A Climatology of the Combined Aster MODIS Emissivity over Land (CAMEL) for use in NWP Data Assimilation

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Abstract

The assimilation of surface-sensitive hyperspectral infrared radiances into Numerical Weather Prediction (NWP) models will benefit from a climatology of the land surface infrared emissivity with the spatial, temporal, and spectral coverage needed for global data assimilation. A 16-year climatology has been developed at the University of Wisconsin-Madison based on the Combined ASTER MODIS Emissivity over Land (CAMEL) monthly mean dataset. The CAMEL monthly dataset was created by a NASA MEaSUREs project and is available for public distribution from a NASA data archive. The climatology described here uses the monthly CAMEL dataset to produce a statistical representation which can be used as an a priori in optimal estimation retrieval methods or as a background first guess in radiative transfer calculations. The CAMEL climatology will be released on the NASA archive as a part of the NASA MEaSUREs project sometime in 2019. The CAMEL climatology will also be included in a future release of the RTTOV radiative transfer software.

INTRODUCTION

Numerical weather prediction (NWP) models require fast radiative transfer algorithms to compute the outgoing emission spectrum at spectral resolutions and channel spacing relevant to satellite observations (Saunders et al. 1999). In the infrared portion of the spectrum both the surface skin temperature and the infrared spectral emissivity is a required input to compute the upwelling surface emission. This surface emission is transmitted through the atmosphere along a slant path where gaseous absorption and emission create additional spectral features. The molecular absorption typically creates narrow line features requiring observations with relatively high spectral resolution to separate the gaseous absorption from the more slowly varying spectral features of surface minerals and vegetation (Salisbury and D'Aria 1992; Knuteson et al. 2004). Prior to the development of global land surface emissivity datasets most NWP models used constant values of 0.98 for all infrared wavelengths. Since the launch of the NASA EOS Terra and Aqua satellites and the EUMETSAT MetOp-A satellite a more realistic representation of the spectral dependence of infrared emissivity has been derived by several groups (Capelle et al. 2012; Péquignot et al. 2008; Wan and Li 1997; Zhou et al. 2011, 2013).

In about 2006, the authors set about to create a unified infrared emissivity database that uses selected emissivity products as input and independent satellite observations for validation. In this paper, the inputs chosen are a combination of NASA MODIS and ASTER sensor narrowband measurements while the hyperspectral infrared MetOp IASI observations are used for validation via infrared radiative transfer. The current approach builds upon the successful UWiremis land surface dataset developed by the authors at the University of Wisconsin-Madison in 2007 (Seeman et al. 2008). MODIS monthly emissivity measurements produced at 5km spatial resolution by the NASA Goddard data processing facility using the Wan day/night algorithm (Wan and Li, 1997) have been extended to high resolution spectral infrared coverage using a principal component representation of measured laboratory data (Seeman et al. 2008). This dataset has been extensively used in research and operational applications primarily through incorporation into the RTTOV radiative transfer model (Borbas and Ruston 2011; Saunders et al. 1999). Subsequently, an emissivity atlas derived from the NASA/JAXA ASTER sensor was incorporated to augment the spectral coverage of the MODIS sensor in critical wavelengths and to stabilize the time dependence of the operational MODIS emissivity product. The ASTER Global Emissivity Dataset (ASTER GED) was created by authors at the Jet Propulsion Laboratory (JPL) to provide thermal emission emissivity measurements at 100 meter resolution (Hulley and Hook 2009; Hulley et al. 2015). The dataset which combines the MODIS and ASTER emissivity products is called the Combined ASTER MODIS Emissivity over Land (CAMEL) dataset (Borbas et al. 2018; Feltz et al. 2018a; Hook 2017). The product was produced with funding from the NASA MEaSUREs program. The CAMEL dataset contains 16+ years of monthly mean averaged data (2000-04-01 to 2016-12-31) at 0.05 degree resolution for non-ocean grid cells. The climatology described here uses the monthly CAMEL dataset to produce create a statistical representation which can be used as an a priori in optimal estimation retrieval methods or as a background first guess in radiative transfer calculations.

DATA

The results shown in this paper are derived from an update to the CAMEL dataset which will be available in 2019 as CAMEL V002. The CAMEL V001 is currently publicly available from NASA at the following link https://lpdaac.usgs.gov/dataset_discovery/measures/measures_products_table/cam5k30em_v001
with the following DOI: 10.5067/MEaSUREs/LSTE/CAM5K30EM.001
The CAMEL data citation is also shown in the reference list (Hook 2017). The CAMEL climatology based on V002 can be obtained prior to public release by contacting Eva Borbas (evab@ssec.wisc.edu).

RESULTS

The details of the climatology methodology will be the subject of a journal article. This conference paper includes the illustrations from the presentation at the 2018 EUMETSAT conference with some descriptive text (Knuteson et al. 2018). Figure 1 contains photos of the snow cover on Mt. Massive, Colorado for spring, early summer, and late summer. The snow and ice emissivity have a very different spectral signature from the bare minerals (quartz silicates) exposed when the snow melts. Some seasonal vegetation is also present which can also cover up the underlying mineral. Hence, we expect that the satellite observation is a linear combination of the various scene types weighted by their area coverage within the footprint.

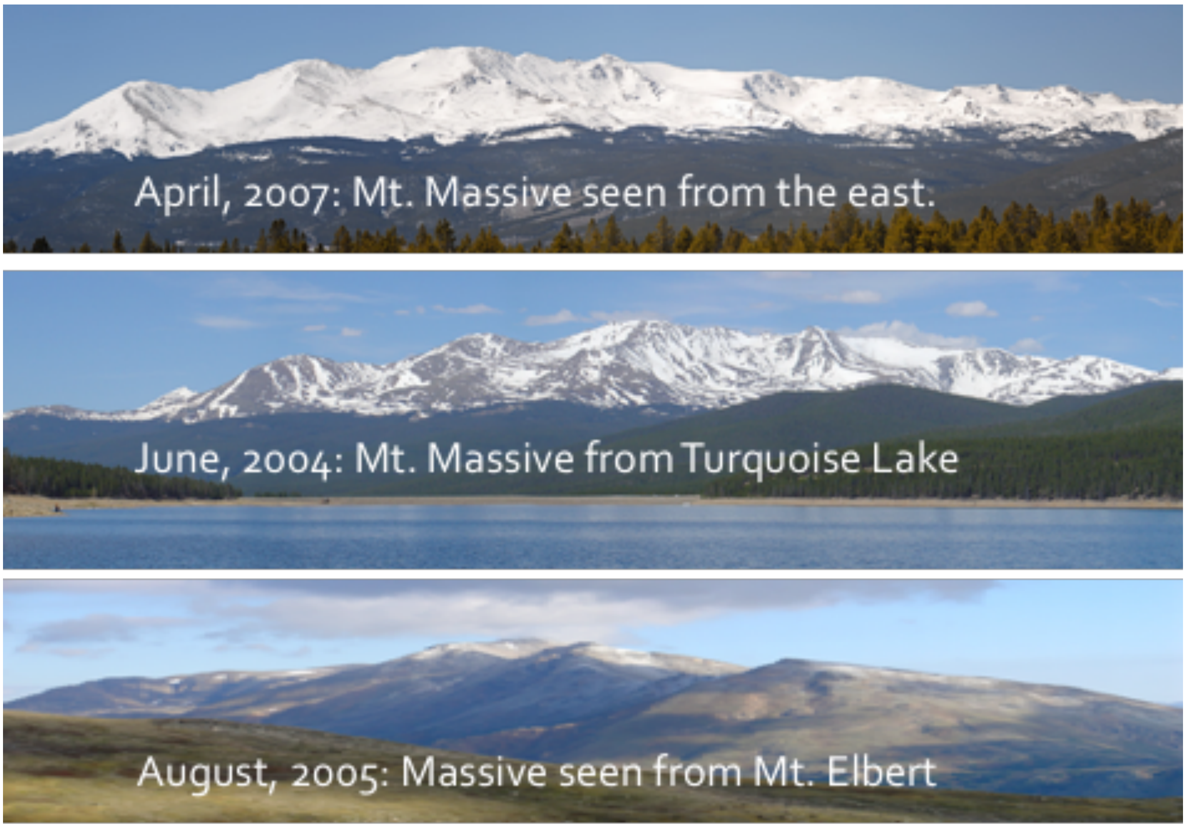

Figure 1. **Mt. Massive in Colorado USA is used as an illustration of the seasonal dependence of snow cover over bare minerals.**

The light blue lines in Figure 2 show the individual monthly emissivity spectra from the CAMEL dataset as high spectral resolution (HSR) spectra for the month of October. Figure 2 illustrates that the snow fraction over Mt. Massive varies from year to year. When the surface is snow covered the spectral emissivity is close to 0.98 for all wavelengths while in other years with snow cover between 0 and 1 there is a mixture of bare mineral and snow emissivity. The strong spectral features near 4.3 microns and 9 microns are due to the exposed bare minerals. Figure 2 shows the HSR climatological mean computed two different ways. The first is by averaging over the HSR emissivities computed for each month (noted as 'HSR Climatology' in the legend), and the second is by using the CAMEL coefficient climatology to compute an HSR emissivity (noted as 'HSR Clim from Coefs' in the legend). Since the two methods are equivalent the coefficients rather than the HSR emissivities are stored in the climatology data file to save storage space. Note that the HSR climatology computed from the 13 channel climatological mean is not the same as the mean of the HSR emissivities calculated from the individual monthly 13 channel emissivity. This is due to the fact that separate snow, vegetation, and bare mineral laboratory datasets are used in a way that depends on the monthly snow fraction amount; some datasets contain a mix of snow, vegetation, and bare minerals (0<snowfrac<1), some years only use snow and ice (snowfrac=1), and some years only vegetation plus bare minerals (snowfrac=0). The HSR climatology represents the proper averaging over the 16 year time period at high spectral resolution after projection of the monthly 13-channel emissivity into the space of laboratory spectra.

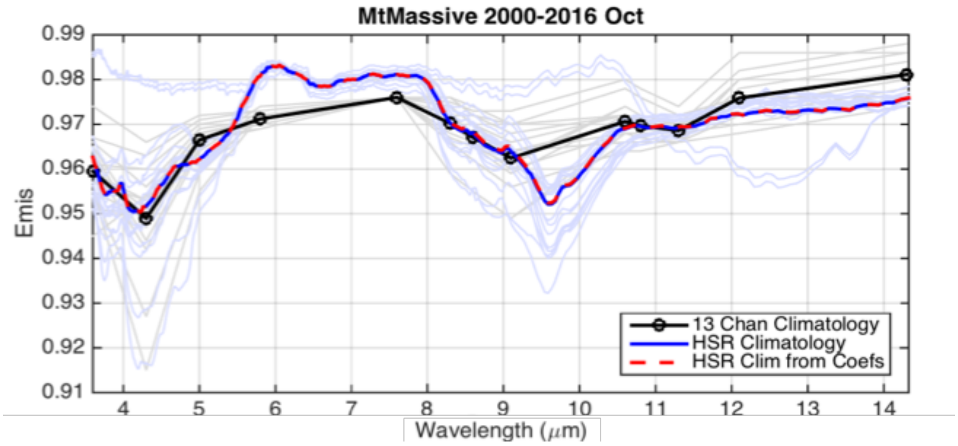

Figure 2. **Monthly emissivity spectra at Mt. Massive, Colorado from 2000-2016. The faded blue lines are the monthly emissivity spectra computed using the HSR algorithm applied to the 13-hinge point CAMEL monthly averages over 16 years.**

Figure 3 illustrates the characteristics of the CAMEL climatological mean for the Mt. Massive example. The top five panels show the time series of the infrared surface emissivity at the indicated spectral wavelengths. The 8.6 and 4.3 micron wavelengths are most sensitive to the presence of bare minerals and show a clear seasonal dependence which is strongly correlated with the MODIS snow fraction shown in the second panel from the bottom. When the snow covers the bare soil, the emissivity is higher for all wavelengths. The ASTER NDVI is also shown which indicates vegetation growth during the summer season. The bottom panel is the CAMEL identification of the laboratory datasets used to represent the emissivity types during that month. The black lines in the top five panels are the actual monthly values of the CAMEL dataset which show variation from month to month, season to season, and year to year. The dotted grey lines are the uncertainty in the CAMEL dataset as described in Feltz et al. 2018a. The red lines are the climatological mean over the 16 years for each month from January through December. The red lines repeat the same monthly climatological values for each year to provide a visual reference to illustrate which years are higher or lower than the 2000-2016 mean.

The difference between the CAMEL time series and the CAMEL climatological mean, i.e. the anomaly, is shown in Figure 4. The bottom two panels of Figure 4 are the same as in Figure 3 and indicate the presence of mountain snow cover when the snow fraction is close to 1. The top five panels are the time series anomaly overlaid with the trend fit over the 2000-2016 time period. The trends are negligibly small for all wavelengths except for the 4.3 micron channel which shows a decreasing trend. This may be due to a problem with the processing of the MODIS Day/Night emissivity product available from the NASA archive. This problem was corrected using ASTER data at 8.6 microns but ASTER does not have a 4.3 micron band and thus cannot be used to stabilize the MODIS product. This issue will be addressed in a future release of the CAMEL dataset which will replace the current Day/Night MODIS emissivity product with a TES algorithm applied to MODIS channels (e.g. MOD21).

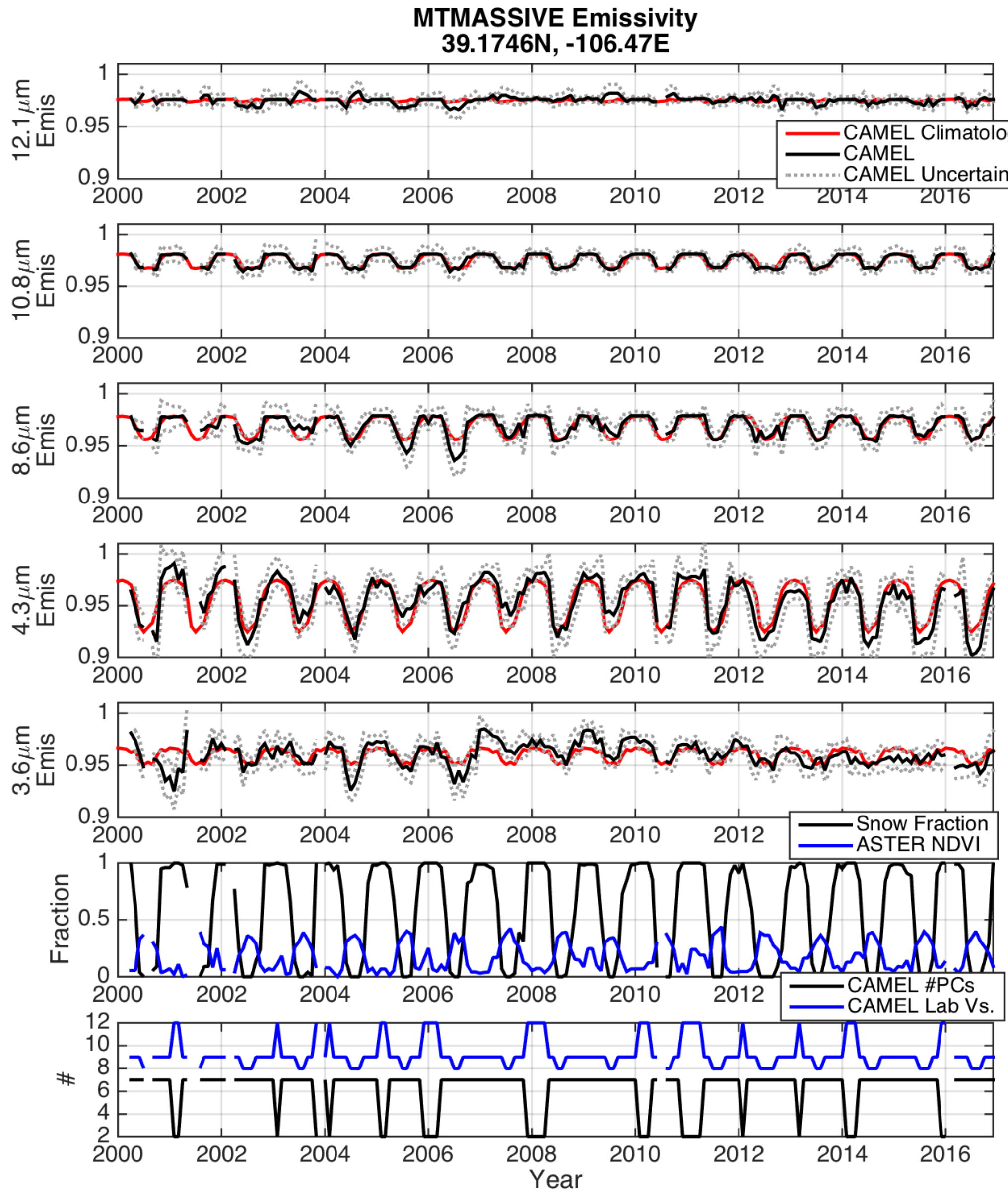

Figure 3. **Example of the CAMEL climatology computed for Mt. Massive from 2000 to 2016 for selected wavelengths.**

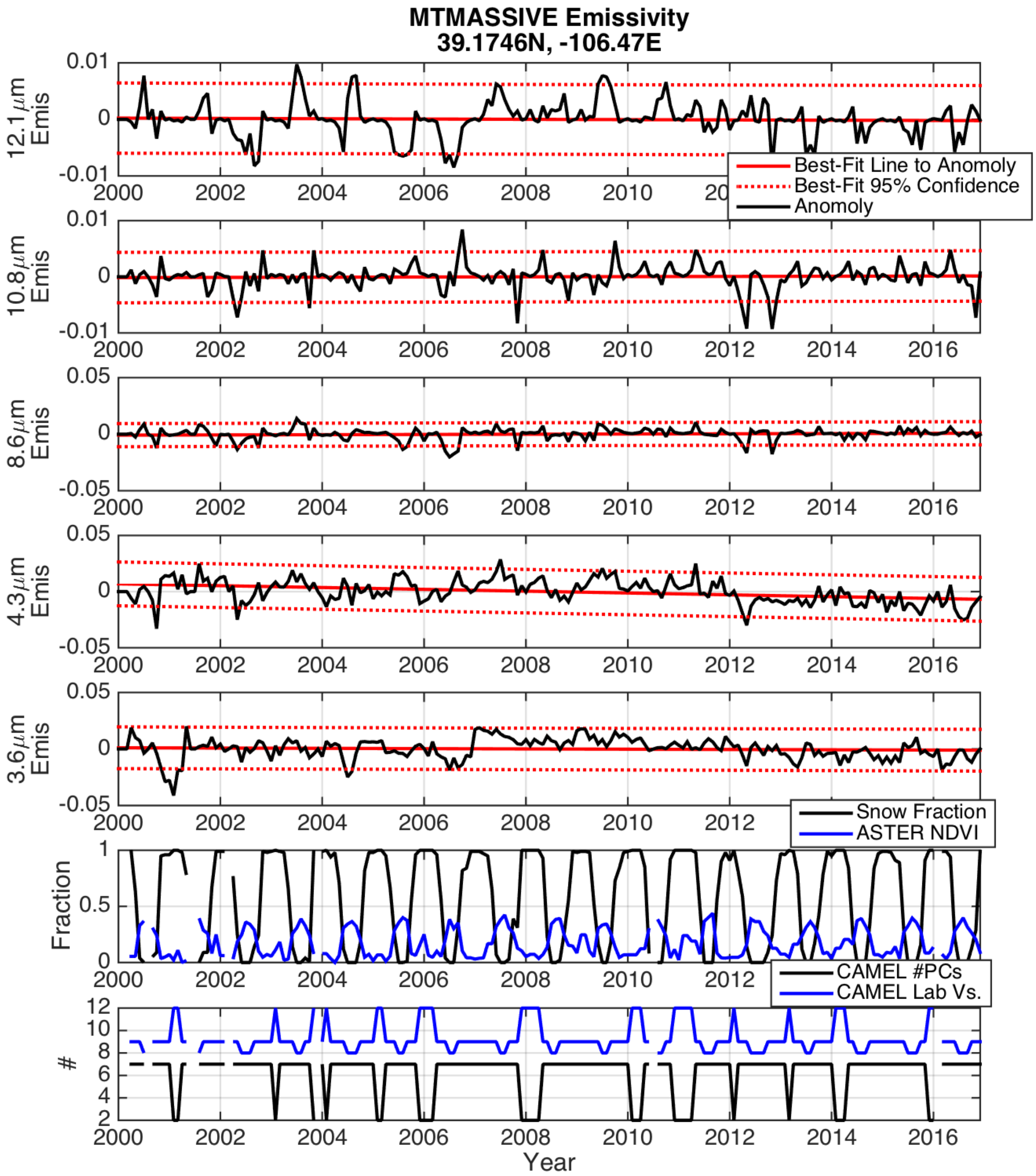

Figure 4. **Time series anomaly and trend fit for Mt. Massive from 2000 to 2016 for selected wavelengths.**

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 the RTTOV model which will contain a module for the use of the CAMEL climatology. However, for the purpose of illustration the full spectral covariance matrix is illustrated in the left panel of Figures 5 and 6. The square root of the diagonal of the matrix is shown as a line plot below the covariances matrices. Figure 5 is computed using the summer months while Figure 6 are the winter months. The largest variability in the summer is seen in the spectral regions sensitive to the bare mineral while during the winter the variability is in the longwave spectral region where the snow and ice emissivity decreases between 12 and 14 microns. Note that in the summer months the 4.3 micron and 8.6 micron region are highly correlated in the off-diagonal elements of the covariance matrix. In contrast the summer months have zero off-diagonal elements at 4.3 and 8.6 microns but the channels in the 12 to 14 micron region are strongly correlated. The proper use of inter-channel correlation of high spectral resolution infrared observations continues to be a topic of ongoing research (e.g. Campbell et al. 2017). The right hand set of panels in Figure 5 and 6 are a reconstruction of the covariance using a Singular Value Decomposition (SVD) to compress the information content of the matrix. The final product is expected to use SVD compression of the covariance matrices to save storage space.

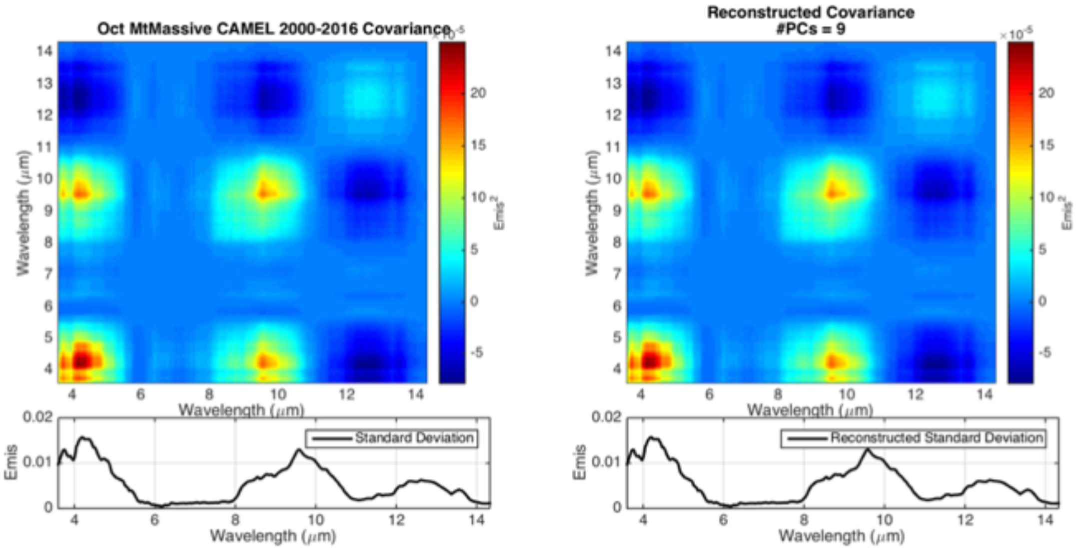

Figure 5. **Spectral covariance for Mt. Massive from 2000 to 2016 for the HSR algorithm using the full covariance (left) and a reconstruction using a compressed set of eigenvectors (right) for October (bare minerals plus vegetation).**

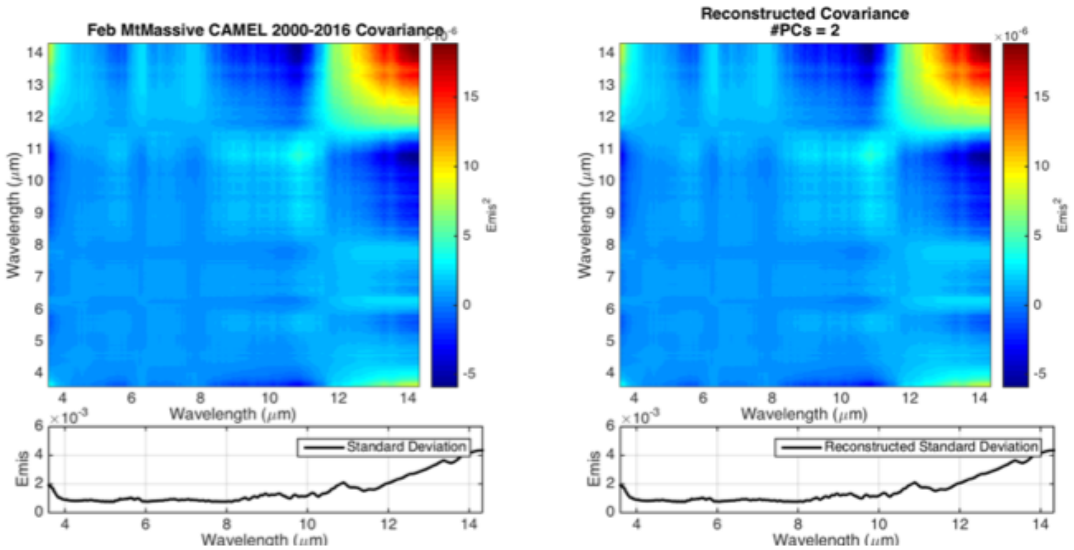

Figure 6. **Spectral covariance for Mt. Massive from 2000 to 2016 for the HSR algorithm using the full covariance (left) and a reconstruction using a compressed set of eigenvectors (right) for February (snow and ice cover).**

The initial integration of the CAMEL dataset into RTTOV was accomplished for RTTOV version 12 and is currently available for download from the UK Met Office (Saunders et al. 2018). A future version of RTTOV will include the changes indicated in Table 1. The changes include the use of CAMEL V002 which includes an improved representation of fractional snow cover and the use of the climatological mean over the 2000-2016 time period. Additional information will be available in a future EUMETSAT NWP SAF visiting scientist report.

	RTTOV12	Proposed RTTOV13 Update
EmisDB:	CAMEL V001	CAMEL CLIMATOLOGY
Spatial Res:	0.05°x0.05°	0.05°x0.05°
Inputs:	UWIREMIS BF (10) ATER-GED (5) MODIS-ASTER Lab	CAMEL V002 2000-2016
Method:	Conceptual hinge-points Method PCA regression	Conceptual hinge-points Method PCA regression
Lab data:	<u>three sets of MODIS/ASTER</u>: 55 general set 82 general+carbonates 4 ice/snow	<u>Five sets of MODIS/ASTER:</u> 55 general set 59 general set+4 ice/snow 82 general+carbonates 86 general+carbonates+4 ice/snow 4 ice/snow
Outputs	Emissivity and error covariance matrix on Instrument spectra	Emissivity, uncertainty and error covariance matrix on Instrument spectra

***Table 1.* Summary of the status of the CAMEL emissivity module as incorporated into RTTOV.**

CONCLUSIONS

The CAMEL database has been created by merging the widely-used UW MODIS-based baseline-fit emissivity database (UWIREMIS) developed at the University of Wisconsin-Madison, and the NASA ASTER Global Emissivity Database (ASTER GED V4) produced at JPL. The first version of the CAMEL database is publicly available globally for the period 2001 through 2016 at 5 km spatial resolution in mean monthly time-steps for 13 spectral bands from 3.6-14.3 micron (Borbas et al. 2018). An algorithm to create high spectral resolution land surface emissivity spectra (417 channels) is also provided for hyperspectral infrared applications. The dataset has been evaluated using 1) data from a global sampling of validation sites, 2) the IASI Emissivity Atlas of Zhou et al. (2013), and 3) through simulated IASI brightness temperatures in the RTTOV forward radiative transfer model (Feltz et al. 2018a). In addition, the CAMEL dataset includes an uncertainty product that combines temporal, spatial, and algorithm variability as part of a total uncertainty estimate for each emissivity spectrum.

To facilitate the use of the CAMEL database in NWP 1-D Var data assimilation, a January-December monthly climatology has been created for use by NWP models. This climatology is intended to provide a high spectral resolution mean infrared emissivity spectra for the 16+ year time period 2000 to 2016 on a spatial grid of 0.05 degree (about 5 km x 5 km). This climatology can be degraded to NWP model resolutions to make it suitable for a first guess to the land surface emissivity for 1-D var data assimilation of infrared sensor data. A self-consistent broadband emissivity (BBE) is also available for use in NWP land surface models (Feltz et al, 2018b).

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