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SEA SURFACE TEMPERATURE ESTIMATION FROM THE DMSP OPERATIONAL LINESCAN SYSTEM USING A SSM/I-DERIVED WATER VAPOR CORRECTION

Douglas A. May

Naval Research Laboratory, Remote Sensing Applications Branch,
Stennis Space Center, MS 39529-5004

Abstract. Atmospheric correction algorithms for Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) single channel infrared (IR) estimation of sea surface temperature (SST) have been derived based on Special Sensor Microwave/Imager (SSM/I) water vapor (WV) content retrievals. It is demonstrated that the OLS single IR channel atmospheric correction can be correlated to WV and that the SSM/I-derived correction algorithms provide significant improvement over uncorrected single IR channel SST estimation. Best results are obtained from a correction algorithm that incorporates a quadratic WV term. Use of the quadratic SSM/I-derived WV correction on properly cloud screened OLS IR data produces SST retrievals accurate to within 1.0°C RMS when compared to moored buoy in situ SST measurements.

Introduction

Satellite IR radiometers have been used to estimate the temperature of the ocean surface for several years [Anding and Kauth, 1970; McMillin, 1975; McClain et al., 1985]. Atmospheric effects, primarily due to water vapor absorption, contaminate the IR signal received by the satellite sensors. These effects result in the satellite sensor observing a brightness temperature (BT) that is colder than the actual SST, requiring an atmospheric correction for accurate SST estimation. The multichannel algorithm correction technique for National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) data is widely employed. This technique to correct for atmospheric effects is based upon the differential absorption properties of WV in two or three IR channel bandwidths available on AVHRR. Many multichannel algorithms have been derived and used operationally [e.g., Barton, 1983; McClain et al., 1985], with the NOAA multichannel SST (MCSST) algorithms demonstrating a consistent global RMSD accuracy less than 0.7°C [McClain, 1989].

Several single-channel correction schemes have also been described [e.g., Kelly and Davis, 1986]. These vary considerably in the extent of atmospheric modeling performed and for the effects of off-nadir viewing. This paper describes a single channel correction scheme obtained for the DMSP OLS IR channel based upon the utilization of coincident SSM/I WV retrievals available from the latest DMSP suite of satellites. The method used to derive the atmospheric correction is described and the algorithms are validated against in situ moored buoy SST measurements.

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Data

The OLS sensor is designed to gather data in the visible and IR spectral bandwidths and transmit to ground receiving stations in either direct readout or stored tape recorder mode. The OLS single IR channel bandwidth covers 10.2 – 12.8 micrometers and has a swathwidth of 3050 km [USAF, 1981]. The OLS sensor utilizes a sinusoidal scanning system motion such that a constant spatial resolution is maintained across the scan.

Oceanographic studies using OLS IR data have been limited due to the single IR bandwidth channel and its digitization level. The sensor can retrieve 6-bit "fine" data with a spatial resolution of approximately 0.6 km or 8-bit "smooth" data that has a spatial resolution of about 2.8 km. The IR detector temperature sensitivity ranges linearly from 190 to 310 K. The fine data thus has a thermal sensitivity of approximately 1.9°C and the smooth data about 0.47°C. Both data type thermal sensitivities are relatively coarse compared to 10-bit AVHRR data which is thermally sensitive to about 0.12°C. This study focuses on the utilization of smooth data since it possesses the greatest thermal sensitivity and best option for retrieving SST estimates from DMSP.

SSM/I is a seven-channel, four-frequency (19.35, 22.235, 37.0, and 85.5 GHz) passive microwave sensor. The SSM/I channels are well suited for retrieving WV. SSM/I swath width is 1394 km, providing about a 25 km spatial resolution. A global algorithm has been developed that retrieves WV at an accuracy of 1.9 kg/m^2 [Hollinger, 1989] and was used in this study to generate WV images.

Theoretical single IR channel corrections that utilize WV have demonstrated a possible $\pm$1K accuracy at estimating sea surface temperature [Cogan and Willand, 1975]. Since DMSP polar orbiting satellites obtain coincident IR and microwave radiometer data centered along the satellite nadir track, this sensor combination can be used to investigate the utility and accuracy of a SSM/I-derived WV correction to OLS IR data. The correction to the 3050 km OLS data swath is limited to the 1394 km SSM/I swath width.

OLS image pixels were directly compared to collocated AVHRR MCSST image pixels to derive an atmospheric correction based on SSM/I WV. The NOAA derived MCSST algorithm utilized for NOAA-12 follows:

$$\begin{aligned} MCSST = {} & 1.0086T11 + 2.4526\ (T11 - T12) \\ & + 0.824\ (T11 - T12)(\mathrm{Sec}\ (\theta) - 1) - 275.72 \end{aligned} \quad (1)$$

where T11 and T12 represent the respective BT for the 11 and 12 micrometer bandwidths in degrees K, and θ represents the satellite zenith angle. As mentioned previously, the accuracy of SST retrievals from AVHRR data is quite good, demonstrating RMSD accuracies within 0.7°C when compared to global drifting buoy data. Thus the MCSST imagery provides a relatively reliable estimate of the actual SST.

Corrected DMSP SST retrievals were also compared to in situ moored buoy SST measurements available from the National Data Buoy Center (NDBC) [Meindl and Hamilton, 1992]. Buoy SST measurement resolution is 0.1°C with an estimated accuracy of 1.0°C. Information from 23 individual buoy locations was obtained from NDBC and used in matchups to DMSP SST retrievals. Buoy station locations used in this study are displayed in Table 1.

TABLE 1. Moored buoy identifications and locations

Buoy	Latitude	Longitude
41001	34.9 N	72.9 W
41002	32.3 N	75.2 W
41006	29 3 N	77.4 W
41008	30.7 N	81.1 W
41009	28.5 N	80.2 W
41010	28.9 N	78.5 W
42001	25.9 N	89.7 W
42002	25.9 N	93.6 W
42003	25.9 N	85.9 W
42007	30.1 N	88.8 W
42019	27.9 N	95.0 W
42020	27.0 N	96.5 W
42025	24.9 N	80.4 W
44004	38.5 N	70.6 W
44005	42.7 N	68.6 W
44007	43.5 N	70.1 W
44008	40.5 N	69.4 W
44009	38.4 N	74.7 W
44011	41.1 N	66.6 W
44012	38.8 N	74.6 W
44013	42.4 N	70.8 W
44014	36.6 N	74.8 W
44025	40.3 N	73.2 W

Approach

Several NOAA-12 and DMSP-10 passes near-coincident in time were processed for the western Atlantic and Gulf of Mexico regions. These two satellites were chosen because orbit times were typically less than 2 hours apart. The satellite passes were received and processed at the Naval Research Laboratory receiving station located at Stennis Space Center in Mississippi.

The NOAA and DMSP images for each individual case were processed at identical projections and spatial resolutions. The individual images were earth-located and registered into 1024 × 1024 Mercator projections best suited to the coverage of both satellites, optimizing the SSM/I coverage. A spatial resolution of 2.8 km was chosen for each image to fully utilize the OLS smooth data spatial resolution. Thus, the projected AVHRR data was spatially degraded from 1.1 km at nadir to 2.8 km. Likewise, the SSM/I WV imagery was interpolated from 25 km to the spatial resolution of the OLS smooth data using methods described in Poe [1990].

Three sets of DMSP and NOAA image matchup comparisons were obtained from October, 1991 and used to derive a WV correction algorithm. Individual pixel comparisons were performed on identically projected NOAA and DMSP images. The comparison case dates and times are listed in Table 2. Each image was initially cloud screened using automated techniques [Gallegos et al., 1992]. The resulting images were then edited interactively to eliminate any remaining questionable pixels and subsampled into 512 × 512 images to limit processing. The cloud free image pixels were then directly compared to relate OLS BT pixels minus NOAA MCSST pixels to SSM/I WV pixels.

Results

Each individual case was limited to specific WV ranges due to respective atmospheric conditions. The results from each case were combined, to obtain a wider range of WV conditions. Figure 1 shows the difference between more than 4700 DMSP-10 OLS and NOAA-12 MCSST pixels plotted versus coincident DMSP-10 SSM/I WV retrievals. The figure clearly demonstrates the increased depression of OLS BT as the WV increases, albeit with a relatively high scatter.

WV amounts range from about 15 to 50 kg/m^2 with a small gap in the 40-45 kg/m^2 range. A simple least squares regression fit of the OLS IR and WV values to MCSST results in

$$OLSST = 1.0676{*}OLS + 0.1269{*}WV - 1.9972 \tag{2}$$

where OLSST represents the atmospherically corrected OLS SST retrieval, OLS represents the OLS IR BT (°C) and WV represents the SSM/I atmospheric water vapor content (kg/m^2). The data distribution about this regression line displays a mean difference of 0 and standard deviation of 0.87. The Chi-square goodness of it value is 0.76, demonstrating that the model output adequately fits the observed data values. The regression model explains 95% of the variation in OLSST (R^2=.95), demonstrating that access to coincident WV data can significantly improve the single IR channel SST estimate.

TABLE 2. NOAA and DMSP image comparison cases

Satellite	Date/Time
NOAA-12	10/13/91 2323 UT
DMSP-10	10/14/91 0020 UT
NOAA-12	10/23/91 2316 UT
DMSP-10	10/24/91 0015 UT
NOAA-12	10/25/91 2353 UT
DMSP-10	10/26/91 0023 UT

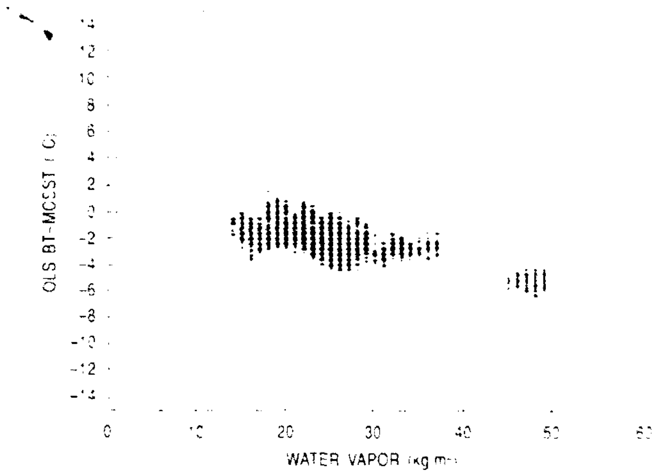

Fig. 1. Colocated DMSP-10 OLS IR BT minus NOAA-12 MCSST pixels versus SSM/I WV.

Cogan and Willand [1975] demonstrated that the addition of a quadratic water vapor term in the equation can theoretically improve the atmospheric correction accuracy. A simple least squares regression fit of such an equation form to MCSST results in

$$\mathrm{OLSST2} = 1.0966{*}\mathrm{OLS} - 0.0604{*}\mathrm{WV} + 0.0029{*}\mathrm{WV}^2 + 0.2896 \tag{3}$$

where OLSST2 represents the quadratic atmospherically corrected form of an OLS SST retrieval. The data distribution about this regression line displays a mean difference of 0 and standard deviation of 0.84, which is a slight improvement over (2). This regression model explains 96% of the variation in OLSST2 (R^2=.96). The additional quadratic term was found to be statistically significant in the regression equation and the Chi-square value of 0.71 improves over the fit obtained by (2), demonstrating a slightly better fit between model output and observed data values.

The OLS correction algorithms were applied to 25 individual DMSP images located in the study region between May 1991 to April 1992 and compared to coincident moored buoy SST measurements to independently test the regression retrieval algorithms. Each image was carefully cloud screened as described previously to eliminate possible cloud contaminated pixels. The correction algorithm image pixels were then compared to coincident moored buoy SST in situ observations. Buoy observations and images were matched to the nearest hour. Buoy SSTs were matched to cloud free image pixels averaged over 3×3 squares centered on the pixel closest to the moored buoy location. A total of 48 satellite-buoy matchups were obtained from all the images. Distinction between daytime and nighttime retrieval accuracies was not investigated due to the limited number of matchups available.

Figure 2 displays the uncorrected OLS BT difference from buoy SST observations versus WV. The satellite-buoy matchups provide information over a wide range of WV conditions varying approximately between 5 and 55 kg/m^2. Note the negative trend in OLS BT depression as WV increases. The majority of matchups are distributed throughout the low and medium WV conditions, with limited matchups in the moist WV conditions.

Figure 3 demonstrates that use of the OLSST algorithm eliminates the negative trend evident in Figure 2. The correction appears to perform best for WV amounts exceeding 20 kg/m^2 with lesser WV retrievals under corrected. The quadratic formula (Figure 4) appears to improve the retrieval correction accuracy at the lower WV levels while slightly elevating the retrievals more than needed at higher WV levels. The number of matchups above 40 kg/m^2 is limited however and conclusions regarding very moist conditions cannot be readily determined with this data set.

Table 3 displays the statistics for the 48 buoy matchup comparisons. On average, uncorrected single channel OLS BT is approximately 2°C colder than the in situ measurements. The high variability of single IR BT with WV conditions is demonstrated in the 2.4°C RMSD. The OLSST algorithm compares favorably with the buoy measurements, resulting in a RMSD of 1.12°C. This is much better than the uncorrected OLS BT which can vary 5 to 6°C from the actual surface temperature depending on WV. The quadratic algorithm provides the best statistical results (RMSD=1.04). This accuracy is remarkable given the OLS IR sensor thermal sensitivity of approximately 0.5°C. The mean difference, however, is nearly

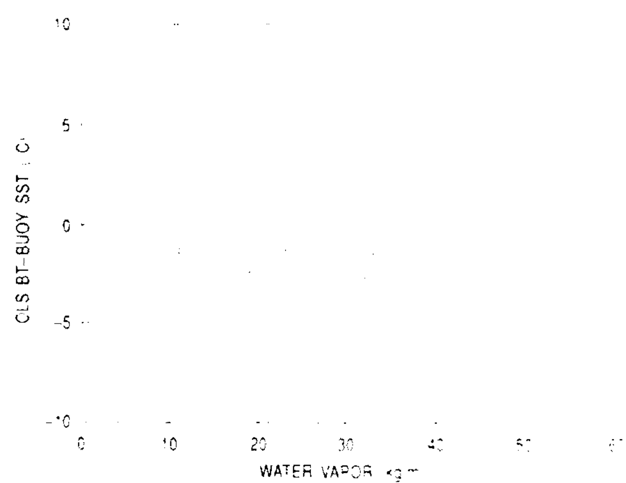

Fig. 2. Uncorrected DMSP OLS IR BT minus moored buoy SST measurements versus SSM/I WV.

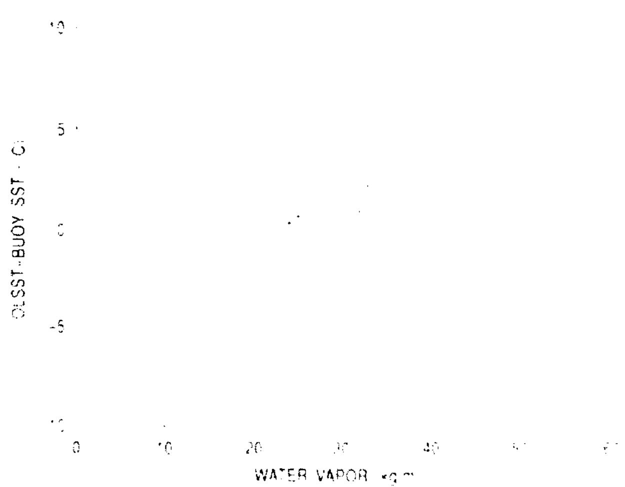

Fig. 3. OLSST minus moored buoy SST measurements versus SSM/I WV.

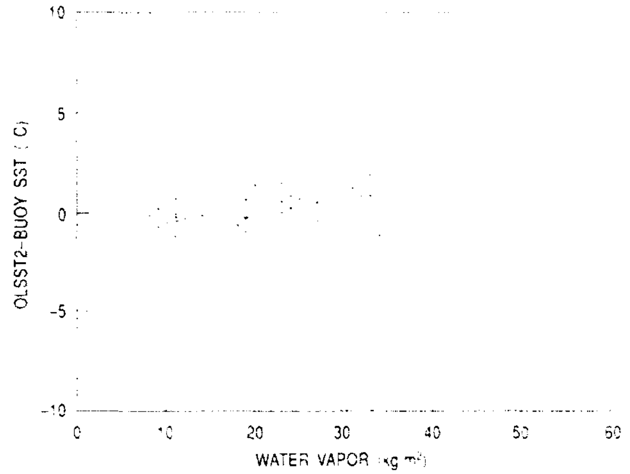

Fig. 4 OLSST2 minus moored buoy SST measurements versus SSM/I WV.

TABLE 3. Satellite-buoy matchup statistics.

Algorithm	Bias	St. Dev.	RMSD	Min.	Max.
OLS	−2.05	1.22	2.40	−5.40	−0.10
OLSST	−0.03	1.12	1.12	−2.18	2.17
OLSST2	0.37	0.97	1.04	−1.65	2.63

0.4°C, suggesting an average overcorrection for atmospheric effects over the total range of WV amounts employed in this independent test. Nevertheless, these results demonstrate that OLS single IR channel estimation of SST can be significantly improved if coincident WV data are available.

Discussion

Estimation of SST with satellite single IR channel sensors is effected by atmospheric contamination of the IR signal, mainly due to variation in WV. Uncorrected DMSP OLS IR BT has been shown to vary up to 5 or 6°C from coincident in situ buoy SST measurements, due to WV, resulting in an overall RMSD accuracy that exceeds 2°C. This study has demonstrated that coincident OLS IR BT and SSM/I-derived WV can be combined to obtain DMSP SST retrievals that are accurate to within approximately 1.0°C RMSD relative to moored buoy SST measurements in the western Atlantic ocean and Gulf of Mexico. These results demonstrate significant improvement over uncorrected single channel data. Best results are obtained with a correction algorithm containing a quadratic WV term.

This technique can be applied only to OLS imagery that has been properly cloud screened. It is important to point out that the atmospheric correction algorithm derived here for OLS data is also limited to the SSM/I swath width, approximately 1400 km, centered on the satellite nadir track. This study focused on data obtained from the western Atlantic ocean and Gulf of Mexico regions only. Thus, the results obtained may be limited to the regions and WV amounts employed in this study. Future studies should investigate other ocean areas and WV conditions to compare results.

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Douglas A. May, Naval Research Laboratory, Remote Sensing Applications Branch, Stennis Space Center, MS 39529-5004.

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