Validation Results and MODTES An Improved Temperature-Emissivity Product for Arid and Semi-Arid Regions

Simon J. Hook, Glynn Hulley, Topher Hughes et al.

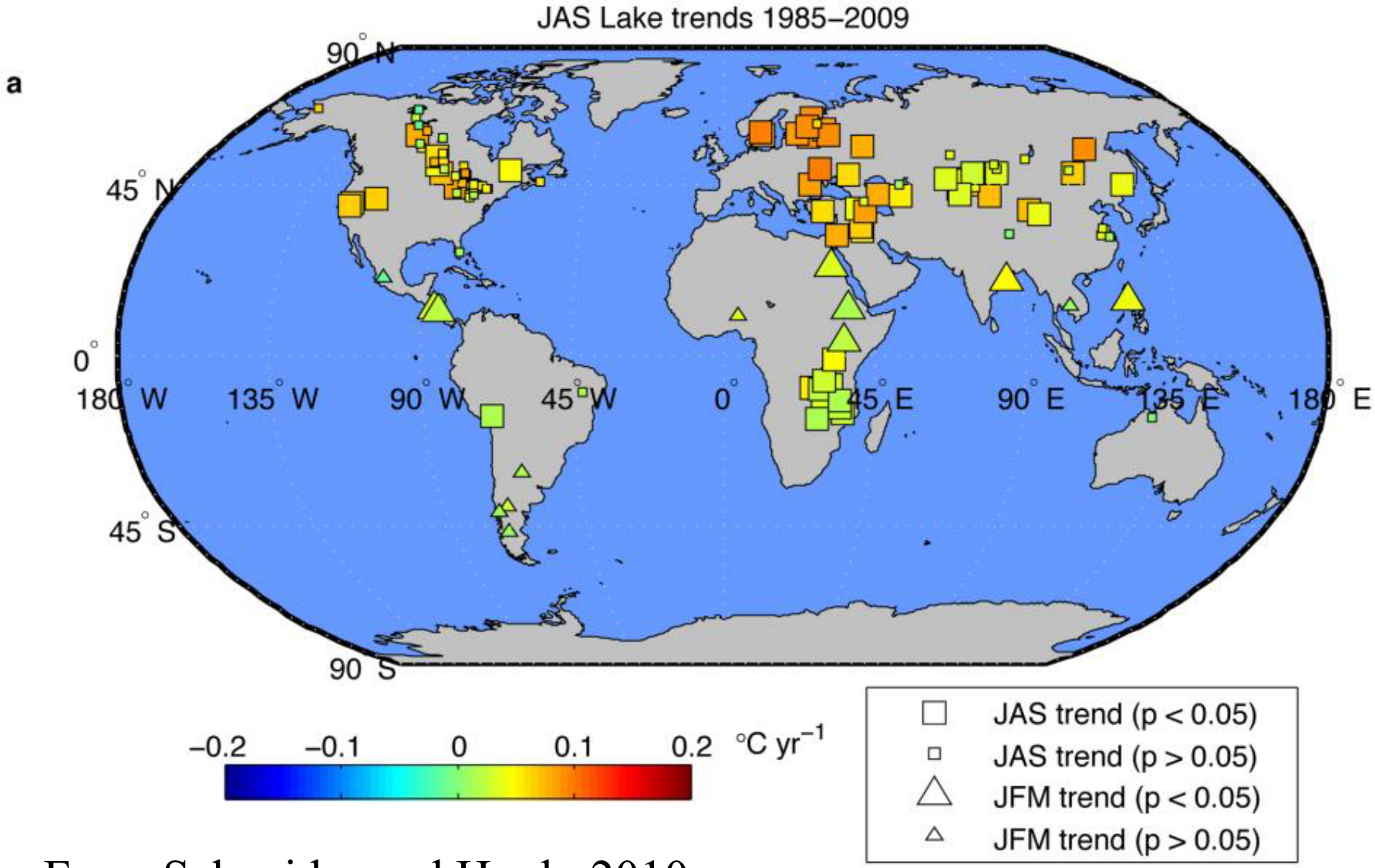
Email:simon.j.hook@jpl.nasa.gov

© 2012 California Institute of Technology. Jet Propulsion Laboratory, California Institute of Technology. Government sponsorship acknowledged.

Outline

- Introduction
- Validation Results
- MODTES (MOD21) 1km T/E product
- Summary and Conclusions

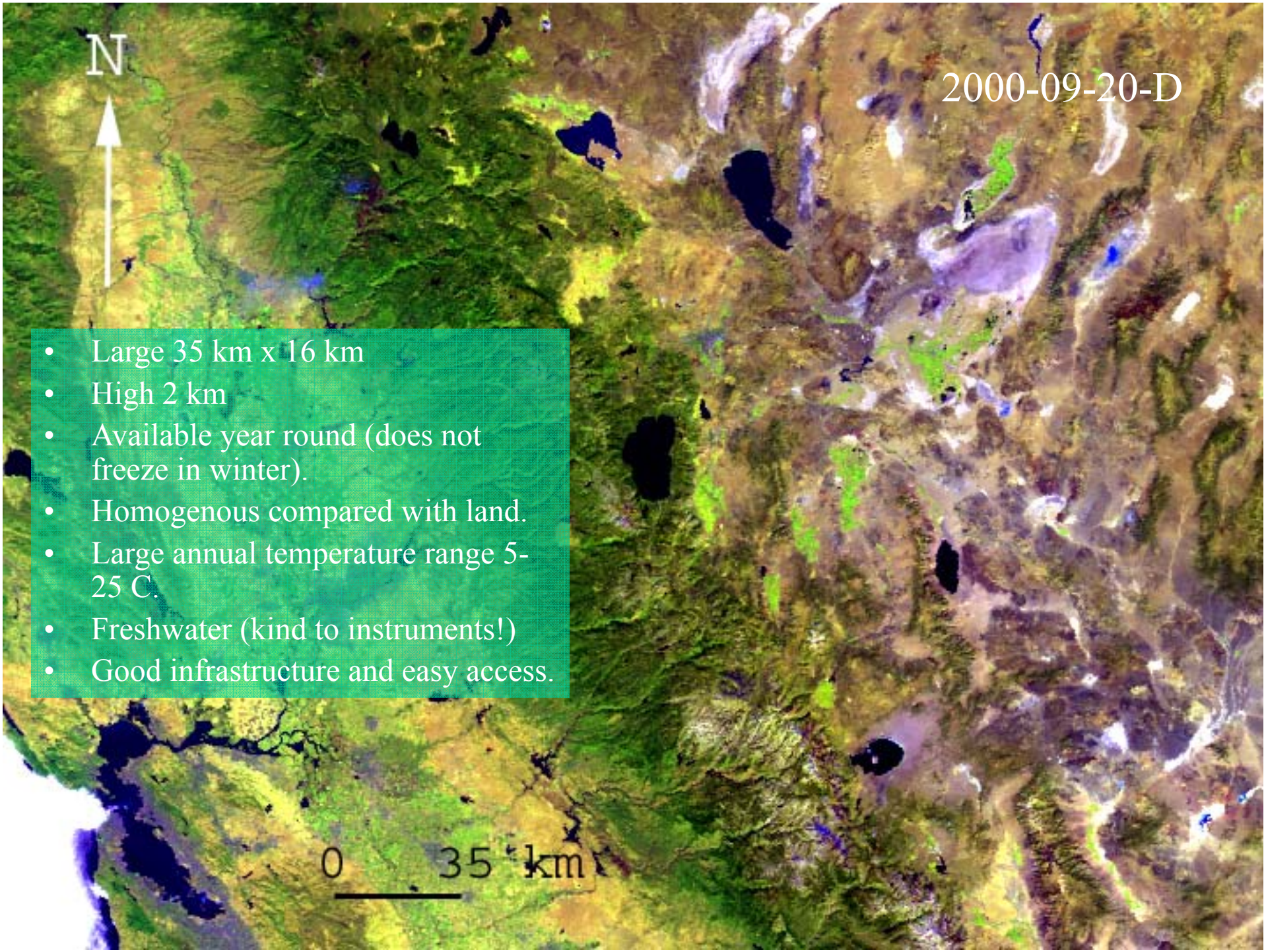
Global satellite-derived seasonal (July, August, September (JAS) and January, February, March (JFM)) nighttime lake surface temperature trends between 1985 and 2009



From Schneider and Hook, 2010

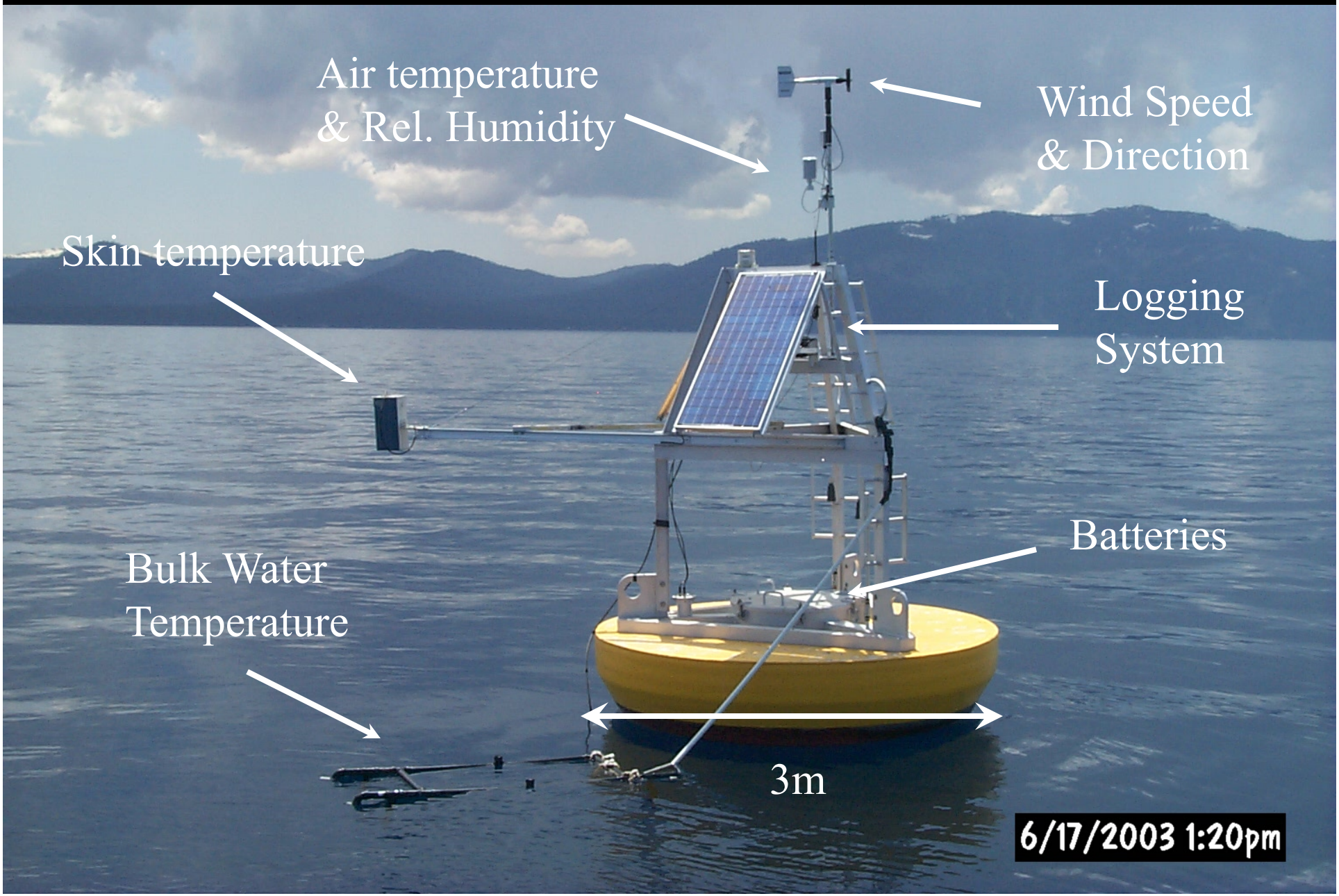
Outline

- Introduction
- <u>Validation Studies at L. Tahoe and Salton Sea</u>
- MODTES (MOD21) 1km T/E product
- Summary and Conclusions



- Large 35 km x 16 km
- High 2 km
- Available year round (does not freeze in winter).
- Homogenous compared with land.
- Large annual temperature range 5-25 C.
- Freshwater (kind to instruments!)
- Good infrastructure and easy access.

TB3 Installed 11-04-2002



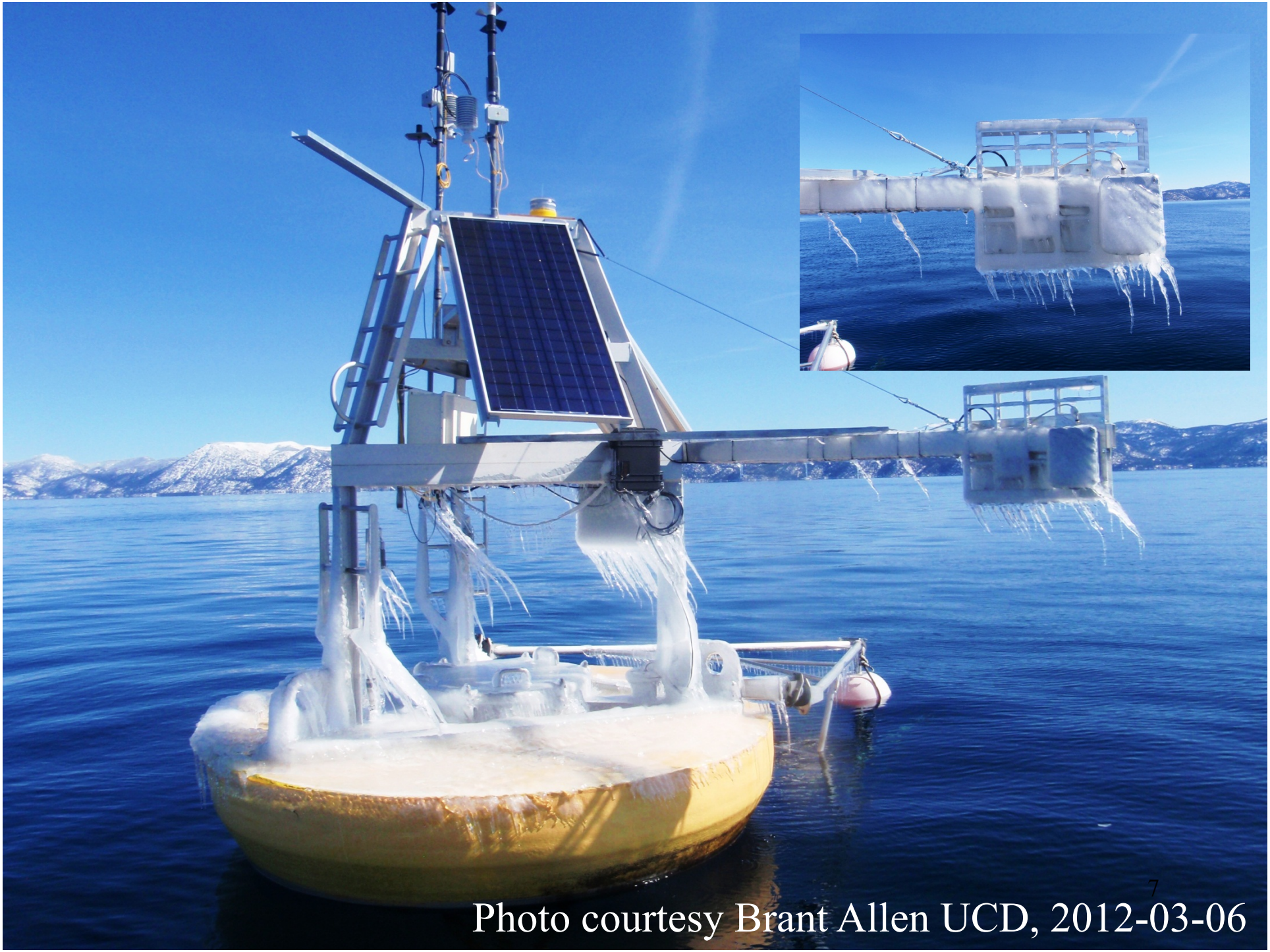
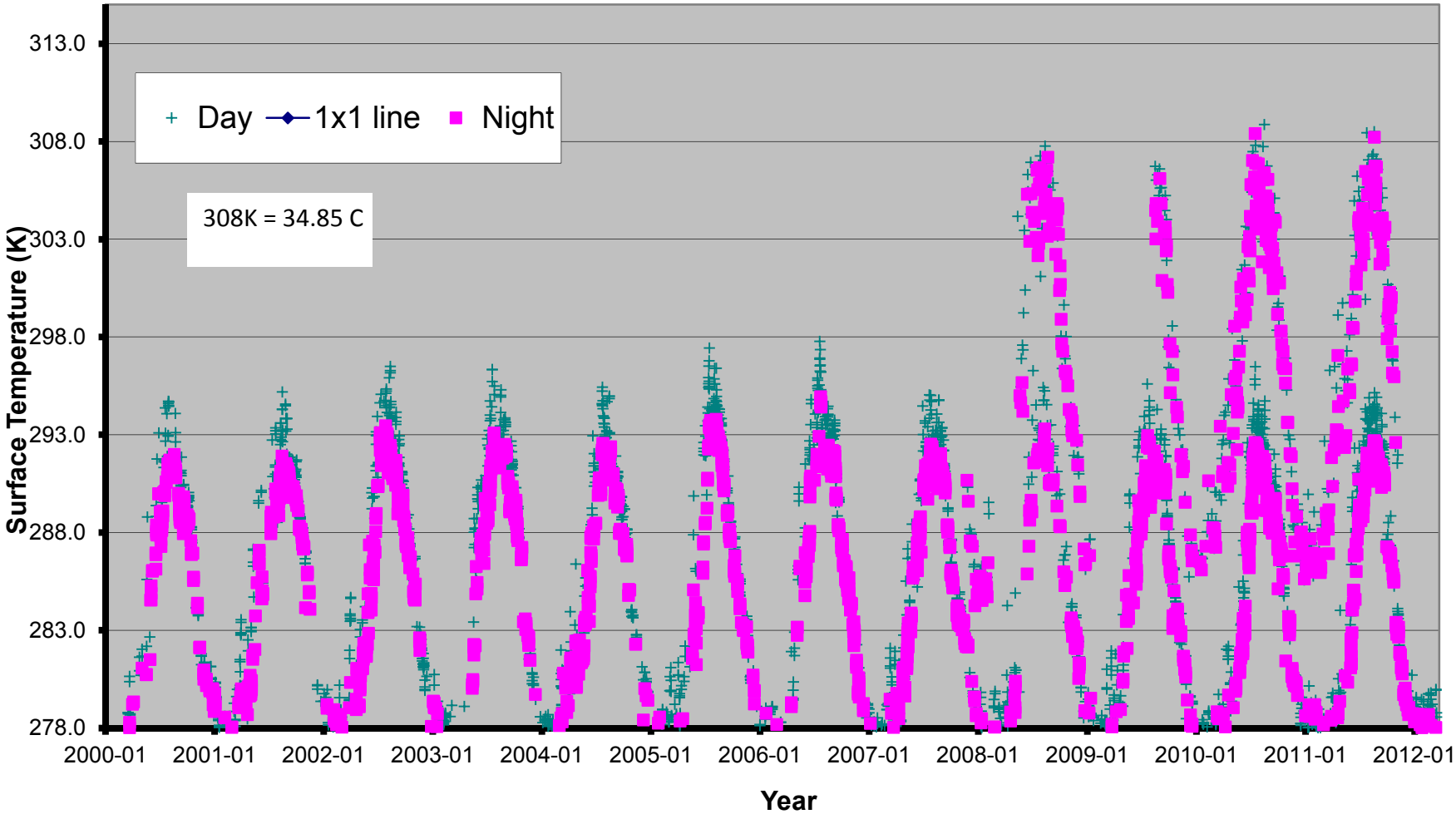
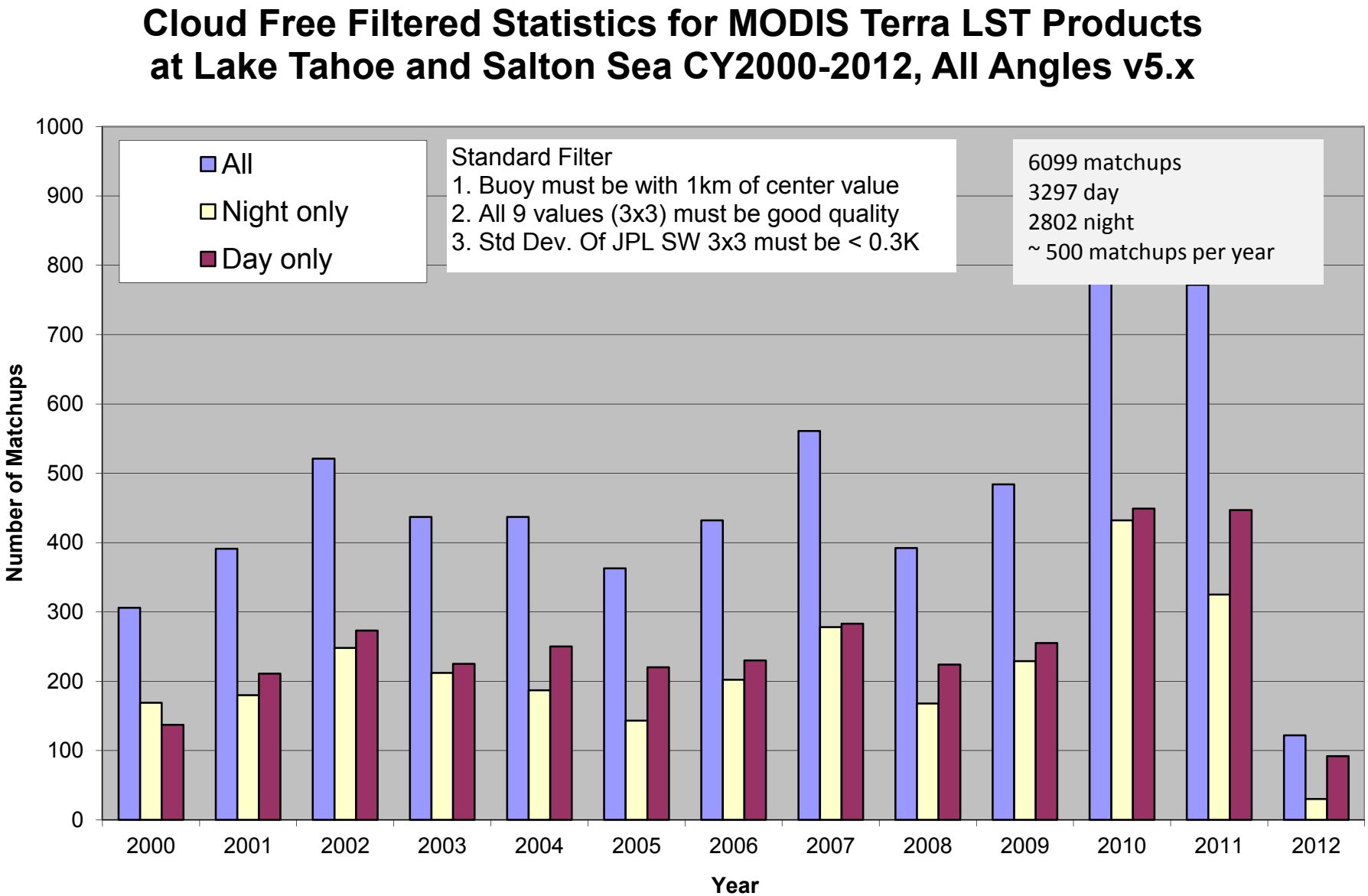


Photo courtesy Brant Allen UCD, 2012-03-06

MODIS Terra Split Window Day and Night Surface Kinetic Temperatures at Lake Tahoe and Salton Sea CY2000-2012 v5.x

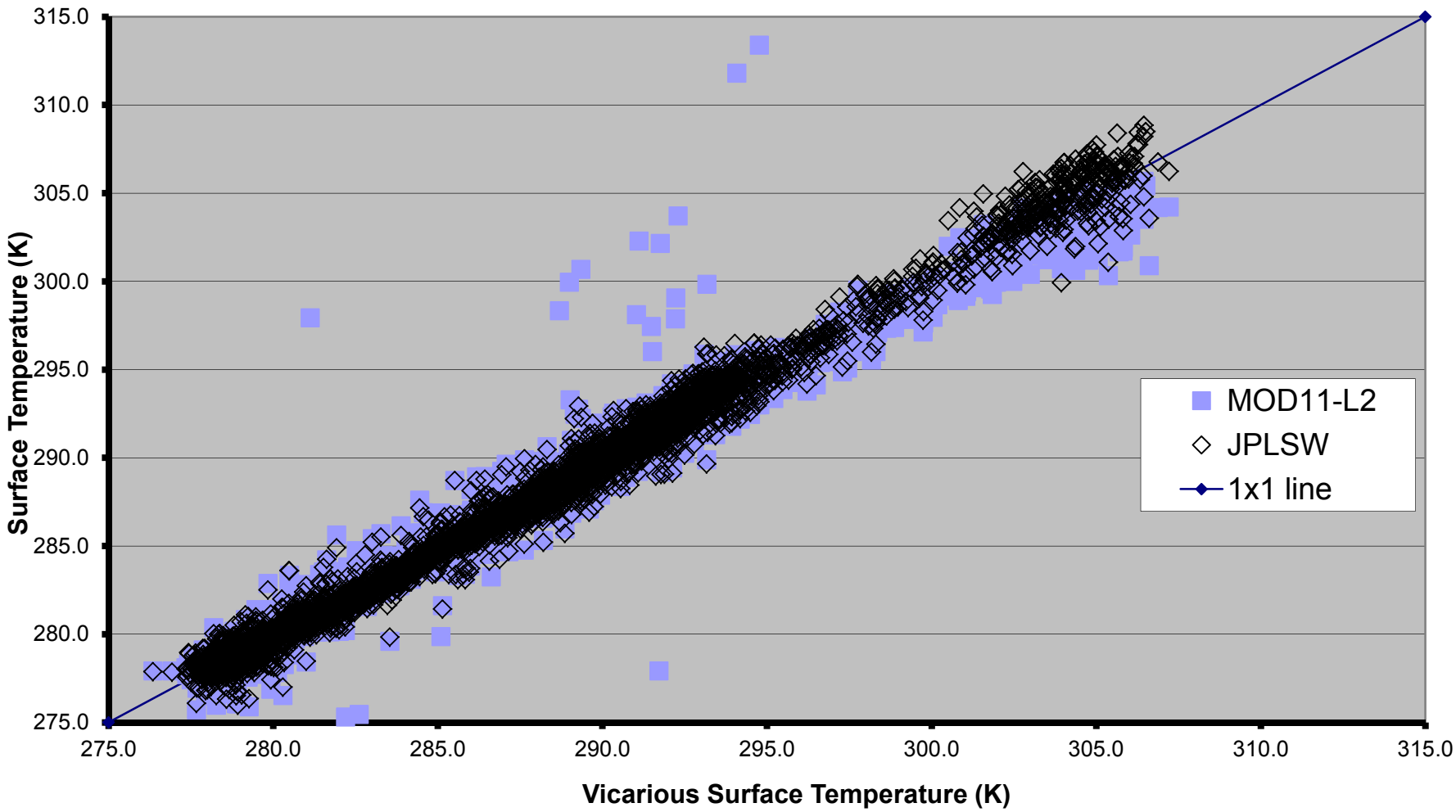


Large range in liquid water temperatures between Tahoe and Salton Sea (4-35 C)



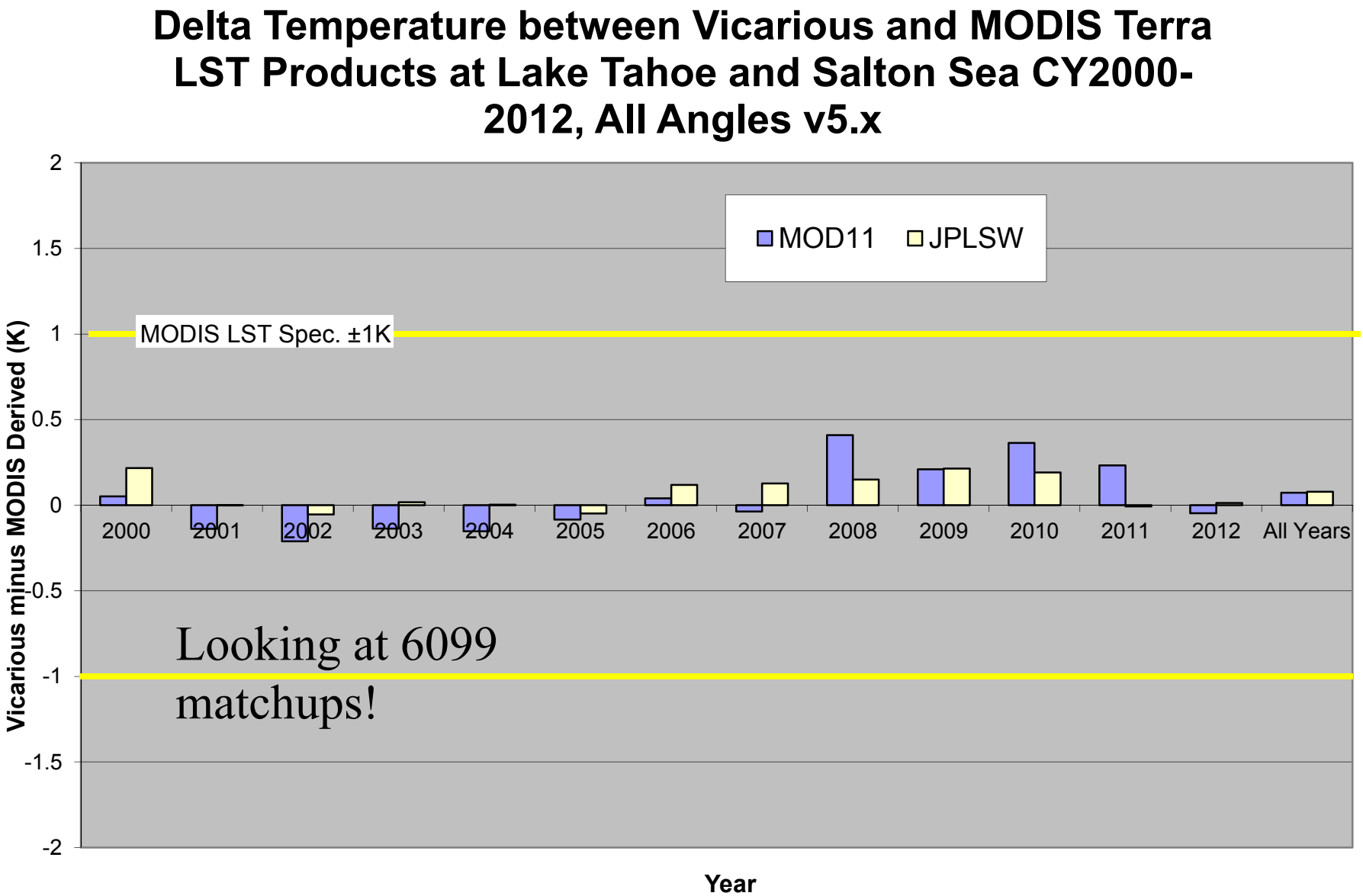
Have large number of matchups, after removal of cloudy pixels have about 500 matchups per year

MODIS Terra and In Situ (Vicarious) Surface Kinetic Temperatures at Lake Tahoe and Salton Sea CY2000-2012 v5.x



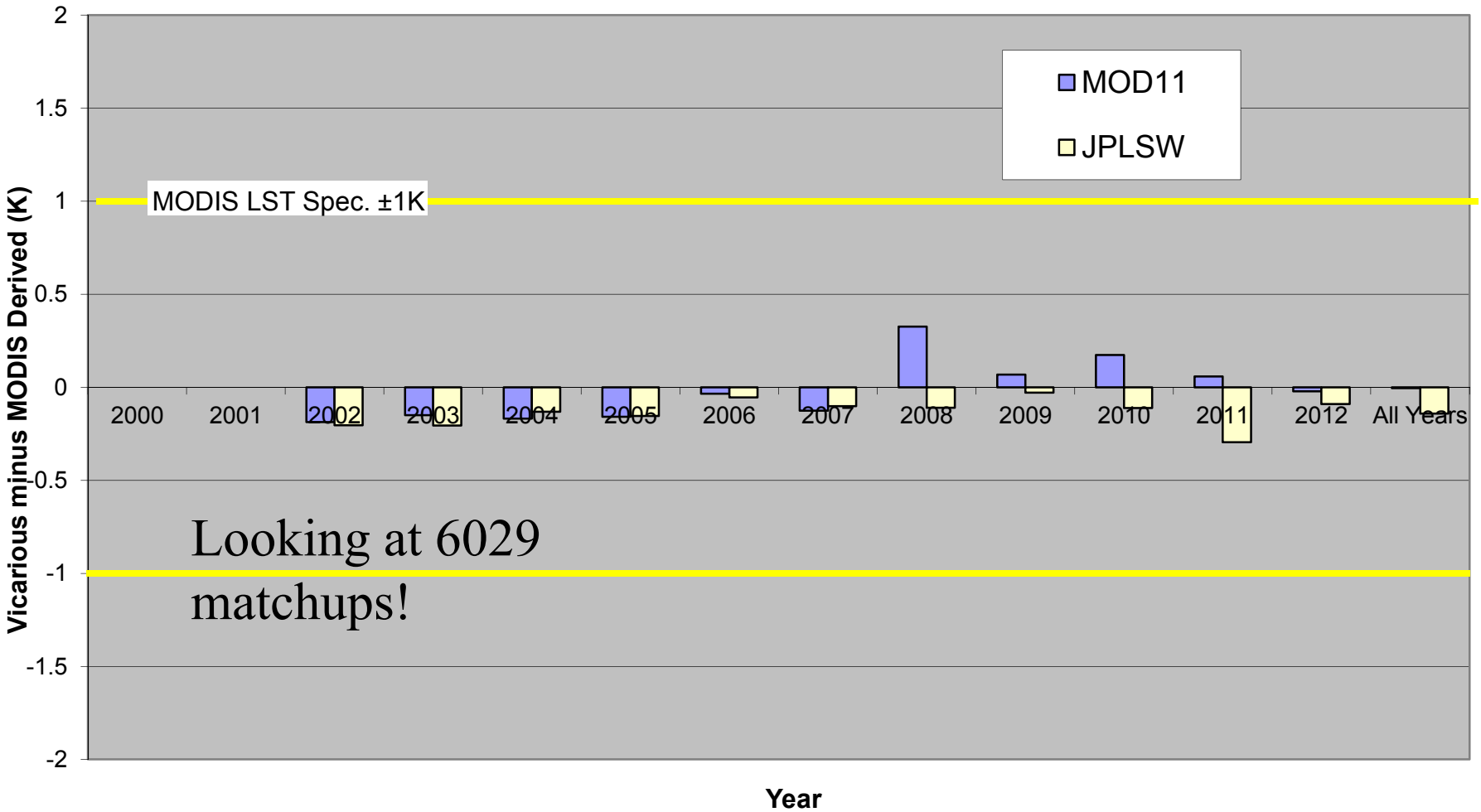
Two algorithms, custom split-window and MOD11.

Generally less scatter in custom algorithm but both algorithms show good agreement.



MOD11 and JPLSW agree well with in situ. MOD11 is well within specification and within a couple of tenths of a degree.

Delta Temperature between Vicarious and MODIS Aqua LST Products at Lake Tahoe and Salton Sea CY2000-2012, All Angles v5.x

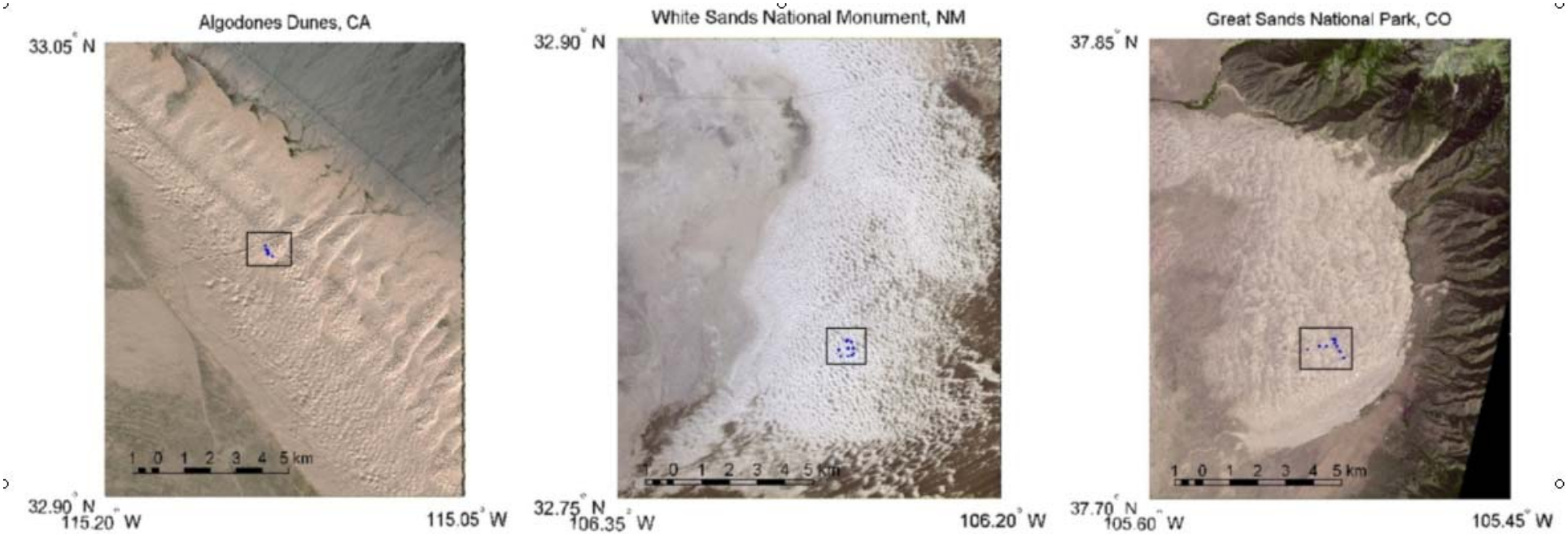


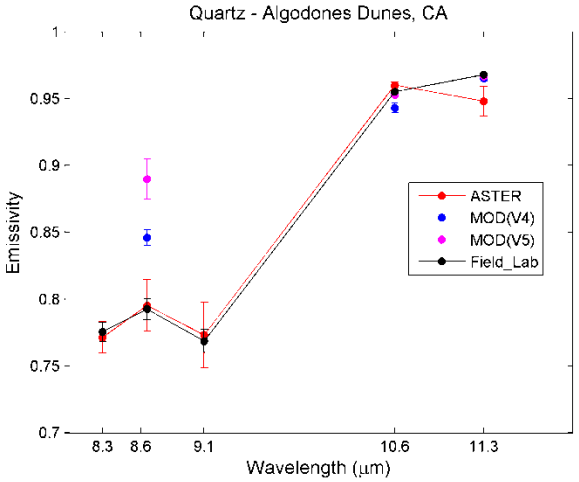
Results for Aqua are very similar to Terra, typically within a few tenths of a degree

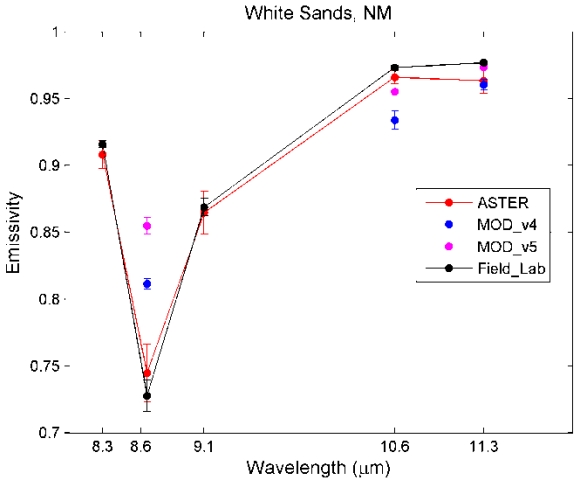
Outline

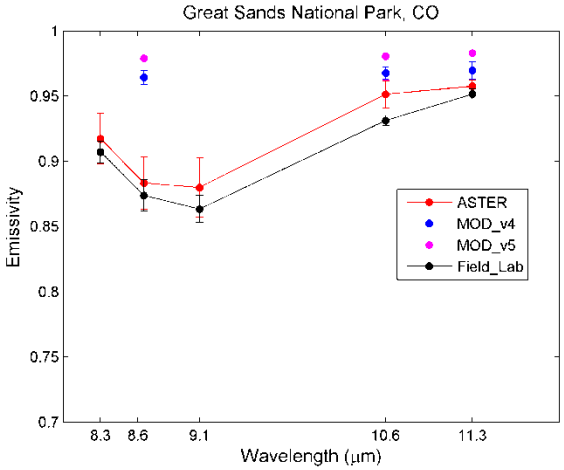
- Introduction
- Validation Studies
- <u>MODTES (MOD21) 1km T/E product</u>
- Summary and Conclusions

MODIS Emissivities are over-estimated



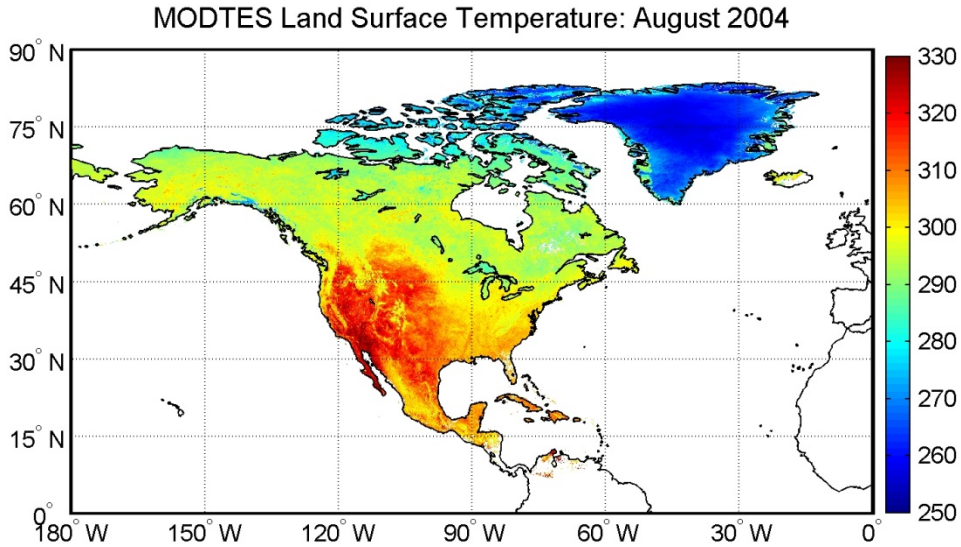






National Aeronautics and Space Administration

A Physics-based MODIS Land Surface Temperature and Emissivity Product (MOD21_L2)



Glynn Hulley, Simon Hook, Christopher Hughes

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

(c) 2012 California Institute of Technology. Government sponsorship acknowledged.

Special thank to the MODAPS team: Teng-Kui Lim, Ginny Kalb, Robert Wolfe, Kurt Hoffman, Jerry Shiles, Sadashiva Devadiga

Outline

1. Temperature Emissivity Separation (TES) Algorithm
2. MODTES testing:
   - Geophysical ‘smell’ test
   - Global variation and distribution check
   - Range checks
3. Uncertainty Analysis
4. Comparison with ASTER-GEM Emissivity
5. Validation results and plans
   - Radiance-based Method
   - Temperature-based Method

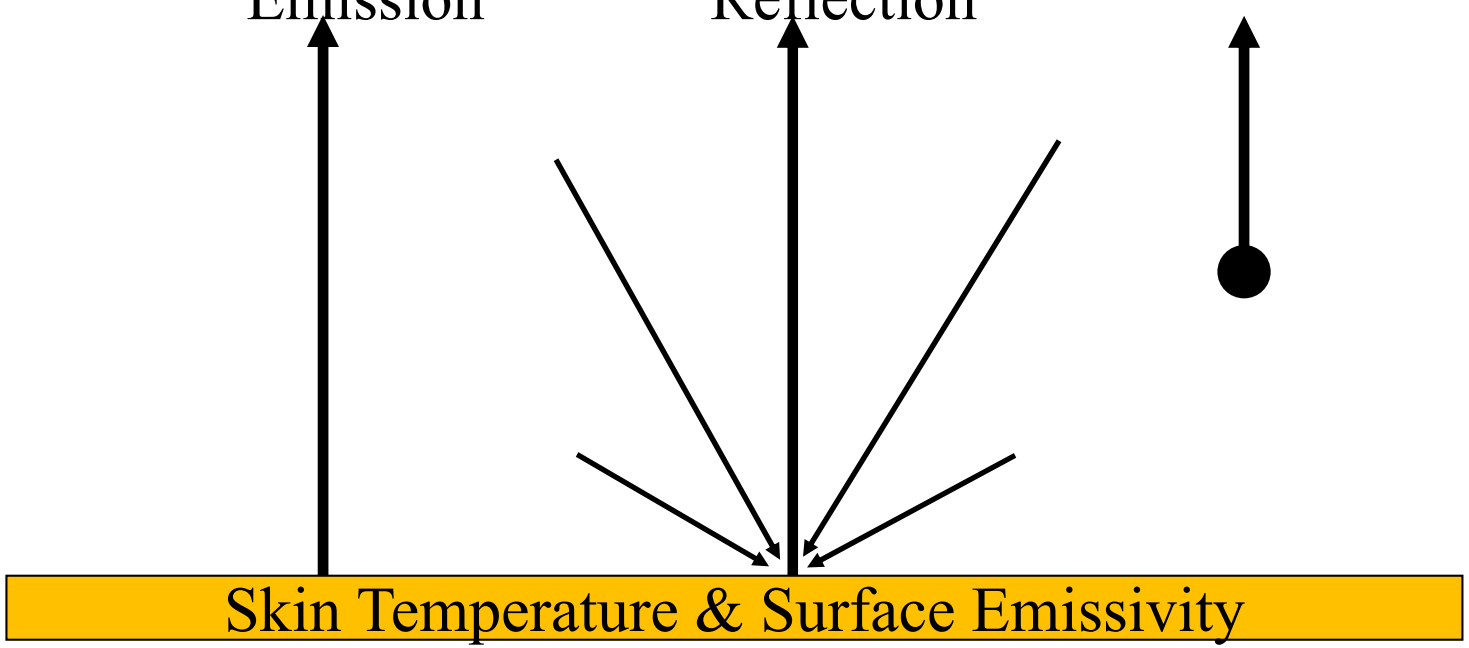
Primary MODIS LST Products

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	Split-Window	- LST - Emissivity (bands 31, 32)
MOD11B1	L3	200 rows 200 columns	6 km	Daily	Day/Night	- LST - Emissivity (bands 20-23, 29, 31,32)
MOD11C3	L3	360x180 deg 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	TES	- LST - Emissivity (bands 29, 31, 32)

Three different algorithms: Split-window, Day/Night and TES
Each has its own strengths and weaknesses

Thermal Infrared Radiative Transfer

$$L_i(\theta) = \overbrace{\underbrace{\tau_i(\theta)\cdot e_i \cdot B_i(T_S)}_{\text{Surface Emission}} + \underbrace{\tau_i(\theta)\cdot(1-e_i)\cdot \overline{L_i}^{\downarrow}}_{\text{Surface Reflection}}}^{\text{Surface Radiance}} + \underbrace{\int B_i(T(P))d\tau_i}_{L_i^{atm\uparrow}}$$



The Temperature Emissivity Separation (TES) Algorithm

Surface Radiance:

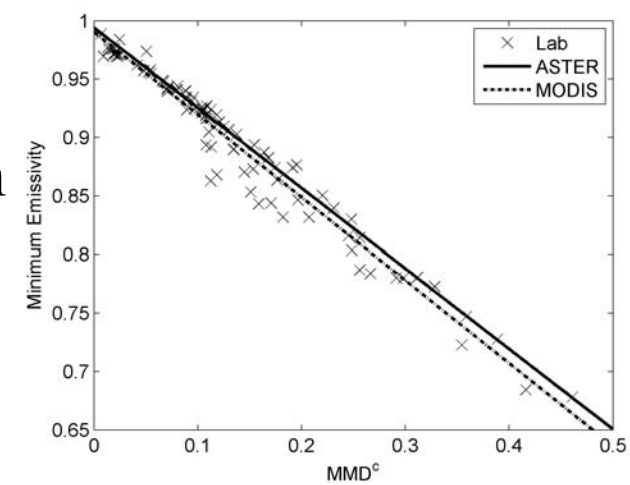
Observed Radiance

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

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

  Estimated using radiative transfer code such as MODTRAN with

  Atmospheric profiles and elevation



Calibration curve for MODIS bands 29, 31, 32:

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

WVS example Over Tokyo Bay with ASTER data

Tonooka, (2005)

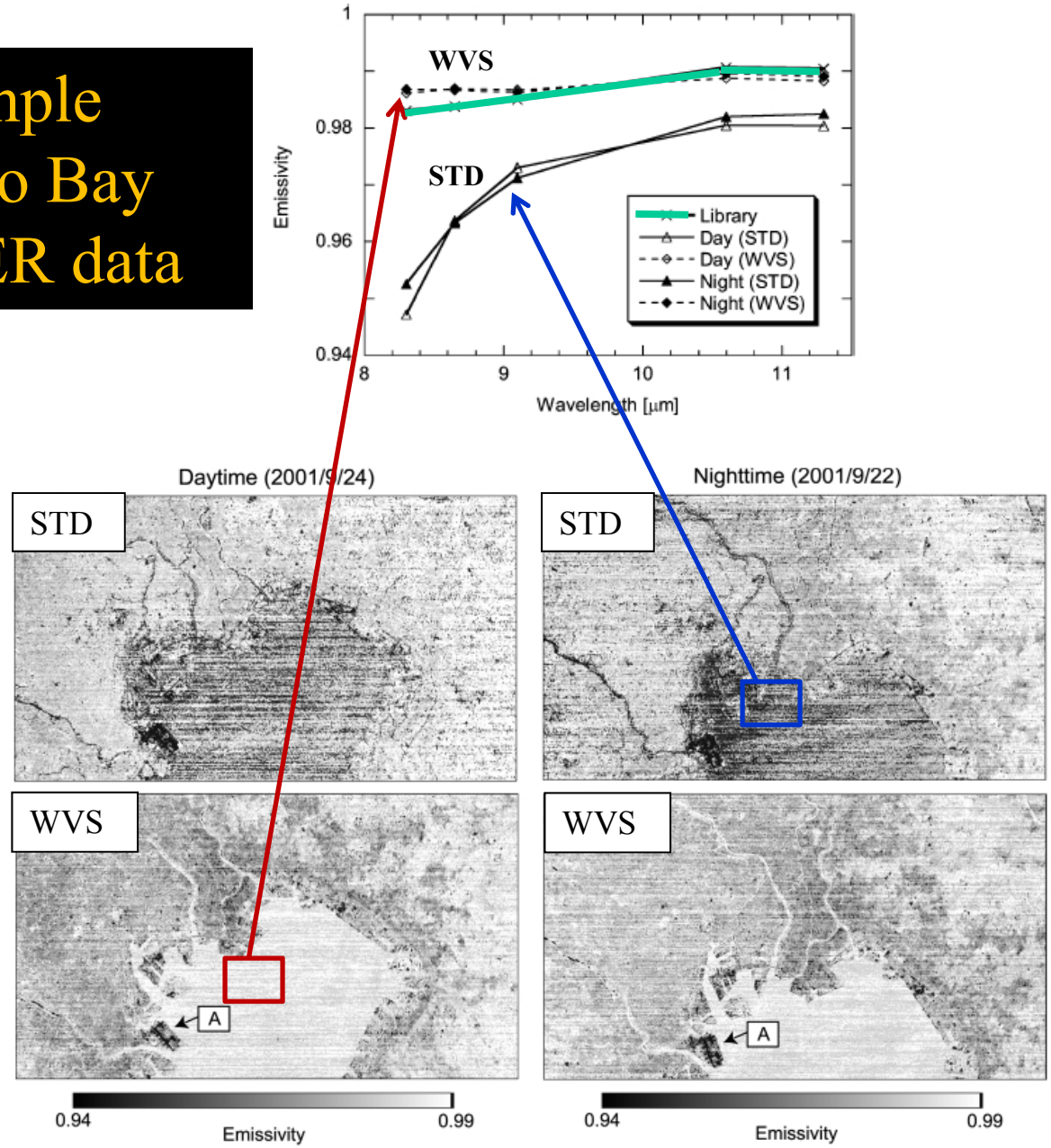
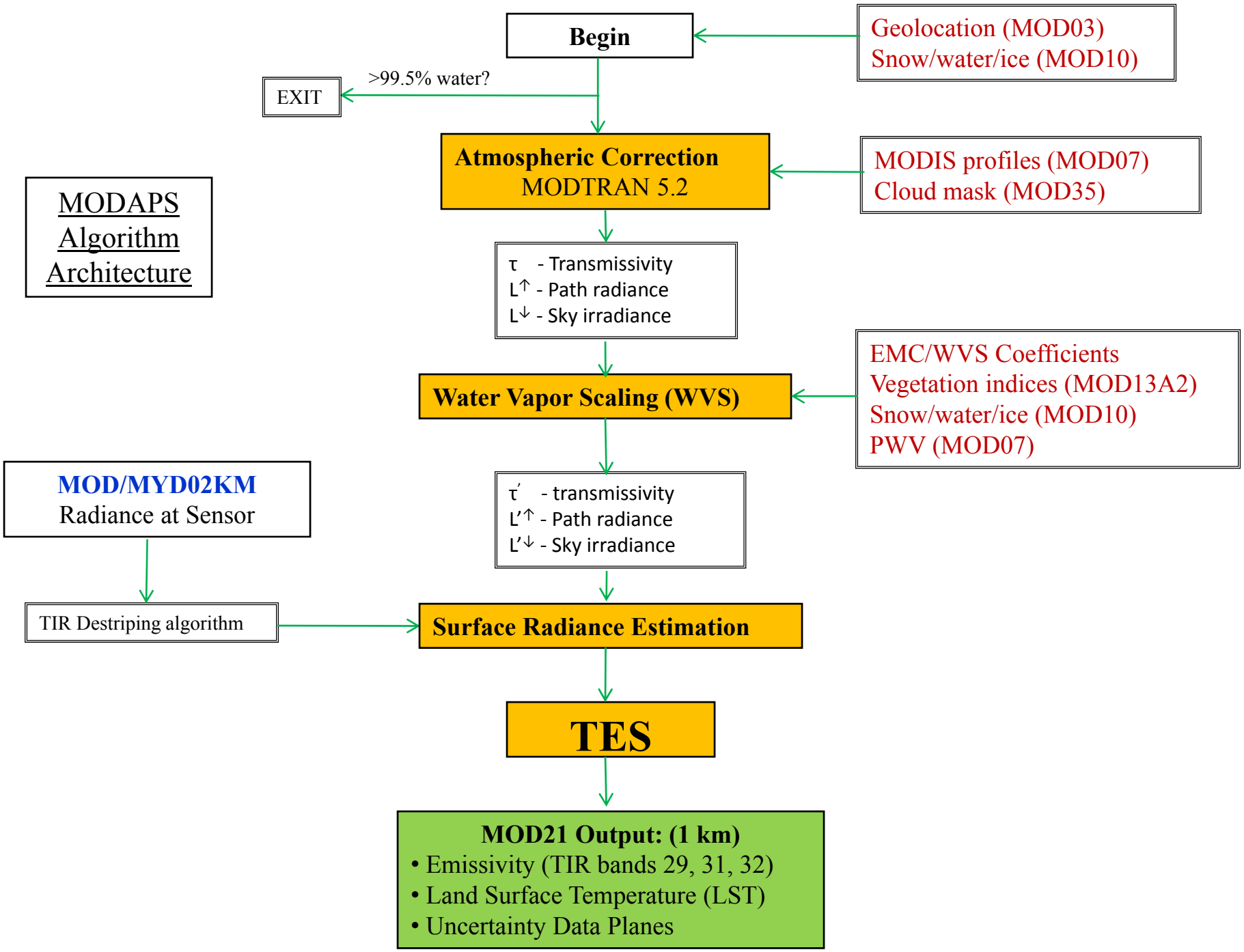
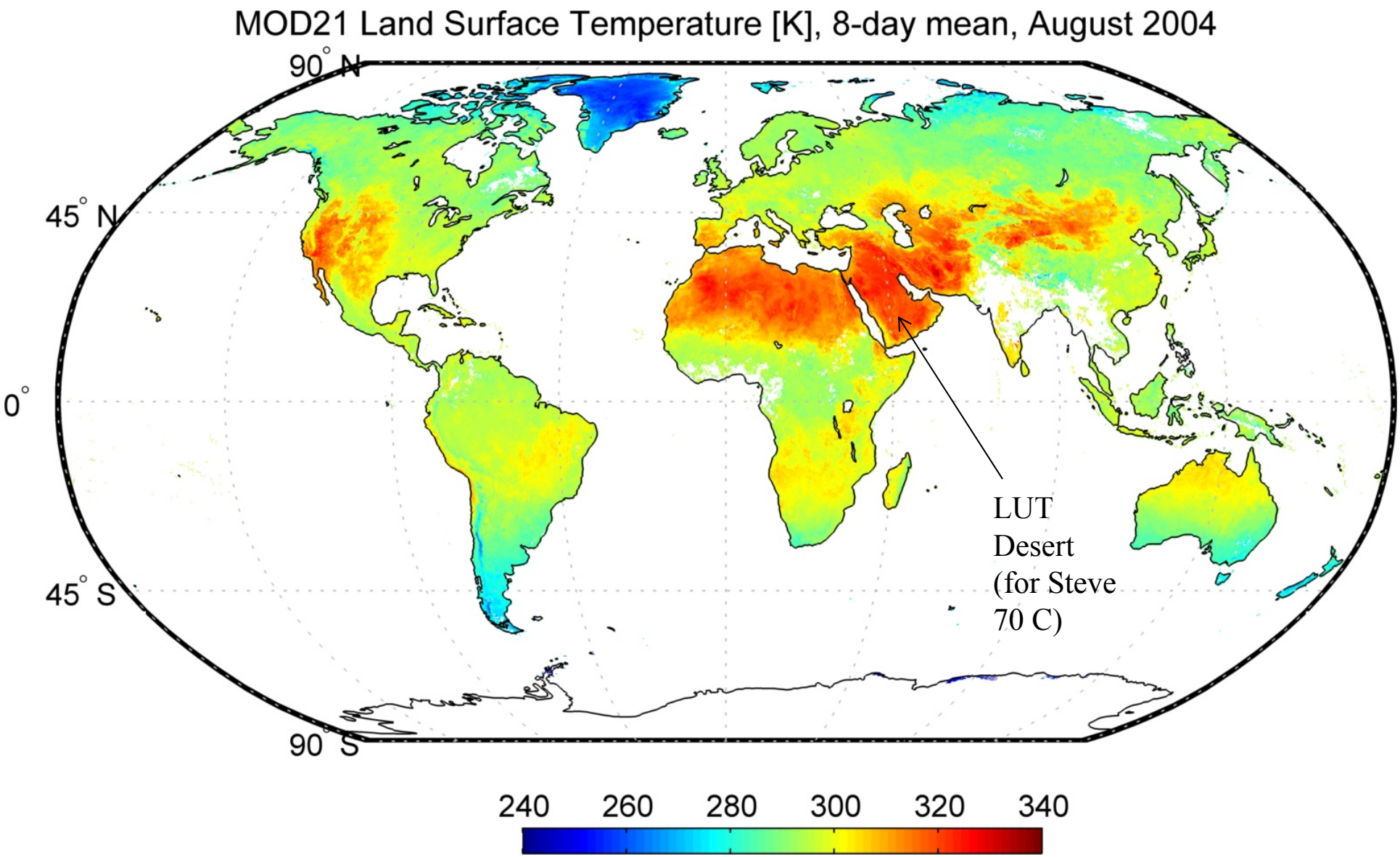


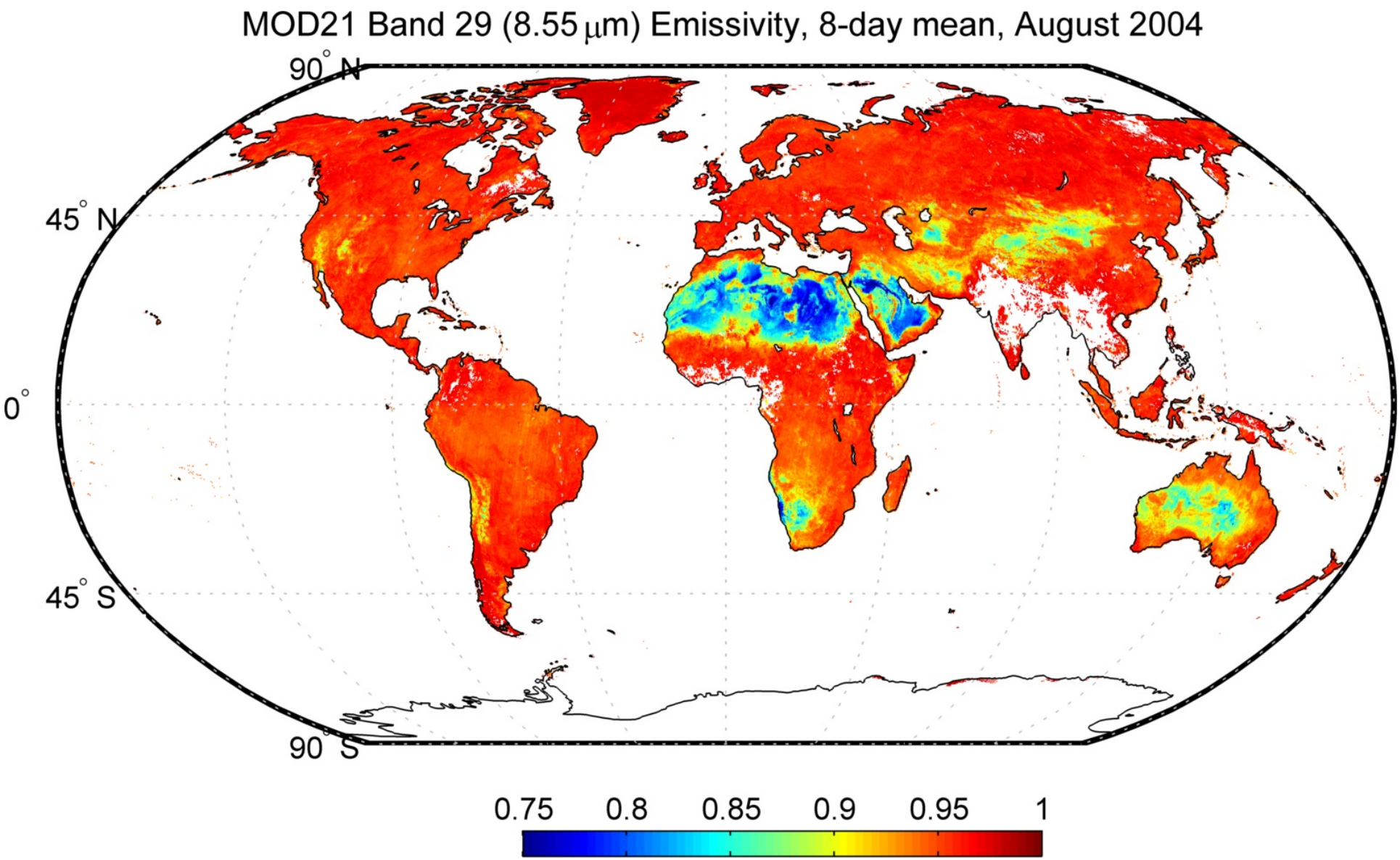
Fig. 20. Emissivity maps of band 12 retrieved from the daytime and nighttime scenes by each method.

Algorithm includes graybody water vapor adjustment

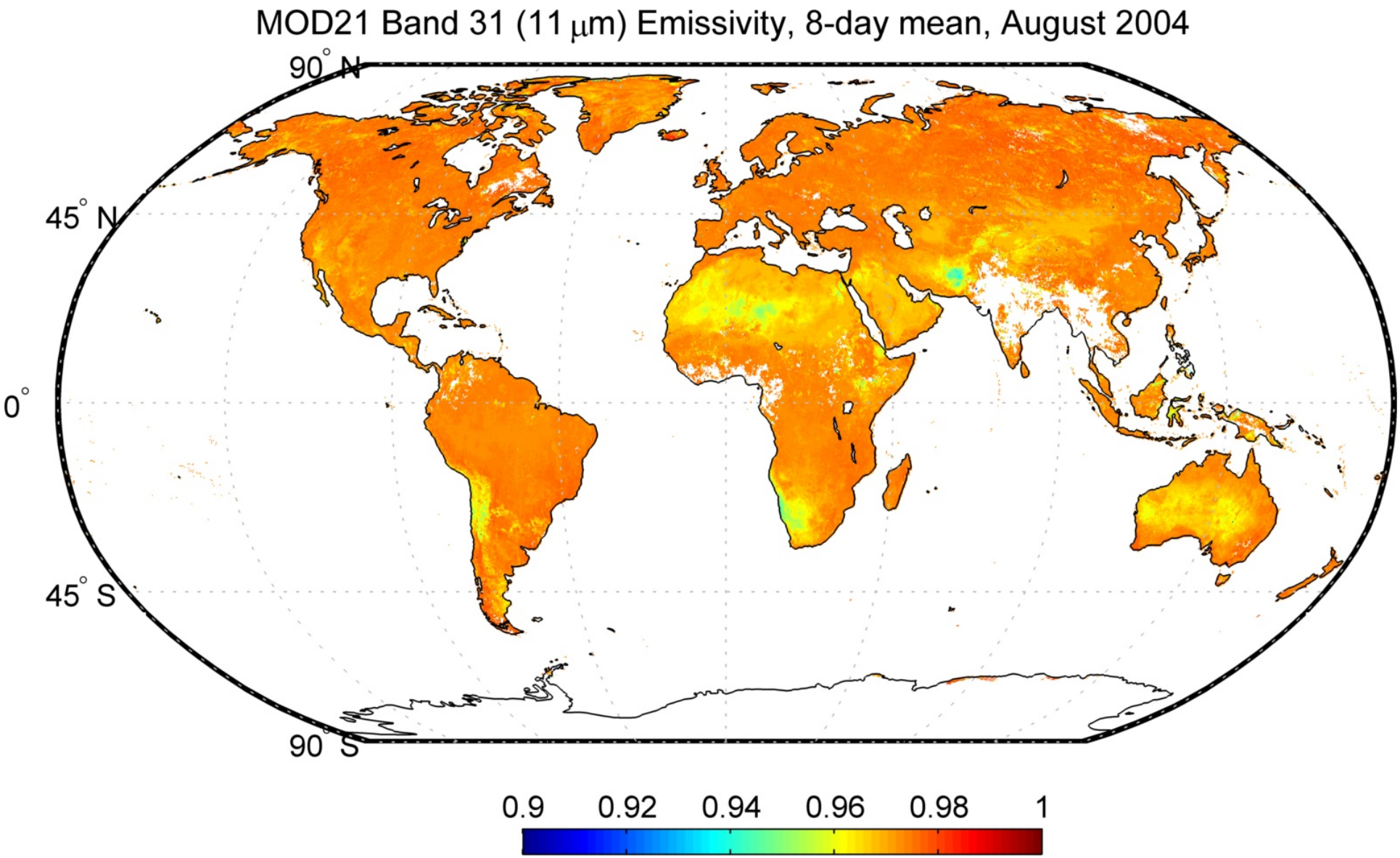

MODAPS Algorithm Architecture
Begin
Geolocation (MOD03)
Snow/water/ice (MOD10)
>99.5% water?
EXIT
Atmospheric Correction
MODTRAN 5.2
MODIS profiles (MOD07)
Cloud mask (MOD35)
τ - Transmissivity
L↑ - Path radiance
L↓ - Sky irradiance
Water Vapor Scaling (WVS)
EMC/WVS Coefficients
Vegetation indices (MOD13A2)
Snow/water/ice (MOD10)
PWV (MOD07)
MOD/MYD02KM
Radiance at Sensor
τ′ - transmissivity
L′↑ - Path radiance
L′↓ - Sky irradiance
TIR Destriping algorithm
Surface Radiance Estimation
TES
MOD21 Output: (1 km)
• Emissivity (TIR bands 29, 31, 32)
• Land Surface Temperature (LST)
• Uncertainty Data Planes



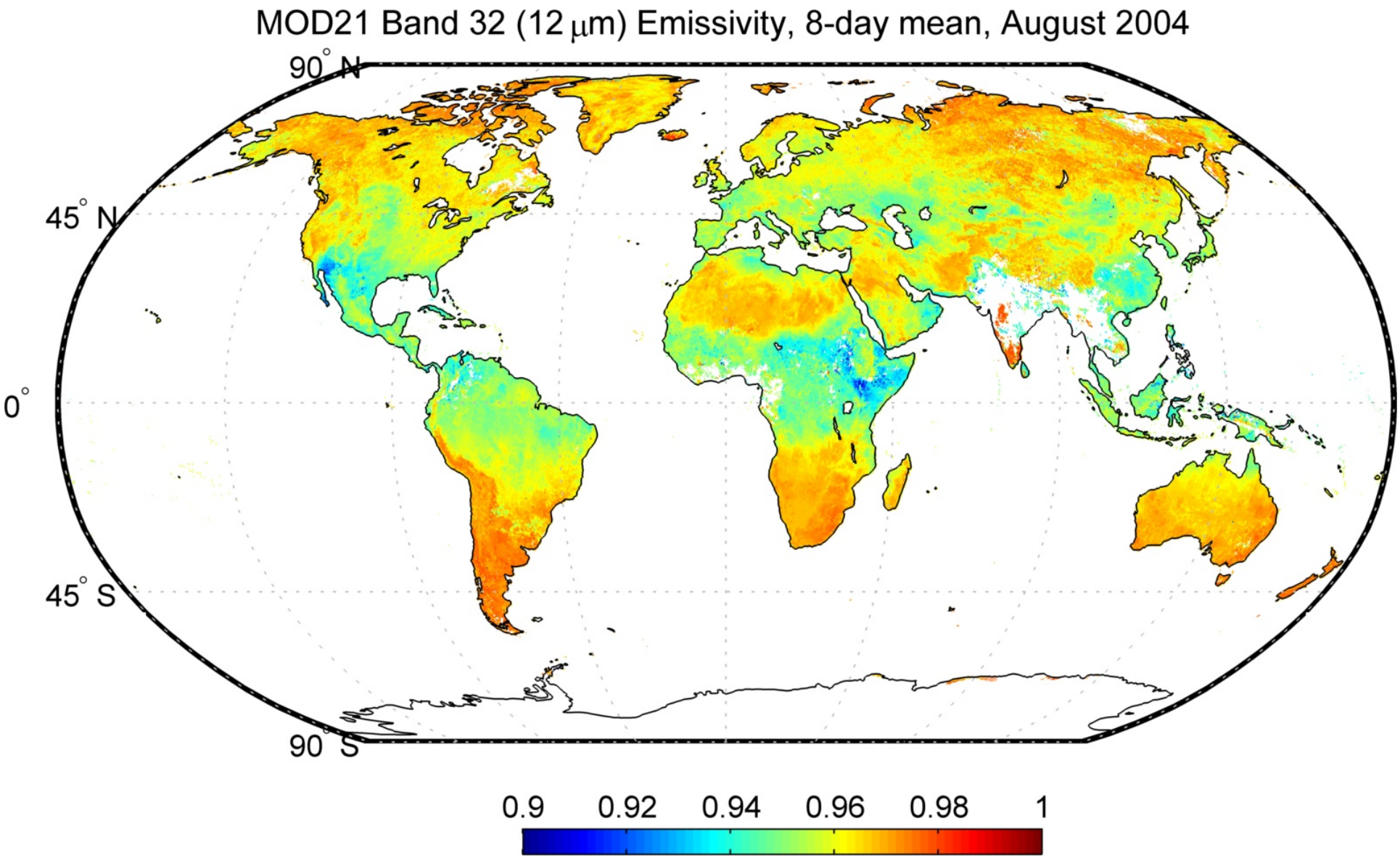
Temperatures are realistic and distributed as expected



Emissivity is extremely important in calculating radiation balance,
Especially in areas of low emissivity, exposed siliceous areas (quartz-rich)

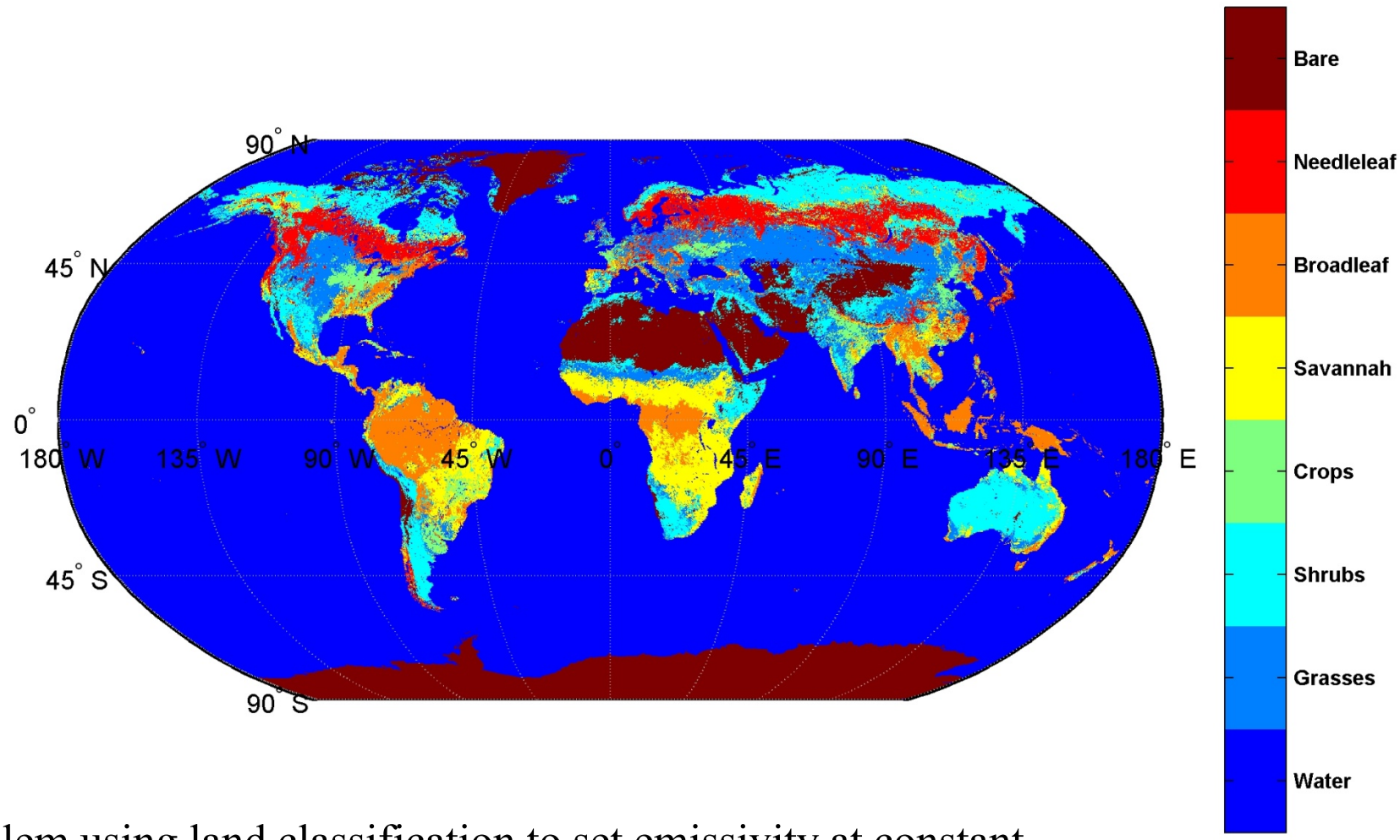


Generally see least variation in emissivity around 11 um



Slightly more variation at 12 um, associated with areas of carbonate

IGBP Land Classification (MOD12)



Problem using land classification to set emissivity at constant when clearly there is considerable variation in emissivity

MOD21 Uncertainty Analysis

- Uncertainty analysis is critical for developing Earth System Data Records (ESDRs), e.g. LST with long-term consistency, continuity and accuracy

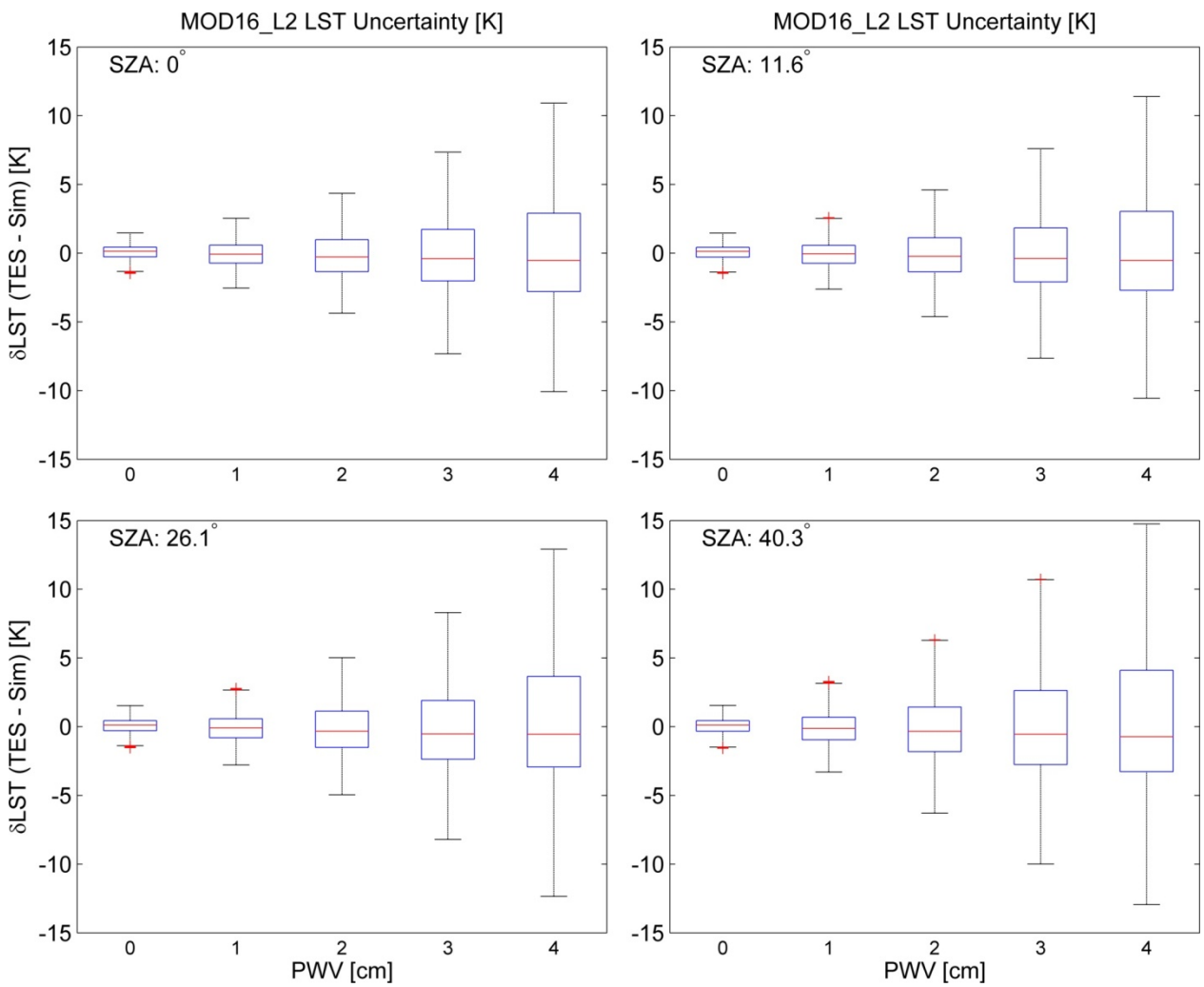
- Current products only include qualitative information in QC data planes

- LST&E Uncertainty Simulator (LSTE-US) developed at JPL
  - Uses wide range of atmospheric profiles (382 from 1-6 cm total water vapor)
  - Used a broad range of surface types (>100 from ASTER spectral library)
  - At-sensor radiances simulated for any given sensor's spectral response
  - Currently the TES and Generalized Split-Window algorithms are being tested

- Following uncertainty statistics are generated for LST&E products based on simulation results:
    - Model or Algorithmic error
    - Atmospheric compensation error
    - Measurement noise error (NEDT)
    - Cloud contamination
    - Calibration error

MOD21 LST Uncertainty

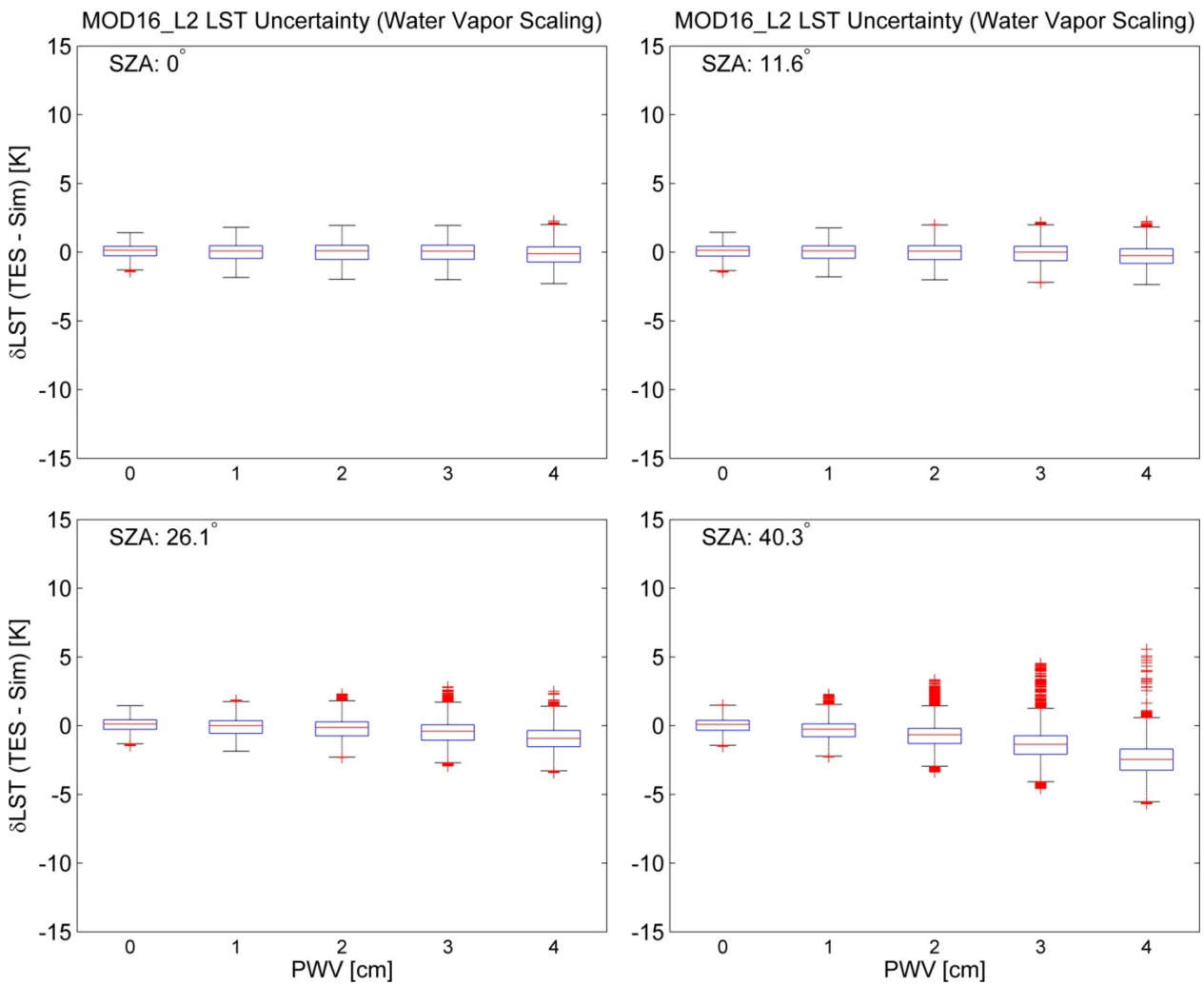
Tot error = model+atmospheric+measurement error



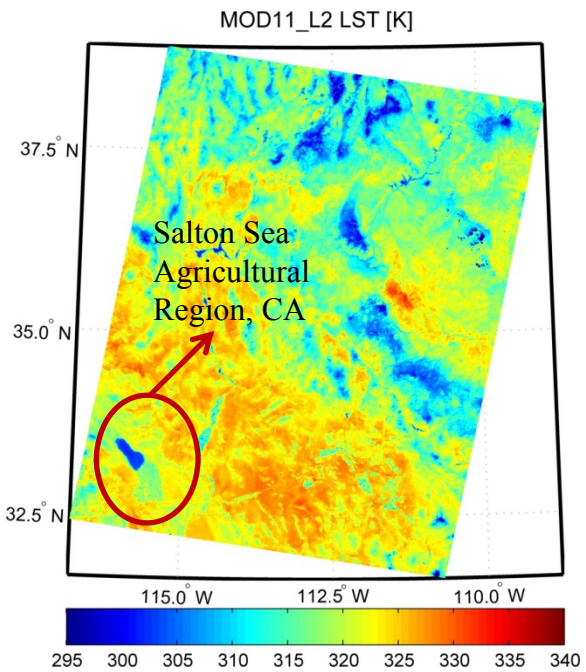
<u>Uncertainties increase above ~2cm Precipitable Water Vapor (PWV) and with Sensor zenith angle (SZA) due to residual errors in atmospheric correction.</u>

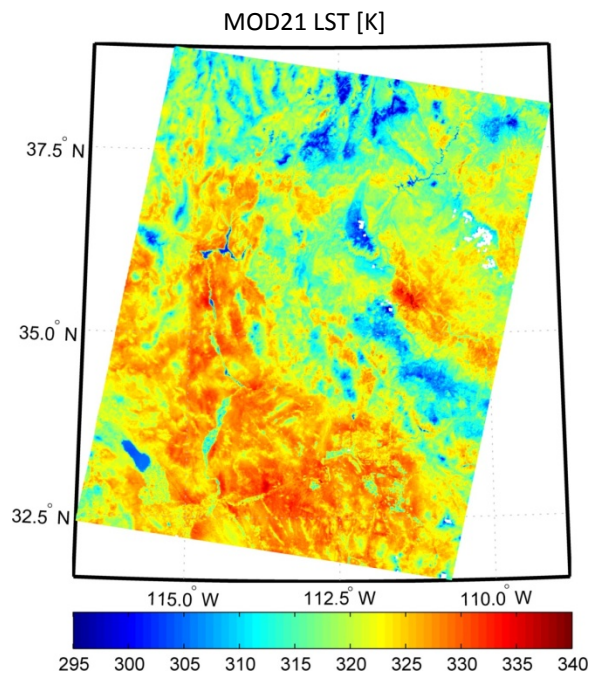
MOD21 LST Uncertainty with Water Vapor Scaling (WVS)

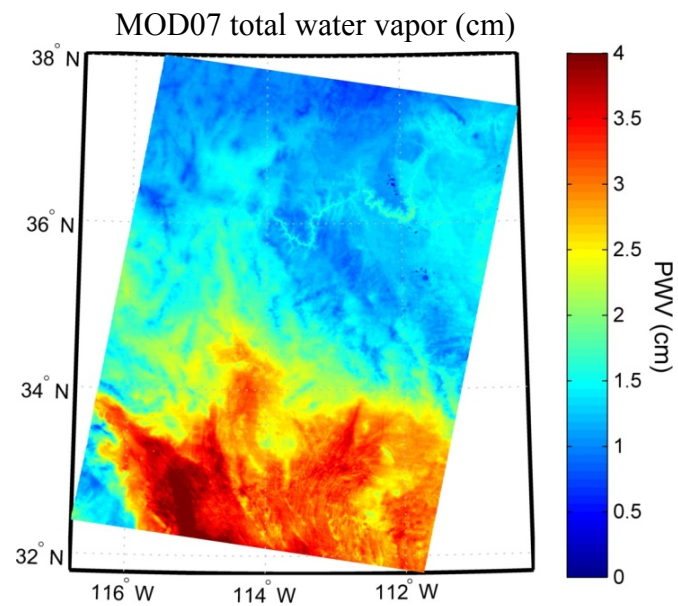
Tot error = model+atmospheric+measurement error

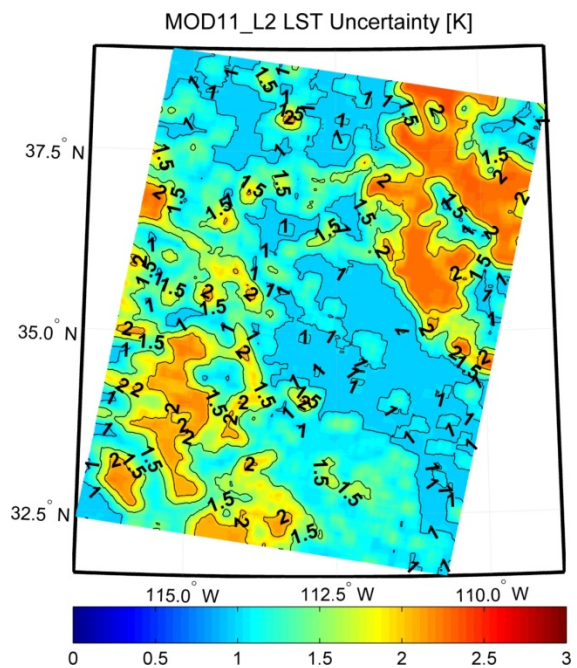


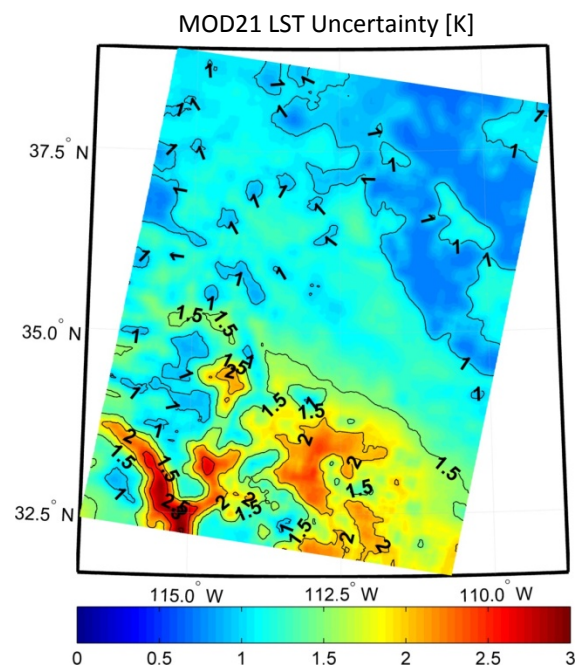
<u>With Water Vapor Scaling, uncertainties are invariable with higher Precipitable Water Vapor (PWV) and degrade slightly larger Sensor zenith angles (SZA). RMS errors ~1K.</u>











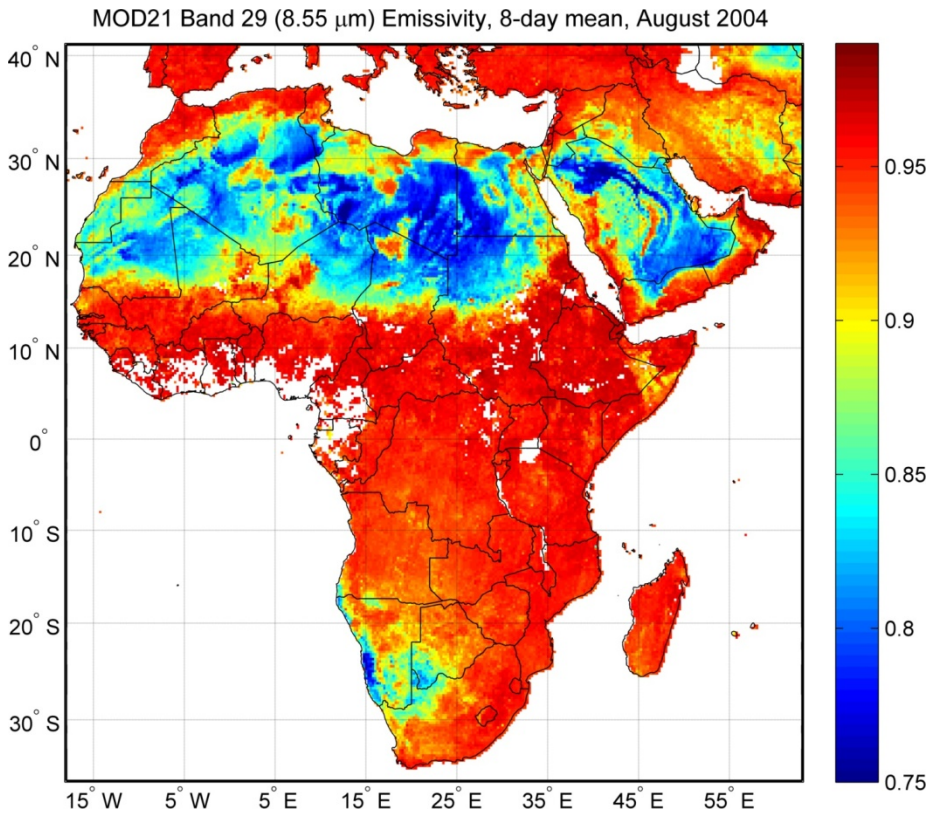
<u>MOD21 and MOD11_L2 are complementary products:</u>

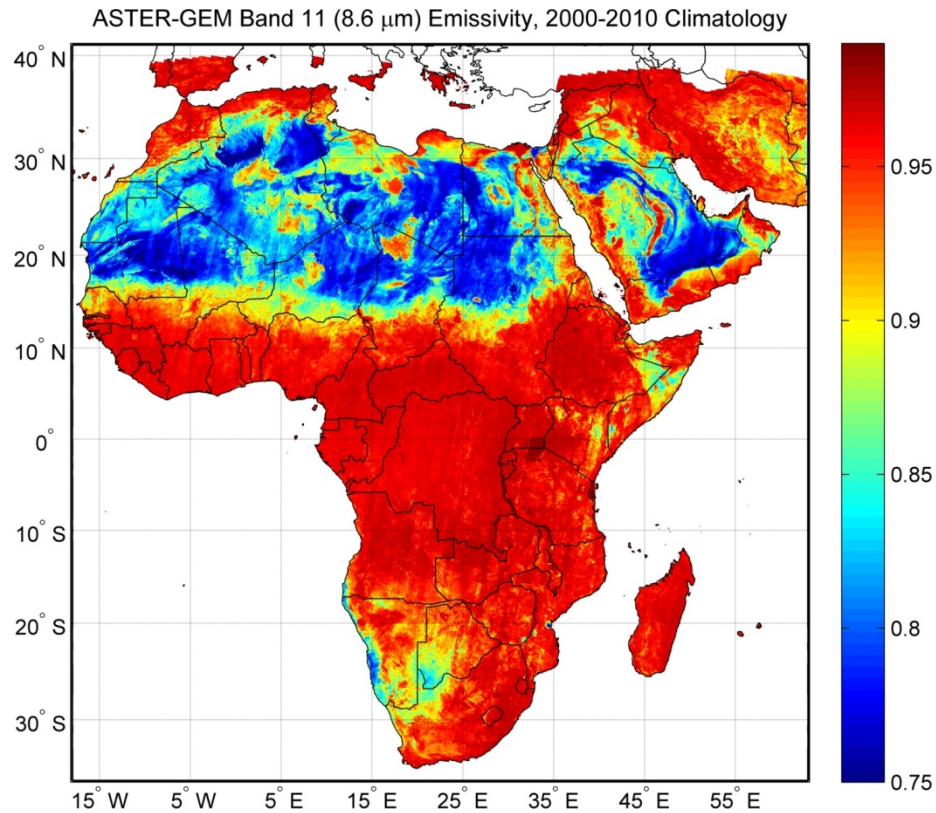
1) MOD21 has higher accuracy over arid regions and lower accuracy over graybody while reverse is true for MOD11.

2) MOD21 has lower accuracy over graybody humid conditions while MOD11 has lower accuracy over dry, arid conditions.

MOD21 Emissivity

ASTER Global Emissivity Map (GEM)

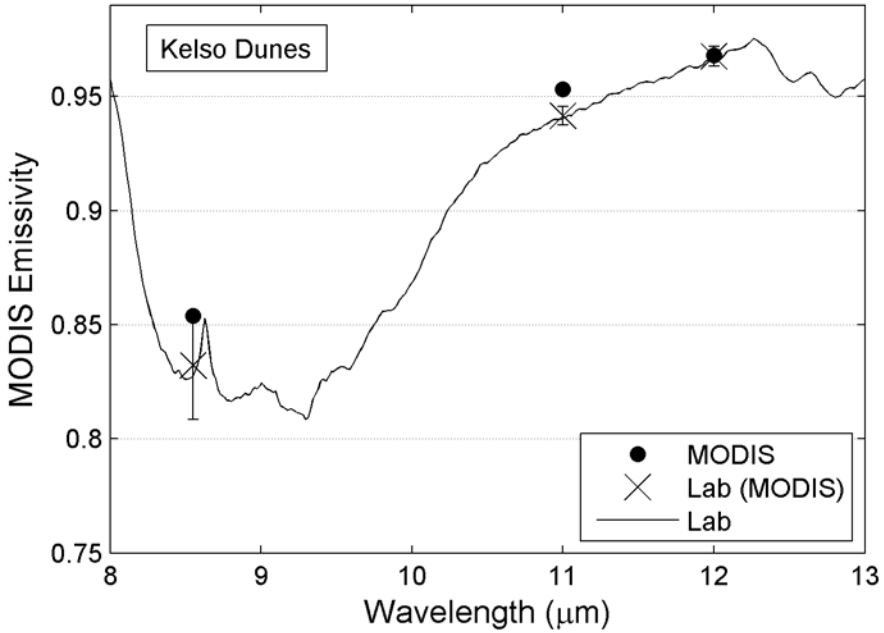




<u>Very good overall spatial correlation. ASTER has deeper emissivity features due to higher resolution (100m) compared to MODTES (1km). Differences also arise due to long term surface changes since ASTER is a mean climatology.</u>

Radiance-based validation plans for MOD21

- LST can vary extensively at small spatial / temporal scales – problematic!
- Instead, compare measured Top Of Atmosphere (TOA) radiance to calculated radiance
- Will use 10 sand dune sites with lab-measured samples collected during 2008
- Use MODTRAN 5.2 for atmospheric model
  - Sample's emissivity from lab
  - AIRS (Aqua) or NCEP GDAS1 (Terra) atmospheric profile data
  - ASTER GDEM elevation data
  - LST from MOD16_L2
    - Initially from 2000 (Terra), 2002 (Aqua), 2005 (both), 2011 (both)
- Repeat, shifting LST by 2 K until measured TOA radiance bracketed by MODTRAN
- Interpolate between bracketing radiance values to find actual LST



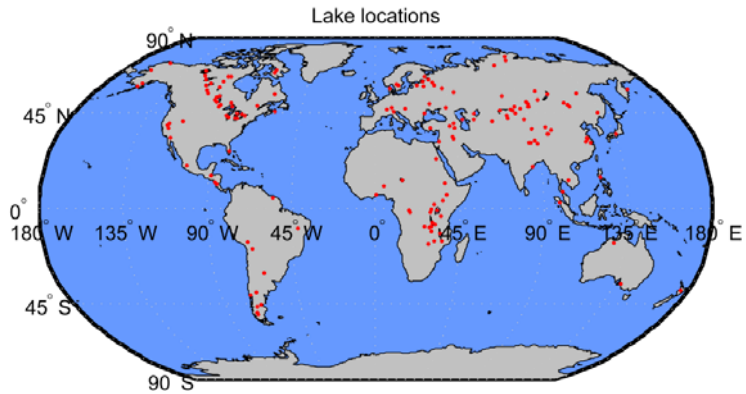
Summary and Conclusions

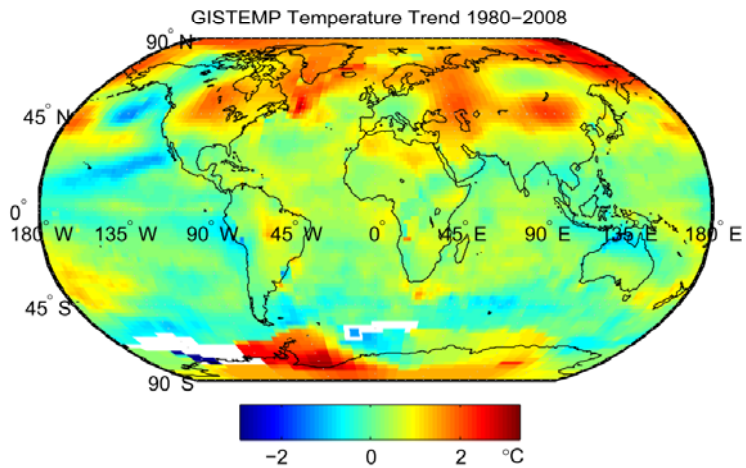
- Established automated sites for validating thermal infrared data at Lake Tahoe CA/NV and Salton Sea CA. Lake Tahoe Site has been operating since 1999.
- Measurements made at the site include skin- bulk- air- temperature, wind speed, wind direction and net radiation at multiple locations every 2 minutes. Multiple locations (4 buoys) allow validation of several points within a scene.
- Validated data from multiple instruments including, AATSR, ASTER, MODIS (Terra, Aqua), Landsat 5 and Landsat ETM+, MTI.
- Results so far for MODIS indicate:
  - MOD11 algorithm works well over water
  - MOD11 algorithm have some issues over arid and sem-arid areas. Version 4.1 better than 5.0, version 6.0 being evaluated.
  - MOD21 algorithm provides emissivity and temperature at 1km
  - Comparing in situ and radiance based validations of MOD11 and MOD16

Backup

Introduction

- The Idea
  - Temperatures of lakes and reservoirs have potential as good indicators of climatic trends
  - Existing in situ data is insufficient in space and time
  - Nearly 30-year record of satellite thermal infrared imagery available
- Project Objectives
  - Use satellite derived water surface temperatures to characterize the temporal thermal behavior of lakes and inland water bodies worldwide
  - Relate changes in the thermal behavior of the water bodies to global and regional climate change as indicated by surface air temperature data
  - Study sites: 165 large lakes worldwide
  - Case study: 6 lakes in California and Nevada





Water Vapor Scaling (WVS) Method

Tonooka, H., (2005), Accurate Atmospheric Correction of ASTER Thermal Infrared Imagery Using the WVS Method, IEEE Trans. Geos. Remote Sens., 43 (12)

EMC/WVD model estimates surface brightness temperature

$$\begin{cases} T_{g,i} = \alpha_{i,o} + \sum_{k=1}^{n} \alpha_{i,k} T_k \\ \alpha_{i,k} = p_{i,k} + q_{i,k} W + r_{i,k} W^2 \quad (k = 0,1,\ldots,n) \end{cases}$$

At-sensor brightness temperature

Total water vapor estimate

$$\gamma^{a_i} = \frac{\ln\left[\dfrac{\tau_i(\gamma_2)^{\gamma_1^{a_i}}}{\tau_i(\gamma_1)^{\gamma_2^{a_i}}} \cdot \left(\dfrac{B_i(T_{g,i}) - L_i^{\uparrow}(\gamma_1)/(1-\tau_i(\gamma_1))}{L_i - L_i^{\uparrow}(\gamma_1)/(1-\tau_i(\gamma_1))}\right)^{\gamma_1^{a_i} - \gamma_2^{a_i}}\right]}{\ln\left(\dfrac{\tau_i(\gamma_2)}{\tau_i(\gamma_1)}\right)}$$

γ <u>Scaling factor usually ranges from [0.8 1.6] and reduces errors in water vapor profiles over graybodies (water, vegetation) used for atmospheric correction in</u>