Level-2 Land Surface Temperature and Emissivity

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\textsuperscript{1} Jet Propulsion Laboratory, California Institute of Technology
\textsuperscript{2} Karlsruhe Institute of Technology
Outline

1. L2 products
2. QC and Cloud Masking
3. Stage-2 Validation

Credit: NASA/SpaceX
## ECOSTRESS Level-2 Science Data Sets (SDS)

<table>
<thead>
<tr>
<th>SDS</th>
<th>Long Name</th>
<th>Units</th>
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<tbody>
<tr>
<td>LST</td>
<td>Land Surface Temperature</td>
<td>K</td>
</tr>
<tr>
<td>Emissivity</td>
<td>Emissivity (bands 1 -5)</td>
<td>n/a</td>
</tr>
<tr>
<td>QC</td>
<td>Quality Control (16-bit)</td>
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</tr>
<tr>
<td>LST_err</td>
<td>LST Uncertainty</td>
<td>K</td>
</tr>
<tr>
<td>Emis_err</td>
<td>Emissivity Uncertainty (bands 1 – 5)</td>
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<tr>
<td>EmisWB</td>
<td>Wideband Emissivity (8 – 12.5 micron)</td>
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</tr>
<tr>
<td>PWV</td>
<td>Precipitable Water Vapor</td>
<td>cm</td>
</tr>
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</table>
Please read the User Guide and pay attention to QC!


<table>
<thead>
<tr>
<th>Bits</th>
<th>Long Name</th>
<th>Description</th>
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<tbody>
<tr>
<td>1 &amp; 0</td>
<td>Mandatory QA flags</td>
<td>00 = Pixel produced, best quality</td>
</tr>
<tr>
<td></td>
<td></td>
<td>01 = Pixel produced, nominal quality. Either one or more of the following</td>
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<tr>
<td></td>
<td></td>
<td>conditions are met:</td>
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<tr>
<td></td>
<td></td>
<td>1. Emissivity in both bands 4 and 5 &lt; 0.95, i.e. possible cloud contamination</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Low transmissivity due to high water vapor loading (&lt;0.4), check PWV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>values and error estimates</td>
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<td></td>
<td></td>
<td>3. Pixel falls on missing scan line in bands 1&amp;5, and filled using spatial</td>
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<tr>
<td></td>
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<td>neural net. Check error estimates.</td>
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<td>Recommend more detailed analysis of other QC information</td>
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<td>3 &amp; 2</td>
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<tr>
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<td>10 = not set</td>
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<tr>
<td></td>
<td></td>
<td>11 = Missing/bad L1B data</td>
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<td>5 &amp; 4</td>
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<tr>
<td>7 &amp; 6</td>
<td>Iterations</td>
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<td>10 = Nominal</td>
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<td>11 = Fast</td>
</tr>
<tr>
<td>9 &amp; 8</td>
<td>Atmospheric Opacity</td>
<td>00 = &gt;3 [K]</td>
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<tr>
<td></td>
<td></td>
<td>01 = 0.2 - 0.3</td>
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<td></td>
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<td>10 = 0.1 - 0.2</td>
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<td></td>
<td></td>
<td>11 = &lt;0.1 (Dry)</td>
</tr>
<tr>
<td>11 &amp; 10</td>
<td>MMD</td>
<td>00 = &gt; 0.15 [1]</td>
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<td></td>
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<td>01 = 0.1 - 0.2</td>
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<td>10 = 0.03 - 0.01</td>
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<tr>
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<td></td>
<td>11 = &lt;0.03 (Vegetation, snow, water, ice)</td>
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<td>13 &amp; 12</td>
<td>Emissivity accuracy</td>
<td>(Average of all bands)</td>
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<td>00 = &gt;0.02 (Poor performance)</td>
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<td>01 = 0.015 - 0.02 (Marginal performance)</td>
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<td>10 = 0.01 - 0.015 (Good performance)</td>
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<td>11 = &lt;0.01 (Excellent performance)</td>
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<tr>
<td>15 &amp; 14</td>
<td>LST accuracy</td>
<td>00 = &gt;2 K (Poor performance)</td>
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<td>01 = 1.5 - 2 K (Marginal performance)</td>
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<td>11 = &lt;1 K (Excellent performance)</td>
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MODIS cloud mask tests

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<th></th>
<th>Daytime Ocean</th>
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<th>Daytime Land</th>
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<th>Daytime Snow/ice</th>
<th>Nighttime Snow/ice</th>
<th>Daytime Coastline</th>
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<td>✓</td>
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<td>✓</td>
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</tbody>
</table>
Cloud Mask Challenges

• ECOSTRESS has two cloud thermal tests:
  1. BT11: Band 4 brightness temperature threshold
     BT11 threshold (day/night, elevation)

  2. BT11 – BT12: Band 4 – 5 brightness temperature difference
     BT11 – BT12 (LUT based on band 4 brightness temperature)

However, ideally:
  1. BT11 threshold (location, time of day, time of year, elevation)

  – Work to be completed this summer and implementation in build 7 reprocessing
Cloud product bit 3 = 1 applied: result of both cloud tests
Cloud product bit 2 = 1
applied: result of both cloud tests plus cloud growing and filling
Or
Bits 1&2 in QC = 0&0
CEOS LST validation best practices

1. Temperature-based validation
2. Radiance-based validation
3. Sensor LST product intercomparisons
4. Time-series analysis
## Status: LST instrumented validation Sites

<table>
<thead>
<tr>
<th>Site Name</th>
<th>State/Prov</th>
<th>Country</th>
<th>Contact</th>
<th>Network / Organisation</th>
<th>Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Tahoe (4 buoys)</td>
<td>CA/NV</td>
<td>USA</td>
<td><a href="mailto:Simon.j.hook@jpl.nasa.gov">Simon.j.hook@jpl.nasa.gov</a></td>
<td>JPL</td>
<td>Radiometer (in-house development)</td>
</tr>
<tr>
<td>Salton Sea</td>
<td>CA</td>
<td>USA</td>
<td><a href="mailto:Simon.j.hook@jpl.nasa.gov">Simon.j.hook@jpl.nasa.gov</a></td>
<td>JPL</td>
<td>Radiometer (in-house development)</td>
</tr>
<tr>
<td>Table Mountain, Boulder</td>
<td>CO</td>
<td>USA</td>
<td><a href="mailto:Jeff.Privette@noaa.gov">Jeff.Privette@noaa.gov</a></td>
<td>SurfRad</td>
<td>Pyrgeometer, Eppley</td>
</tr>
<tr>
<td>Fort Peck</td>
<td>MT</td>
<td>USA</td>
<td><a href="mailto:Jeff.Privette@noaa.gov">Jeff.Privette@noaa.gov</a></td>
<td>SurfRad</td>
<td>Pyrgeometer, Eppley</td>
</tr>
<tr>
<td>Desert Rock</td>
<td>NV</td>
<td>USA</td>
<td><a href="mailto:Jeff.Privette@noaa.gov">Jeff.Privette@noaa.gov</a></td>
<td>SurfRad</td>
<td>Pyrgeometer, Eppley</td>
</tr>
<tr>
<td>Sioux Falls</td>
<td>SD</td>
<td>USA</td>
<td><a href="mailto:Jeff.Privette@noaa.gov">Jeff.Privette@noaa.gov</a></td>
<td>SurfRad</td>
<td>Pyrgeometer, Eppley</td>
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<tr>
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<td>MS</td>
<td>USA</td>
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<td>Pyrgeometer, Eppley</td>
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<td>USA</td>
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<td>Pyrgeometer, Eppley</td>
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<td>Pyrgeometer, Eppley</td>
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<tr>
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<td>USA</td>
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<td>Pyrgeometer, Eppley</td>
</tr>
<tr>
<td>ARM NSA</td>
<td>AL</td>
<td>USA</td>
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<td>Pyrgeometer, Eppley</td>
</tr>
<tr>
<td>Lake Constance (ferry)</td>
<td></td>
<td></td>
<td><a href="mailto:frank.goettsche@kit.edu">frank.goettsche@kit.edu</a></td>
<td>KIT</td>
<td>KT15.85 IIP, Heitronics</td>
</tr>
<tr>
<td>Evora</td>
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<tr>
<td>Dahra</td>
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<td><a href="mailto:frank.goettsche@kit.edu">frank.goettsche@kit.edu</a></td>
<td>KIT</td>
<td>KT15.85 IIP, Heitronics</td>
</tr>
<tr>
<td>Farm Helmat (Kalahari)</td>
<td>Namibia</td>
<td><a href="mailto:frank.goettsche@kit.edu">frank.goettsche@kit.edu</a></td>
<td>KIT</td>
<td>KT15.85 IIP, Heitronics</td>
<td></td>
</tr>
<tr>
<td>Gobabeb Windmast (GBB Wind)</td>
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<td><a href="mailto:frank.goettsche@kit.edu">frank.goettsche@kit.edu</a></td>
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<td>KT15.85 IIP, Heitronics</td>
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</tr>
<tr>
<td>Gobabeb Plains (GBB Plains)</td>
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<td>KT15.85 IIP, Heitronics</td>
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</tr>
<tr>
<td>Neumayer Station III (Germany)</td>
<td>Antarctica</td>
<td><a href="mailto:Gert.Koenig-Langlo@awi.de">Gert.Koenig-Langlo@awi.de</a></td>
<td>BSRN</td>
<td>Pyrgeometer, Eppley</td>
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<td><a href="mailto:Jeff.Privette@noaa.gov">Jeff.Privette@noaa.gov</a></td>
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<td>SI-111, Apogee; broadband hemispherical radiances</td>
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<td>BSRN</td>
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<td>BSRR</td>
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<tr>
<td>Valencia</td>
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<td><a href="mailto:cesar.coll@uv.es">cesar.coll@uv.es</a></td>
<td>BSRR</td>
<td>University of Valencia</td>
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<td>University of Valencia</td>
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<tr>
<td>Cabo de Gata</td>
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<td><a href="mailto:Jose.Sobrino@uv.es">Jose.Sobrino@uv.es</a></td>
<td>University of Valencia</td>
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<tr>
<td>OzFlux ASM site</td>
<td>Australia</td>
<td><a href="mailto:James.Cleversiy@uts.edu.au">James.Cleversiy@uts.edu.au</a></td>
<td>TERN</td>
<td>CNR1, Kipp &amp; Zonen (broadband hemispherical radiances)</td>
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<tr>
<td>Etna</td>
<td>Italy</td>
<td><a href="mailto:fabrizia.buoniglomo@ingv.it">fabrizia.buoniglomo@ingv.it</a></td>
<td>INGV</td>
<td>University of Valencia</td>
<td></td>
</tr>
<tr>
<td>Almeria (2 sites)</td>
<td>Spain</td>
<td><a href="mailto:Jose.Sobrino@uv.es">Jose.Sobrino@uv.es</a></td>
<td>University of Valencia</td>
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</tr>
</tbody>
</table>
JPL Cal/Val sites: Lake Tahoe and Salton Sea, CA

Lake Tahoe operating 24x7 since 1999

Salton Sea since 2007
Bias = -0.4 K
RMSE = 0.8 K
N = 168
Nighttime

07/2018 – 02/2020

Bias = -1.2 K
RMSE = 1.3 K
N = 197
Each safehold = warmup deicing cycle
## JPL Cal/Val sites: Russell Ranch, CA

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<th>Data Collected</th>
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<td>Wind speed indicator (MET)</td>
<td>The values are in counts and are converted to meters per second (m/s²)</td>
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<td>Wind direction indicator (MET)</td>
<td>The values are in counts and are converted to degrees with respect to magnetic north</td>
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<tr>
<td>Air Temperatures with Gill radiation shield (MET)</td>
<td>The values are in counts and are converted to degrees Celsius (the air temperatures and relative humidity sensor are integrated together)</td>
</tr>
<tr>
<td>Relative Humidity (RH) (MET)</td>
<td>The values are in counts and are converted to percent</td>
</tr>
<tr>
<td>Barometric Pressure with Pressure Port (MET)</td>
<td>The values are in counts and are converted to hectopascals or millibars (hPa or mBar). The pressure port is used to prevent any errors in pressure due to wind over the sensor</td>
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<tr>
<td>Li-COR Photosynthetically Active Radiation (PAR) sensor</td>
<td>Sensor measures Photosynthetic Photon Flux Density (PPFD) in both natural and artificial light</td>
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<tr>
<td>Net Radiometer</td>
<td>Incoming solar radiation (short wave), reflected solar radiation, incoming far infrared radiation (long wave), outgoing far infrared radiation, sky temperature and ground temperature</td>
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<tr>
<td>JPL-built Radiometer</td>
<td>Land surface temperature</td>
</tr>
<tr>
<td>Eddy Covariance System</td>
<td>Air temperature, sonic air temperature, barometric pressure, absolute carbon dioxide and water vapor densities and the orthogonal wind components (three-dimensional)</td>
</tr>
</tbody>
</table>
• Crops are sown in ~April (usually tomatoes)
• Harvesting occurs in late September
• Tower has a visible camera taking daily snapshots of field condition
• Two radiometers pointing perpendicular to crop rows
ECOSTRESS LST Validation: Russell Ranch, CA

MBE = -0.2 K
RMS = 1.1 K

*Only matchups with field in fully vegetated state selected to minimize emissivity correction issues
Gobabeb, Namibia

Day:
Bias = -0.1 K
RMS = 1.2 K

Night:
Bias = -1.0 K
RMS = 1.3 K
Radiance-Based Temperature Validation

Compare radiances: CALC1 – OBS?

Sensor Radiance (CALC1)  
Sensor Radiance (CALC2)

Tr = interp1([CALC1 CALC2], [T1 T2], OBS);
Terror = Tr – T1

Requirements:
- Accurate Emissivity
- Accurate Profile:
  \[ T_d(\text{calc}) = T_b(11\mu m) – T_b(12\mu m) \]
  \[ T_d(\text{obs}) = T_b(11\mu m) – T_b(12\mu m) \]
  \[ T_d(\text{calc}) – T_d(\text{obs}) < 0.5 \text{ K} \]

Atmospheric Profile (ECMWF) (Tair, RH)

Retrieved Temp (T1)  
T2 = T1 ± 2 K  
Measured Emissivity

Measured Emissivity
LST Validation: Arid sites: 08/2018-01/2020

MSE = -0.14 K
RMS = 1.12 K
r = 0.997
n = 499
Algodones Dunes, CA

5-band Emissivity: Algodones Dunes, CA

3-band Emissivity: Algodones Dunes, CA
ECOSTRESS 3 vs 5-band TES accuracy

07/2018 – 3/2019

ECOSTRESS 5-band

Bias = 0.14 K
RMS = 0.97 K
$r^2 = 0.997$
n = 117

05/2019 – 02/2020

ECOSTRESS 3-band

Bias = -0.10 K
RMS = 1.07 K
$r^2 = 0.997$
n = 216

0.1 K higher error for 3-band TES, negligible change in Bias
LST error vs atmospheric water vapor
(Algodones dunes, CA)

(a) Day
Fire smoke contamination (08/17/2018)

(b) Night

LST Error [K]

Total Column Water [cm]
LST error vs satellite view angle

(a) Day

Fire smoke contamination (08/17/2018)

(b) Night
CEOS LST Validation Recommendations

1. Temperature-based validation
   – Ground instrumented sites
   – Sensor LST matched to ground temperature measurements with NIST traceable standards

• Advantages:
  – Most direct and accurate method of validation
  – Can also be used for calibration purposes

• Disadvantages
  – Requires accurately matched measurements
  – Site and instrument maintenance is costly
CEOS LST Validation Recommendations

2. Radiance-based validation

- Radiative closure simulation experiment
- Requires accurate site emissivity data and atmospheric profiles (NWP or radiosonde)

• Advantages:
  - Can be used to validated coarser resolution sensors
  - Can be applied on global scales day and night

• Disadvantages
  - Requires accurate atmospheric profiles and emissivity
  - Requires sensor with at least two bands at 10-12 micron
CEOS LST Validation Recommendations

3. Sensor LST scene intercomparisons
   - Comparisons with contemporaneous LST from other well calibrated/validated sensors
   - e.g. Landsat vs ASTER, or Landsat vs GOES-16

4. Time-series comparisons
   - Comparisons between LST products over time to identify sensor drift, calibration, cloud detection issues
<table>
<thead>
<tr>
<th>Stage 0 Validation</th>
<th>No validation results have been reported.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1 Validation</td>
<td>Product accuracy is assessed from a small (typically &lt; 30) set of locations and time periods by comparison with in situ or other suitable reference data.</td>
</tr>
<tr>
<td>Stage 2 Validation</td>
<td>Product accuracy is estimated over a significant set of locations and time periods by comparison with reference in situ or other suitable reference data. Spatial and temporal consistency of the product with similar products has been evaluated over globally representative locations and time periods. Results are published in the peer-reviewed literature.</td>
</tr>
<tr>
<td>Stage 3 Validation</td>
<td>Uncertainties in the product and its associated structure are well quantified from comparison with reference in situ or other suitable reference data. Uncertainties are characterized in a statistically robust way over multiple locations and time periods representing global conditions. Spatial and temporal consistency of the product and consistency with similar products has been evaluated over globally representative locations and periods. Results are published in the peer-reviewed literature.</td>
</tr>
<tr>
<td>Stage 4 Validation</td>
<td>Validation results for stage 3 are systematically updated when new product versions are released and as the time-series expands.</td>
</tr>
</tbody>
</table>
• Spatial representativeness is key
• Sites should be homogeneous at a scale of at least 3x3 satellite pixels

Bondville SURFRAD site measures different proportions of vegetation depending on time of year making it unsuitable for LST validation
LST validation good practices

- Observing & understanding various surface temperatures of Earth
- Describes progress by domain (air, land, sea, lakes and ice)
- Rigorous validation chapter