Land Surface Temperature and Emissivity (LST&E) products for MODIS and VIIRS Continuity

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Outline

1. MOD21 LST&E Product
2. MOD21 LST&E Updates
3. New NASA VIIRS LST&E Product
4. MODIS-VIIRS Continuity

Current MODIS/VIIRS LST&E Products

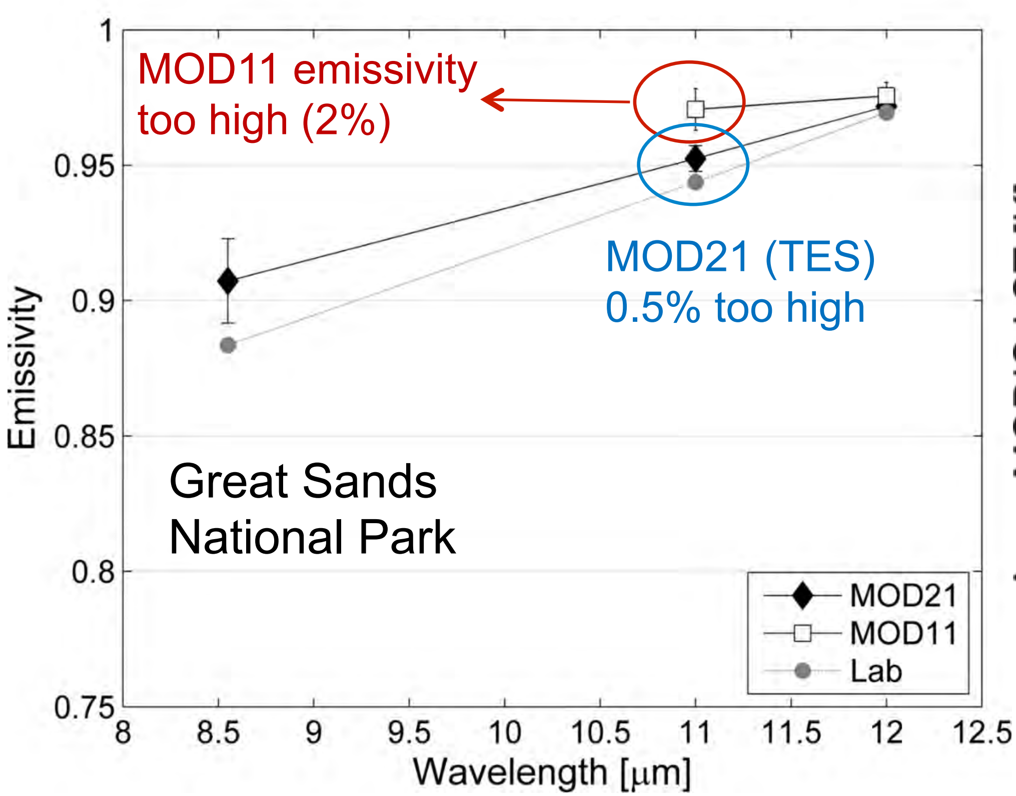
Core Products	Status	Spatial	Formats	Algorithm	SDS
MOD11 (C4, 5, 6*)	Collection 6 in processing	1-km	L2 Swath, L2G 2X Daily	Generalized Split Window (GSW) *Wan et al. 1996, 2008*	- LST
MOD11B1 (C4, 4.1, 5)	?	5-km (C4*) 6-km (C5)	Sinusoidal 2X Daily	Day/Night Algorithm *Wan and Li, 1997*	- LST - Emissivity bands 20-23, 29, 31, 32
VIIRS VLST (IDPS)	Mx8*	750 m	L2 Swath, L2G 2X Daily	Single Split-Window *Yu et al. 2005*	- LST

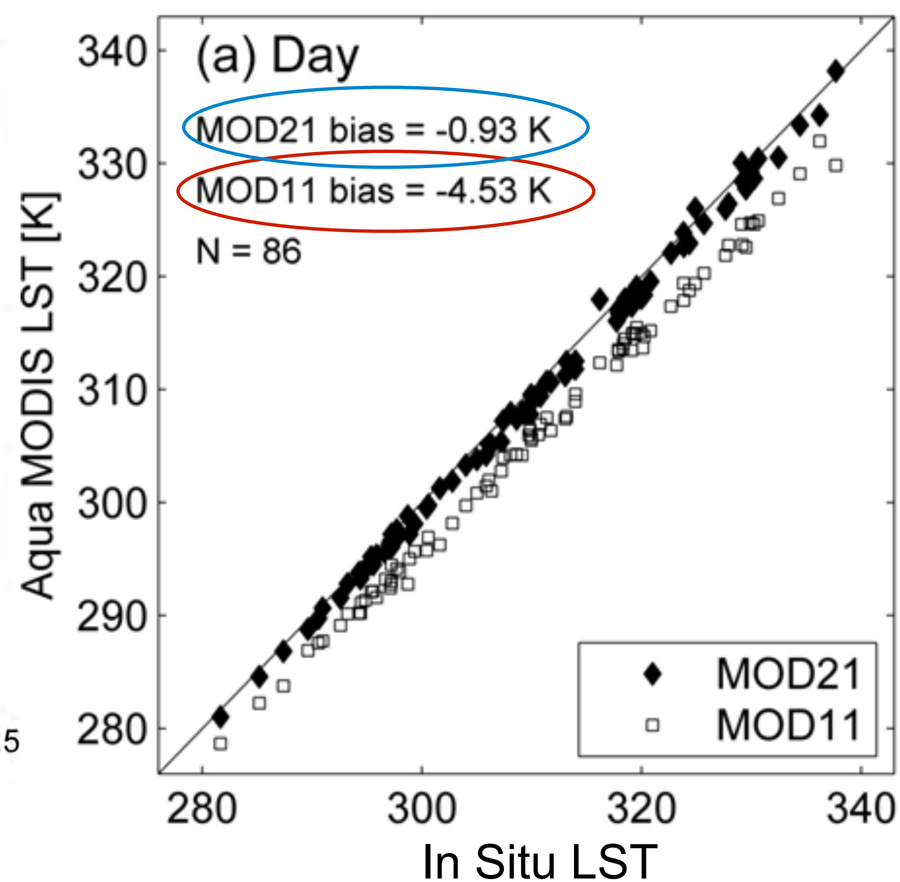
New MODIS/VIIRS LST&E Products (JPL)

New Products	Status	Spatial	Formats	Algorithm	SDS
MODIS-TES (MOD21 C6)	Final testing, released with Collection 6 (Tier-2)	1-km	L2 Swath, L2G 2X Daily L3G Monthly	Temperature Emissivity Separation (TES)	- LST - Emissivity bands 29, 31, 32
VIIRS-TES	Under production at JPL (Algorithm delivery First quarter 2016)	750 m	L2 Swath, L2G 2X Daily L3G Monthly	Temperature Emissivity Separation (TES)	- LST - Emissivity bands 14, 15, 16

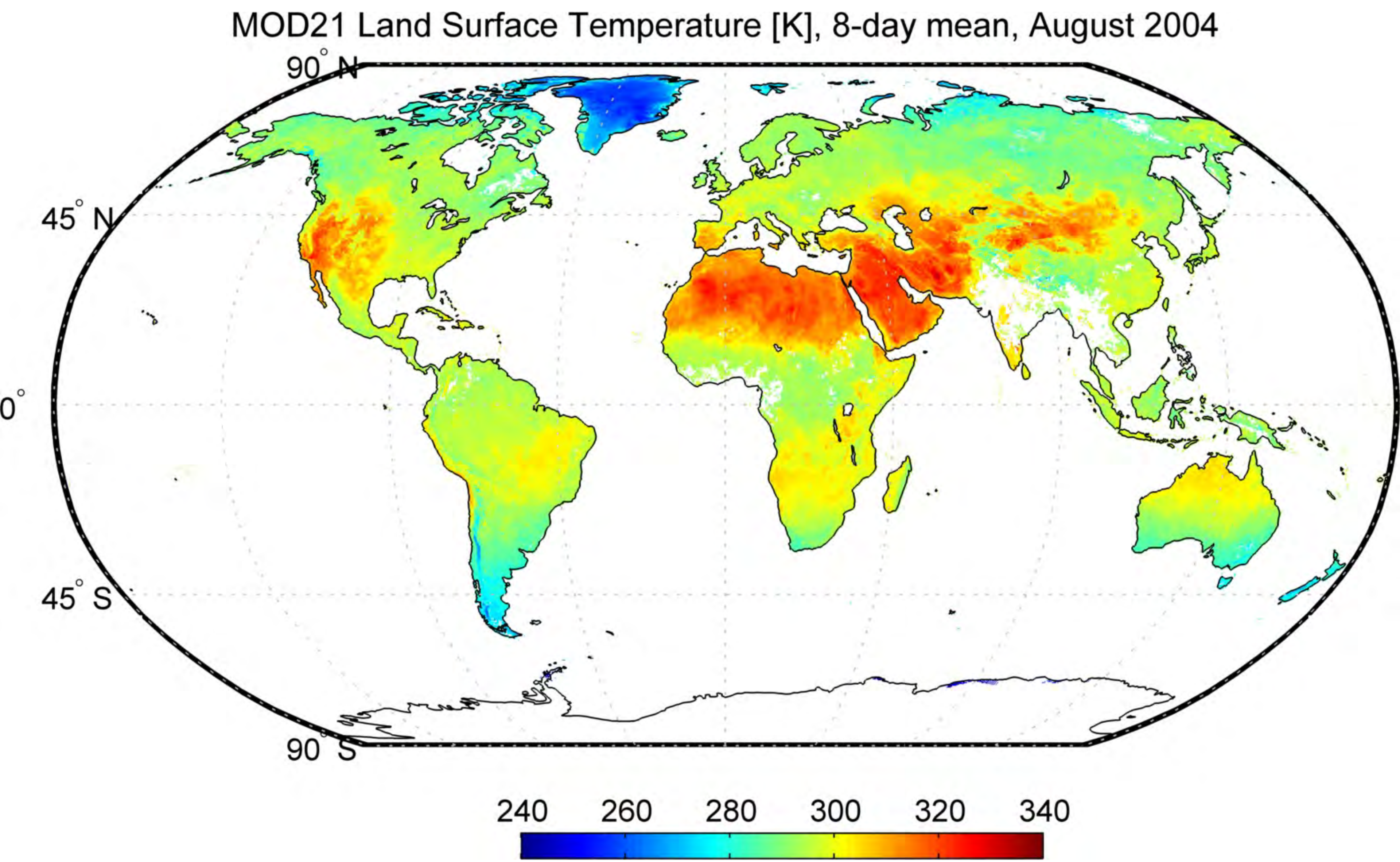
LST/Emissivity Error Dependency

- Overestimation of emissivity leads to underestimation of LST and vice versa.
- Split-window (11-12 micron) fixes emissivity based on land cover classification (IGBP)
- TES physically retrieves emissivity and temperature (minimum 3 bands)



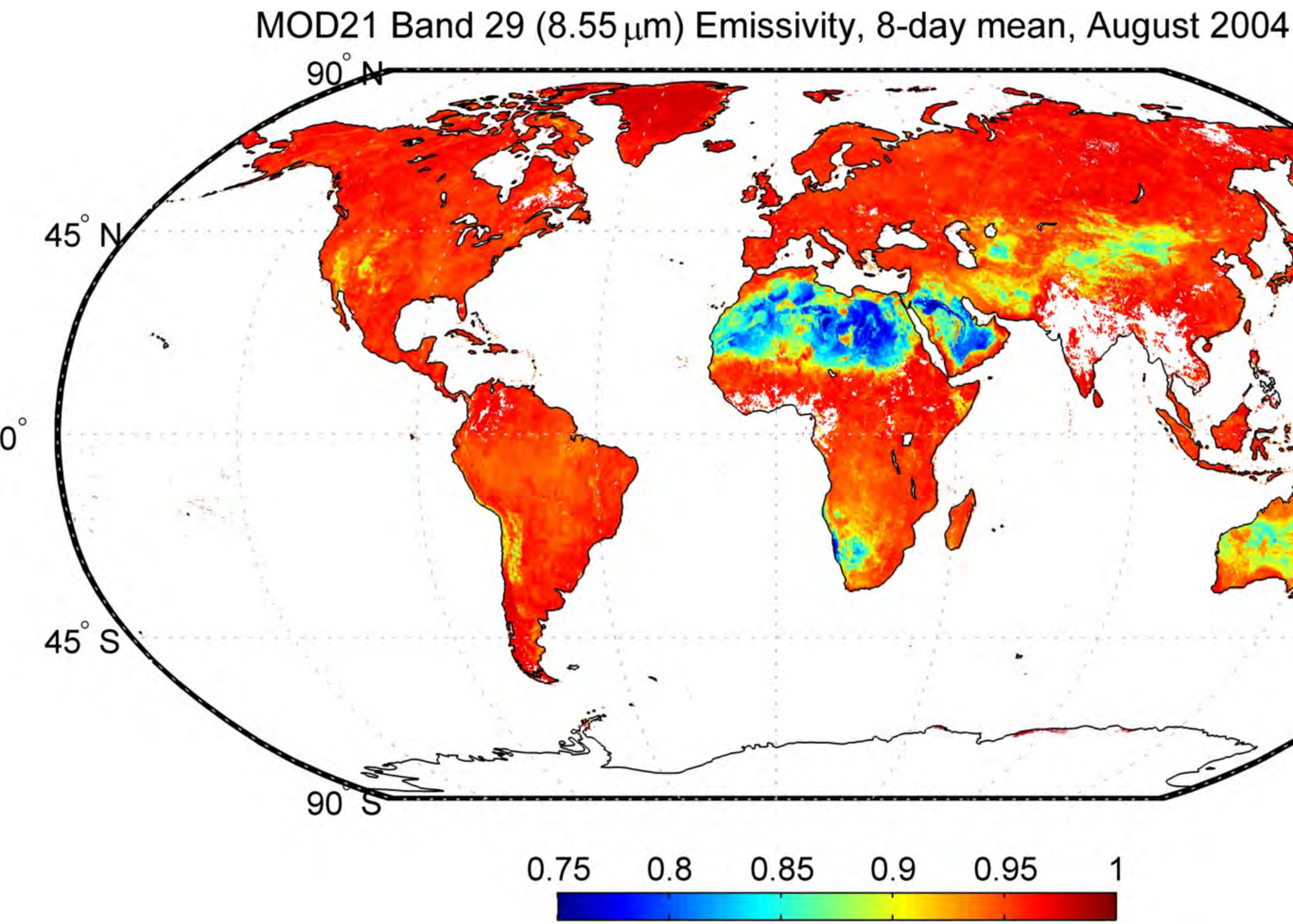


MOD21 LST



Generated using prototype MOD21 algorithm at MODAPS

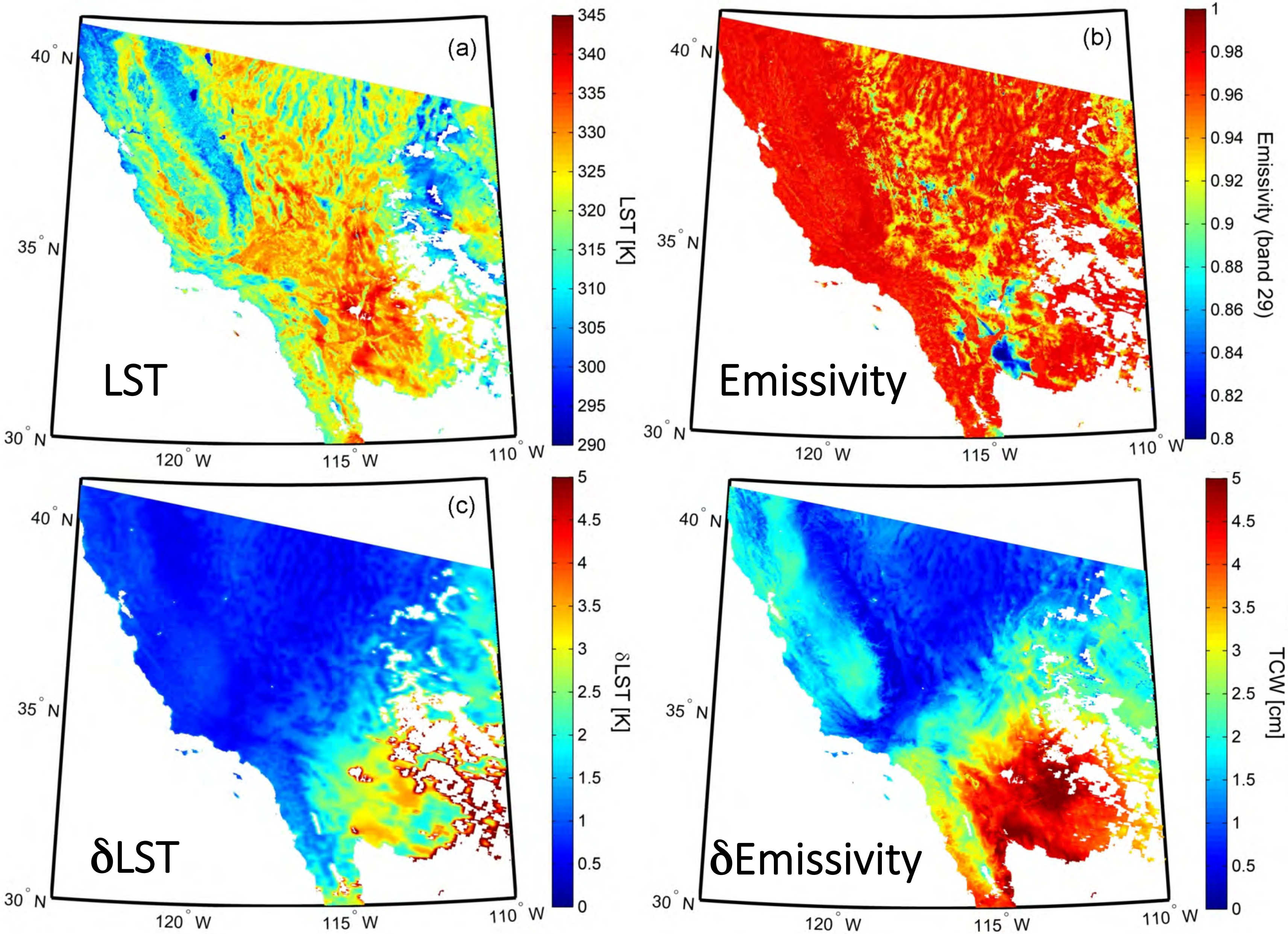
MOD21 Band 29 Emissivity



Generated using prototype MOD21 algorithm at MODAPS

MOD21 C6 LST&E Uncertainty estimates

ROSES 2009: Earth System Data Records Uncertainty Analysis



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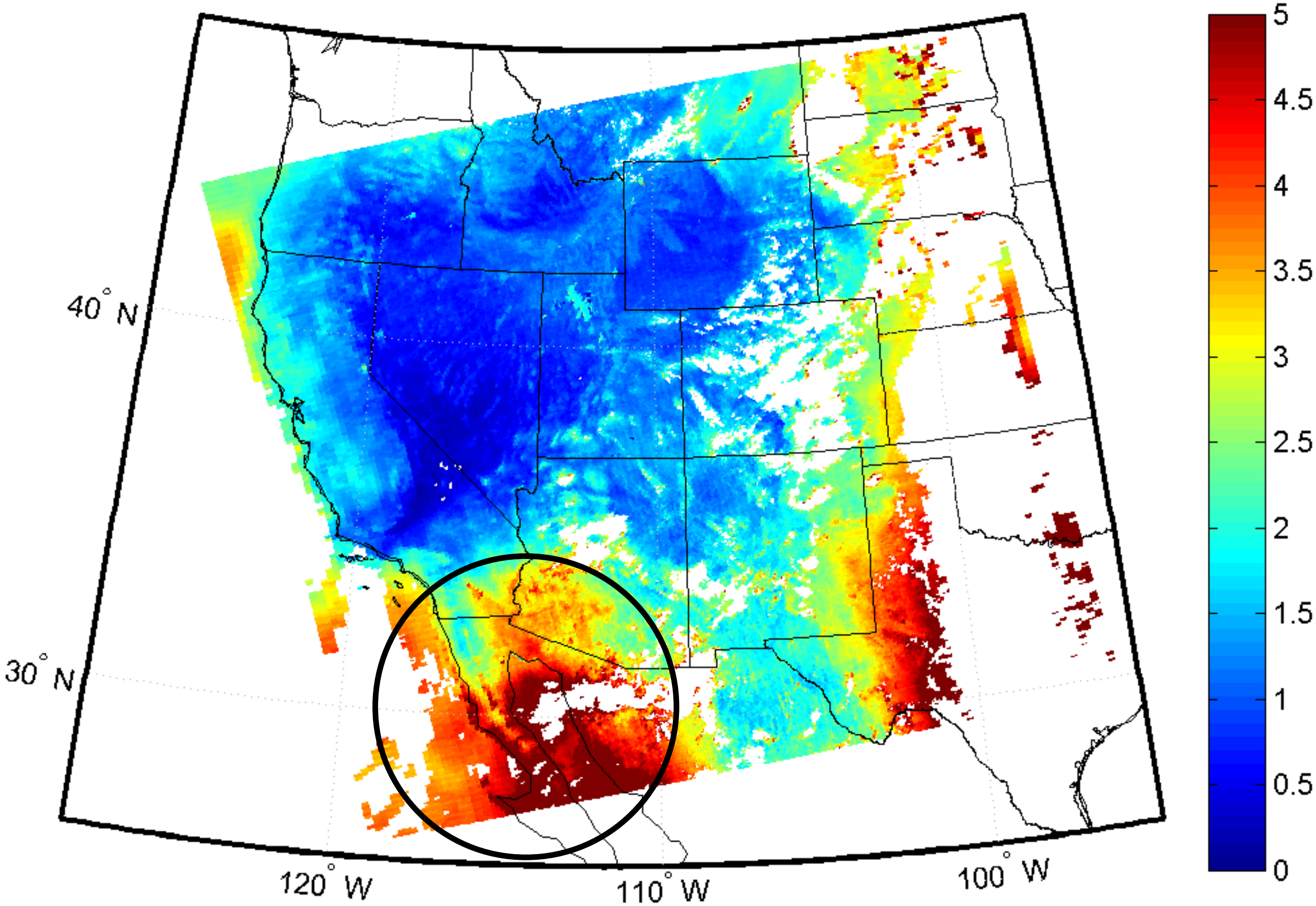
MOD21 Updates and Refinements

Parameter	MOD21 (JPL v2)	MOD21 (JPL v5) (C6)
Radiative Transfer Model	MODTRAN (MOD07 at 25 km)	RTTOV (MOD07 at 5 km)
Water Vapor Scaling (WVS) coefficients	V2	V5 (day/night and view angle dependent)
TES algorithm	One calibration for all surfaces	Two calibrations for Graybody and Bare surface types

Problem Case: Very humid/warm conditions

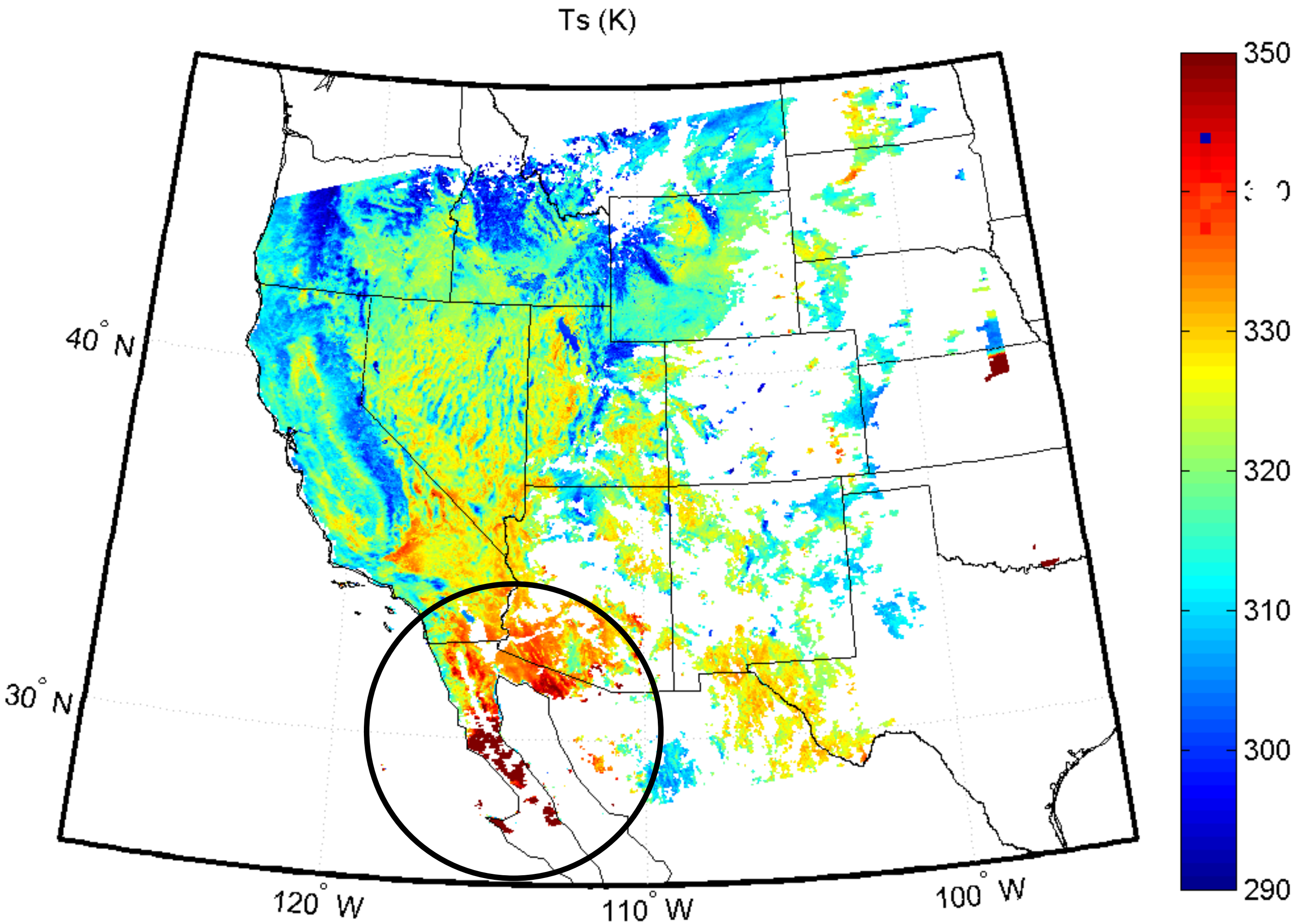
Precipitable Water Vapor – MYD07



Summertime monsoonal conditions

MODTRAN Atmospheric Correction

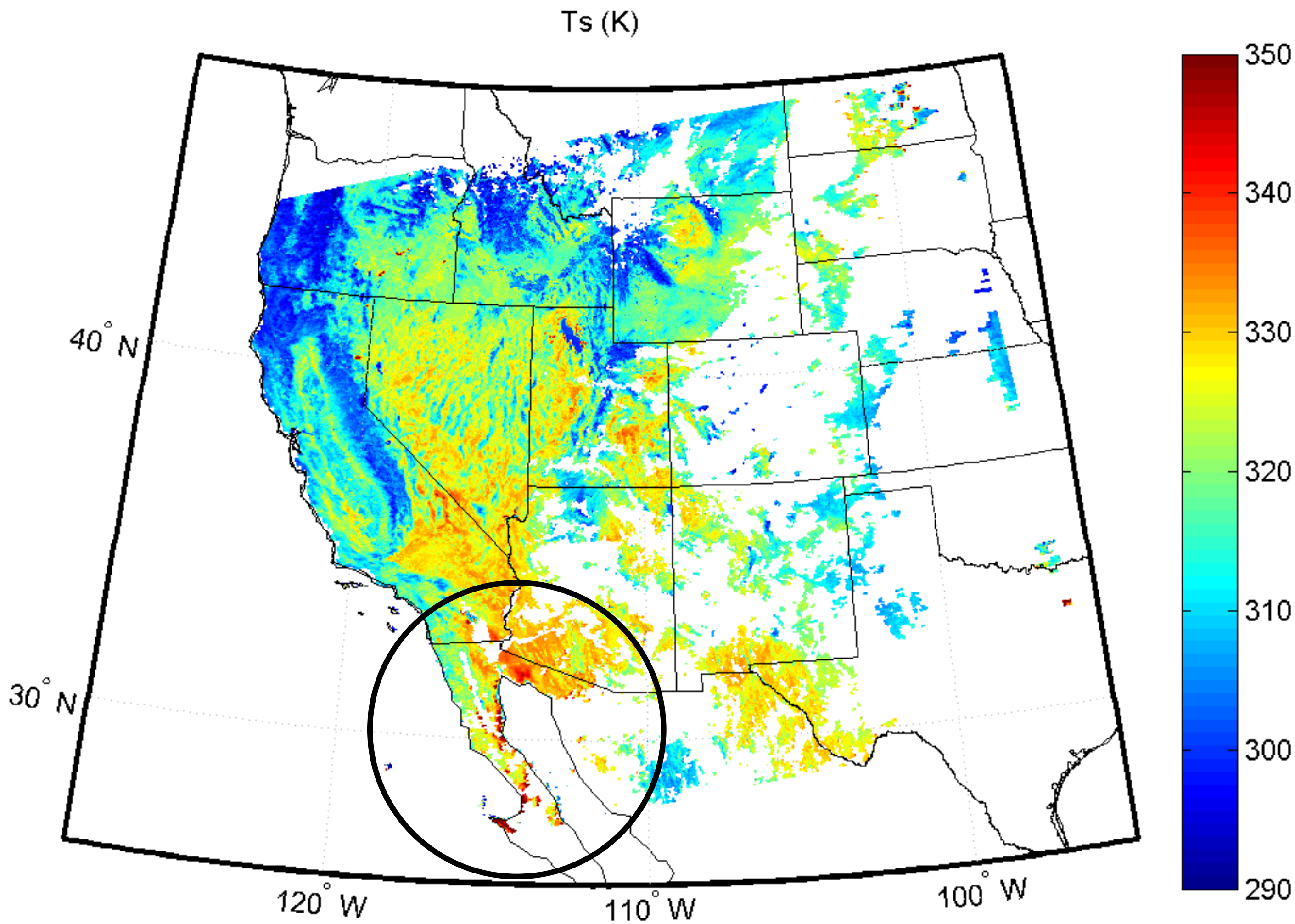
Degraded MOD07 C6 Resolution (25 km)



Temperatures overestimated in very humid conditions!

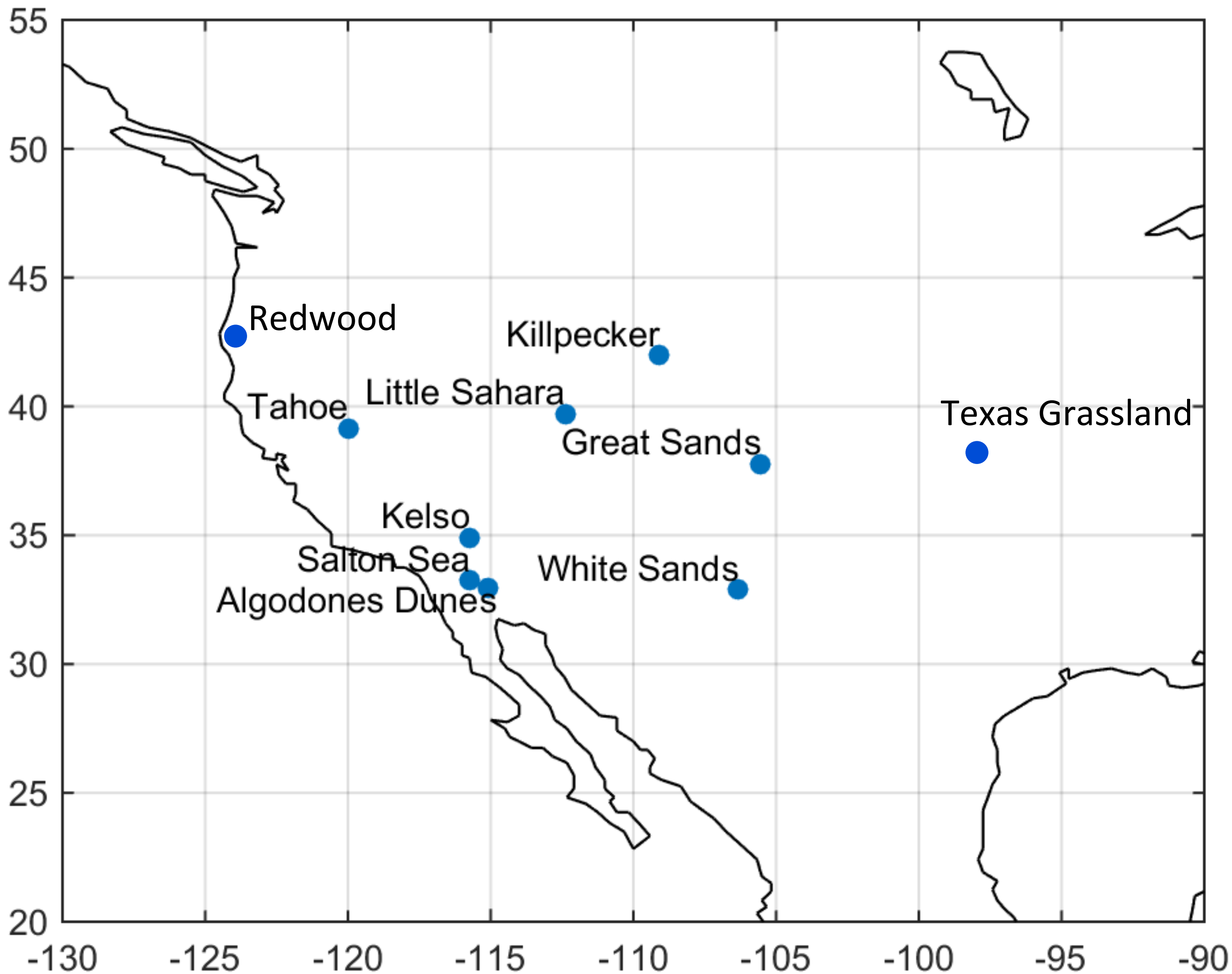
RTTOV Atmospheric Correction

Full MOD07 C6 Resolution (5 km)



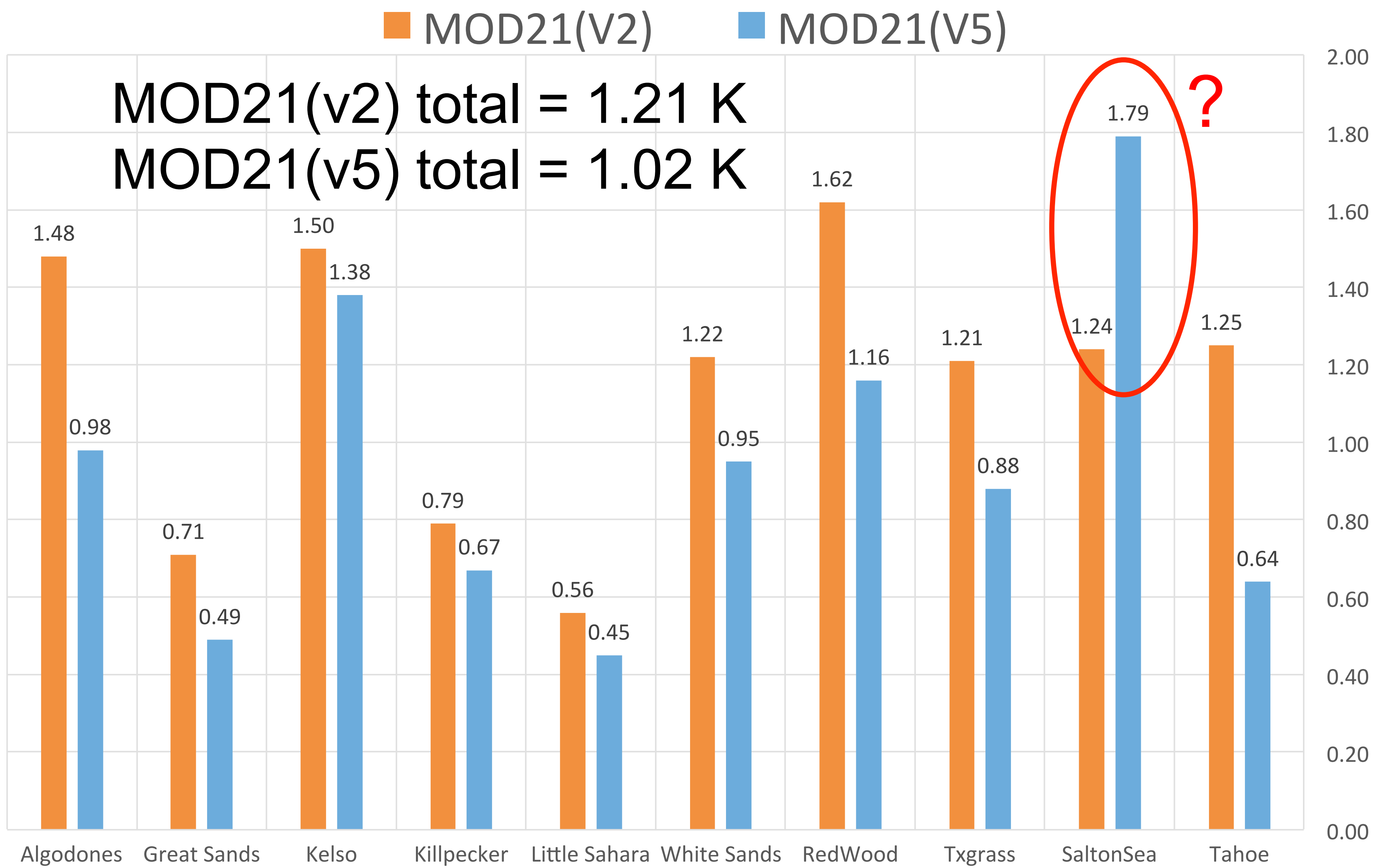
Improved with RTTOV Implementation

LST&E Validation Sites (Stage 1)



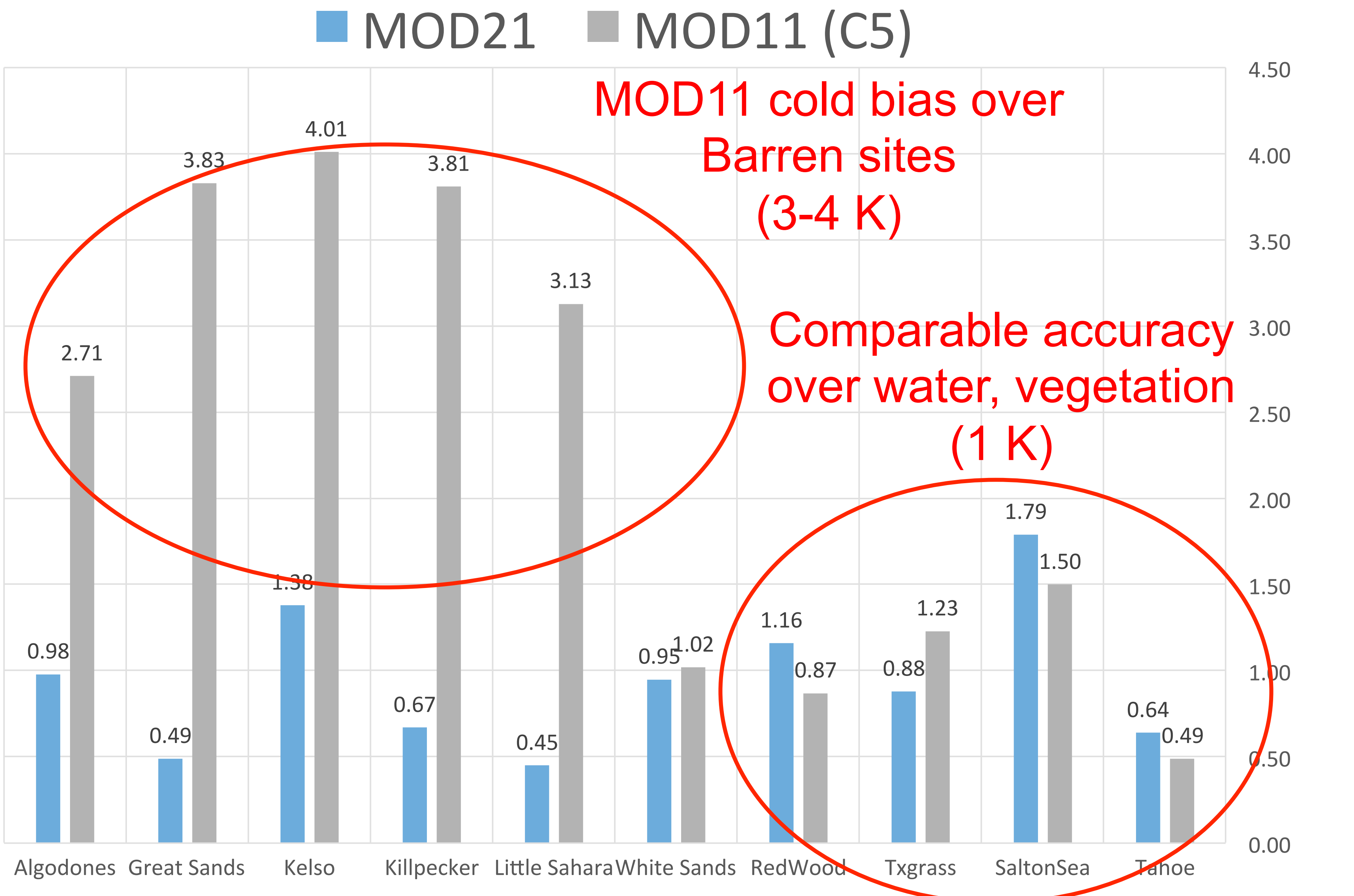
Land Surface Temperature RMSE (K)

2003-2005



Land Surface Temperature RMSE (K)

2003-2005



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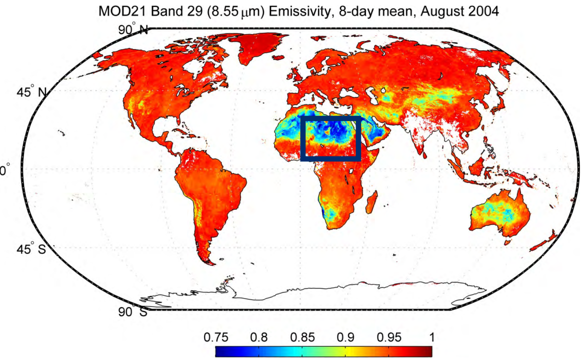
NASA VIIRS/MODIS Products

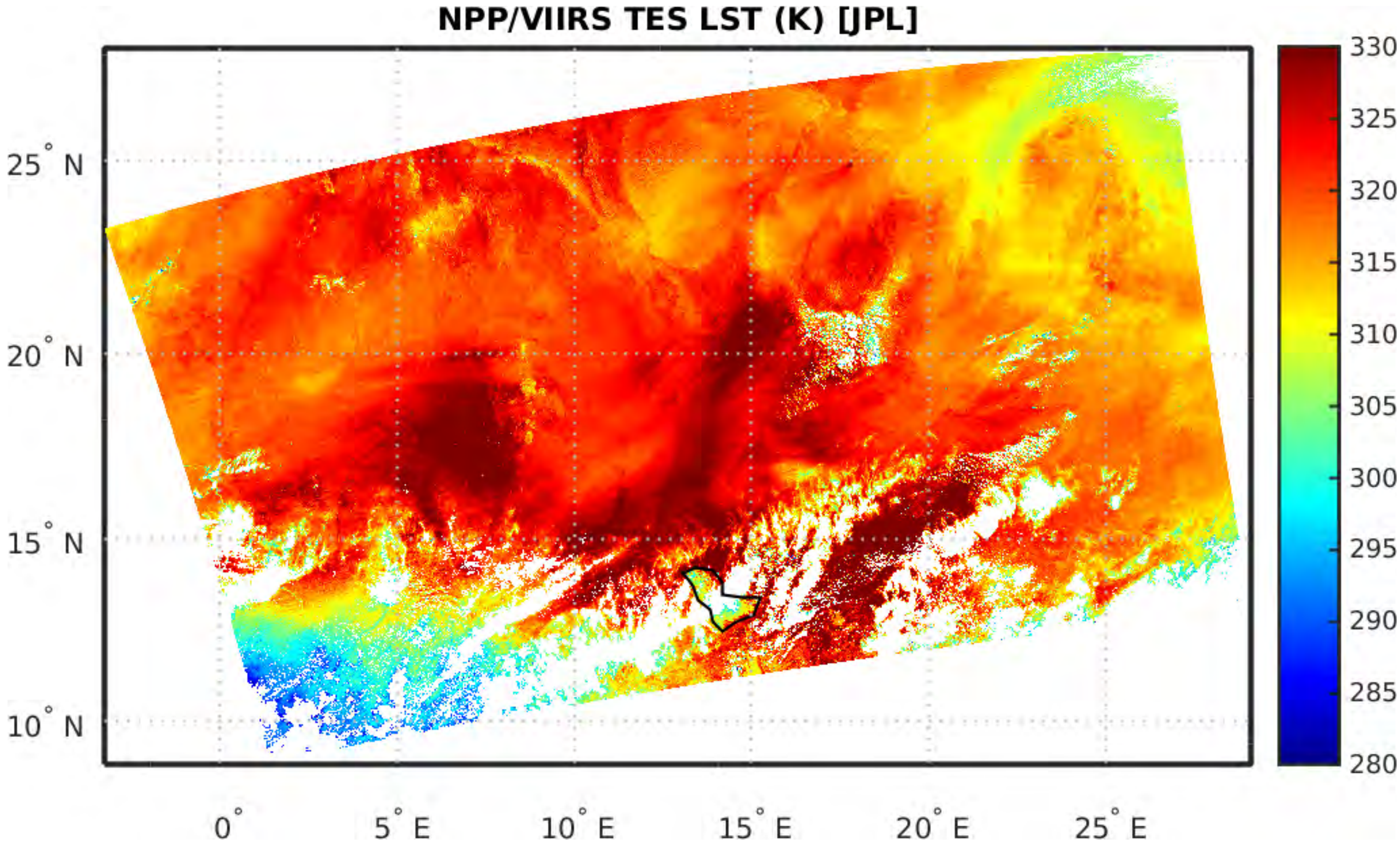
LST&E Product Characteristics	MOD21 (C6)	VIIRS-TES
Algorithm	Temperature Emissivity Separation (TES)	Temperature Emissivity Separation (TES)
Bands used	29 (8.55 µm) 31 (11 µm) 32 (12 µm)	14 (8.55 µm) 15 (10.76 µm) 16 (12 µm)
Radiative Transfer Model	RTTOV	RTTOV
Atmospheric Profiles (T, RH)	MOD07 C6	MERRA, ~~NUCAPS? ECMWF?, NCEP?~~
Algorithm Software	C++/Matlab	C++/Matlab
Data Product Types	L2, L2G Daily (1 km) L3 8-day, (1 km) L3 Monthly (0.05°)	L2, L2G Daily (750 m) L3 8-day, (1 km) L3 Monthly (0.05°)
Science Data Products	- LST - Emissivity (bands 29, 31, 32)	- LST - Emissivity (bands 14, 15, 16)

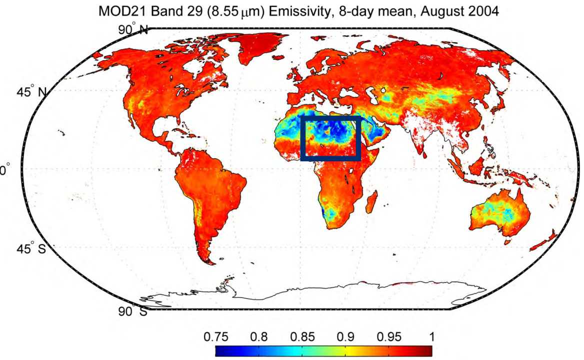
Primary difference



Prototype VIIRS-TES LST&E Retrieval:

Sahel-Sahara test granule





VIIRS M14 (8.55 micron) Emissivity

First use of VIIRS M14 other than cloud mask, RGB's?

Past Studies have shown 8.55 micron emissivity useful for:

- Land Degradation (desertification) monitoring

e.g. French et al. 2008, Hulley et al. 2012

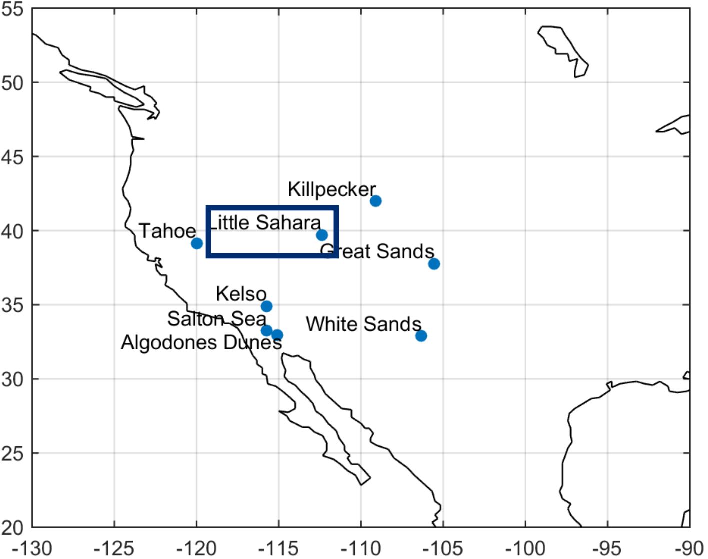
- Soil Moisture relationships

e.g. Mira et al. 2007, Hulley et al. 2009, Masiello et al. 2013

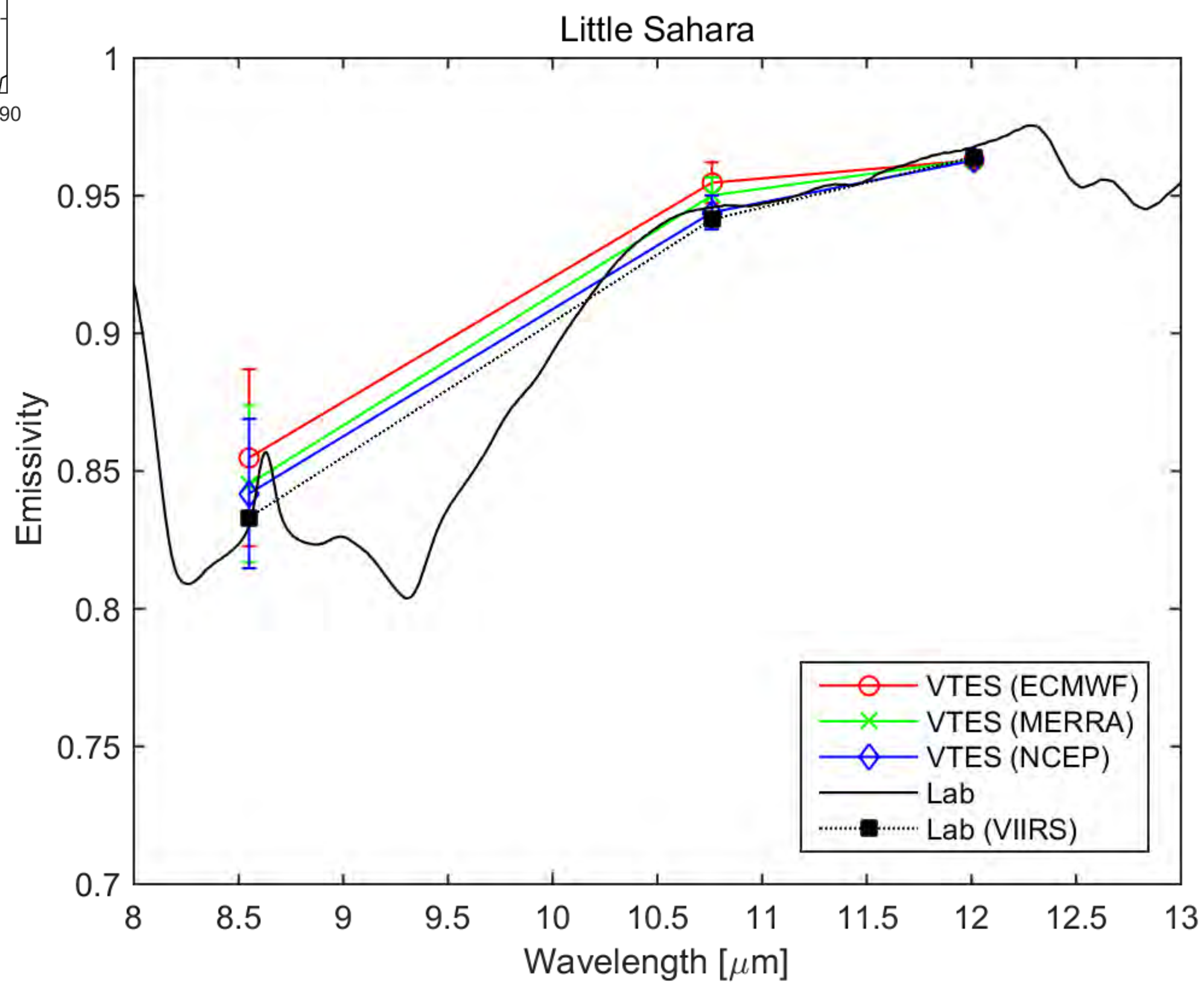
- Land cover, land use change

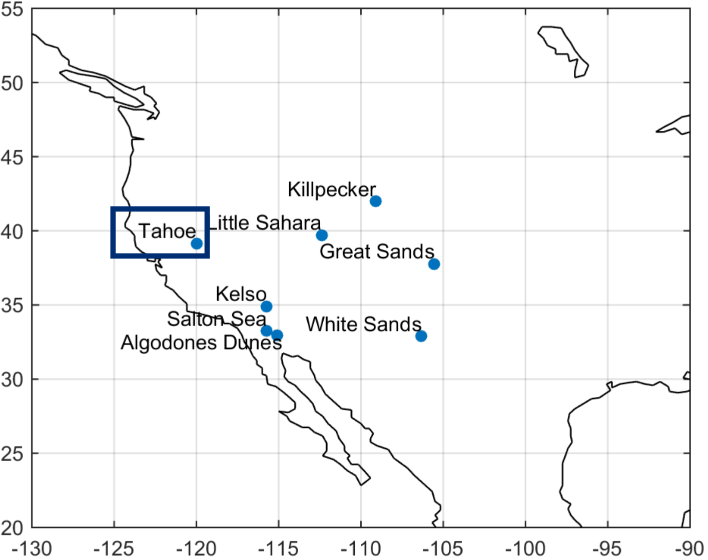
e.g. French et al. 2008, French et al. 2012

0 5 E 10 E 15 E 20 E 25 E



VIIRS Emissivity Validation (2014 data)





VIIRS LST Validation

Site	NWP Model	Bias (K)	RMSE (K)
Lake Tahoe (2014)	ECMWF	-0.14	1.06
	MERRA	-0.13	1.15
	NCEP	-0.23	1.13

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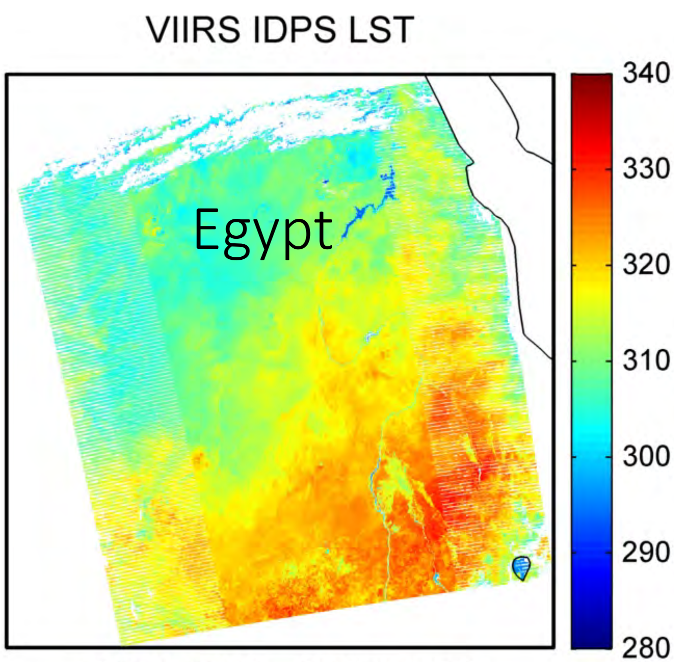
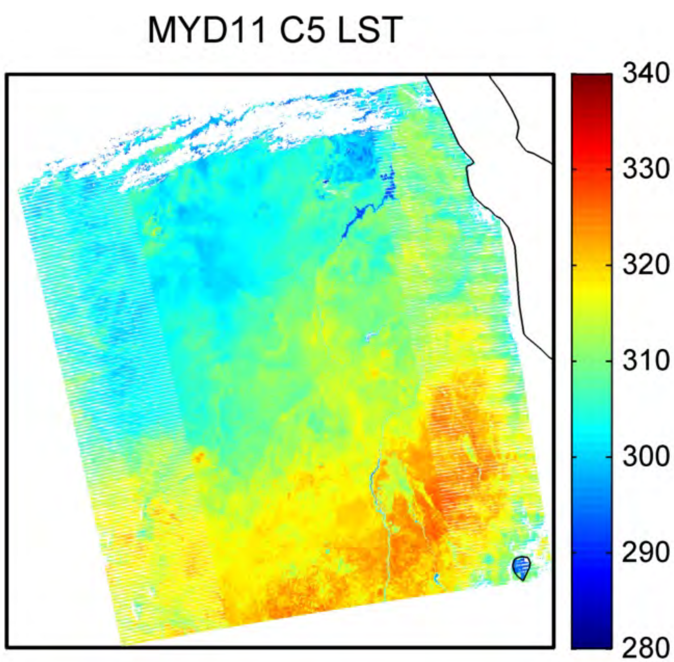
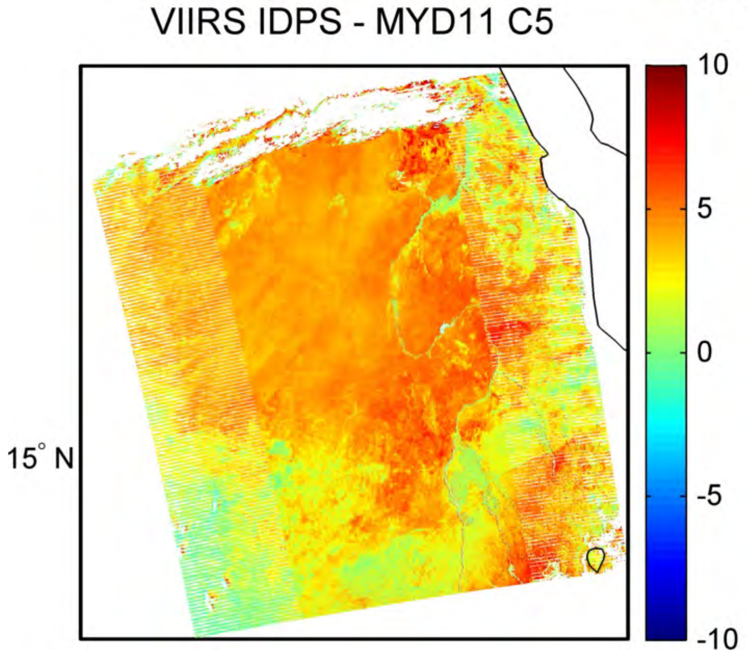
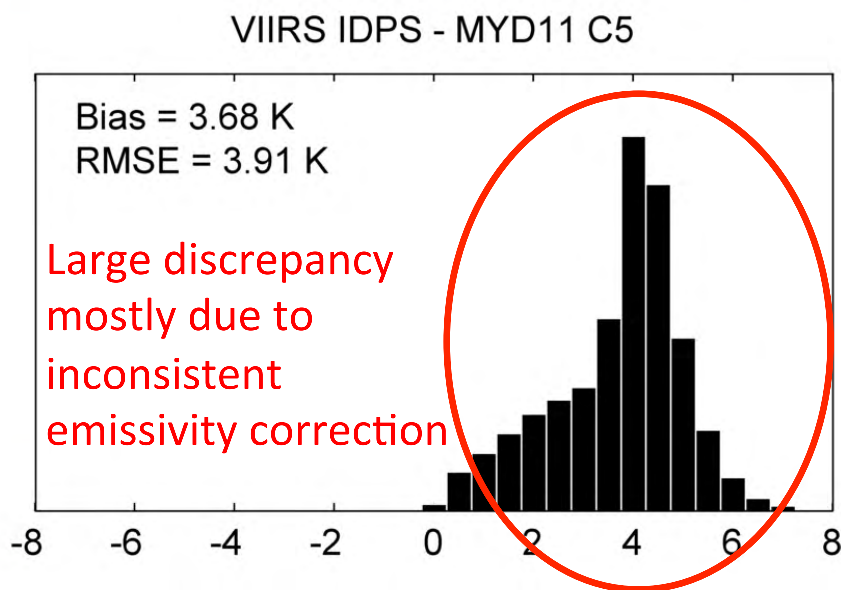
MODIS/VIIRS Split-window Continuity (current)

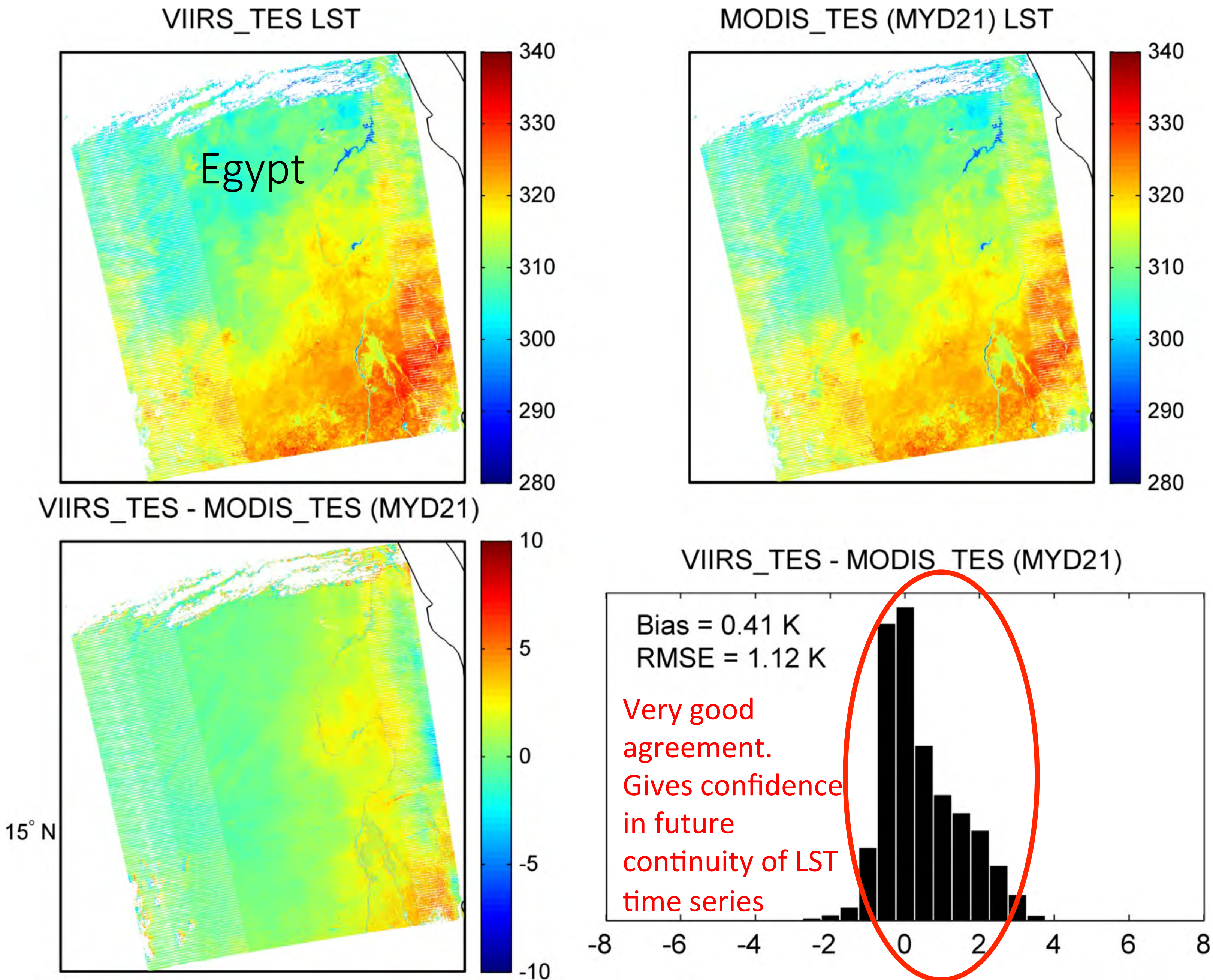








MODIS/VIIRS TES Continuity (planned)



Future Goal(s):

1. Reduce total number of standard LST products for VIIRS/ MODIS (currently 3 different MODIS LST!).
2. Generate Unified products for MODIS and VIIRS standard LST products using uncertainty analysis approach.
3. Evaluate MOD/MYD11 C6 LST

- Unified MODIS LST:
  - Merge MOD11 and MOD21 products (Aqua and Terra)
  - MEaSURES Project Objective (2016)

- Unified VIIRS LST:
  - Merge VLST (IDPS) and VIIRS-TES products**

  *** Contingent upon characterization of VLST Uncertainty*
  - ROSES VIIRS Projective Objective (2017)

The End

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

MODIS LST&E Heritage

MODIS LST Products	Dimensions	Spatial Resolution	Temporal Resolution	Algorithm	Output Products
MOD11	2030 lines 1354 pixels/line	1 km at nadir	Swath 2x daily	Split-Window	- LST
MOD11B1	200 rows 200 columns	~5 km (C4) ~6 km (C5)	Sinusoidal 2x daily	Day/Night	- LST - Emissivity (bands 20-23, 29, 31,32)
MOD21 (Collection 6)	2030 lines 1354 pixels/line	1 km at nadir	Swath 2x daily 8-day	Temperature Emissivity Separation (TES)	- LST - Emissivity (bands 29, 31, 32)

Why MOD21?

- Consistent LST accuracy across all surfaces
- Higher spatial resolution dynamic emissivity (1-km)
- **Current plan is to merge MOD21/MOD11 using Uncertainty Analysis (MEaSUREs)

MOD21 Science Data Sets

Well characterized uncertainties!

Table 1. The Scientific Data Sets (SDSs) in the MOD21 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	0	n/a	n/a
Emis_29	Band 29 emissivity	uint8	n/a	1-255	0	0.002	0.49
Emis_31	Band 31 emissivity	uint8	n/a	1-255	0	0.002	0.49
Emis_32	Band 32 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_29_err	Band 29 emissivity error	uint16	n/a	0-65535	0	0.0001	0.0
Emis_31_err	Band 31 emissivity error	uint16	n/a	0-65535	0	0.0001	0.0
Emis_32_err	Band 32 emissivity error	uint16	n/a	0-65535	0	0.0001	0.0
View_angle	MODIS view angle for current pixel	uint8	Deg	0-180	0	0.5	0.0
NDVI	Normalized Difference Vegetation Index	uint16	n/a	0-65535	0	0.0001	0.0
PWV	Precipitable Water Vapor	uint16	cm	0-65535	0	0.001	0.0
Oceanpix	Ocean-land mask	uint8	n/a	1-255	0	n/a	n/a
Latitude	Pixel Latitude	float32	Deg	-90 to 90	999.99	n/a	n/a
Longitude	Pixel Longitude	float32	Deg	-180 to 180	999.99	n/a	n/a

MOD21 QC

Table 2. Bit flags defined in the QC SDS in the MOD21_L2 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, unreliable quality, emissivity out of physical range (band 32 emissivity < 0.95), or retrieval affected by nearby clouds, or low transmissivity due to opaque atmospheric conditions or high sensor view angles >55°, recommend further examination of QA. 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)
3&2	Data quality flag	00 = Good data quality of L1B bands 29, 31, 32 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	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	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 (Based on Band 31 performance)	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)

MOD21 has well defined Quality Control (QC) parameters based on TES algorithm outputs

JPL LST&E Validation Sites

Site name	Site type	Lat	Lon	Elevation (km)	Emissivity source	IGBP cover type (MOD12)	IGBP fraction (%)	Data availability
Bondville, IL	SURFRAD	40.05 N	88.37 W	0.213	ASTER (NAALSED)	Cropland	7.13	1994-present
Boulder, CO	SURFRAD	40.12 N	105.24 W	1.689	ASTER (NAALSED)	Grassland	5.87	1995-present
Fort Peck, MT	SURFRAD	48.31 N	105.10 W	0.634	ASTER (NAALSED)	Grassland	5.87	1994-present
Goodwin Creek, MS	SURFRAD	34.25 N	89.87 W	0.098	ASTER (NAALSED)	Cropland/Natural Vegetation	8.04	1994-present
Penn State, PA	SURFRAD	40.72 N	77.93 W	0.376	ASTER (NAALSED)	Cropland/Natural Vegetation	8.04	1998-present
Desert Rock, NV	SURFRAD	36.63 N	116.02 W	1	ASTER (NAALSED)	Shrublands	17.7	1998-present
Sioux Falls, SD	SURFRAD	43.73 N	96.62 W	0.473	ASTER (NAALSED)	Cropland	7.13	2003-present
Algodones, CA	PI Sand dune	32.95 N	115.07 W	0.094	In situ/Lab	Bare	9.11	n/a
Coral Pink, UT	PI Sand dune	37.04 N	112.72 W	1.78	In situ/Lab	Bare	9.11	n/a
Great Sands, CO	PI Sand dune	37.77 N	105.54 W	2.56	In situ/Lab	Bare	9.11	n/a
Kelso, CA	PI Sand dune	34.91 N	115.73 W	0.8	In situ/Lab	Bare	9.11	n/a
Killpecker, WY	PI Sand dune	41.98 N	109.1 W	2	In situ/Lab	Bare	9.11	n/a
Little Sahara, UT	PI Sand dune	39.7 N	112.39 W	1.56	In situ/Lab	Bare	9.11	n/a
Stovepipe Wells, CA	PI Sand dune	36.62 N	117.11 W	0	In situ/Lab	Bare	9.11	n/a
White Sands, NM	PI Sand dune	32.89 N	106.33 W	1.216	In situ/Lab	Bare	9.11	n/a
Namib desert, Namibia	PI Sand dune	24.45 S	15.35 E	0.828	In situ/Lab	Bare	9.11	n/a
Kalahari desert, Botswana	PI Sand dune	27.325 S	21.226 E	0.917	In situ/Lab	Shrublands	17.7	n/a
Redwood, CA	Graybody	41.4 N	123.7 W	0.796	ASTER speclib	Evergreen Needleleaf forest	4.12	n/a
Texas Grassland, TX	Graybody	36.29 N	102.57 W	1.28	In situ (Wan)	Grassland	5.87	n/a
Greenland	Graybody	70 N	41 W	0	ASTER speclib	Snow and Ice	~34	n/a
Tahoe, CA	EOS Cal/Val	39.153 N	120 W	1.9	ASTER speclib	Water	tbd	2000-present
Salton Sea, CA	EOS Cal/Val	33.248 N	115.725 W	0	ASTER speclib	Water	tbd	2008-present
Gobabeb, Namibia	LSA-SAF	23.55 S	15.05 E	0.408	In situ/Box Method	Bare	9.11	2008-present
Dahra, Senegal	LSA-SAF	15.34 N	15.49 W	0.09	Lab endmember fraction	Grassland	5.87	2009-present
Evora, Portugal	LSA-SAF	38.9 N	8.00 W	0.016	Lab endmember fraction	Savannas	4.23	2008-present

SURFRAD = NOAA Surface Radiation Budget Network (http://www.esrl.noaa.gov/gmd/grad/surfrad/index.html)

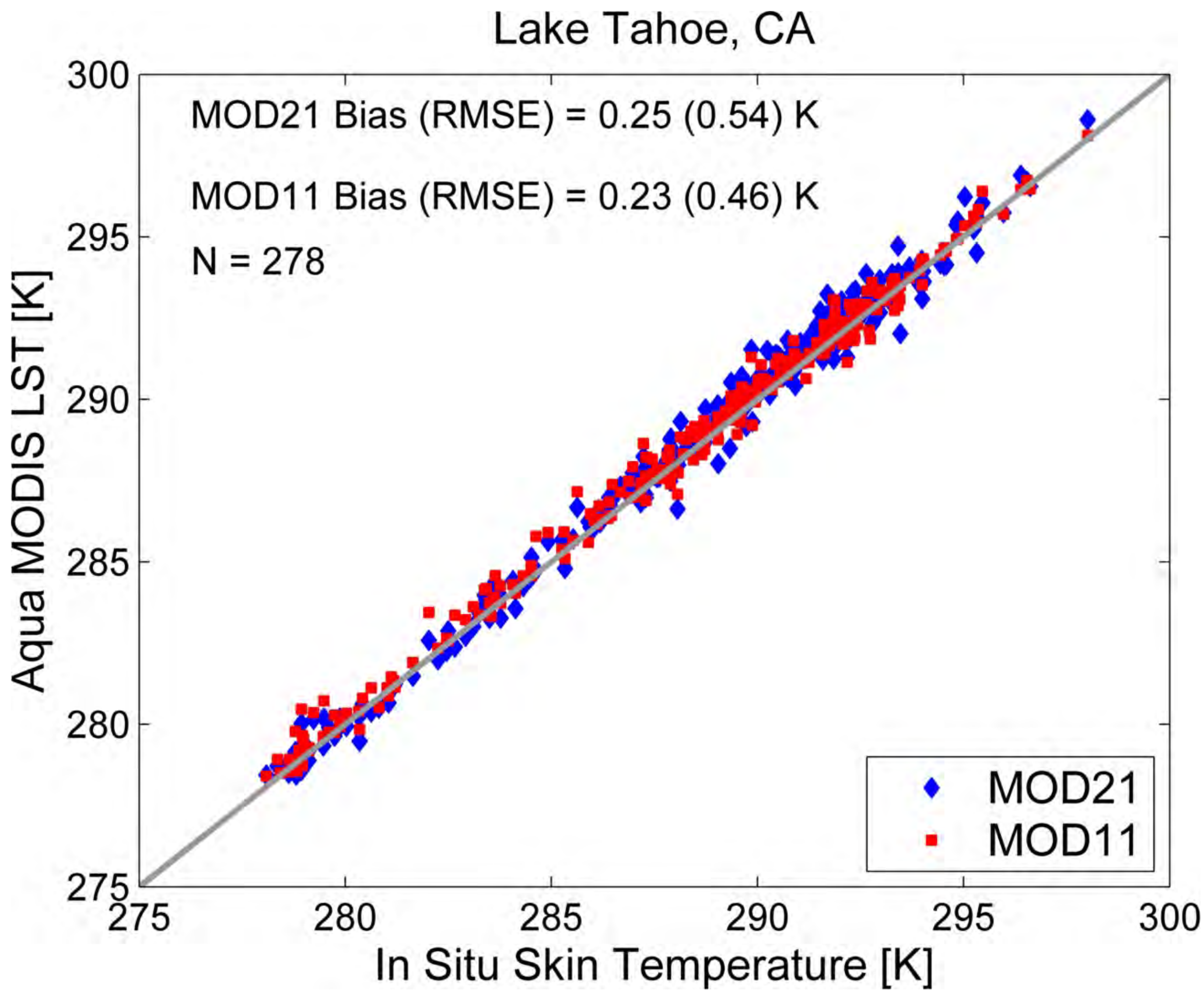
PI Sand dune = Pseudo-invariant sand dune sites (JPL, http://emissivity.jpl.nasa.gov/validation)

Graybody = graybody sites used for R-based validation at JPL

In situ/Lab = Sand samples collected in the field and measured using a Nicolet spectrometer at JPL during 2008

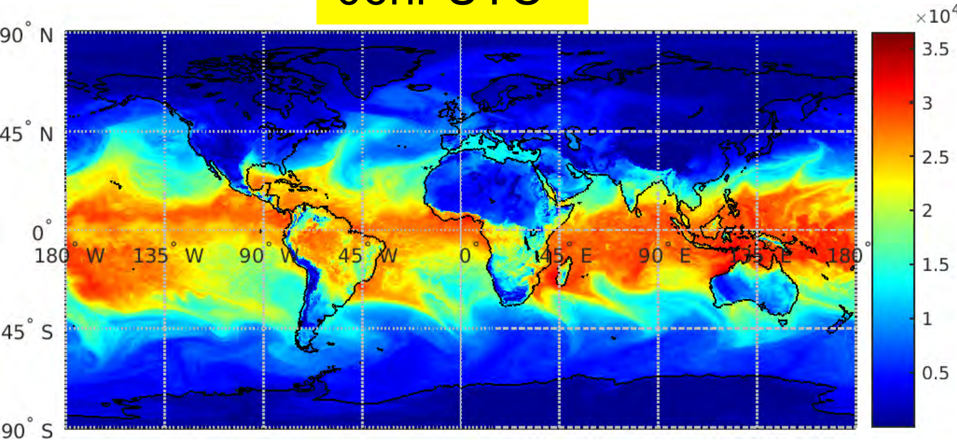
In situ (Wan) = Surface emissivity measured with a sun-shadow method in Dallam County, Texas in April 2005 by Zhengming Wan


6/17/2003 1:20pm

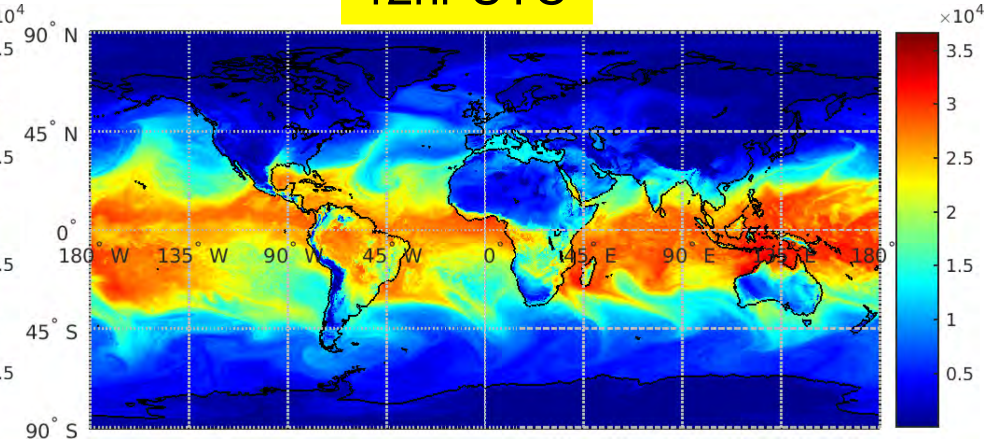

Lake Tahoe, CA
MOD21 Bias (RMSE) = 0.25 (0.54) K
MOD11 Bias (RMSE) = 0.23 (0.46) K
N = 278
Aqua MODIS LST [K]
In Situ Skin Temperature [K]
300
295
290
285
280
275
275
280
285
290
295
300
MOD21
MOD11

MERRA Global Water Vapor (2m)

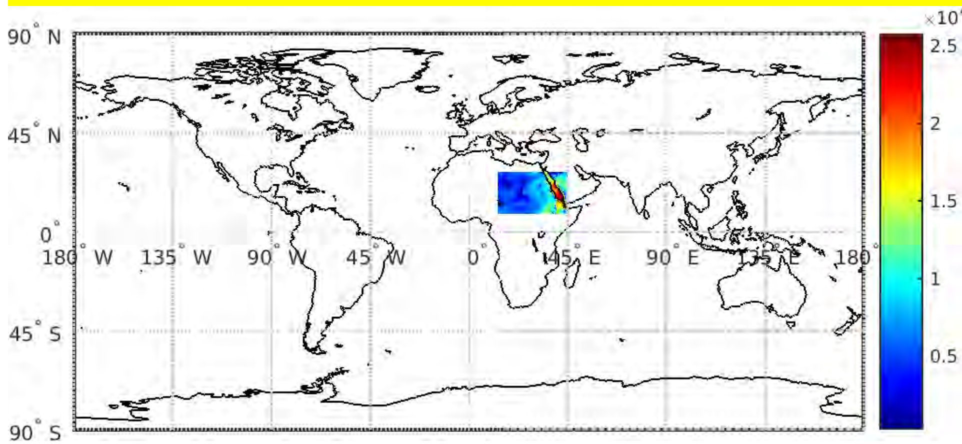
06hr UTC



12hr UTC

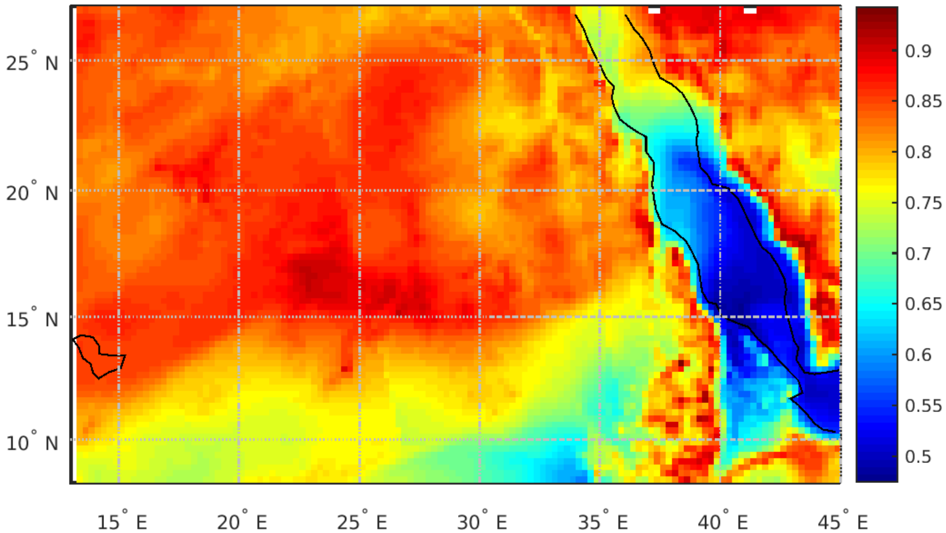


Time Interpolated at 11hr VIIRS UTC

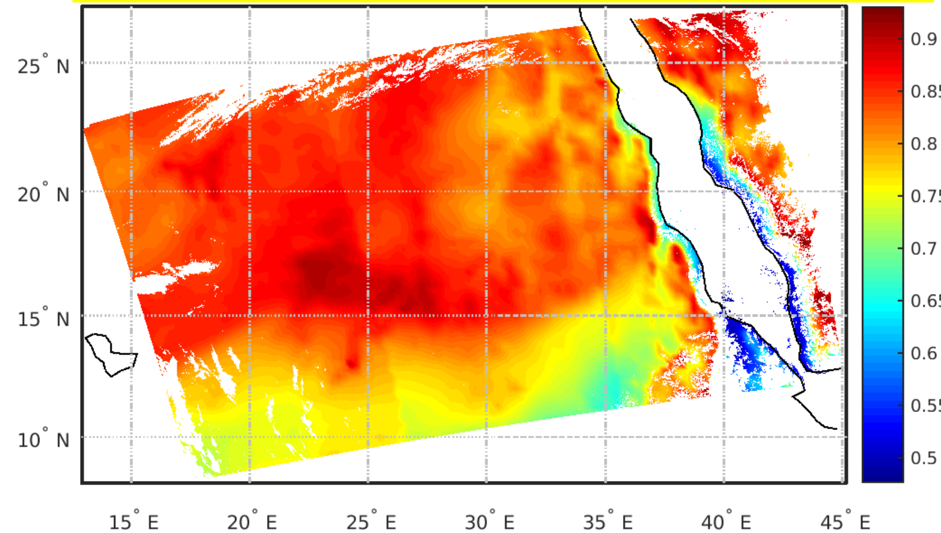


Final Transmittance Field

Native Grid – 11hr UTC

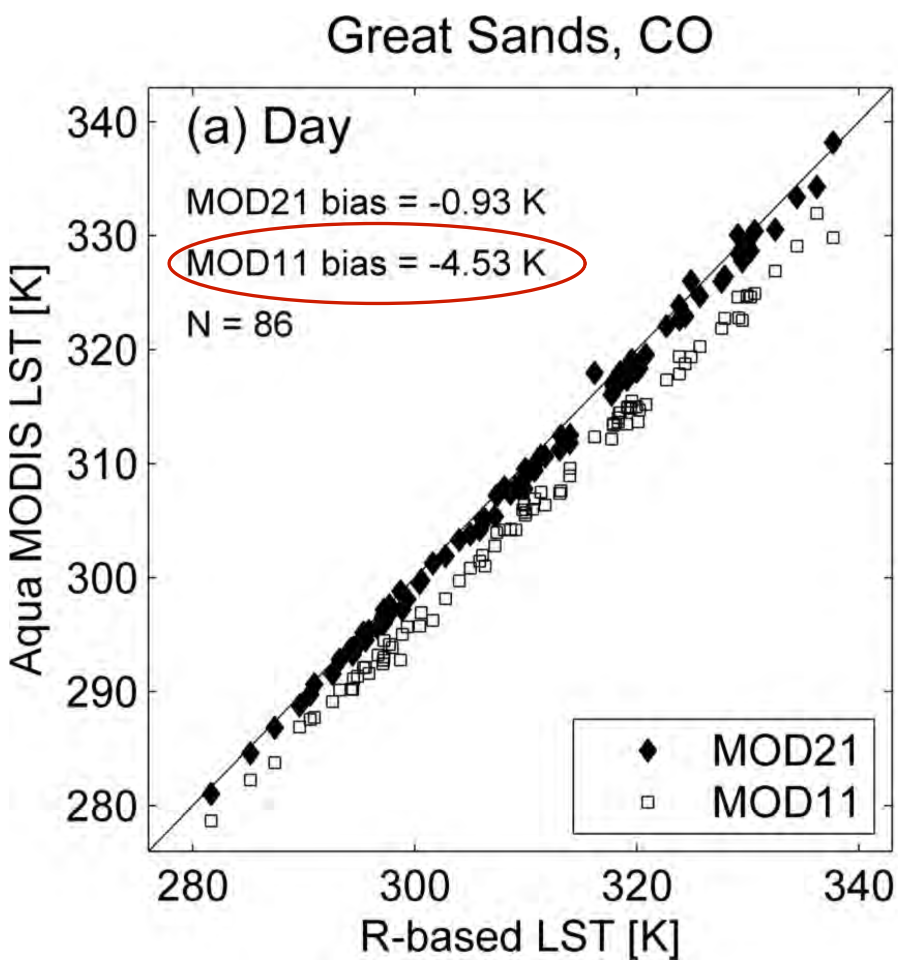


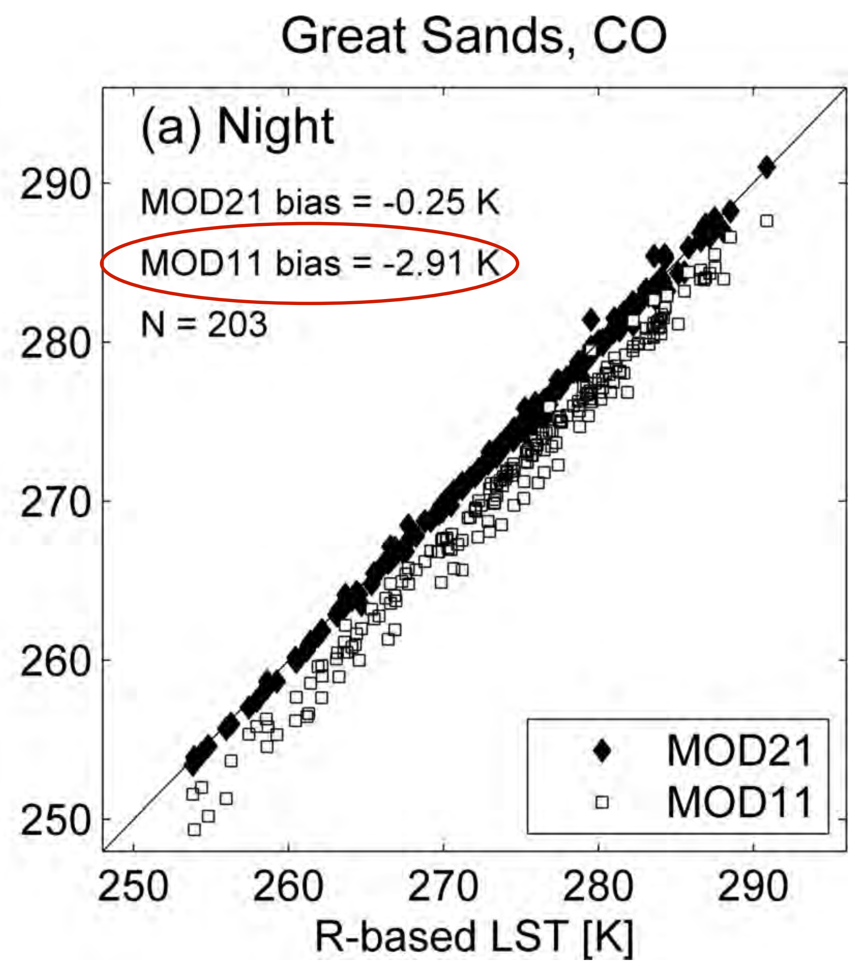
Geolocated to VIIRS – 11hr UTC



Triangulation-based
Interpolation

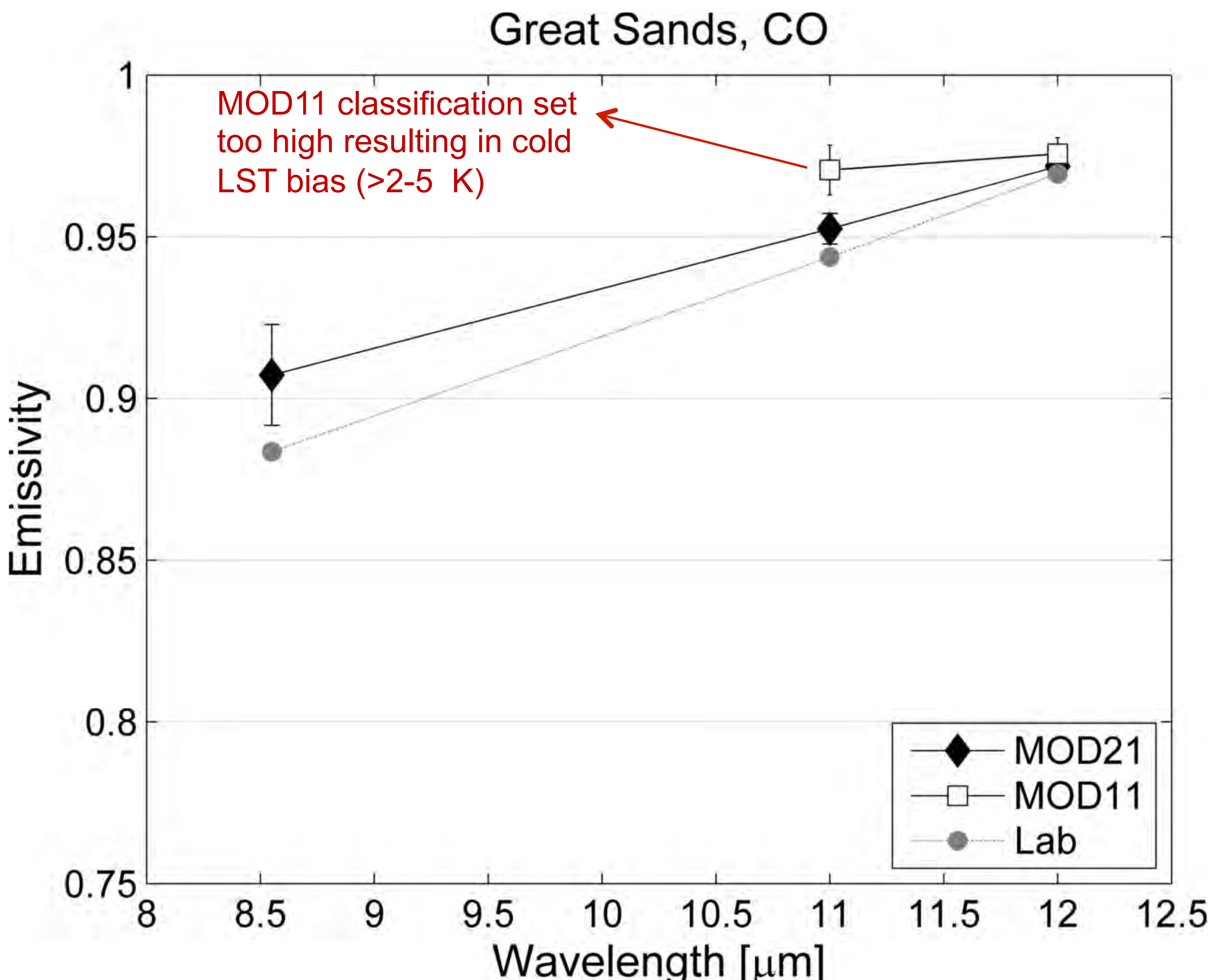
MODIS LST Validation: Great Sands, Colorado





** Radiance-based LST validation using lab-measured sand samples collected at dune site

MODIS Emissivity Validation: Great Sands, Colorado



MOD21/MOD11 LST Validation summary: Graybody surfaces (forest, snow/ice, grassland)

		Aqua Day		Aqua Night	
		MOD11	MOD21	MOD11	MOD21
Redwood Forest, CA 41.4 N, 123.7 W	Bias [K]	0.32	-0.34	0.19	-0.61
	RMSE [K]	0.56	0.61	0.60	0.96
Greenland 70 N, 41 W	Bias [K]	0.61	-0.33	0.34	-0.18
	RMSE [K]	0.73	0.50	0.56	0.35
Texas Grassland 36.29 N, 102.57 W	Bias [K]	0.59	0.24	0.66	0.59
	RMSE [K]	0.85	0.54	1.02	0.98

MOD21 and MOD11 have similar accuracy over graybody surfaces (<1 K)

MOD21/MOD11 LST Validation summary: Bare surfaces (pseudo-invariant sand sites)

Sites	Obs	MOD11	MOD21		MOD11	MOD21
		Bias (K)			RMSE (K)	
Algodones, CA	956	-2.89	-0.05		3.04	1.07
Great Sands, CO	546	-4.53	-0.93		4.63	1.17
Kelso, CA	759	-4.55	-1.48		4.62	1.67
Killpecker, WY	463	-4.51	-1.19		4.58	1.42
Little Sahara, UT	670	-3.71	-0.60		3.79	0.89
White Sands, NM	742	-0.73	-0.29		1.07	0.95

MOD11 C5 cold bias of up to ~5 K over bare sites

(due to overestimated classification emissivity)

Future Work and Summary

- MOD21 PGE in final stages of testing and development in preparation for Collection 6
- Reprocessing of MODIS Terra/Aqua to begin May/June
- Development and optimization of MOD21 algorithm will continue under NASA TERAQ award from 2014-2016
- MOD21 LST&E products are physically retrieved with TES algorithm resulting in similar accuracy (<1.5 K) over all land cover types and a dynamic spectral emissivity product for detection and monitoring of landscape changes
- A unified MOD21/MOD11 LST product is in production for a NASA MEaSUREs project at JPL

Theoretical Basis: Planck Function

$$B_\lambda = \frac{c_1}{\lambda^5 \left[\exp\left(\frac{c_2}{\lambda T_s} \right) - 1 \right]}$$

$$T_s = B_\lambda^{-1}$$

where :

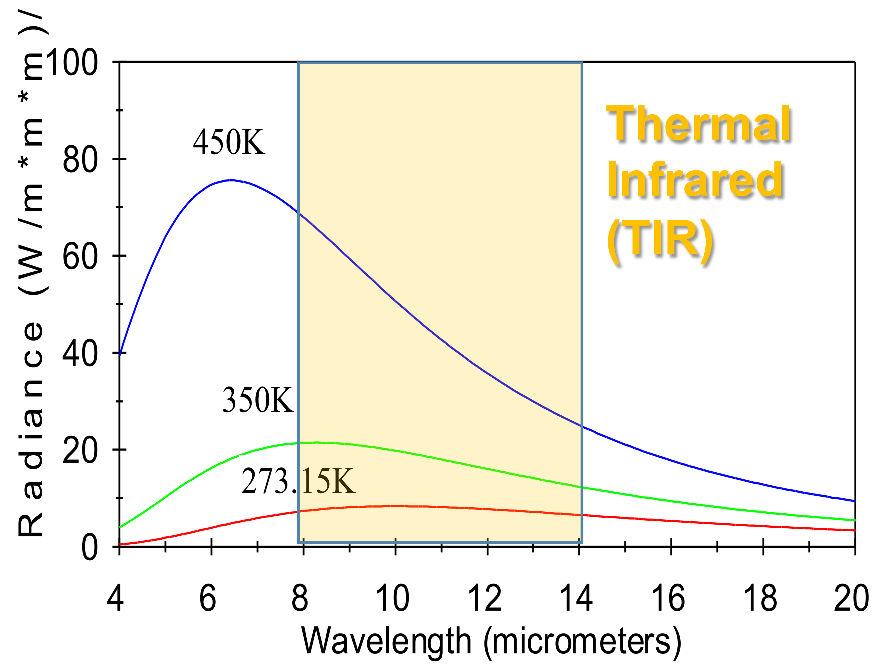
B_λ = blackbody spectral radiance

λ = wavelength

T_s = Surface Temperature

c_1 = first radiation constant

c_2 = second radiation constant



As the temperature increases the peak in the Planck function shifts to shorter and shorter wavelengths

Temperature/Emissivity retrieval algorithms

To solve the under-determined temperature-emissivity problem:

N spectral measurements (N radiances) with N + 1 unknowns (N emissivity, 1 Temperature)

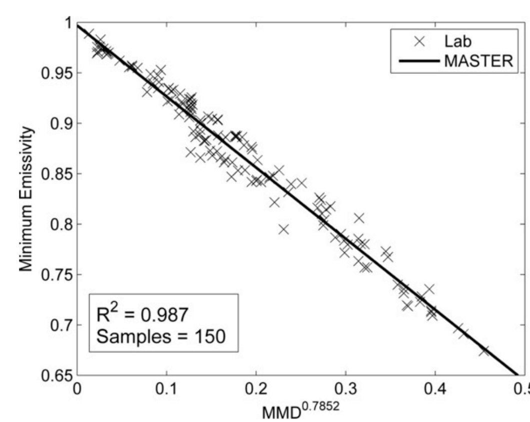
1. Split window approach

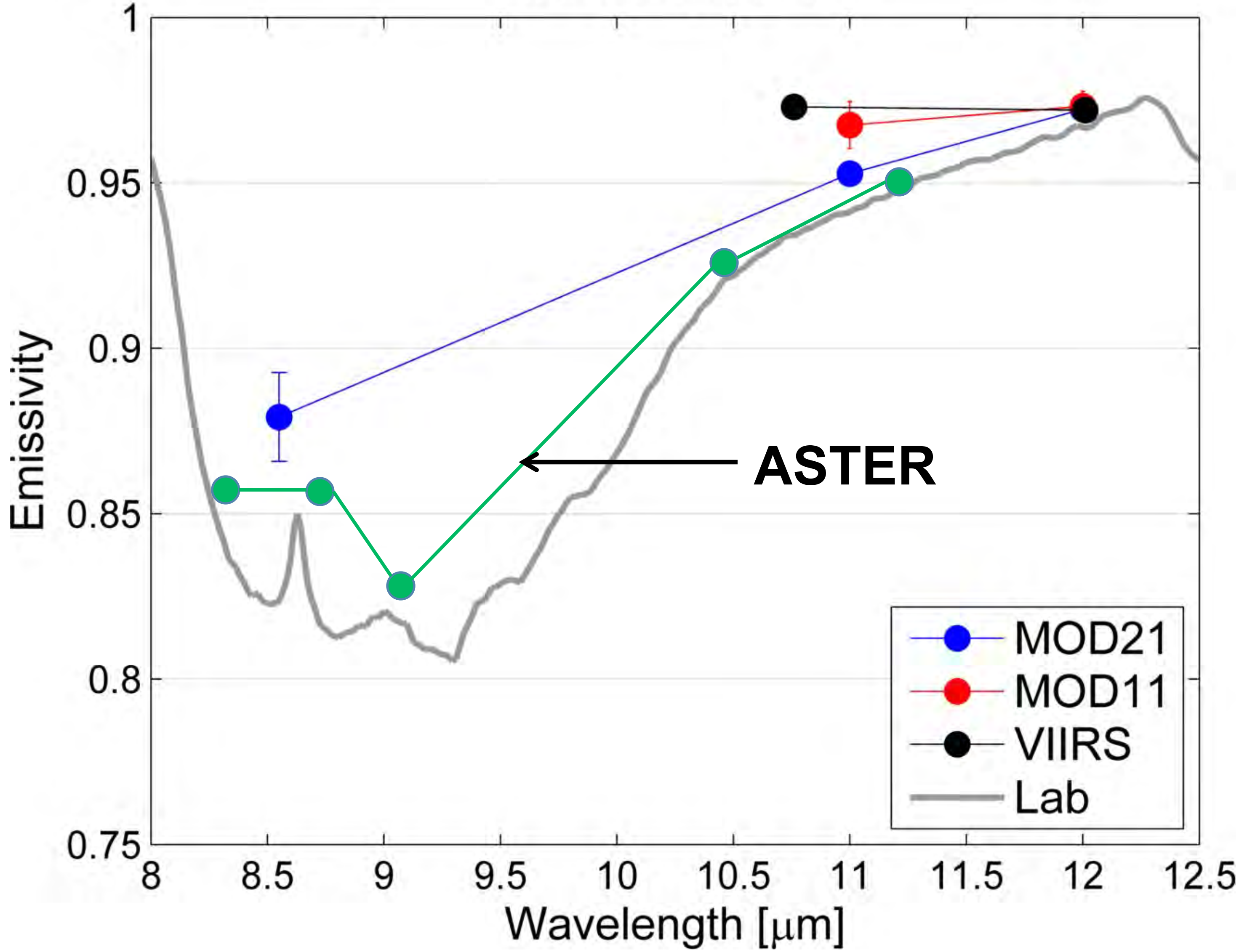
$$LST = a_0 + a_1 T_{11\mu m} + a_2 (T_{11\mu m} - T_{12\mu m})$$

- Requires 2 bands
- Prescribed spectral emissivity
- Regression coefficients should represent all configurations (atmospheric water content, view angle, surface T_{air}, …)

2. Temperature-Emissivity Separation (TES) – ASTER approach

- Multispectral (minimum 3 bands)
- Requires atmospheric profiles for full atmospheric correction with Radiative Transfer Model
- Based on Emissivity model (Calibration Curve)





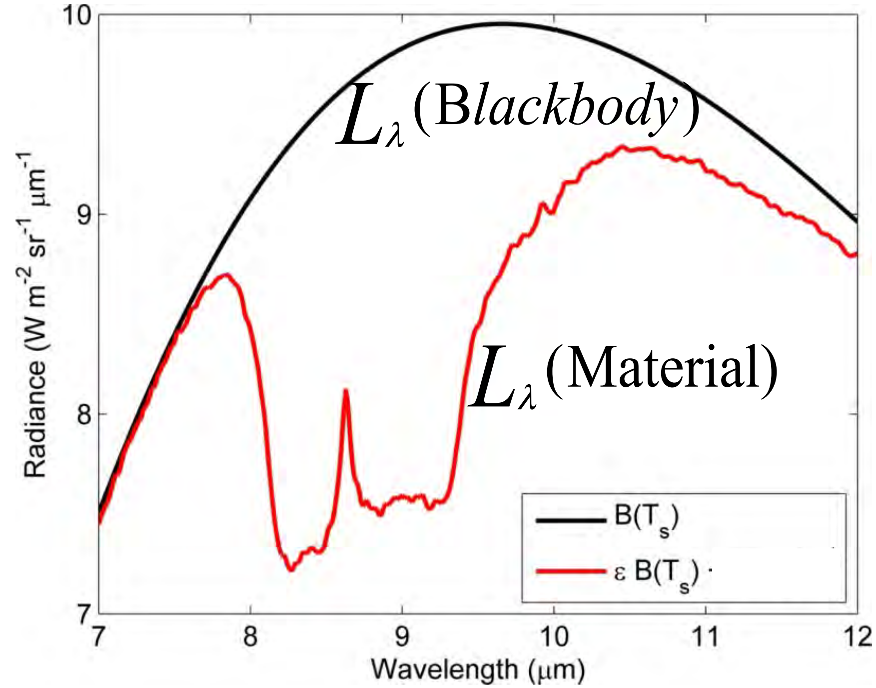
Emissivity
Wavelength [μm]
ASTER
MOD21
MOD11
VIIRS
Lab
1
0.95
0.9
0.85
0.8
0.75
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5

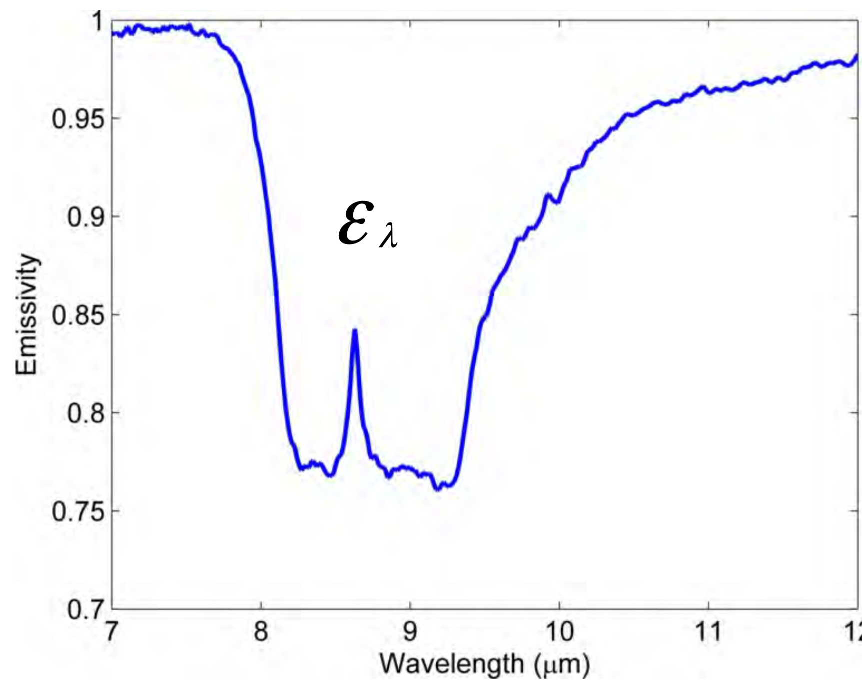
Spectral Emissivity

Emissivity: ratio of the spectral radiance of a material to that of a blackbody at the same temperature:

$$\varepsilon_\lambda = \frac{L_\lambda(\text{Material})}{L_\lambda(\text{Blackbody})}$$

L_λ = Spectral Radiance





VIIRS –TES Processing Steps	Test Code Implementation	Evaluation
Read L1B and Cloud Mask Data (Fill radiances – bowtie)	✓	✓
NWP atmospheric data (read, geolocate, interpolate)	✓	✓
Run RTTOV Radiative Transfer	✓	✓
Test NWP Accuracy (ECMWF, MERRA, NCEP)	✓	*In progress*
Implement Water Vapor Scaling (WVS) Model	✗	✗
Temperature Emissivity Separation (TES)	✓	✓
Validation	✓	*In progress*