

Validation of AMSR2 Sea Surface Temperature

Gentemann and Hilburn, In situ validation of GCOM-W1 AMSR2 sea surface temperatures, JGR-Oceans, submitted.

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Importance of SST

- Daily global gridded SST is needed for numerical weather prediction
 - Surface heat fluxes from warm Agulhas Current enhance low-level cyclogenesis [*Singleton and Reason, 2003*]
 - Study of Hurricane Sandy found SST anomalies produce lower pressure, greater wind speed, and more precipitation [*Magnusson et al., 2014*]
 - Extra-tropical transition of Typhoon Tokage, both its intensity and track, is sensitive to SST [*Bond et al., 2010*]
 - Teleconnections between tropical Pacific SST anomalies and post-1998 decline in Greater Horn of Africa long rains [*Lyon, 2014; Yang et al., 2014; Moron et al., 2013*]
- Daily global gridded SST is needed for ecological models and fisheries
 - SST anomalies of 2.8 K at Sesoko Island in 1998 produced extensive coral bleaching to the point of localized extinction [*Loya et al., 2001*]
 - Even short periods of high temperatures are highly stressful to Great Barrier Reef corals [*Berkelmans et al., 2004*]
 - Heat content anomalies in Seychelles-Chagos thermocline ridge in early 2007 made tuna less susceptible to fishing techniques, and limited to just western Indian Ocean [*Vialard et al., 2009*]
- SST anomalies vary on time scales from sub-daily to multi-decadal

Satellite Measurements of SST

Vastness of Earth's oceans makes satellite SST only practical way to produce daily global gridded SST analyses, but each measurement has strengths and weaknesses:

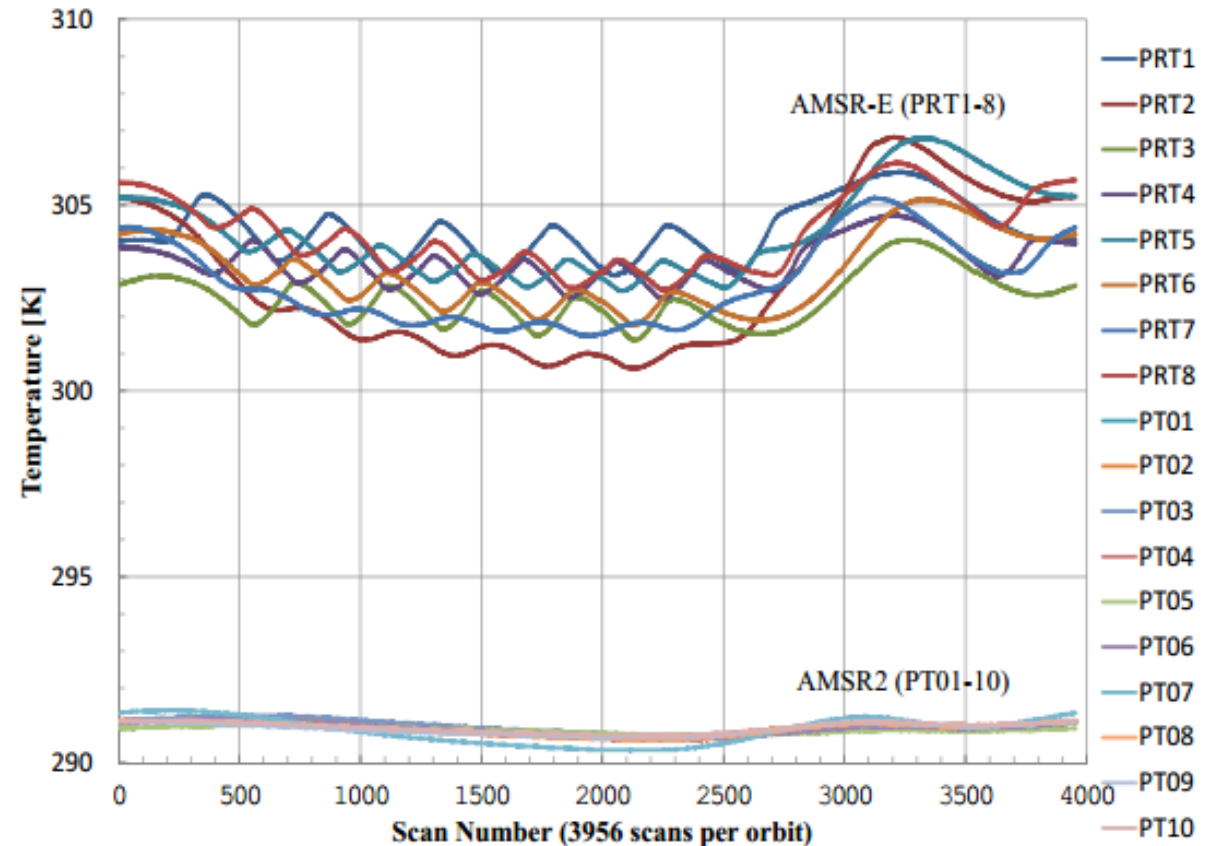
	Infrared SSTs	Microwave SSTs
Data starts	1981 (global)	1998 (tropical), 2002 (global)
Spatial resolution	1-4 km	25 km
Missing data	Clouds	Rain, near land, RFI, near ice, sunglint
Errors	Sensitivity to aerosol [<i>Nalli and Stowe, 2002; Diaz et al., 2001</i>] Atmospheric water vapor attenuation [<i>Emery et al., 1994</i>]	Measurements in cold water requires 6 GHz [<i>Gentemann et al., 2010</i>] Accuracy diminishes at high winds, cold SSTs [<i>Meissner and Wentz, 2013</i>]
Accuracy	AVHRR: 0.53 K [<i>Marsouin et al., 2013</i>] MODIS: 0.58 K [<i>Gentemann, 2014</i>]	TMI: 0.57 K standard deviation [<i>Gentemann et al., 2004</i>] AMSR-E: 0.48 K standard deviation [<i>Gentemann et al., 2014</i>]

Satellite Data

- AMSR2 has several key improvements on AMSRE
 - Hot load has improved thermal stability
 - New 7.3 GHz channel
 - Largest rotating reflector in orbit (2.0 m) gives better spatial resolution (35x62 km) compared with AMSRE (43x75 km)
- But is not without challenges
 - Nonlinearities of several degrees in all channels; only in 6 GHz for AMSRE
 - Intercalibration to AMSRE requires use of slow rotation (2 rpm) AMSRE data
- This study uses data from RSS calibration of AMSR2

AMSR2 Thermal Stability

- Thermistors on AMSR-E highly variable. They don't track each other very well and there is high inter-orbit variability.
- Thermistors on AMSR2 track each other well and have low variability

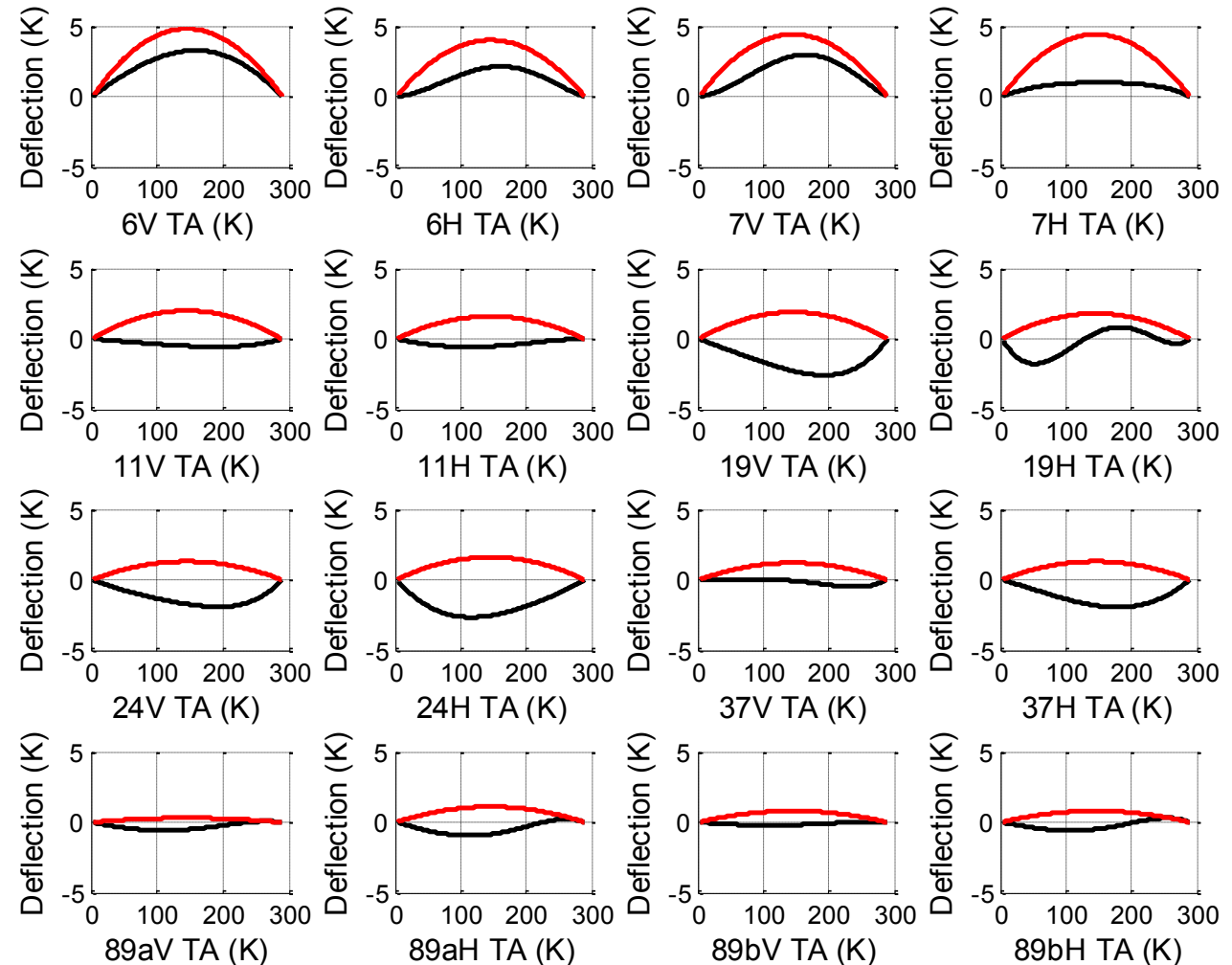


AMSR2 Nonlinearity

Red Curves are JAXA Non-Linear Correction (Marehito Kasahara 21 Feb 2013 X-Cal presentation)

Black Curves are values coming from RSS analysis.

- We have not seen these strong nonlinearities in all channels before. Not present in AMSR-E
- JAXA developed pre-launch
- RSS developed post-launch using RTM model
- 0-5K nonlinearities. JAXA and RSS estimates do NOT match



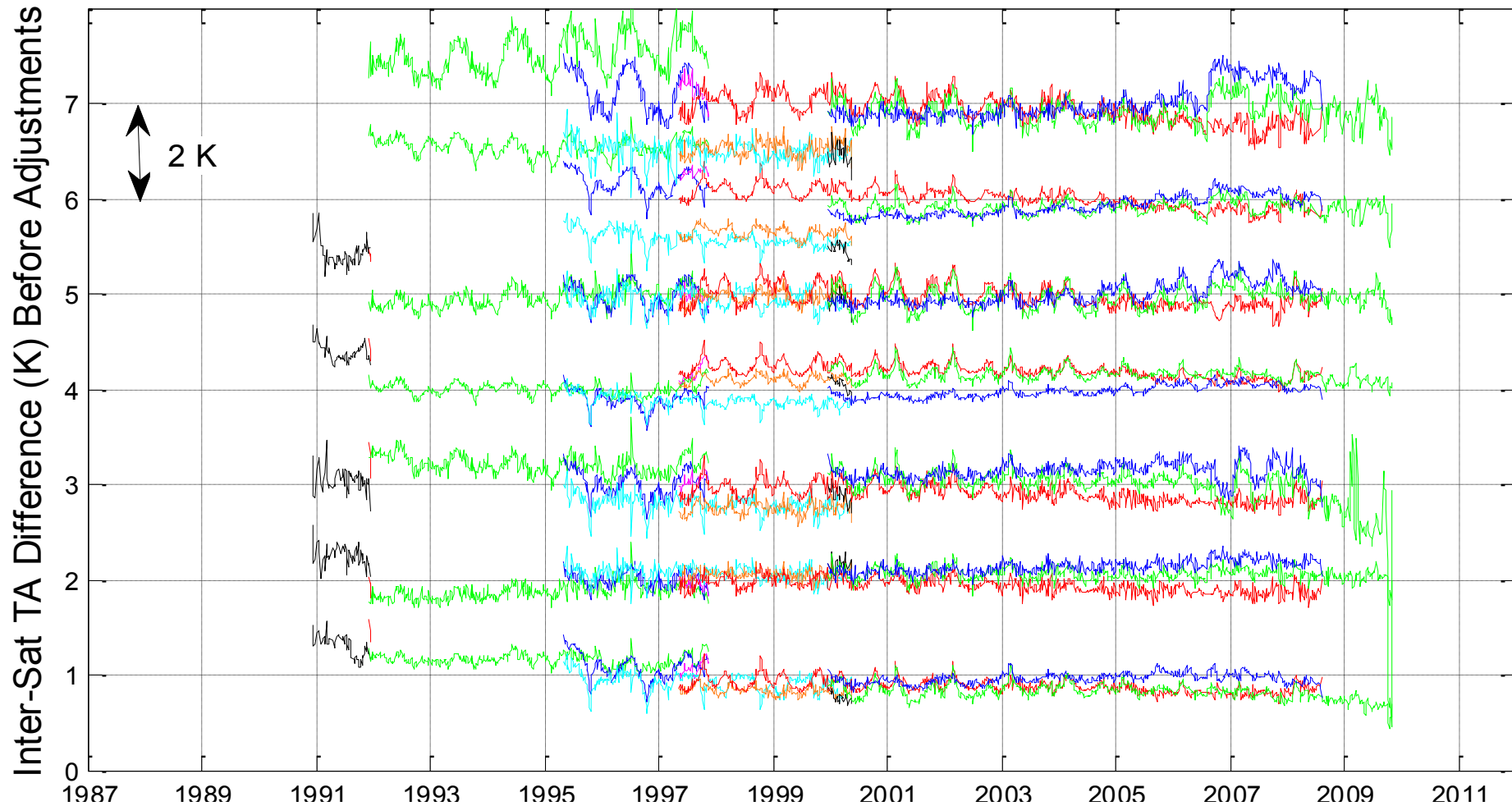
Intercalibration Methodology

- Calibration to an accurate ocean radiative transfer model (RTM) in rain-free conditions [*Meissner and Wentz, 2012*]
- Requires knowledge of: wind speed, water vapor, and cloud water
 - Obtained from other intercalibrated satellites, namely SSM/I and WindSat
 - SST from Reynolds OI and wind direction from NCEP
- The spillover, cross-polarization, hot load offset, and non-linearity are adjusted to obtain best intercalibration [*Wentz, 2013*]
- Reliability at higher temperatures verified using Amazon comparisons

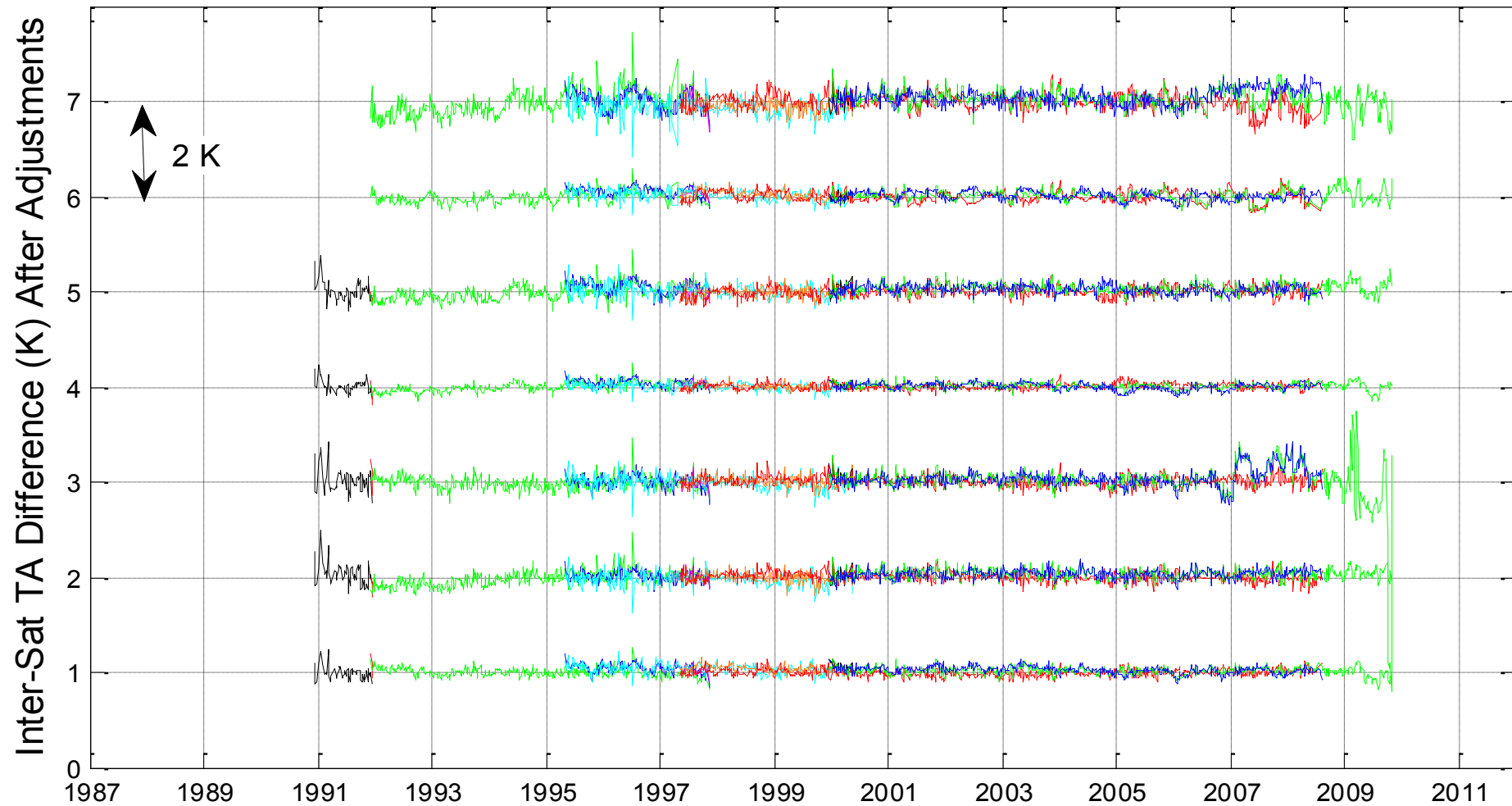
Advantages of the RTM Intercalibration Methodology

- The RTM in a relative sense over the full range of environmental conditions (excluding rain) is predicting TB to an accuracy near 0.2 K and certainly better than 0.5 K.
- Considering that the prelaunch error in the absolute calibration of the SSM/I due to knowledge error in the antenna spillover and effective target temperatures can easily be 2 K, the ocean RTM is the better calibration reference
- Can easily
 - Handle orbit gaps (overlap no longer required)
 - Adjust for different channel sets and viewing angles (i.e. SSM/I and WindSat)
 - Provides a precise definition of absolute calibration that can be applied to all sensors
 - Closure analysis (W,V, L into RTM to get $TB_{\text{predicted}}$, compare this to the TB_{measured})
- Results suggest calibration is applicable over ocean, land, and ice. Separate calibration for land and ice is not necessary.

Before calibration



After calibration

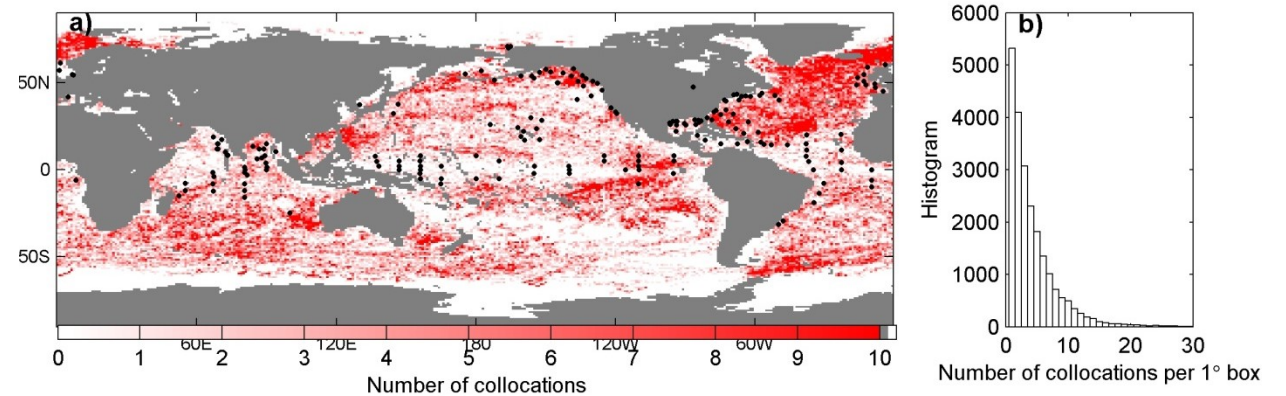


Geophysical Retrieval Methodology

- SST retrieval algorithm based on RTM
 - *Meissner and Wentz, 2012; Chelton and Wentz, 2005; Wentz and Meissner, 2000*
 - Radiosondes to specify atmospheric temperature and humidity
 - Train by randomly prescribing sea surface temperature, wind speed and direction, and cloud amount and height
- Placed on 0.25-deg cylindrical Earth grid, separating day and night passes; data are quality controlled for contamination by rain, sea ice, sun glint, and radio frequency interference (RFI)
- This presentation specifically uses AMSR2, RSS Version 7.2, which includes:
 - Small water vapor correction [*Gentemann, 2014*]
 - New RFI detection (discussed in this presentation)
 - Seasonal correction for 10V channel
 - Several explanations for this: noise, RFI, non-linearity from out-of-bounds thermistors

In Situ Data

- Moored buoys, drifting buoys, and ship measurements from US Global Ocean Data Assimilation Experiment (USGODAE) server
- Map shows the two-year data coverage
- Histogram shows that most 1 deg boxes have zero observations (white areas on map)
- Uses observations with probability of gross error less than 0.6 K [Cummins, 2011; Castro, 2012]
- CMAN have largest STD by far, 1.28 K
- Other ship measurements next highest from 0.72 – 0.87 K
- CMAN and engine room intake have largest biases, 0.17 K
- Consistent with previous assessments of ship SST measurements [Kaplan et al., 1998; Rayner et al., 2006]
- Buoys (both moored and drifting) have lowest STD, 0.55 K
- Gentemann [2014] used AMSRE, MODIS, buoy triple collocation to separate satellite error (0.28 K) from buoy error (0.20 K)
- Errors in ship SST too large; not using



In situ comparison type	Bias	STD	Number
ship engine room intake	0.17	0.86	2513
moored buoy	-0.01	0.57	7817
drifting buoy	-0.05	0.55	101533
ship bucket	0.08	0.78	202
ship hull	0.08	0.70	2284
cman	0.17	1.28	24

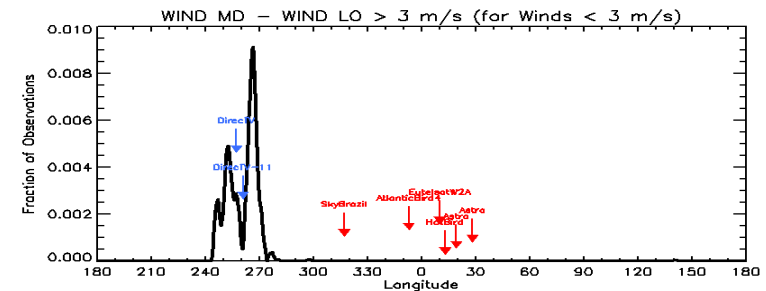
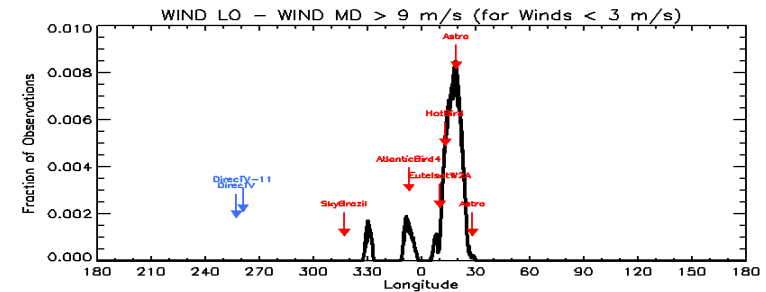
Table: Mean bias (AMSRE2 – in situ), standard deviation (STD), and number of collocations for July 25, 2012 – October 9, 2014.

Validation Methodology Challenges

- Space and time sampling
 - Satellite: average over footprint
 - In situ: point measurement
 - Solution: statistics over appropriate space/time averages
- Measurement depth
 - Satellite (microwave): few mm
 - In situ: 0.2-1.5 m, depending on instrumentation
 - Solution: Remove data with conditions favorable to diurnal warming
- RFI contamination
 - Satellite: Difficult problem, ongoing problem
 - In situ: not a problem
 - Solution: RFI detection technique based on retrieval differences

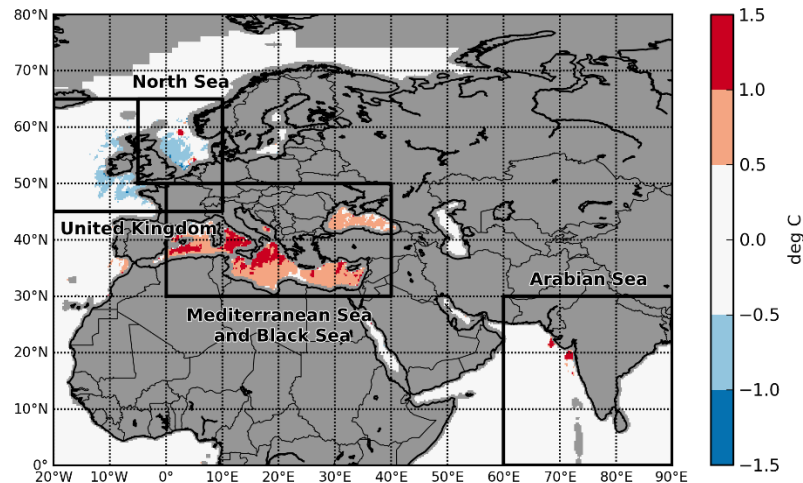
RFI Sources

- ITU regulations prohibit operation of transmitters above a specified power level within protected bands
- AMSR2 channels centered in bands, but
 - The complete bandwidth not protected
 - There is out-of-band emission
- Four main sources for AMSR2
 - GEO space-based, ocean-reflected (satellite TV)
 - LEO space-based, ocean-reflected (satellite phones)
 - GEO space-based into the cold mirror
 - Surface-based, direct (oil and gas rigs, cities, military/naval activity)
- GEO space-based RFI occurs in the Southern Hemisphere for ascending passes and Northern Hemisphere for descending passes where the reflection vector is towards the Equator
- GEO space-based ocean-reflected RFI can be identified by tracking the boresight reflection vector back up to geostationary altitude where it originates
 - Must cross at latitude near Equator
 - Histogram of longitudes form peaks
 - Higher winds spread the signal over a larger area on Earth

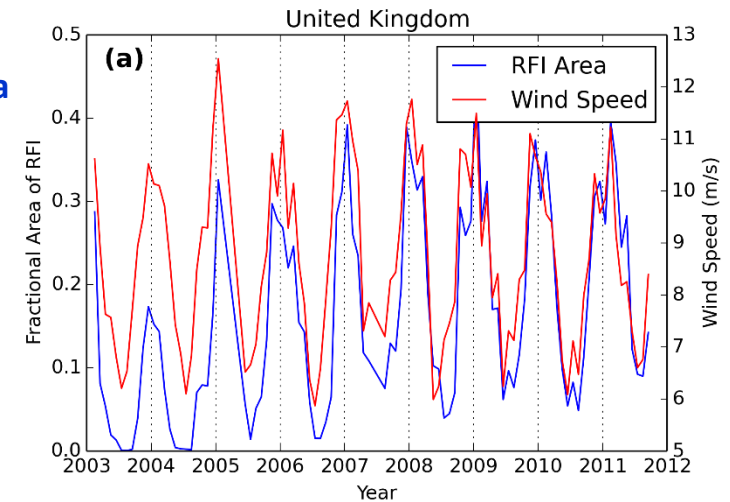


RFI Variability

- RFI is highly variable in space and time
 - For both human and environmental reasons
- Analysis of AMSR-E [Hilburn et al., 2014] also found seasonal variability resulting from environmental conditions
- RFI adds to brightness temperature signal, but this can produce either positive or negative SST anomalies depending on the frequency and polarization of the channel
 - Positive SST impact from 6H, 10V, 18H
 - Negative SST impact from 6V, 10H, 18V
- Wind spreading of RFI signal around United Kingdom
- Cloud attenuation of RFI over Mediterranean Sea

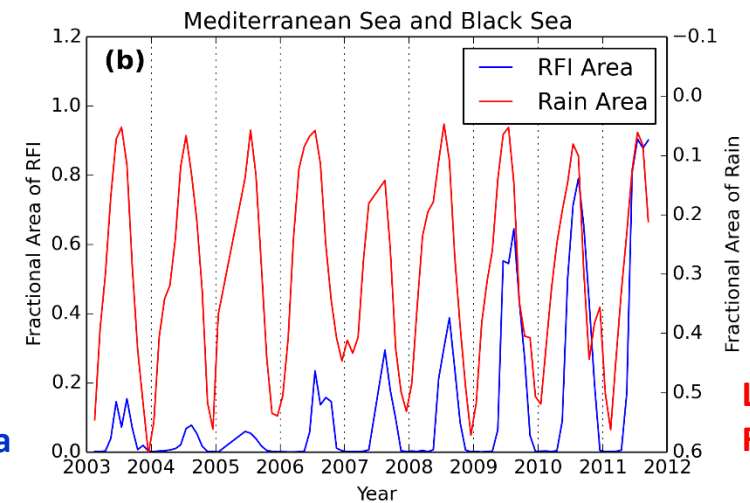


Larger
RFI Area



Higher
Wind Speed

Smaller
RFI Area



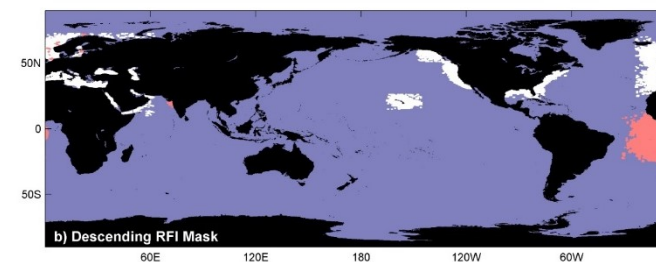
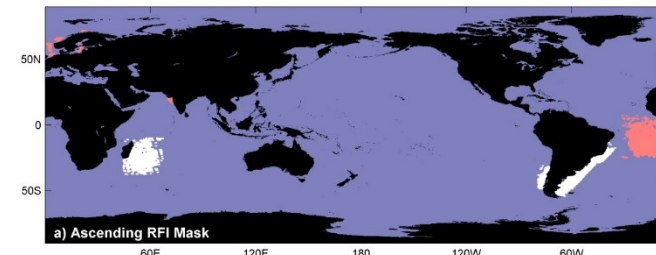
Larger
Rain Area

RFI Detection and Removal Methodology

- Simplest: mean and standard deviation of brightness temperatures [*Njoku et al., 2005*]
 - Works well on strong RFI, unable to distinguish weak RFI from natural geophysical variability
- Adding additional information about channel correlations and probability-distribution functions [*Li et al., 2006; Truesdale, 2013*] extends this approach, but detecting weak RFI is still difficult
- Better yet: to separate RFI from natural signals, use RTM to specify expected brightness temperature [*Adams et al., 2010; Adams et al., 2014; Hilburn et al., 2014*]
 - Adams used chi-square goodness-of-fit
- Our approach: differences of SST and wind retrievals made using different channel combinations
 - Retrieval uses RTM, so this information is implicit in technique
 - Disadvantage: retrieval mixes channels, so technique does not directly tell what frequency is the culprit
 - Advantage: spatial patterns in SST and wind have physical meaning, making RFI easier to identify, and making cross-talk with high wind or rain evident

RFI Methodology Details

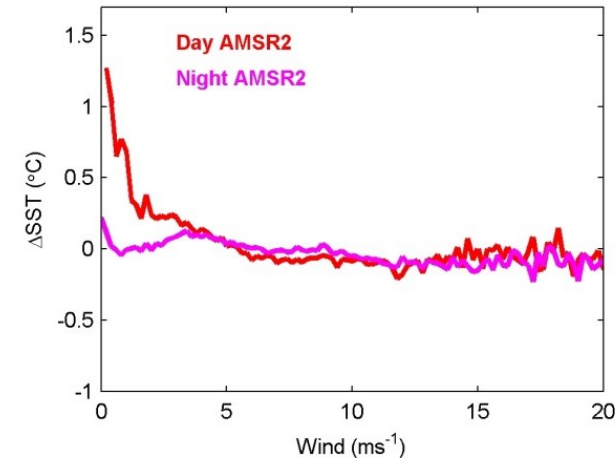
- Figure shows the RFI mask
 - White regions are space-based
 - Red regions are surface-based
 - This is maximum extent; RFI covers a much smaller area on any given day
- Each RFI type is given an ID number and added to table
- Provides information on type, occurrence in day/night passes, start/end dates, latitude/longitude bounds
- Then use the indicated difference check against the provided min/max values
- Difference checks:
 - 1 = (SST 6) – (SST 10)
 - 2 = (SST 6) – (SST Rey)
 - 6 = (Wind 6) – (Wind 10)
 - 9 = (Wind 10) – (Wind 18)



ID	type	Asc/Dsc	Start		End		Longitude		Latitude		Diff Check	Value	
			Year	Day	Year	Day	Min	Max	Min	Max		Min	Max
1	S	D	2012	1	2025	0	235	279	-22	19	9	-99	-0.8
2	S	D	2012	1	2025	0	316	346	-16	10	9	1	99
3	S	D	2012	1	2025	0	340	360	-15	20.00	9	1	99
4	S	D	2012	1	2025	0	0	5	-14	9.00	9	1	99
5	S	D	2012	1	2025	0	0	50	-30	20.00	9	0.8	99
6	S	D	2012	1	2025	0	350	360	-10	14.00	9	1	99
7	S	D	2012	1	2025	0	0	10	-10	14.00	9	1	99
8	S	D	2012	1	2025	0	340	360	-15	4.00	1	-99	-0.9
9	S	D	2012	1	2025	0	0	5	-15	4.00	1	-99	-0.9
10	S	A	2012	1	2025	0	4	25	-10	13.00	9	0.6	99
11	S	A	2012	1	2025	0	289	305	-8	12.00	9	0.8	99
12	S	A	2012	1	2025	0	311	327	-4	8.00	9	0.8	99
13	S	A	2012	1	2025	0	295	315	-7	10.00	9	0.8	99
14	S	A	2012	1	2025	0	4	25	-10	13.00	1	1	99
15	G	D	2012	1	2025	0	331	360	-25	-15.00	1	1.3	99
16	G	D	2012	1	2025	0	0	2	-25	-15	1	1.3	99
17	G	D	2012	1	2025	0	331	360	-20	15	1	-99	-1.3
18	G	D	2012	1	2025	0	0	2	-20	15	1	-99	-1.3
19	G	D	2012	1	2025	0	1	4	58	62	2	4	99
20	G	D	2012	1	2025	0	5	9	63	67	2	4	99
21	G	D	2012	1	2025	0	3	5	52	55	2	4	99
22	G	D	2012	1	2025	0	11	13	34.5	37	2	4	99
23	G	A	2012	1	2025	0	70	73	17.5	21	6	4	99
24	G	A	2012	1	2025	0	330	359	-25	4	2	-99	-1.5
25	G	A	2012	1	2025	0	330	359	-25	4	1	1.5	99
19	G	A	2012	1	2025	0	1	4	58	62	2	4	99
20	G	A	2012	1	2025	0	5	9	63	67	2	4	99
21	G	A	2012	1	2025	0	3	5	52	55	2	4	99
26	G	A	2012	1	2025	0	2	4	56	58	2	4	99
23	G	A	2012	1	2025	0	70	73	17.5	21	6	4	99
22	G	D	2012	1	2025	0	11	13	34.5	37	2	4	99

Diurnal Warming

- *Price et al. [1986]* examined R/F Flip, found 0.05 to 0.4 K warming, with most day-to-day variability due to wind stress
- *Soloviev and Lukas [1997]* found warming of more than 3 K in top 1 m in western Pacific warm pool
- *Gentemann et al. [2003]* examined TMI and AVHRR, found magnitude of 2.8 K during favorable conditions
- *Ward [2006]* examined SkinDeEP on R/V Melville in Gulf of California, found warming as high as 4.6 K
- *Gentemann et al. [2008]* found events 5-7 K over regions of 1000 km in extra-tropics
- *Matthews et al. [2014]* examined CINDY/DYNAMO and found 0.8 K warming in afternoon in Indian Ocean
- Thus, diurnal warming signal is large compared with microwave SST bias/STD, and is also highly variable in time [*Gentemann and Minnett, 2008*]



- Figure shows SST bias as a function of wind speed for day and night
- Figure gives estimate of the difference between diurnal warming at a few mm depth vs 0.2-1.5 m depth
- Best to avoid, rather than trying to model it
- Exclude all collocations between 10 AM and 4 PM local time with winds < 6 m/s

Overall Results

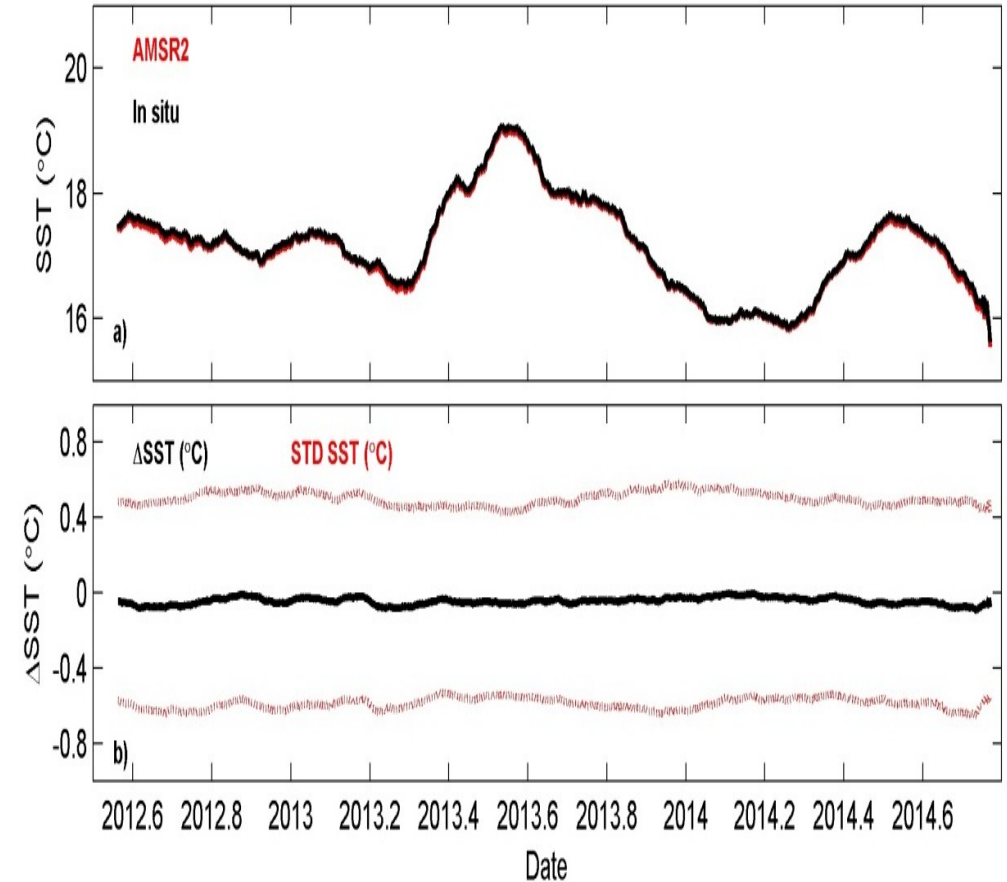
- Overall, AMSR2 SST are slightly cooler (-0.04 K) than the buoys
- SST retrievals provide a particularly stringent requirement on brightness temperature, 0.25 K errors in 6 GHz v-pol would produce a 0.50 K error in SST [Meissner and Wentz, 2012]
- Thus, AMSR2 absolute calibration is accurate to 0.02 K, which is sufficiently small to use AMSR2 in climate studies
- The small day/night difference (0.06 K) implies that AMSR2 relative calibration is accurate to within 0.03 K
- Relative calibration errors (e.g., errors vs scan/orbit position) would increase STD, but day and night both have STD of 0.55 K, which are slightly better than TRMM [Gentemann et al., 2004]

	Bias	STD	Num
All	-0.04	0.55	109350
Day	-0.09	0.55	40997
Night	-0.02	0.54	68353

Table: Mean bias (AMSR2 – in situ), standard deviation, and number of collocations for July 25, 2012 – October 9, 2014.

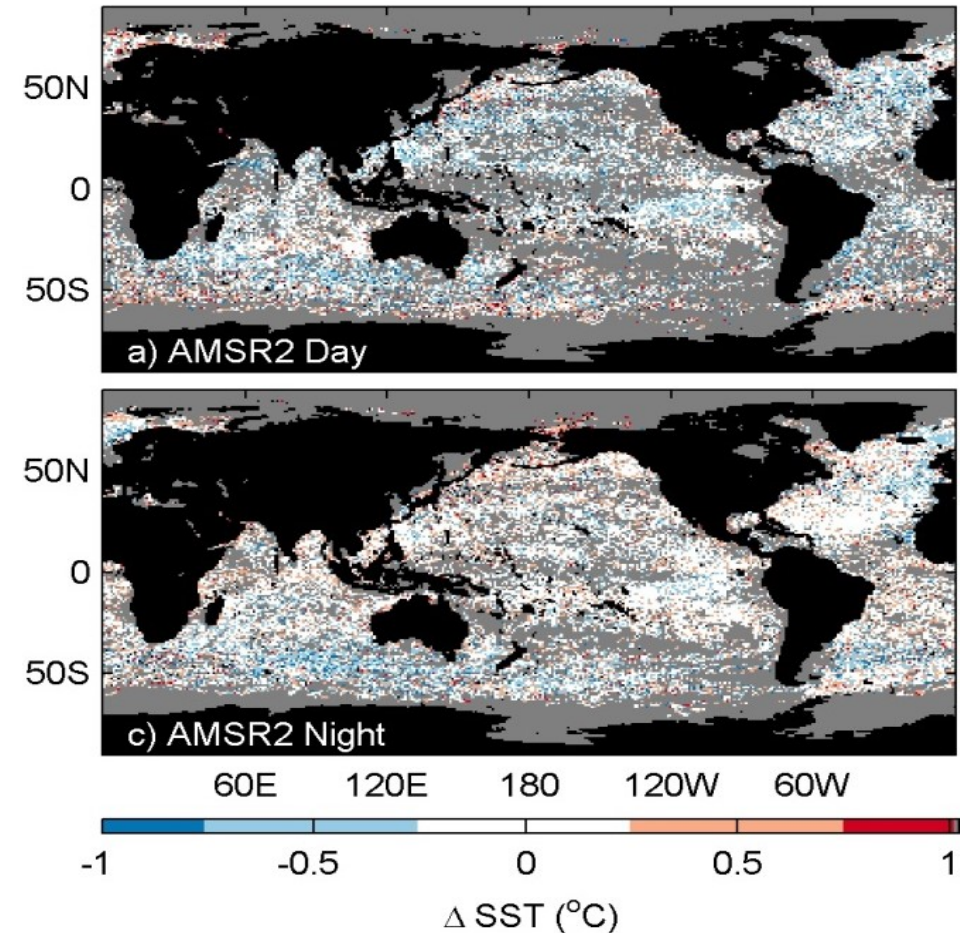
Time Variability

- When relative calibration errors are present, they often manifest themselves as a spurious piece-wise linear trend or as a spurious annual cycle, but our results show no evidence of this
- Top panel shows that AMSR2 and buoy SST agree so well they overlap
- Bottom panel shows bias and STD
- Time variation in bias is on the order of the bias itself, 0.04 K
- This implies AMSR2 calibration is stable in time on the order of 0.02 K
 - Demonstrates that nonlinearities are stable and calibration developed during initial period has not changed
- STD does exhibit some time variability
- With two complete annual cycles, see that STD is smaller in boreal summer and larger in boreal winter
- Is this evidence of minor calibration error or SST retrieval errors?



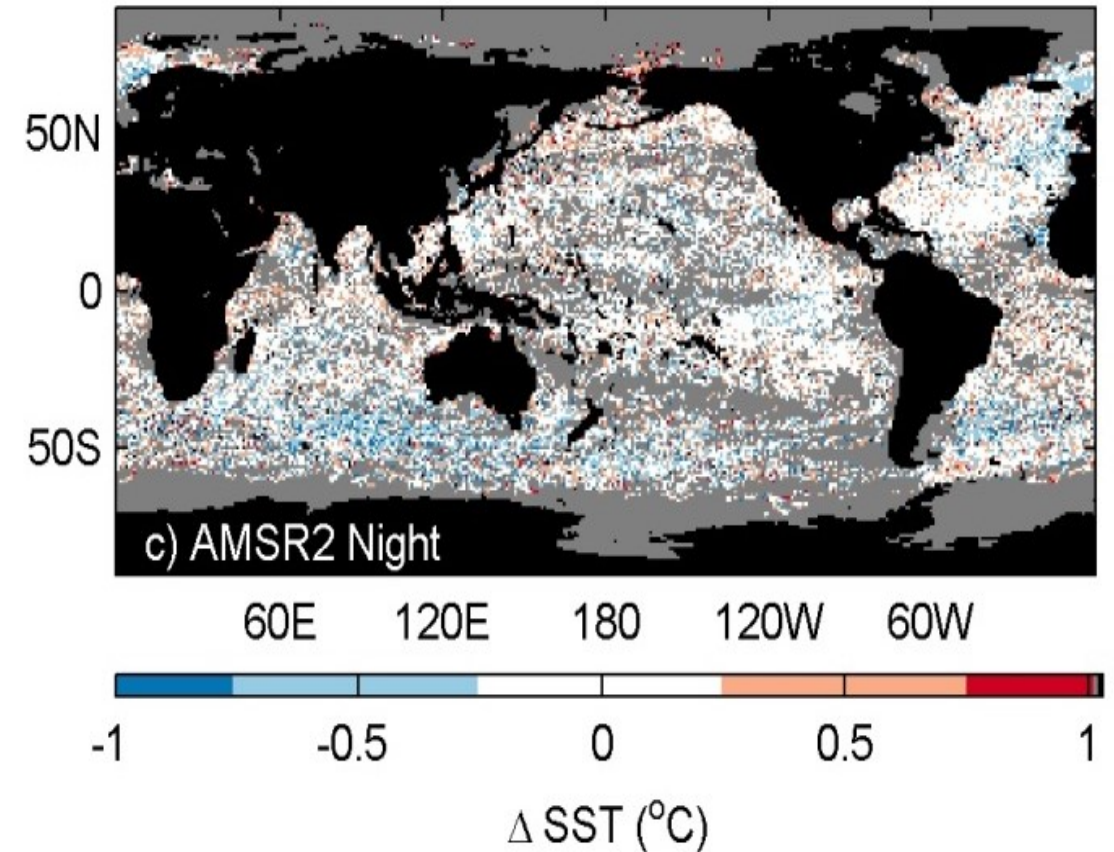
Spatial Variability: Day vs Night

- Daytime differences are slightly cooler, as already seen
- In most locations, the daytime map resembles the nighttime map, with slight shift cooler
 - Would imply that difference is a minor relative calibration error
 - Not true in Labrador Sea and Davis Strait, where nighttime biases are warm and large (0.5 K)... problem with satellite or drifters?
 - Also not true in far southern extent of Southern Ocean, daytime biases are warmer and strikingly zonally symmetric
 - Zonally symmetry could imply calibration error depending on orbit position
 - Warmer daytime consistent with diurnal warming, but not consistent with high winds in region that mix-out stratification effects



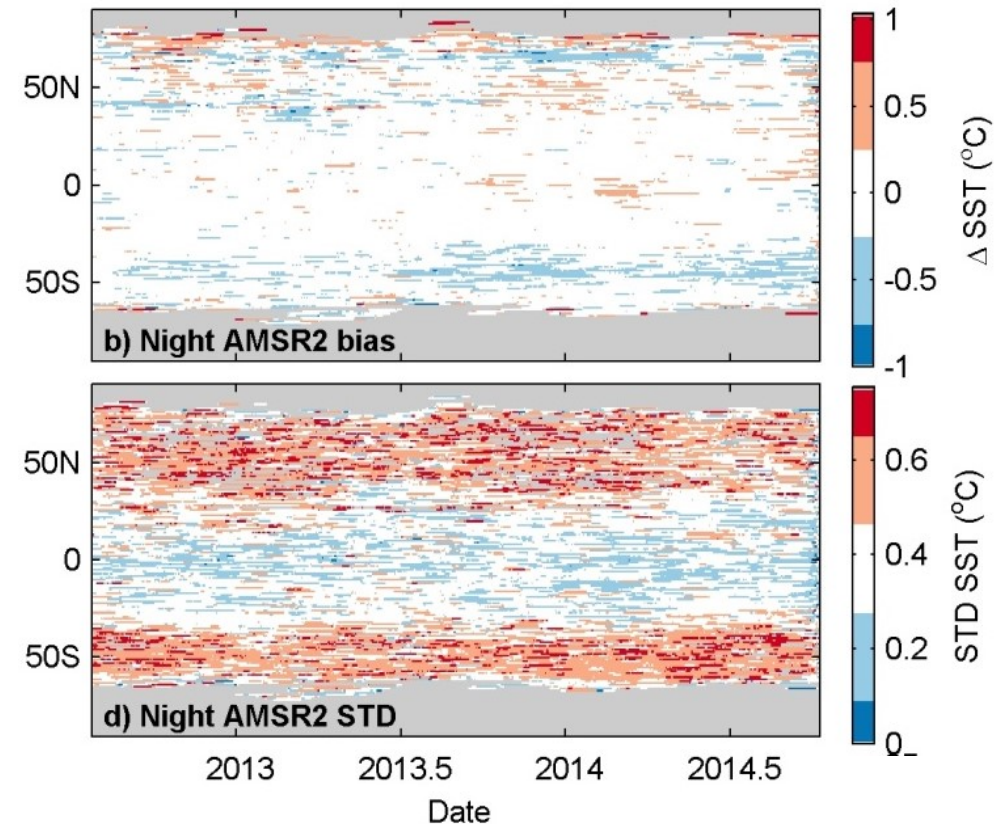
Spatial Variability Patterns

- Warm biases
 - Kuroshio-Oyeshio and northward through Bering Strait and into Chukchi Sea
 - California coast
- Cool biases
 - Peru coast westward to Marquesas
 - Arabian Sea relative to Bay of Bengal
 - Northeastern Atlantic
 - Southern Ocean (northern part)
- Comparison with TRMM and AMSRE
 - Also found warm biases off California and cool biases off Peru [Gentemann *et al.*, 2004; Gentemann, 2014]
 - AMSR2 did not find large warm biases in Gulf of Mexico present in earlier version of TRMM [Gentemann *et al.*, 2004]
 - AMSRE also found warm biases in Kuroshio and cool biases in N. Atlantic and S. Ocean
 - Similarity in SST difference patterns among different satellites suggests these are SST retrieval or in situ data



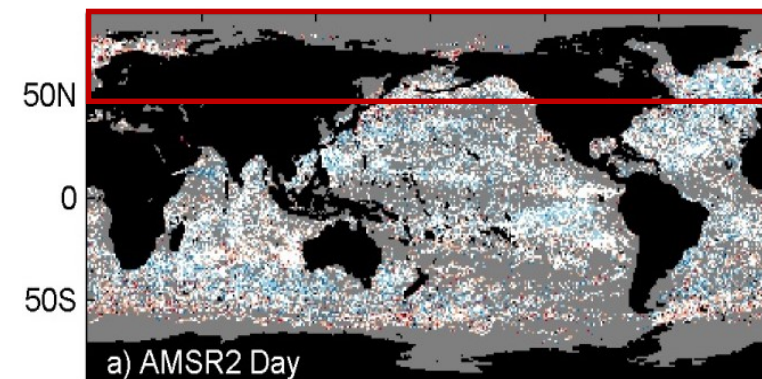
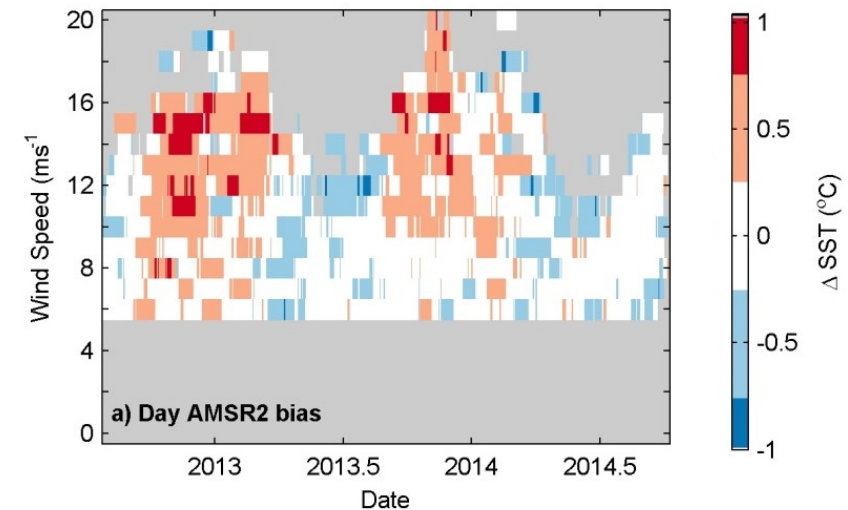
Seasonal Variability

- What is time variability of the warm biases in North Pacific and cool biases in North Atlantic?
- Time-latitude plot shows the warm differences in boreal winter and cool differences in summer
- The largest SST error occurs where SST is coolest [*Gentemann et al., 2010*]
- In Northern Hemisphere, there is very little data in the Pacific, results are primarily from the Northern Atlantic and Arctic Ocean north of Europe
- Since warm bias in NH is in winter, not artifact of un-removed diurnal warming
- In Southern Hemisphere, cool bias is nearly constant throughout the year



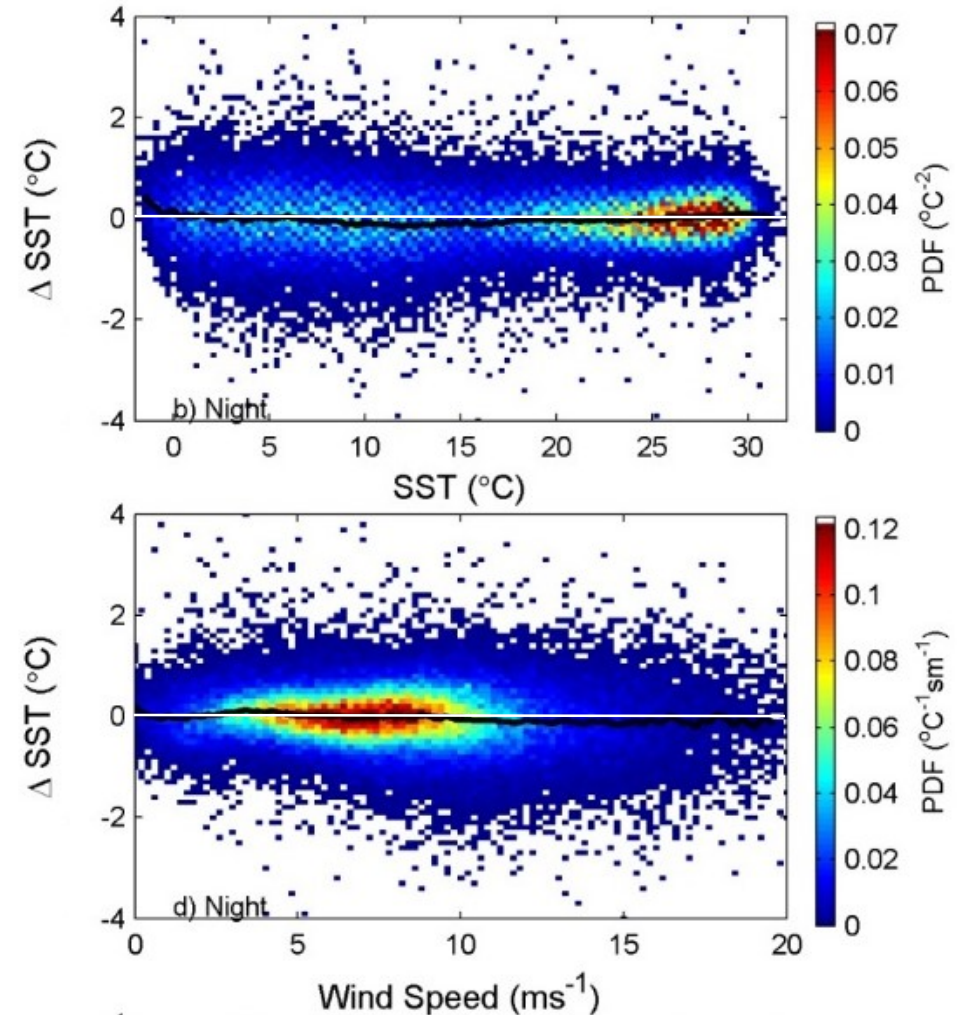
Seasonal Biases Depend on Wind Speed

- Figure shows the SST bias vs time and wind speed for the sub-region shown on map
- Daytime has few observations below 6 m/s because of diurnal warming exclusion criteria
- The N. Hem. winter warm biases occur in high winds (> 10 m/s)
- *Meissner and Wentz [2013]* demonstrated that RT modeling of ocean is most uncertain at high winds and cold water
- Also, at high winds, errors from incorrect wind direction knowledge are largest
- Keep in mind that 86% of winds are below 12 m/s, so the large areas of red shading in these figures are small fraction of all data



Bias vs SST, Wind

- Bias in SST is flat with respect to SST, except for warm bias in coldest SSTs
- Bias in wind is flat with respect to wind speed
- Uncertainty increases for SST below 15 deg C
- Uncertainty increases for winds above 8 m/s
- The seasonal biases are not evident on these plots because the biases come from the combination of cool SST and high wind speed
- Biases as a function of water vapor and cloud water are flat



Summary

- AMSR2 estimates of SST were compared with buoys for a two year period
- Excluded potential diurnal warming and RFI
- Overall mean bias is -0.04 K
- Overall standard deviation is 0.55 K
- Results show that errors are stable in time
- There is a seasonally-occurring warm bias in cold water and high winds; appears to be a retrieval error, rather than a calibration error

Conclusions

- Results imply an absolute calibration accuracy of 0.02 K
- AMSR2 STD is 0.55 K (this is over the whole globe)
 - TMI is 0.57 K
 - AMSR-E is 0.48 K
 - There are now a much higher number of drifting buoys at high latitudes where MW SSTs have a higher error than when AMSR-E was operating. The AMSR2 STD is 0.49 K when collocations are restricted to ± 40 latitude. Comparable to the AMSR-E result.
- There are some new RFI sources (intra-satellite) that we are not masking out, but it is unlikely this would significantly contribute to the error.
- Overall: AMSR2 SST are of comparable quality to AMSR-E SST and contribute to the continuation of the climate MW SST record