Insights Gained from a TRMM Microwave and Infrared Sea Surface Temperature Comparison

Lucrezia Ricciardulli and Frank J. Wentz, Remote Sensing Systems

Remote Sensing Systems
438 First St., Suite 200
Santa Rosa, CA, 95401, USA
Ricciardulli@Remss.com

Abstract- **A detailed comparison of Sea Surface Temperatures obtained from one year of infrared and microwave satellite observations was performed on data from the VIRS and TMI sensors, both onboard the Tropical Rainfall Measurement Mission (TRMM). Using VIRS radiances, we developed daily maps of infrared SSTs and compared them to microwave SST daily maps derived from TMI. The intercomparison aims at identifying and minimizing errors in each dataset. Results from the analysis of the correlation of SST differences and possible sources of error (i.e., high winds, diurnal variations of skin layer temperature, atmospheric water vapor, undetected clouds, satellite maneuvers and calibration errors) are discussed. The intercomparison of four tested IR algorithms and the TMI SSTs facilitates the choice of the optimal IR algorithm for use in future data processing. We investigated how co-located MW observations of water vapor help IR SST retrievals by improving the cloud detection algorithm. In addition, the MW retrievals can benefit from the comparison with IR observations, which highlights the effects of land contamination in the TMI retrievals.**

I. INTRODUCTION

The availability of both infrared (VIRS) and microwave (TMI) sensors onboard TRMM provided the first opportunity to perform an intercomparison of Sea Surface Temperature (SST) retrievals from perfectly co-located infrared and microwave sensors. While infrared SST retrievals have better spatial resolution (of the order of few Km or less) than microwave ones, they are affected by water vapor and clouds in the atmosphere, and therefore limited to clear sky observations. On the other hand, the microwave (MW) sensor's ability to observe the ocean through cloudy sky provides very valuable supplemental information to IR SST retrievals. In addition to SST, the microwave sensor TMI allows co-located retrievals of surface wind speed, atmospheric columnar water vapor, cloud liquid water and rainfall.

The comparison of co-located SSTs from IR and MW data, combined to the ancillary dataset that includes winds and water vapor, proves to be a simple and efficient tool for error characterization in each dataset. Our analysis quantifies the sensitivity of IR retrievals to the amount of atmospheric water vapor, and explores the use of alternative IR algorithms for SST retrievals with more explicit dependence on water vapor than currently adopted algorithms. The availability of co-located MW retrievals plays also an important role in the identification of cloud-contaminated IR observations, therefore improving the IR SST data quality.

On the other side, microwave retrievals can be improved with the aid of IR SSTs, i.e. identifying the MW SST bias in presence of high winds, or due to proximity to land.

Finally, both the datasets can be used to investigate the amplitude of diurnal variation of SSTs, because of the variable time of observation due to TRMM inclined orbit.

A rigorous study of error characteristics and uncertainties for the two observational methods presented here is valuable for the development of a future generation of SST datasets which will combine MW and IR observations, taking advantage of the strengths of each method.

II. DATA PREPARATION

A. *VIRS SSTs*

The creation of a VIRS dataset for SSTs involved three major steps: the development of an efficient cloud detection algorithm, calculation of the regression coefficients for the SST algorithm using another observational SST dataset as ground truth, and finally the calculation of SSTs from infrared radiances.

1) Cloud detection algorithm

For the development of a cloud detection algorithm, we relied on our previous experience with a cloud mask used for data from the AVHRR infrared sensor onboard the NOAA satellites [1]. However, since VIRS is on an inclined orbit rather than polar like AVHRR, the VIRS cloud mask needs to address a wider variety of sun-satellite configurations. In particular, for high solar zenith angles or when the satellite looks in the direction of specular reflection (sunglint) of sunlight, the ocean reflectivity is very high and IR observations can be erroneously identified as cloud-contaminated. In order to maximize the number of VIRS SST retrievals, we developed a method to adjust the reflectivity to normal conditions for these particular cases. Using one year of clear sky VIRS data, we calculated an empirical adjustment to reflectivity as a function of solar zenith angle, sunglint angle and satellite scan angle. The empirical adjustment proved to be particularly efficient in allowing retrievals even in sunglint regions.

The cloud detection algorithm we applied on VIRS radiances is a suite of tests on reflectivity, on spatial coherence, and on detection of cirrus and low stratus clouds by comparing the brightness temperatures detected by pairs of IR channels.

2) SST algorithm: regression coefficients

After applying the cloud mask, SSTs can be derived from the VIRS radiances observed with three IR channels, One algorithm is the non-linear sea surface temperature algorithm (NLSST) in (1.1), conventionally adopted for AVHRR radiances and described in [1]. In addition, we tested the linear multi-channel SST algorithm (MCSST) (1.2) described in [2] and adopted by NASDA [3] in their processing of VIRS SSTs. As atmospheric water vapor content directly affects the Earth radiation detected by the IR sensor, we also experimented two alternative IR SST algorithms (1.3-1.4) that include co-located MW water vapor, rather than the brightness temperature channel difference.

$$NLSST = a + bT_4 + c(T_4 - T_5)SST_{fg} + d(T_4 - T_5)F_\vartheta \quad (1.1)$$

$$MCSST = a + bT_4 + c(T_4 - T_5) + d(T_4 - T_5)F_\vartheta \quad (1.2)$$

$$WVSST_1 = a + bT_4 + cT_5 + d \cdot W_v + e \cdot W_v F_\vartheta \quad (1.3)$$

$$WVSST_2 = a + bT_4 + cT_5 + d(T_4 - T_5)SST_{fg} + e \cdot W_v + f \cdot W_v F_\vartheta . \quad (1.4)$$

Here, T_4, and T_5 are the brightness temperatures observed by channel 4 and 5 on VIRS, respectively; SST_{fg} is a first guess SST (in our case from TMI), F_ϑ is a function of the satellite zenith angle ϑ; and W_v is the co-located water vapor from TMI. The four algorithms displayed in (1.1-1.4) refer to daytime. Night algorithms are slightly different as they also include brightness temperatures T_3 from the near-IR channel 3.

$$NLSST = a + bT_4 + c(T_3 - T_5)SST_{fg} + d \cdot F_\vartheta \quad (1.5)$$

$$MCSST = a + bT_4 + c(T_4 - T_5) + d(T_4 - T_5)F_\vartheta + e(T_3 - T_5) + f(T_3 - T_5)F_\vartheta \quad (1.6)$$

$$WVSST_1 = a + bT_3 + cT_4 + dT_5 + e \cdot W_v + f \cdot W_v F_\vartheta \quad (1.7)$$

$$WVSST_2 = a + bT_3 + cT_4 + dT_5 + e(T_3 - T_5)SST_{fg} + f \cdot W_v + g \cdot W_v F_\vartheta . \quad (1.8)$$

The coefficients a, b, c, d, e, f and g were estimated by regressing cloud-free VIRS radiances to one year of co-located TMI SSTs, separately for day and night and for each algorithm. TMI data in presence of wind speeds greater than 12 m/s were excluded from the regression in order to avoid biases in microwave SST retrievals due to high winds.

3) Creation of VIRS SST datasets

Four sets of orbital VIRS SSTs for the year 1998 were created using algorithms (1.1-1.8) at a resolution of approximately 4 Km. The orbital data were then gridded on daily 40N-40S maps with 0.125 degree resolution in both longitude and latitude, which correspond approximately to 12.5 Km resolution.

B. TMI SSTs

Microwave SSTs from the 10.7 GHz channel of the TMI sensor are routinely processed at Remote Sensing Systems [4]. The data, from Dec 1997 until present, are stored as 0.25 deg daily maps. For our comparison, we interpolated TMI SSTs on 0.125 deg daily maps.

C. Ancillary data

For each daily map of VIRS and TMI SSTs, we stored additional co-located geophysical variables obtained from the TMI sensor [5]: water vapor, 10-m wind speed and time of observation. In addition to the TMI co-located variables, we stored 0.125 deg daily maps of SSTs interpolated from the 100 Km resolution weekly maps of Optimum Interpolated (OI) SSTs developed at the National Meteorological Center (NMC) [6,7]

III. IR/MW SST COMPARISON

A. Validation of VIRS SSTs

Daily maps of VIRS SSTs for the entire 1998 were compared to daily co-located TMI SSTs, OI SSTs and the VIRS SST daily maps provided by NASDA, showing general agreement. The adjustment applied on reflectivities resulted in successful retrievals even in sunglint regions, unlike the maps provided by NASDA. Moreover, the accurate calibration of VIRS radiances with TMI SSTs produced SSTs without discontinuities between day and night retrievals.

When compared to TMI observations for the entire 1998, VIRS SSTs did not show any bias, as expected. The average standard deviation of (VIRS-TMI) daily SST maps was found to be 0.7 C, for both day and night retrievals with the NLSST algorithm. Slightly higher values for the standard deviation, up to 0.8 C, were found for the other three algorithms especially those not constrained by the first guess TMI SST.

Comparison of VIRS SSTs with OI SSTs also did not show any bias for 1998 data. An average standard deviation of 0.7 C was found when comparing daily VIRS maps versus diurnally interpolated OI. A similar value was found for the standard deviation of daily TMI SST versus daily-interpolated OI SST.

Finally, to complete the validation of our VIRS SSTs, we compared them to daily maps of VIRS SST provided by NASDA. In this case the standard deviation was 0.45 C without bias.

B. Analysis of error and uncertainty characteristics

Despite the average bias for VIRS data compared to TMI or OI SST is zero, temporal variations in a 0.5 C range do occur, as shown in Fig. 1 for the NLSST-TMI comparison.

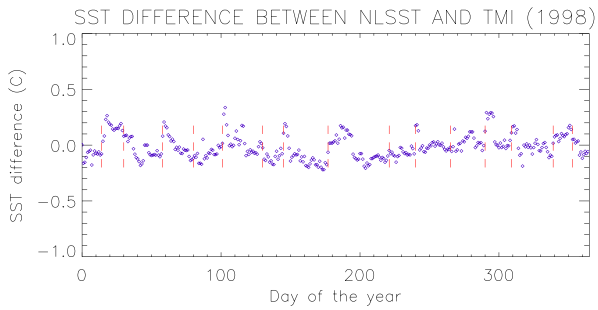

Fig.1: SST difference between daily VIRS SSTs determined with the NLSST algorithm and the co-located TMI SSTs, for 1998 data. The vertical dashed lines refer to a change in satellite yaw.

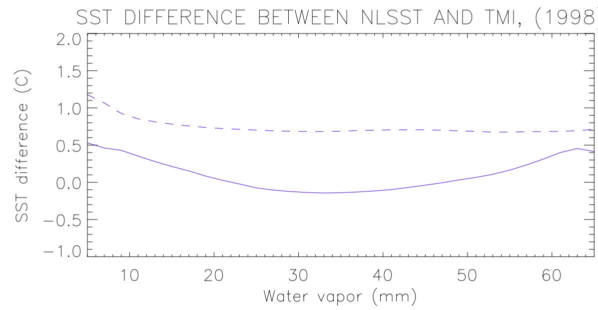

Fig. 2: SST difference (solid line) between VIRS (NLSST) and TMI SSTs in 1998, for day and night retrievals. The dashed line represents the standard deviation.

The red vertical lines in Fig. 1 are placed in correspondence of a yaw change in the TRMM satellite, and suggest that greater differences between VIRS and TMI SSTs are found soon after changing yaw.

In order to understand the sources of errors and uncertainties in both IR and MW retrievals, we stratified the VIRS, TMI and OI daily SSTs in terms of latitude, time of observation, wind speed, and water vapor.

As an example, in Fig. 2 we show the SST difference between VIRS and TMI retrievals as a function of the co-located water vapor. The figure clearly shows that, despite the $(T_4 - T_5)$ terms in the NLSST algorithm (1.1 and 1.5) to account for the atmospheric water vapor, a residual dependence of SST retrievals on water vapor is still found, mostly due to night retrievals. Despite the higher bias at extreme values of water vapor, the average bias is still zero because most of the SST retrievals are done in the range between 15 and 50 mm. Differences between VIRS and TMI SSTs vanished when the WVSST1 algorithm was used. Similar analyses were performed comparing VIRS and TMI SSTs to the OI dataset.

The effect of wind on microwave retrievals was investigated by comparing VIRS and TMI SSTs as a function of co-located wind speed. As expected, wind speeds greater than 12 m/s affected the uncertainties associated with microwave SST retrievals, mostly increasing the standard deviation (from 0.7 at 10 m/s to 1.5 at 20 m/s), with just a slight cold bias.

The comparison between VIRS and TMI SSTs as a function of latitude did not show any significant bias, except for small warm bias at extratropical latitudes, at the edge of TRMM orbital swath.

The diurnal variability of skin SST [8,9] was investigated by stratifying the difference between VIRS and the OI SSTs in terms of local time of observation, for all retrievals or only for low winds (less than 3 m/s). The OI SSTs are interpolated from weekly data and therefore do not contain any diurnal signal. A significant diurnal variability of VIRS SSTs was found when the winds are low, as a result of the solar warming of the skin layer. The amplitude of the diurnal signal was of the order of 1 C, with a peak value at about 2 PM, slowly decaying until midnight. A similar diurnal signal was found also for TMI retrievals in low wind conditions, consistent with other studies [10].

Finally we investigated the effects of land proximity to microwave retrievals, due to the large footprint (approximately 40 by 60 Km) of the TMI sensor at 10 GHz. The comparison with VIRS SSTs showed a significant land contamination resulting in TMI SSTs in coastal waters warmer by 1 C, and with increased uncertainty (standard deviation greater than 1 C).

IV. CONCLUSIONS

The analyses presented here aim at understanding the error characteristics of SST retrievals from infrared and microwave observations, and develop strategies to minimize errors and uncertainties. A manuscript that will provide a more detailed description of this investigation is in preparation

These results showed that both infrared and microwave observation of the ocean temperature can benefit from the comparison. After the major reasons for differences between VIRS and TMI SSTs are excluded (high winds, diurnal signal, water vapor, etc.), the residual differences might be due to undetected clouds or aerosols in infrared retrievals. In particular, a correlation range between brightness temperature differences and water vapor can be used as an additional cloud test. Therefore, the IR/MW comparison can also lead to an improvement in the efficiency of the cloud mask.

The comparison of SSTs obtained from of a number of IR algorithms with other independent SST observations (TMI, OI or buoys) aims at defining the optimal algorithm in terms of accuracy.

Moreover, only after similar rigorous investigations of the characteristics and differences for the two observational methods, MW and IR retrievals can be combined to produce a blended SST dataset that takes advantage of each method's strength.

In the future, we plan to: extend this work to more years of VIRS data, and investigate the presence of any temporal drift in the observations; and develop a new cloud mask which adopts a test on water vapor; compare MW and IR SSTs from AMSR-E and MODIS, respectively.

Acknowledgments

This work was accomplished at Remote Sensing Systems and supported by NASA contract NAS5-00217 and JPL-1228578. Ms. Frances Bergmann at NASA Goddard Space Flight Center DAAC kindly provided the VIRS level-1B01 data. The NASDA version of VIRS data VIRSSST (ver. 1.0), used in some of the comparisons with RSS VIRS SSTs, was produced and supplied by the Earth Observation Research Center, National Space Development Agency of Japan. The authors are very grateful to Drs. Douglas May and Daniel Olszewski for helpful discussions about the AVHRR cloud mask.

References

[1] D.A. May, M.M. Parmeter, D.S., Olszewski, and B.D. McKenzie, "Operational processing of satellite sea surface temperature retrievals at the Naval Oceanographic Office," *Bull. Amer. Meteor. Soc*., vol. 79, pp. 397-407, March 1998.

[2] L. McMillin, and D. Crosby, "Theory and validation of the multiple window sea surface temperature tecnique," *J. Geophys. Res*., vol. 89, pp 3655-3661, 1984.

[3] H. Murakami, "Sea surface temperature estimation using Visible and Infrared Scanner (VIRS)", http://www.eorc.nasda.go.jp/TRMM/imgdt/day_vrs/virs_sst.pdf.

[4] F.J. Wentz, C. Gentemann, D. Smith, and D. Chelton, "Satellite measurements of sea surface temperature through clouds," *Science*, vol. 288, pp. 847-850, 2000.

[5] F.J. Wentz, "A well calibrated ocean algorithm for special sensor microwave imager," *J. Geophys. Res*., vol. 102, pp. 8703-8718, 1997.

[6] R.W. Reynolds, and T.M. Smith 1994, "Improved global sea surface temperature analyses using optimum interpolation," J. Climate, Vol. 7, pp. 929-948, 1994.

[7] R.W. Reynolds, N.A. Rayner, T.M. Smith, D.C. Stokes, and W. Wang, "An improved in situ and satellite analysis for climate," *J. Climate*, vol. 15, pp. 1609-1625, 2002.

[8] W.J. Emery, S. Castro, G.A. Wick, P. Schluessel, and C. Donlon, "Estimating sea surface temperature from infrared satellite and in situ temperature data," *Bull. Amer. Meteor. Soc.*, vol. 82, pp. 2773-2785, December 2001.

[9] C.J. Donlon, P.J. Minnett, C.L. Gentemann, T.J. Nightingale, I.J. Barton, B. Ward, and M.J. Murray, "Toward improved validation of satellite sea surface skin temperature measurements for climate research," *J. Climate*, vol. 15, pp. 353-369, February 2002.

[10] C.L. Gentemann, C.J. Donlon, A. Stuart-Menteth, F.J. Wentz, "Diurnal signals in satellite sea surface temperature measurements," Geophys. Res. Lett., vol. 30, pp. 40/1-4, 2003.