Long-term global time series of MODIS and VIIRS SSTs

Peter J. Minnett, Katherine Kilpatrick, Guillermo Podestá, Yang Liu, Elizabeth Williams, Susan Walsh, Goshka Szczodrak, and Miguel Angel Izaguirre

Ocean Sciences
Rosenstiel School of Marine & Atmospheric Science
University of Miami

GHRSSST XVIII
Ocean University of China, June 2017
SST continuity
EOS MODIS to SOUMI NPP VIIRS

• Inter-sensor consistency can be achieved by using comparable atmospheric correction algorithms, cloud-screening methods, and approaches to estimate errors and uncertainties.

• The objective is to evaluate the accuracy and continuity of the SST measurements observed by MODIS (Terra and Aqua) and those of S-NPP VIIRS.

• A consistent multi sensor data record forms the foundation of any CDR
  • Continuity alone, however, is not enough. LWIR SST CDR’s require SI traceability with direct measurements of skin SST by ship-board radiometers calibrated to NIST, or NPL, standards.

• SST CDR accuracy requirements are very stringent: absolute accuracy of 0.1K, and decadal stability of 0.04K (Ohring et. al. 2005)

GHRSS XVIII
Ocean University of China, June 2017
SST Algorithm Continuity

\[
\text{SST}_{\text{sat}} = a_0 + a_1 T_{11} + a_2 (T_{11} - T_{12}) T_{\text{sfc}} + a_3 (\sec(\theta) - 1)(T_{11\mu m} - T_{12\mu m}) + a_4 (\text{mirror.side}) + a_5 (\theta) + a_6 (\theta^2)
\]

- Non Linear atmospheric correction algorithm (NLSST Walton et. al. 1999) with coefficients tuned to average atmospheric conditions using collocated sub-surface buoy SST
  - AVHRR Pathfinder wet/dry atmospheres monthly
  - R2014.0C6 MODIS/VIIRS R2016.0– latitude/month of year

- \(a_4\) term for MODIS 2-sided mirror

- \(a_5, a_6\) terms extend retrievals towards edge of VIIRS & MODIS swaths.
Cloud mask

- IR algorithms are only accurate in cloud free and atmospherically “clean” pixels.
- PF/EOS MODIS Binary Decision Tree.
- Persistent clouds and differences in ability to detect clouds between day and night and inter-swath differences can impact sampling/binning of higher level products (Liu and Minnett, 2016).
  - Differences in gap fraction between sensors.
- S-NPP VIIRS Ensemble classification Alternating Decision Trees (ADTree) methods to increase number of valid retrievals and reduce gap fraction and misclassification errors.
L2 Median residual and robust standard deviation
MODIS- AVHRR -VIIRS
Matchups Level-2 1km

2002-2016
MODIS + VIIRS skin SST
median global bias IQR = 0.036

RSD range ~ 0.2 – 0.4

GHRSSST XVIII
Ocean University of China, June 2017
Median L2 Matchups with buoy SST residuals
1 degree grid

MODIS-T V6 median q10 NSST skin corrected buoys residuals

MODIS-A V6 median q10 NSST skin corrected buoys residuals

AVHRR_N19 V6 median q10 NSST skin corrected buoys residuals

VIIRS V6 median q10 NSST skin corrected buoys residuals

GHRSSST XVIII
Ocean University of China, June 2017
Cloud Classification Methods

Pathfinder and MODIS R2014.0 use a Binary decision tree
1 branch 1 vote per pixel binary yes/no which is often very conservative.

VIIRS R2016.0 uses an Alternating Decision Trees* an ensemble collection of both weak and strong classifiers with each binary decision nodes ending with a prediction node containing vote. Each vote is scaled to the predictive power of the test.

A combined vote from a collection of weak prediction nodes when voting together as a block can modify or over-ride the vote of a single strong prediction node.

When combined with boosting algorithms during training a very accurate classification models can be developed.

* Freund and Mason, 1999; Pfahringer et. al., 2001
Ensemble ADtree classifiers

MODISA R2014.0 Day

VIIRS R2016.0 Day

MODIS-A R2017.0 planned

GHRSSST XVIII
Ocean University of China, June 2017
Ensemble of ADTree classifiers improves retention of good quality pixels at frontal boundaries

June 19 2014 L2 over Gulf Stream

MODIS –A SST R2014.0/C6
Standard decision tree

MODIS –A SST R2017
ADtree decision tree

VIIRS SST R2016.0
ADtree classifier

GHRSSST XVIII
Ocean University of China, June 2017
Accuracy of Level-3 SST products

• Connecting Level-2 clouds/quality mask to both sampling and mis-classification errors in level-3 binned products.
• The accuracy of SST (<0.5K, 1σ) is usually assessed at Level 2, based on point-to-point match-up.
• But this is NOT always the accuracy or consistency of global SST products (Level 3 or 4) often applied in climate research.

➢ L3 Sampling errors introduced by missing observations (clouds and inter-swath gaps) can be significant and the differences in the gap fraction need to be quantified and evaluated when analyzing long term trends from multiple sensors
➢ Consistent L2 cloud/quality methods are as important as having a consistent atmospheric correction algorithm

How accurate?

• Determine the uncertainties by comparing the satellite-derived temperatures with independent surface based measurements of equal or better accuracy.

• This approach integrates the errors and uncertainties from all sources.

• Satellite SST requirements for climate research*:
  - Uncertainty = 0.1K
  - Stability = 0.04 K/decade

Drifter numbers over *Aqua* mission

Highest quality MODIS - buoy matchups per month by latitude band.

<table>
<thead>
<tr>
<th>Lat. Band</th>
<th>Year</th>
</tr>
</thead>
</table>
VIIRS 2015 differences wrt buoy temperatures

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean</th>
<th>St Dev</th>
<th>Median</th>
<th>Robust St Dev</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>-0.200</td>
<td>0.400</td>
<td>-0.175</td>
<td>0.271</td>
<td>18810</td>
</tr>
<tr>
<td>February</td>
<td>-0.165</td>
<td>0.419</td>
<td>-0.141</td>
<td>0.265</td>
<td>17738</td>
</tr>
<tr>
<td>March</td>
<td>-0.211</td>
<td>0.415</td>
<td>-0.178</td>
<td>0.274</td>
<td>19019</td>
</tr>
<tr>
<td>April</td>
<td>-0.268</td>
<td>0.444</td>
<td>-0.215</td>
<td>0.296</td>
<td>16163</td>
</tr>
<tr>
<td>May</td>
<td>-0.286</td>
<td>0.439</td>
<td>-0.245</td>
<td>0.300</td>
<td>19901</td>
</tr>
<tr>
<td>June</td>
<td>-0.248</td>
<td>0.485</td>
<td>-0.218</td>
<td>0.297</td>
<td>17612</td>
</tr>
<tr>
<td>July</td>
<td>-0.226</td>
<td>0.513</td>
<td>-0.205</td>
<td>0.299</td>
<td>20675</td>
</tr>
<tr>
<td>August</td>
<td>-0.216</td>
<td>0.478</td>
<td>-0.192</td>
<td>0.292</td>
<td>21515</td>
</tr>
<tr>
<td>September</td>
<td>-0.214</td>
<td>0.449</td>
<td>-0.185</td>
<td>0.290</td>
<td>20239</td>
</tr>
<tr>
<td>October</td>
<td>-0.207</td>
<td>0.401</td>
<td>-0.178</td>
<td>0.265</td>
<td>20910</td>
</tr>
<tr>
<td>November</td>
<td>-0.195</td>
<td>0.395</td>
<td>-0.164</td>
<td>0.270</td>
<td>16364</td>
</tr>
<tr>
<td>December</td>
<td>-0.189</td>
<td>0.405</td>
<td>-0.158</td>
<td>0.277</td>
<td>15984</td>
</tr>
</tbody>
</table>

Matchups are required to be within 30 minutes and 10km of satellite observations.

All temperature differences are in K.
VIIRS accuracies wrt drifters

January, 2015

GHRSS XVIII
Ocean University of China, June 2017
VIIRS accuracies wrt drifters
Research ship radiometer deployments
Current cruise ship deployments

Collaboration with Royal Caribbean Cruise Lines

## Error budget of M-AERI measurements

### At $\lambda = 10.0 \, \mu m$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type A Uncertainty in Value [ K ]</th>
<th>Type B Uncertainty in K</th>
<th>Uncertainty in Brightness temp K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability of Measurement</td>
<td>0.014</td>
<td>0.0058 (0.0035)</td>
<td>0.014</td>
</tr>
<tr>
<td>Reproducibility of Measurement</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.0003</td>
</tr>
<tr>
<td>Linearity of radiometer</td>
<td>0.0097</td>
<td>0.0097</td>
<td>0.0097</td>
</tr>
<tr>
<td>Primary calibration</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Drift since calibration</td>
<td>0.0152 (0.0144)</td>
<td>0.0102</td>
<td>0.0182 (0.0176)</td>
</tr>
<tr>
<td>RMS total</td>
<td>0.0152 (0.0144)</td>
<td>0.0102</td>
<td>0.0182 (0.0176)</td>
</tr>
</tbody>
</table>

### At $\lambda = 7.7 \, \mu m$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type A Uncertainty in Value [ K ]</th>
<th>Type B Uncertainty in K</th>
<th>Uncertainty in Brightness temp K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability of Measurement</td>
<td>0.0349</td>
<td>0.0178</td>
<td>0.0349</td>
</tr>
<tr>
<td>Reproducibility of Measurement</td>
<td>0.0178</td>
<td>0.0089</td>
<td>0.0178</td>
</tr>
<tr>
<td>Linearity of radiometer</td>
<td>0.0086</td>
<td>0.0086</td>
<td>0.0086</td>
</tr>
<tr>
<td>Primary calibration</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Drift since calibration</td>
<td>0.0392 (0.0360)</td>
<td>0.0091</td>
<td>0.0402 (0.0372)</td>
</tr>
<tr>
<td>RMS total</td>
<td>0.0392 (0.0360)</td>
<td>0.0091</td>
<td>0.0402 (0.0372)</td>
</tr>
</tbody>
</table>

---

GHRSSST XVIII
Ocean University of China, June 2017
# MODIS SSTs & ship radiometers

## MODIS Skin SST vs M-AERI and ISAR Skin SST. Temperatures in K

<table>
<thead>
<tr>
<th>Satellite and Algorithm</th>
<th>Mean</th>
<th>Median</th>
<th>Standard Deviation</th>
<th>Robust St. Deviation</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terra SST Day</td>
<td>0.082</td>
<td>0.080</td>
<td>0.567</td>
<td>0.409</td>
<td>1025</td>
</tr>
<tr>
<td>Terra SST Night</td>
<td>0.048</td>
<td>0.034</td>
<td>0.467</td>
<td>0.337</td>
<td>2454</td>
</tr>
<tr>
<td>Terra SST4 Night</td>
<td>0.016</td>
<td>0.023</td>
<td>0.339</td>
<td>0.244</td>
<td>2467</td>
</tr>
<tr>
<td>Aqua SST Day</td>
<td>0.105</td>
<td>0.107</td>
<td>0.666</td>
<td>0.480</td>
<td>910</td>
</tr>
<tr>
<td>Aqua SST Night</td>
<td>0.020</td>
<td>0.027</td>
<td>0.489</td>
<td>0.353</td>
<td>1752</td>
</tr>
<tr>
<td>Aqua SST4 Night</td>
<td>-0.010</td>
<td>0.016</td>
<td>0.396</td>
<td>0.285</td>
<td>1858</td>
</tr>
</tbody>
</table>
Some remaining issues

• Limitations of the split window regression approach, sensitivity is small in very moist atmospheres.
• Sampling errors in the drifter data used to derive coefficients.
• Measurement uncertainties in the drifter thermometers – for coefficient derivation and retrieval validation.
• $T_{\text{depth}}$ to $\text{SST}_{\text{skin}}$ correction.
• Aerosol effects.
• Sampling errors in validating data, both buoys and radiometers.
Summary

✓ The accuracy of the EOS MODIS SST record remains very stable over the 16 year period.
✓ Excellent agreement between S-NPP VIIRS and both MODIS LWIR SST algorithm based on L2 MUDB.
✓ New VIIRS Cloud classification using an ensemble of Alternating Decision Trees reduces misclassification and increases number of valid SST retrievals and reduces global L3 sampling errors.
✓ L3 night VIIRS R2016.0 images are generally warm relative to MODISA R2014.0 believed due to differences in the cloud masks increased retrievals capture more variability (improved cloud classification?)
✓ Inter-sensor consistency at both L2 and L3 can achieved by reprocessing of NASA MODIS, NASA/NOAA PFSST and VIIRS with a consistent atmospheric correction and cloud masking with potential for 4 decades global LWIR SST measurements.
✓ Accuracy objectives of an SST CDR are not yet met.
• Thank you for your attention.