Satellite Microwave SST: Accuracy, Comparisons to AVHRR and Reynolds SST, and Measurement of Diurnal Thermocline Variability

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ABSTRACT

A global understanding of the spatial/temporal variability of the diurnal thermocline is necessary for accurate parameterization of skin-bulk differences. Satellite microwave radiometers offer vital observations pertinent to this research, as they are capable of global, daily, coincident retrievals of skin sea surface temperature (SST), wind-stress, cloud cover, and rain rate. These variables can be compared with a bulk SST, such as the Reynolds Optimum Interpolated SST, to examine skin-bulk relationships.

INTRODUCTION

A thin "skin" layer of water, less than 1mm thick, is usually cooler relative to the layer directly beneath. This gradient is a function of the net ocean-atmosphere heat flux. During the daytime, low wind speeds and increased solar insolation can cause thermal stratification of the upper ocean, a few meters thick [6]. At the base of this layer, the "bulk" water temperature [1,2,6] is free of diurnal forcing. Understanding the temporal variability and depth dependence of skin-bulk differences is important for monitoring the ocean-atmosphere heat flux, modeling oceanic uptake of CO_2, and multi-sensor data merging efforts. We have been studying the skin-bulk differences as part of our effort to merge microwave, infrared, and *in situ* SST measurements. Satellite retrievals of sea-surface temperature (SST) penetrate from a few microns (infrared) to about 1mm (microwave). *In situ* sensors are typically located at a depth of 1m. Skin-bulk differences define the relationship between these three measurements. Since the accurate retrieval of SST from microwave data has been developed relatively recently, we first present a summary of our validation efforts for this product.

VALIDATION OF TMI SST

The Tropical Rainfall Measuring Mission (TRMM) satellite was launched in November 1997. Aboard TRMM, the TRMM Microwave Imager (TMI) is the first well-calibrated microwave radiometer with a channel suite capable of measuring SST. The SST retrieval algorithm is a physically based retrieval algorithm [7,8,9], derived using a radiative transfer model developed at Remote Sensing Systems. No *in situ* or satellite retrievals were used to derive the coefficients of the algorithm. The only 'tuning' of the algorithm was to set the mean TMI SST equal to the mean NCEP Optimum Interpolated (OI) SST for 1998. The 9 channels on TMI allow for simultaneous retrieval of SST, wind speed, columnar water vapor, cloud liquid water, and rain rate. All data are freely available for viewing and downloading at the website, www.remss.com.

A comparison of TMI SSTs with hourly *in situ* measurements from the Tropical Atmosphere Ocean (TAO) moored buoy array is shown in Fig. 1. We included collocations within 0.5º and one hour for 1998 and 1999 were included in this analysis. We plot the collocated TMI SSTs as a function of Buoy SSTs in Fig. 1A. The TMI SSTs are in excellent agreement with buoy SSTs, with a standard deviation of 0.52ºC and a mean bias of –0.13ºC. This level of accuracy and precision is a significant achievement given that buoy SSTs were not used in the development of the radiative transfer based retrieval algorithm [8,9].

We expect that the accuracy found in the tropical Pacific may be extended to the entire TMI SST dataset with the understanding that the largest sources of error in the microwave retrievals is due to occasional undetected rain attenuation, which can cause a warm bias in the retrieval, or high wind speeds (> 12 m/s). Since the TAO array is located in a region with very low wind speeds, few collocations in this study have wind speeds above 10 m/s (Fig. 1B). Over

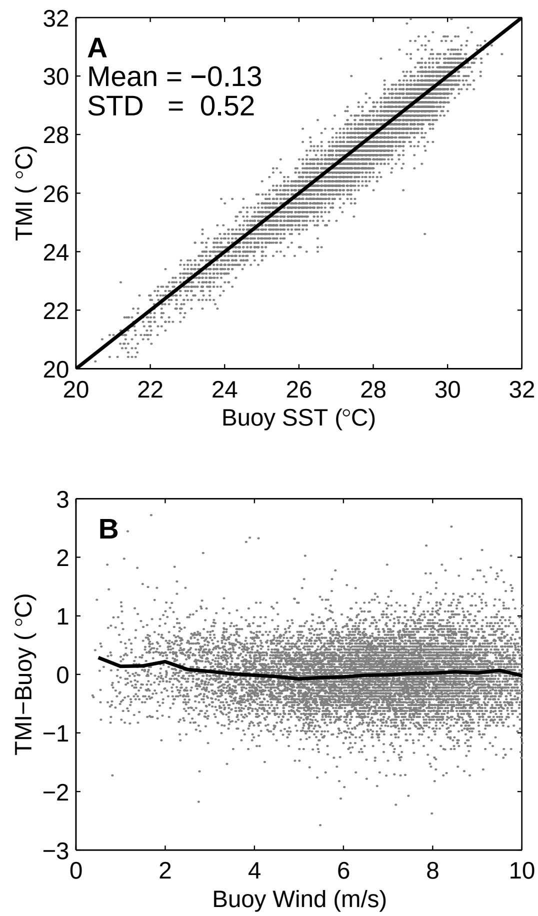

Fig. 1. TMI SST comparisons to TAO/TRITON Buoy SST. 1998 and 1999 data were collocated to within one hour and 0.5º. A) TMI SST versus Buoy SSTs. B) TMI – Buoy SSTs versus Buoy wind speeds.

this restricted wind-speed range, the data in Fig. 1B show that TMI has little dependence on wind speed. We have done additional validation studies which reveal a cool bias (~0.1ºC) in the TMI SSTs at wind speeds above 12 m/s [9].

To check for systematic differences between the TMI and OI SSTs, we performed a multi-year analysis of spatial/temporal behavior of the TMI– OI difference. Weekly maps from 1999 and 2000 were collocated and compared. The mean, trend, annual, and semi-annual harmonics of the SST were calculated for each 25 km grid cell. Regions with virtually constant cloud cover or lacking *in situ* measurements are of a particular interest, since the infrared retrieval accuracy has remained virtually untested in these regions. Comparisons reveal regionally specific biasing. Determination of which dataset is biased is complicated, since the larger mean biases occur in regions devoid of *in situ* measurements from fixed platforms. The North Pacific has a negative mean bias while the South Indian Ocean and South Atlantic show positive biasing. We show an example of a bias in the SST trend in Fig. 2. In the region to the west of Peru and Chile, there is an unexplained temporal trend in the difference TMI - OI. This is a region with persistent cloud cover and no moored *in situ* instrumentation. Drifters have been deployed in this region but are not useful for studying long-term trends of this magnitude. Prior to any data merging effort, these differences must be explained.

MEASUREMENT OF SKIN BULK DIFFERENCES

TMI and buoy *in situ* measurements both include SST as well as wind speed. Therefore, the skin-bulk difference can best be analyzed using the three residuals that have collocated wind speed data, PF – *in situ*, TMI – *in situ*, and TMI – OI. Fig. 3 shows satellite - *in situ* comparisons, averaged over all TAO buoy collocations. In Fig. 3A the TMI – buoy SST difference is plotted against the buoy wind speed. We included collocations within 0.5º and one hour for 1998 and 1999. The nighttime/daytime data are collocations with a local time of 2AM/2PM. Fig. 3B shows the difference, PF SST - buoy SST versus buoy wind speeds. These data are from the 1998 Pathfinder Matchup Database distributed by the Rosenstiel School of Marine and Atmospheric Science at the University of Miami. The PF SST had several obviously cloud-contaminated retrievals that caused it to be up to 20ºC colder than the *in situ* measurements. To remove the most obviously cloud-contaminated pixels, PF SSTs more than 5ºC cooler than the corresponding buoy SST were excluded. The satellite-*in situ* differences for night/day are plotted in red/black dots, with the mean difference plotted as a red/black line. Vertical bars on the mean difference lines indicate one standard deviation.

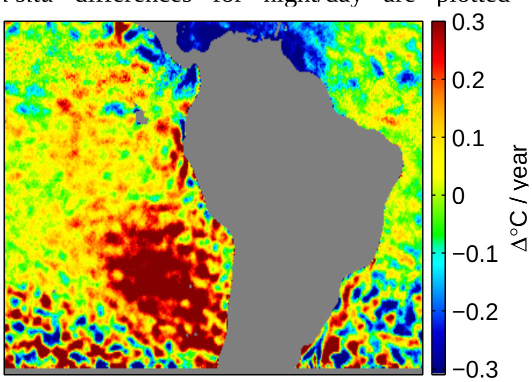

Fig. 2. Trend in the difference: TMI SST - OI SST.

Fig. 3A clearly shows a strong diurnal thermocline at wind speeds below about 4 m/s. The thermocline is less clear, but still evident, at wind speeds below 3 m/s in Fig. 3B. Nighttime skin-bulk differences show a cool skin (~0.5ºC) in Fig. 3A but is less clear in Fig. 3B. A global examination of the skin bulk temporal variability and its dependence wind speed is shown in Fig. 4. Collocated TMI SST and OI SST were differenced and plotted as a function TMI 10m wind speed. TMI is in an equatorial orbit, yielding measurements throughout the diurnal cycle. This allows the calculation of the skin-bulk difference throughout the day as a function of wind speed. Fig. 4A shows the difference, TMI – OI, as a function of local time and wind speed. At wind speeds below 2 m/s the diurnal effect is strongest, showing a cool skin at night and a warm skin during the day. The peak in the warm skin is at 2pm local time and has a magnitude of 1.6ºC. Fig. 4B show hourly averages of the TMI-OI difference as a function of wind speed. Daytime averages are plotted in red, nighttime averages in black. A strong diurnal thermocline at wind speeds below 4 m/s is clearly evident, in contrast with the results of Donlon *et al* [1], which show diurnal warming for wind speeds less than 6 m/s. At very low wind speeds (< 1 m/s), afternoon retrievals show a 1.5ºC skin-bulk difference

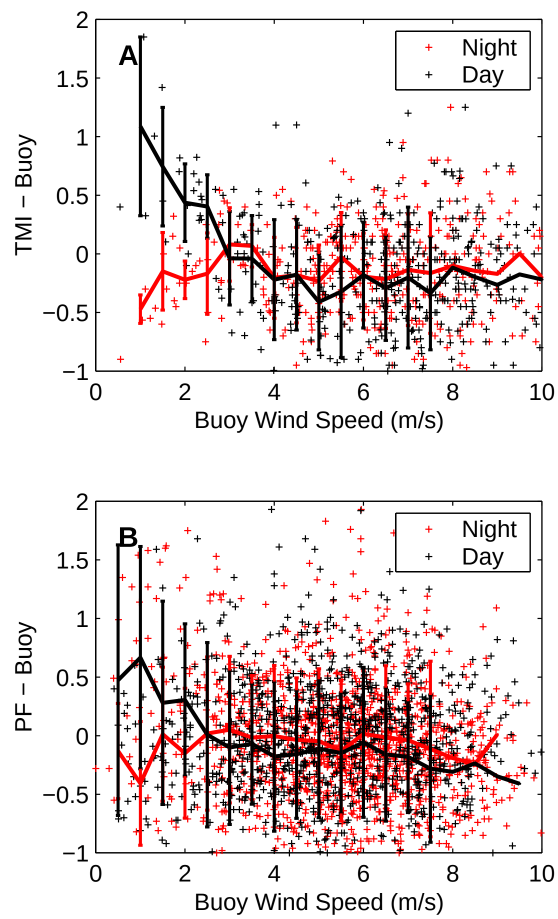

Fig. 3. Diurnal skin effects from satellite SSTs. A) TMI - Buoy SST versus Buoy Wind Speed. B) Pathfinder – Buoy SST versus Buoy Wind Speed. In both figures, black is used for daytime data and red for nighttime data. Pathfinder has an equatorial crossing time of 2:30.

while nighttime retrievals have a –0.4ºC difference. Preliminary studies of the effect of cloud cover, as retrieved by TMI, on the skin-bulk difference show no conclusive results. This may be partially due to the large footprint (50km) of TMI.

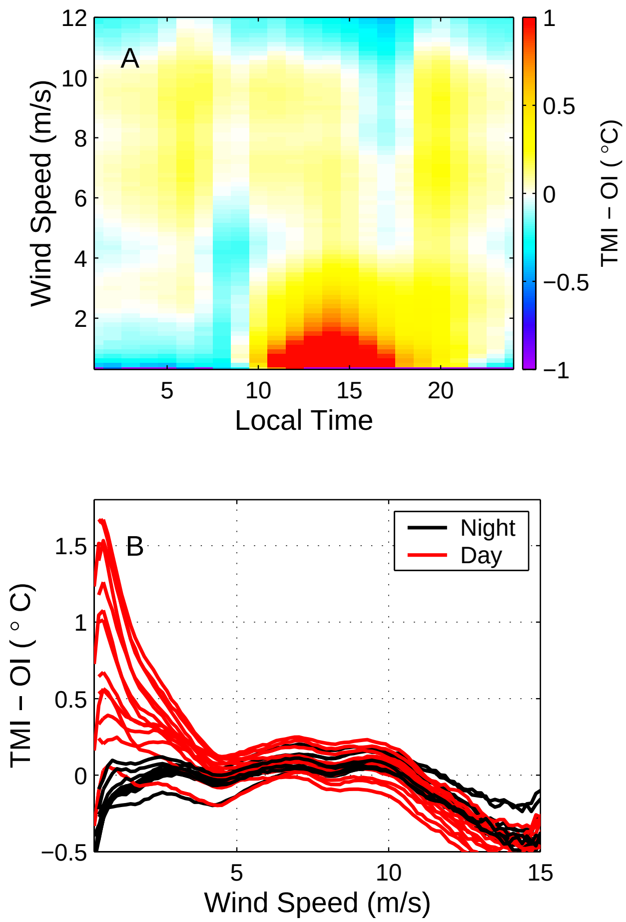

Fig. 4. Diurnal skin effects from TMI and OI SSTs. A) Image of the average difference, TMI - OI as a function of local time and wind speed. B) Average difference, TMI - OI SST, for each local time hour, versus wind speed. Nighttime data is presented in black, daytime in red.

Conclusion

The magnitude of the skin-bulk differences underscores the importance of understanding this effect before any data merging effort. The AVHRR instruments are mounted on NOAA polar orbiters have fixed morning and afternoon crossings. The upcoming polar orbiters ADEOS-II and AQUA, both with microwave radiometers capable of accurate SST retrieval, will have morning and afternoon crossings. There are hourly buoy *in situ* retrievals and hourly geostationary infrared SSTs. Combining these data into a merged SST product requires an exact understanding of the diurnal thermocline. The TMI instrument, mounted on the TRMM platform with a rapidly evolving local measurement time, is crucial for determining the diurnal dependence of the bulk-skin SST difference.

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References

[1] Donlon C. J. and I. S. Robinson, Observations of the oceanic thermal skin in the Atlantic Ocean, J. Geophys. Res, 102, 18585-18606, 1997.
[2] Grassl, H., On the dependence of the measured cool skin of the ocean on wind stress and total heat flux, Meteorology, 10, 465-474, 1996.
[3] Podesta, G. P., S. Shenoi, J. W. Brown, and R. H. Evans, AVHRR Pathfinder Oceans Matchup Database 1985-1993 (Version 18), Report from the University of Miami, Rosenstiel School of Marine and Atmospheric Science, 33 pp., June 1995.
[4] Reynolds, R. W. and T. M. Smith, 1994: Improved global sea surface temperature analyses using optimum interpolation. J. Climate, 7, 929-948.
[5] Vazquez, J. and A. Tran, R. Sumagaysay, E. A. Smith and M. Hamilton, NOAA/NASA AVHRR Oceans Pathfinder Sea Surface Temperature Data Set User's Guide Version 1.2, JPL Tech. Rep., 53 pp., 1995.
[6] Ward, B. and P. J. Minnett, An autonomous profiler for near surface temperature measurements. In "Gas Transfer at Water Surfaces." American Geophysical Union Monograph.
[7] Wentz, F. J., C. Gentemann, and D. Smith, Satellite measurements of sea surface temperature through clouds, Science 288, 847-850, 2000.
[8] Wentz, F. J., P.Ashcroft, C. L. Gentemann, T. Meissner, The retrieval of ocean products from AMSR, IGARSS 2001.
[9] Wentz, F. J., 1996: AMSR ocean algorithm, RSS Tech. Report 120296.