of July. At (c) Mt. Massive, ECOSTRESS emissivity is significantly lower than the CAMEL climatology, potentially due to small changes in landcover over a heterogeneous site, since the two measurements do not overlap temporally.

8. Conclusions

The CAMEL Version 2 product was released in March 2019 from the NASA LP DAAC and provides global infrared land surface emissivity at 0.05 degrees (~5 km) and monthly resolution. CAMEL Version 2 provides an update to the previous Version 1, focusing on improvements over partially snow-covered scenes through the addition of two more lab datasets for use in the HSR emissivity regression. Both a 13 hinge-point and high spectral resolution product are available with uncertainty estimates for every channel and grid pixel. A climatology of the CAMEL V002 product is also now available at the same spatial, temporal, and spectral resolution and covers the CAMEL V002 record from 2000 to 2016. This climatology was detailed and illustrated in this paper.

Four selected case sites were used to show examples of emissivity characteristics over four different land cover types including quartz, carbonate, mid-latitude grassland, and a partially snowy mountainous scene. For the example month of April, while each site had distinct spectral regions of greater variation over the CAMEL record, all sites had

larger variations in the 3.6 to 5 μm region, which are likely due to incomplete correction of reflected solar radiation, with both the quartz dominant Namib Desert and carbonate dominant Yemen sites having the largest variations. Corresponding covariances for the month of April at each site highlighted correlations between the channels. The mountainous case site result highlighted the inter-channel relationships due to the influence of variable snow cover. Time series of the monthly CAMEL V002 emissivity at the four case sites revealed artifacts present in the dataset that are known to be from processing artifacts in the MODIS MYD11C3 input to CAMEL. These processing artifacts are believed to be due to issues with initialization of the MYD11C3 algorithm that affect the record over multiple years.

Statistics over IGBP land cover categories were also presented. The grouping by land cover type is important to look at due to its common use in the parameterization of emissivity in numerical modeling. In this paper, time series of the monthly mean CAMEL V002 emissivity for selected IGBP categories showed realistic seasonal changes but also revealed artifacts caused by the MODIS MYD11C3 data processing. One such type of artifact were subtle discontinuities in the data around the year 2007, which are caused by a change in the MYD11C3 Col. 4.1 algorithm—prior to the year 2007, the algorithm used the Col. 4 cloud mask and after the year 2007 it used the Col. 5 cloud mask. Additionally, the MODIS MYD11C3 emissivity decreases significantly especially in the long wave region, from January 2009 onwards, likely due to aforementioned issues with initialization of the algorithm. This decrease in the MYD11C3 emissivity is largely mitigated in the CAMEL dataset by the incorporation of the ASTER GED product, which is much more stable over the record. While the monthly CAMEL V002 dataset is still affected by some of these MODIS processing artifacts, the use of the CAMEL V002 climatology mitigates many of these time dependent errors by providing an emissivity estimate which is representative of the 16-year long record.

The use of the CAMEL V002 climatology in the RTTOV v12 emissivity module was demonstrated and was used as an assessment of the CAMEL V002 climatology. Comparisons of observed IASI BTs to calculated RTTOV IASI BTs using the current CAMEL V002 climatology and the previously used CAMEL V001 single year of 2007 were performed. De-biased variances of the calculated minus observed BTs for three thermal infrared window regions were used to measure the CAMEL emissivity's ability to reduce the spectral brightness temperature variance caused by incorrect assumptions of surface emissivity, e.g., a constant emissivity for all wavelengths. Global results for four case days representing the four seasons were broken down by the IGBP land cover categories and showed overall that the V002 climatology and V001 year 2007 are in close agreement with each other relative to the IASI observations.

Lastly, preliminary comparisons of the CAMEL V002 climatology to ECOSTRESS data provided very optimistic results. For the select case sites and months where enough ECOSTRESS data were available, ECOSTRESS agreed with CAMEL within the CAMEL 2 sigma uncertainty estimate, with an exception for the Mt. Massive case site, which can have varied ground cover from year to year. While the CAMEL V002 climatology does not cover the same years as the ECOSTRESS data (which are available starting in 2018), future comparisons of new CAMEL versions to ECOSTRESS will offer very valuable information.

While the CAMEL V002 data should not be used to create climate trends yet due to the aforementioned processing artifacts found within its inputs, it is expected that in the future, by using the latest MYD11 Collection 6.1 and the newer MYD21 and VNP21 emissivity products [10] in CAMEL, Version 3 will improve the product accuracy and reduce systematic and time dependent errors that have been identified here. In the meantime, the CAMEL V002 climatology offers more stable and representative emissivity estimates over the 2000–2016 time period than previous versions.

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