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

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ROSENSTIEL SCHOOL of MARINE & ATMOSPHERIC SCIENCE

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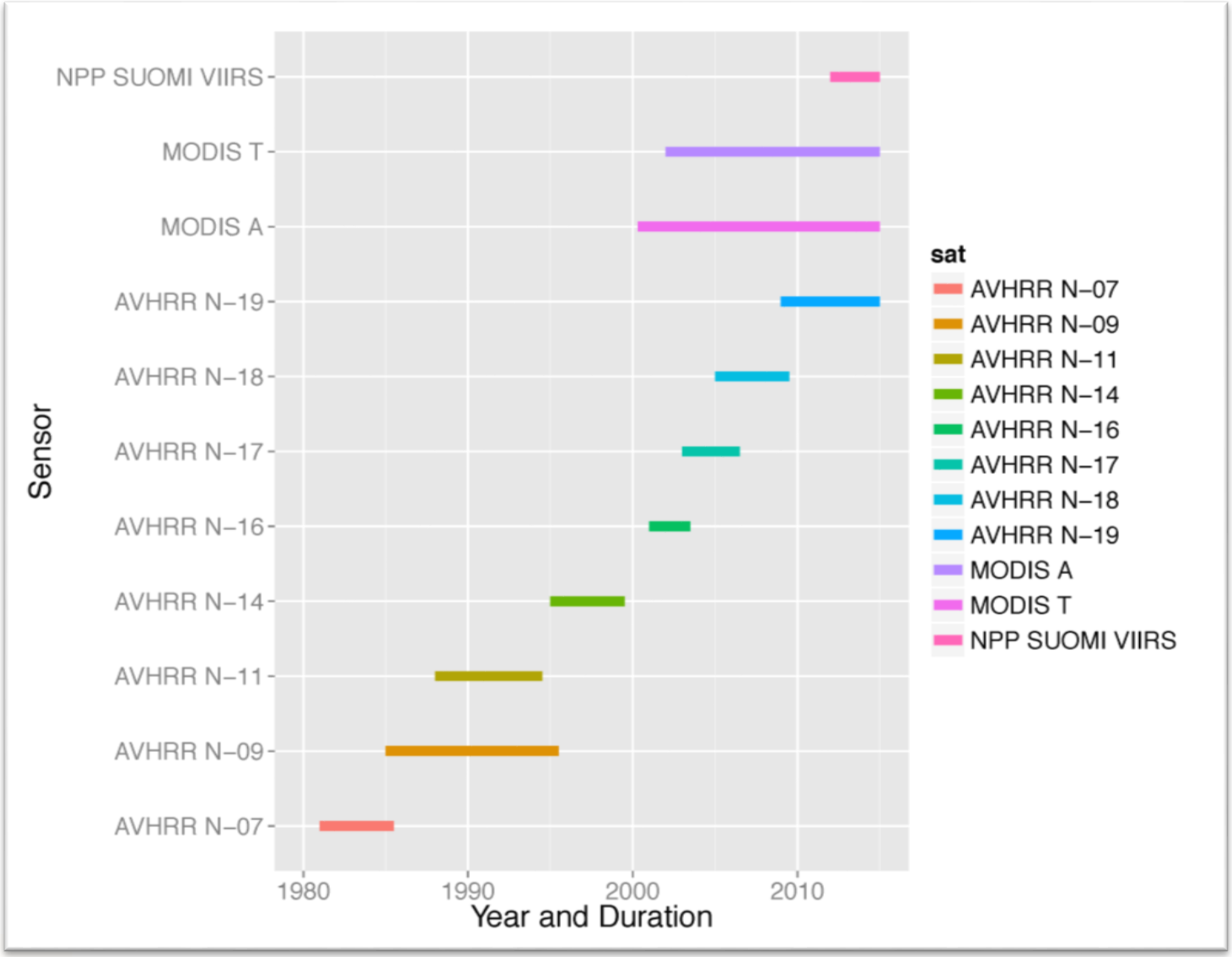
SST continuity
EOS MODIS to SOUMI NPP VIIRS

- 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)

US Polar orbiting LWIR Sensors 1980-2016



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SST Algorithm Continuity

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

- 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

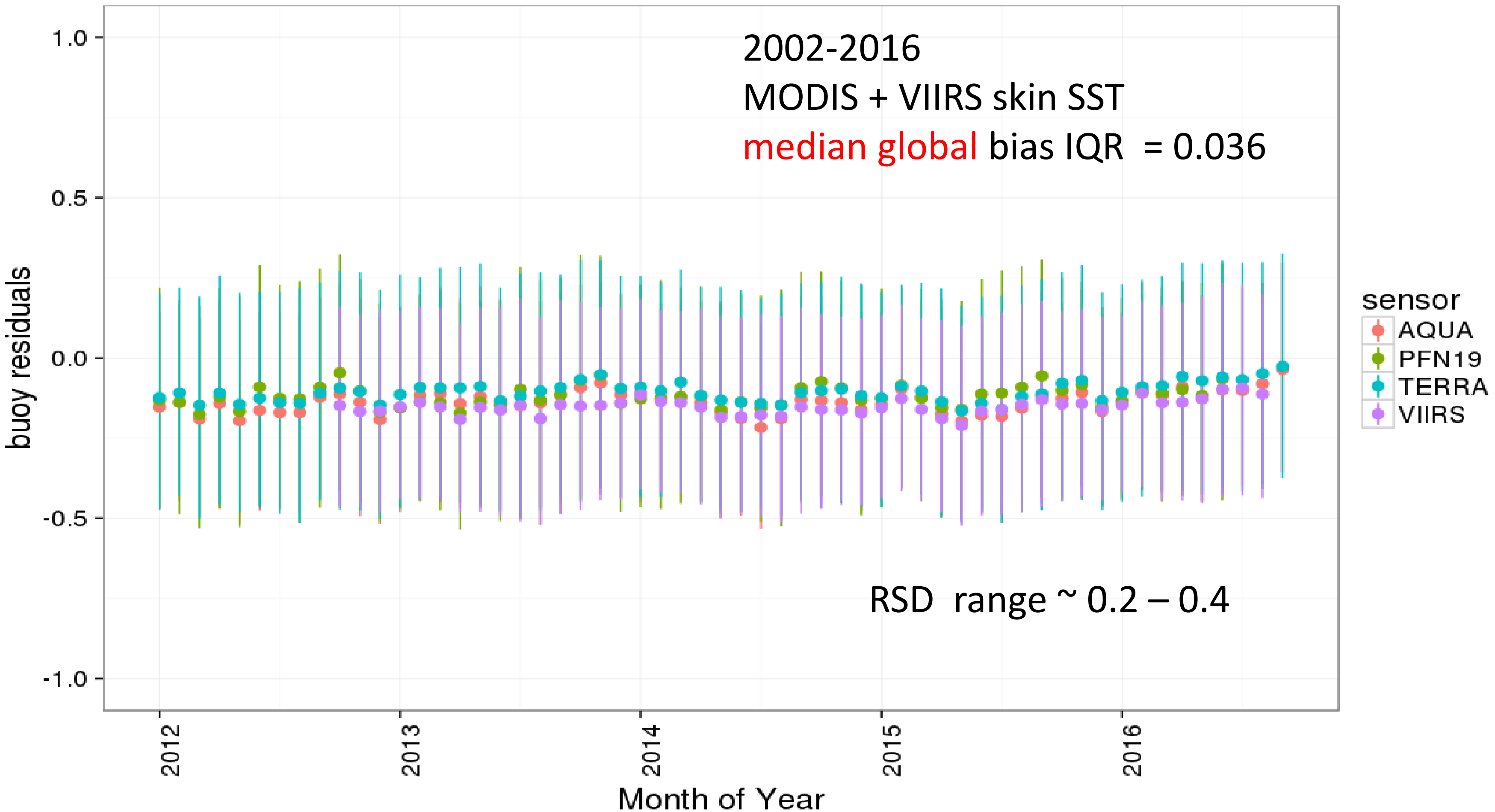
- a_5, a_6 terms extend retrievals towards edge of VIIRS & MODIS swaths.

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



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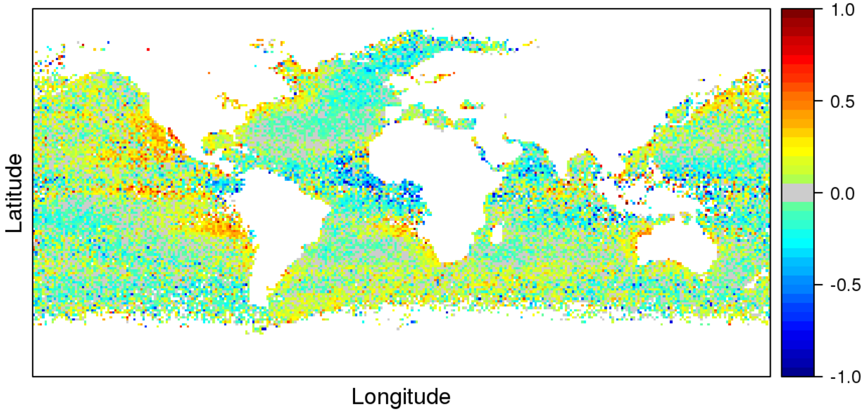
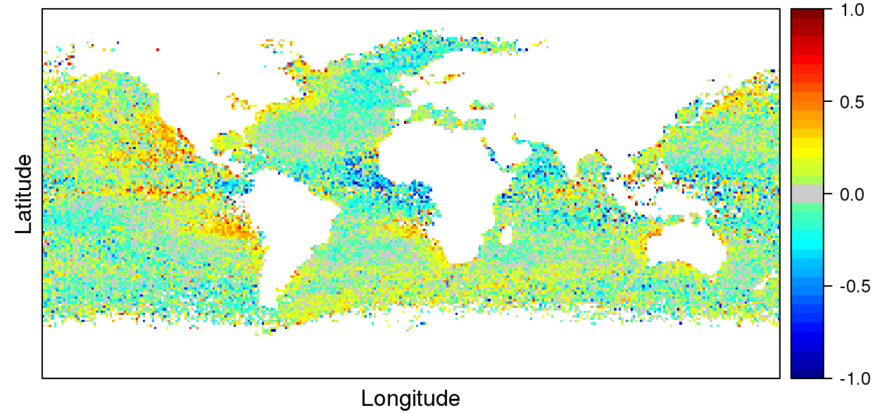
Median L2 Matchups with buoy SST residuals
1 degree grid

MODIS-T V6 median ql0 NSST skin corrected buoys residuals



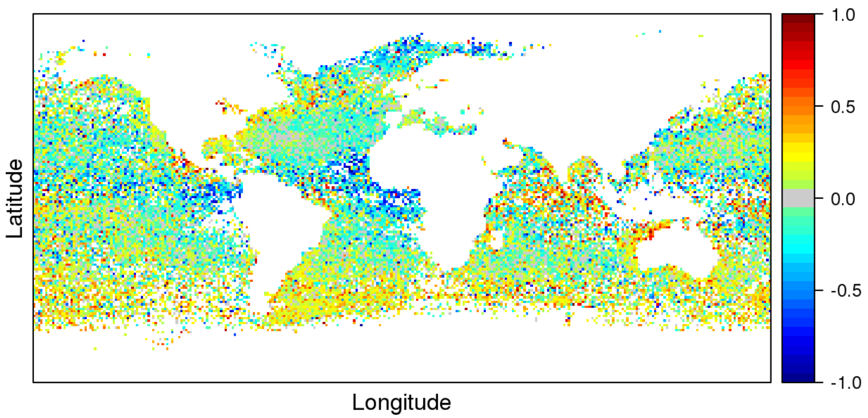
1 degree resolution grid

MODIS-A V6 median ql0 NSST skin corrected buoys residuals



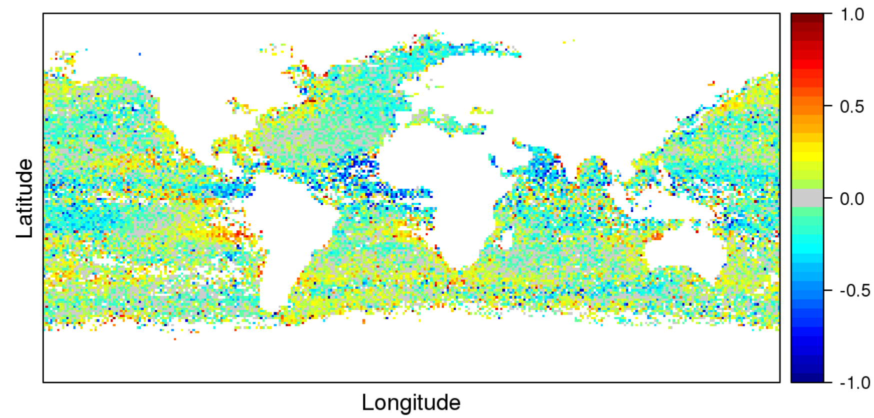
1 degree resolution grid

AVHRR_N19 V6 median ql0 NSST skin corrected buoys residuals



1 degree resolution grid

VIIRS V6 median ql0 NSST skin corrected buoys residuals



1 degree resolution grid

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.

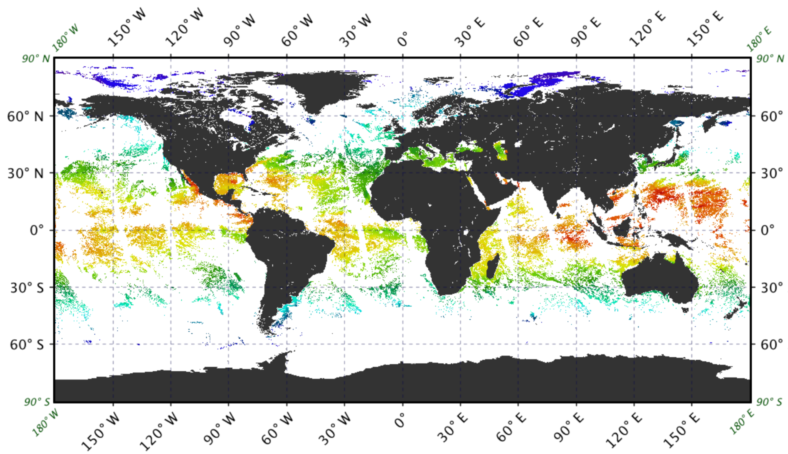
VIIRS R2016.0 uses an Alternating Decision Trees* an ensemble collection of both weak and strong classifiers with each binary decision nodes ending with a prediction node containing vote. Each vote is scaled to the predictive power of the test.

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.

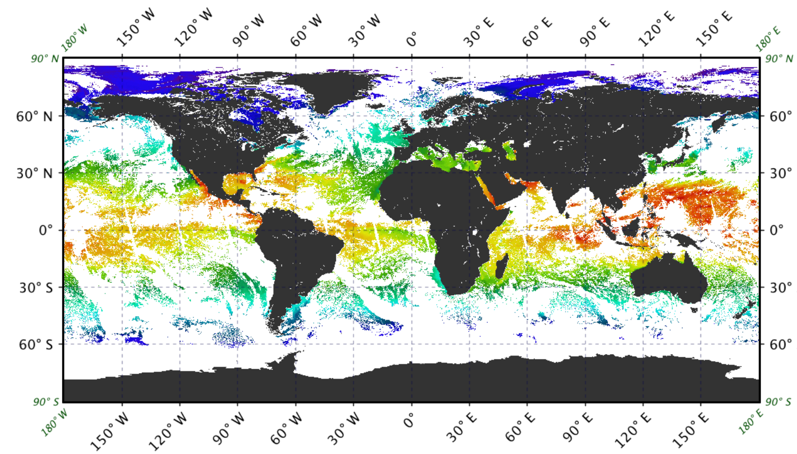
* Freund and Mason, 1999; Pfahringer et. al., 2001

Ensemble ADtree classifiers

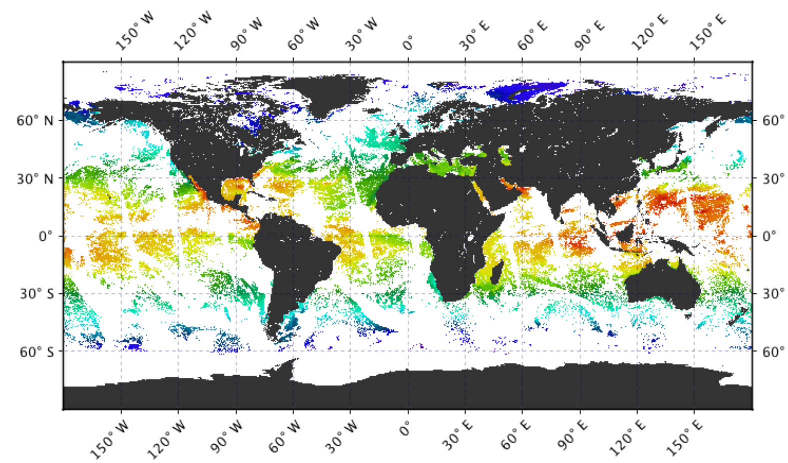
MODISA R2014.0 Day

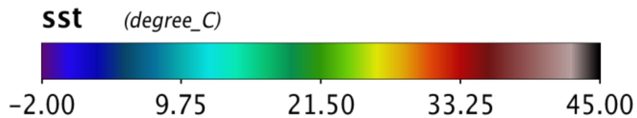


VIIRS R2016.0 Day



MODIS-A R2017.0 planned





June 19 2014

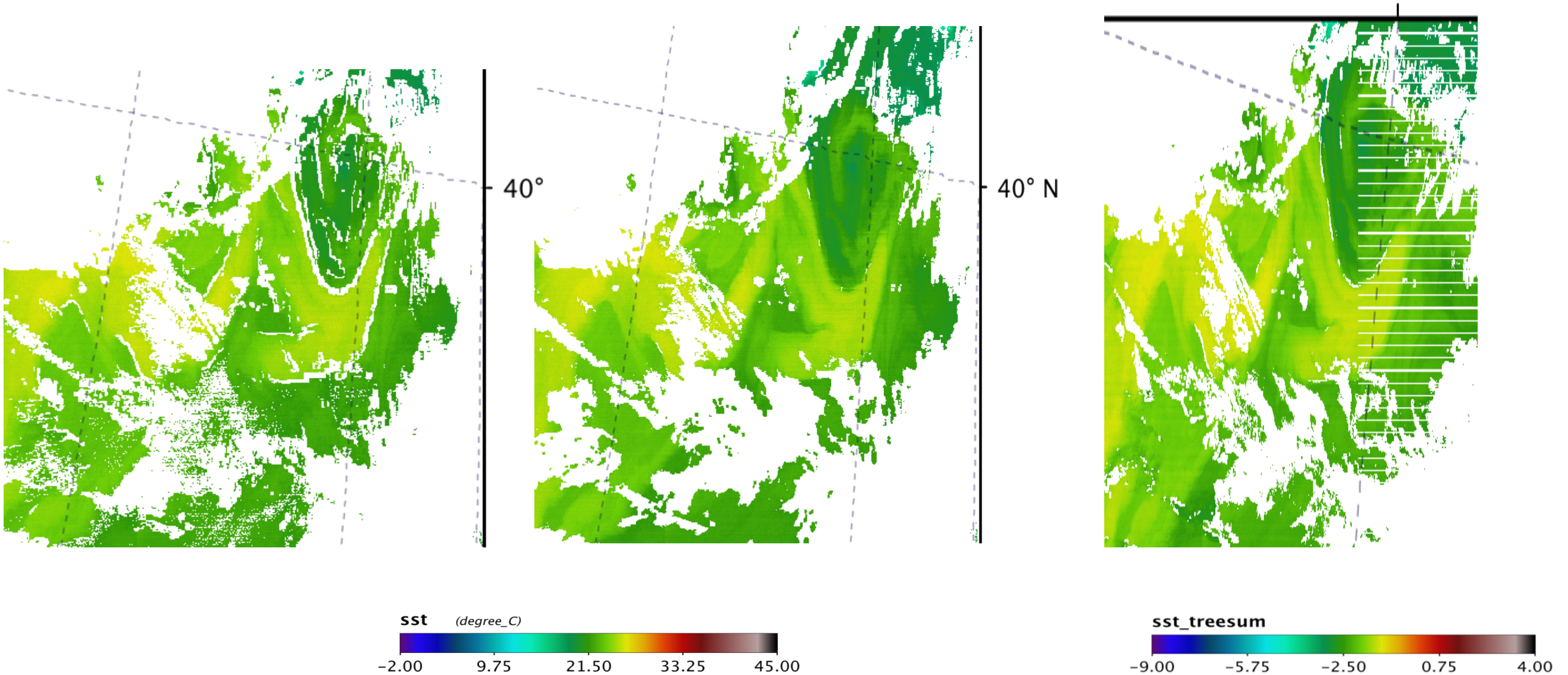
Ensemble of ADTree classifiers improves retention of good quality pixels at frontal boundaries

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



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Accuracy of Level-3 SST products

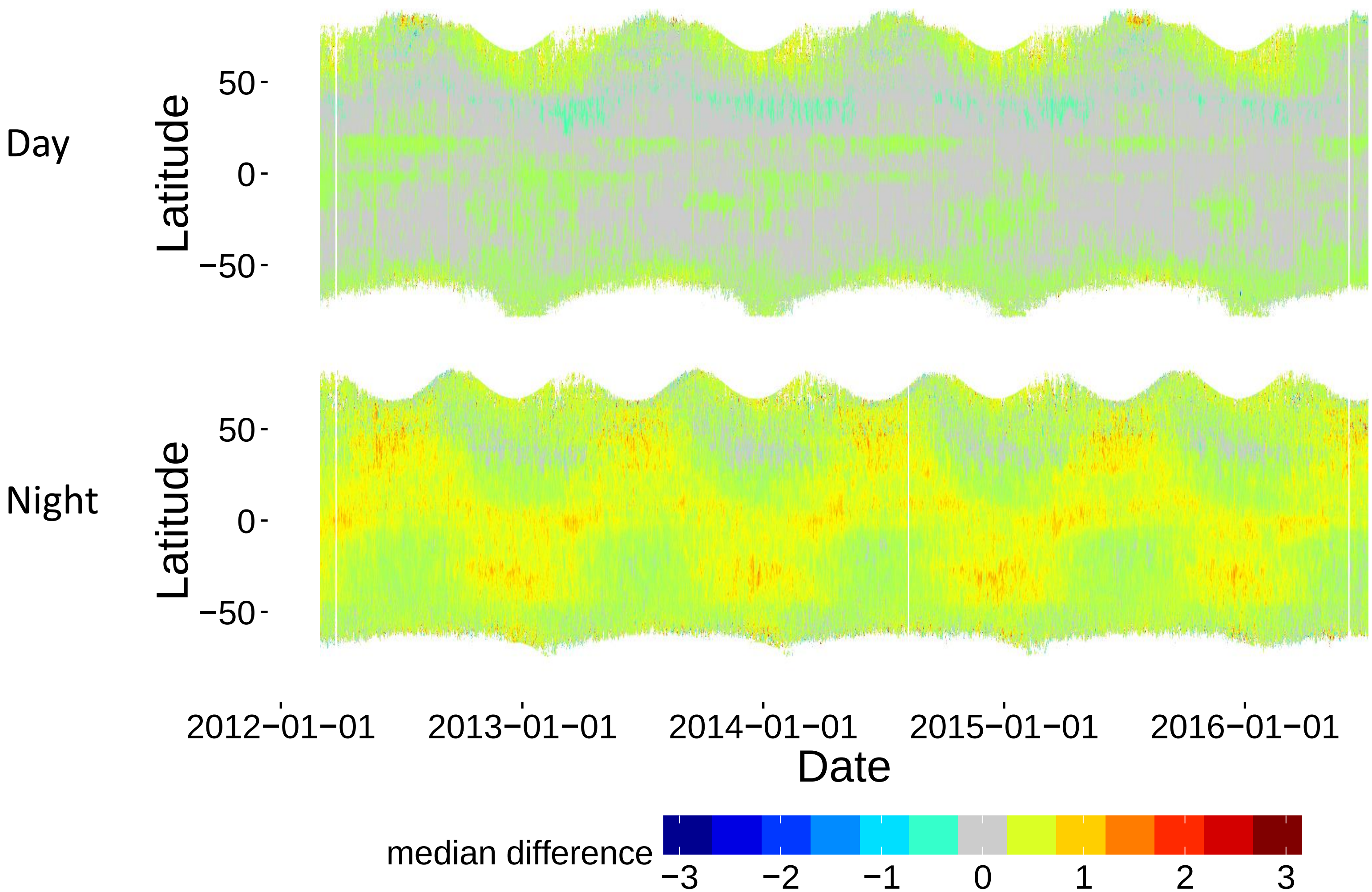
- Connecting Level-2 clouds/quality mask to both sampling and mis-classification errors in level-3 binned products.
- The accuracy of SST (<0.5K, 1σ) is usually assessed at Level 2, based on point-to-point match-up.
- But this is **NOT always the accuracy or consistency of global SST products** (Level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

Liu, Y., & Minnett, P.J. (2016). Sampling errors in satellite-derived infrared sea-surface temperatures. Part I: Global and regional MODIS fields. Remote Sensing of Environment, 177, 48-64
Liu, Y., Chin, M., & Minnett, P.J. (2017). "Sampling Errors in Satellite-Derived Infrared Sea-Surface Temperatures. Part II: Sensitivity and Parameterization." Remote Sensing of Environment. In review.

L3 VIIRS R2016.0 - MODISA R2014.0/C6



9km daily zonal median difference

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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

*Ohring, G., et al. (2005). "Satellite Instrument Calibration for Measuring Global Climate Change: Report of a Workshop." Bulletin of the American Meteorological Society **86**(9): 1303-1313.

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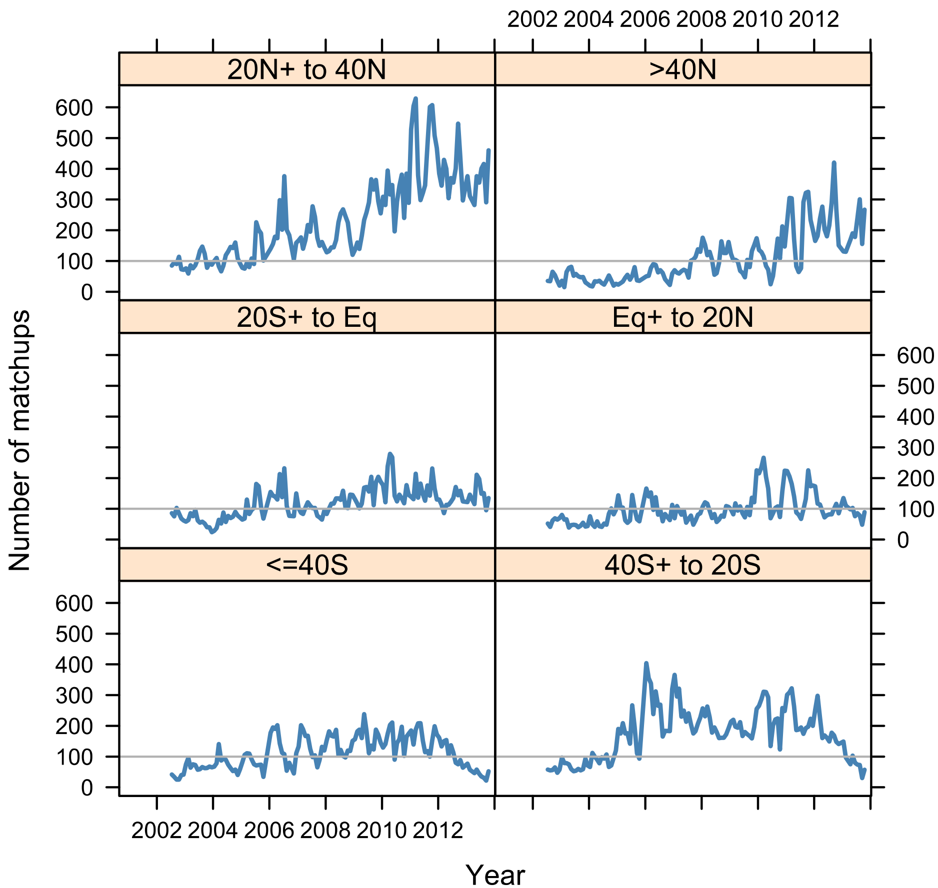
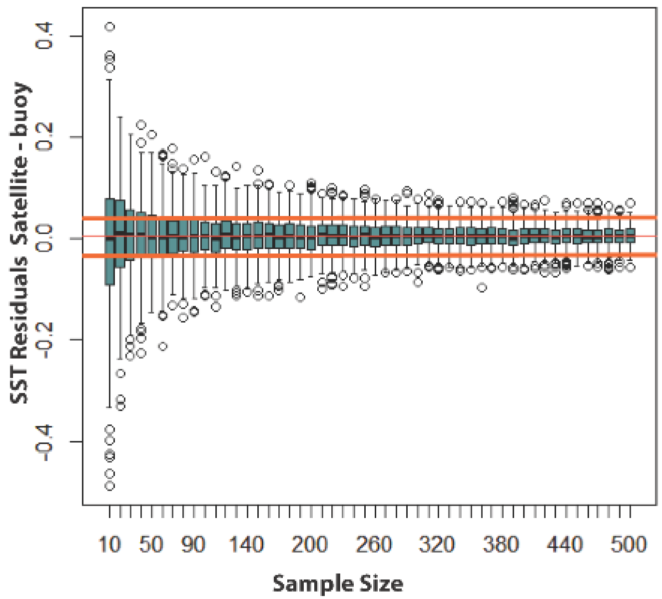
Drifter numbers over *Aqua* mission



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



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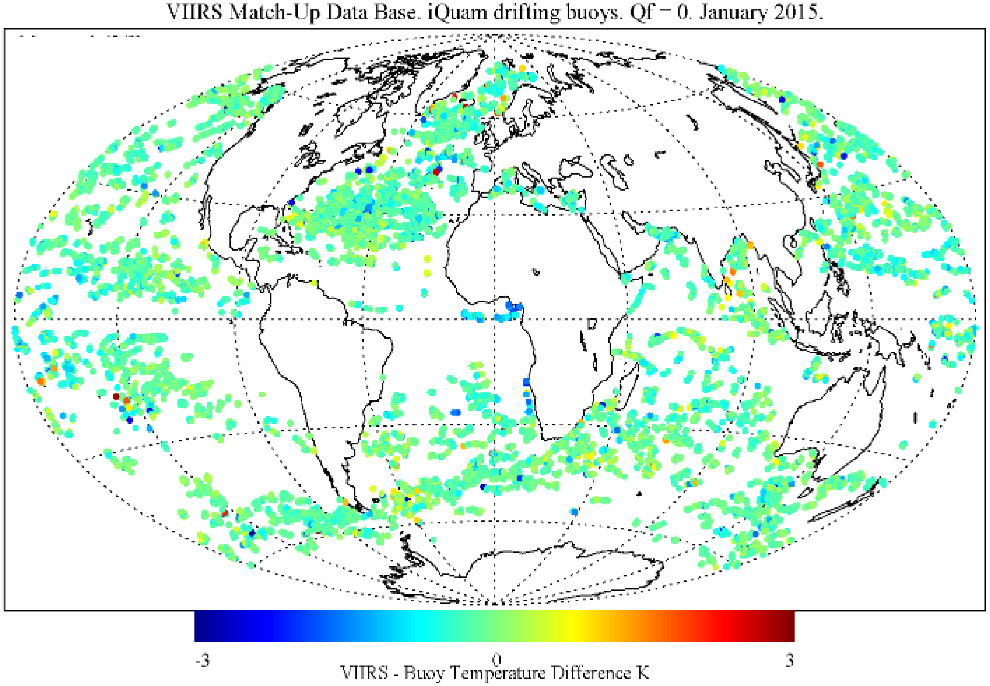
VIIRS 2015 differences wrt buoy temperatures

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

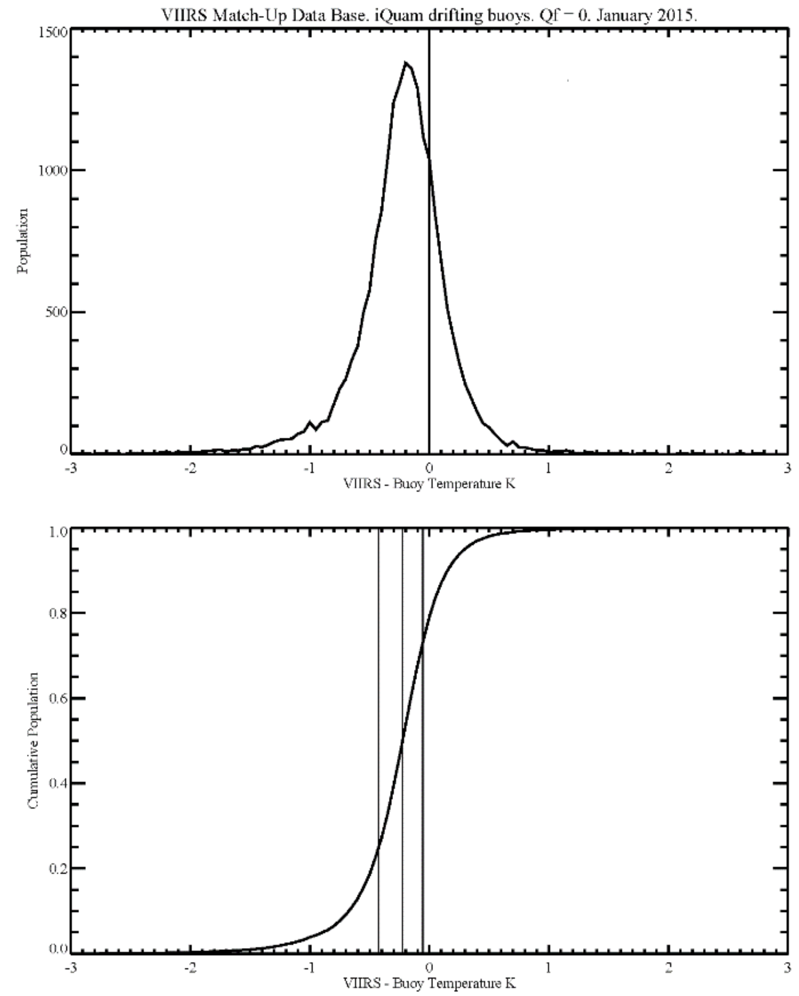
Matchups are required to be within 30 minutes and 10km of satellite observations.

All temperature differences are in K.

VIIRS accuracies wrt drifters



January, 2015



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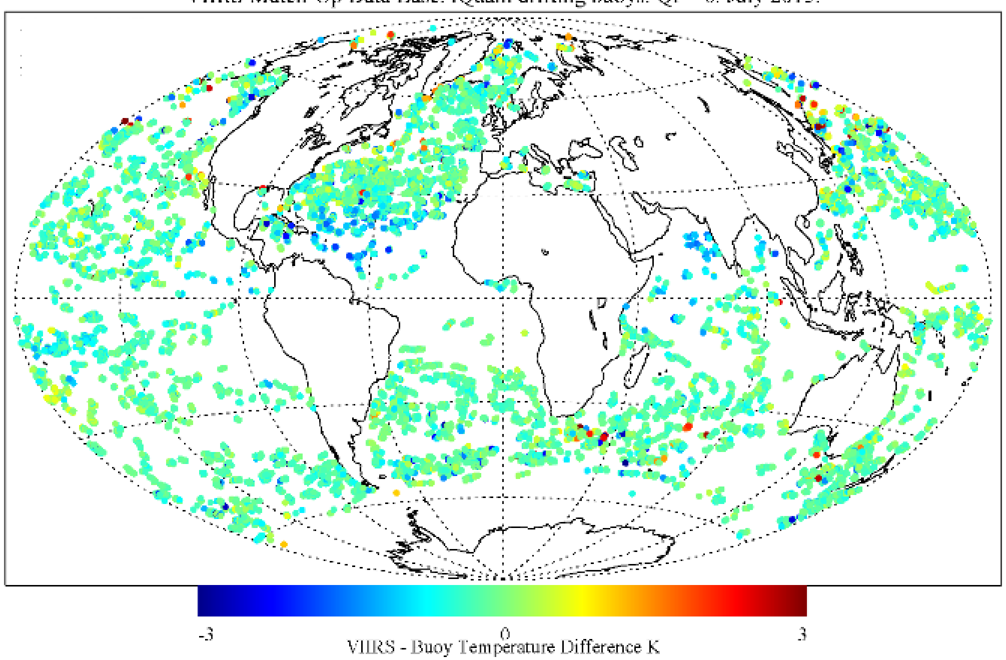
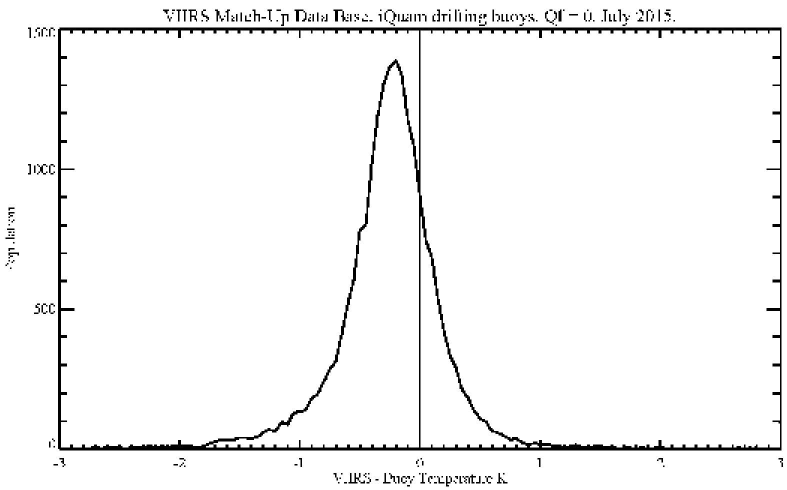
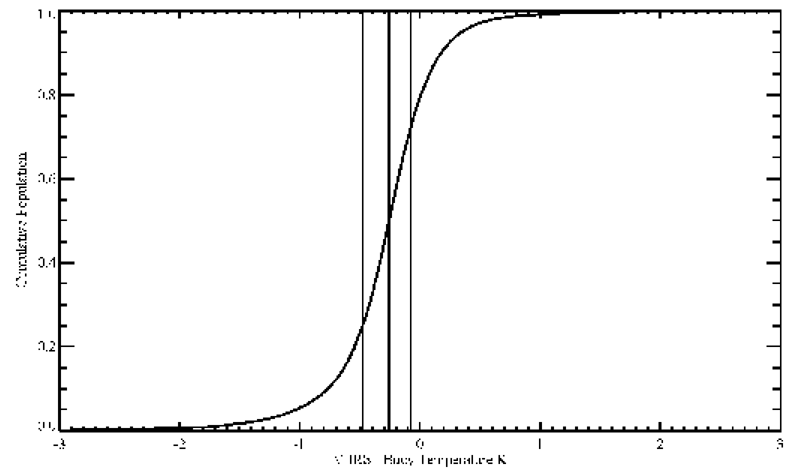
VIIRS accuracies wrt drifters



July, 2015





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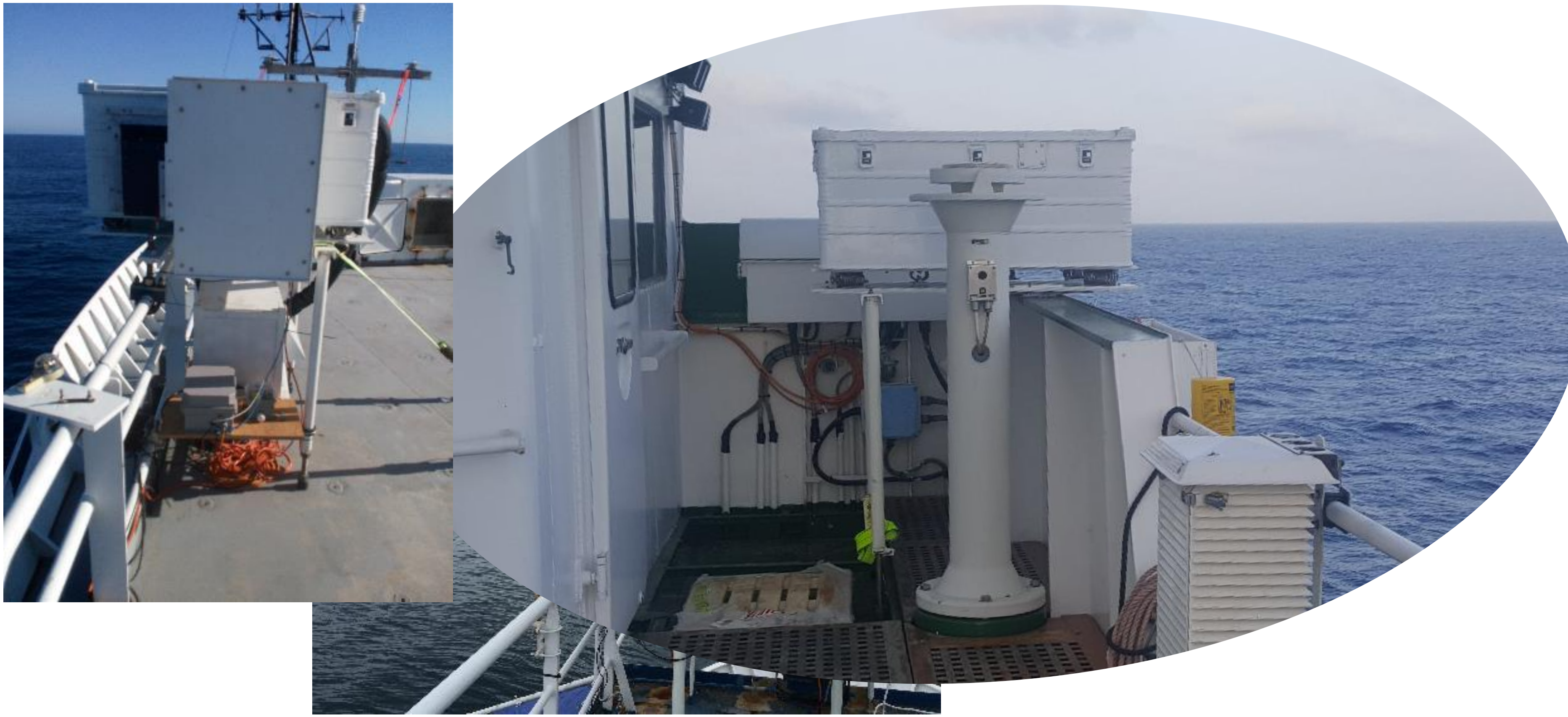
Research ship radiometer deployments



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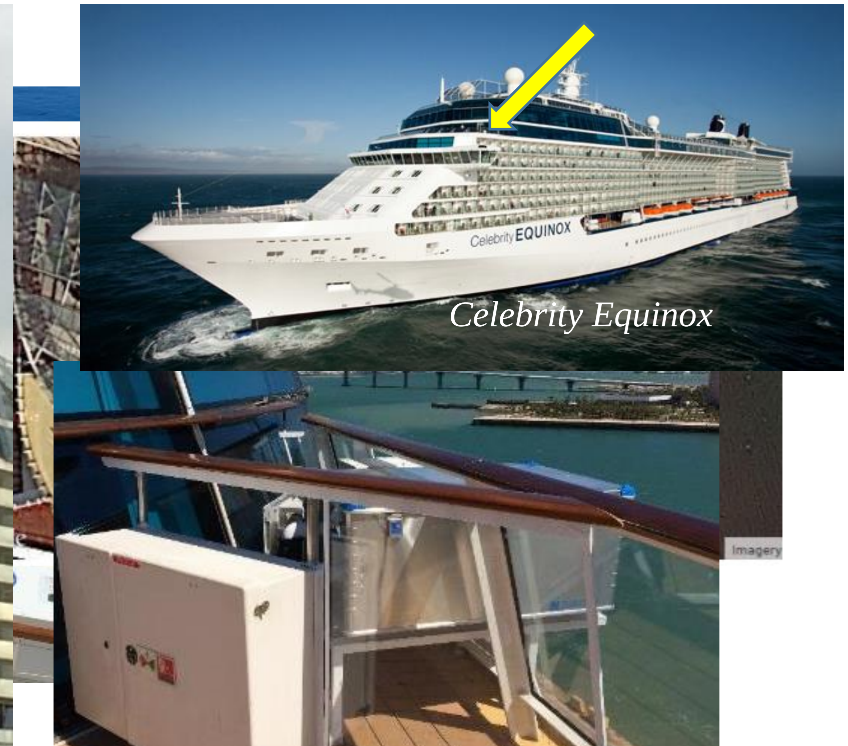
Current cruise ship deployments

Collaboration with Royal Caribbean Cruise Lines



Adventure of the Seas installation in August 2017.

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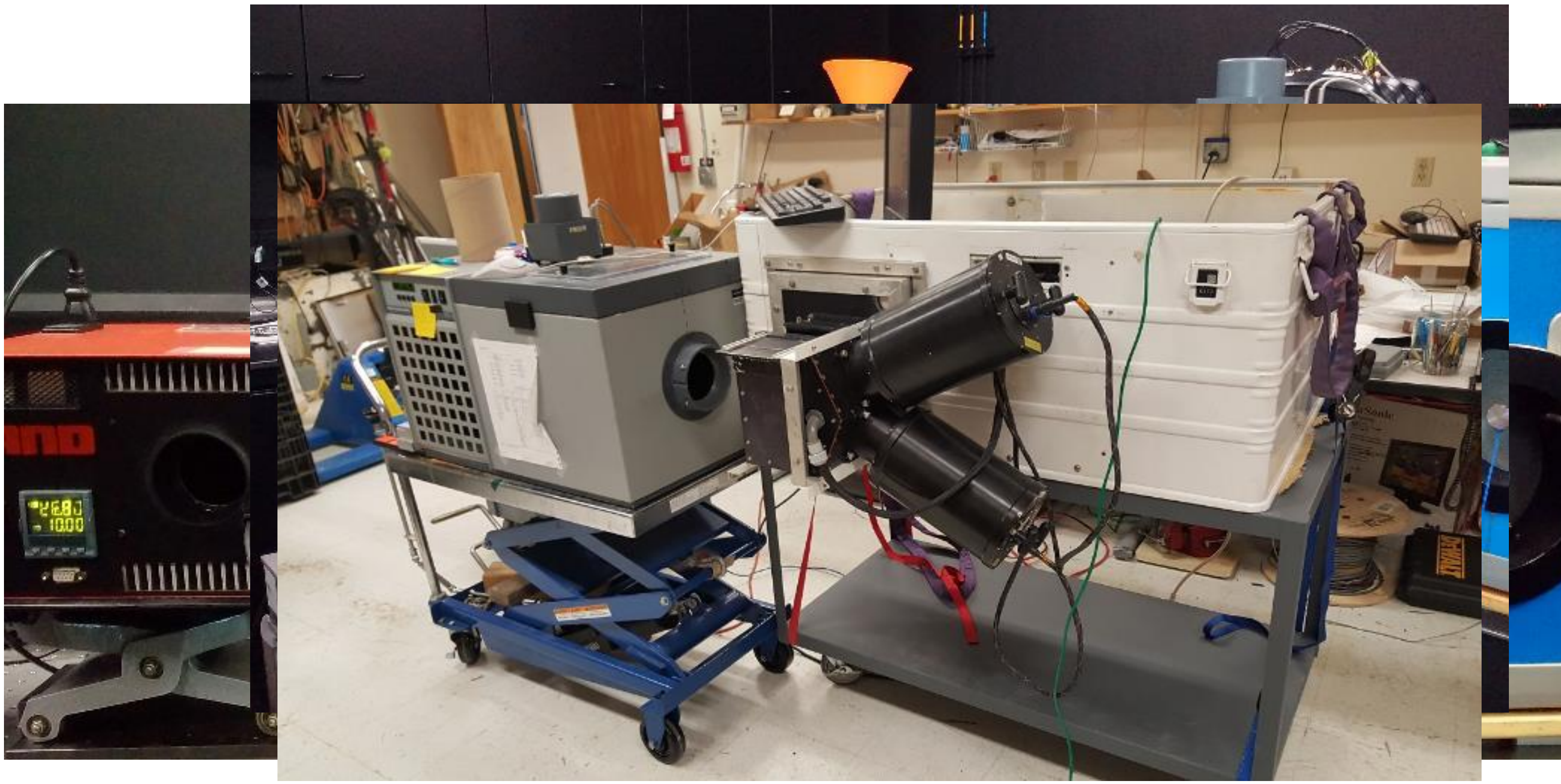
Fiducial Measurements for Surface Temperatures Workshop – NPL, June 2016.



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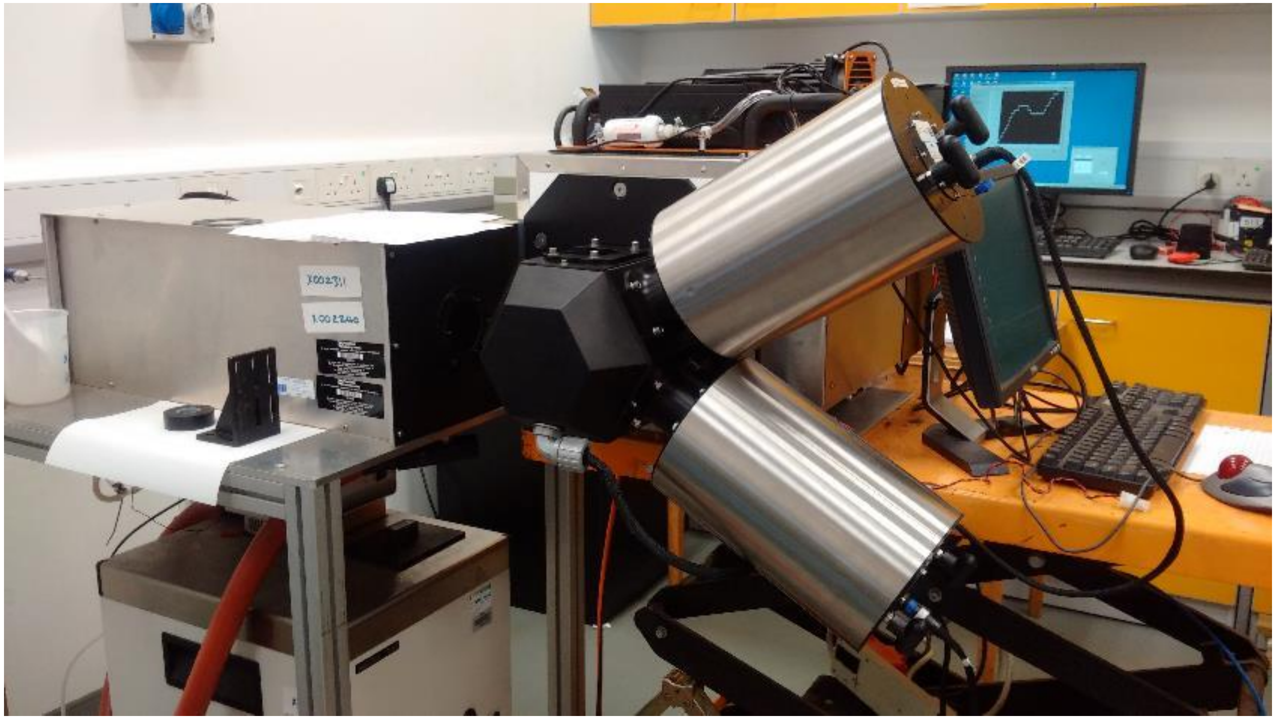

Error budget of M-AERI measurements

At λ= 10.0 µm			
Parameter	Type A Uncertainty in Value [K]	Type B Uncertainty in K	Uncertainty in Brightness temp K
Repeatability of Measurement	0.014		0.014
Reproducibility of Measurement	0.0058 (0.0035)		0.0058 (0.0035)
Linearity of radiometer		0.0003	0.0003
Primary calibration		0.0097	0.0097
Drift since calibration			0
RMS total	0.0152 (0.0144)	0.0102	0.0182 (0.0176)

At λ= 7.7 µm			
Parameter	Type A Uncertainty in Value [K]	Type B Uncertainty in K	Uncertainty in Brightness temp K
Repeatability of Measurement	0.0349		0.0349
Reproducibility of Measurement	0.0178 (0.0089)		0.0178
Linearity of radiometer		0.0003	0.0003
Primary calibration		0.0086	0.0086
Drift since calibration			0
RMS total	0.0392 (0.0360)	0.0091	0.0402 (0.0372)

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MODIS SSTs & ship radiometers

MODIS Skin SST vs M-AERI and ISAR Skin SST. Temperatures in K					
Satellite and Algorithm	Mean	Median	Standard Deviation	Robust St. Deviation	Number
Terra SST Day	0.082	0.080	0.567	0.409	1025
Terra SST Night	0.048	0.034	0.467	0.337	2454
Terra SST4 Night	0.016	0.023	0.339	0.244	2467
Aqua SST Day	0.105	0.107	0.666	0.480	910
Aqua SST Night	0.020	0.027	0.489	0.353	1752
Aqua SST4 Night	-0.010	0.016	0.396	0.285	1858

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_{depth} to SST_{skin} correction.
- Aerosol effects.
- Sampling errors in validating data, both buoys and radiometers.

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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.