SENSOR SPECIFIC ERROR STATISTICS: A CASE STUDY OF THE AVHRR-DERIVED ADRIATIC SST

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Abstract

The sea surface temperature (SST) derived from the Advanced Very High Resolution Radiometer (AVHRR) sensors is well investigated parameter but due to the empirical nature of the regression coefficients, SST algorithms need calibration and validation with in situ measurements. In the era of operational monitoring and global forecasting of the ocean there is further emphasis on accuracy of the SST products (less then 0.4 K), hard to obtain with just one-sensor measurements. The recently initiated Global High-Resolution Sea Surface Temperature Pilot Project (GHRSST-PP) aims to combine several independent SST measurements into a single product with well defined error bounds. With such requirements in mind, we have carried out a detailed Adriatic centered investigation of sensor specific error statistics (SSES) for the AVHRR sensors aboard NOAA 16 and NOAA 17, for both daytime and nighttime passes. Results are compared with SSES statistics for MODIS aboard AQUA and TERRA.

Various parameters were investigated to assess the magnitude of the SSES changes in time and space. Two different in situ databases (drifter buoys and fixed-platform SST measurements), and two sets of algorithms were used in the analysis. Traditional split-window multi-channel algorithms and NOAA/NESDIS operational algorithms (non-linear split for day and multi-channel triple for night (“Andy”)) were used to derive daytime and nighttime SST estimates. To investigate a possible Adriatic sub-domain SSES variability the Adriatic Sea was divided in different domains: the open sea, the coastal zone and the Po-river influenced coastal zone. The third consideration was given to the influence of wind, derived from LAMI atmospheric model output (at 7 km resolution). Wind data were interpolated at matchup points and SSES were derived for low winds (below 2.5 m/s), medium winds (between 2.5 and 6 m/s) and high winds (higher than 6 m/s).

Results exhibit lowered nighttime scatter (~0.3 K) for algorithms using short IR channels, for all sensors and satellites and regardless of algorithm form. Daytime results for both algorithms were masked by diurnal warming effect, exhibiting constant positive bias (0.3 K) with higher scatter (0.7 K) in summer season for both satellites. The comparison of Adriatic domains suggests a small, but increased bias for coastal regions, for afternoon passes and the downstream of the Po delta in particular.

1 INTRODUCTION

The satellite infrared (IR) sensor measures radiation from the skin layer (at ~10 μm depth) of the sea surface attenuated by the absorption in the atmosphere. The main IR absorbent in the atmosphere, water vapor, has regional and seasonal variations which lead to the deviation from average global atmospheric state. The temperature of the skin layer differs from the temperature at the depth of in situ measurements and should be adequately parameterized depending on the wind speed and insolation. Semiempirical SST algorithm, used historically for satellite SST estimation, tries to overcome these problems by calculating coefficients from regression of satellite data with in situ data. This leads to the errors due to the deviation of the real atmospheric state from the average atmospheric state and the deviation of the real upper ocean state from the average upper ocean state.

The recently initiated GHRSTT-PP tries to combine several complementary satellite and in situ SST to deliver integrated global high resolution SST products [Donlon et al, 2007]. Combining different satellite sensors [Notarstefano et al., 2006] requires detailed knowledge of each sensor specific error. To that end we performed an extensive SST validation derived from two different IR sensors (AVHRR/3 and MODIS) aboard four different platforms (NOAA 16&17, AQUA & TERRA). Validation were performed by utilizing high quality in situ datasets from drifting buoys and a fixed platform which allow making detailed temporal and spatial error statistics for the Adriatic Sea. Different parameters were investigated and following analysis were performed: overall analysis of in situ datasets and satellite products, comparison of different SST algorithms, sensitivity of spatial subdomains and at the end, influence of the wind in SST retrieval.

2 DATA

2.1 In situ SST

The in situ SST data used for validation and assessment of satellite SST data come from two sources with distinct space and time resolution: drifter buoys and the platform IVANA-A. Drifter buoys were released in the Adriatic Sea in 2003 as part of DOLCEVITA program [Poulain et al., 2001]. There were 118 drifter buoys with the thermistors positioned 40 cm below the surface. On average there were 140 in situ SST data per day located mainly in upper half of the Adriatic Sea. The SST data from platform IVANA-A represent a very high temporal resolution data (every 20 minutes) measured at 1 meter depth during year 2004. Since the time spans of the two sets do not overlap it was not possible to directly compare the different in situ SST sources.

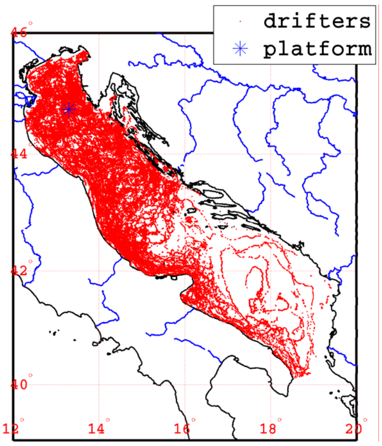


***Figure 1*: Position of the drifter buoys and the Ivana-A platform in the Adriatic Sea.**

2.2 Satellite SST

Four sets of SST satellite data were used in the validation to show the variability of sensor errors throughout the years 2003 and 2004. Two datasets (AVHRR NOAA 16 and NOAA 17) were based on the data received at locally operated HRPT satellite station at Rudjer Boskovic Institute, Zagreb [Tomazic et al, 2006], while the other two datasets (Modis AQUA and TERRA) were retrieved as L2 products from the Ocean Biology Processing Group (OBPG) at NASA. All datasets have the highest available resolution with the nominal pixel size of 1.1 km at nadir.

The data from the HRPT stream were processed to L1B format by ATOVS and AVHRR Pre-processing Package (AAPP) supplied by EUMETSAT (NWP SAF) [Atkinson and Dohery, 2005]. Additional navigation correction is performed by Automatic Navigation Adjustment (ANA-3.1) application supplied by METEO FRANCE, CMS [Brunel and Marsouin, 2002]; a further processing to L2 product is done with an “in-house” software. The SST was derived by semiempirical NASA/NESDIS operational algorithms: nonlinear split (NLSST) for daytime SST (uses long-wave IR channels) and multichannel triple (“MCAndy”) for nighttime SST (uses short-wave and long-wave IR channels) (*Table 1*). The multichannel split (MCSST) SST algorithm was used as initial, first guess, temperature for deriving NLSST. Coefficients for NLSST and MCAndy are different for each satellite platform and for day and night.

Two MODIS SST products were used in this study: SST derived with long-wave IR algorithm (LongSST) for daytime passes and SST derived with short-wave IR algorithm (ShortSST) for nighttime passes (*Table 1*). Both algorithms are semiempirical with monthly satellite-platform dependant coefficients. The LongSST algorithm coefficients depend additionally on T11-T12 differences (similar to the Pathfinder programme). The LongSST algorithm during daytime uses Raynolds oisst product as initial input (first guess), while the LongSST during nighttime uses ShortSST algorithm as initial input.

Instr.	Short	Day/Night	SST algorithm	Tsfc	Coeffs
AVHRR	MCSST	D/N	A1*T11 + A2*(T11-T12) + A3*(T11-T12)*(secΘ-1)+A4	-	Fixed
AVHRR	NLSST	D	A1*T11 + A2*Tsfc*(T11-T12) + A3*(T11-T12)*(secΘ-1)+A4	MCSST	Fixed
AVHRR	MCAndy	N	A1*T11+A2*T3.7+A3*T12+ A4*(T3.7-T12)*(secΘ-1) +A5*(secΘ-1)+A6	-	Fixed
MODIS	LongSST	D/N	A1*T11 + A2*Tsfc*(T11-T12) + A3*(T11-T12)*(secΘ-1)+A4	Reynolds/ ShortSST	Monthly
MODIS	ShortSST	N	A1*T3.9 + A2*(T3.9-T4.0) + A3*(secΘ-1)+A0	-	Monthly

***Table 1*: SST algorithms used in comparison between different sensors and products.**

3 METHODS

Validation of the satellite SST, estimated with the semiempirical algorithms, is based on a matchup database of temporal and spatial coincident satellite and in situ measurements. The following criteria were used in creation of the matchup database:

- 1h absolute temporal difference between satellite and in situ measurement
- In situ measurement located within an AVHRR/MODIS pixel

AVHRR specifics:

- cloud free pixel
- satellite zenith angle below 50°
- pixels with standard deviation less than 0.12 K of Ch4 and Ch5 values in 3x3 window around the central pixel

MODIS specifics:

- highest quality flag (0)

The time range was limited to two periods to ensure quasi-continues series of residuals (satellite – in situ) for all sensors for both day and night:

- 10.01.2003 – 17.09.2003 (for drifter buoy data)
- 10.02.2004 – 17.09.2004 (for platform data)

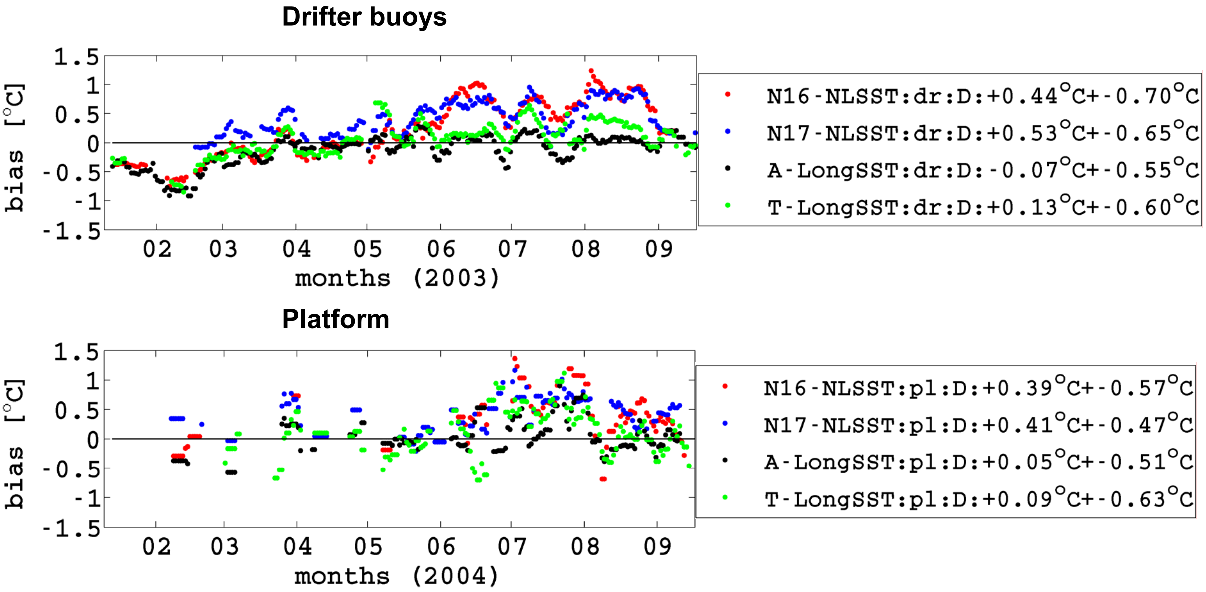
To show the temporal variability of the SSES error, residuals are filtered with 7-day moving average window, centered at each day. Each point in the results represents at least 10 averaged residuals. On average, there were 30 residuals for drifter buoy dataset and 15 residuals for platform dataset, for each defined period and for 7-day interval.

4 VALIDATIONS

Different parameters were investigated to assess the magnitude of the SSES changes in time and space. The first analysis includes all operational satellite SST products and in situ datasets to show overall performance with contributing errors. A second validation includes comparison of different SST algorithms: linear vs. nonlinear, fixed coefficients vs. monthly variable coefficients and algorithms with short-wave vs. long-wave IR channels. The third analysis includes influence of a coastal region and the Po-influenced zone, while the fourth analysis explores the wind impacted SSES variability.

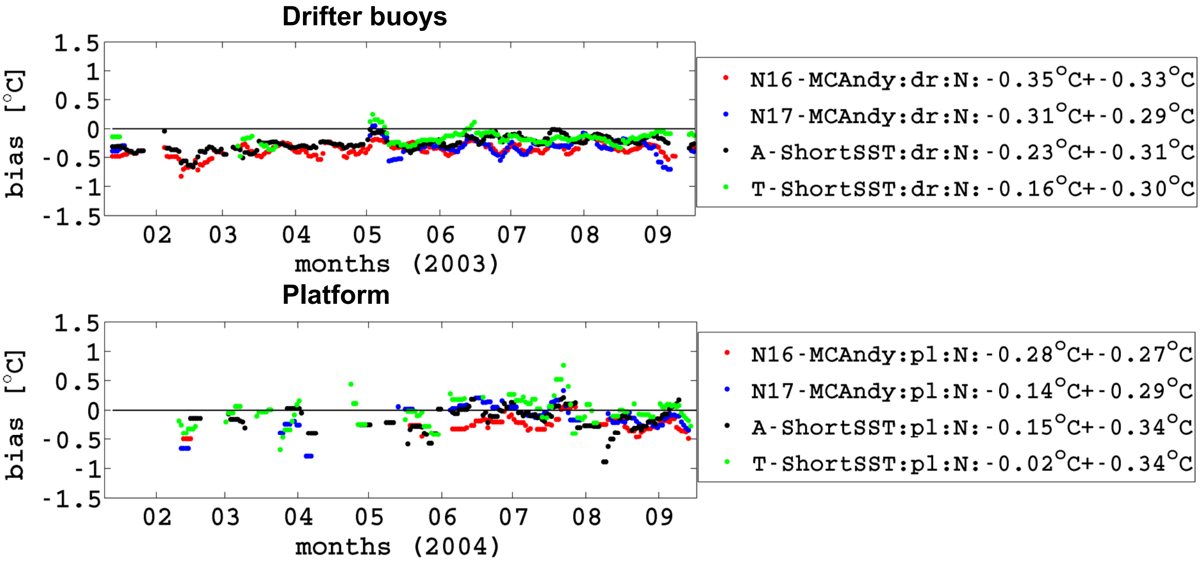
4.1 Satellite/in situ analysis

The SST SSES from two different sensors (AVHRR & MODIS) aboard four different satellites (NOAA 16 & 17, AQUA & TERRA) were analyzed. A comparison was performed separately for day and night and for drifter and fix-platform datasets.


Drifter buoys

Platform

***Figure 2*: Daytime SST biases of NOAA 16 & 17, AQUA and TERRA (N16, N17, A, T) satellites based on validation with the drifter buoys (upper figure) and the fixed-platform (lower figure) in situ datasets. Legend shows satellite name, SST algorithm, in situ dataset, day/night time and overall bias and scatter.**


Drifter buoys

Platform

***Figure 3*: Nighttime SST biases of NOAA 16 & 17, AQUA & TERRA satellites based on validation with the drifter buoys (upper figure) and the fixed-platform (lower figure) in situ dataset.**

Daytime AVHRR SST exhibits overall bias between 0.4°C and 0.5°C (depending on the platform and in situ dataset) with a highly seasonal variability (*Figure* 2). Maximum biases occur in summer season when weekly bias values can exceed 1°C. Overall MODIS bias has smaller values between -0.1°C and 0.1°C, with a maximum values also in summer season, but usually bellow 0.5°C. The most negative biases occurred in the mid of February 2003, regardless of sensor and algorithm, with values around -0.7°C. Zero bias occurs in the mid of April for all satellites, which suggests that in this period the Adriatic Sea upper layer and atmospheric conditions above it exhibit highest similarity to the average global upper layer and atmospheric conditions. Platform biases are for up to 0.1°C smaller compared to drifter buoys biases but due to the smaller number of matchup pairs, especially in the first two quarters of the year, the results are not directly comparable. Although the platform in situ data were available only for the year 2004, the results suggest similar seasonal trend, visible in drifter buoys data.

Nighttime scatters (*Figure 3*) from all satellites and for both in situ datasets are around 0.3°C (0.27°C – 0.34°C), which is similar to the AATSR nighttime scatters obtained in comparison to buoy in situ data (Corlett et al, 2006). Biases for MODIS are (again) closer to zero compared to the AVHRR biases, and platform dataset has smaller biases than the drifter dataset.

4.2 Algorithm analysis

Three different algorithm comparisons were performed in this analysis: 1) linear vs. nonlinear (MCSST vs. NLSST); 2) fixed vs. monthly-variable coefficients (NLSST vs. LongSST); and use or no-use of short-wave IR channels in estimating nighttime SST (MCAndy, ShortSST) (*Figure 4*).
Using the non-linear NLSST algorithm during daytime doesn't seem to improve SST estimation, compared to using the standard MCSST algorithm. The seasonal trend is the same and the overall bias and scatter is even higher (about 0.05°C), for both AVHRR platforms, NOAA 16 & 17. The reason could be the use of MCSST values as a first guess in the NLSST algorithm, which may introduce an additional noise in SST estimation, therefore corrupting the final result.

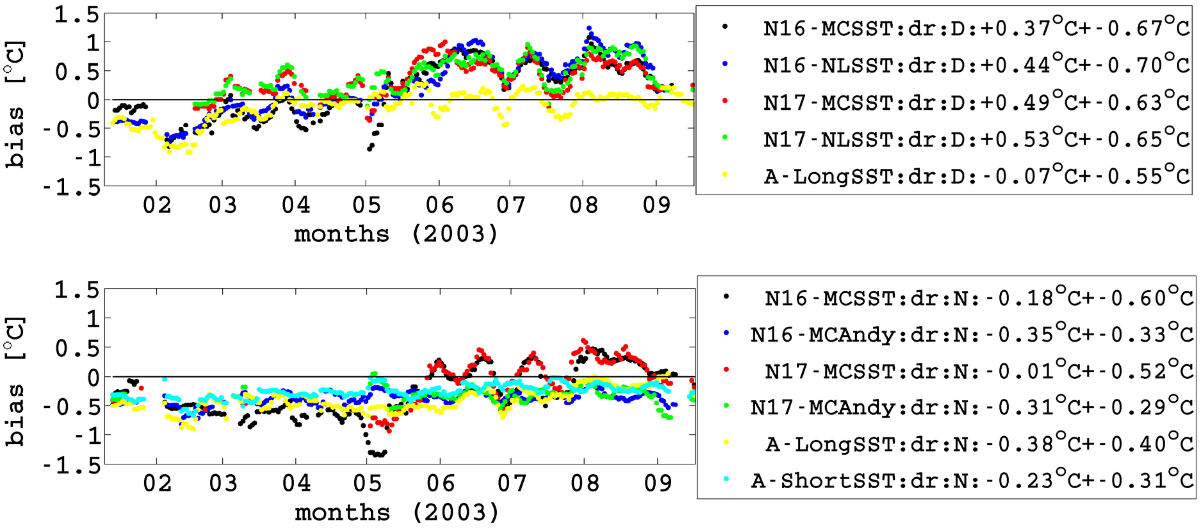


***Figure 4*: Daytime (upper figure) and nighttime (lower figure) SST biases comparison of linear and nonlinear algorithms (MCSST vs. NLSST) and algorithms with fixed and monthly variable coefficients (MCSST, NLSST, MCAndy vs. LongSST, ShortSST).**

Comparison between daytime, algorithm with monthly variable coefficients (LongSST) shows improvement in resolving seasonal variability especially over fixed-coefficients algorithm (NLSST). Winter daytime seasonal result is similar to NLSST values and exhibit negative biases. Besides time-dependant coefficients, the observed improvement is also attributed to the coefficients dependant on the T11-T12 differences.
During nighttime any algorithm which uses short-wave IR channel has similar SSES statistics: biases are negative (around -0.3°C) and scatter is rather small (around 0.3°C). Using long-wave IR channels during night reduces overall biases with degradation in overall scatter. Overall bias appears improved due to the cancellation of positive biases during the summer season and negative biases during the winter season. The MODIS LongSST algorithm actually uses ShortSST values as initial SST input and therefore is not pure long-wave IR algorithm.

Similar nighttime results, when using short-wave IR algorithms in different forms (fixed and monthly variable coefficients, different sensors and platforms), show the importance of using the IR channels in this spectral region.

4.3 Domain analysis

Adriatic Sea is divided in several domains to investigate possible Adriatic SSES sub-domain variability, and the influence of the river Po fresh water outflow in particular. The domains are: the open sea (more then 15 km from the coast), the coastal zone (15 km from the coast) and the Po-river influenced coastal zone (downstream from the river Po mouth).

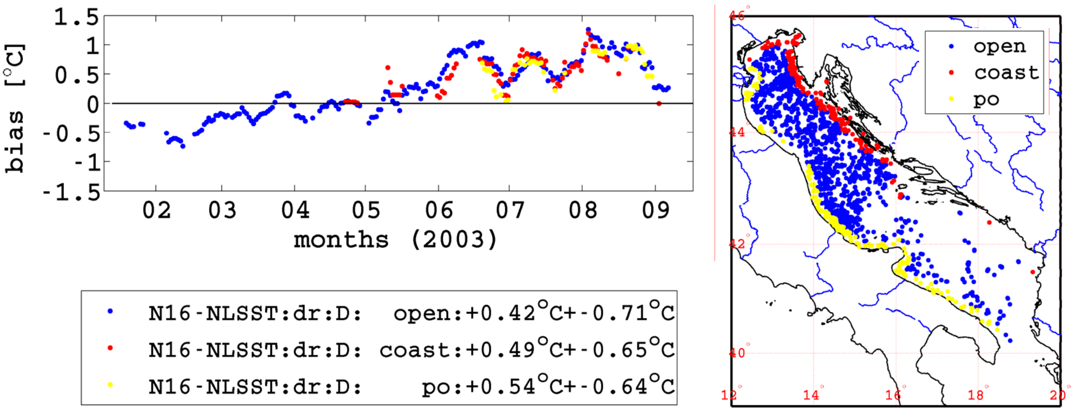


Figure 5**: Daytime SST biases (left) for three different domains: the open ocean, the coastal region and the river Po influcened coastal zone (right).**

The results show a small increase in overall bias toward the coastal area and the river Po influenced domain (0.42°C → 0.49°C → 0.54°C) with lowering of overall scatter particularly for NOAA 16 afternoon passes. This increase can be also a problem of uneven distribution of residuals since in the first quarter there are data only from the open sea. Another issue is the river Po outflow which is the lowest in the third quarter when there were available majority of matchup data.

4.4 Wind analysis

Wind has an important role in mechanical mixing of the upper boundary layer and creating vertical temperature homogeneity. Semiempirical NLSST algorithm uses coefficients derived from regression of satellite data and in situ data at bulk depth (SST_{depth}). The wind regime in Adriatic Sea is different (*Figure 6*) compared to the open ocean wind regime which could contribute to the errors in retrieving SST with global coefficients. We used two sources of wind speed data. The first is the output from LAMI (Limited Area Model Italy) model at 7 km resolution where wind data were interpolated to the matchup points. These data were used in analysis of residuals. The second is the QuikScat data from COGOW [Risien and Chelton, 2006] climatology at 0.5 degree resolution. These data were used to compare overall wind regime in Adriatic, Mediterranean and equatorial Pacific Ocean where TOGO-TAO buoys are located. TOGO-TAO in situ SST data represent about 10% of in SST data used in derivation of global coefficients [Kilpatrick et al., 2001]. Residuals are analyzed separately for winds between 0 and 2.5 m/s (low), 2.5 and 6 m/s (medium) and winds higher than 6 m/s (high).

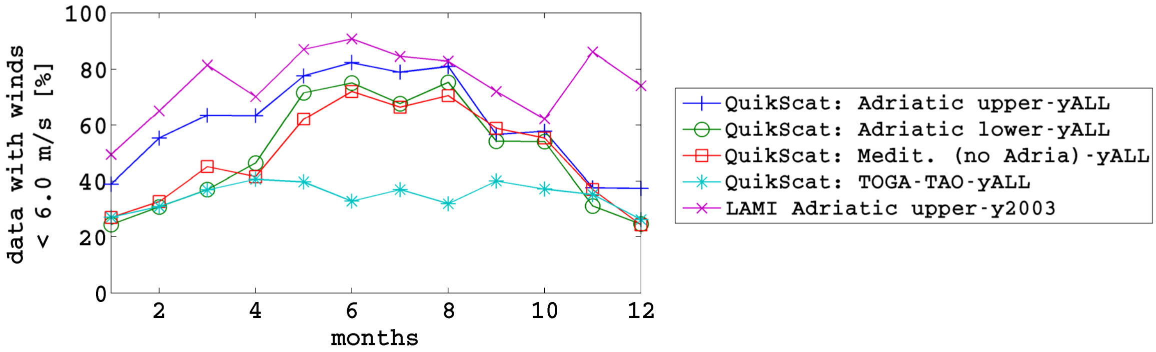


***Figure 6*: Percentage of data with the wind speed lower then 6 m/s. Wind data are derived from QuikScat COGOW climatology (Adriatic, Mediterrane, TOGA-TAO) for period between 1999 and 2004 and from the LAMI model wind data which correspond to matchup points (upper half of Adriatic sea) for year 2003.**

Statistics show a very high percentage of low and medium winds (80%) over the Adriatic Sea during the second and the third quarter, which leads to inadequate mixing of upper layer [Donlon et al, 2002]. For the same period the percentage of low and medium winds at TOGA-TAO stations, for example, is around 30%. This difference suggests that the Adriatic wind regime is different when compared to the wind regime in which global matchup data were collected. The difference should be recognized when estimating SST in low-wind seasons. Looking specifically at year 2003 from COGOW climatology the winds over Adriatic Sea are even lower and corresponds well with LAMI values which were actually used in matchup analysis.

Daytime results of wind analysis show substantial decrease in overall bias when using residuals with corresponding higher winds for NOAA 16 and 17 (not shown). Overall bias is reduced as the wind speeds become higher (~0.15°C from low to medium wind speeds and ~0.2°C from medium to high wind speeds) while the scatter stays rather high (around 0.7°C). Nighttime results (not shown) doesn't show much differences (less then 0.05°C) regardless of wind speed change.

5 CONCLUSIONS

Rich in situ datasets combined with four available satellite SST datasets allows investigation of many different parameters focused on a specific region. The main purpose of this study was to compare global satellite SST estimates and determine the absolute errors for the available in situ measurements in the Adriatic Sea. To that end we used NOAA 16 & 17 data from local HRPT station and MODIS AQUA & TERRA retrieved from OBGP at NASA. These data were validated with extensive drifter buoys and fixed-platform datasets. NOAA/NESDIS operational algorithms (NLSST/MCSST triple) were compared to the historical MCSST split algorithm, different domains were utilized to investigate possible spatial variability and wind analysis were performed to show the effects of wind speed on using bulk temperature data for the validation of satellite SST data.

The main result is a quite small nighttime scatter of 0.3°C (AATSR accuracy) regardless of sensor type, but sizable negative nighttime bias in the range between -0.30°C and -0.15°C. During daytime there is a high variability in signal bias, visible in all SST datasets which needs further validation. Comparison of different algorithms shows that those with monthly-variable coefficients (LongSST) better capture summer daytime variability, reinforcing the use of AVHRR Pathfinder-like coefficients in SST algorithm. Nighttime MCSST split-window algorithm still shows variability similar to daytime, whereas nighttime MCSST triple-window algorithm does not. This suggests that the atmospheric correction is a problem and further investigation is needed to resolve observed bias variability. Wind analysis shows a big improvement (for 0.3°C) in overall bias reduction when using matchups with higher winds (> 6 m/s). This corresponds well with the fact that the Adriatic Sea has a significantly higher frequency of lower winds (especially in second and third quarter – 80%-90%) compared to the frequency of lower winds at TOGA-TAO stations (30%) or for the whole world from the SSM/I sensor (30%) (Donlon et al., 2002). The global coefficients derived in higher wind regimes won't be adequate for Adriatic area which is visible from this analysis.

Acknowledgments

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