Remote Sensing of Environment 113 (2009) 1313–1318

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Intercomparison of versions 4, 4.1 and 5 of the MODIS Land Surface Temperature and Emissivity products and validation with laboratory measurements of sand samples from the Namib desert, Namibia

Glynn C. Hulley *, Simon J. Hook

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

ARTICLE INFO

Article history:
Received 15 January 2009
Received in revised form 17 February 2009
Accepted 18 February 2009

Keywords:
Emissivity
Land surface temperature
MODIS
Validation
Thermal infrared
Namib

ABSTRACT

Eight new refinements were implemented in the MODIS Land Surface Temperature and Emissivity (LST&E) product suite when transitioning from version 4 (V4) to version 5 (V5). The refinements were designed to improve the spatial coverage, stability, and accuracy of the product suite. Version 4.1 (V4.1) is an interim collection which uses V5 input products (MOD02, MOD03, MOD07, MOD10, and MOD35), but the LST&E retrieval algorithm is unchanged from V4 in which the split-window and day/night temperature retrieval algorithms are only partially incorporated, and not fully incorporated as in V5. A test dataset for the V4.1 product was produced by MODAPS for a 3-month period from July through September 2004, and after an initial evaluation period, it was decided to generate the V4.1 product from mission period 2007001 onwards as a continuation of previous years of V4 data. This paper compares MODIS retrieved surface emissivities between V4, V4.1 and V5 using the level-3 MODIS daily LST&E product, MOD11B1.Comparisons of MOD11B1 retrieved surface emissivity during the Jul–Sep 2004 test period with lab measurements of sand samples collected at the Namib desert, Namibia result in a combined mean absolute emissivity difference for bands 29 (8.55 μm), 31 (11 μm) and 32 (12 μm) of 1.06%, 0.65% and 1.93% for V4, V4.1 and V5 respectively. Maximum band 29 emissivity differences with the lab results were 4.10%, 2.96% and 8.64% for V4, V4.1 and V5 respectively. These results indicate that over arid and semi-arid areas, users should consider using MODIS V4 or V4.1 data instead of V5. Furthermore, users should be careful not to develop time series from a mixture of product versions that could introduce artifacts at version boundaries.

© 2009 Published by Elsevier Inc.

1. Introduction

Land Surface Temperature and Emissivity products (LST&E) are generated by spaceborne sensors such as the Atmospheric Infrared Sounder (AIRS) (Susskind et al., 2003), the Moderate-Resolution Imaging Spectrometer (MODIS) (Wan, 2008) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Gillespie et al., 1998; Hulley et al., 2008). LST&E products are key parameters in land surface processes, climate modeling, and surface–atmosphere interactions. For example, hydrologists and ecologists use land surface temperature information to study evapotranspiration, desertification, and deforestation; climate modelers use emissivity to compute surface radiation budgets (Zhou et al., 2003; Jin & Liang, 2006) and in surface–atmosphere interactions, errors in the retrievals of atmospheric temperature and moisture profiles are strongly dependent on the accuracy of the surface emissivity (Li et al., 2007). An emissivity error of 1.5% at 8.6 μm will result in a surface temperature error of approximately 1 K, for a material at 300 K. Generating reliable and consistent long-term series of LST&E products are critical for the broad scientific community in monitoring and better understanding land-use and land-cover change and potential impacts of climate variability. Consequently, the impacts of version changes for LST&E products from sensors such as MODIS need to be well characterized so that users can understand the impact of any version changes on their studies. In this study we have analyzed the temporal and spatial variations of the MOD11B1 LST&E product for versions 4, 4.1, and 5, and validated each product version with laboratory emissivity measurements of sand samples collected at the Namib desert in Namibia.

2. MOD11B1 product

The MOD11B1 product is a daily level-3 LST&E product in a sinusoidal projection with a spatial resolution of 5 km (exactly 4.63 km) for V4 and V4.1, and 6 km (exactly 5.56 km) for V5 (Wan, 2008). The change in spatial resolution from V4 to V5 was made to avoid re-sampling in the latitude direction when computing the MOD11C3 Climate Model Grids (CMG). The MOD11C3 product provides monthly averaged LST&E values at 0.05° spatial resolution

* Corresponding author. Jet Propulsion Laboratory, 4800 Oak Grove Dr, Pasadena, CA, 91109, USA.
E-mail address: glynn.hulley@jpl.nasa.gov (G.C. Hulley).

0034-4257/$ – see front matter © 2009 Published by Elsevier Inc.
doi:10.1016/j.rse.2009.02.018

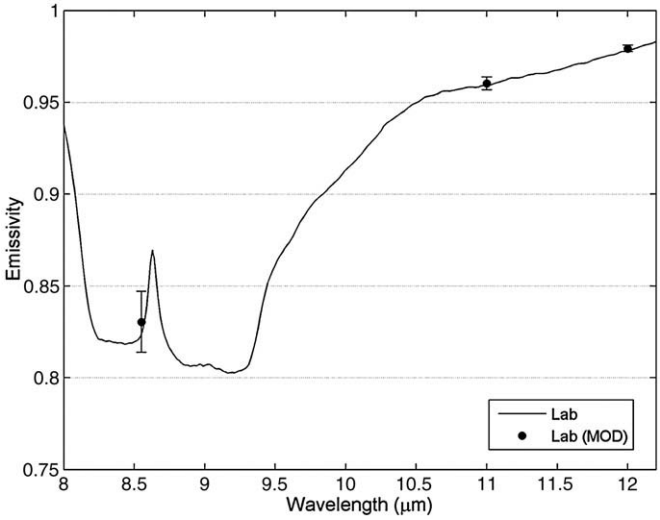

Fig. 1. Laboratory mean emissivity spectra of eight sand samples from the Namib desert (solid line), and the mean emissivity and standard deviation of the eight samples convolved to the MODIS spectral response functions for bands 29 (8.55 μm), 31 (11 μm) and 32 (12 μm) (errorbars).

and is not used in this analysis since the spatial re-sampling and temporal averaging can obscure and complicate the biases and uncertainties between the different product versions.

The results presented here use the MOD11B1 product, tile h19v11, covering Namibia and parts of Botswana and South Africa with geographic coordinates at top left (20.00° S, 10.65° E), top right (20.00° S, 21.28° E), bottom right (30.00° S, 11.55° E) and bottom left (30.00° S, 23.09° E). One tile contains 240 × 240 pixels in V4 and V4.1 and 200 × 200 pixels in V5. In order to facilitate comparison with ground measurements, the data were re-projected from sinusoidal to geographic latitude/longitude. Bad observations were removed using the Quality Control (QC) information included with the MOD11B1 product (MODIS LST Users guide, 2006). Observations were removed if, (1) the LST was not produced due to cloud effects or other reasons, (2) the LST was affected by nearby cloud or ocean and (3) the emissivity error flag indicated the average emissivity error was greater than 0.04 (4%). In this assessment, MODIS retrieved surface emissivity data from TIR bands 29, 31, and 32 centered on 8.55, 11, and 12 μm respectively will be used for comparisons and validation.

3. Validation data

3.1. The Namib desert

The Namib desert in Namibia forms part of the Naukluft-Namib National Park that occupies 80,900 km^2 and comprises some of the

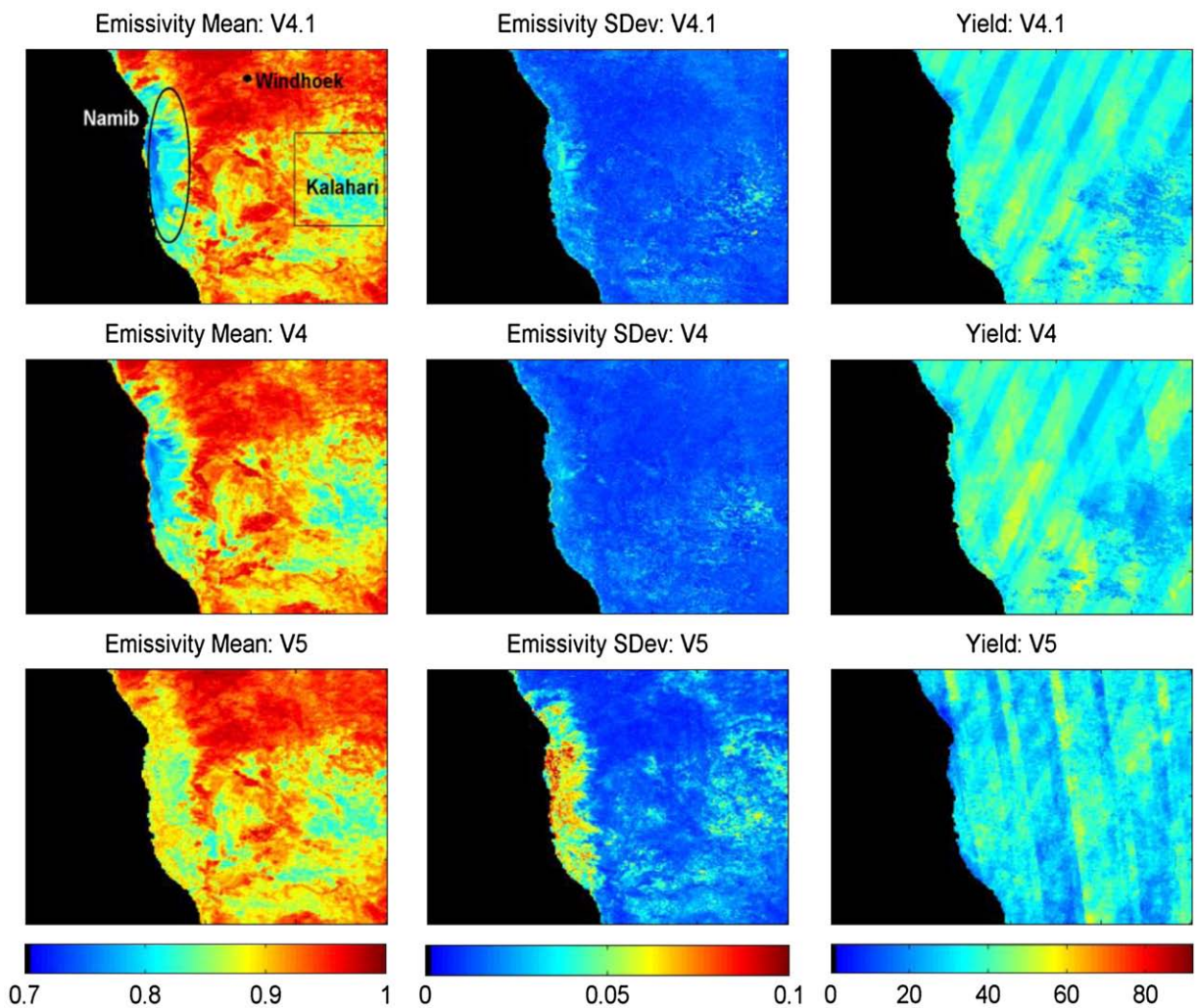

Fig. 2. Mean emissivity (left panels), standard deviation in emissivity (middle panels), and total yield (right panels) using MOD11B1 tile h19v11 for band 29, and for version 4.1 (top panels), 4 (middle panels), and 5 (bottom panels) from July to Sep, 2004.

oldest (55 million years) and highest (300 m) dunes in the world. The dunes are primarily composed of sand-sized particles of quartz, with traces of hematite—an iron mineral which gives the dunes a dark red color. The Namib is a hyper-arid ecoregion and receives a low and highly unpredictable annual rainfall of between 5 mm in the east and 85 mm in the west (Lovegrove, 1993). The vast expanse of shifting dunes are almost completely devoid of vegetation except for sparse perennial grasses (White, 1983). These factors contribute to the overall stability of the dunes in terms of their spatial uniformity and temporal stability, making them an ideal target for the long-term calibration and validation of remote sensing data (Bannari et al., 2005).

3.2. Laboratory measurements

During July 2008, eight sand samples were collected at Sossussvlei in the Naukluft-Namib Park, an area famous for its 300 m high dunes and one of the few accessible areas available to the public. Four samples were collected on a dune crest at approximately 24.693° S, 15.489° E, and four on an interdune area at 24.699° S, 15.474° E. The directional hemispherical reflectance of the samples were measured in the lab at JPL using a Nicolet 520 FTIR spectrometer with incident angle fixed at 10° from nadir (Baldridge, Hook, Grove, & Rivera, 2009). The reflectance was then converted to emissivity using Kirchhoff's law and convolved to the MODIS spectral response functions for bands 29 (8.55 μm), 31 (11 μm) and 32 (12 μm). The uncertainty associated with the FTIR lab emissivities is 0.002 (0.2%), but larger deviations from Kirchhoff's law do occur due to steep thermal gradients in the infrared skin depth, from fine volcanic ash for example (Korb et al., 1999). Fig. 1 shows the lab mean emissivity spectra of the eight sand samples in the 8–12 μm range (black line), and the mean emissivity and standard deviation convolved to MODIS bands 29, 31, and 32 (circles with errorbars).

4. Results and discussion

Fig. 2 shows the MOD11B1 tile h19v11 mean emissivity and standard deviation for band 29 (8.55 μm), and the total number of observations (yield) used during the 92-day period from July to Sep, 2004 for V4.1 (top panels), V4 (middle panels), and V5 (bottom panels). The results indicate that the emissivity for V4.1 and V4 are comparable in magnitude, spatial variability and total yield over arid regions of the Namib and Kalahari desert (areas indicated in Fig. 2) and over vegetated areas south of Windhoek in the Highland savanna region. The V5 emissivity results are similar to V4 and V4.1 over vegetated areas, but have higher emissivities of up to 20% and larger temporal variations of approximately 10% over parts of the Namib desert (Fig. 2).

The results for band 32 (12 μm) in Fig. 3 show a similar pattern, with V4.1 and V4 emissivities matching closely over arid regions,

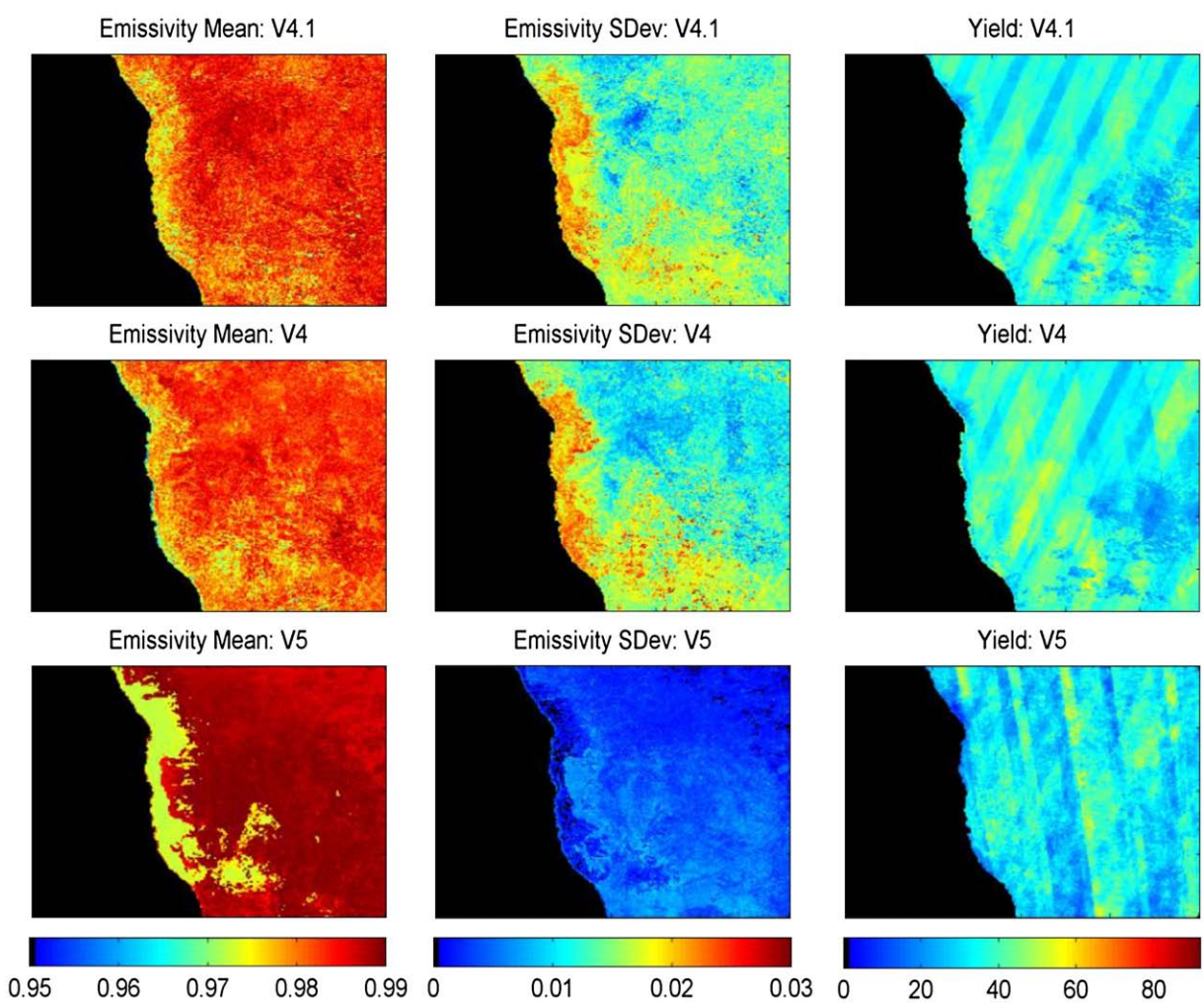

Fig. 3. Same as Fig. 2 except that results are for band 32.

although it appears V4.1 has slightly larger emissivities over vegetated regions than V4. The V5 results show a distinct step from emissivity values over the Namib, to more vegetated shrublands to the east. This artificial discontinuity in emissivity is a direct consequence of the tighter coupling of the split-window and day/night LST retrieval algorithms (Wan & Dozier, 1996; Wan & Li, 1997) in V5 in which emissivities are based on using a land-cover classification approach. Over vegetated regions, V5 emissivities are generally higher than V4 and V4.1 in band 32 and with lower temporal variations (0.5%) when compared to V4 and V4.1 which have larger fluctuations of up to 3% over the Namib.

Spatial and temporal emissivity changes over the Namib for the Jul–Sep period were analyzed by extracting all MOD11B1 pixels over a 0.5°×0.5° test area just north of Sossussvlei between coordinates: 24–24.5° S and 15–15.5° E. Temporal variations are expected to be low for the Jul–Sep period due to infrequent winter rainfall over this area and the absence of fog, which is common along the coastal areas to 50 km inland. Spatial variations in emissivity, expected to be small, would depend on the varying sand mineralogy between dune crests and interdunal areas, and also sparse vegetation cover. The spatial uniformity over the 0.5°×0.5° test area was first assessed by computing the coefficient of variation (CV) using band 11 (8.6 μm) Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) TIR emissivity data at 90 m spatial resolution. The CV is a good measure of dispersion and is defined as the ratio of standard deviation over the average for a given quantity. Using the ASTER data, a 5×5 pixel window (~500×500 m) was used to compute CV over the test area with a sampling step of 500 m. The average CV for fourteen mosaicked ASTER scenes covering the test area was 0.63%, where CV values less than 2% are generally considered to be low-variance (Bannari et al., 2005). Furthermore, the lab emissivity spectra of the eight sand samples also had a small variance in emissivity, with standard deviations of 1.6% for band 29, 0.36% for band 31, and 0.18% for band 32 (Fig. 1). From these two results we can conclude that the lab emissivity spectra of the sand samples should be a reasonably good approximation of the effective emissivity over the test area.

Figs. 4 and 5 show a time series of daily mean MOD11B1 emissivity in bands 29 and 31 over the Sossussvlei test area, with errorbars indicating the spatial variability for versions V4.1, V4 and V5. Fig. 6 shows the percent spatial coverage for each product version after the quality control bits were applied. Only data points with percent spatial coverage greater than 10% over the 0.5°×0.5° area were used for the analysis. The solid lines in Figs. 4 and 5 are the mean emissivity of the eight lab spectra convolved to the appropriate MODIS spectral response function. The results in Table 1 for band 29 indicate that V4.1 and V4 have similar temporal (1.33% and 0.94% respectively) and mean spatial variations (3.32% and 2.61%), whereas V5 has much larger fluctuations with a temporal variation of 2.45% and mean spatial variation of 5.71%. Band 31 emissivities for V5 are on average higher by 1.68% when compared to the lab results, and roughly three times larger than V4 and V4.1. Mean absolute differences of all three bands with the lab results indicate that V4.1 performs the best with a 0.65% difference, followed by V4 with 1.06%, and V5 with 1.93%. It should be noted that isolating and identifying the specific causes of

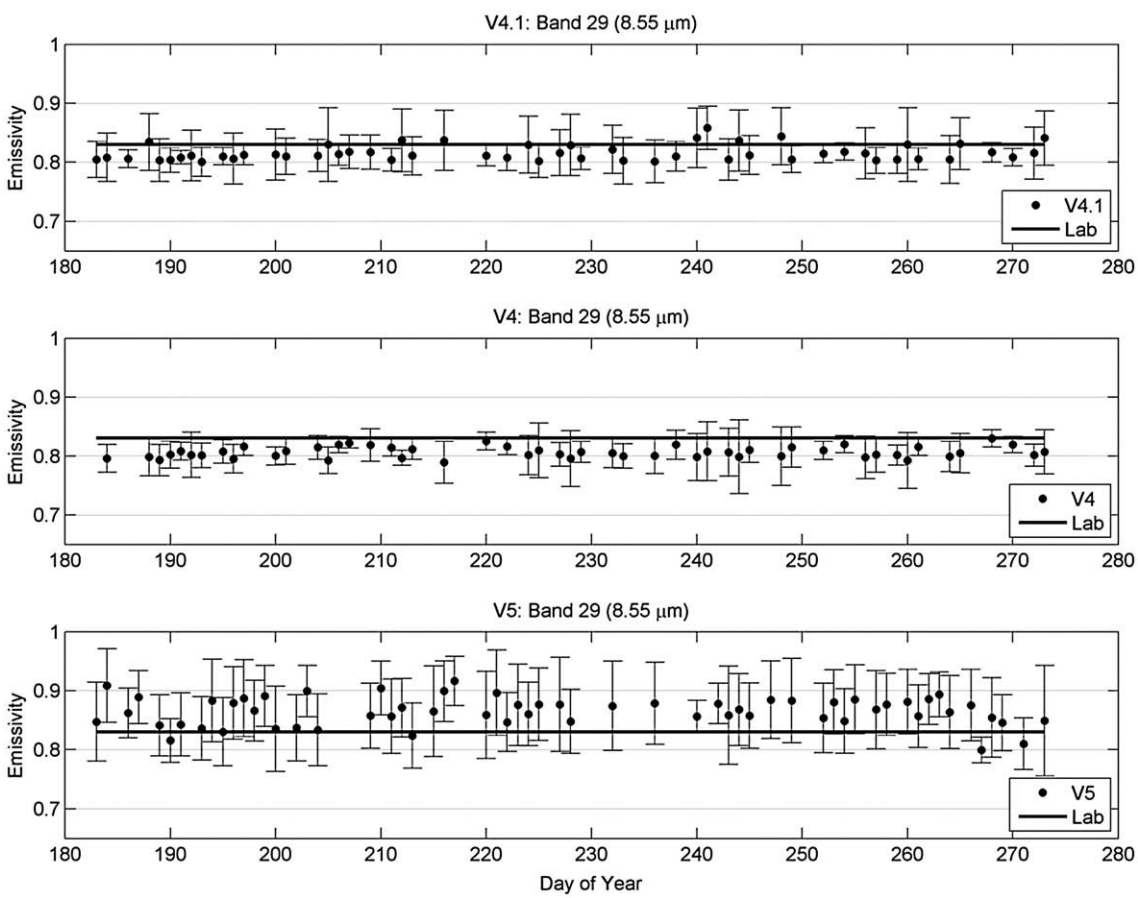

Fig. 4. Time series of MOD11B1 mean emissivity for band 29 from July 1 to Sep 30, 2004 with errorbars indicating the spatial variability within a 0.5°×0.5° test area over the Namib dunes for V4.1 (top), 4 (middle) and 5 (bottom). The *x*-axis shows the day of year from July through September, 2004. The solid line shows the mean lab emissivity of eight sand samples collected at Sossussvlei in the Namib desert, and convolved to the MODIS spectral response function for band 29.

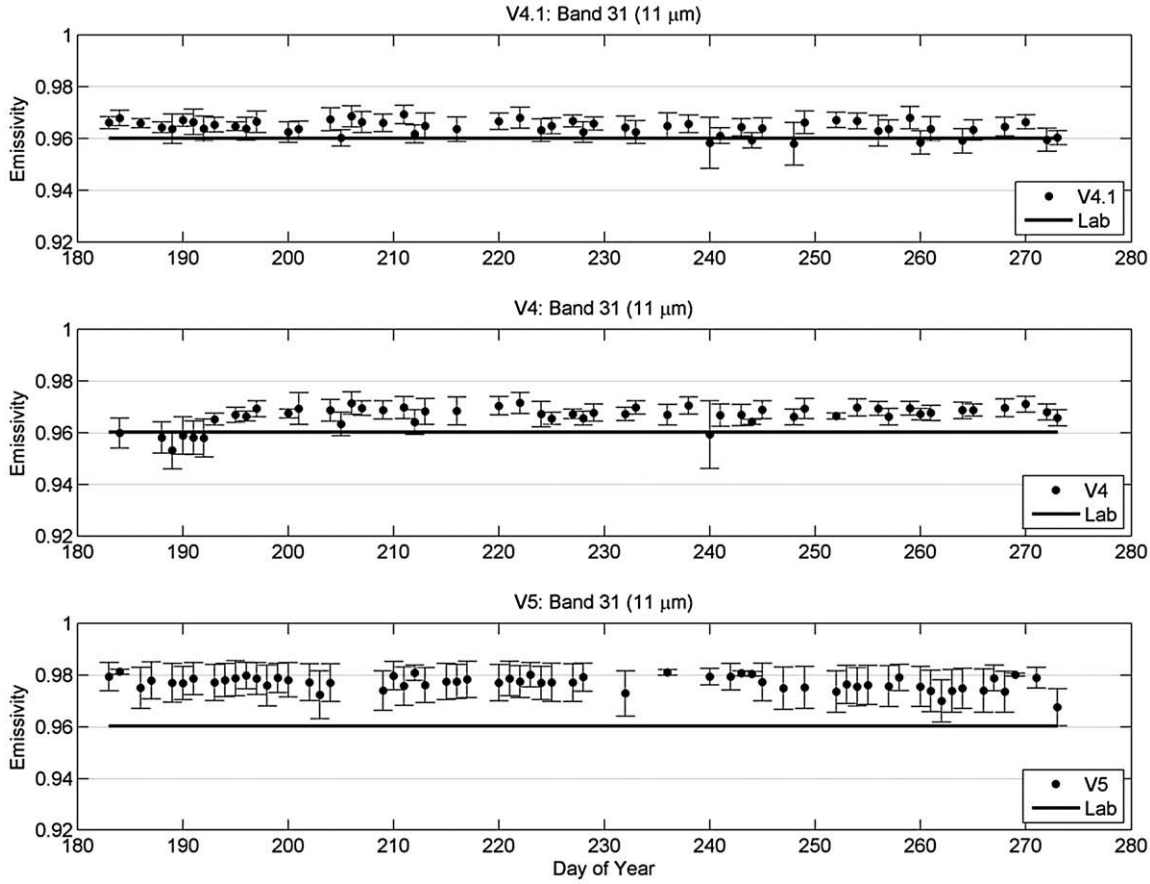

Fig. 5. Same as Fig. 4 except that results are for band 31.

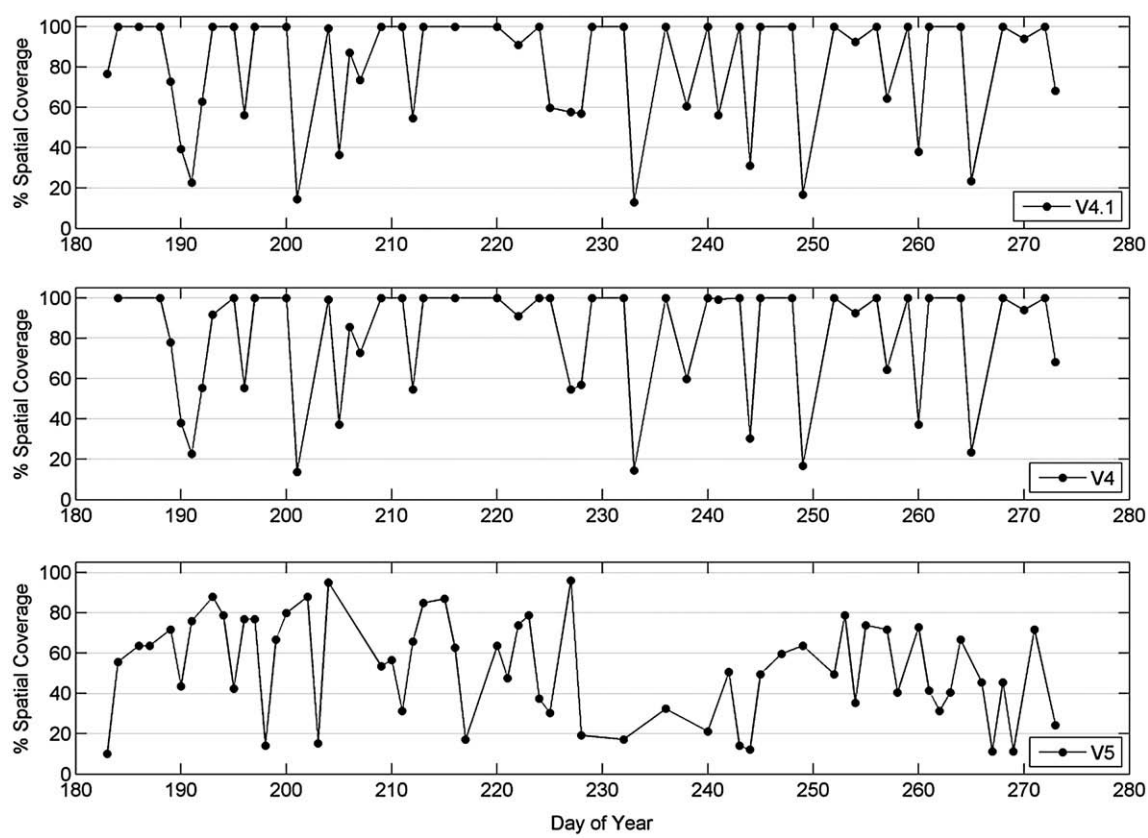

Fig. 6. Percent spatial coverage for MOD11B1 retrieved emissivity pixels for the 0.5° × 0.5° test area after quality control bits were applied.

differences in temporal variability between the three product versions is difficult due to their varying spatial coverage, different viewing angles, and different cloud mask settings in the MODIS LST retrieval algorithms.

Fig. 7 shows the emissivity spectra for all versions, combined with the lab results which are convolved to the MODIS bandwidths. Errorbars show the mean and temporal standard deviation in emissivity over the three-month period. From the figure it is clear the V5 has higher emissivities in all bands when compared to the lab, V4.1, and V4 results, and also larger variation in band 29.

5. Conclusions

Comparisons of the daily MOD11B1 emissivity product with lab measurements of field samples collected over the Namib desert, Namibia indicates that the V4.1 emissivity values most closely match the lab results with a combined mean absolute difference of 0.65% using bands 29, 31, and 32, followed by V4 with 1.06% and V5 with a 1.93% difference. These results indicate that the full incorporation of the split-window with the day/night algorithm in V5 degrades the accuracy of the derived emissivities over arid and semi-arid regions. A similar, tightly coupled land classification scheme is planned for use in the LST&E products from the VIIRS instrument (MODIS follow-on) and will likely yield equally problematic results over desert regions. In summary, V4x emissivities for band 29 are more accurate and stable than V5 over desert regions, although V4x band 32 emissivities are more unstable with larger fluctuations than in V5. V5 emissivities over desert regions are overestimated (LST underestimated) in all bands when compared to the lab results, although they may be more accurate and stable over water and vegetated areas. Lastly, V4.1 LST&E products from 2007 onwards will be consistent with previous years of V4 data, and great care should be taken to avoid mixing data from V4 and V5.

Acknowledgements

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under the contract with the National Aeronautics and Space Administration. We kindly thank Peter and Anne Hulley for providing the Namib dunes sand samples from Namibia. The geolocation code for the MOD11B1 tiles was provided by Dr. Zhengming Wan from the University of California Santa Barbara, and developed by Sadashiva Devadiga from NASA Goddard Space Flight Center.

Table 1
Emissivity statistics for MOD11B1 V4.1, V4 and V5 products over the Sossussvlei area (24°–24.5° S, 15°–15.5° E) for the July–Sep, 2004 time period.

Version	Band	ε_m	$\delta\varepsilon_s$ (%)	$\delta\varepsilon_t$ (%)	$\varepsilon_{lab}-\varepsilon_m$ (%)
V4.1	29	0.816	3.32	1.33	1.44
	31	0.964	0.39	0.28	−0.41
	32	0.978	1.61	0.75	0.10
$\lvert\varepsilon_{lab}-\varepsilon_m\rvert_{avg}$					0.65
V4	29	0.806	2.61	0.94	2.41
	31	0.967	0.39	0.40	−0.64
	32	0.981	1.53	0.79	−0.12
$\lvert\varepsilon_{lab}-\varepsilon_m\rvert_{avg}$					1.06
V5	29	0.865	5.71	2.45	−3.45
	31	0.977	0.63	0.27	−1.68
	32	0.986	0.72	0.30	−0.66
$\lvert\varepsilon_{lab}-\varepsilon_m\rvert_{avg}$					1.93

Values are the emissivity mean (ε_m), spatial standard deviation ($\delta\varepsilon_s$), temporal standard deviation ($\delta\varepsilon_t$), difference with the lab results ($\varepsilon_{lab}-\varepsilon_m$), and average of the absolute differences in all bands ($\lvert\varepsilon_{lab}-\varepsilon_m\rvert_{avg}$). Bands 29, 31, and 32 are centered on 8.55 μm, 11 μm, and 12 μm respectively.

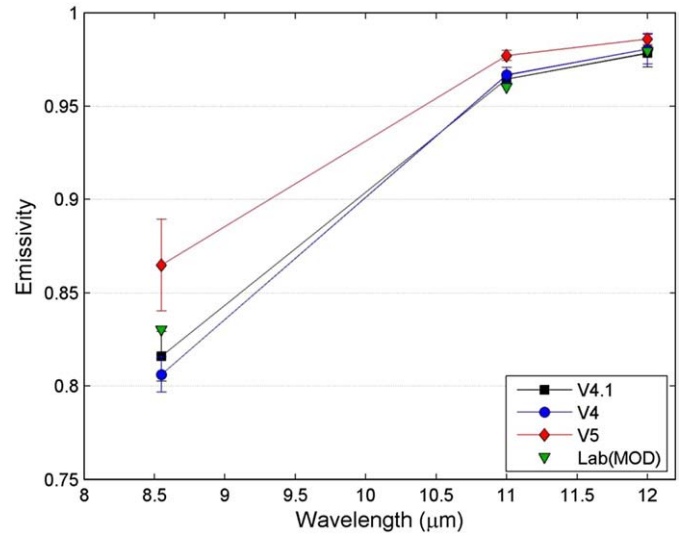

Fig. 7. Mean MOD11B1 emissivity for V4.1 (black), V4 (blue), V5 (red) and the convolved lab measurements (green). Errorbars show the mean and temporal standard deviation in emissivity for the Jul–Sep period for an area over Sossussvlei, Namibia.

References

Baldridge, A. M., Hook, S. J., Grove, C. I., & Rivera, G. (2009). The ASTER spectral library version 2.0. *Remote Sensing of Environment*, *113*(4), 711−715.

Bannari, A., Omari, K., Teillet, P. M., & Fedosejevs, G. (2005). Potential of Getis statistics to characterize the radiometric uniformity and stability of test sites used for the calibration of Earth observation sensors. *IEEE Transactions on Geoscience and Remote Sensing*, *43*(12), 2918−2926.

Gillespie, A. R., Rokugawa, S., Hook, S., Matsunaga, T., & Kahle, A. B. (1998). A temperature and emissivity separation algorithm for Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images. *IEEE Transactions on Geoscience and Remote Sensing*, *36*, 1113−1126.

Jin, M., & Liang, S. (2006). Improving land surface emissivity parameter of land surface models in GCM. *Journal of Climate*, *19*, 2867−2881.

Hulley, G. C., Hook, S. J., & Baldridge, A. M. (2008). ASTER land surface emissivity database of California and Nevada. *Geophysical Research Letters*, *35*, L13401. doi:10.1029/2008GL034507

Korb, A. R., Salisbury, J. W., & D'Aria, D. M. (1999). Thermal-infrared remote sensing and Kirchhoff's law. 2. Field measurements. *Journal of Geophysical Research*, *104*(B7), 15,339−15,350.

Li, J., Li, J., Weisz, E., & Zhou, D. K. (2007). Physical retrieval of surface emissivity spectrum from hyperspectral infrared radiances. *Geophysical Research Letters*, *34*, L16812. doi:10.1029/2007GL030543

Lovegrove, B. (1993). *The living deserts of southern Africa.* Vlaeberg: Fernwood Press.

MODIS LST User Guide (2006). http://www.icess.ucsb.edu/modis/LstUsrGuide/usrguide.html

Susskind, J., Barnet, C. D., & Blaisdell, J. M. (2003, Feb). Retrieval of atmospheric and surface parameters from AIRS/AMSU/HSB data in the presence of clouds.*IEEE Transactions on Geoscience and Remote Sensing*, *41*(2) (EOS Aqua Special Edition).

Wan, Z. (2008). New refinements and validation of the MODIS Land-Surface Temperature/Emissivity products. *Remote Sensing of Environment*, *112*, 59−74.

Wan, Z., & Dozier, J. (1996). A generalized split-window algorithm for retrieving land-surface temperature from space. *IEEE Transactions on Geoscience and Remote Sensing*, *34*, 892−905.

Wan, Z., & Li, Z. -L. (1997). A physics-based algorithm for retrieving land-surface emissivity and temperature from EOS/MODIS data. *IEEE Transactions on Geoscience and Remote Sensing*, *35*, 980−996.

White, F. (1983). *The vegetation of Africa, a descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa (3 plates, Northwestern Africa, Northeastern Africa, and Southern Africa, 1:5,000,000).* Paris: UNESCO.

Zhou, L., Dickinson, R. E., Tian, Y., Jin, M., Ogawa, K., Yu, H., et al. (2003). A sensitivity study of climate and energy balance simulations with use of satellite derived emissivity data over the northern Africa and the Arabian peninsula. *Journal of Geophysical Research*, *108*(D24), 4795. doi:10.1029/2003JD004083