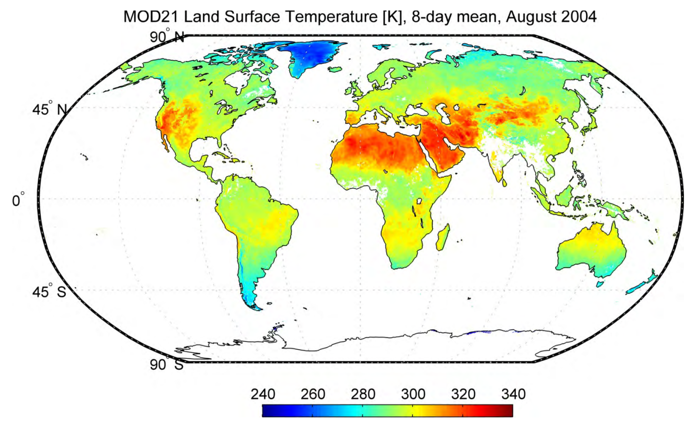
National Aeronautics and Space Administration

The MODIS Land Surface Temperature and Emissivity (LST&E) Products



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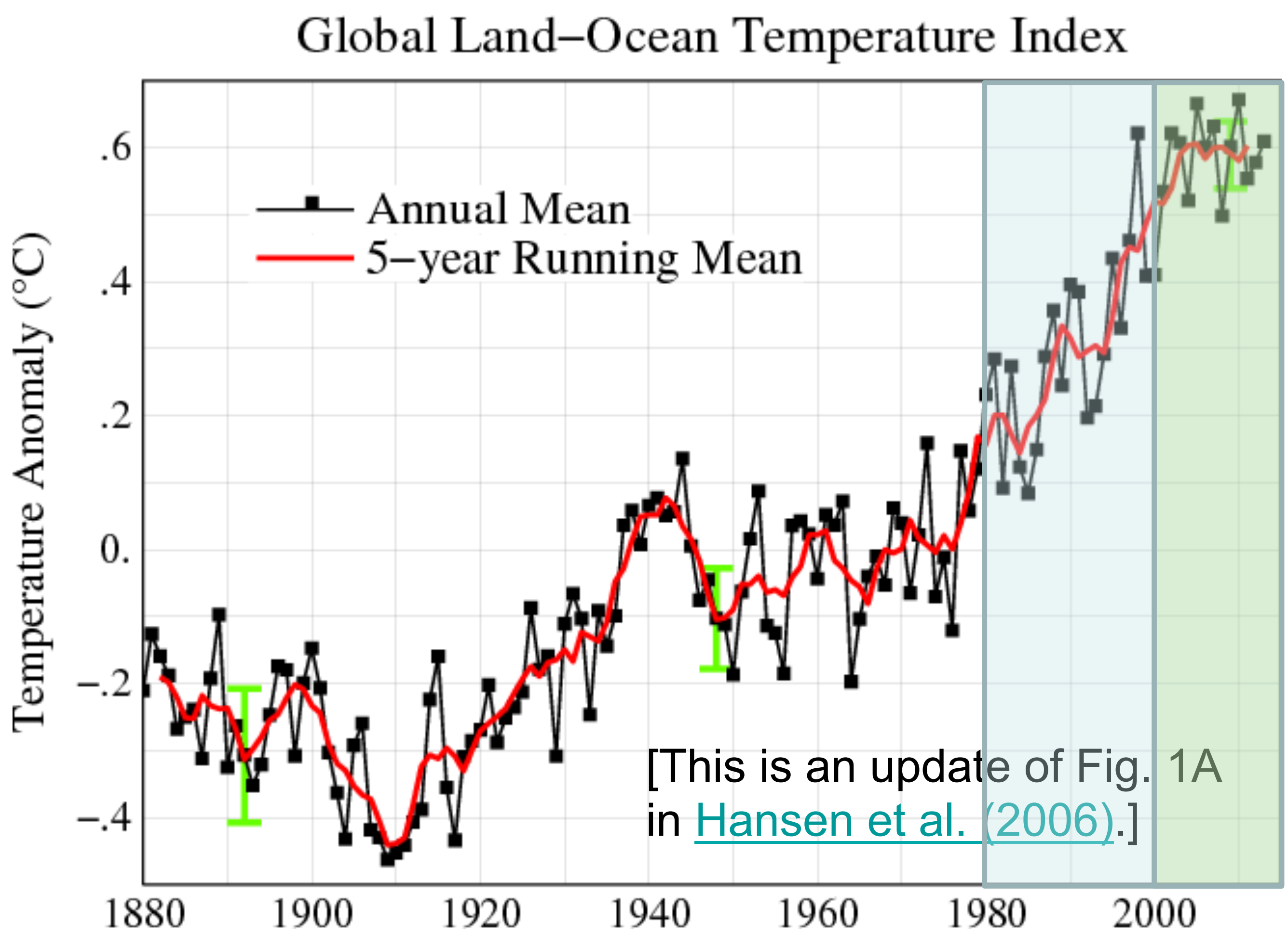
MODIS Science Team Meeting, Columbia, MD, 29 April – 1 May, 2014

Outline

1. Use of LST&E products in Earth Science
2. The MOD21 LST&E product and applications
3. Comparisons with the MOD11 product
4. Validation results
5. Summary

Introduction

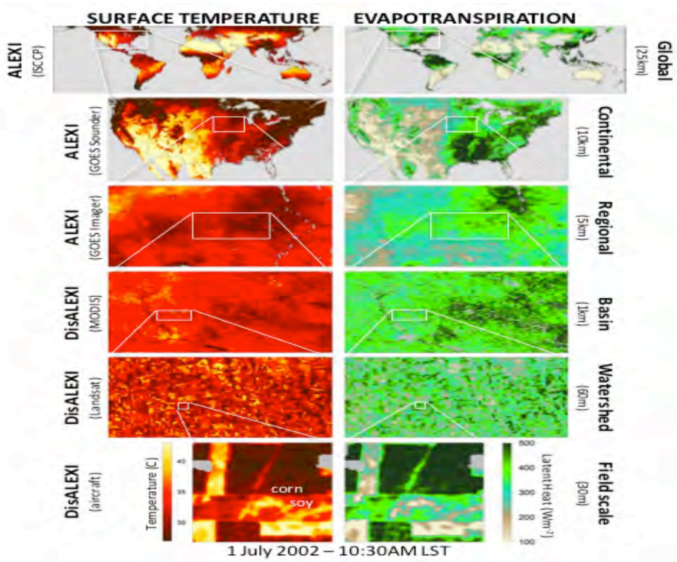
Line plot of global mean land-ocean temperature index, 1880 to present, with the base period 1951-1980. The dotted black line is the annual mean and the solid red line is the five-year mean. The green bars show uncertainty estimates.



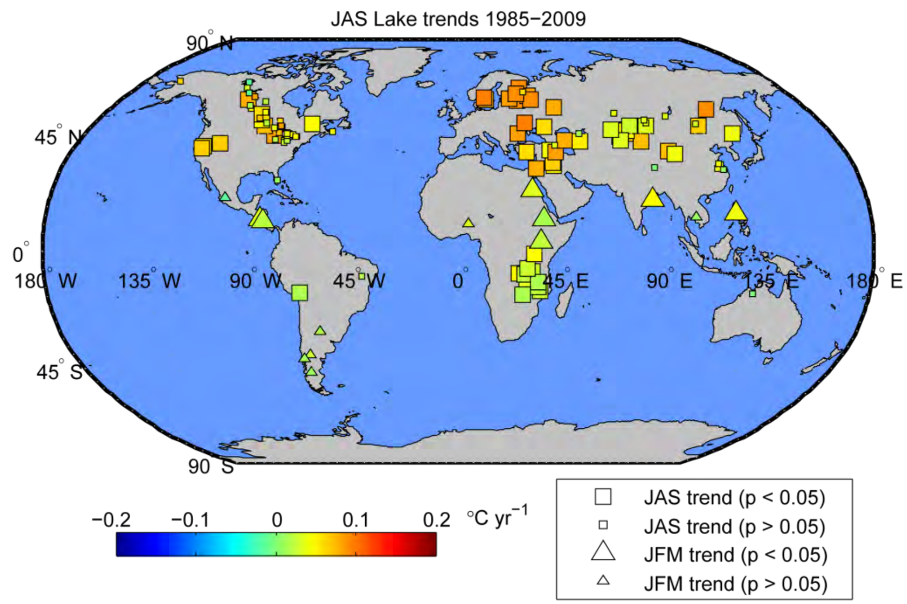
Air temperatures used over land

Earth Science Use of LST&E

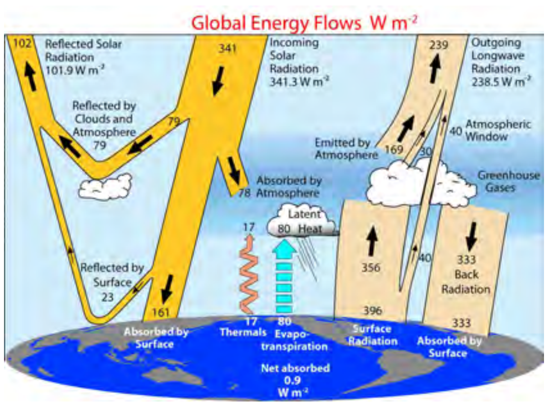
Evapotranspiration (drought monitoring)



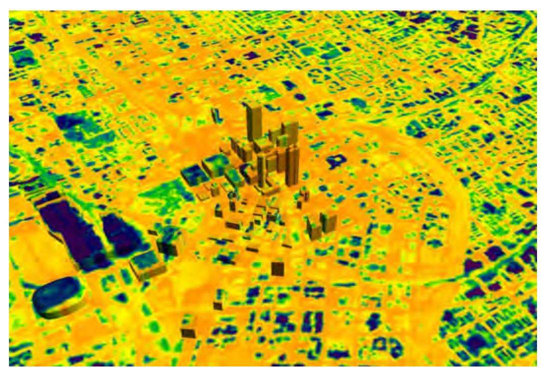
Understanding Climate Change



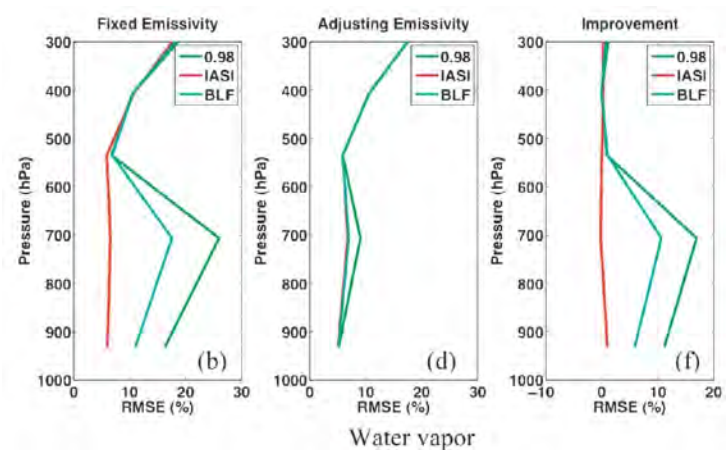
Surface Energy Balance



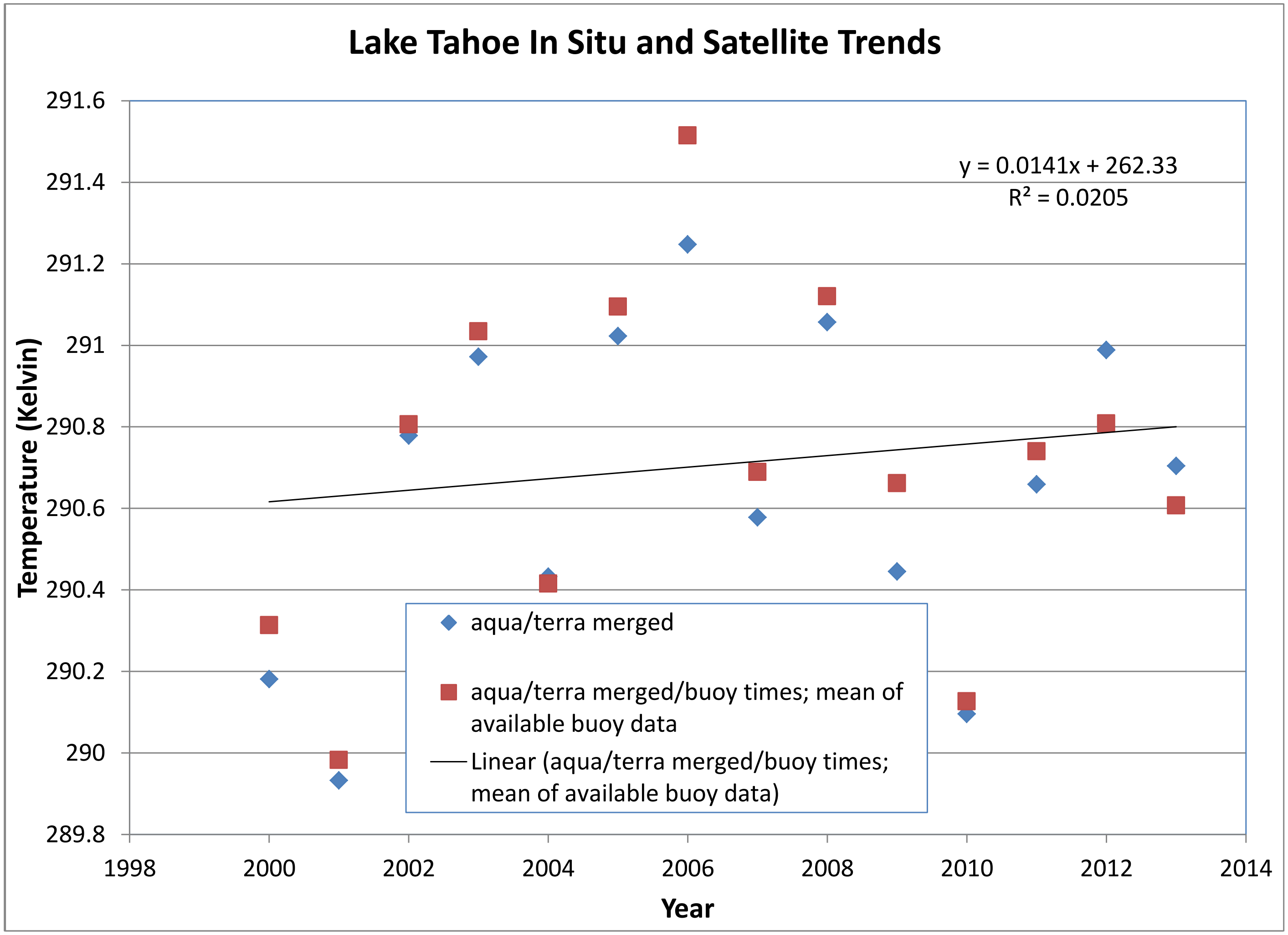
Urban Heat Island Studies

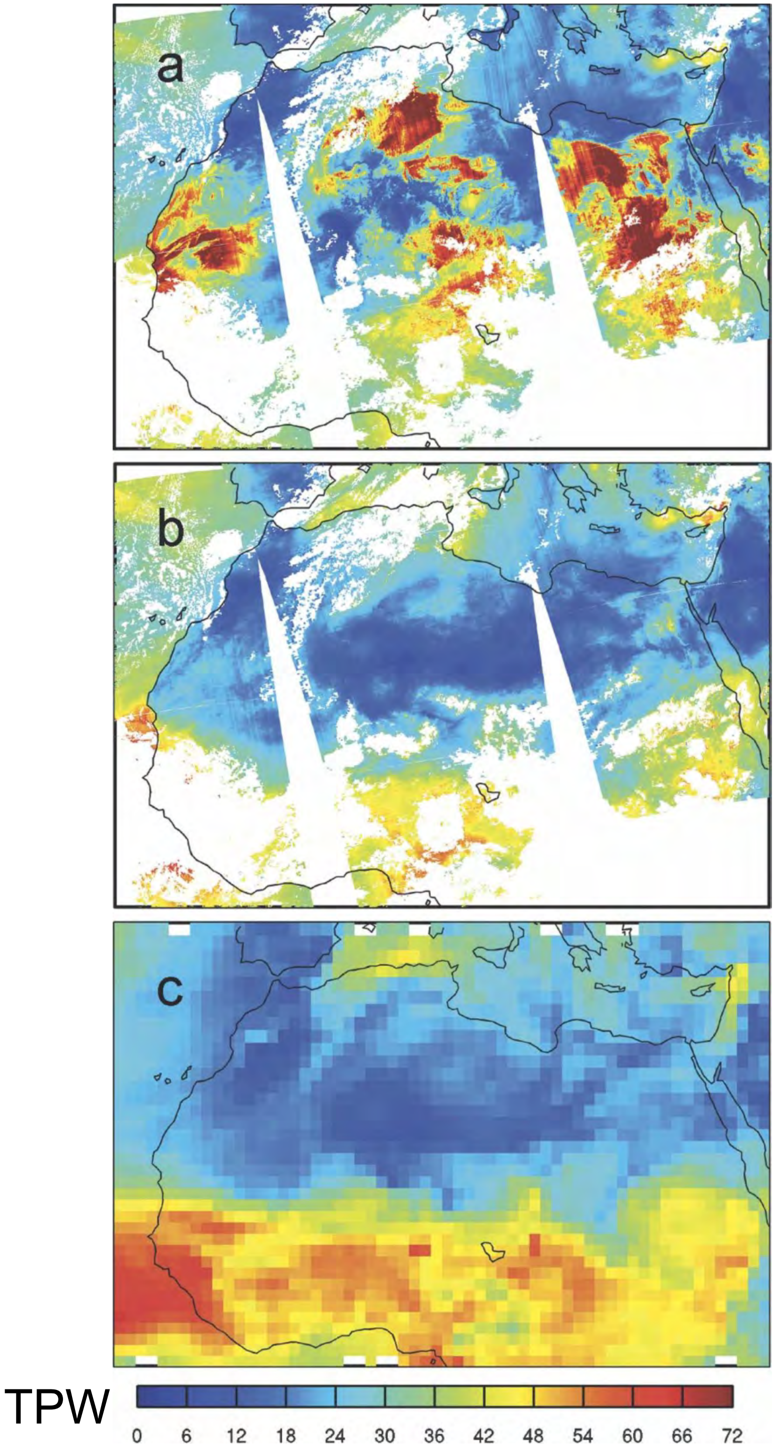


Atmospheric profile retrievals



The Importance of Record Length





Total precipitable water (TPW) images in mm retrieved from MODIS over North Africa using two approaches in the training dataset,

(a) Fixed emissivity = 0.95,

(b) MODIS Baseline-fit Emissivity Database (Wisconsin)

(c) Standard NCEP GDAS product

Using a constant emissivity, TPW values are noisy and overestimated by up to 90 mm over regions of North Africa (Seemann et al. 2008), while using a physically retrieved emissivity results in a close agreement with NCEP GDAS product.

Current MODIS LST&E Products

MODIS LST Products	Product Level	Dimensions	Spatial Resolution	Temporal Resolution	Algorithm	Output Products
MOD11_L2	L2	2030 lines 1354 pixels/line	1km at nadir	Swath 2x daily	Split-Window	- LST
MOD11B1	L3	200 rows 200 columns	~5 km (C4) ~6 km (C5)	Sinusoidal 2x daily	Day/Night	- LST - Emissivity (bands 20-23, 29, 31,32)
MOD11C3	L3	360ºx180º Global	0.05º x 0.05º	Monthly	Day/Night + Split-Window	- LST - Emissivity (bands 20-23, 29, 31-32)
MOD21_L2	L2	2030 lines 1354 pixels/line	1km at nadir	Swath 2x daily 8-day	TES	- LST - Emissivity (bands 29, 31, 32)

The MOD21 & ASTER Temperature Emissivity Separation (TES) Algorithm Basics

Surface Radiance:

Observed Radiance

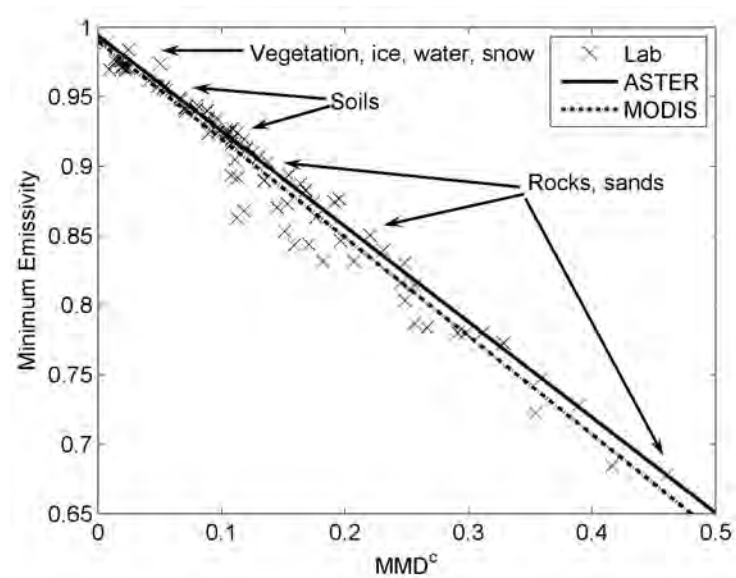
$$L_{surf,i} = e_i \cdot B_i(T_S) + (1 - e_i) \cdot \overline{L}_i^{\downarrow} = \frac{L_i(\theta) - L_i^{\uparrow}(\theta)}{\tau_i(\theta)}$$

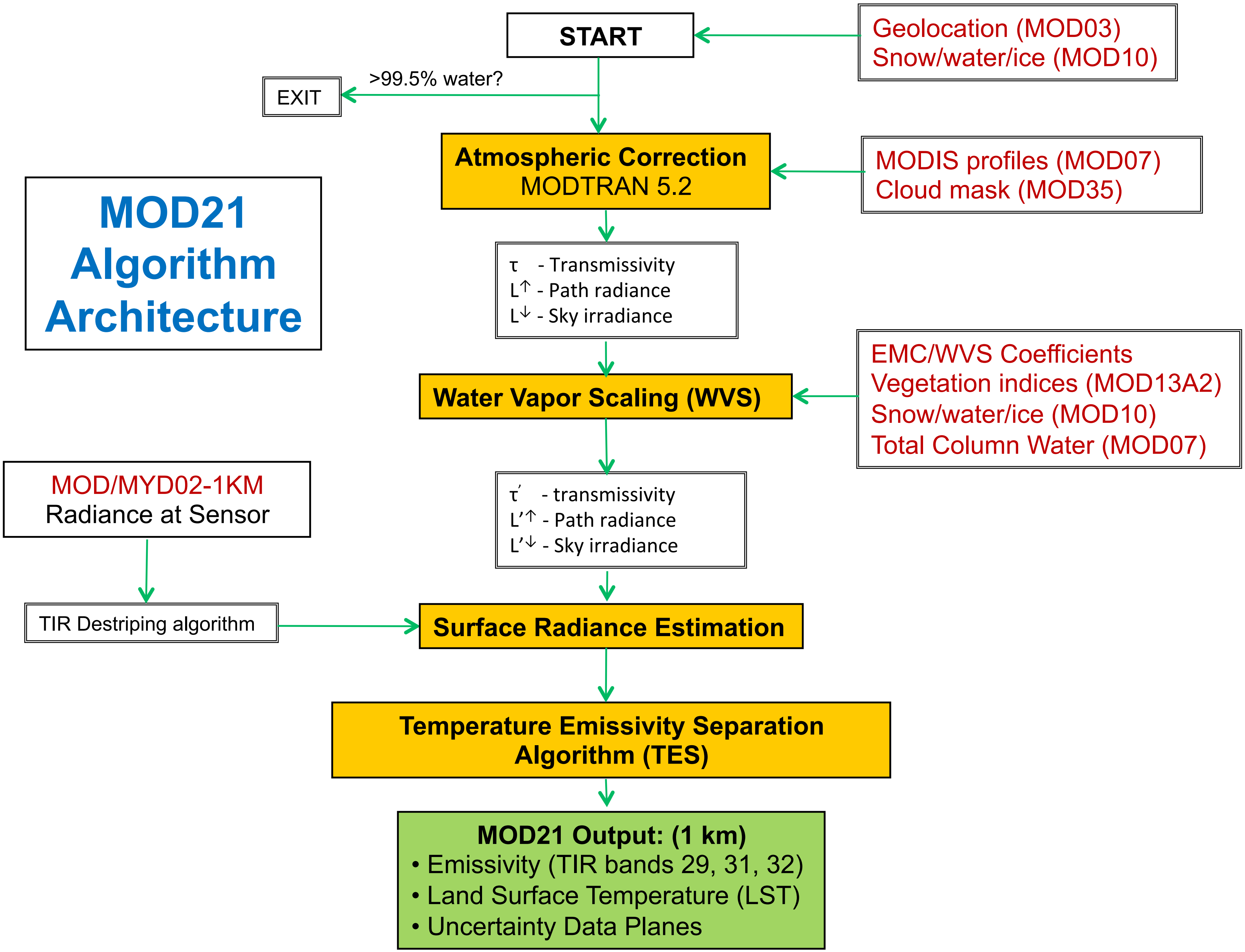
- **Atmospheric Parameters:** $\tau_i(\theta)$, $L_i^{\uparrow}(\theta)$, $L_i^{\downarrow}(\theta)$

  Estimated with MODTRAN (5.2)

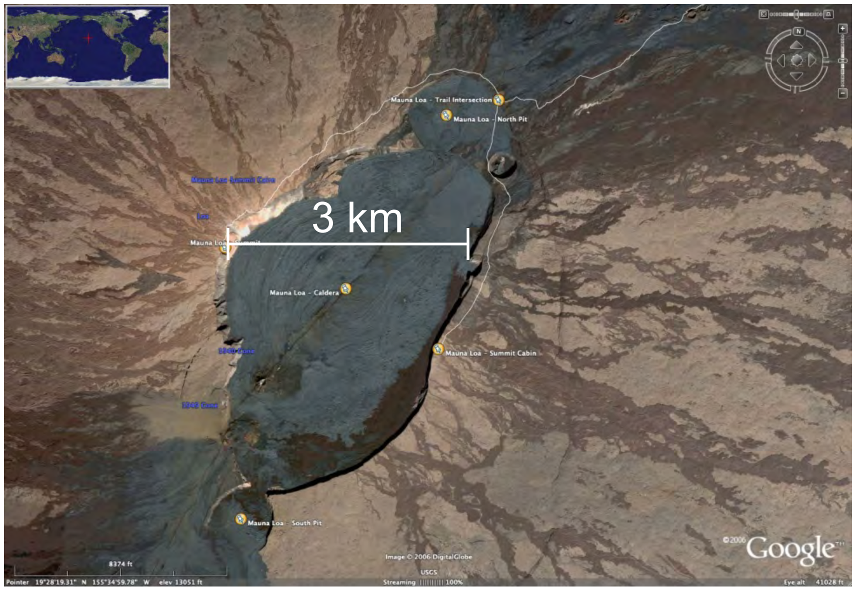
Calibration curve for MODIS bands 29, 31, 32:

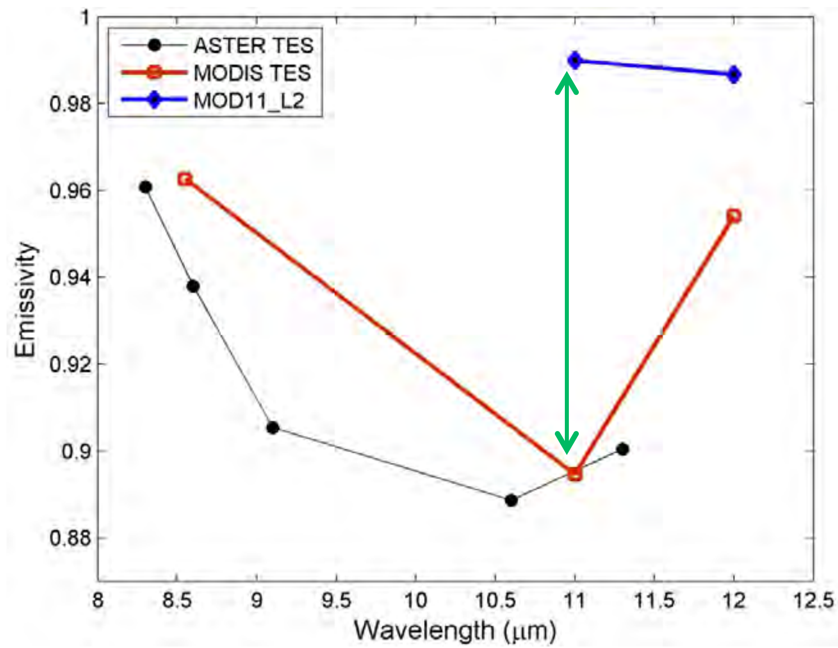
$$\varepsilon_{\min} = 0.994 - 0.687 \cdot MMD^{0.737}$$



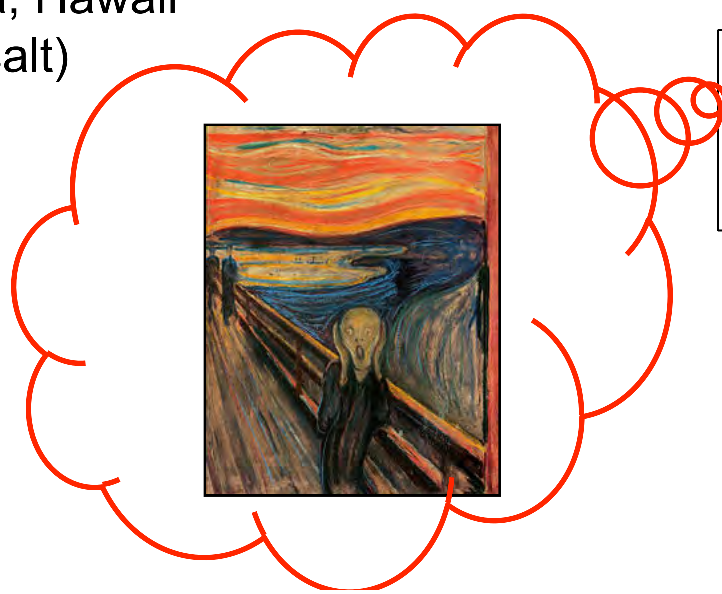

START
Geolocation (MOD03)
Snow/water/ice (MOD10)
>99.5% water?
EXIT
Atmospheric Correction
MODTRAN 5.2
MODIS profiles (MOD07)
Cloud mask (MOD35)
MOD21
Algorithm
Architecture
τ - Transmissivity
L↑ - Path radiance
L↓ - Sky irradiance
EMC/WVS Coefficients
Vegetation indices (MOD13A2)
Snow/water/ice (MOD10)
Total Column Water (MOD07)
Water Vapor Scaling (WVS)
MOD/MYD02-1KM
Radiance at Sensor
τ′ - transmissivity
L′↑ - Path radiance
L′↓ - Sky irradiance
TIR Destriping algorithm
Surface Radiance Estimation
Temperature Emissivity Separation
Algorithm (TES)
MOD21 Output: (1 km)
• Emissivity (TIR bands 29, 31, 32)
• Land Surface Temperature (LST)
• Uncertainty Data Planes

Motivation for a Physically Retrieved MODIS LST and Emissivity Product



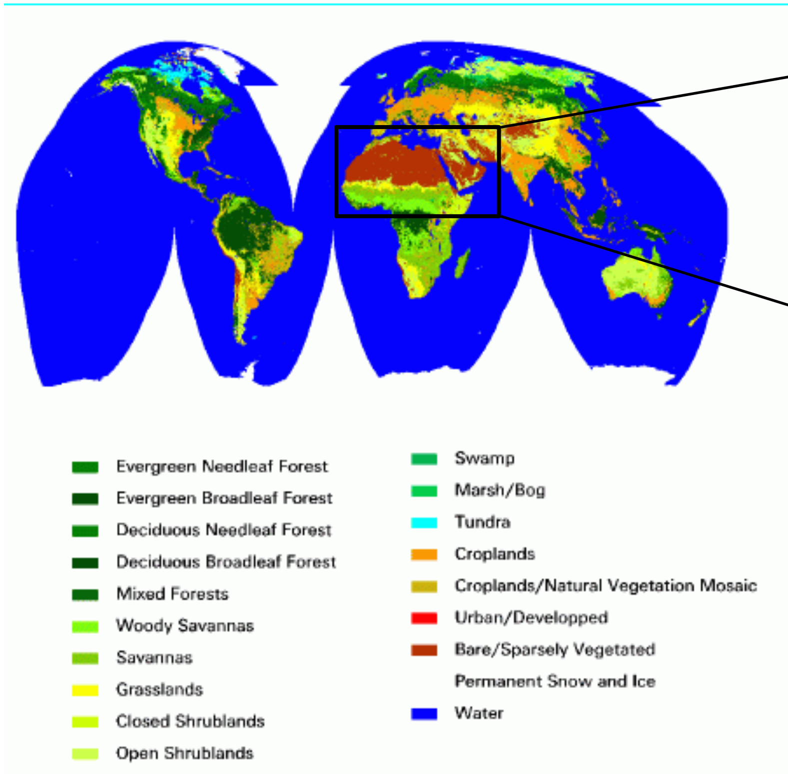


- Mauna Loa Caldera, Hawaii
- Mafic lava flow (basalt)

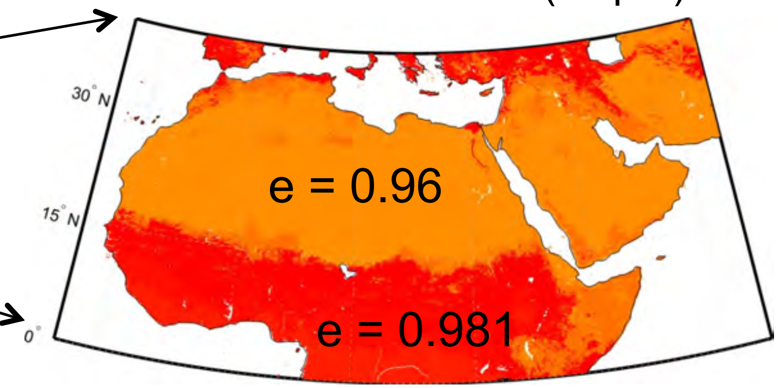


Average temperatures over Caldera	
ASTER TES:	322 ±1 K
MODIS TES (MOD21):	324 ±0.8 K
MOD11_L2:	310 ±0.5 K

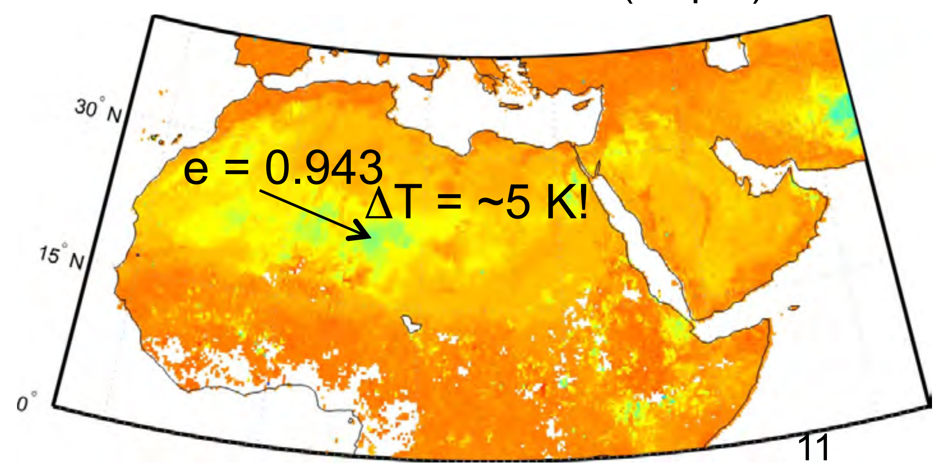
Split-Window versus TES physical retrieval



Split-window:
MOD11 band 31 (11 µm)

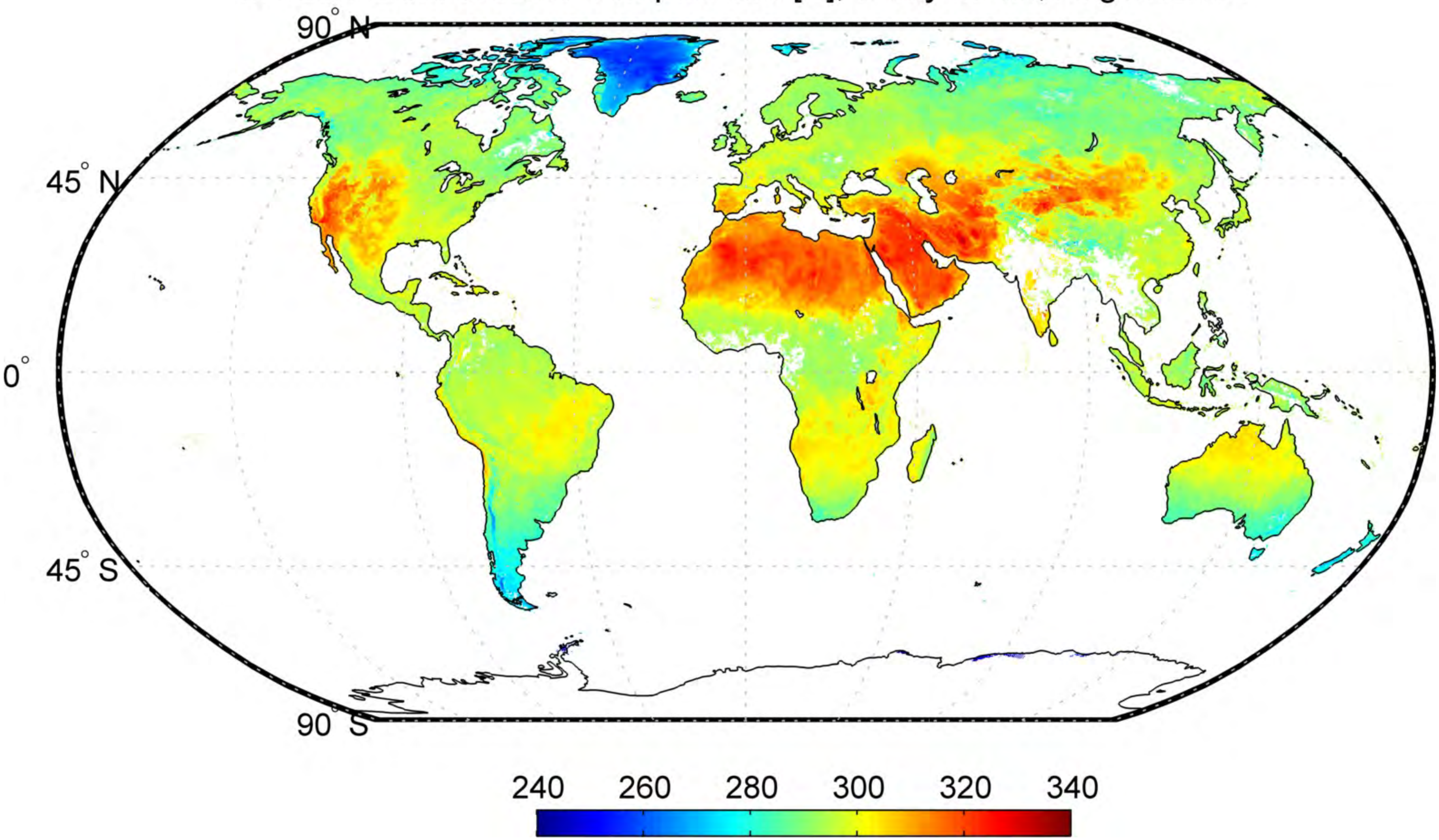


TES Retrieval:
MOD21 band 31 (11 µm)

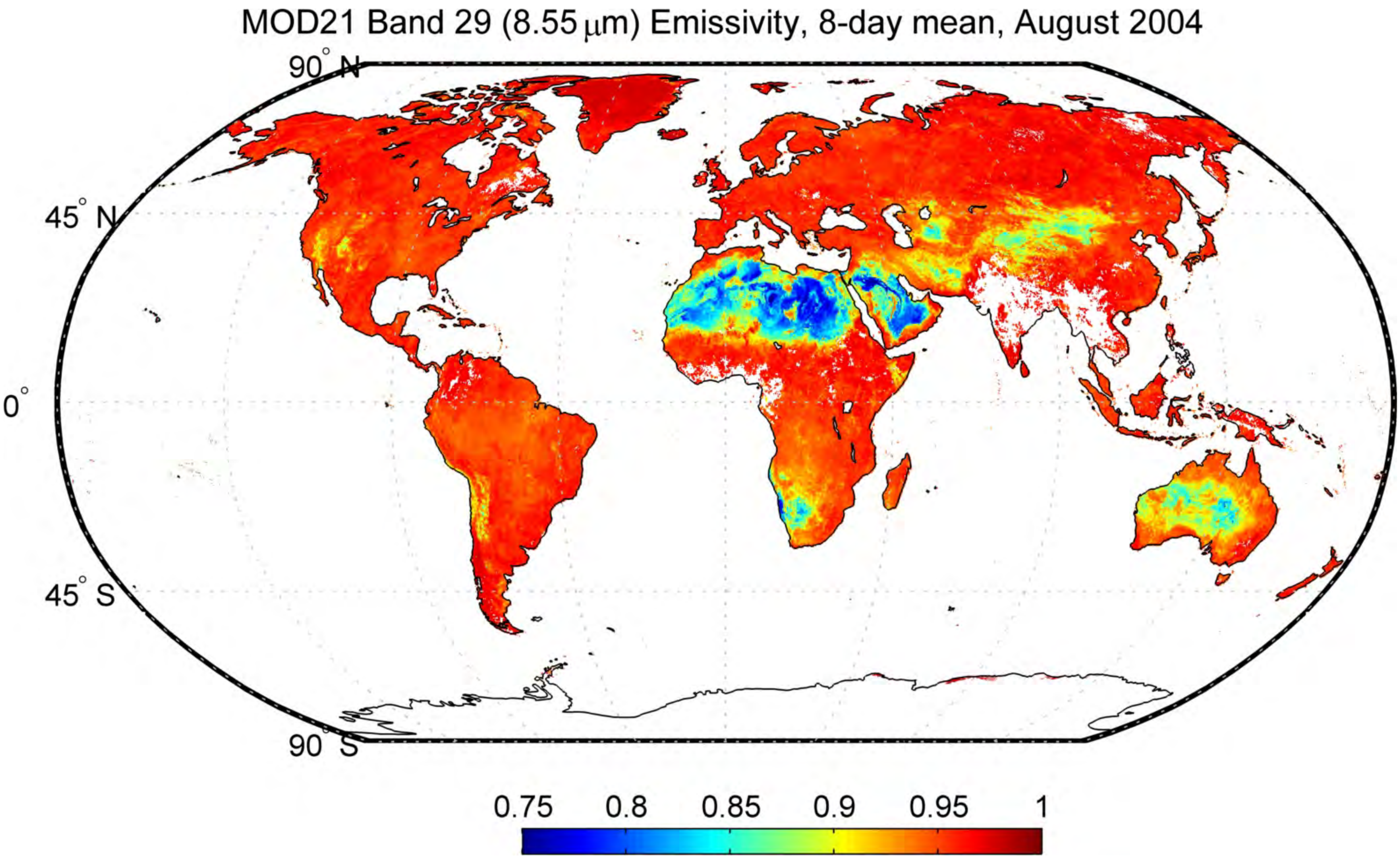


MOD11 classified as bare and assigned single emissivity but a wide range in emissivity as seen with MOD21 (TES)

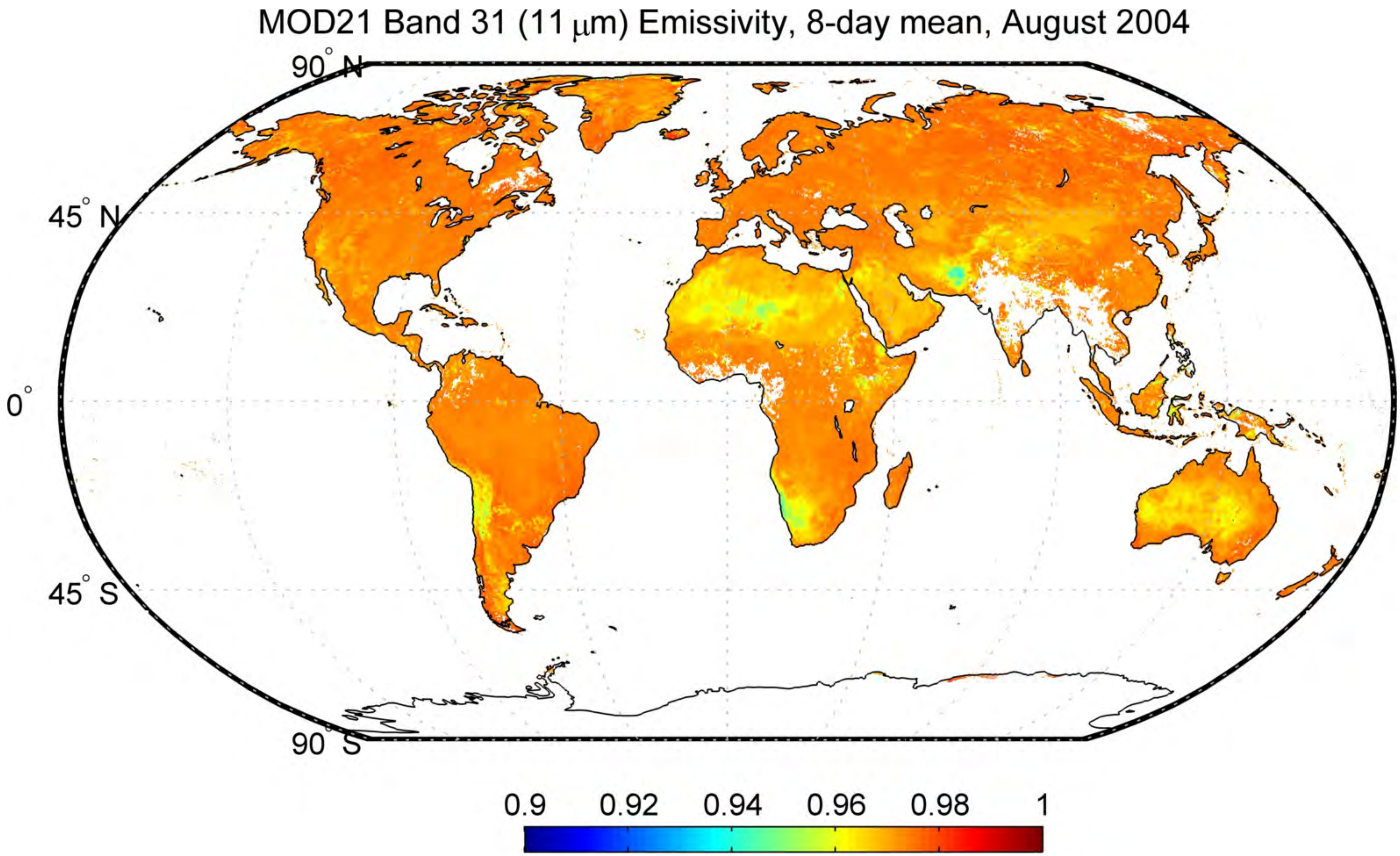
MOD21 Land Surface Temperature [K], 8-day mean, August 2004



Generated using prototype MOD21 algorithm at MODAPS

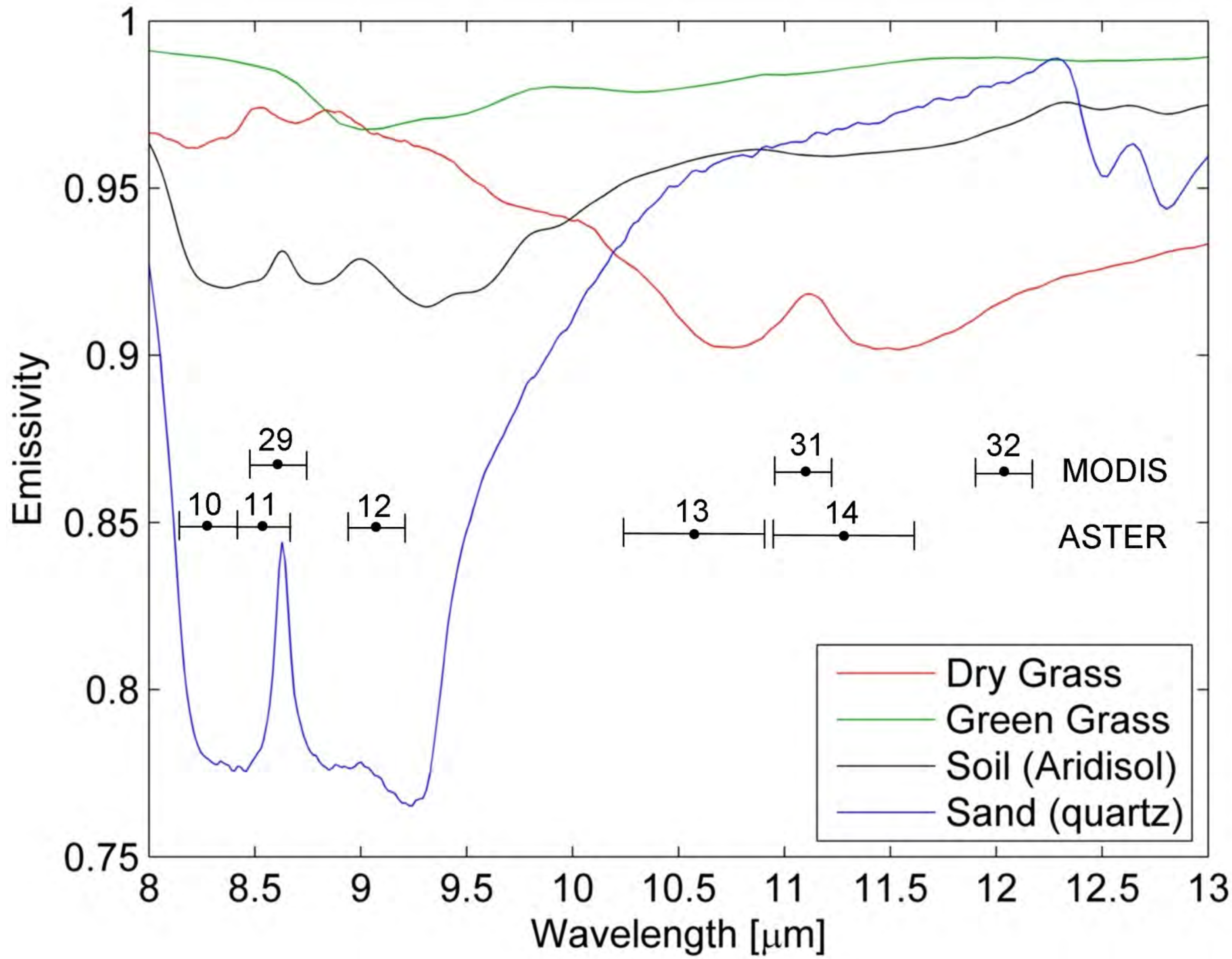


Generated using prototype MOD21 algorithm at MODAPS

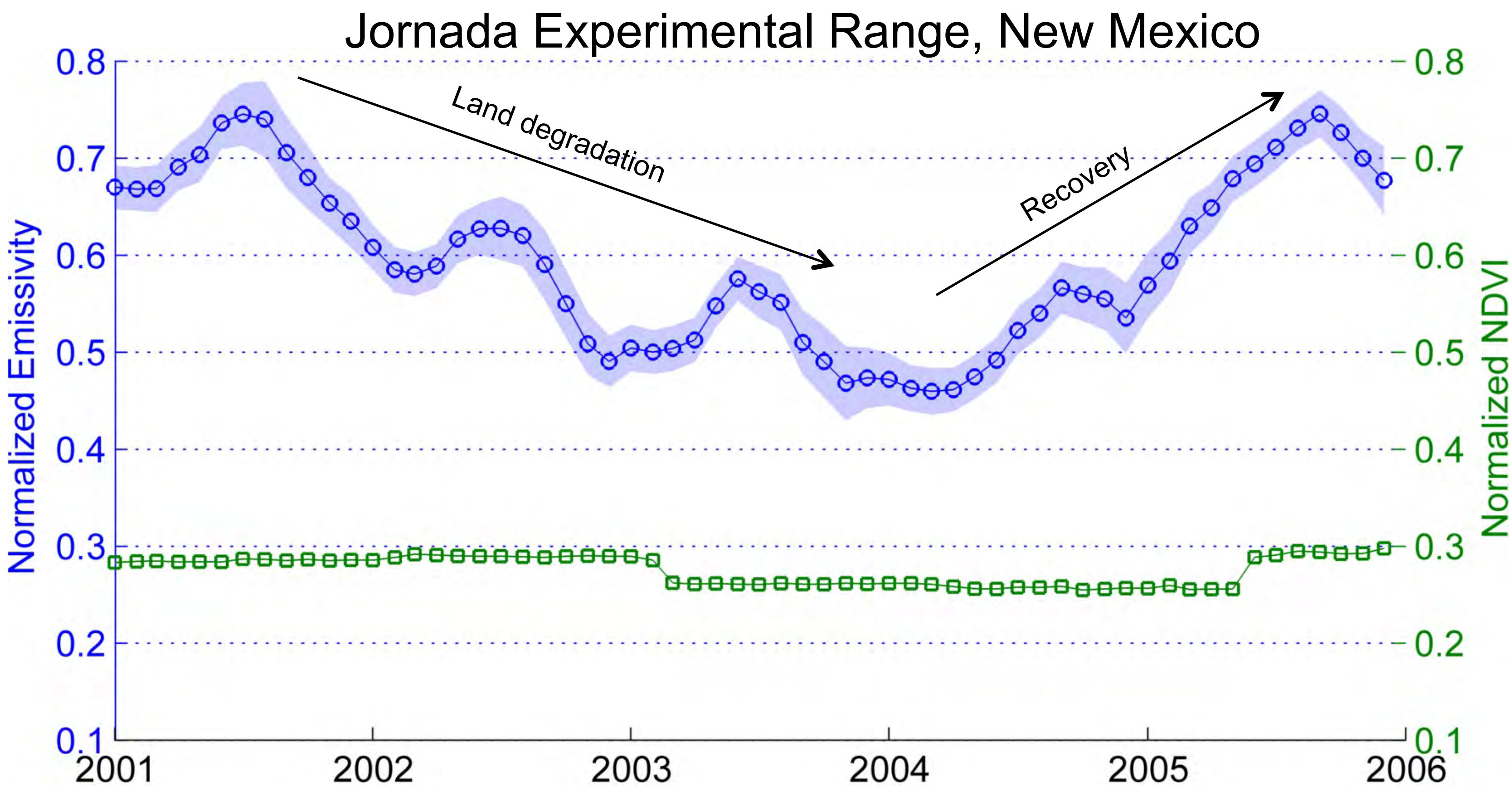


Generated using prototype MOD21 algorithm at MODAPS

MOD21 emissivity can be used for surface composition studies and monitoring land cover change



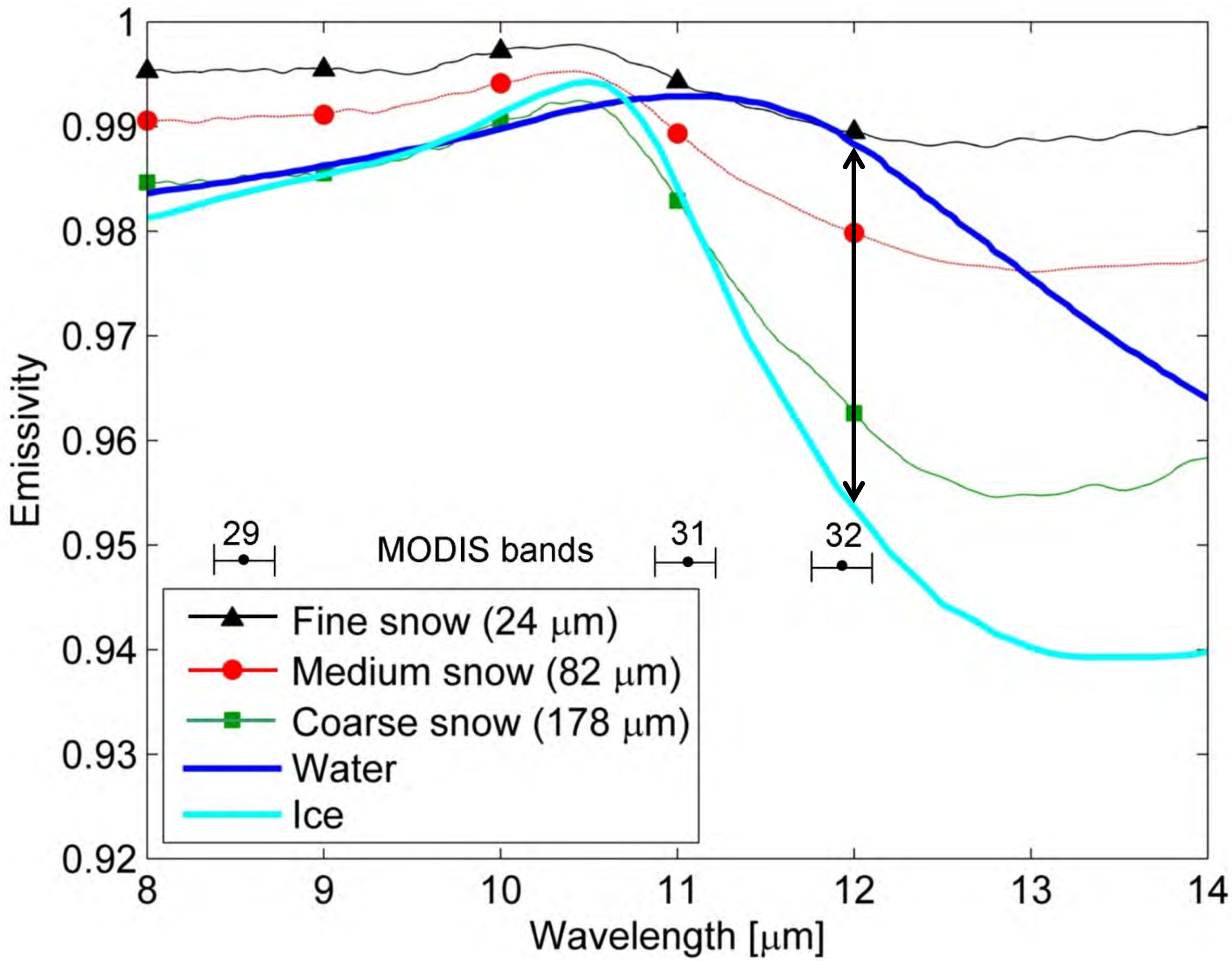
Desertification monitoring with MOD21 band 29 emissivity



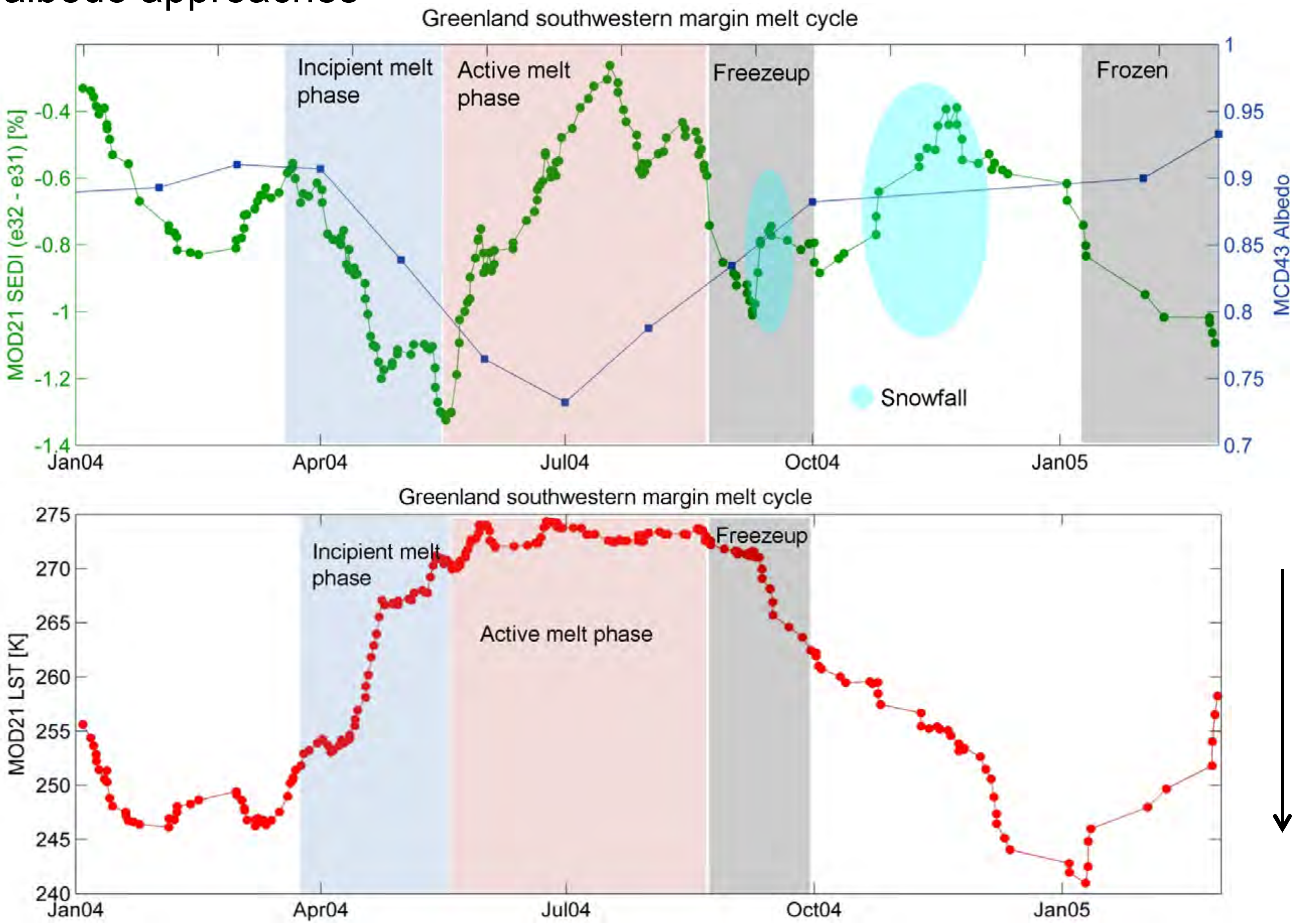
- MOD21 band 29 emissivity sensitive to background soil and dry/green vegetation
- NDVI unable to make distinction between background soil and dry vegetation
- MOD21 emissivity able to better capture seasonal trends and interannual trends than NDVI

Hulley, G., S. Veraverbeke, S. Hook, (2014), Thermal-based techniques for land cover change detection using a new dynamic MODIS multispectral emissivity product (MOD21), Rem. Sens. Environ, 140, p755-765

Difference between MOD21 band 31 and 32 emissivity can be used for distinguishing between snow, ice and water



Time series of MOD21 emissivity (b32 – b31) able discriminate in more detail different melt and freeze phases on glaciers and ice sheets than traditional albedo approaches



e32-e31

Water
Fine
Medium
Coarse
Ice

Hulley, G., S. Veraverbeke, S. Hook, (2014), Thermal-based techniques for land cover change detection using a new dynamic MODIS multispectral emissivity product (MOD21), Rem. Sens. Environ, 140, p755-765

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).

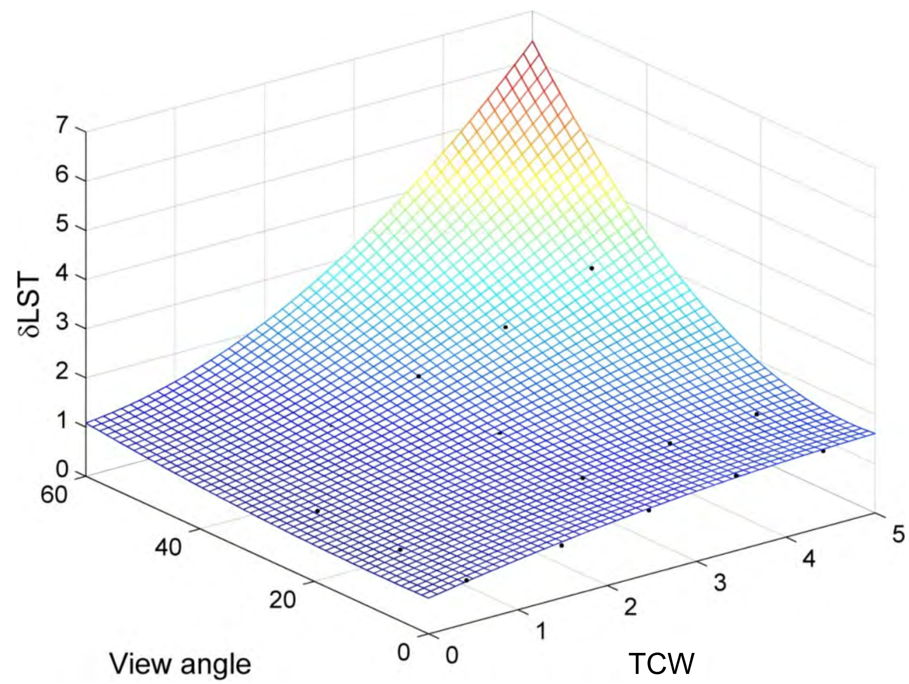
Bits	Long Name	Description
1&0	Mandatory QA flags	00 = Pixel produced, good quality, no further QA info necessary 01 = Pixel produced, unreliable quality, emissivity out of physical range (band 32 emissivity < 0.95), or retrieval affected by nearby clouds, or low transmissivity due to opaque atmospheric 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

MOD21 Uncertainty Modeling

$$\delta LST_{MODIS} = a_o + a_1 TCW + a_2 \mathrm{SVA} + a_3 TCW \cdot SVA + a_4 TCW^2 + a_5 SVA^2 \qquad (10)$$

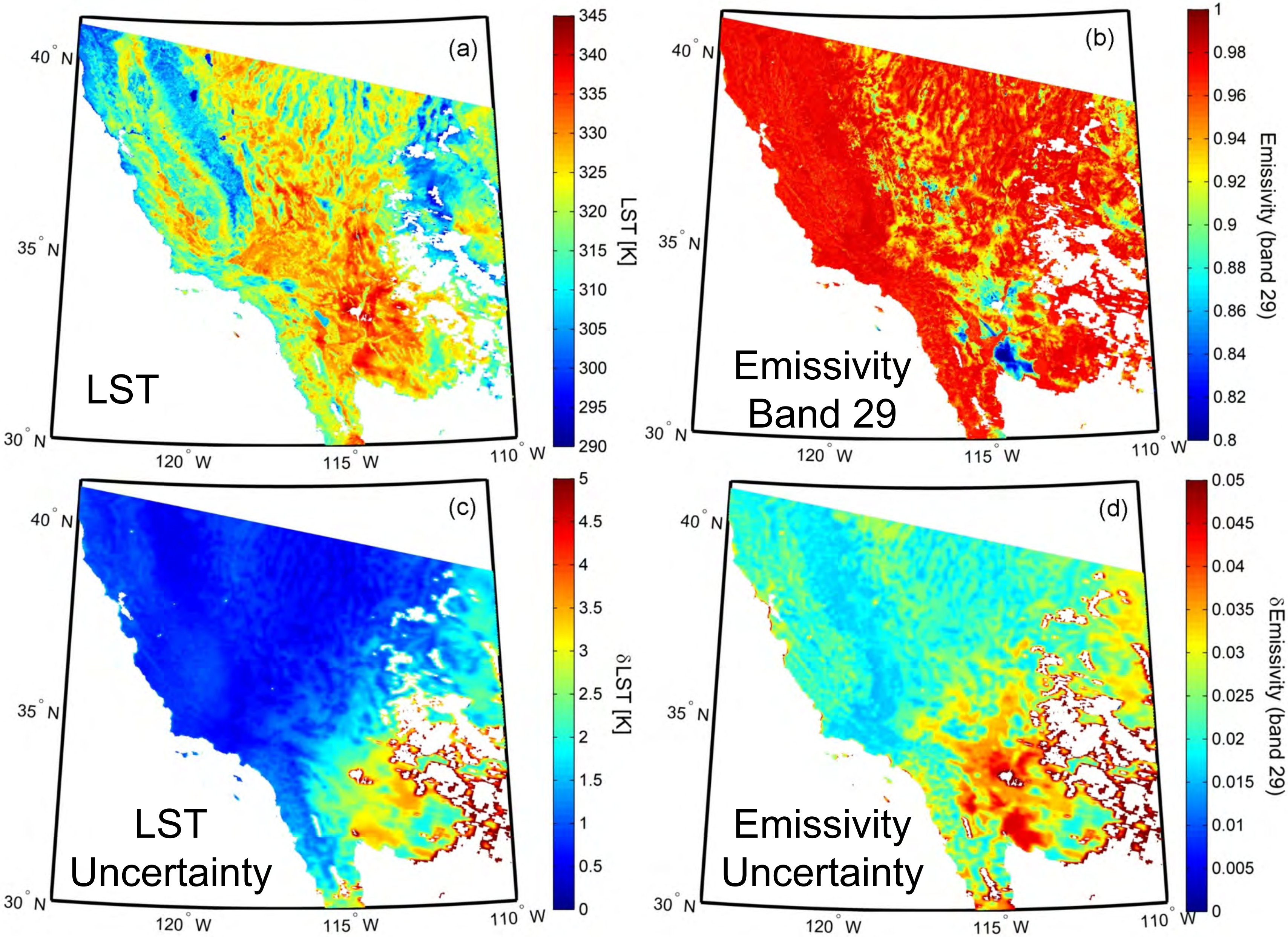
$\boldsymbol{a_i}$ = regression coefficients dependent on surface type (gray, bare, transition)
SVA = sensor view angle
TCW = total column water estimate (cm), e.g. from MOD07, NCEP



Important for climate models

Hulley, G. C., T. Hughes, and S. J. Hook (2012), Quantifying Uncertainties in Land Surface Temperature (LST) and Emissivity Retrievals from ASTER and MODIS Thermal Infrared Data, J. Geophys. Res. Lett, 117, D23113, doi:10.1029/2012JD018506.

MOD21 LST&E Retrievals with Uncertainty



TES (MOD21) vs Split-window (MOD11, VIIRS) Uncertainty Analysis

			LST Uncertainty (K)		
Surface type	**Emissivity Samples**	**Simulations**	**MOD21** (3-band TES) RMSE (Bias)	**MOD11** (2-band Split-Window) RMSE (Bias)	**VIIRS** (2-band Split-Window) RMSE (Bias)
Vegetation, Water, Ice, Snow	8	660,096	2.19 (0.66)	1.59 (-0.53)	1.77 (-0.97)
Rocks	48	3,960,576	1.44 (-0.73)	4.31 (-3.32)	4.29 (-3.69)
Soils	45	3,713,040	0.89 (0.09)	1.27 (-0.25)	1.81 (-1.43)
Sands	10	825,120	1.12 (-0.12)	2.38 (-1.79)	3.11 (-2.69)
Total	**111**	**9,158,832**	**1.49 (-0.24)**	**2.66 (-1.85)**	**2.93 (-2.49)**

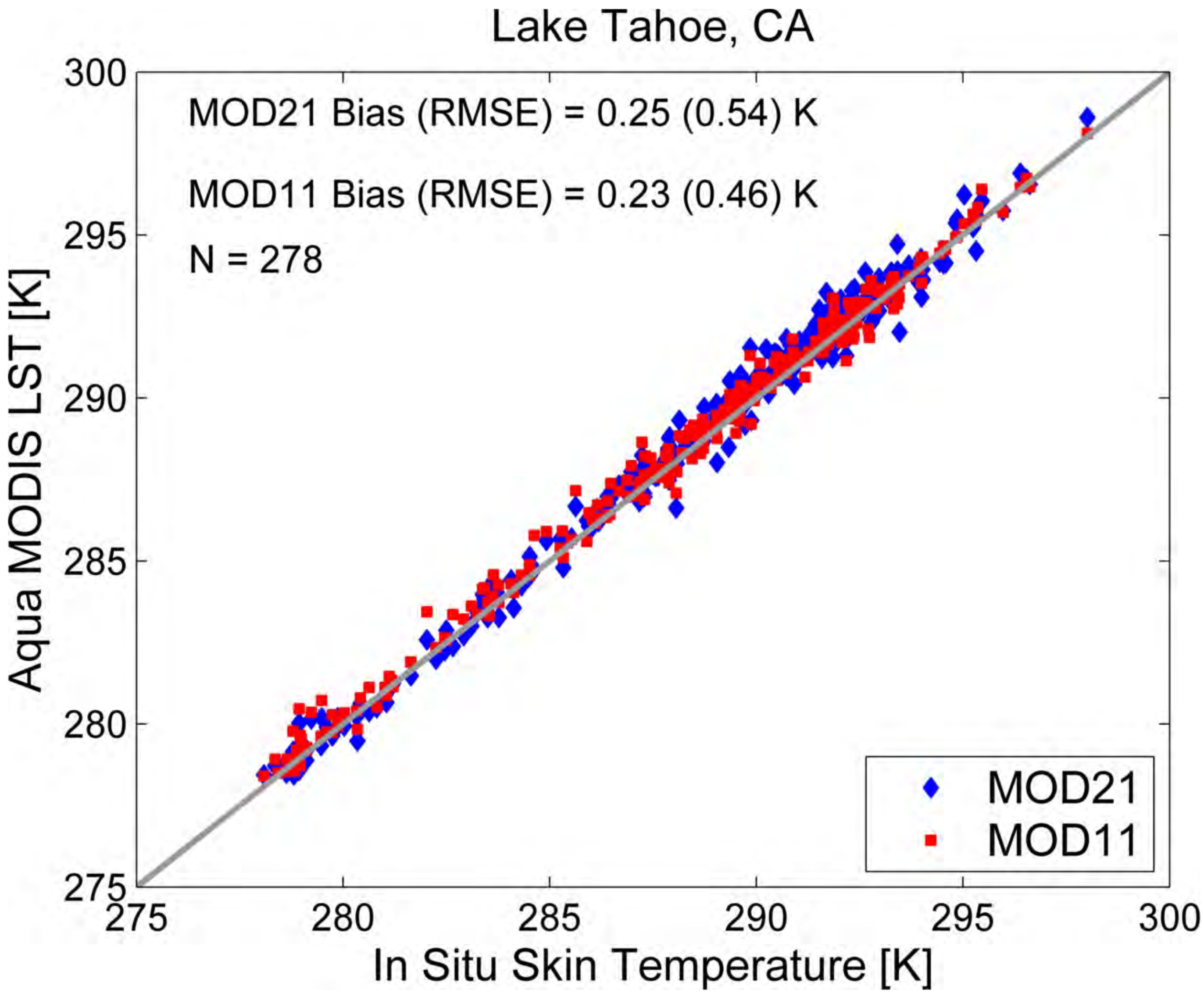
<u>MOD21 has slightly larger scatter over graybodies, but lowest Uncertainty on average by more than 1 K over all surface types compared to split-window approaches</u>

JPL LST&E Validation Sites

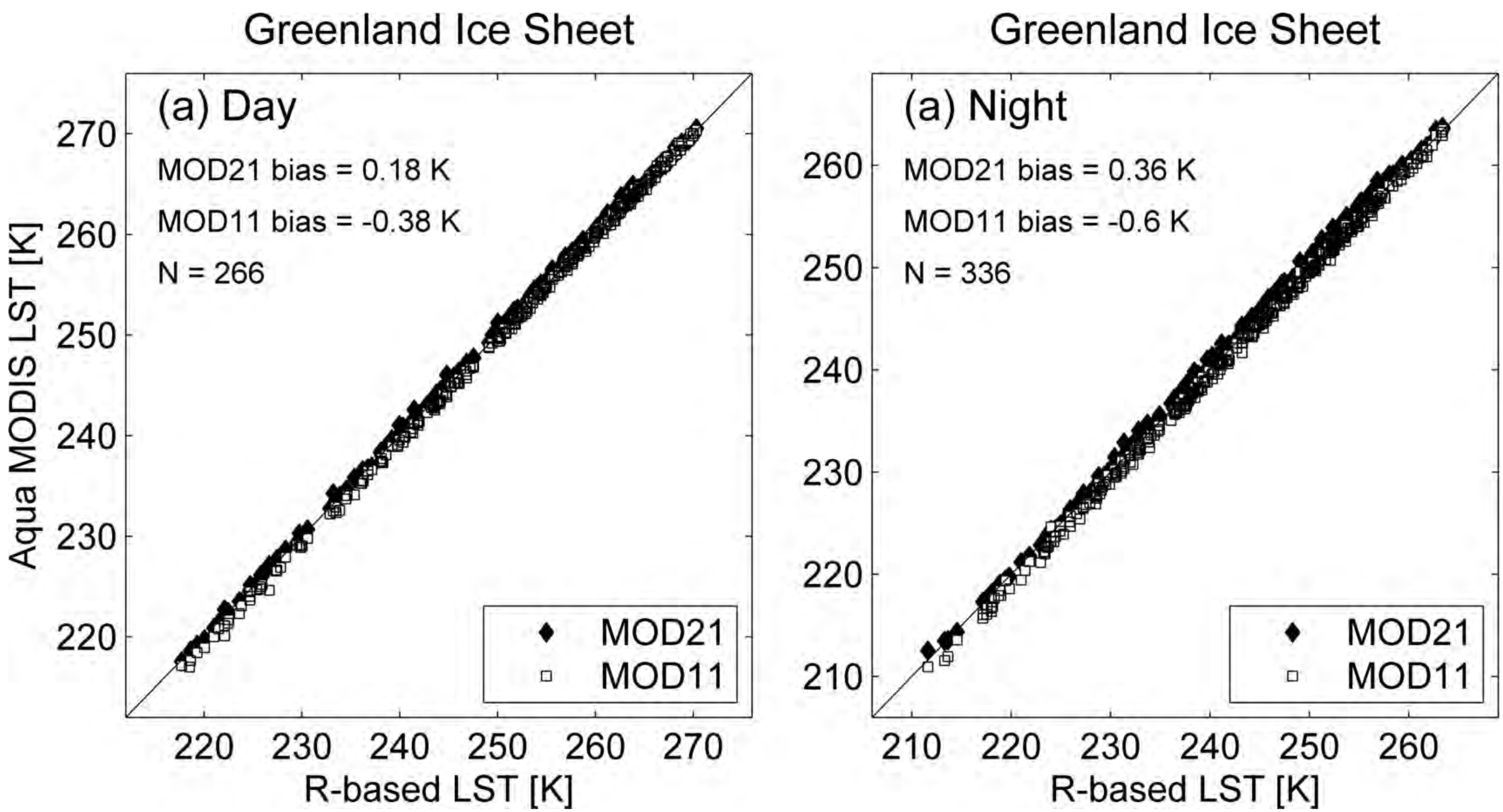
Site name	Site type	Lat	Lon	Elevation (km)	Emissivity source	IGBP cover type (MOD12)	IGBP fraction (%)	Data availability
Bondville, IL	SURFRAD	40.05 N	88.37 W	0.213	ASTER (NAALSED)	Cropland	7.13	1994-present
Boulder, CO	SURFRAD	40.12 N	105.24 W	1.689	ASTER (NAALSED)	Grassland	5.87	1995-present
Fort Peck, 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

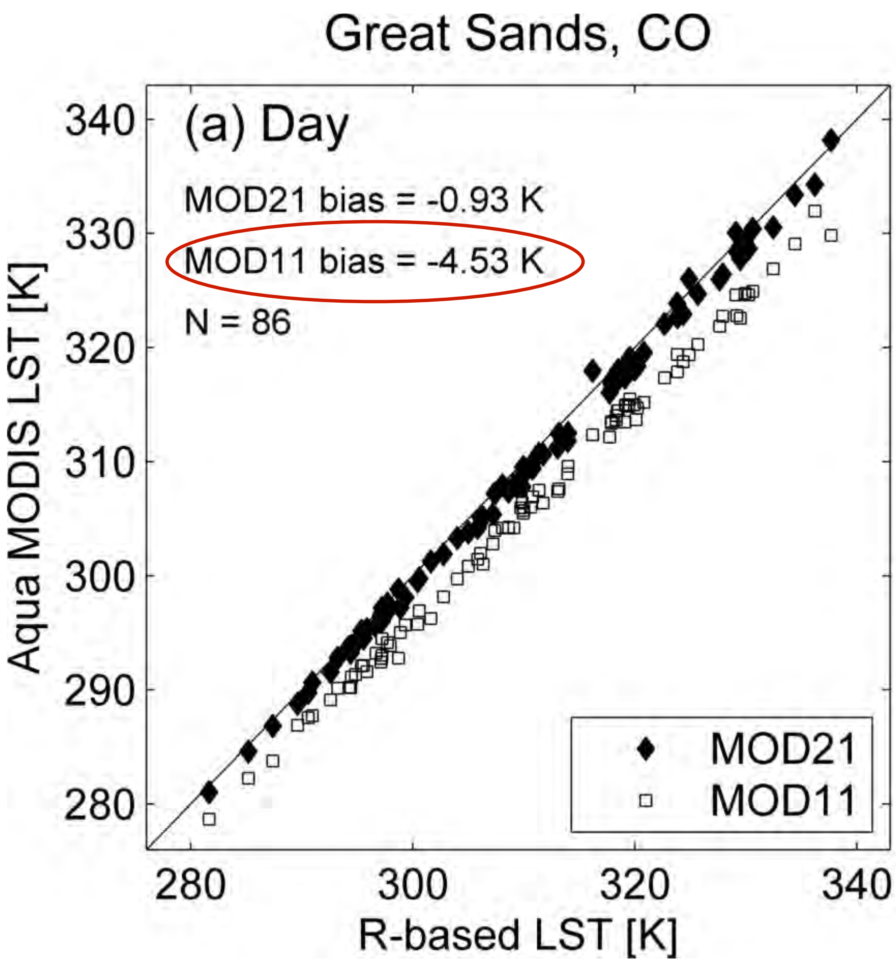

Lake Tahoe, CA
MOD21 Bias (RMSE) = 0.25 (0.54) K
MOD11 Bias (RMSE) = 0.23 (0.46) K
N = 278
MOD21
MOD11
Aqua MODIS LST [K]
In Situ Skin Temperature [K]
275
280
285
290
295
300

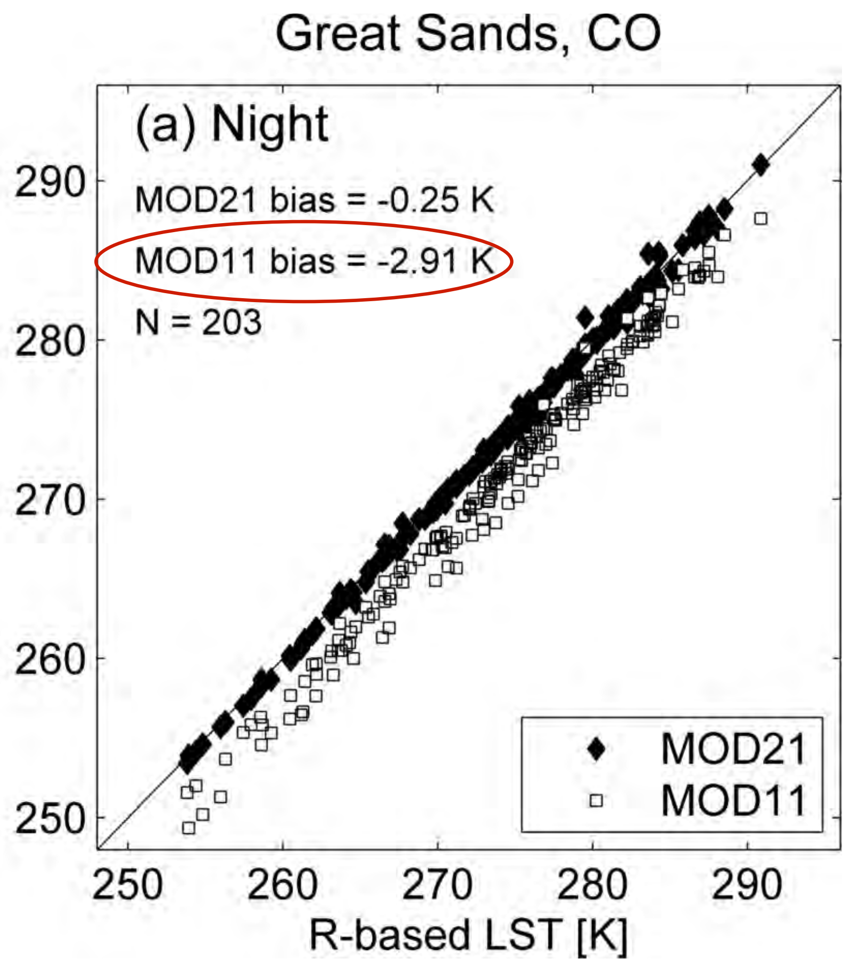
MODIS LST Validation: Greenland ice sheet



Similar accuracy over Greenland (<1 K)

MODIS LST Validation: Great Sands, Colorado





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

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

The End

National Aeronautics and Space Administration

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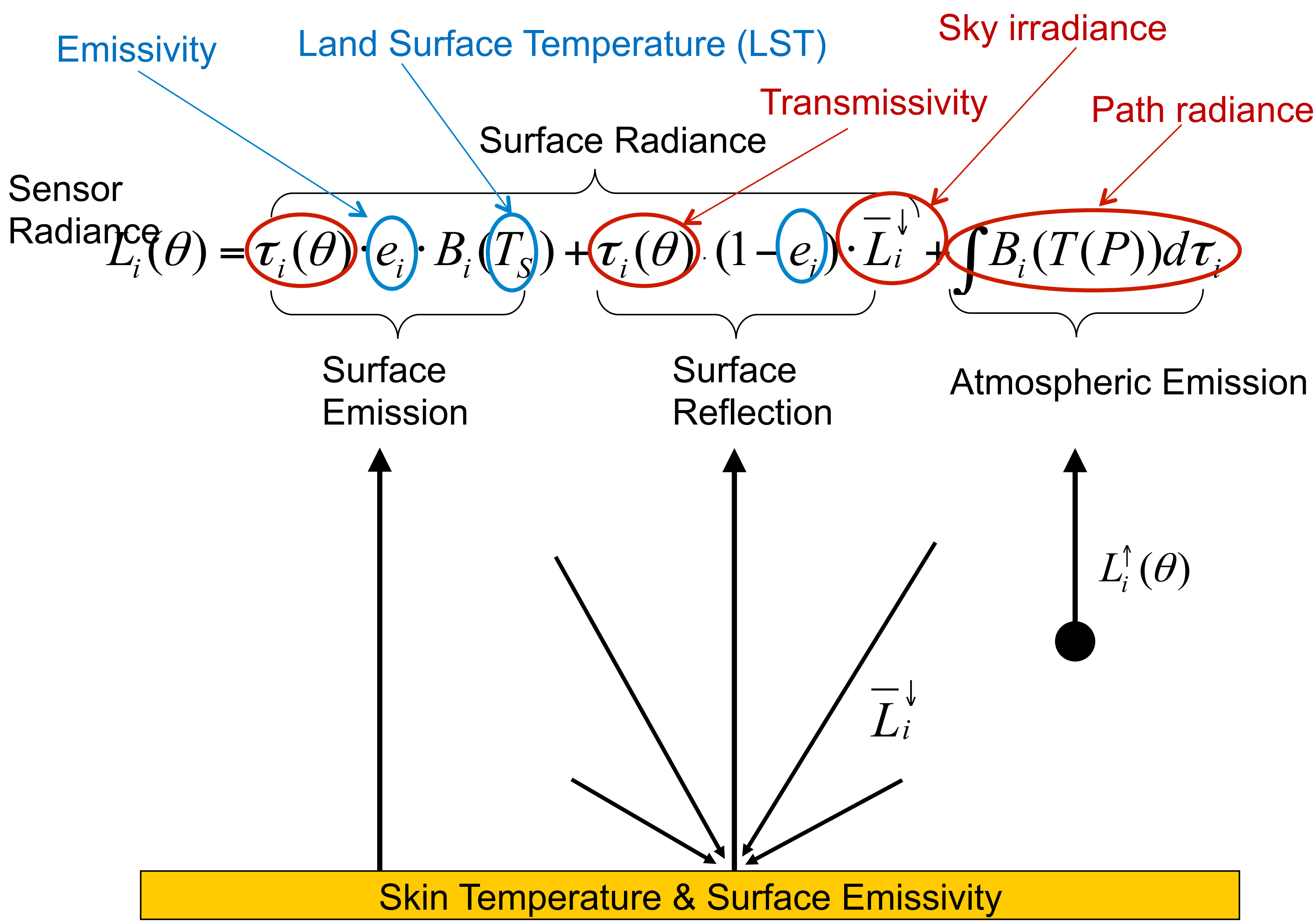
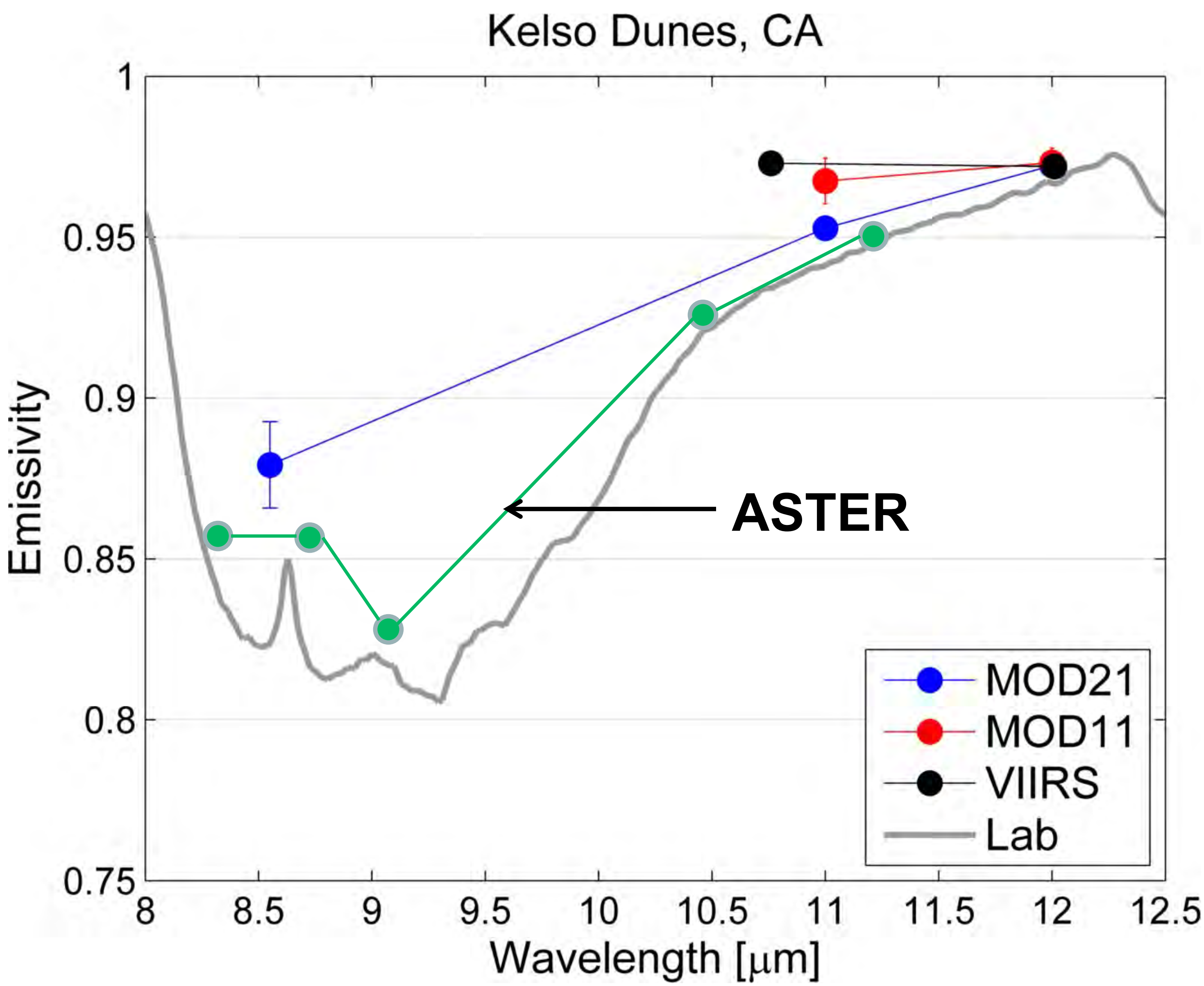
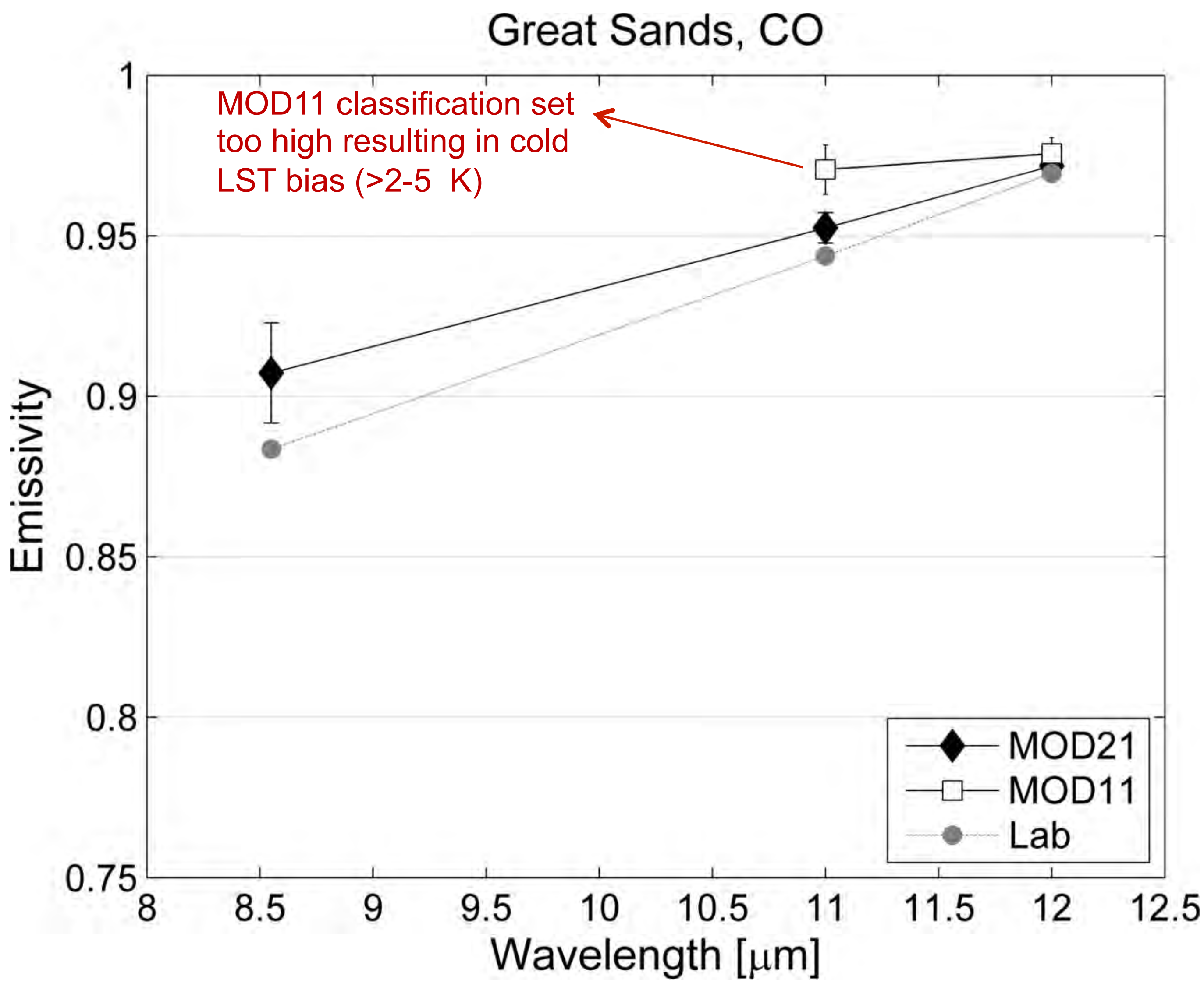
Thermal Infrared Radiative Transfer



Classification emissivity (MOD11, VIIRS) are set too high over bare surfaces, only Physical algorithms (MOD21, ASTER) able to retrieve correct spectral shape (more bands the better).



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)