Visible Infrared Imaging Radiometer Suite (VIIRS) Land Surface Temperature and Emissivity Product (VNP21) User Guide

Collection 2

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Note:

The primary purpose of this User Guide is to provide an overview of the new VIIRS Land Surface Temperature and Emissivity (LST&E) product (VNP21) to potential users. For more algorithm-specific details, please consult the Algorithm Theoretical Basis Document (ATBD). This User Guide is designed to serve as a living document that describes the current state-of-the-art, and is revised as we evaluate and further develop the LST&E product.

Change History Log

Revision	Effective Date	Modifications by	Description of Changes
First Draft	12/06/2016	Glynn Hulley, Robert Freepartner	First draft of User Guide C1 for VNP21 products based on the VNP21 product
Draft	5/25/2017	Glynn Hulley	Updated to include detail of NRT processing with NCEP GFS data
Draft	06/29/2017	Glynn Hulley	Minor edits to fix mismatches between User Guide metadata and product metadata
Draft	08/15/2017	Glynn Hulley	Incorporation of feedback from Bhaskar and Sadashiva from MODAPS. Updates to references
Draft	05/08/2018	Glynn Hulley	Change LST valid max range from 20000 to 65535 to be consistent with MODIS. Included metadata field to signify which NWP data source (MERRA2 or NCEP) was used.
Draft	05/23/2018	Glynn Hulley, Robert Freepartner	Added 'NWPSource' to metadata
Draft	07/24/2018	Robert Freepartner	Corrections to Fill Values in 2.2
Draft	08/20/2018	Robert Freepartner	Corrections to metadata details
Draft	09/05/2018	Glynn Hulley	Minor correction to metadata (MMD) and typos
Draft	11/2/2018	Jaime Nickeson Glynn Hulley	Typos, clarity, other editing. Included 'lunar intrusion' as reason for missing/bad L1B in QC
Final	06/24/2021	Glynn Hulley	Added sections 5,-8 describing the new CMG products in C2 and comparisons with the J1 equivalent products.

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1 Introduction

The NASA Suomi-National Polar-orbiting Partnership (S-NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) is a scanning radiometer that collects radiometric measurements in the visible and infrared spectrums emphasizing global observations of the land, atmosphere, cryosphere, and oceans. VIIRS is one of five instruments onboard S-NPP, and will also be included on payloads for future Joint Polar Satellite System (JPSS) satellite missions.

The VIIRS Land Surface Temperature and Emissivity (LST&E) algorithm and data products (VNP21) in Collection 1 (C1) are developed synergistically with the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 (C6) LST&E algorithms and data products (VNP21) using the same algorithmic approach and input atmospheric products (Islam et al. 2017; Malakar and Hulley 2016). The overall objective for NASA VIIRS C1 products is to make the algorithms and products compatible with the C6 MODIS Terra and Aqua algorithms in order to ensure data product continuity and enable development of consistent, long term, and well characterized climate data records (CDR) from NASA's EOS satellites to the JPSS platforms. A long, stable record of LST is critical for monitoring climate trends, reducing systematic biases in land surface models, and is particularly useful for model evaluation in regions where few in situ measurements of surface air temperatures exist. Current differences between the NASA MOD21 C6 and the VNP21 C1 LST&E algorithms originate only from the physical differences between the MODIS and VIIRS instruments such as spatial resolution, band locations, and instrument noise. Analysis has shown that these differences at the <0.5 K level in retrieved surface temperature for a wide range of land surface and atmospheric conditions as illustrated in Figure 1 (Islam et al. 2017). The NASA VIIRS LST&E data products are produced in the NASA Land Science Investigator-led Processing System (LSIPS) and use a substantially different algorithm approach than the LST data products generated in the NOAA- Interface Data Processing Segment (IDPS) that were based on a split-window algorithm approach. The LSIPS is the NASA equivalent of the Land Product Evaluation and Analysis Tool Element (LPEATE) which had the task of generating and evaluating algorithms and products generated with IDPS algorithms. The LSIPS is currently receiving and beg(Malakar et al. 2018)inning to produce and distribute the NASA VIIRS data products.

The NASA VNP21 LST&E product uses a physics-based algorithm to dynamically retrieve both the LST and emissivity simultaneously for the three VIIRS thermal infrared bands M14 (8.55 µm), M15 (10.76 µm), and M16 (12 µm) at a spatial resolution of 750 m at nadir. The VNP21 algorithm is based on the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Temperature Emissivity Separation (TES) algorithm which is currently used to produce the new MOD21 LST&E product in MODIS Collection 6. TES uses full radiative transfer simulations for the atmospheric correction, and an emissivity model based on the variability in the surface radiance data to dynamically retrieve both LST and spectral emissivity at native pixel resolution. The TES algorithm is combined with an improved Water Vapor Scaling (WVS) atmospheric correction scheme to stabilize the retrieval during very warm and humid conditions. Simulations and validation results available in the ATBD have shown consistent accuracies at the 1 K level over all land surface types including vegetation, water, and deserts. Results also show that the TES

algorithm addresses the well-documented 3-5 K cold bias found in the heritage MOD11 products over arid and semi-arid regions due to an overestimation of emissivity for the barren land cover class (Malakar and Hulley 2016).

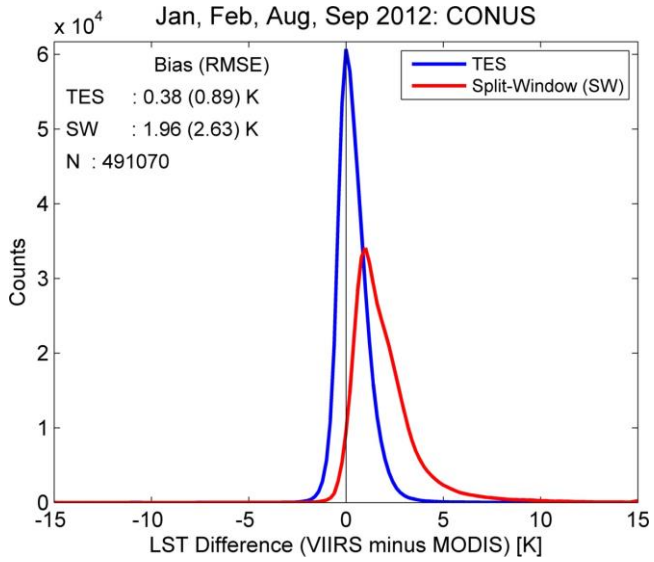

Figure 1. Histogram demonstrating the differences between VIIRS and MODIS LST products for all observations over continental USA (CONUS) during Jan, Feb, Aug, and Sep 2012 for two different algorithms: TES and split-window. The TES algorithm is currently used to produce the NASA LST&E products for MODIS and VIIRS (MOD21 and VNP21), while the split-window algorithm is used to produce the heritage MOD11 product(s) and the NOAA VIIRS LST product (VLSTO).

The VNP21 product will include a Level 2 (L2) swath (scene) product twice-daily (day/night) at 750 m resolution, and Level 3 (L3) gridded daily and eight-day gridded products in sinusoidal projections at 1 km resolution. The algorithms and data content of these LST products are briefly described in this guide with the purpose of providing a user with sufficient information about the content and structure of the data files to enable the user to access and use the data, in addition to understanding the quality control and uncertainties involved with the product. Overviews of the file format and sequence of VNP21 products are given first. Descriptions of the algorithm and product content are presented in subsequent sections. Publications and documents related to the VIIRS LST products are listed in the references section.

A description of the major components of the VNP21 algorithm implemented in the version 1 daily LST Product Generation Executive (PGE) code are shown in Table 1 and described in depth in the ATBD. A schematic detailing the flow of the VNP21 PGE within the LSIPS Science Data System is detailed in Figure 2. The primary purpose of this document is to supply a user with sufficient information about the content and structure of the data files so that the users will be able to access and use the data.

1.1 File Format of the LST&E Products

The VNP21 LST&E products are distributed in NetCDF4/HDF5 format compliant with NetCDF Climate and Forecast (CF) Metadata Conventions Version 1.6, and are readable by either NetCDF4 or HDF5 software. Information on NetCDF4.2 is available at www.unidata.ucar.edu/software/netcdf/docs/index.html, and information on Hierarchical Data Format 5 (HDF5) may be found at https://www.hdfgroup.org/HDF5/. The HDF format was developed by NCSA, and has been widely used in the scientific domain. HDF5 can store two primary types of objects: datasets and groups. A dataset is essentially a multidimensional array of data elements, and a group is a structure for organizing objects in an HDF5 file. HDF5 was designed to address some of the limitations of the HDF4. Using these two basic objects, one can create and store almost any kind of scientific data structure, such as images, arrays of vectors, and structured and unstructured grids. They can be mixed and matched in HDF5 files according to user needs. HDF5 does not limit the size of files or the size or number of objects in a file. The scientific data results are in the scientific data sets (SDSs) within the product file, along with local attributes including summary statistics and other information about the data.

The VNP21 LST&E data product files contain one set of attributes (metadata) describing information relevant to production, archiving, user services, input products, geolocation and analysis of data, as well as provenance and a Digital Object Identifier (DOI) for the product. The metadata attributes (listed in Table 4) are not described further in this user guide.

1.2 LST&E Products

The VNP21 LST&E C1 data consists of three different products from L2 to L3, these are; 1) L2 swath, 2) daily gridded sinusoidal tiles, and 3) 8-day mean gridded sinusoidal tiles. The L2 swath product will be released first from the LPDAAC followed by the tiled products at a later date to be determined by the LPDAAC/LAADS. The VIIRS swath has a nadir resolution of 750 m with 3232 pixels along track and 3200 pixels per line for each six minutes of the VIIRS scans. The VNP21 swath products are aggregated to produce the L3 global daily (VNP21A1) and 8-day mean (VNP21A2) products. Figure 3 shows an example of the LST and emissivity products for a granule over Northeast Africa. Table 1 shows a summary of products that will be available for VNP21 and their characteristics. EOSDIS labels products as Earth Science Data Types (ESDTs). The ESDT label, or "shortname" VNP21, is used to identify the LST&E data products. Each LST&E product in the sequence is built from the previous products. These products are identified in part by EOSDIS product levels that indicate the amount of processing applied to the data.

Data product levels briefly described: Level 1B (L1B) is a swath (scene) of measured VIIRS radiance data geolocated to latitude and longitude centers of 750 m resolution pixels. An L2 product is a geophysical product retrieved from the L1B data that remains in latitude and longitude orientation; it has not been temporally or spatially manipulated. The next step produces a Level 2 gridded (L2G) product in a gridded format of the sinusoidal projection for VIIRS land products. At L2G the data products are referred to as tiles, each tile being 10° x 10° (~1113 km by 1113 km) in

sinusoidal global map projection. L2 data products are gridded into L2G tiles by mapping the L2 pixels into cells of a tile in the map projection grid. The L2G algorithm creates a gridded product necessary for the L3 products that have been temporally and/or spatially manipulated, usually in a gridded map projection.

Table 1: Summary of the VNP21 LST&E product.

Earth Science Data Type (ESDT)	Product Level	Data Dimension	Spatial Resolution	Temporal Resolution	Map Projection
VNP21	L2	3232 lines by 3200 pixels per line	750 m at nadir	Swath, Twice-daily	None, (lat, lon tagged)
VNP21A1D/ VNP21A1N	L3	1200 rows by 1200 columns	1 km	Day and Night	Sinusoidal
VNP21A2	L3	1200 rows by 1200 columns	1 km	Eight day	Sinusoidal

The first product, VNP21, is the L2 swath LST product at 750 m spatial resolution. This product is generated from the TES algorithm (Hulley et al. 2012a). The next products, VNP21A1D and VNP21A1N, are tiles of the daily LST produced for Day and Night at 1 km spatial resolution. They are generated by mapping the pixels in the VNP21 products for the Day and Night overpasses to the Earth locations in the sinusoidal projection. The third product, VNP21A2, is an eight-day LST product created by averaging two to eight days of the VNP21A1D and VNP21A1N products using only good quality data pixels based on the QC information provided in the file.

2 VNP21 LST Product

2.1 Algorithm Description

For a full detailed description of each module within the algorithm please see the VNP21 ATBD (https://viirsland.gsfc.nasa.gov/PDF/VNP21_LSTE_ATBD_v2.1.pdf). The VNP21 product uses a physical-based Temperature and Emissivity Separation (TES) algorithm to retrieve the Land Surface Temperature and Emissivity (LST&E) products (Gillespie et al. 1998; Hulley and Hook 2011). The atmospheric correction of the VIIRS thermal infrared (TIR) bands M14, M15 and M16 is performed using the RTTOV radiative transfer model (Matricardi 2008; Saunders et al. 1999) with input atmospheric profiles from Numerical Weather Prediction (NWP) model data. Standard processing will use data from the MERRA-2 NWP model (Rienecker et al. 2011), MERRA-2 is a reanalysis product produced by the NASA Global Modeling and Assimilation Office (GMAO) and typically have a data latency of 1-2 months delivery at the LSIPS. As a result, the PGE has an option to run operationally in near real time (NRT) mode using data from the NCEP Global Forecast

System (GFS) available in near real time. VNP21 products retrieved from the NCEP data will be made available from the LAADS server in a 2-month rolling archive for use by NRT users, however, this data will be reprocessed with MERRA-2 once available, and distributed to the LDPAAC. NRT users should be aware that differences as large as 5 K could be found between the NRT version and the operational version of LST as a result of NCEP and MERRA-2 input, mostly due to differences in spatial resolution of the water vapor fields in the NCEP (~100 km) and MERRA-2 (~50 km) products during warm and humid conditions. Preliminary validation of 3 years of data with MERRA-2 and NCEP have shown that on average their accuracy is similar to within <1 K at the Lake Tahoe validation site, and to within <1% difference in emissivity over a set of sand dune validation sites in the US Southwest. More detailed information on MERRA-2 and NCEP and their characteristics and effects on LST retrieval are presented in the ATBD available here: (https://viirsland.gsfc.nasa.gov/PDF/VNP21_LSTE_ATBD_v2.1.pdf). Future plans are to use GEOS5-FP atmospheric fields from the GMAO for the atmospheric correction, which are available at a higher resolution (~25km) and in near real time for instrument and data product teams.

A Water Vapor Scaling (WVS) model is further employed to improve the atmospheric correction accuracy under conditions of heavy water vapor loadings on a pixel-by-pixel basis (Tonooka 2005). The WVS model reduces LST uncertainties from 3 K down to the 1 K level in difficult LST retrieval conditions, such as around clouds and in high humidity. The VNP21 product is produced globally over all land cover types for all cloud-free pixels, and includes LST and emissivity for the three VIIRS TIR bands 14, 15, and 16 at 750 m resolution. The product also includes a full set of uncertainty information, with estimated errors for LST and the emissivity fields generated from a LST&E uncertainty model (Hulley et al. 2012b). Figure 2 shows a schematic detailing the flow of the VNP21 PGE within the LSIPS, including the primary input datasets and subprocesses.

Similar to the heritage MOD21 product, the VNP21 LST&E retrieval in a VIIRS swath is constrained to pixels that:

(1) Have nominal Level 1B radiance data in bands M14, M15, and M16

(2) Are over land or inland water,

(3) Are collected in clear-sky conditions (defined by the cloud mask product, VNP35) at a confidence of >= 95% over land. Data inputs to the VNP21 LST algorithm are listed in Table 2. Clouds are masked with the VNP35 at >=95% confidence over land. The algorithm is only run over land pixels, so masking of oceans is accomplished with the land/water mask within the VIIRS L1B product.

The ASTER Global Emissivity Database v3 (GED v3) emissivity product (Hulley et al. 2015) is used to assign the correct emissivity-dependent coefficients in the WVS model on a scene-by-scene basis. Details of this method are available in the VNP21 ATBD.

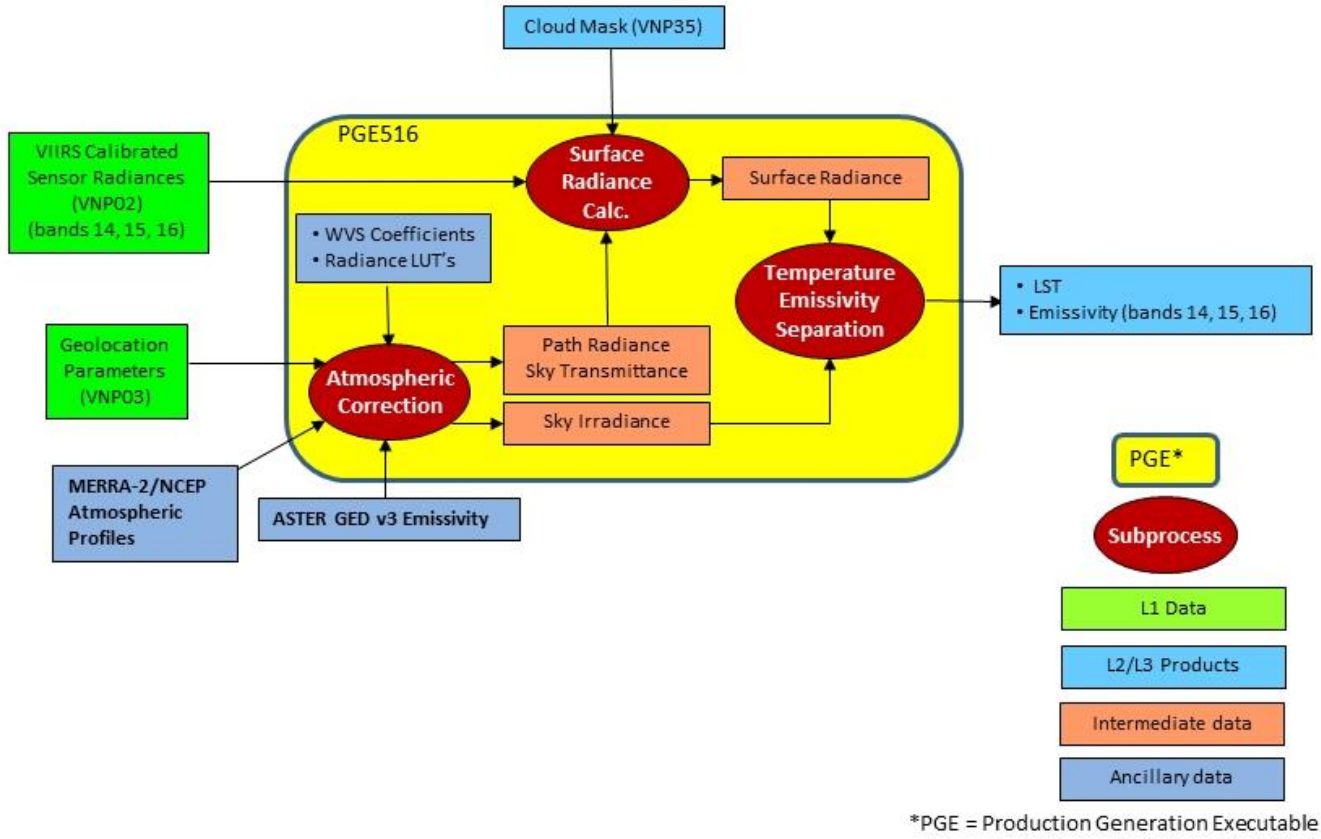

Figure 2. Schematic detailing the flow of the VNP21 PGE within the LSIPS Science Data System.

Table 2: This table describes the VNP21 LST&E product and other ancillary input data required to produce the product.

Ancillary Data Set	Long Name	Data Used
VNP02MOD	VIIRS Level-1B calibrated radiances	M14, M15, M16
VNP03	VIIRS Geolocation	Height Sensor and Solar Zenith Angles Latitude, Longitude
VNP35	VIIRS Cloud Mask	Cloud mask, Ocean mask
ASTER GEDv3	ASTER Global Emissivity Database v3	Emis11 Emis13 Emis14 NDVI
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2	Pressure Temperature Specific Humidity Surface Pressure
NCEP	National Centers for Environmental Prediction	Pressure Temperature Relative Humidity Surface Pressure

2.2 Scientific Data Sets (SDS)

The VIIRS L2 LST&E product contains 15 scientific data sets (SDSs): LST, LST_err, QC, Emis_14, Emis_15, Emis_16, Emis_14_err, Emis_15_err, Emis_16_err, View_angle, Emis_ASTER, PWV, Oceanpix, Latitude and Longitude. All SDS data are output at 750 m pixels. The SDSs with *_err appended to the name are calculated using a LST&E uncertainty simulator and include the maximum total uncertainty for a specific pixel based on view angle, total water vapor, and land cover type (Hulley et al. 2012b). Furthermore, a spatially and temporally interpolated Precipitable Water Vapor (PWV) estimate from MERRA-2 is included in the SDS as an indicator for the amount of water vapor present in the atmosphere, the primary driving factor for LST uncertainty. Details of each SDS including fill and scale factors are shown in Table 3.

Table 3. The SDSs in the VNP21 product.

SDS	Long Name	Data type	Units	Valid Range	Fill Value	Scale Factor	Offset
LST	Land Surface Temperature	uint16	K	7500-65535	0	0.02	0.0
QC	Quality control for LST and emissivity	uint16	n/a	0-65535	n/a	1	0
Emis_14	M14 emissivity	uint8	n/a	1-255	0	0.002	0.49
Emis_15	M15 emissivity	uint8	n/a	1-255	0	0.002	0.49
Emis_16	M16 emissivity	uint8	n/a	1-255	0	0.002	0.49
LST_err	Land Surface Temperature error	uint8	K	1-255	0	0.04	0.0
Emis_14_err	M14 emissivity error	uint16	n/a	1-65535	0	0.0001	0.0
Emis_15_err	M15 emissivity error	uint16	n/a	1-65535	0	0.0001	0.0
Emis_16_err	M16 emissivity error	uint16	n/a	1-65535	0	0.0001	0.0
View_angle	VIIRS view angle for current pixel	uint8	degrees	0-180	255	0.5	0.0
Emis_ASTER	ASTER GED Emissivity (minimum of 5 band values)	uint8	n/a	1-255	0	0.002	0.49
PWV	Precipitable Water Vapor	uint16	cm	0-65535	n/a	0.001	0.0
Oceanpix	Ocean-land mask	uint8	n/a	0=land 1=water 2=inland water	n/a	1	0
Latitude	Latitude data	float32	degrees north	-90 to 90	-999.0	1	0
Longitude	Longitude data	float32	degrees east	-180 to 180	-999.0	1	0

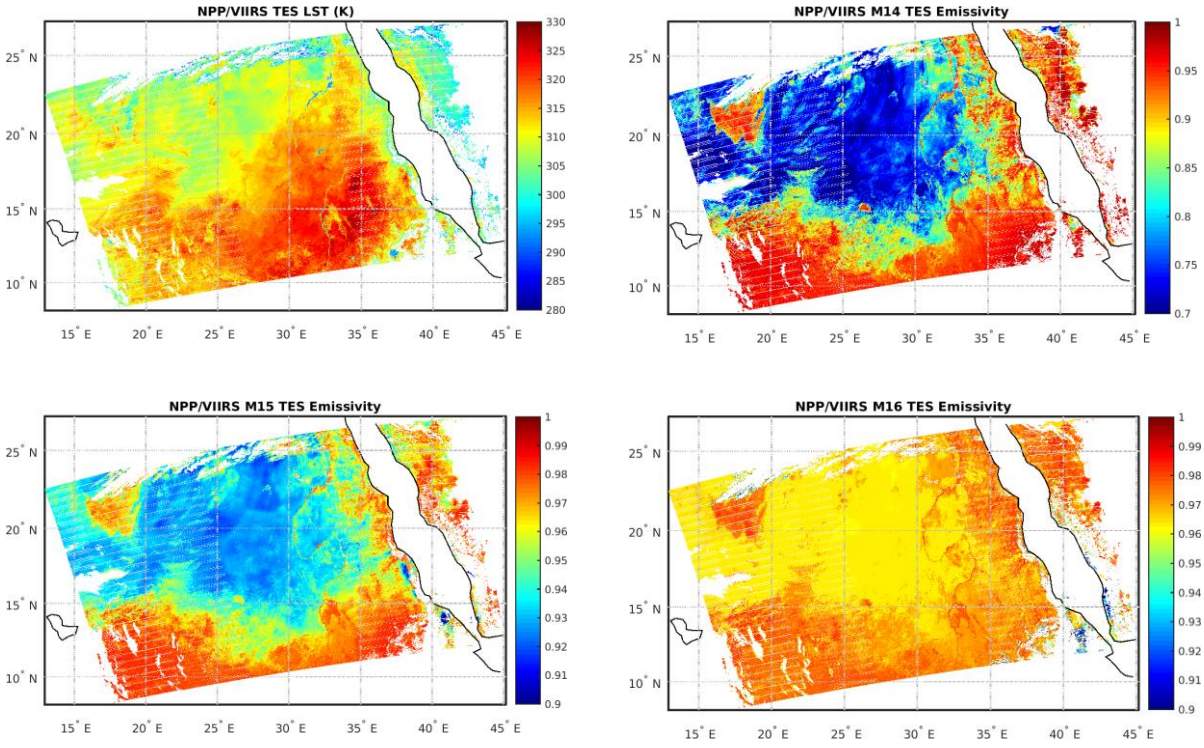

Figure 3. VNP21 Land Surface Temperature (LST) L2 swath (top left), band M14 (8.55 µm) emissivity (top right), band M15 (10.76 µm) emissivity (bottom left), and band M16 (12 µm) emissivity (bottom right) for a granule over northeast Africa on 13 January 2014.

2.3 Attributes

Archived with the SDS are attributes (metadata) describing characteristics of the data. Contents of these attributes were determined and written during generation of the product and are used in archiving and populating the EOSDIS database to support user services. They are stored as very long character strings in parameter value language (PVL) format. Descriptions of the attributes are given here to assist the user in understanding them.

Examples include information compiled about the product during product generation, geographic location of swath, and production times. These data may be useful in determining what version of the algorithm was used to generate the product. The content of the full set of attributes with sample values for one swath are listed in Table 4. The user wanting detailed explanations of the attributes and related information should query the EOSDIS related web sites.

Table 4. Listing of objects in the attributes associated with the VNP21 product.

Object Name	Sample Value	Comment
AlgorithmType	"NPP_OPS"	
Conventions	"CF-1.6"	

DayNightFlag	“Day”	Day, Night, or Both
EastBoundingCoordinate	36.8315	Degrees Longitude
EndTime	"2015-09-20 00:00:00.000"	
GRingLatitude	-38.0443, -43.6647, -64.2115, -55.6749	Degrees Latitude
GRingLongitude	-1.95001, 34.7509, 36.8315, -19.4949	Degrees Longitude
InputPointer	"VNP02MOD.A2015262.2354.001.2016034205923.nc,VNP35_L2.A2015262.2354.001.20163263191640.hdf,VNP03MOD.A2015262.2354.001.2015337202805.nc"	Input file names
InstrumentShortname	“VIIRS”	
LSIPS_AlgorithmVersion	"NPP_PRLST 1.5.08.03"	
LUTs_used	"MERRA2_400.inst6_3d_ana_Np.20140113.nc4,wvs_coeff_npp_viirs.h5"	
LocalGranuleID	"VNP21.A2015262.2354.001.2016326225444.nc"	Output file name
LongName	"VIIRS/NPP Land Surface Temperature and Emissivity"	
NorthBoundingCoord	-38.0443	Degrees Latitude
NWPSource	“MERRA2”	MERRA2 or NCEP
OrbitNumber	20183	
PGEVersion	1.0.1	
PGE_EndTime	"2015-09-20 00:00:00.000"	
PGE_Name	“PGE516”	
PGE_StartTime	"2015-09-19 23:54:00.000"	
Platform_Short_Name	“NPP”	
ProcessVersion	“001”	
ProcessingEnvironment	"Linux minion9999 2.6.18-416.el5 #1 SMP Fri Oct 28 11:52:49 UTC 2016 x86_64 x86_64 x86_64 GNU/Linux"	
Product_authority	"http://dx.doi.org"	
Product_doi	"10.5067/VIIRS/VNP21.001"	
ProductionDateTime	"2016-11-21T22:57:26.823Z"	
RangeBeginningDate	"2015-09-19"	
RangeBeginningTime	"23:54:00.000"	

RangeEndingDate	"2015-09-20"	
RangeEndingTime	"00:00:00.000"	
SatelliteInstrument	"NPP_OPS"	
ShortName	"VNP21"	
SouthBoundingCoord	-64.2115	Degrees Latitude
StartOrbitNumber	20183	
StartTime	"2015-09-19 23:54:00.000"	
StopOrbitNumber	20183	
StructMetadata.0	"GROUP=SwathStructure GROUP=SWATH_1 SwathName="VIIRS_Swath_LSTE" GROUP=Dimension OBJECT=Dimension_1 DimensionName="Along_Track" Size=3232 END_OBJECT=Dimension_1 … etc.	Metadata definition of the file structure conforming to HDF-EOS convention
WestBoundingCoord	-19.4949	Degrees Longitude
cdm_data_type	“swath”	
creator_email	"modis-ops@lists.nasa.gov"	
creator_url	"http://ladsweb.nascom.nasa.gov"	
date_created	"2015-12-01T00:25:59.000Z"	
endDirection	"Descending"	Ascending or Descending
format_version	2	
gringpointsequence	1, 57, 405614944, 0	
history	"NPP_PR01.exe P1570826VIIRSSCIENCEAT15263034243301.PDS P1570011AAAAAAAAAAAAAT15263034142601.PDS_pad P1570008AAAAAAAAAAAAAT15263034132401.PDS_pad P1570000AAAAAAAAAAAAAT15263034045801.PDS_pad 6	

	VNP01.A2015262.2354.001.2015335001026.nc"	
institution	"NASA Goddard Space Flight Center"	
instrument	"VIIRS"	
instrument_number	2	
keywords_vocabulary	"NASA Global Change Master Directory (GCMD) Science Keywords"	
license	"http://science.nasa.gov/earth-science/earth-science-data/data-information-policy/"	
naming_authority	"gov.nasa.gsfc.VIIRSland"	
number_of_filled_scans	202	
processing_level	“L2”	
processing_version	“V1.0”	
product_name	"VNP21.A2015262.2354.001.2016251185033.nc"	
project	"VIIRS L2 Project"	
publisher_email	"modis-ops@lists.nasa.gov"	
publisher_name	“LAADS”	
publisher_url	"http://ladsweb.nascom.nasa.gov"	
startDirection	"Descending"	Ascending or Descending
stdname_vocabulary	"NetCDF Climate and Forecast (CF) Metadata Convention"	
time_coverage_end	"2015-09-20T00:00:00.000Z"	
time_coverage_start	"2015-09-19T23:54:00.000Z"	
title	"VIIRS Land Surface Temperature and Emissivity Data"	

2.4 Quality Assurance (QA)

Indicators of quality are described exclusively in the quality control (QC) SDS, generated during production. In addition to data quality, the QC SDS provides information on algorithm metrics for each pixel (e.g. convergence statistics). The QC SDS unsigned 16-bit data are stored as bit flags in the SDS. This QC information can be extracted by reading the bits as 16-bit unsigned integer. The purpose of the QC SDS is to give the user information on algorithm results for each pixel that can be viewed in a spatial context. The QC information helps the user determine if algorithm results

were nominal, abnormal, or if other defined conditions were encountered for a pixel. The QC information should be used to help determine the usefulness of the LST and Emissivity data for a user's needs. The bit flags in the QC SDS are listed in Table 5 and consist of flags related to data quality, cloud, TES algorithm diagnostics, and error estimates.

A value of 0 in the QC bit flags means good, cloud-free data quality and no further analysis of the QC bits is necessary. Users may use data of 'unreliable quality' (bits 1&0 = 01), but caution should be taken since any of the following are possible: the retrieved emissivity is suspect (emissivity in both longwave bands M14 and M15 < 0.95, indicating possible cloud), the pixel is within 2 pixels of nearby detected cloud, or the pixel had transmissivity less than 0.4, indicating possible cloud or high humidity, resulting in higher uncertainty in the TES retrieval. A value of 11 for bits 1&0 indicates that either the pixel was not produced because it is an ocean pixel, the L1B uncertainty index flag indicated poorly calibrated radiance data, or the TES algorithm failed to converge (usually due to undetected cloud, but rare).

Note: For potential undetected cloud contamination and cloud edge effects, the M15 emissivity band can be further examined for data quality, for example, values <0.9 are usually indicative of a cloud-contaminated pixel. However, the user should pay attention to surface type, since over mafic rocks (e.g. basalt flows near volcanoes) emissivity values are expected to be <0.9 in the longwave bands (M15, M16).

Table 5. Bit flags defined in the QC SDS in the VNP21 product. (Note: Bit 0 is the least significant bit).

Bits	Long Name	Description
1&0	Mandatory QA flags	00 = Pixel produced, best quality, no further QA info necessary 01 = Pixel produced, nominal quality. Either one or more of the following conditions are met: emissivity in both bands M14 and M15 < 0.95, retrieval affected by nearby cloud, low transmissivity due to high water vapor loading (<0.4). Recommend more detailed analysis of other QC information 10 = Pixel not produced due to cloud 11 = Pixel not produced due to reasons other than cloud (e.g. ocean pixel, poorly calibrated input radiance, TES algorithm divergence flag, pixel-trim fill values, lunar intrusion)
3 & 2	Data quality flag	00 = Good data quality of L1B bands 01 = Missing pixel

		10 = Fairly calibrated 11 = Poorly calibrated, TES processing skipped
5 & 4	Cloud flag	00 = Cloud-free pixel 01 = Thin cirrus 10 = Pixel within 2 pixels of nearest cloud (~2km) 11 = Cloud pixel
7 & 6	TES Iterations (k)	00 = ≥7 (Slow convergence) 01 = 6 (Nominal) 10 = 5 (Nominal) 11 = <5 (Fast)
9 & 8	Atmospheric Opacity $L_\lambda^\downarrow / L'$	00 = ≥0.3 (Warm, humid air; or cold land) 01 = 0.2 - 0.3 (Nominal value) 10 = 0.1 - 0.2 (Nominal value) 11 = <0.1 (Dry, or high altitude pixel)
11 & 10	Min-Max Difference (MMD). Difference between minimum and maximum emissivity for bands M14, M15, M16	00 = >0.15 (Most silicate rocks) 01 = 0.1 - 0.15 (Rocks, sand, some soils) 10 = 0.03 - 0.1 (Mostly soils, mixed pixel) 11 = <0.03 (Vegetation, snow, water, ice, some soils)
13 & 12	Emissivity accuracy	00 = >0.017 (Poor performance) 01 = 0.015 - 0.017 (Marginal performance) 10 = 0.013 - 0.015 (Good performance) 11 = <0.013 (Excellent performance)
15 & 14	LST accuracy	00 = >2.5 K (Poor performance) 01 = 1.5 - 2.5 K (Marginal performance) 10 = 1 - 1.5 K (Good performance) 11 = <1 K (Excellent performance)

3 VNP21A1 Daily LST Product

The VNP21 level 3 LST&E day and night product at 1 km spatial resolution is a tile of daily LST&E product gridded in the sinusoidal projection. A tile contains 1200 x 1200 grids in 1200 rows and 1200 columns. The exact grid size at 1 km spatial resolution is 0.928km by 0.928km.

3.1 Algorithm Description

The daily VNP21A1D/VNP21A1N LST products are compiled from daily gridded L2G intermediate products (VNP21GD/VNP21GN). The L2G process maps the daily VNP21 granules onto a sinusoidal grid and stores all observations falling over a gridded cell for a given day. The total number of observations for a day are determined not only by the number of orbits passing over that cell but also by the spread of observations from off-nadir coverage.

The VNP21A1 algorithm sorts through all these observations for each cell and for a given day and estimates the final LST value as a weighted average over all observations that are cloud-free and have good LST and emissivity accuracies, weighted by the observation coverage for that cell. Only observations having observation coverage more than a certain threshold (15%) are considered for this averaging. This process is repeated for the day and night granules separately to create separate VNP21A1D (day) and VNP21A1N (night) products. The final quality byte for the output product reflects the lowest quality values from all observations that went into the final averaging.

3.2 Scientific Data Sets (SDS)

The SDSs in the VNP21A1D/VNP21A1N product are detailed in Table 6 and include:

- LST_1KM: Daily 1 km Land-surface temperature
- QC: Daily QA bytes for LST and emissivity.
- View_Angle: View zenith angle of LST
- View_Time: Time of LST observations
- Emis_14: Daily Band M14 emissivity
- Emis_15: Daily Band M15 emissivity
- Emis_16: Daily Band M16 emissivity

Table 6. The SDSs in the VNP21A1D/VNP21A1N product.

SDS	Long Name	Data type	Units	Valid Range	Fill Value	Scale Factor	Offset
LST_1KM	Land Surface Temperature	uint16	K	7500-65535	0	0.02	0.0
QC	Quality control	uint16	n/a	0-65535	n/a	1	0
Emis_14	Band M14 emissivity	uint8	n/a	1-255	0	0.002	0.49

Emis_15	Band M15 emissivity	uint8	n/a	1-255	0	0.002	0.49
Emis_16	Band M16 emissivity	uint8	n/a	1-255	0	0.002	0.49
View_Angle	VIIRS view angle	uint8	deg	0-130	255	1	-65
View_Time	Time of VIIRS observation	uint8	hrs	0-240	255	0.1	0

3.3 Attributes

The attributes for SDS, LST_1KM will be similar to those in Table 4.

3.4 Quality Assurance

The bit flags defined for the quality assurance SDS QC are listed in Table 7.

Table 7. Bit flags defined in the QC SDS in the VNP21A1D/VNP21A1N product. (Note: Bit 0 is the least significant bit).

Bits	Long Name	Description
1&0	Mandatory QA flags	00 = Pixel produced, good quality, no further QA info necessary 01 = Pixel produced but unreliable quality. Either one or more of the following conditions are met: emissivity in both bands 14 and 15 < 0.95, retrieval affected by nearby cloud, low transmissivity due to high water vapor loading (<0.4), Recommend more detailed analysis of other QC information 10 = Pixel not produced due to cloud 11 = Pixel not produced due to reasons other than cloud
3 & 2	Data quality flag	00 = Good data quality of L1B bands 14, 15, 16 01 = Missing pixel 10 = Fairly calibrated 11 = Poorly calibrated, TES processing skipped
5 & 4	Cloud Flag	00 = Cloud-free 01 = Thin cirrus 10 = Pixel within 2 pixels of nearest cloud 11 = Cloudy pixels

7 & 6	Iterations	00 = Slow convergence 01 = Nominal 10 = Nominal 11 = Fast
9 & 8	Atmospheric Opacity	00 = >=3 (Warm, humid air; or cold land) 01 = 0.2 - 0.3 (Nominal value) 10 = 0.1 - 0.2 (Nominal value) 11 = <0.1 (Dry, or high altitude pixel)
11 & 10	MMD	00 = > 0.15 (Most silicate rocks) 01 = 0.1 - 0.15 (Rocks, sand, some soils) 10 = 0.03 - 0.1 (Mostly soils, mixed pixel) 11 = <0.03 (Vegetation, snow, water, ice, some soils)
13 & 12	Emissivity accuracy	00 = >0.02 (Poor performance) 01 = 0.015 - 0.02 (Marginal performance) 10 = 0.01 - 0.015 (Good performance) 11 = <0.01 (Excellent performance)
15 & 14	LST accuracy	00 = >2 K (Poor performance) 01 = 1.5 - 2 K (Marginal performance) 10 = 1 - 1.5 K (Good performance) 11 = <1 K (Excellent performance)

4 VNP21A2 Eight-day LST Product

An eight-day compositing period was chosen because double that period is the exact ground track repeat period of the S-NPP platform. LST over eight days is the averaged LSTs of the VNP21A1 product over eight days. The VNP21A1 product will not be included in initial release of the product, but will be released at a later date from the LPDAAC/LAADS.

4.1 Algorithm Description

A simple average method is used in the current algorithm for the VNP21A2 product. The averaging is done for day and night separately for LST, QC, View angle and Viewing time, while for the band

M14, M15, and M16 emissivities the averaging is done over both day and night. The averaging process includes only daily values that are cloud-free.

4.2 Scientific Data Sets (SDS)

In the VNP21A2 product, the day and night daily VNP21A1 products are combined into a single product, but it has different SDS layers for LST, QC, View angle and View time for day and for night respectively. The day and night specific SDSs in VNP21A2 are listed below and in Table 8.

- LST_Day_1KM
- QC_Day
- View_Angle_Day
- View_Time_Day
- LST_Night_1KM
- QC_Night
- View_Angle_Night
- View_Time_Night
- Emis_14
- Emis_15
- Emis_16

Table 8. The SDSs in the VNP21A2 product.

SDS	Long Name	Data type	Units	Valid Range	Fill Value	Scale Factor	Offset
LST_Day_1KM	Day Land Surface Temperature	uint16	K	7500-65535	0	0.02	0.0
QC_Day	Day Quality control	uint8	n/a	1-255	0	1	0
View_Angle_Day	Day view angle	uint8	deg	0-130	255	1	-65
View_Time_Day	Day time of observation	uint8	hrs	0-240	255	0.1	0
LST_Night_1KM	Night Land Surface Temperature	uint16	K	7500-65535	0	0.02	0.0
QC_Night	Night Quality control	uint8	n/a	1-255	0	1	0
View_Angle_Night	Night view angle	uint8	deg	0-130	255	1	-65
View_Time_Night	Night time of observation	uint8	hrs	0-240	255	0.1	0
Emis_14	Average Day/Night Band 14 emissivity	uint8	n/a	1-255	0	0.002	0.49

Emis_15	Average Day/Night Band 15 emissivity	uint8	n/a	1-255	0	0.002	0.49
Emis_16	Average Day/Night Band 16 emissivity	uint8	n/a	1-255	0	0.002	0.49

4.3 Attributes

Similar to VNP21A1.

4.4 Quality Assurance

The bit flags defined for the quality assurance SDSs QC_Day and QC_Night are listed in Table 9.

Table 9. Bit flags defined in the QC_Day and QC_Night SDS in the VNP21A2 product. (Note: Bit 0 is the least significant bit).

Bits	Long Name	Description
1&0	Mandatory QA flags	00 = Pixel produced, good quality, no further QA info necessary 01 = Pixel produced but unreliable quality. Recommend more detailed analysis of other QC information 10 = Pixel not produced due to cloud 11 = Pixel not produced due to reasons other than cloud
3 & 2	Data quality flag	00 = Good data quality of L1B bands 14, 15, 16 01 = Missing pixel 10 = Fairly calibrated 11 = Poorly calibrated, TES processing skipped
5 & 4	Emissivity accuracy	00 = >0.02 (Poor performance) 01 = 0.015 - 0.02 (Marginal performance) 10 = 0.01 - 0.015 (Good performance) 11 = <0.01 (Excellent performance)
7 & 6	LST accuracy	00 = >2 K (Poor performance) 01 = 1.5 - 2 K (Marginal performance) 10 = 1 - 1.5 K (Good performance) 11 = <1 K (Excellent performance)

5 VNP21C1 Daily CMG LST&E Product

The daily Climate Modeling Grid (CMG) global LST&E product is a NetCDF4/HDF5 Grid Data file that provides LST and emissivity values at 0.05° latitude/longitude equal-angle grids. The exact areal size of the equal angle grids varies with latitude, and it is 5.6 km by 5.6 km at the Equator.

5.1 Algorithm Description

The LST&E products in VNP21C1 are derived by reprojection and average of the values in the daily VNP21 Level-2 swath product. VNP21 pixels are selected for averaging based on the following criteria.

1. The Mandatory QA Flag of the input pixel must be 00 (good quality) or 01 (nominal quality).
2. The VNP21 pixel must not have a fill value in LST, Emis_14, Emis_15, or Emis_16.
3. Emis_16 must not be less than 0.95 (high probability of undetected cloud)

If all the data included in the averages for a grid cell has a Mandatory QA of “good” the grid cell will have a Mandatory QA value of “good.” If a grid cell contains nominal quality data in the average, it will have a Mandatory QA value of “nominal.” If a grid cell has no produced data, but one or more input pixels was designated as “not produced due to cloud,” the Mandatory QA flag will have a value of “not produced due to cloud.” Otherwise, the Mandatory QA will have a value of “not produced due to reasons other than cloud.” Such reasons include having no input pixels that map to a grid cell, or all pixels that mapped to the grid cell were not produced for reasons other than cloud.

Emissivity error estimates are recalculated as a function of Precipitable Water Vapor (PWV) based on the LST&E uncertainty model detailed in (Hulley et al. 2012b) as follows.

$$Emis\_14\_err = 0.0347 + 0.0036 * PWV$$

$$Emis\_15\_err = 0.0084 + 0.0058 * PWV$$

$$Emis\_16\_err = 0.0097 + 0.0018 * PWV$$

The error values in the CMG data are the root-mean-square-error (RMSE) of the input LST error estimates and the recalculated emissivity errors.

The Percent_land_in_grid dataset is based on VNP21 oceanpix data. This dataset does not depend on the selection criteria for averaging. All pixels have a discrete value for land or ocean. If a grid cell has no matching pixels from any input file, the percent land will contain a fill value.

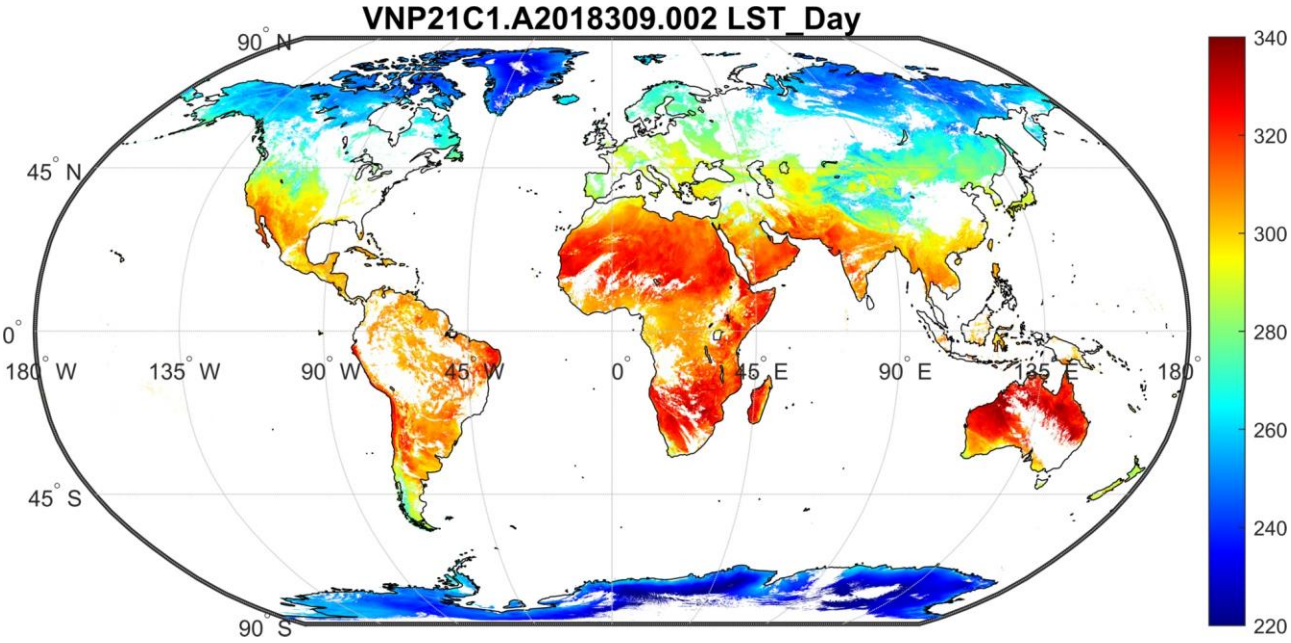

Figure 4. **Example VNP21C1 LST daytime product in Collection 2.**

5.2 Scientific Data Sets (SDS)

The VNP21C1 product combines the day and night daily products (LST, Emis, QC, view angle, error estimates) into a single product. The day and night specific SDS in VNP21C1 are listed in Table 13.

Table 10**. The SDSs in the VNP21C1 product.**

SDS	Long Name	Data type	Units	Valid Range	Fill Value	Scale Factor	Offset
LST_Day	Average Daytime Land Surface Temperature	uint16	K	7500-65535	0	0.02	0.0
LST_Day_err	Root-mean-square-error Daytime Land Surface Temperature	uint8	K	1-255	0	0.04	0.0
QC_Day	Quality Control for Daytime LST and Emissivity	uint8	n/a	0-255	n/a	n/a	n/a
Day_view_angle	Average Daytime View Zenith Angle	uint8	deg	0-130	255	1	-65

Day_view_time	Average Daytime View Time (UTC)	uint8	hrs	0-120	255	0.2	0
Count_Day	Count of Daytime Input Values	uint16	n/a	1-65535	0	n/a	n/a
LST_Night	Average Nighttime Land Surface Temperature	uint16	K	7500-65535	0	0.02	0.0
LST_Night_err	Root-mean-square-error Nighttime Land Surface Temperature	Uint8	K	1-255	0	0.04	0.0
QC_Night	Quality Control for Nighttime LST and Emissivity	uint8	n/a	0-255	n/a	n/a	n/a
Night_view_angle	Average Nighttime View Zenith Angle	uint8	deg	0-130	255	1	-65
Night_view_time	Average Nighttime View Time (UTC)	uint8	hrs	0-120	255	0.2	0.0
Count_Night	Count of Nighttime Input Values	uint16	n/a	1-65535	0	n/a	n/a
Emis_14_Day	Average Daytime Band 29 Emissivity	uint8	n/a	1-255	0	0.002	0.49
Emis_14_Day_err	Root-mean-square-error Daytime Band 29 Emissivity	Uint16	n/a	1-65535	0	0.0001	0.0
Emis_15_Day	Average Day Band 31 Emissivity	uint8	n/a	1-255	0	0.002	0.49
Emis_15_Day_err	Root-mean-square-error Daytime Band 31 Emissivity	uint16	n/a	1-65535	0	0.0001	0.0
Emis_16_Day	Average Daytime Band 32 Emissivity	uint8	n/a	1-255	0	0.002	0.49

Emis_16_Day_err	Root-mean-square-error Daytime Band 32 Emissivity	Uint16	n/a	1-65535	0	0.0001	0.0
Emis_14_Night	Average Nighttime Band 29 Emissivity	uint8	n/a	1-255	0	0.002	0.49
Emis_14_Night_err	Root-mean-square-error Nighttime Band 29 Emissivity	uint16	n/a	1-65535	0	0.0001	0.0
Emis_15_Night	Average Nighttime Band 31 Emissivity	uint8	n/a	1-255	0	0.002	0.49
Emis_15_Night_err	Root-mean-square-error Nighttime Band 31 Emissivity	uint16	n/a	1-65535	0	0.0001	0.0
Emis_16_ Night	Average Nighttime Band 32 Emissivity	uint8	n/a	1-255	0	0.002	0.49
Emis_16_Night_err	Root-mean-square-error Nighttime Band 32 Emissivity	uint16	n/a	1-65535	0	0.0001	0.0
Percent_land_in_grid	Percent of Land Detections in Grid Cell	uint8	percent	0-100	255	1	0.0

5.3 Local Attributes

Similar to VNP21 L2.

5.4 Global Attributes

Similar to VNP21 L2.

5.5 Quality Assurance

The bit flags defined for the quality assurance SDSs QC_Day and QC_Night are listed in Table 9.

6 VNP21C2 8-Day CMG LST&E Product

The 8-day Climate Modeling Grid (CMG) global LST&E product is NetCDF4/HDF5 Grid Data file that provides LST and emissivity values at 0.05° latitude/longitude equal-angle grids. The exact areal size of the equal angle grids varies with latitude, and it is 5.6 km by 5.6 km at the Equator.

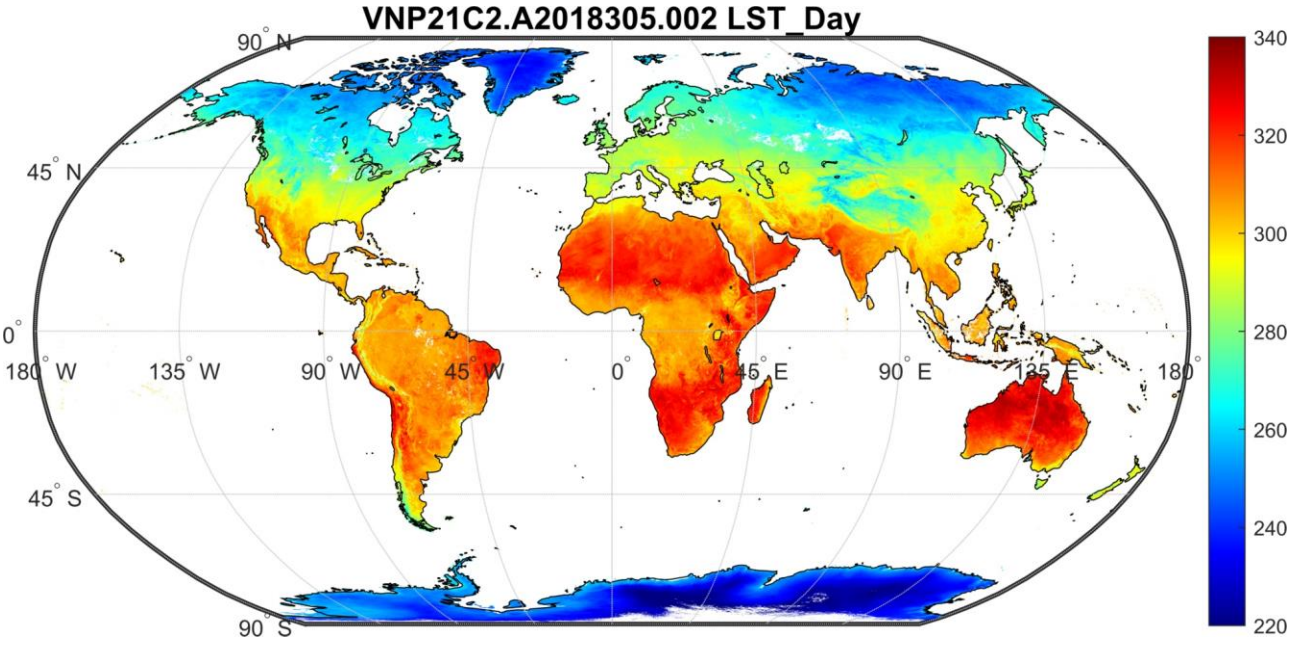

Figure 5**. Example VNP21C2 LST daytime product in Collection 2.**

6.1 Algorithm Description

The LST&E products in VNP21C2 are derived by averaging of the values in a set of the daily VNP21C1 CMG products at 0.05 degree resolution. Because Count_Day and Count_Night are included in the VNP21C1 product, the results are equivalent to an averaging of the values from all the VNP21 swaths that were included in the input VNP21C1 files.

VNP21C2 also includes bitmaps of clear sky days and clear sky nights. Each bit in the 8-bit unsigned integer indicates clear-sky (1) or not (0) in the corresponding day or night. Bit 00 is for the first day or night, and bit 07 is for the last day or night in the 8-day period.

6.2 Scientific Data Sets (SDS)

The VNP21C2 product averages the data from eight Daily CMG (VNP21C1) products. The SDS in VNP21C2 that are common to VNP21C1 are listed in Table 13. Two additional SDS are listed in Table 10.

Table 11**. Additional SDSs in the VNP21C2 product.**

SDS	Long Name	Data type	Units	Valid Range	Fill Value	Scale Factor	Offset
Clear_sky_days	Bitmap of Clear Sky Days (1 = clear, LSB = 1st day)	uint8	none	0-255	n/a	n/a	n/a
Clear_sky_nights	Bitmap of Clear Sky Nights (1 = clear, LSB = 1st day)	uint8	none	0-255	n/a	n/a	n/a

6.3 Local Attributes

Similar to VNP21 L2.

6.4 Global Attributes

Similar to VNP21 L2.

7 VNP21C3 Monthly CMG LST&E Product

The monthly Climate Modeling Grid (CMG) global LST&E product is a NetCDF4/HDF5 Grid Data file that provides LST and emissivity values at 0.05° latitude/longitude equal-angle grids. The exact areal size of the equal angle grids varies with latitude, and it is 5.6 km by 5.6 km at the Equator.

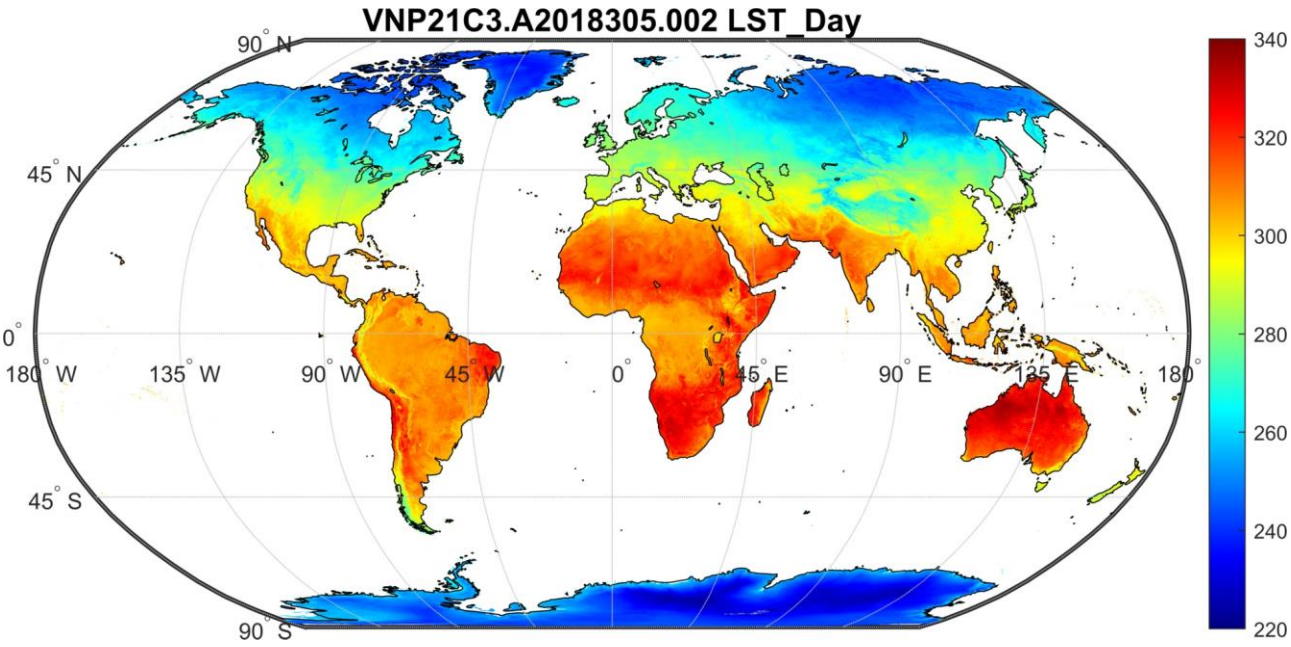

Figure 6**. Example VNP21C3 LST daytime product in Collection 6.1.**

7.1 Algorithm Description

The LST&E products in VNP21C3 are derived by averaging of the values in a set of the daily VNP21C1 CMG products at 0.05 degree resolution. The processing is much like the processing for the VNP21C2 product, but the inputs are the Daily CMG files for a period of one month.

VNP21C3 also includes bitmaps of clear sky days and clear sky nights. Each bit in the 32-bit unsigned integer indicates clear-sky (1) or not (0) in the corresponding day or night. Bit 00 is for the first day or night, and up to 31 bits may be used to contain a bitmap for the days in one month.

7.2 Scientific Data Sets (SDS)

The VNP21C3 product averages the data from one month of Daily CMG (VNP21C1) products. The SDS in VNP21C3 that are common to VNP21C1 are listed in Table 10. Two additional SDS are listed in Table 12.

Table 12**. Additional SDSs in the VNP21C3 product.**

SDS	Long Name	Data type	Units	Valid Range	Fill Value	Scale Factor	Offset
Clear_sky_days	Bitmap of Clear Sky Days (1 = clear, LSB = 1st day)	uint32	none	0-2147483647	n/a	n/a	n/a
Clear_sky_nights	Bitmap of Clear Sky Nights (1 = clear, LSB = 1st day)	uint32	none	0-2147483647	n/a	n/a	n/a

7.3 Local Attributes

Similar to VNP21A1.

7.4 Global Attributes

Similar to VNP21A1.

8 SNPP and JPSS-1/NOAA-20 VIIRS continuity

The VIIRS TES algorithm for SNPP C1 was successfully adapted and used to generate LST&E test products with NASA JPSS-1/NOAA-20 VIIRS L1B data. The two VIIRS algorithms are identical except for some slight modifications to the code and look up tables as a result of spectral response function differences of the thermal bands. The first test by the Land SIPS compared the LST climate modeling grid products for two months in 2018 (test AS 3194). Figure 7 shows an example of the VNP21C3 LST product (mean monthly, Jan 2018) and difference between VNP21 and new VJ121 equivalent LST product. For Jan 2018, daytime LST percent differences were mostly less than 1%, with some localized differences of up to 3% likely due to differences in observation time and/or cloud masking (e.g. northeast USA, Greenland).

The histogram summaries of the VNP21/VJ121 differences in Figure 8 show negligible day and nighttime biases for Jan 2018 with RMSE's of 1.32 K (daytime) and 1.45 K (nighttime). For summertime data (Aug 2018), a ~0.5 K bias was found for day and nighttime data. However, a diurnal related summertime bias was expected since SNPP and NOAA-20 orbits are up to one hour apart resulting in larger temperatures differences during summertime (especially deserts) when more rapid changes in LST are typical as the land surface heats up and cools down.

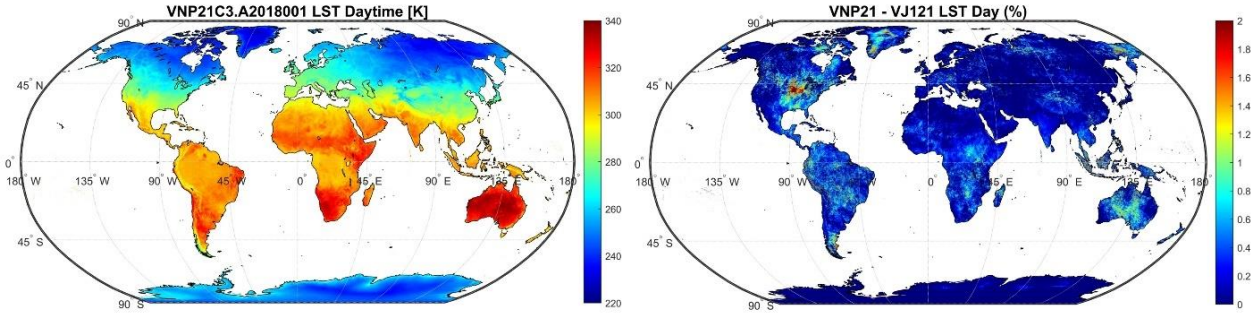

Figure 7. VIIRS mean monthly LST daytime product (VNP21C3) for Jan 2018 (left), and % difference with the equivalent VJ121C3 LST product (right). LST percent differences were generally <1% as expected, with some localized differences of up to 3% due to differences in observation time and/or cloud masking.

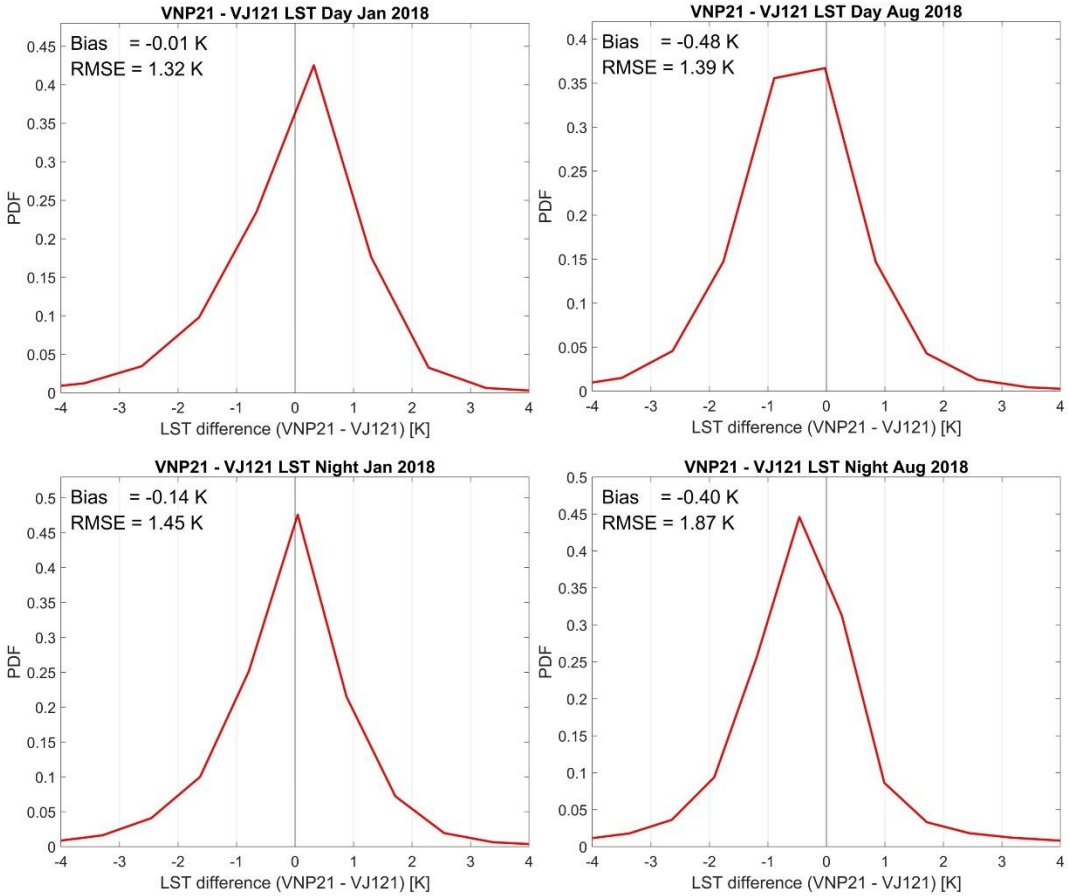

Figure 8. Global average VNP21 minus VJ121 LST histograms for daytime (top row), nighttime (bottom row) and for two different times of year (Jan 2018, left and Aug 2018, right). Negligible day and nighttime biases were found for Jan 2018, while a small ~0.5 K bias was found for Aug 2018 day and nighttime data. However, a summertime bias was expected since SNPP and NOAA-20 orbits are ~50min to one hour apart resulting in larger temperatures differences during summertime (especially deserts) when more rapid changes in LST are typical as the land surface heats up and cools down.

Continuity between the LST&E time series of MODIS and VIIRS products (MYD21 to VNP21 to VJ121) will result in a consistent LST&E data record from NASA's EOS satellites to SNPP to the next-generation JPSS platforms, allowing the creation of continuous, long term and well characterized time series of data from projects such as the NASA MEaSUREs. These types of datasets are critical for our understanding and monitoring of climatic changes in Earth system behavior related to surface temperature. We will continue to monitor continuity and product quality in the LST time series of the SNPP/NOAA-20 products as changes are made to update L1 calibration and reprocessing, and also changes in the VIIRS land cloud mask algorithms.

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