Outline

• Introduction
  – Science Use
• Theoretical Basis
  – Methods
• L1 and L2 Product Flow
• Validation
  – T-val
  – R-val
• Uncertainties
• Summary and Conclusions
Earth Science Use of LST&E

Evapotranspiration (drought monitoring)

Understanding Climate Change

Surface Energy Balance Models

Urban Heat Island Studies
Theoretical Basis: Planck Formula

\[ B_\lambda = \frac{C_1}{\lambda^5 \left[ \exp\left( \frac{C_2}{\lambda T} \right) - 1 \right]} \]

where:

- \( B_\lambda \) = blackbody spectral exitance.
- \( \lambda \) = wavelength
- \( T \) = absolute 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.
Theoretical Basis: Temperature and Spectral Emissivity

Materials are not perfect blackbodies, but instead emit radiation in accordance with their own characteristics. The ability of a material to emit radiation can be expressed as the ratio of the spectral radiance of a material to that of a blackbody at the same temperature. This ratio is termed the spectral emissivity:

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

or for a material at a given wavelength

$$L = \varepsilon \ B (T)$$
Thermal Infrared Radiative Transfer

\[ L_i(\theta) = \tau_i(\theta) \cdot e_i \cdot B_i(T_S) + \tau_i(\theta) \cdot (1 - e_i) \cdot \bar{L}_i + \int B_i(T(P)) \, d\tau_i \]

- **Surface Radiance**
  - Surface Emission
  - Surface Reflection
- **Atmospheric Emission**
- **Skin Temperature & Surface Emissivity**
Thermal Infrared Physics

\[ L_{sat,\lambda} = \left[ \varepsilon_{\lambda} B_{\lambda}(LST) + (1 - \varepsilon_{\lambda}) L_{\text{sky},\lambda}^{\uparrow} \right] \tau_{\lambda} + L_{\text{sky},\lambda}^{\uparrow} \]
ECOSTRESS L1/L2 Product Flow

Legend

Process

Product

L0 – Raw Data

Calibration

L1 – Radiance at Sensor or Brightness Temperature

Atmospheric Correction

L2 – Radiance at Surface

T/E Separation

System response functions Blackbody temperatures and radiances

Atmospheric Profiles, Scene graybodies, Cloud Masks

Calibration Curve

L2 - Temperature

L2 - Emissivity
## NASA L2 LST&E Product Characteristics

<table>
<thead>
<tr>
<th></th>
<th>ECOSTRESS</th>
<th>ASTER</th>
<th>MODIS*</th>
<th>AIRS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Algorithm</strong></td>
<td>TES Calibration Curve with WVS</td>
<td>TES Calibration Curve with WVS</td>
<td>TES Calibration Curve with WVS</td>
<td>Regression plus retrieval</td>
</tr>
<tr>
<td><strong>Temporal sampling</strong></td>
<td>5 day repeat (varying times)</td>
<td>16 day repeat (1030 AM/PM)</td>
<td>Twice-daily (10:30/1:30 AM/PM)</td>
<td>Twice-daily (10:30 AM/PM)</td>
</tr>
<tr>
<td><strong>Nadir Spatial resolution</strong></td>
<td>40 x 60 m</td>
<td>90 m</td>
<td>1 km</td>
<td>13 km</td>
</tr>
<tr>
<td><strong>Spectral resolution</strong></td>
<td>5 TIR bands (8-12 µm)</td>
<td>5 TIR bands (8-12 µm)</td>
<td>7 MIR/TIR bands (3.7-14 µm)</td>
<td>39 ‘hinge-points’ (3.7-15.4 µm)</td>
</tr>
<tr>
<td><strong>Swath Width</strong></td>
<td>384 km</td>
<td>60 km</td>
<td>2330 km</td>
<td>1650 km</td>
</tr>
</tbody>
</table>

* VIIRS also available at 1 km
L1 Calibration and Validation

• Calibration
  – Two blackbodies, one temperature controlled

• Validation
  – Water targets

Lake Tahoe CA/NV

Salton Sea CA
PHyTIR Test Configuration

- Instrument is in air. Vacuum enclosure around focal-plane is evacuated (to be described in detail in mechanical presentation). Scan mirror rotating.

Blackbodies Added for ISS

Room-temperature reference blackbody. Flat plate with corrugated, painted surface. Emissivity <1 acceptable.

Test Sources Placed Within PhyTIR Scan Range

- Radiometric
  Variable-temperature blackbody: ≥ room temperature. Flat plate with corrugated, painted surface. Emissivity <1 acceptable.

- Spatial
  MCS Target Projector with slit source. Will underfill PHyTIR aperture.

- Saturation
  Small hot source. 295K to > 500 K.
ECOSTRESS Design Layout
- 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.
Radiometer Calibration
Residual Error after Calibration

Rad 409 Validation at 4C, 4%

Chubb Temperature (C*100)

Rad Temperature Error (mK)
Data clearly fall on 1x1 line. High radiance values from Salton Sea
Excellent best fit lines obtained in all bands. Rsquared is typically 0.98. Data follow 1x1 line.
If you look at the individual points they typically scatter between +/- 1K with a few outliers. ASTER specification for 270-340K is 1K. Need to check outliers more!
If look at mean radiance differences for each year they are typically less than 0.5% or 0.3K.
If look at individual bands see that night data problem in 2005
If look at different between day and night for two clear TIR channels (minimum atmospheric effect) see that daytime values tend to be lower than nighttime. Cause for this is unknown but is observed with other sensors, e.g. Landsat. Likely explanation is RT model or bulk-skin effect.
Channels 13 and 14 used to check bias since least affected by the atmosphere. Band 10 is most affected by the atmosphere.
Level 2 Validation – Temperature and Emissivity

- Good correlation at regional scale, but differences when look in detail. Differences due to different spatial, spectral, and temporal characteristics of the sensors, including algorithmic differences.
- Currently validate data LST&E data from ASTER, MODIS, AIRS, Landsat, VIIRS, will use same techniques with ECOSTRESS
NAALSED Summertime Emissivity (Jul-Sep 2000-2010), Band 12 (9.1 µm), 5km

Lowest emissivity over southwest

Number of pixels averaged for a given location ->
ASTER-GEM Band 12 emissivity (9.1 µm)
5km resolution: 2000-2010 (~112,000 scenes)

Certain regions have far more coverage than others!
ASTER-GEM Band 12 emissivity (9.1 µm)
5km resolution: 2000-2010 (~57,446 scenes)
L2 Validation

• Two methods:
  – Temperature validation (Tval) – measure the temperature at the same time as the overpass and compare with the temperature retrieved by the satellite
  – Radiance validation (Rval) – measure the emissivity and the atmospheric profile independently. Forward calculate the ground temperature needed to match the at-sensor radiance and compare to retrieved temperature.
<table>
<thead>
<tr>
<th>Method</th>
<th>Requirements</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-val</td>
<td>Accurate radiometer measurement(s) at the same time of overpass</td>
<td>Direct comparison</td>
<td>Requires in situ measurement at time of overpass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Can also be used to validate calibration of sensor</td>
<td>Difficult to perform over targets where temperatures vary rapidly over short distances</td>
</tr>
<tr>
<td>R-val</td>
<td>Surface emissivity measurement (not coincident with overpass)</td>
<td>Does not require in situ emissivity measurement at time of overpass</td>
<td>Requires atmospheric profile at time of overpass</td>
</tr>
<tr>
<td></td>
<td>Atmospheric profile at the time over overpass</td>
<td></td>
<td>Requires surface emissivity measurement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Indirect measurement cannot be used to validate calibration of sensor</td>
</tr>
</tbody>
</table>

Both approaches are typically used over homogenous targets (either in temperature or emissivity)
The MODIS product is accurate to (± 0.2K), while the ASTER product has a bias of 1-2 K due to residual atmospheric correction effects.
Pseudo-invariant sand dune validation sites
Pseudo-Invariant Sand Dune Validation Sites

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

ASTER MINUS LAB EMISSIVITY (%) < 1.6% (~1 K)
Radiance-based LST Validation at Algodones Dunes
Summary and Conclusions

- Land surface temperature and emissivity (LST&E) are important measurements for understanding the earth system. They are used in a wide variety of studies from measuring evapotranspiration to predicting volcanic eruptions.
- LST&E measurements are available at a variety of spatial, spectral and temporal resolutions and generated using multiple algorithms. Different algorithms result in one product performing better in one region and a different product performing better in a different region.
- Well understood procedure to calibrate to L1 data using 2 blackbodies but must also validate in-flight to obtain independent validation. Will use large lakes to validate L1 radiance at sensor.
- L2 LST&E data can be validated using two approaches T-val and R-val. Approaches complement each other and allow validation over a broader range of cover types.
Questions?