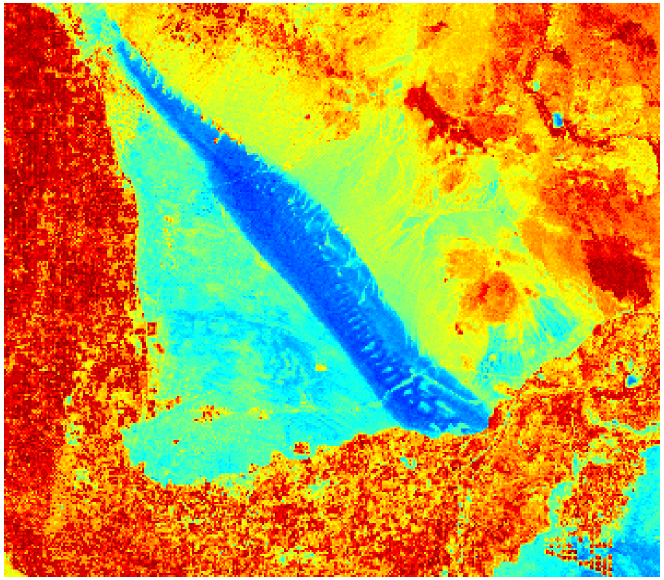
The North American ASTER Land Surface Emissivity Database (NAALSED) Version 3.0



Glynn Hulley, Simon Hook

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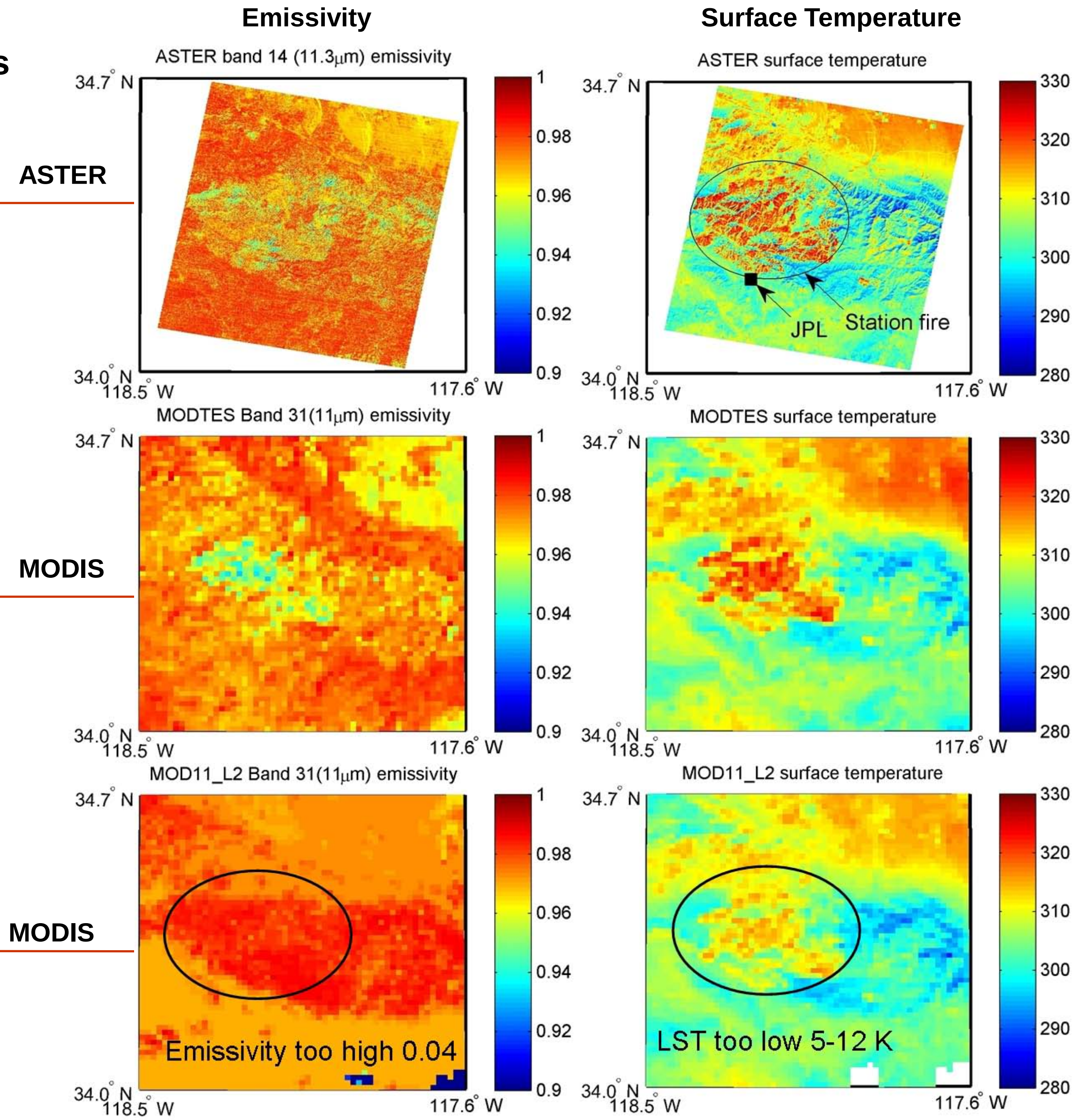
HyspIRI Science Workshop, Pasadena, CA, 24-26 August 2010

HyspIRI TIR Land Surface Temperature (LST) and Emissivity Relevance

- Physical: Emissivity error 1.5% = 1 K LST error
- Split-window: Emissivity error 0.5% = 1 K LST error
- LST Required for:
  - Measurements of fire parameters (Giglio, Csaszar)
  - Evapotranspiration models (Anderson)
  - Ecosystem function and Biodiversity (Asner, Townsend, Serbin, Roberts)
  - Modeling Urban heat islands (Weng)
  - Volcano monitoring, lava flows (Abrams, Realmuto, Vaughan, Wright)
  - Climate models (CDR's) (Huemmrich, Minnett)
  - Surface composition, soil moisture (Ramsey, Scheidt)

Station Fire, Angeles National Forest, California



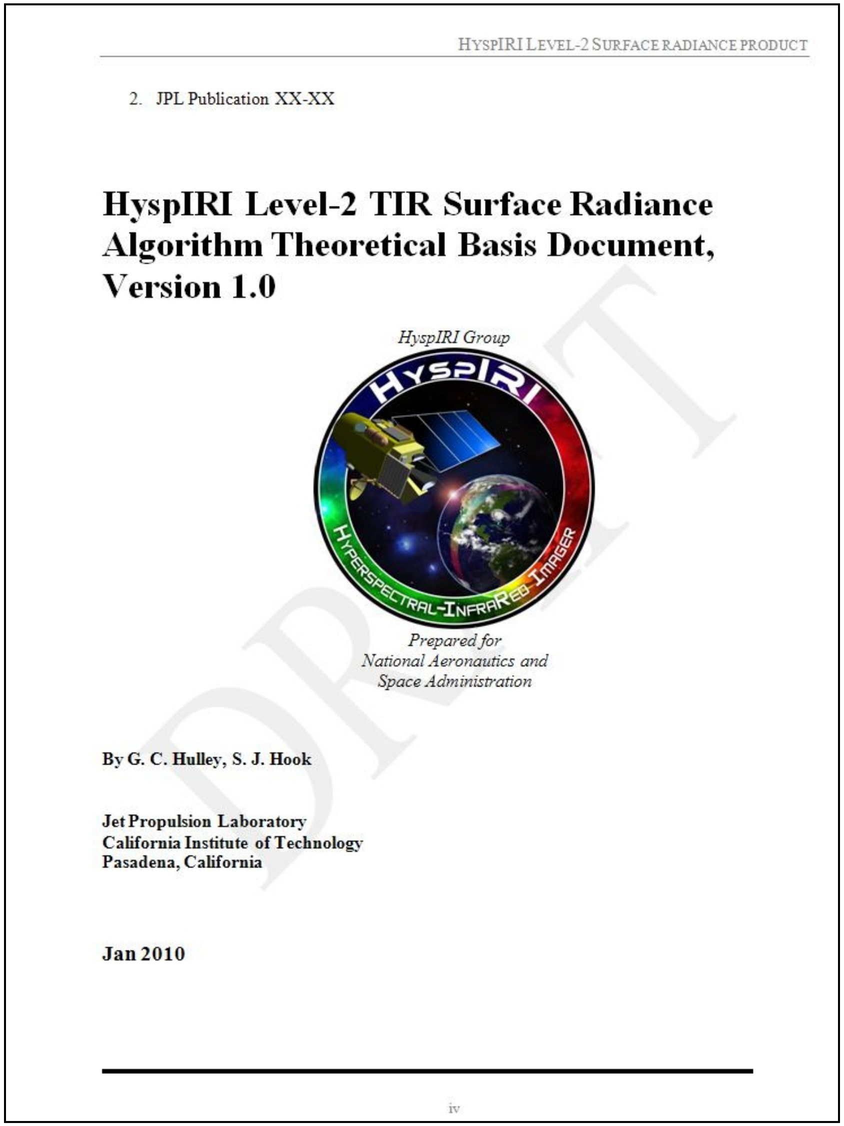
Temperature Emissivity Separation (TES) Algorithm

- Physical retrieval of LST and emissivity
- ASTER standard products

MODIS Split-window

- Emissivity assigned according to land cover classification
- Does not capture dynamic land cover changes

HyspIRI TIR Product ATBD's



2. JPL Publication XX-XX

HyspIRI Level-2 TIR Surface Radiance Algorithm Theoretical Basis Document, Version 1.0

HyspIRI Group

Prepared for
National Aeronautics and
Space Administration

By G. C. Hulley, S. J. Hook

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ASTER and HyspIRI TIR Product Characteristics

	ASTER	**HyspIRI**
Satellite	Terra (2000)	Expected launch: 2021+
Calibration	<0.3 K	<0.2 K
LST&E Algorithm	TES Calibration Curve	TES Calibration Curve
Atmospheric Correction	Water Vapor Scaling + MODTRAN	Water Vapor Scaling + MODTRAN
LST Product Accuracy	1.5 K	1 K
Product versions	Version 3	n/a
Temporal sampling	16 day repeat (1030 AM/PM)	5 day repeat (1030 AM/PM)
Spatial resolution	90 m	60 m
Spectral resolution	5 TIR bands (8-12 μm)	8 TIR bands (4-12 μm)
Swath Width	60 km	600 km

The North American ASTER Land Surface Emissivity Database (NAALSED)

Mapping Earth's emissivity at 100 m

- ASTER produces L-2 LST/emissivity products at 90m (AST 05, 08)
- Scenes (60 x 60 km) produced on demand, limited repeat (16 days) => no L-3 gridded datasets!
- **Solution:** Produce an ASTER seasonal surface emissivity map for North America (NAALSED) and extend to Global product
  - Summertime (Jul-Sep), 2000-2009
  - Wintertime (Jan-Mar), 2000-2009
- Applications:
  - ➢ Evaluating emissivity products from coarser resolution sensors: eg. MODIS (5 km), AIRS (45 km)
  - ➢ Geological mapping and resource exploration
  - ➢ Inputs to Climate and Ecology Models
  - ➢ Validation dataset and simulation of future sensors, eg. HyspIRI
  - ➢ Generate a long-term LST climate data record from Landsat

http://emissivity.jpl.nasa.gov

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North American Land Surface Emissivity Project

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« June 2010 »

Mo	Tu	We	Th	Fr	Sa	Su
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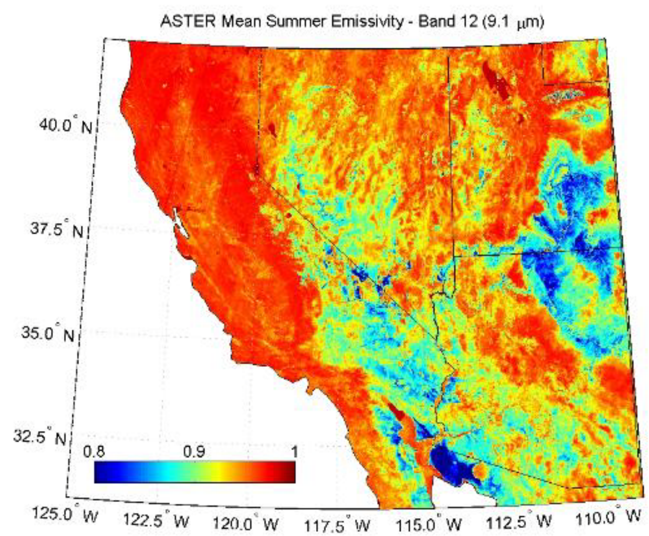
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30				

North American Land Surface Emissivity Project

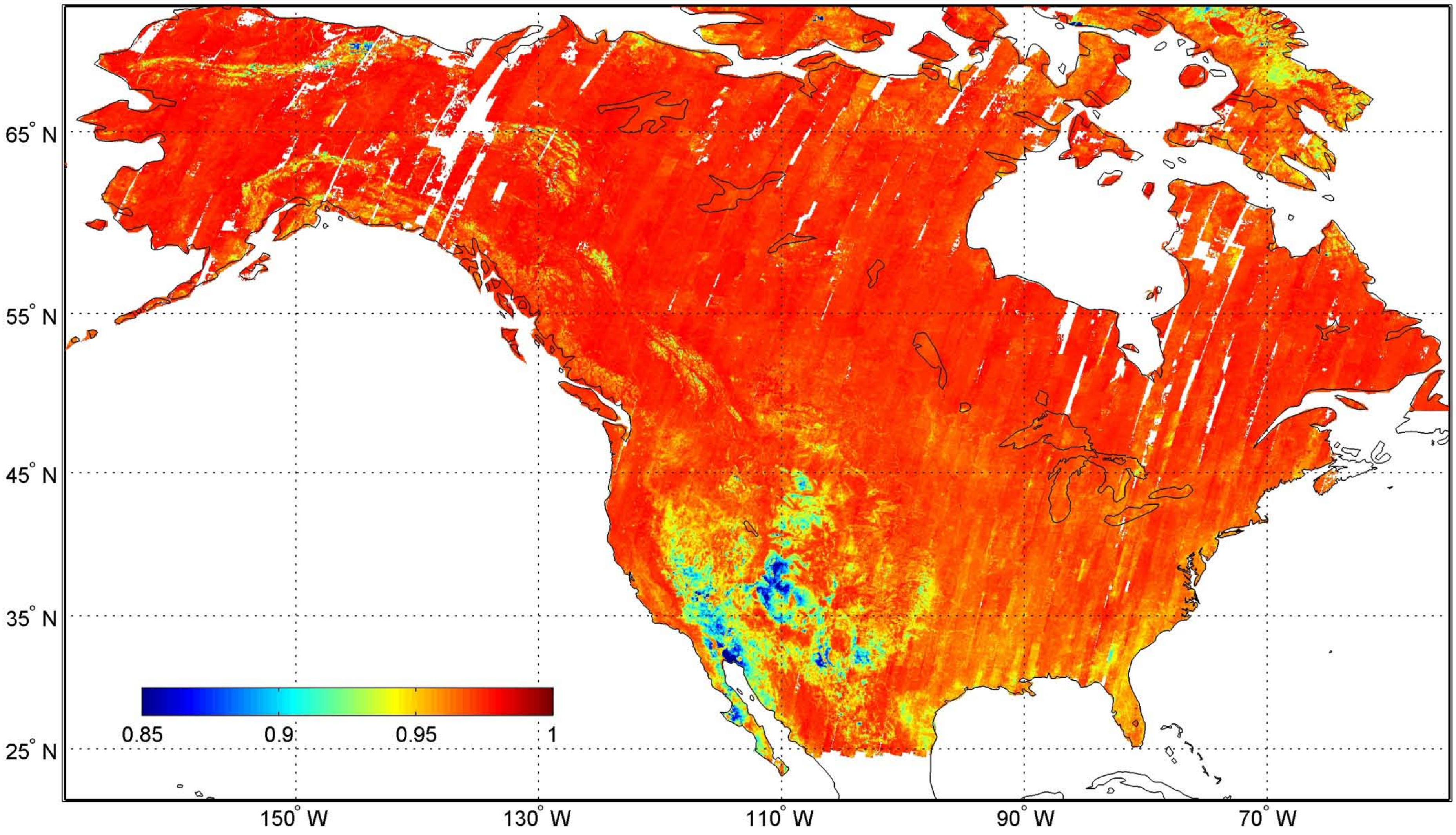
Welcome to the website for the North American Land Surface Emissivity Project. The goal of the project is to create a seamless database of emissivity from standard ASTER emissivity products for use in climate research. The Earth emits energy at wavelengths we cannot normally see, that energy is a function of the temperature and the emissivity of the surface. The surface emissivity primarily depends on the composition of the surface. Thus as the surface composition changes through, for example, land cover land use change, so does the surface emissivity. The land surface emissivity is measured by several instruments mounted on satellites and aircraft. Some of the most well known satellite sensors are AIRS, ASTER and MODIS.

Of these three satellite sensors, ASTER provides the most detailed emissivtiy images with a pixel spatial resolution of 90m. The image below was created by merging together all the ASTER emissivity data ever acquired over California, Nevada, Arizona and Utah under clear skies from 2000-2008 for the months July, August and September.



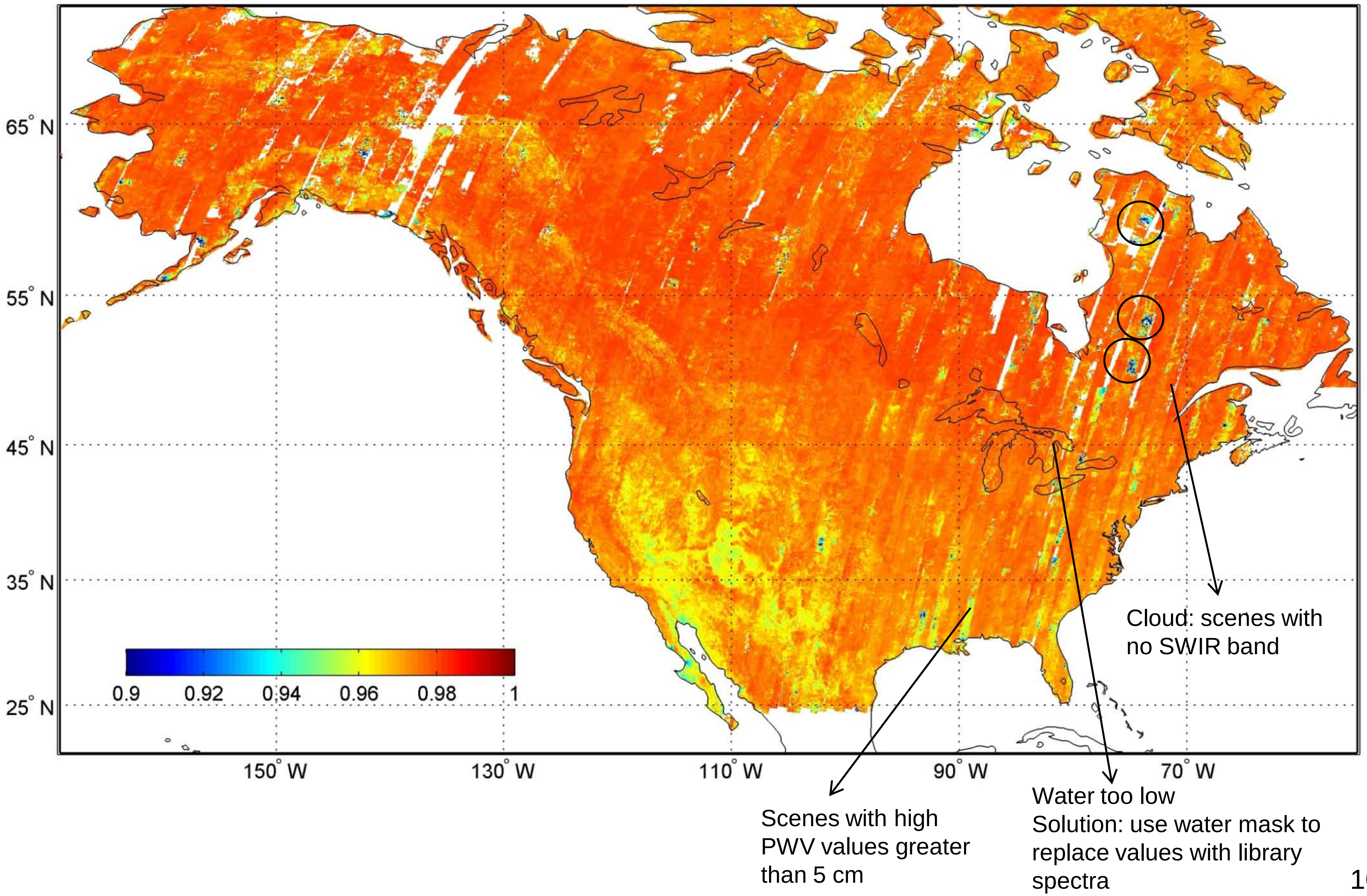
	NAALSED v2.0	NAALSED v3.0
Temporal coverage	2000-2008	2000-2010
Products	Emissivity Temperature NDVI Land/Water Map	Emissivity Temperature NDVI Land/Water Map DEM
Cloud mask	v1.0	v3.2
Atmospheric Profiles	NCEP GDAS - Temporal interpolation - 100 km - TOMS ozone	Terra MODIS (MOD07) - Coincident - 5 km - MOD07 ozone
Atmospheric Correction	Standard MODTRAN™3.5	Water Vapor Scaling (WVS) (Tonooka, 2005) MODTRAN™5.2 (Berk et al. 2005)
Temperature Emissivity Separation (TES) algorithm	Standard TES (Gillespie et al. 1998)	Standard TES (Gillespie et al. 1998)

NAALSED Summertime Emissivity (Jul-Sep 2000-2009), Band 12 (9.1 µm)
Degraded from 100 m to 5 km

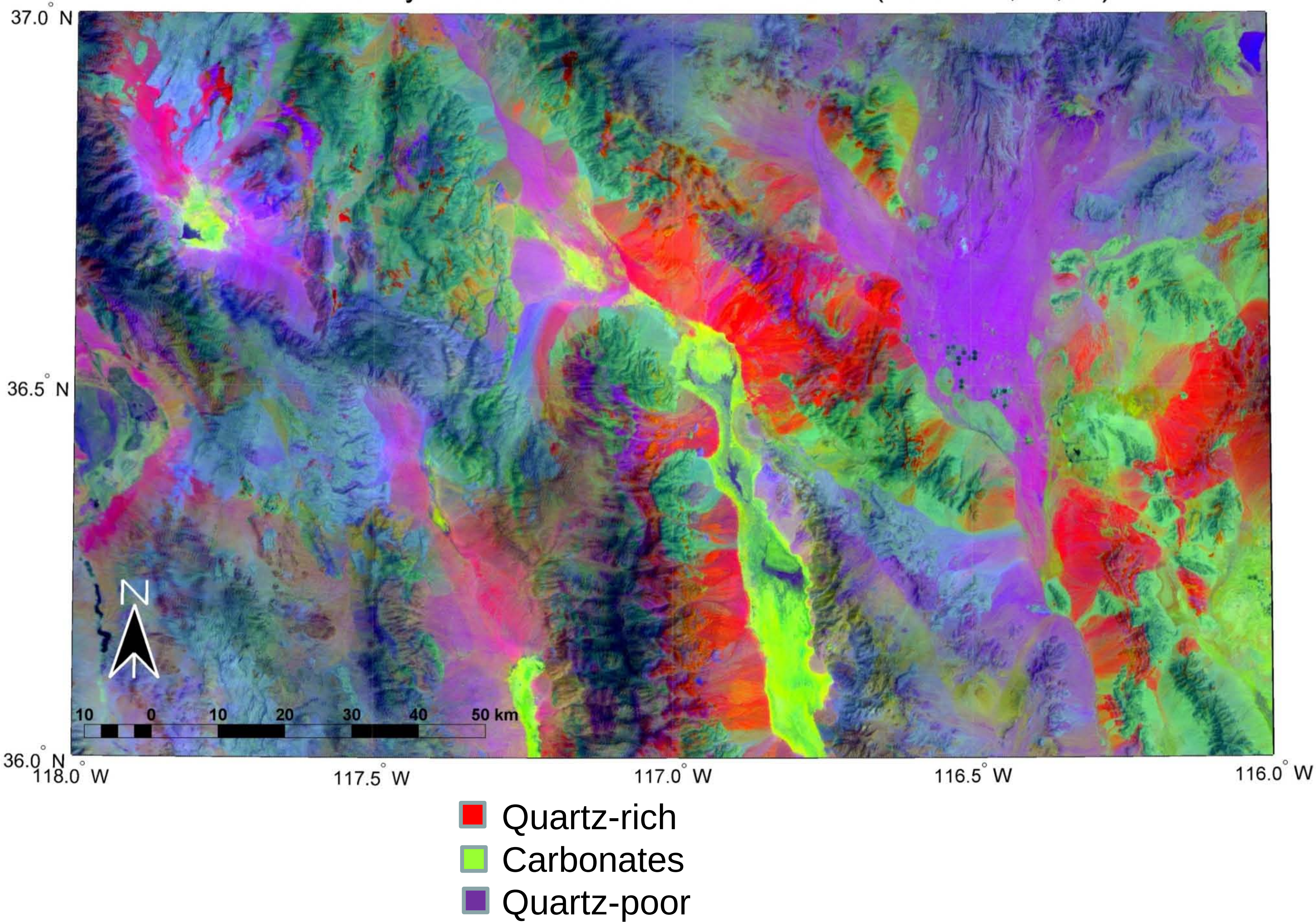


Total Scenes: 64,149
Usable: 39,848 (Cloud<80%)

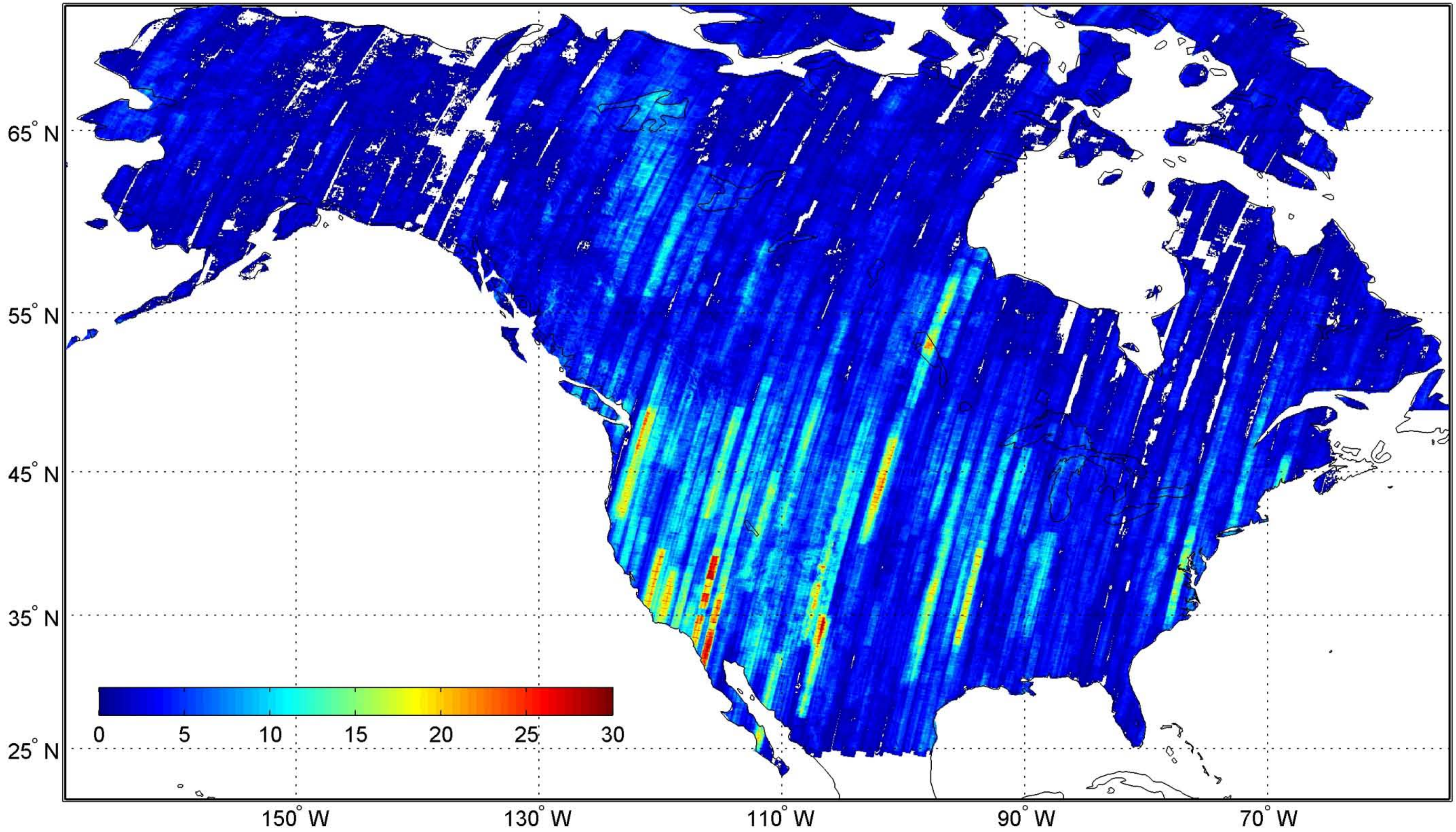
NAALSED Summertime Emissivity (Jul-Sep 2000-2009), Band 14 (11.3 µm)

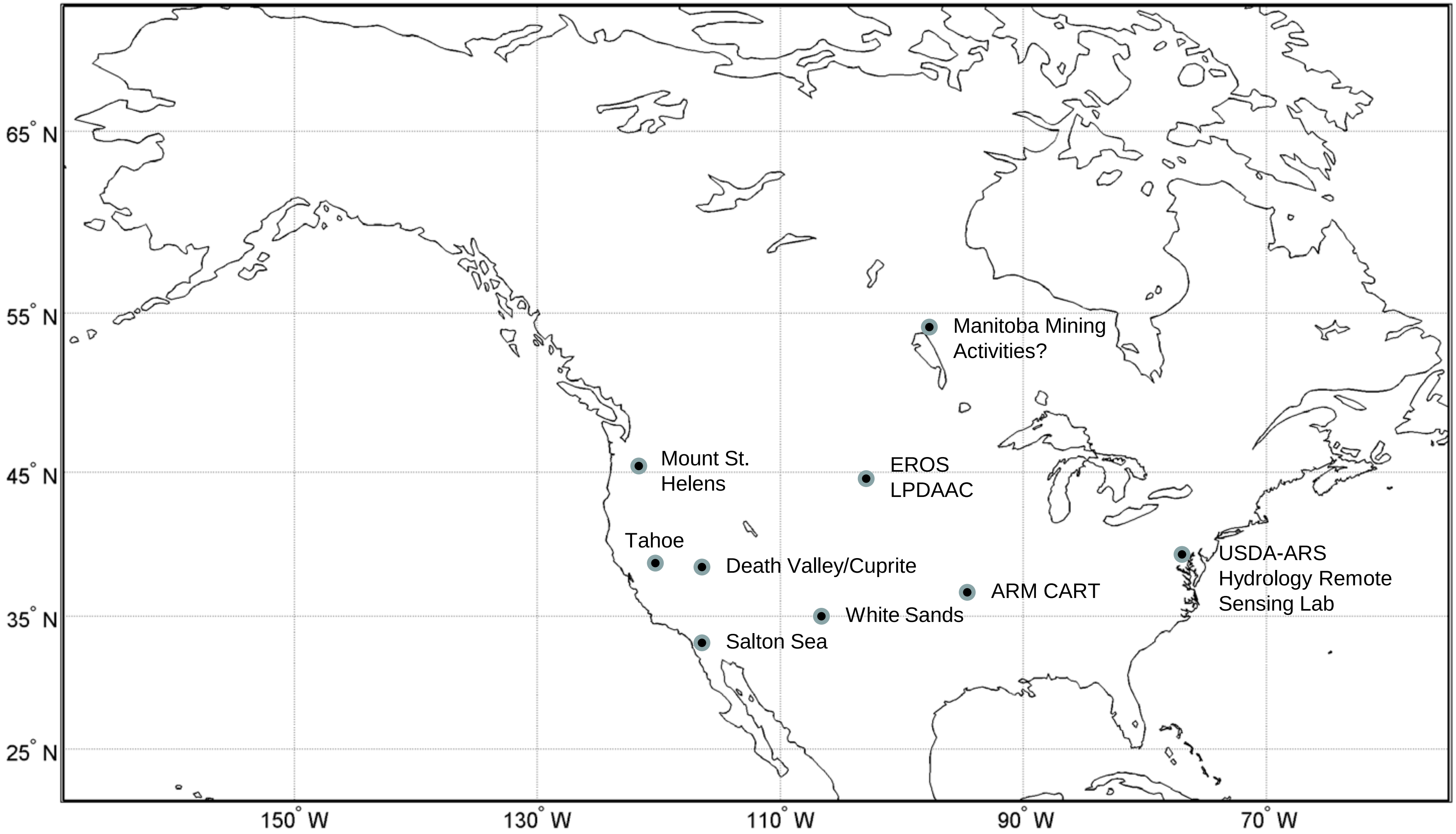


Death Valley - Decorrelation Stretch - RGB (Band 14,12,10)

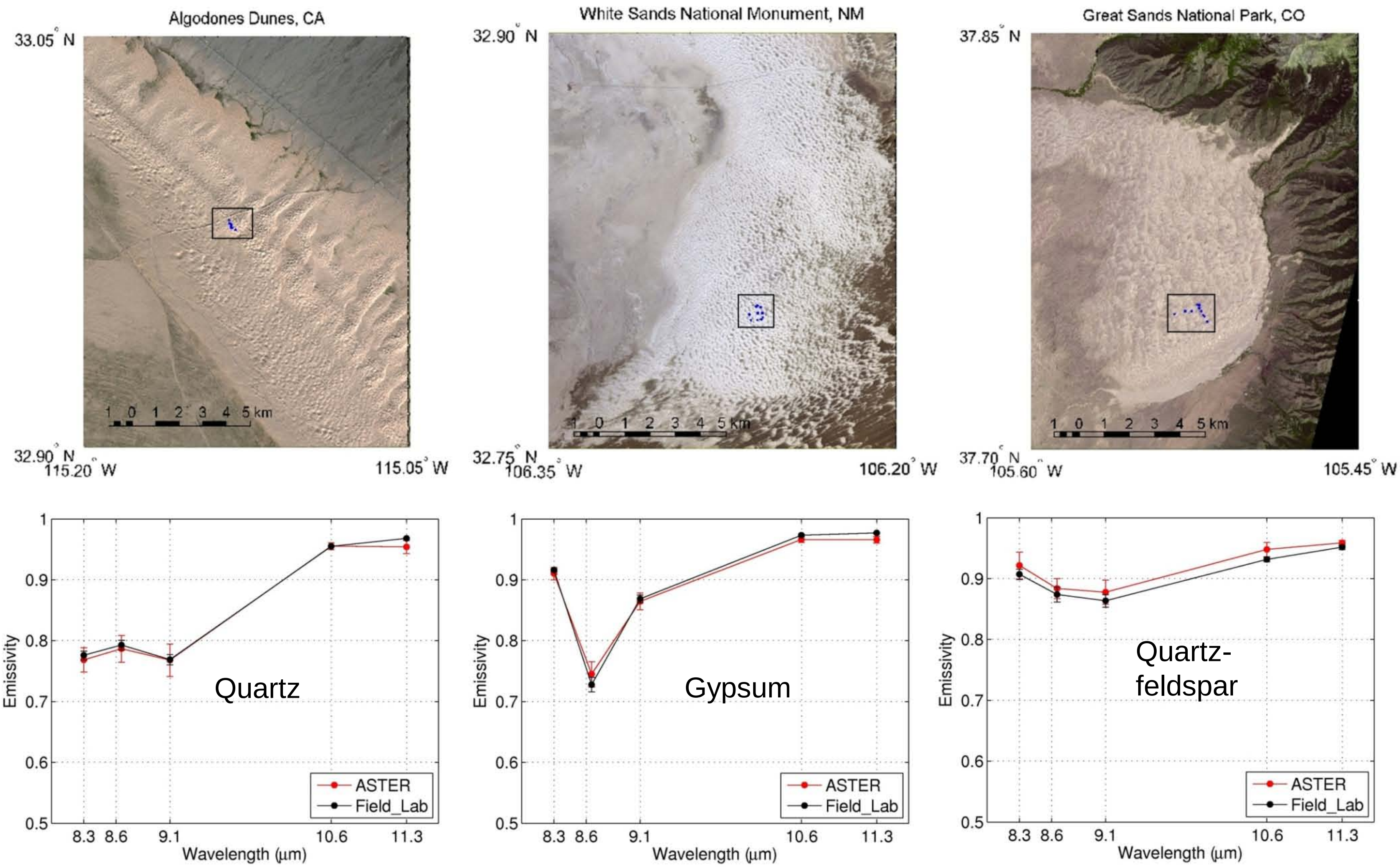


NAALSED Total Summertime Observations (Jul-Sep 2000-2009)




65° N
55° N
45° N
35° N
25° N
150° W
130° W
110° W
90° W
70° W
Manitoba Mining Activities?
Mount St. Helens
EROS LPDAAC
Tahoe
Death Valley/Cuprite
ARM CART
USDA-ARS Hydrology Remote Sensing Lab
White Sands
Salton Sea

Pseudo-invariant Sand Dune Emissivity Validation Results



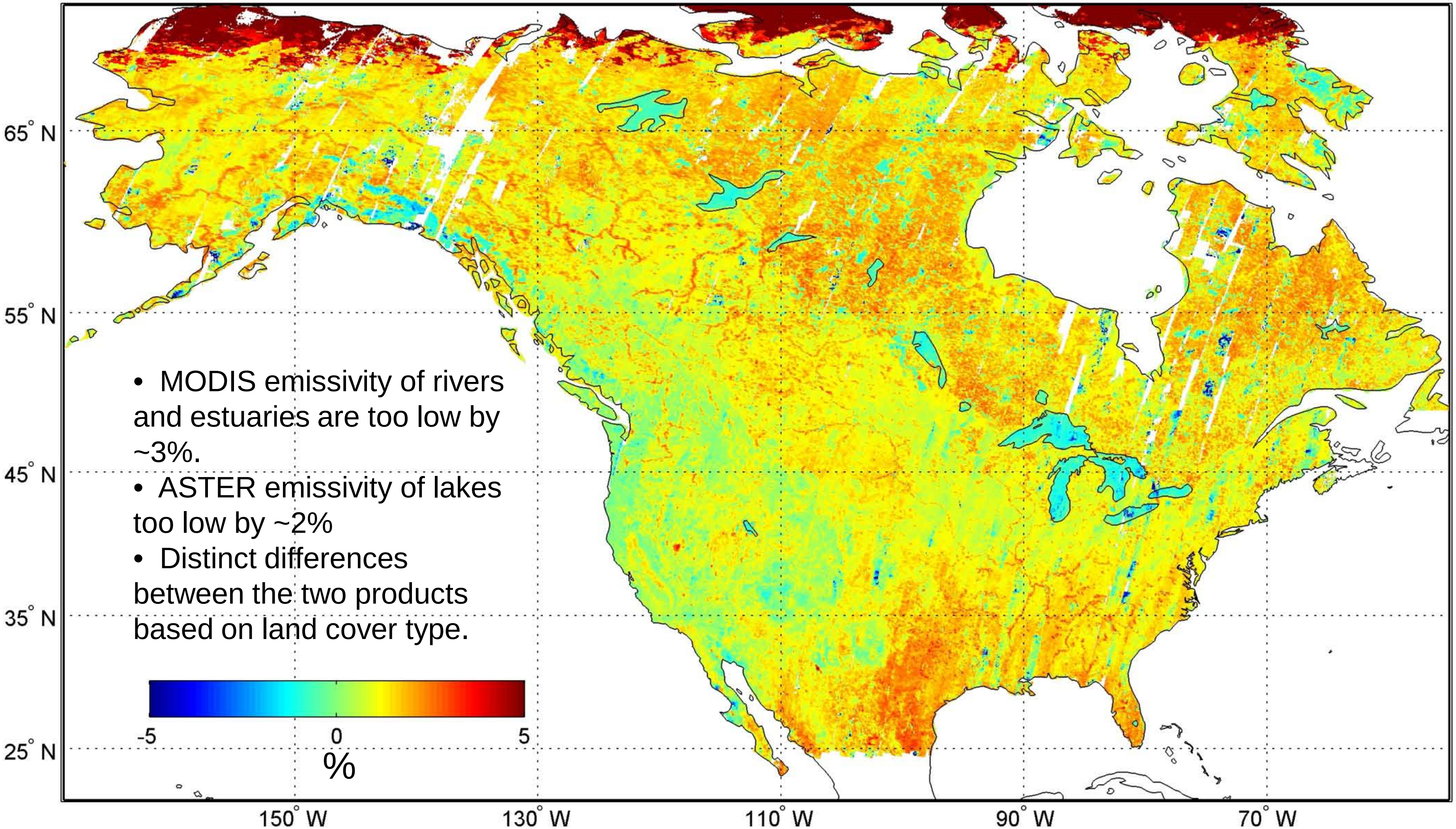
Hulley, G. C., Hook, S. J., and A.M. Baldridge, Validation of the North American ASTER Land Surface Emissivity Database (NAALSED) Version 2.0, *Remote Sensing of Environment* (2009), accepted

ASTER validation with pseudo-invariant sand dune sites

	ASTER MINUS LAB EMISSIVITY (%)					
Dune site	**Band 10**	**Band 11**	**Band 12**	**Band 13**	**Band 14**	**Mean**
Algodones	0.68	0.60	0.13	0.02	1.40	**0.57**
Stovepipe Wells	0.17	0.77	1.02	0.34	0.37	**0.53**
White Sands	0.34	2.76	0.16	0.92	1.08	**1.05**
Kelso Dunes	1.57	1.04	1.33	1.91	0.81	**1.33**
Great Sands	1.44	0.97	1.42	1.64	0.69	**1.23**
Moses Lake	0.69	0.52	0.42	0.61	1.01	**0.65**
~~Sand Mountain~~	~~7.74~~	~~6.47~~	~~9.01~~	~~1.82~~	~~1.10~~	~~**5.23**~~
Coral Pink	7.48	6.44	7.32	2.50	1.70	**4.90**
Little Sahara	3.55	2.39	2.60	0.96	0.19	**1.94**
Killpecker	2.34	1.99	2.26	1.33	0.81	**1.75**

< 1.6% (1 K)

NAALSED Band 14 (11.3 µm) minus MODIS Band 31 (10.8 µm)



- MODIS emissivity of rivers and estuaries are too low by ~3%.
- ASTER emissivity of lakes too low by ~2%
- Distinct differences between the two products based on land cover type.

HyspIRI Cloud Detection Methodology

- Accurate and reliable cloud masking is critical for generating high quality HyspIRI Level-2 and Level-3 data products
- Daytime Cloud masking relies heavily on thresholding VSWIR reflectance tests
- HyspIRI VSWIR swath (150 km) and TIR swath (600 km) will not overlap
- HyspIRI Cloud Detection Options:
  - Generate separate VSWIR-only and TIR-only cloud masks?
  - Use external data source to fill in VSWIR gap in TIR swath?
  - Use NAALSED-based cloud detection (Landsat methodology)?
    - Pass-1: Uses combined VSWIR reflectances and TIR data to develop cloud signature
    - Pass-2: Use thermal classification to identify remaining clouds on TIR-only swath

NAALSED/Landsat Pass-1 Cloud Spectral Tests

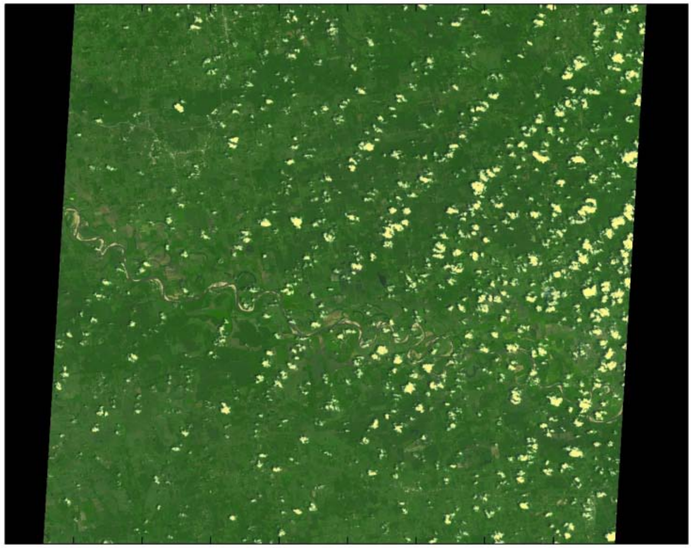
Table 1. Pass-1 Filters and Threshold Tests Using Reflectance, r_i and Temperature, T_{sat}, Values From Equations (1) and (2)

Filter	Threshold Test	Function
1 Brightness Threshold	$r_2 > 0.08$	Eliminates low reflectance, dark pixels
2 Snow Threshold	$NDSI = (r_1 - r_4)/(r_1 + r_4) < 0.7$	Eliminates snow
3 Temperature Threshold	$T_{sat} < 300$	Eliminates warm surface features
4 Band 4/5 Composite	$(1 - r_4)T_{sat} < 240 \Rightarrow$ snow present $(1 - r_4)T_{sat} < 250 \Rightarrow$ snow absent	Eliminates cold surfaces - snow, tundra
5 Growing vegetation	$\frac{r_3}{r_2} < 2$	Eliminates reflective growing vegetation
6 Senescing vegetation	$\frac{r_3}{r_1} < 2.3$	Eliminates reflective senescing vegetation
7 Rocks and Sand	$\frac{r_3}{r_4} > 0.83$	Eliminates reflective rocks and sand
8 Warm/Cold Cloud	$(1 - r_4)T_{sat} > 235 \Rightarrow$ warm cloud $(1 - r_4)T_{sat} < 235 \Rightarrow$ cold cloud	Warm and cold cloud classificiation
Cloud Shadow	$r_3 < 0.05$ and $\frac{r_3}{r_1} > 1.1$	Detects cloud shadows

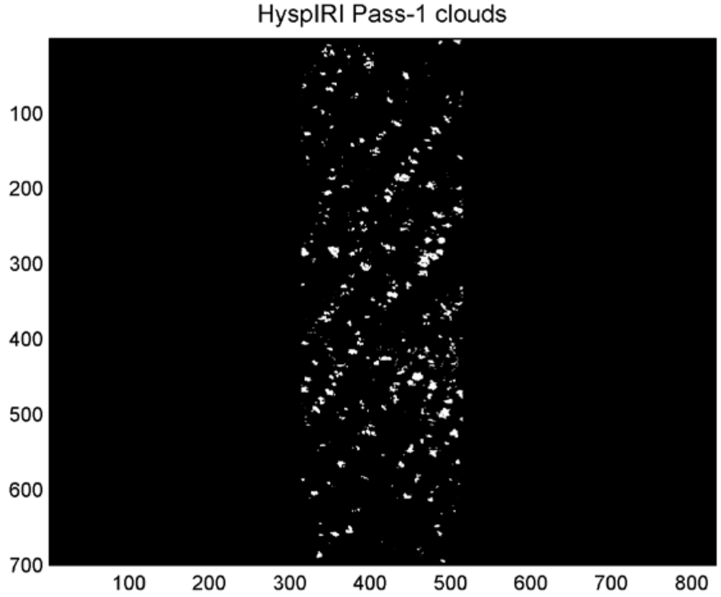
NAALSED/Landsat Pass-2 Cloud Spectral Tests

- Pass-2 is applied to all ‘uncertain/ambiguous’ pixels identified from Pass-1 processing
- Thermal cloud signature is developed from Pass-1 clouds and new thermal thresholds determined based on statistical analysis (e.g. Max, min and mean cloud temperature, skewness etc.)

ASTER visible RGB

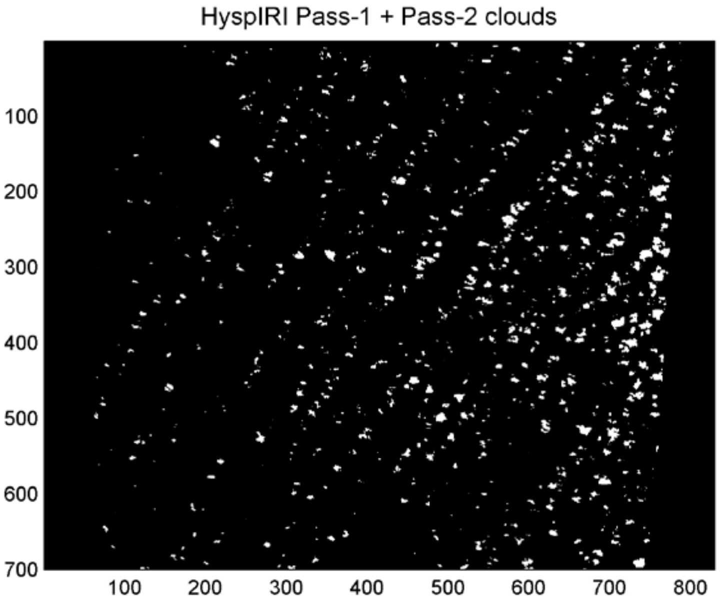


HyspIRI Simulated Pass-1

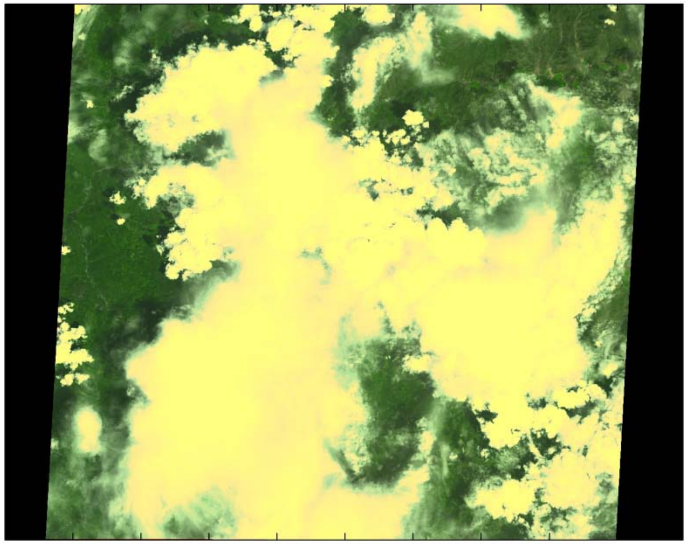


Mean Temperature: 292.22 K
Max Temperature: 299.96 K
Min Temperature: 287.89 K
Standard Deviation: 2.2 K
Skewness: 0.848

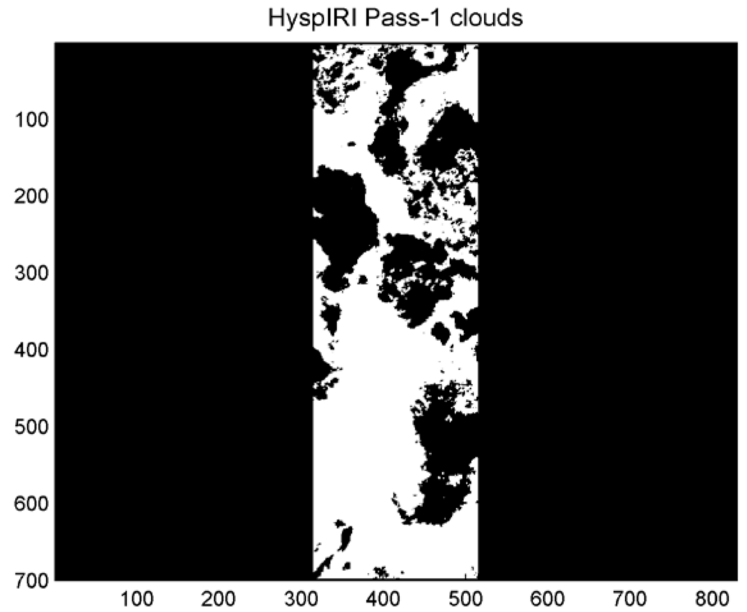
HyspIRI Simulated Pass-2



ASTER visible RGB

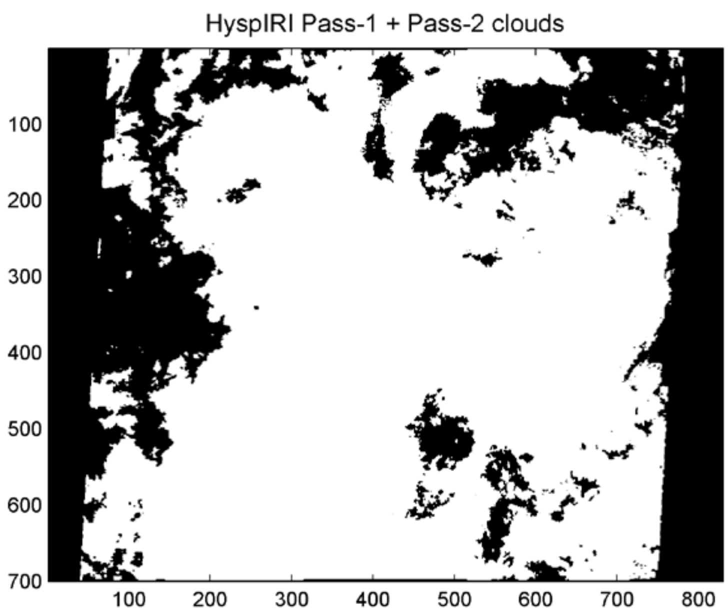


HyspIRI Simulated Pass-1



Mean Temperature: 252.42 K
Max Temperature: 299.88 K
Min Temperature: 231.52 K
Standard Deviation: 10.7 K
Skewness: 0.357

HyspIRI Simulated Pass-2



Future Work

- Acquire remaining scenes needed to fill gaps in NAALSED
- Release NAALSED v3.0 for North America
- Extend NAALSED to global coverage: North Africa – AIRS/IASI/MODIS products have large uncertainties in emissivity here
- Continue developing HyspIRI thermal infrared product ATBD’s
- Continue developing HyspIRI cloud detection methodology

The End

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Pasadena, California

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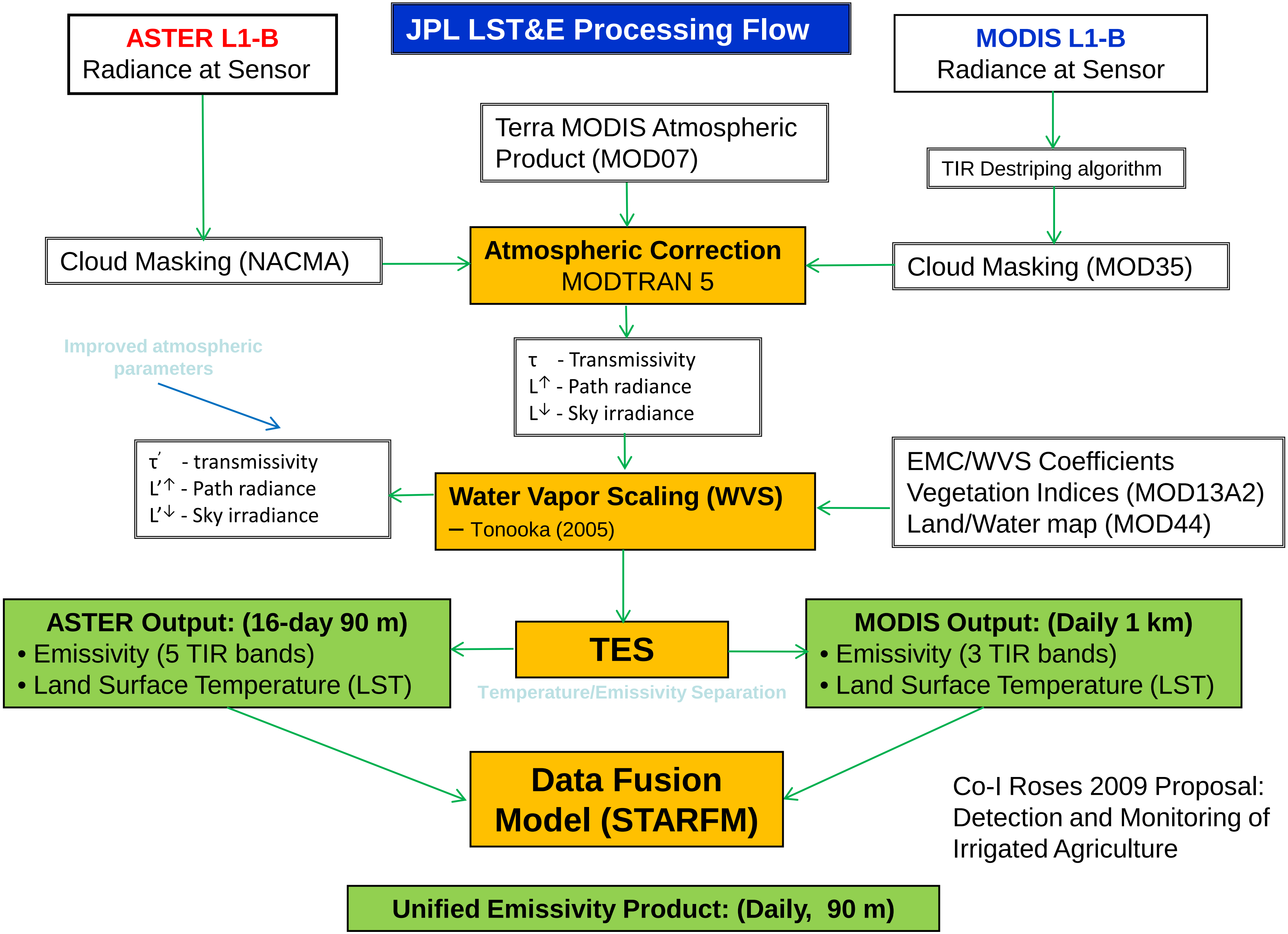
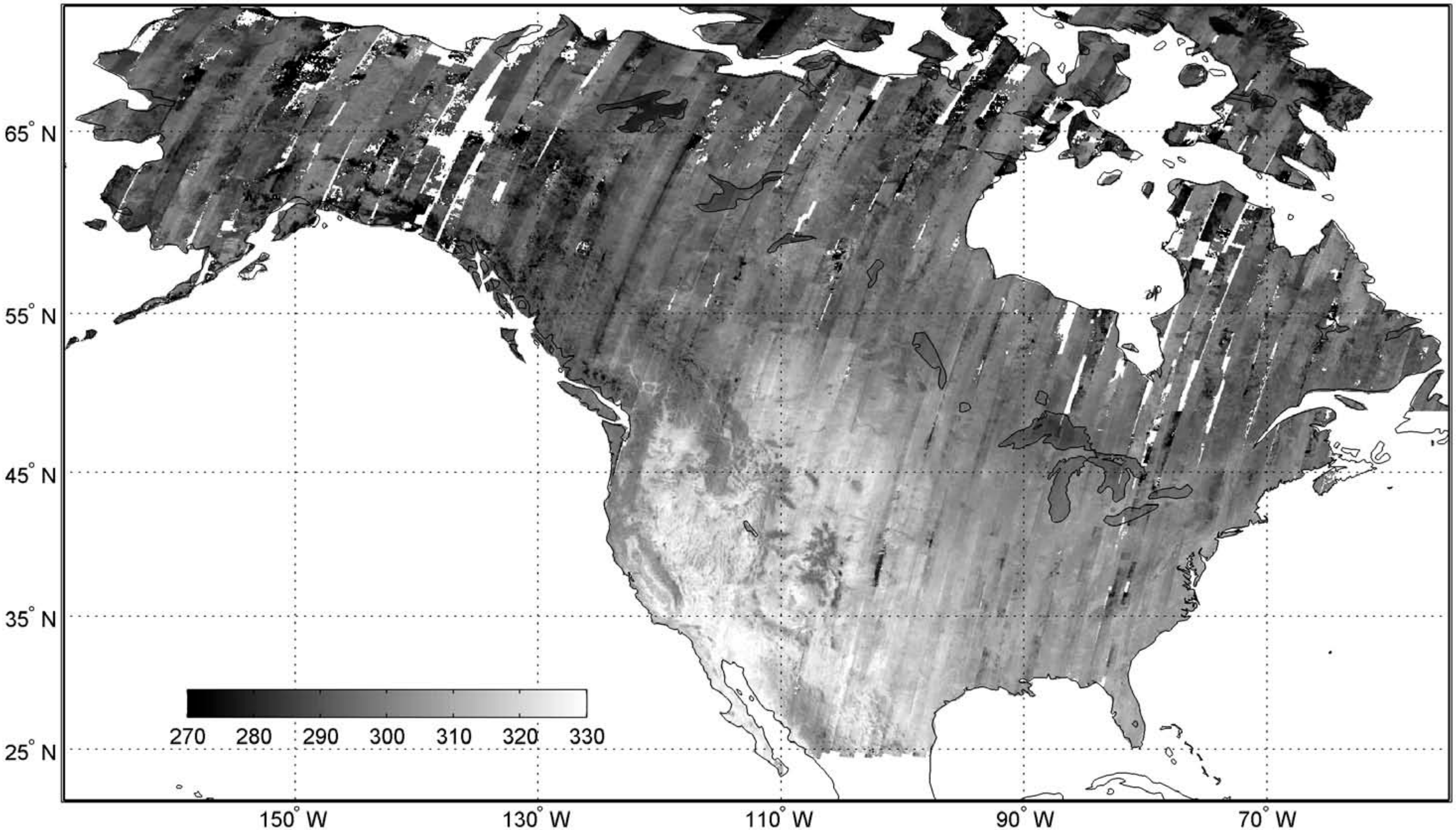
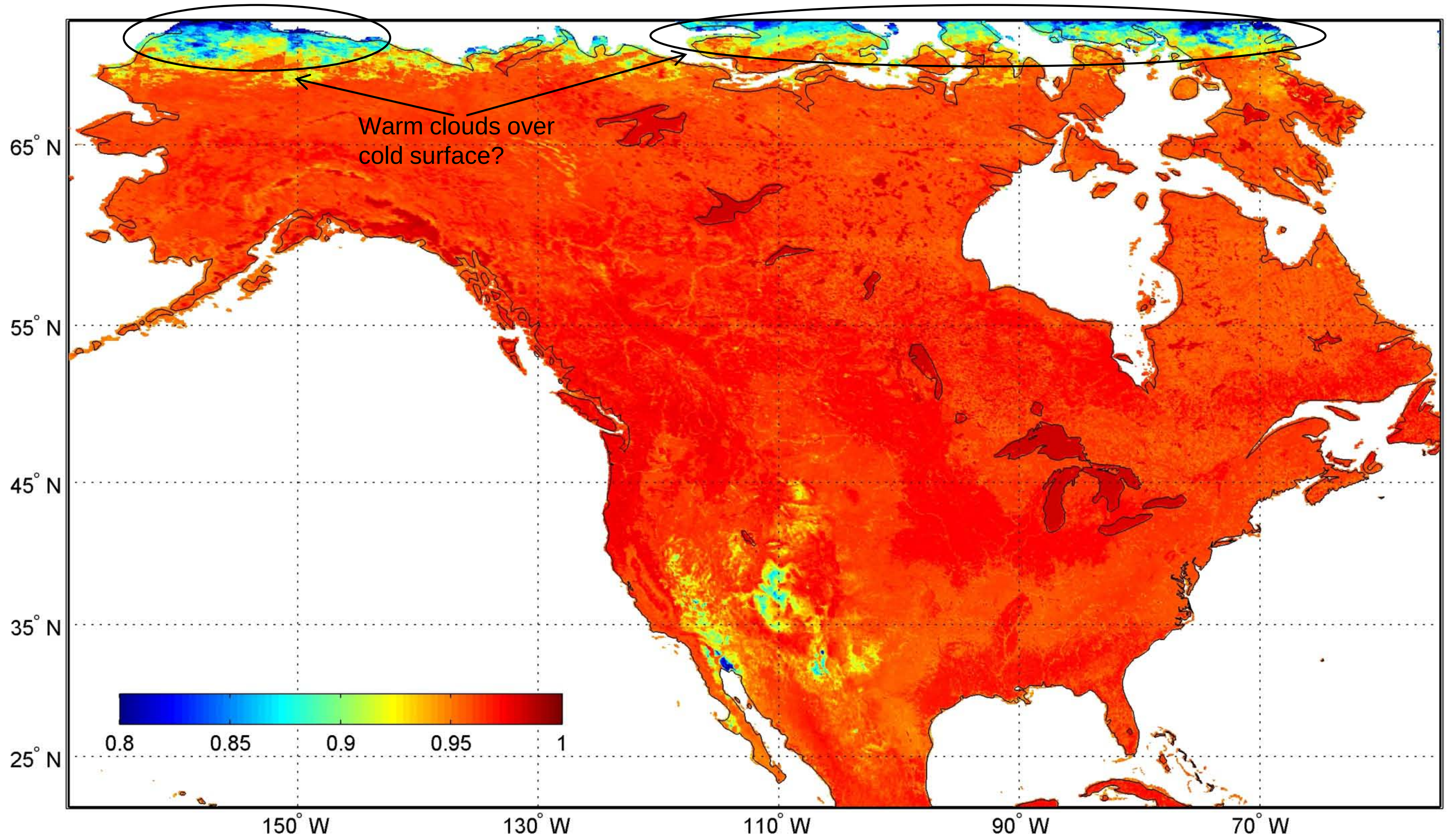
JPL 400-1278 7/06


JPL LST&E Processing Flow
ASTER L1-B
Radiance at Sensor
MODIS L1-B
Radiance at Sensor
Terra MODIS Atmospheric Product (MOD07)
TIR Destriping algorithm
Cloud Masking (NACMA)
Atmospheric Correction
MODTRAN 5
Cloud Masking (MOD35)
Improved atmospheric parameters
τ - Transmissivity
L↑ - Path radiance
L↓ - Sky irradiance
τ′ - transmissivity
L′↑ - Path radiance
L′↓ - Sky irradiance
Water Vapor Scaling (WVS)
– Tonooka (2005)
EMC/WVS Coefficients
Vegetation Indices (MOD13A2)
Land/Water map (MOD44)
ASTER Output: (16-day 90 m)
• Emissivity (5 TIR bands)
• Land Surface Temperature (LST)
TES
Temperature/Emissivity Separation
MODIS Output: (Daily 1 km)
• Emissivity (3 TIR bands)
• Land Surface Temperature (LST)
Data Fusion
Model (STARFM)
Co-I Roses 2009 Proposal:
Detection and Monitoring of
Irrigated Agriculture
Unified Emissivity Product: (Daily, 90 m)

NAALSED Summertime Surface Temperature (Jul-Sep 2000-2009)



MODBF Summertime Emissivity (Jul-Sep 2003-2006), Band 29 (8.6 µm)

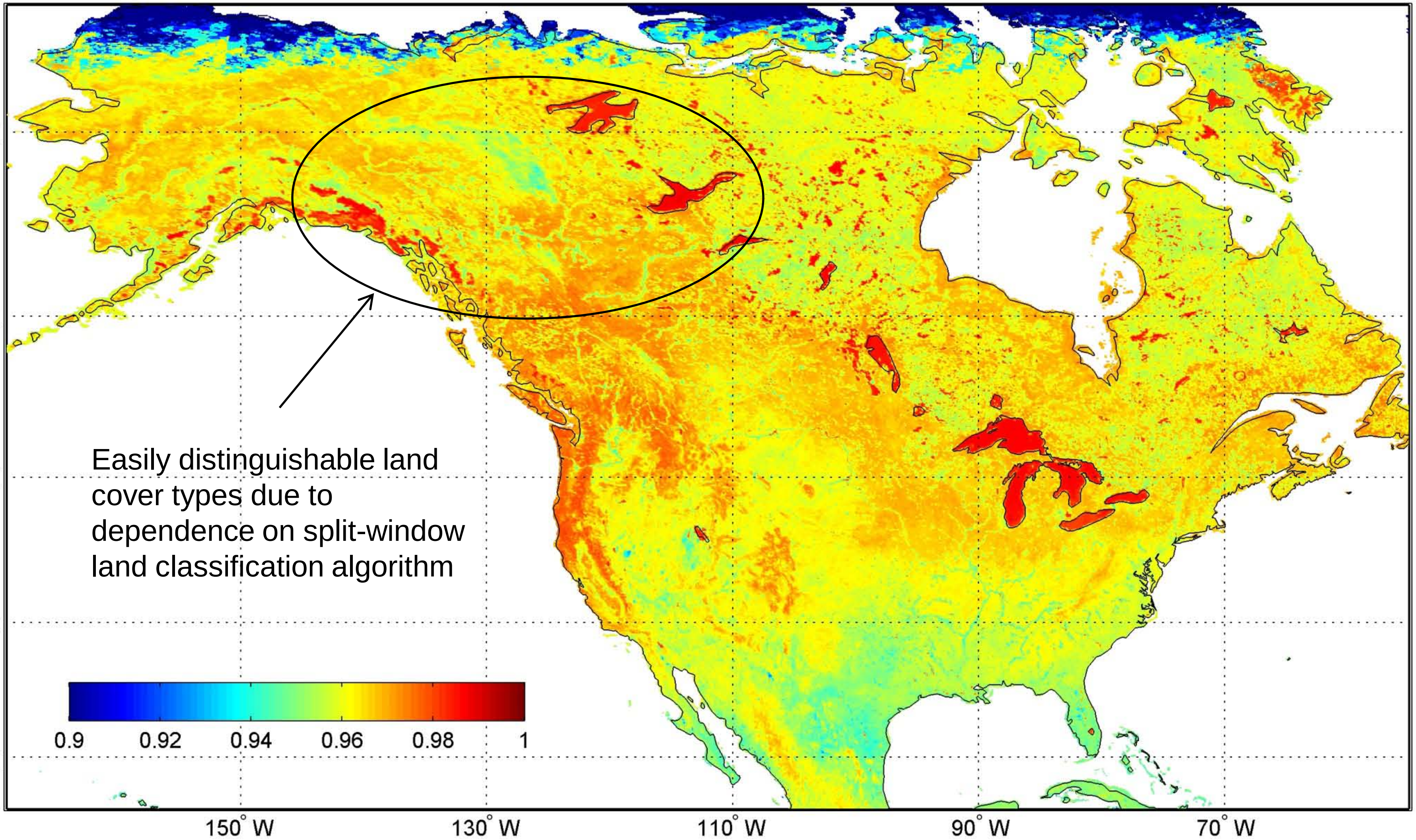


Pass-2 Processing (Landsat-7 Approach)

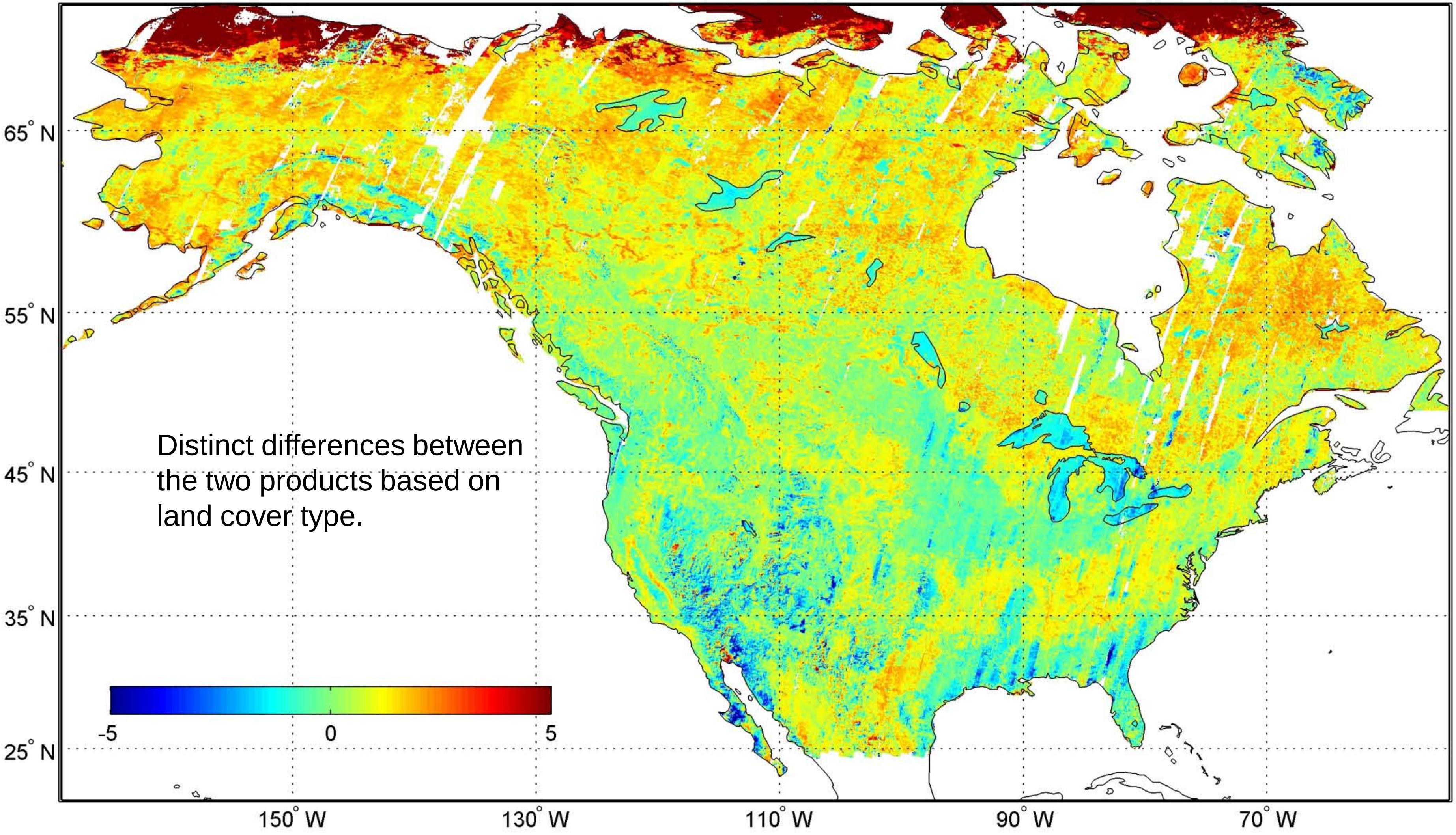
- Pass-2 involves using a thermal analysis to classify ‘ambiguous’ pixels from Pass-1 processing
- Thermal cloud signature is developed based on warm/cold cloud class identified in Pass-1 processing (eg. Max T, min T, mean T, skewness etc..)
- New temperature thresholds set for Pass-1 warm and cold cloud signatures based on statistical analysis (eg. Threshold adjusted for skewness)
- Decision tree used to accept one or both of cloud populations in final mask

- HyspIRI Cloud Processing Option:
  - Use VSWIR and TIR data to classify clouds using Pass-1 filters for VSWIR swath (150 km)
  - Set remaining pixels falling outside swath to ambiguous (600 km)
  - Use Pass-2 processing to classify remaining clouds on TIR swath

MODBF Summertime Emissivity (Jul-Sep 2003-2006), Band 31 (10.8 µm)



NAALSED Band 11(8.6 µm) minus MODBF Band 29 (8.6 µm)



Relevance to Future JPL Missions

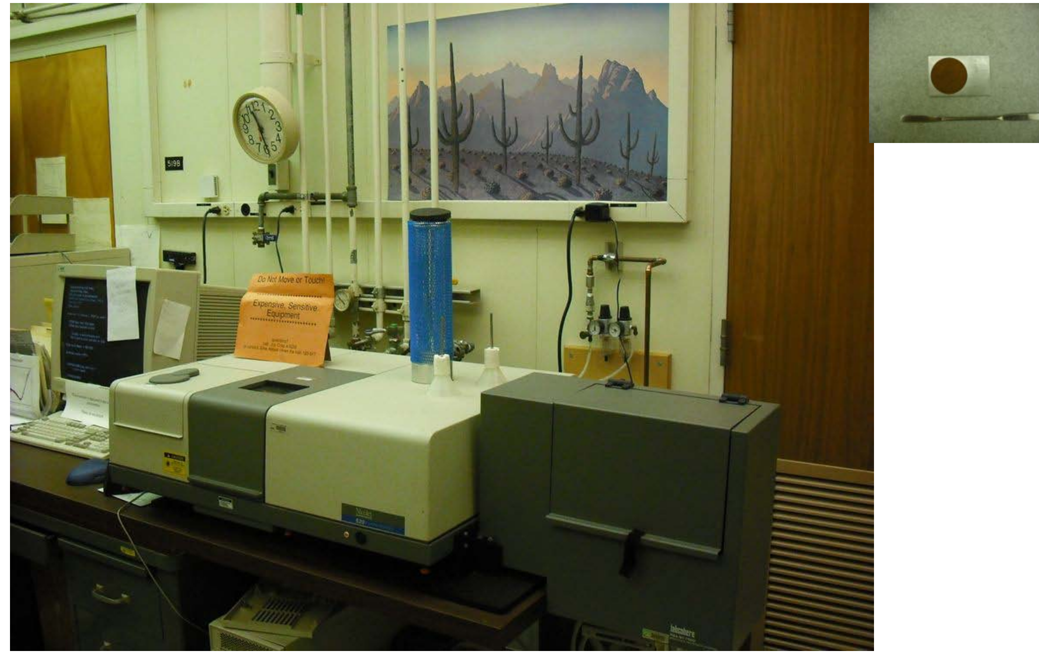
HyspIRI – **Tier 2 (2015-2020)**
Hyperspectral Infrared Imager

- Ecosystem response to natural and human-induced changes
- Monitoring natural hazards
- Land surface composition

- North American ASTER Land Surface Emissivity Database (NAALSED) – proxy HyspIRI dataset
- Algorithm development (thermal IR)
  - What is the appropriate temperature/emissivity separation algorithm for HyspIRI?
  - What atmospheric correction technique, and profiles to be used?
  - Cloud detection methodology?
- Level-2 Product Definition and ATBD’s

Sand samples collected in field

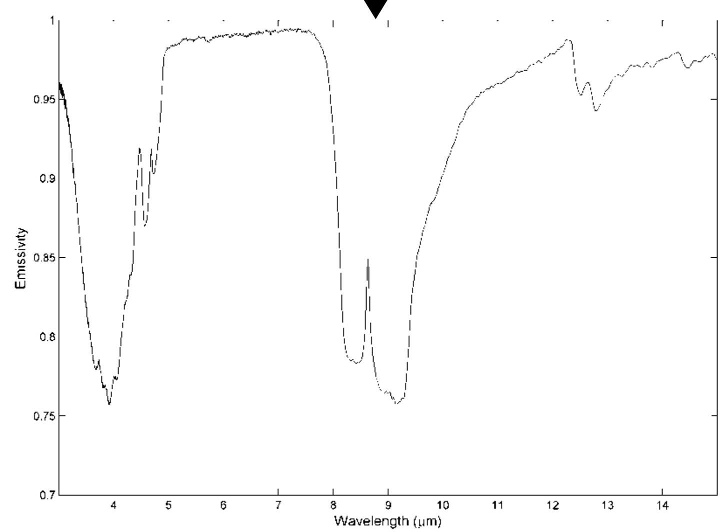
Reflectance measured using Nicolet 520 FTIR spectrometer



JPL

LAB MEASUREMENTS

$\varepsilon = 1 - r$



spectral range: 2.5 – 15 μm

spectral resolution: 4 cm^{-1}

1000 scans in 10 minutes

Pseudo-Invariant Sand Dune Sites

Table 1

Summary of the major characteristics of each dune site including locality, elevation, surface area, dune height, grain size, sand source and bulk mineralogy.

Dune site	Locality	Surface area (km^2)	Elevation/max dune height (m)	Grain size	Sand source	Mineralogy (XRD)
Algodones (32.95° N, 115.07° W)	Southeast CA, Eastern margin of the Salton Trough	720	94/80	Medium to coarse sand	Beach sand from Lake Cahuilla	Major: quartz
Coral Pink (37.04° N, 112.72° W)	Sand Valley, just north of UT–AZ border, west Kanab	13.6	1780/10	Medium sand	Navajo, Page and Estrada Jurassic sandstones of the Vermillion Cliffs	Major: quartz
Great Sands (37.77° N, 105.54° W)	San Luis Valley, CO, adjacent to Sangre de Cristo, NE of Alamosa	104	2560/230	Medium to coarse sand	Quartz and volcanic fragments derived from Santa Fe and Alamosa formations, recent fluvial (Rio Grande) deposits	Major: quartz Minor: potassium feldspar
Kelso (34.91° N 115.73° W)	Mojave Desert, CA, southeast of Baker	115	800/195	Medium sand	Derived from sedimentary, metamorphic, igneous terrains from Mojave River alluvial apron	Major: quartz Minor: potassium feldspar Trace: magnetite
Killpecker (41.98° N 109.10° W)	Southwest WY, from Eden across Rock Springs into Red Desert	550	2000/45	Medium sand	Sandstone and siltstone of the Laney member of the Green River Formation	Major: quartz Trace: magnetite Minor: plagioclase feldspar, epidote
Little Sahara/Lynndyl (39.7° N 112.39° W)	West-central UT, Sevier River drainage basin, west of Lynndyl	575	1560/200	Fine sand	Deltaic and shoreline sediments from the Provo shoreline of Lake Bonneville	Major: quartz Minor: plagioclase feldspar, pyroxene, carbonate, magnetite
Stovepipe Wells (36.62° N, 117.11° W)	Central Death Valley, CA, near Stovepipe Wells	7.7	−12/40	Medium sand	Mixed lithic fragments and quartz from Emigrant Pass to the west and Furnace Wash to the east	Major: quartz Minor: plagioclase feldspar, potassium feldspar
Moses Lake (47.05° N, 119.31° W)	Quincy Basin in central WA	40	345/18	Fine sand	Basaltic sand from the east bank of the Columbia River	Major: quartz, albite
White Sands (32.89° N, 106.33° W)	South-central NM, Tularosa Valley	704	1216/10	Fine sand	Paleo-lake Otero, present playa Lake Lucero to the southwest	Major: gypsum

Hulley, G. C., Hook, S. J., and A.M. Baldridge, (2009), Validation of the North American ASTER Land Surface Emissivity Database (NAALSED) Version 2.0, *Remote Sensing of Environment*, 113, 2224-2233

Thermal Infrared Radiative Transfer

Surface Radiance

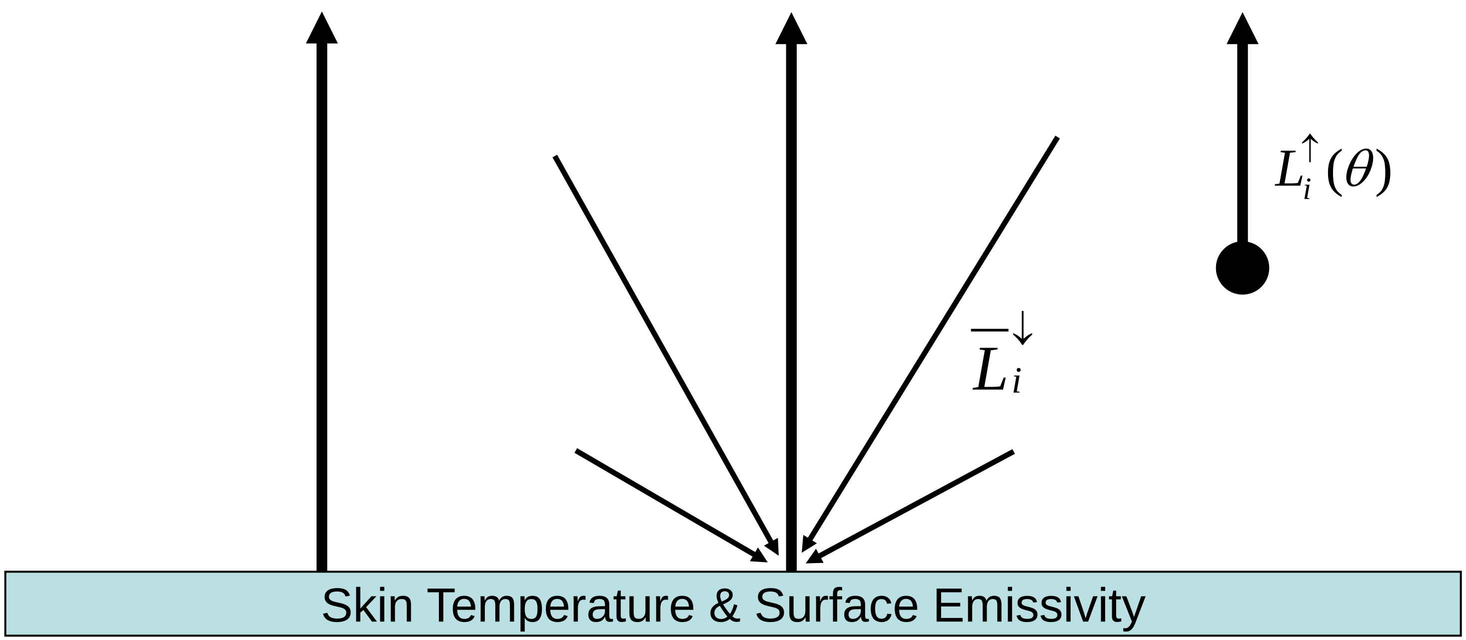
TOA Radiance

$$L_i(\theta) = \tau_i(\theta)\cdot e_i \cdot B_i(T_S) + \tau_i(\theta)\cdot(1-e_i)\cdot \overline{L}_i^{\downarrow} + \int B_i(T(P))\,d\tau_i$$

Surface Emission

Surface Reflection

Atmospheric Emission



NAALSED Users and Applications

- ~100 registered NAALSED users *http://emissivity.jpl.nasa.gov*
- Current projects and applications:
  - **Arizona State University: JMARS (Java Mission-planning and Analysis for Remote Sensing) is a Java-based geospatial information system developed by Arizona State University**
  - **UW-Madison: NAALSED comparisons with MODIS baseline-fit emissivity product, used for retrieval of MOD07 profiles**
  - **JPL: AIRS (Atmospheric Infrared Sounder) and IASI (Infrared Atmospheric Sounding Interferometer) emissivity validation and intercomparison with NAALSED**
  - **JPL: Tropospheric Emission Spectrometer (TES) group will be using NAALSED as a first guess emissivity in retrieval of Ozone**
  - **Beijing Normal University: Developing an empirical relationship between NAALSED emissivity and NDVI products**
  - **JPL: Generate a land surface temperature product for Landsat**

Atmospheric Correction

Observed Radiance

Surface 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 using radiative transfer code such as MODTRAN with Atmospheric profiles and elevation data

- Derivation of e_i and T_s is an undetermined problem

  The number of parameters (T_s ,e_i in N channels) is always greater than the number of simultaneous equations needed to solve the problem (N)

  =>Additional, independent constraint is needed

MODIS Baseline-Fit (MODBF) Emissivity Product

- Input data: MODIS MYD11 (Aqua) Day-night emissivity retrieval with values at 8.6, 11 and 12 µm in TIR
- MODBF is characterized by model with inflection points at 8.3, 9.3, 10.8 and 12.1 µm in TIR
- MOD11 values at 8.6 um are assigned to inflection points at 8.3 and 9.3 µm , while MOD11 emissivity values at 11 and 12 µm are used to extend line from hinge points 10.8 and 12.1 µm.
- MODBF can be linearly interpolated between inflection points for comparisons with other instruments
- An eigenvector approach is used to produce emissivity at high spectral resolution from the inflection points for use with atmospheric retrieval algorithms

Motivation for Land Surface Temperature and Emissivity (LST&E) Products:

- Climate Modeling/Earth Surface Radiation Budget
    - Emissivity decrease of 0.1 results in 7 W/m^2 underestimation longwave radiation estimates (greenhouse gases, ~2 W/m^2)

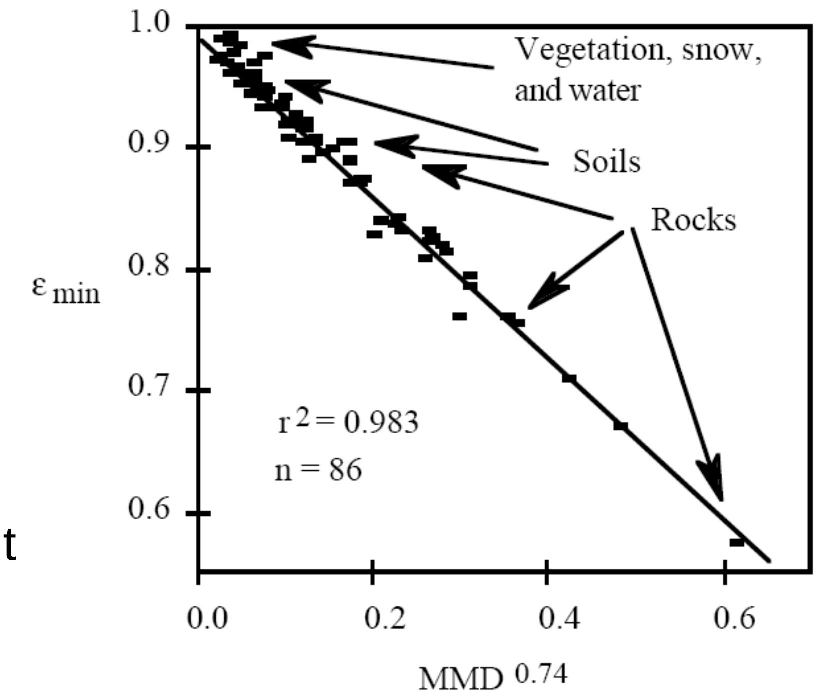
- Atmospheric Retrievals
    - Emissivity error of 0.15 leads to more than 3º C error in boundary layer air temperature and up to 20% in boundary moisture profiles

- Land use, Land cover change (LCLUC)
    - Increased demand for agricultural land, and significant land cover changes from extreme climatic events => increased demand for high spatial and temporal resolution LST&E products for monitoring these events

- Soil Moisture Mapping
    - Evapotranspiration models require LST&E to characterize surface energy balance
    - LST will be critical input for NASA's future Soil Moisture Active & Passive (SMAP) mission

ASTER Temperature Emissivity Separation (TES) Algorithm

- Inversion of T and ε are underdetermined
- In TES, additional constraint arises from minimum emissivity (ε_{min}) vs spectral contrast (MMD) using calibration curve derived from lab results (see plot).
- Requires atmospherically corrected surface radiance, and downward sky irradiance as input
- Three error sources:
  - Reliance on empirical function
  - Atmospheric corrections
  - Radiometric calibration errors
- Reported accuracy:
  - T within 1.5 K and ε within 0.015 (1.5 %)



$$\varepsilon_{min} = 0.994 - 0.687 \cdot MMD^{0.74}$$

ASTER TIR Bands

Band 10	8.125 – 8.475 µm
Band 11	8.475 – 8.825 µm
Band 12	8.925 – 9.275 µm
Band 13	10.25 – 10.95 µm
Band 14	10.95 – 11.65 µm

NAALSED Status

- North America (22-71º N, 169-55° W) Summertime Product completed: (Jul- Aug) 2000-2009

- Products (100m):
  - Emissivity (5 TIR bands)
  - Surface Temperature
  - NDVI
  - Land/Water mask
  - DEM
  - Lat/Lon

	NAALSED v3.0
Temporal coverage	2000-2009
Total ASTER Summertime Scenes	64,149
Usable Scenes (Cloud <80%)	39,848
Cloud mask	v3.0 - Improved snow/cloud filter - Elevation dependent brightness temperature thresholding (GTOPO30) - Improved cirrus filter
Atmospheric Profiles	MODIS (MOD07) - 5 km Coincident Obs - MOD07 ozone
Atmospheric Correction	Water Vapor Scaling (Tonooka, 2005) MODTRAN 5
TES algorithm	Standard TES (Gillespie, 1998)