A Multiplatform-Merged (MPM) SST Analysis

WANQIU WANG AND PINGPING XIE

NOAA/NWS/NCEP/Climate Prediction Center, Camp Springs, Maryland

(Manuscript received 29 November 2005, in final form 14 March 2006)

ABSTRACT

Previous observational studies indicated that local sea surface temperatures (SSTs) near the west coast of the United States, in the Gulf of California, and in the Gulf of Mexico have strong impacts on the North American monsoon (NAM) system. Simulations of the NAM by numerical models are also found to be sensitive to the specification of SSTs. Accordingly, a reliable SST dataset is essential for improving the understanding, simulation, and prediction of the NAM system. In this study, a new fine-resolution SST analysis is constructed by merging in situ observations from ships and buoys with retrievals from National Oceanic and Atmospheric Administration (NOAA) satellites (NOAA-16 and NOAA-17), Geostationary Operational Environmental Satellites (GOES), the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), and the Advanced Microwave Scanning Radiometer (AMSR). Called the multiplatform-merged (MPM) SST analysis, this new product of 3-hourly SST is defined on a 0.25°×0.25° latitude–longitude grid over the Western Hemisphere (30°S–60°N, 180°–30°W). The analysis for the period of 15 May–30 September 2004 shows that the MPM is capable of capturing small-scale disturbances such as those associated with the tropical instability waves. It also depicts local sharp gradients around Baja California and the Gulf Stream with reasonable accuracy compared with the existing analyses. Experiments have been conducted to examine the impacts of the addition of satellite observations on the quality of the MPM analysis. Results showed that inclusion of observations from more satellites progressively improves the quantitative accuracy, especially for diurnal amplitude of the analysis, indicating the importance of accommodating observations from multiple platforms in depicting critical details in an SST analysis with high temporal and spatial resolutions.

1. Introduction

Observational studies have revealed that sea surface temperatures (SSTs) have strong local effects in the seasonal evolution and interannual variation of the North American monsoon (NAM) system. Mitchell et al. (2002) showed that the timing, intensity, and regional extent of the NAM rainfall are strongly related to the Gulf of California (GoC) SSTs. Monsoon rainfall did not occur until GoC SSTs became warmer than 26°C and about 75% of the rainfall in the Arizona–New Mexico region occurred after GoC SSTs exceeded 29°C. The NAM monsoon was also found to be positively correlated with SSTs over the Gulf of Mexico (Huang and Lai 1998; Markowski and North 2003) and negatively correlated with SSTs along the west coast of the United States (Carlton et al. 1990). Numerical studies have been conducted to investigate the impacts of SSTs on the simulation of the NAM. Stensrud et al. (1995) found that the NAM rainfall can be reasonably reproduced by the hydrostatic version of the fourth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM4) when SSTs in the GoC were greater than 29.5°C. Mo and Juang (2003) investigated the influence of GoC SST anomalies on NAM rainfall with the National Centers for Environmental Prediction (NCEP) Regional Spectral Model and found that warm (cold) SSTs in the GoC are responsible for more (less) rainfall along the western slopes of the Sierra Madre Occidental. Li et al. (2005) showed that the simulated NAM rainfall from the PSU–NCAR MM5 was sensitive to the specified SSTs. In addition, accurate estimate of SSTs are also found to be important in the monitoring and forecast of hurricane activities in the Gulf of Mexico and the western Atlantic (Bender and Ginis 2000), which have strong potential impacts over North America.

Results from these studies indicate that an accurate
SST analysis is essential for understanding the mechanisms of the NAM variability and for its satisfactory simulations and predictions. Two of the widely used operational SST datasets are the weekly optimum interpolation (OI) SST analysis of Reynolds and Smith (1994) and Reynolds et al. (2002), and the real-time global (RTG) daily analysis of Thiébaux et al. (2003). Both analyses are generated by combining in situ observations and SST retrievals derived from multichannel infrared observations of the Advanced Very High Resolution Radiometer (AVHRR) on board the polar-orbiting National Oceanic and Atmospheric Administration (NOAA) satellites (May et al. 1998). While the weekly OI and daily RTG SST analyses have been applied successfully in monitoring weather/climate and forcing numerical models as boundary conditions for weather/climate simulation and prediction, further desirable improvements in their quantitatively accuracy and time–space resolution are limited largely due to the infrequent sampling of polar-orbiting NOAA satellites and the inability of the AVHRR observations to estimate SST under cloudy sky.

The recent availability of several new satellite-based SST observations makes it possible to construct fine-resolution SST analyses with improved quality. In particular, passive microwave observations from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI; Kummerow et al. 1998; Wentz et al. 2000) and the Advanced Microwave Scanning Radiometer (AMSR; Wentz and Meissner 1999) have been used to derive SST estimates over both clear and cloudy skies. Multichannel infrared observations from the Geostationary Operational Environmental Satellites (GOES; Wu et al. 1999; Maturi et al. 2004), meanwhile, provide hourly and 3-hourly SST maps over cloud-free regions. Guan and Kawamura (2004) and Reynolds et al. (2005) showed that including information from additional satellites will enhance the SST analysis based on observations from in situ and NOAA AVHRR. Potential improvements upon the widely used OI and RTG analyses may be also made through refining the interpolation algorithm. One concern with the OI and RTG analyses is their capability in resolving the disturbances of small spatial scales such as the contrast between the GoC and the eastern Pacific to its west, tropical instability waves, and structures of sharp spatial gradient such as the Gulf Stream. Chelton and Wentz (2005) showed that one difficulty of the weekly OI analysis is that it was not able to sufficiently resolve these features, largely due to the use of a large spatial background error correlation scale (600–800 km). The RTG analysis was performed with a smaller spatial background error correlation scale (100–450 km) and was found to improve the representation of these features. When used as the lower boundary condition for an atmospheric model, the RTG analysis has been found to dramatically improve the surface wind stress compared with the use of the OI analysis (Chelton 2005). However, the amplitude of spatial SST gradient in the RTG was still too small compared with that in the AMSR observations (Chelton and Wentz 2005).

One strong component in the SST variability is the diurnal cycle, which has not been included in the existing SST analyses. In regions where wind speeds are low (e.g., Gulf of Mexico), diurnal changes may exceed 3 K (Weller and Anderson 1996; Wu et al. 1999; Gentemann et al. 2003). In the GoC, one of the primary regions of the North American Monsoon Experiment (NAME), wind speeds are often very low or calm, making the SST there susceptible to relatively large diurnal SST variations. Using 4-km, 3-hourly SST from GOES, Mitchell et al. (2002) showed that diurnal SST changes in the northern GoC during June were typically 2–3 K, but could be as large as 4 K. Through its impact on the surface heat and moisture budget, the SST diurnal cycle may strongly affect the boundary layer structure, precipitation, and cloud amount in the atmosphere (Dai and Trenberth 2004). Diurnal cycles in SST may also help organize the convection on intraseasonal time scales (Woolnough et al. 2001). The NAM system, which is strongly affected by local SST anomalies, also contains substantial diurnal variations (Xie et al. 2005). An SST analysis that resolves the diurnal cycle will be useful for examining the role of SSTs in the diurnal anomalies of the NAM system.

Recently, a new fine-resolution SST analysis has been created at the NOAA/Climate Prediction Center (CPC). Called the multiplatform-merged (MPM) SST analysis, this analysis is developed by merging in situ observations with satellite retrievals from NOAA-16, NOAA-17, TMI, AMSR, and GOES satellites. The MPM is calculated on a 0.25° × 0.25° latitude–longitude grid with a spatial background error correlation scale of 50 km and a time interval of 3 h, thus allowing oceanic eddies, tropical instability waves, local sharp spatial gradients, as well as the diurnal cycle to be reasonably resolved. Currently, the MPM analysis is calculated over the Western Hemisphere (30°S–60°N, 180°–30°W). This paper focuses on 15 May–30 September 2004, the period of the North American Monsoon Experiment (NAME) Model Assessment Project 2 (NAMAP2; Gutzler et al. 2005). We will describe the input SST observations, document the algorithms used to construct the analysis, and present a preliminary comparison with existing SST analyses.
2. Input data and preprocessing

Construction of an SST analysis of high spatial and temporal resolution requires the utilization of SST data from as many individual sources as possible. In defining the OI and the RTG global SST analyses, satellite observations are combined with in situ observations to enhance the observational coverage (Reynolds and Smith 1994; Reynolds et al. 2002; Thiébaux et al. 2003). Only the satellite-retrieved SST fields from the Advanced Very High Resolution Radiometer (AVHRR) aboard the polar-orbiting NOAA satellites, however, are included in these two analyses, limiting their ability to resolve SST variations associated with synoptic and mesoscale systems. The recent availability of SST observations from several new operational and experimental satellites makes it possible to construct an SST analysis of higher resolution. In particular, the 3-hourly SST retrievals from GOES geostationary satellites makes it possible to create an SST analysis of subdaily time scales over the Western Hemisphere. In this work, we perform a 3-hourly SST analysis on a 0.25° × 0.25° latitude–longitude grid over a regional domain from 30°S to 60°N, 180° to 30°W using SST observation data from multiple platforms, including in situ observations and satellite retrievals from NOAA-16, NOAA-17, GOES, TMI, and AMSR. All raw individual observations within a 3-h time step and within a grid box of 0.25° × 0.25° latitude–longitude are first averaged to form superobservations. The resulting superobservations for each grid box and time step are then subject to quality control and bias correction before being used as the input for the analysis.

a. Input observations

Despite their sparse distribution, SST measurements by ships and buoys have been widely used as a mainstay of many SST analyses, due to their extended record period and relatively uniform availability over most of the global oceans (Kaplan et al. 1998; Rayner et al. 1996; Reynolds 1988; Reynolds et al. 2002; Smith et al. 1996; Thiébaux et al. 2003). Quantitative accuracy of individual in situ SST reports is not high, often at 1°C or worse. Mean values of these measurements, however, are stable and present little regionally and seasonally dependent bias, making them useful for determining the overall magnitude in a merged SST analysis. The ship- and buoy-observed SST reports used in this work are the same as those used in creating the OI and RTG analyses. On average, about 400–500 of the 0.25° × 0.25° latitude–longitude grid boxes over our target domain have at least one report for a 3-hourly time period.

Infrared measurements of the AVHRR aboard polar-orbiting NOAA satellites have long been used to estimate SSTs over the global oceans. Pixels contaminated with clouds are first screened and quality controlled. Atmospheric influences (mainly the water vapor) are then quantified and SST values are calculated for the cloud-free pixels from the AVHRR multichannel observations through a set of retrieval models (May et al. 1998; Ignatov et al. 2004). While several AVHRR-based SST products are available, AVHRR SST retrievals generated by the U.S. Navy are used in this study. During our data period from 15 May to 30 September 2004, the AVHRR SST data are available from two polar-orbiting satellites: NOAA-16 and NOAA-17, providing up to 4 times a day of SST observations on a footprint of 1 km over cloud-free regions.

The SST retrievals from radiometer observations of the Geostationary Operational Environmental Satellites (GOES) are very similar to those with the NOAA AVHRR. SST values at cloud-free pixels are computed through the combined use of radiometer observations at several infrared channels. Although the high temporal resolution of the GOES observations provides the possibility of detecting fast-moving clouds through the comparison of successive images (Wu et al. 1999), the coarser pixel size of ~4 km and the existence of extensive and slow-moving marine stratus clouds make it more difficult to screen out cloud-contaminated pixels with the GOES observations. Routine operation has been started recently at NOAA’s National Environmental Satellite, Data, and Information Service (NESDIS) to generate SST maps at a resolution of hourly (4 km)−1 for three geostationary satellites: GOES-9, -10, and -12, located at 155°E, 135°W, and 75°W, respectively (Maturi et al. 2004). SST maps from GOES-10 and -12 are used to cover the target domain of this study.

One of the major shortcomings of the SST retrievals from the AVHRR and GOES observations is their inability to estimate SST under cloudy sky. While in situ observations may provide some sparse information over cloudy areas, satellite observations of transparent clouds are highly desirable to achieve quasi-complete spatial coverage of the SST variations. With the commencement of the microwave observations from the Tropical Rainfall Measuring Mission (TRMM) satellite, such an all-sky SST retrieval product became available from December 1997. A high quality dataset of SST retrievals has been created by Wentz et al. (2000) from the passive microwave radiance at 10.7 GHz measured by the TRMM Microwave Imager (TMI). While the footprint size of 46 km is larger than the 1- and 4-km resolutions of the AVHRR and GOES satellites,
respectively, SST retrievals may be derived from TMI observations for all situations except for heavy rainfall regions. The TRMM satellite observes the tropical belt of $40^\circ$S–$40^\circ$N about twice a day on a precessing orbit.

In addition to the TMI product, SST retrieval from microwave observations of the Advanced Microwave Scanning Radiometer (AMSR) aboard the Earth Observing System (EOS) Aqua satellite is also used as input in our merged SST analysis. Similar to that of the TMI, the AMSR SST is defined by the combined use of the microwave channel observations (Wentz and Meissner 1999; Chelton and Wentz 2005). Available from June 2002, the AMSR covers the entire global ocean twice a day on a polar orbit with a spatial resolution of 56 km.

While the individual input SST datasets described above have different temporal and spatial resolutions, 3-hourly mean values are defined for each $0.25^\circ \times 0.25^\circ$ latitude–longitude grid box over the entire analysis domain and used as the inputs (superobservations) for the merging algorithm. Figure 1 shows the distribution of mean SST for 2 July 2004, for the individual input data sources. None of the individual SST datasets provides complete spatial coverage over the entire domain, with the in situ observations exhibiting the sparsest distribution. These individual data sources present similar patterns of spatial distribution; their local magnitudes, however, differ from each other. For example, SSTs in the Caribbean Sea from GOES appear to be colder than those from the TMI and AMSR, indicating the necessity of bias correction. Another feature from the comparison of the spatial distribution of different observations is that retrievals from different satellites may be complementary for local areas. For example, the Gulf of California and other coastal regions for which observations are not available from the TMI and AMSR due to land contamination are covered by NOAA-16, NOAA-17, and/or GOES. On the other hand, infrared retrievals from GOES, NOAA-16, and NOAA-17 for southeast Pacific areas are frequently affected by large stratus cloud amounts, which has little effect on the observations from the TMI and/or AMSR. Observations for the Pacific north of $30^\circ$N are largely missing in NOAA-17 and are not available in TMI, but are available from AMSR and GOES for most of this region. Figure 2 shows the number of daily total super-observations. Fluctuations in the total number of observations are small throughout the period, with the smallest number from ship observations and largest number from GOES retrievals. Observations from NOAA-16 and NOAA-17 are less than half of those from the TMI and AMSR, indicating the importance of including microwave retrievals.

b. Data screening

Before individual SST datasets are used as inputs to construct the merged SST analysis, a quality control (QC) procedure is performed to remove wrong and inaccurate reports. This is done for each day and for each $0.25^\circ \times 0.25^\circ$ latitude–longitude grid box by cross-checking with all available data sources. For this purpose, daily mean SST maps are created by spatially interpolating the median values of all input observations available at each grid box. Original 3-hourly in situ reports and satellite estimates are then compared with this daily map and those with an absolute difference of $3^\circ$C or more are removed as outliers. For example, the very low temperatures in the southeast Pacific from GOES in Fig. 1, apparently due to cloud contamination, are $3^\circ$C colder than the average of other observations and are removed.

This QC procedure is repeated after the bias inherent in the individual satellite observations is removed as described in section 3a, but with stricter criteria. The daily mean SST maps are redefined using the in situ and bias-corrected satellite observations. Three-hourly observations that are $2.0^\circ$C warmer or $1.5^\circ$C colder than the corresponding daily mean values are tossed away as bad reports. The asymmetric criterion amplitudes for diurnal deviations ($1.5^\circ$C for negative deviations and $2.0^\circ$C for positive deviations) are designed to reduce the risk of including infrared-based SST estimates (AVHRR, GOES) with cloud contamination. The threshold values used here are based on preliminary tests with the real data to achieve the best results of removing as many cloudy pixels as possible while retaining all correct SST observations. The maximum allowed daily SST changes of $3.5^\circ$K, however, implies that some of the SST data presenting large diurnal variations may be tossed away in the quality control process. In the future, this might be improved by adopting a set of regionally and seasonally changing thresholds in the screening processes.

3. Algorithms

a. Bias correction

As an important step in constructing our SST analysis, biases inherent in the input satellite observations must be corrected by comparison with the corresponding in situ observations. Reynolds et al. (1989) and Reynolds and Smith (1994) demonstrated that a bias correction is necessary for satellite-based SST estimates to remove errors associated with volcanic or other aerosols. The SST bias correction method developed by Reynolds (1988) has been used in both the OI and RTG
Fig. 1. SST (°C) for 2 Jul 2004, from in situ observations and retrievals from GOES, NOAA-16, NOAA-17, TRMM/TMI, and AMSR observations.
analyses (Reynolds and Smith 1994; Reynolds et al. 2002; Thiebaux et al. 2003). The bias in this method is obtained by solving Poisson’s equation so that large-scale satellite biases and gradients can be adjusted relative to the in situ data. In this paper, we apply a different technique to adjust the satellite retrievals through matching their probability density function (PDF) against that based on in situ observations. One advantage of this technique is that it is capable of correcting retrieval errors that are range dependent.

Applied widely in correcting satellite observation biases with high range dependency (Turk et al. 2003; Huffman et al. 2003; Joyce et al. 2004), the PDF matching technique corrects the bias inherent in the satellite estimates by adjusting the satellite observation values to match the PDF of the corresponding in situ observations. First, matching pairs of in situ and satellite-observed 3-hourly SST data are collected. A PDF function is then defined for the in situ and satellite observations, respectively, as a table of SST values and their corresponding percentiles. Assuming that the PDF of the satellite-observed SST should be the same as that of the in situ data, the bias of the satellite observations is defined as the difference between the satellite-retrieved SST and the in situ observations at the same percentiles.

In practice, PDFs are calculated for each 1° × 1° latitude–longitude grid box and for each day using the matching 3-hourly SST data pairs available during a 46-day period prior to the target analysis day. Data over the target grid box and its nearby regions are used so that at least 500 pairs of data are included to define the PDF functions. For the TMI and AMSR SST estimates, a single bias correction is applied to both the ascending and descending orbits, assuming that the bias is less dependent on the observation time. For the SST estimates from the NOAA-16 and -17 polar-orbiting satellite estimates, a bias correction is performed separately for their daytime and nighttime observations to account for the different bias structures caused by the different channels and algorithms used in the retrieval. For the SST estimates from GOES, PDF tables are created for each 3-h interval to reflect the changes in the infrared data and retrieval equations used.

The bias correction procedures are implemented for each of the input satellite observations for the entire period from 15 May to 30 September 2004. Shown in the top panel of Fig. 3 are SST histograms of in situ observations, original and PDF bias-corrected estimates from TMI over the entire domain (30°S–60°N, 180°–30°W) for summer 2004 (15 May–30 Sep). (bottom) Same as in the top panel except for NOAA-17 Daytime observations for a period from 2 Jul to 30 Sep 2004. Results for bias-corrected SSTs through solving the Poisson equation are printed in blue for comparison.
TMI tends to overestimate SSTs over warm surfaces, while missing the peak of the SST histogram at \( \approx 28.1^\circ C \) as shown in the in situ observations. The PDF matching technique corrected the bias in the original TMI successfully, resulting in a histogram that matches closely with that of the in situ observations throughout the entire SST range. The bottom panel of Fig. 3 presents a comparison of the bias corrections for the SST estimates derived from the daytime observations of NOAA-17 through the PDF matching and the Poisson equation methods. The correction of the Poisson method is obtained with the bias correction code and observational input data used in the NCEP operational OI analysis. SST histograms have been computed over the entire data domain and for the time period from 2 July to 30 September 2004. The calculation of a different period for the bottom panel of Fig. 3 from that for the top panel is due to the switch from NOAA-16 to NOAA-17 in the NCEP operational OI analysis starting 2 July 2004. While both methods yielded histograms of corrected SSTs that are close to that of the in situ observations, better agreement with the in situ observations is seen for SSTs corrected through the PDF matching technique.

b. Statistical analysis

The MPM analysis is produced on a grid of \( 0.25^\circ \times 0.25^\circ \) latitude–longitude based on a statistical interpolation method, and is calculated as an increment relative to a background first guess. Inputs are taken as superobservations on the analysis grid, which are the average of individual observations within each grid box. A 3-h time step is used for the analysis to resolve the diurnal cycle. The background first guess is taken as the analysis of the previous step plus the increments of the seasonal daily mean and the diurnal cycle. A set of statistics needs to be specified for the analysis, including observations error amplitude and background first-guess error amplitude. The treatment of the background first guess in the MPM results in a dependence of the first-guess error amplitude on the analysis itself. A preliminary analysis was first created with a first-guess error amplitude estimated from the daily RTG analysis to diagnose the error amplitude of the first guess for the MPM. A final analysis is then produced with the diagnosed error amplitude.

1) Numerical schemes

The MPM analysis follows the numerical schemes of Reynolds and Smith (1994) with different specifications of error statistics. The increment at an analysis grid point is a weighted average of the increments of the surrounding observations. The weight is a function of the background and observation error covariance, and is defined such that the expected error variance of the analysis is minimized (Lorenc 1981; Daley 1991; Reynolds and Smith 1994). Errors in observations after the bias correction are assumed uncorrelated and only the error variance needs to be specified. Background error covariance is assumed to follow a Gaussian distribution with a specified spatial scale. This background error correlation scale determines the spatial extent of the influence on the observations surrounding each analysis grid point. The larger the error correlation scale, the smoother the resulting analysis. A scale of 600–800 km is used in the OI analysis of Reynolds and Smith (1994) and the scale used in the RTG SST analysis is 100–450 km (Thiébaux et al. 2003). A scale of 50 km is used in the MPM analysis to resolve the important small-scale structures, such as the tropical instability waves, the Gulf Stream, and large gradients near costal regions. In particular, the use a smaller correlation scale in our analysis compared with that in the OI and RTG enables the separation of the Gulf of California and the west coastal areas of Baja California in defining the SST analysis. The analysis is computed for each \( 1^\circ \times 1^\circ \) box using observations within a cocentric square box with a side length of about 275 km.

Observation error variance is estimated using collocated different types of observations. Let \( V_{BUOY} \), \( V_{AMSR} \), and \( V_i \) denote the error variance of three observation types BUOY, AMSR, and \( i \), with \( i \) representing other types of observations: SHIP, NOAA-16 Daytime, NOAA-16 Nighttime, NOAA-17 Daytime, NOAA-17 Nighttime, TMI, and GOES. Using SD(BUOY, AMSR), SD(AMSR, \( i \)), and SD(BUOY, \( i \)) to represent the mean squared differences between observations and assuming different observation types after bias correction are not correlated, it is straightforward to get

\[
V_{BUOY} = SD(BUOY, AMSR)/2 + SD(BUOY, i)/2 - SD(AMSR, i),
\]

\[
V_{AMSR} = SD(BUOY, AMSR)/2 + SD(AMSR, i)/2 - SD(BUOY, i), \quad \text{and}
\]

\[
V_i = SD(BUOY, i)/2 + SD(AMSR, i)/2 - SD(BUOY, AMSR).
\]

Using collocated observations for each group of three observation types, the error variance can be estimated. BUOY and AMSR are used for the calculation for each
of other observations because of their availability for different regions. Varying the three observation types within each group does not change the results substantially. Here, \( V_{\text{BUOY}} \) and \( V_{\text{AMSR}} \) are taken as the average of the resulting values from each group. A domain average of the error variance is used for the current version of the MPM analysis. The diagnosed amplitude of the observation error (square root of the error variance) is given in Table 1.

2) Preliminary Analysis

A preliminary analysis was created for 1 May–30 September 2004, using the diagnosed observation error statistics and with a background error amplitude of 0.32 K, estimated based on the daily mean RTG analysis. The seasonal cycle of the daily mean is computed from daily values interpolated from the OI weekly analysis and is taken as the annual mean plus the first four annual harmonics of the 23-yr average of 1982–2004. A zonal mean diurnal cycle estimated based on GOES observations is used for the preliminary analysis.

3) Final Analysis

The preliminary analysis was used to rediagnose the background first-guess error in a way similar to that for diagnosing the observation error variance described above by replacing the observation type \( i \) with the preliminary analysis. The domain average of the rediagnosed error amplitude is 0.38 K. A diurnal cycle is also

![Daily mean SST (°C) for 2 Jul 2004, as defined by the MPM SST analysis.](image-url)
rediagnosed based on the preliminary analysis. The re-
diagnosed diurnal cycle for each grid point and for each
day is taken as a spatial and temporal average. The
spatial average is over a 20° box centered at the grid
point. The temporal average spans 31 days centered at
the analysis day, except for 1–15 May and 16–30 Sep-
tember, for which the values within 15 days of the cen-
ter day from the available preliminary analysis are used
for the calculation of the average.

4) EXAMPLES FROM THE ANALYSIS

The final MPM analysis is produced with the rediag-
nosed background error and diurnal cycle. Figure 4
shows the daily mean SST from the MPM analysis for
2 July 2004. The analysis synthesizes the complemen-
tary information from all available observations for
many areas shown in Fig. 1. Interesting features cap-
tured in the analysis include the sharp contrast between
the region west of Baja California and the Gulf of Cali-
ifornia, the strong SST gradient near the west coast of
Baja California, the instability waves in the tropical
eastern Pacific north of the equator, and the waves
along the Gulf Stream. One of the main features of this
analysis is that it resolves the diurnal cycle. A time
series of the total SST for 15 May–30 September 2004 is
shown in Fig. 5 for an analysis grid box in the southern
GoC, with a zoom-in for a 10-day period from 1 to 10
July 2004. Seasonal, day-to-day, as well as diurnal varia-
tions of SST can be clearly seen. The mean SST rises
steadily from ~26°C in the middle of May to ~31°C
during late August and early September. SST variations
of synoptic time scales are observed, implying the ex-
istence of an atmospheric influence to the Gulf of Cali-
forina. A spatial distribution of the diurnal cycle (de-
viation from daily mean) averaged for the entire data
period from 15 May to 30 September 2004 is presented
in Fig. 6 for the northeastern Pacific between the equa-
tor and 35°N, and the Gulf of Mexico. Local minimum

---

**Fig. 5.** Time series of the 3-hourly SSTs (°C) on a 0.25° × 0.25° lat-lon grid box centered at 26.125°N, 109.875°W as defined by the MPM SST analysis, for (top) the entire data period from 15 May to 30 Sep 2004 and (bottom) for a subperiod of 10 days from 1 to 10 Jul 2004 for careful inspection. The dot inside the map inserted in the top panel indicates the location of the 0.25° × 0.25° lat-lon grid box whose time series are displayed.
Fig. 6. Departures of the 3-hourly SSTs (°C) from the daily mean averaged over the entire data period from 15 May to 30 Sep 2004.
and maximum SSTs are observed during the early morning and afternoon, respectively, over most regions. The mean diurnal amplitude is about 0.5 K.

4. Comparison with OI and RTG analyses

This section compares the MPM analysis with the OI and RTG analyses. The comparison is conducted on the grid of the RTG by interpolating the MPM analysis on the 0.25° × 0.25° latitude–longitude grid and OI analyses on the 1° latitude–longitude grid to the 0.5° × 0.5° latitude–longitude grid of the RTG. Differences in seasonal mean SST for June–August 2004 between the analyses are shown in Figs. 7a–c for the areas near the Gulf of California and the Gulf of Mexico. The differences between OI and MPM show that the SST in the OI analysis is too cold in the northern and southwestern Gulf of California, while it is too warm near the west coast of Baja California (Fig. 7a). This is considered to be due to the large spatial background error correlation scale (600–800 km) used in the OI analysis (Reynolds and Smith 1994), which allows a mixing in the analysis of the colder SSTs in the west coastal region of Baja California with warmer SSTs in the Gulf of California. In addition, a large portion of the Gulf of Mexico appears too cold in the OI compared with that in the MPM (Fig. 7a). Differences between the OI and RTG (Fig. 7c) are similar to those between the OI and MPM (Fig. 7a), and the differences between the RTG and MPM (Fig. 7b) are smaller than those between the OI and PM (Fig. 7a). The right panels in Fig. 7 are the mean differences between the analyses and the available in situ observations (Figs. 7d and 7e). Overall, the amplitude of the differences between the analysis and the in situ observations is smaller for the MPM (Fig. 7c) than that for the OI and RTG (Figs. 7d and 7e). To examine how well the temporal SST variations are depicted in the analyses, SST time series from the moored buoy observations and the three analyses are shown in Fig. 8 for four 0.25° × 0.25° latitude–longitude grid boxes selected to represent different regions in the analysis domain. Both the MPM and RTG analyses generally captured the observed day-to-day variability, while the OI analysis is only capable of representing variability at lower frequencies. In addition, an episodic bias can also be seen in the OI analysis.

Mean differences for the entire analysis period (15 May–30 September 2004) and for the entire analysis domain between analyses are shown in Fig. 9. A major difference between OI and MPM, and between RTG and MPM, is that both OI and RTG produce colder SSTs in most of coastal regions than does MPM. MPM and RTG show similar differences from OI over the Gulf Stream region, indicating that these differences are associated with the analysis resolution and background error correlation spatial scale. The RTG appears to be warmer than both MPM and OI in the North Pacific between 180° and 150°W near 40°N. The cause for the warmer RTG SSTs in this area is not clear.

Chelton and Wentz (2005) showed that one undesirable feature of the weekly OI analysis is that it was not able to sufficiently resolve the systems of small spatial scales such as the Gulf Stream and disturbances associated with tropical eastern Pacific instability waves, due to the use of a large grid size (1° × 1°) and a large spatial background error correlation scale (600–800 km), which result in local spatial gradients that are too weak compared with the estimate from the high-resolution observations. This difficulty was largely alleviated in the RTG analysis, which was based on the same observations as the OI but was performed daily with a smaller spatial background error correlation scale (100–450 km) on a 0.5° × 0.5° latitude–longitude grid. The RTG, however, still showed smaller amplitudes for the spatial SST gradients than did the AMSR observation (Chelton and Wentz 2005). Figures 10a–c compares the SSTs for 10 August 2004 from OI, RTG, and MPM. Both RTG and MPM resolve small-scale disturbances, with MPM showing finer structures. The tropical eastern Pacific waves north of the equator appear to be stronger in the MPM and the local maxima along the Gulf Stream are narrower in the MPM. The OI analysis is much smoother than either RTG or MPM. The amplitude of the spatial SST gradient is given in Figs. 10d–f. The local large gradient is weakest in the OI and strongest in the MPM.

Scatterplots of the SST gradient amplitude are given in Fig. 11 for the tropical eastern Pacific (10°S–10°N, 130°–70°W; left panels) and the Gulf Stream (25°–55°N, 85°–35°W; right panels) to further quantify the comparisons among the three analyses. Few grid points in the OI analysis show a spatial gradient larger than 2 K (100 km)−1 in the tropical eastern Pacific and 3 K (100 km)−1 in the Gulf Stream region. Both RTG and MPM show a large fraction of grid points at which the spatial gradient is larger than these values for the respective regions. In particular, the MPM showed an even larger amount of points of large spatial gradient. Although the large spatial gradient in the MPM seems to be encouraging, according to the study of Chelton and Wentz (2005), which suggested that the amplitude of the spatial gradient in the RTG, while larger than that in the OI, was still too small, the interpretation of the large spatial gradient must be given with cautions. While the small background error correlation scale enables the resolution of small-scale disturbances, it also
allows analysis errors to be generated at small scales, which may result in a spatial gradient of large amplitude. Independent observations are needed to verify the accuracy of the MPM and determine if the enhancement of the spatial gradient is realistic.

5. Impact of addition of satellite observations

As seen in Fig. 1, the satellite observations are complementary for many local areas. The studies by Guan and Kawamura (2004) and Reynolds et al. (2005)
suggested that combining observations by NOAA satellites with retrievals from other satellites may result in an improved SST analysis compared with the analysis that uses NOAA satellite observations alone. The complementarity of the satellite observations in Fig. 1 implies that the addition of more satellites may increase the quality of the SST analysis. A set of analysis experiments was carried out to test this. Moored buoy observations are excluded in all of these experiments and will be used for verification. Given in Table 2 are RMS differences in the daily mean between the analysis experiments and the moored buoy (MBOUY), and the mean diurnal amplitude (RMS of the diurnal deviations from the daily mean) for collocated analysis grid points and moored buoys. The values in Table 2 are average for all moored buoys and for all days on which all eight 3-hourly time levels of moored buoy observations are available. Although the moored buoy observations contain errors, the RMS differences between the analysis experiments and moored buoy observations can be considered as a relative measure of analysis accuracy because errors in moored buoy observations and in the analysis are completely independent. It is seen that the analysis error is largest when a single satellite (NOAA-16 or NOAA-17) is used. Generally, a more accurate analysis is achieved when more satellites are used, especially when GOES is included. The diurnal amplitude is also found to become more realistic when more satellites are used, especially when GOES or microwave retrievals (TMI and AMSR) are included. Both daily mean and diurnal amplitude are most realistic when all satellite observations are used.

6. Summary and discussion

The current availability of SST observations from multiple satellites provided a great opportunity to construct a new SST analysis with improved accuracy and refined resolution compared with existing products, which have been mostly based on the combination of in situ observations and retrievals from a single satellite. Previous studies have shown that such an enhancement
is necessary for the improvement of our understanding of the North American monsoon (NAM) system and for its satisfactory simulation and prediction. This study describes the development of an SST analysis for the NAM areas (30°S–60°N, 180°–30°W), called the multi-platform merged (MPM) analysis, using in situ observations and retrievals from five satellites including NOAA-16, NOAA-17, GOES, TMI, and AMSR.

SST retrievals from these individual satellites are found to be complementary over local areas and their combination results in an almost complete daily coverage of the analysis domain, allowing the analysis to be performed at a high spatial resolution. In addition, the overall twice-a-day sampling from NOAA-16, NOAA-17, TMI, and AMSR, as well as hourly sampling from GOES, allows the diurnal cycle to be resolved. The MPM developed in this study is calculated on a 0.25° × 0.25° latitude–longitude grid at a 3-h interval with a spatial background error correlation scale of 50 km.

The analysis for 15 May–30 September 2004 indicates that the MPM captures the large-scale geographical features of SSTs as in the optimum interpolation (OI) analysis of Reynolds and Smith (1994) and Reynolds et al. (2002), and the real-time global (RTG) analysis of Thiébaux et al. (2003). The MPM has also been found to capture local features of small spatial scales such as the waves in the Gulf Stream region and disturbances associated with tropical instability waves, which have been shown to be insufficiently resolved in OI and RTG (Chelton and Wentz 2005).

Analysis experiments were performed to examine the impact of addition of satellite observations. It is found that the use of more satellite retrievals progressively improves the analysis accuracy and enhances the diurnal amplitude. This suggests that as more reliable satellite observations become available in the future, an analysis system like MPM that is capable of accommodating multiple satellites may become useful in providing an SST analysis for monitoring, simulating, and predicting weather and climate.

While an analysis system like MPM is expected to be useful for SST information at high resolutions in both space and time, its utility should not be overexaggerated. The major limitation of such an analysis is that the required multisatellite retrievals are available only for the recent period from June 2002 when all individual inputs are accessible. In contrast, the weekly OI analysis is available back to November 1981 (Reynolds et al. 2002). In addition, the multichannel AVHRR SST data extend back to 1981 at spatial resolutions of 9, 18, and 54 km and temporal resolutions of daily and weekly (information online at http://podaac.jpl.nasa.gov). A new improved daily version of the OI analysis is planned to be produced for the last two decades on a 0.25° × 0.25° latitude–longitude grid using AVHRR retrievals with smaller spatial error correlation scales (Reynolds et al. 2006). Accordingly, the existing analysis, such as the OI and its revisions, will continue to be of vital importance in the research and forecast of cli-

![Fig. 9. Differences in SSTs averaged for 15 May–30 Sep 2004 between (a) OI and MPM, (b) RTG and MPM, and (c) RTG and OI. Values are shaded at an interval of 0.25 K.](image-url)
mate variability and long-term variations of subseasonal variability, while the MPM-type analysis is expected to provide desirable high-frequency details at finer resolution.

Another concern with the MPM analysis is with its representation of the diurnal cycle. While the diurnal cycle is resolved by the analysis, its reliability is dependent on the richness of the input data. During the pe-
period when input data are insufficient, the diurnal deviation is dominated by the prespecified first guess of the diurnal cycle. Currently, the first guess of the diurnal cycle is based on temporal (31 day) and spatial (20° box) averages. This specification may substantially underestimate the instantaneous diurnal amplitude for individual grid points when the diurnal variation is not resolved by the input observations. A desirable im-

![Figure 11: Scatterplot of amplitude of SST spatial gradient](image)

Fig. 11. Scatterplot of amplitude of SST spatial gradient: (a) OI vs MPM for the tropical eastern Pacific (10°S–10°N, 130°–70°W), (b) as in (a) except for RTG vs MPM, (c) as in (a) except for OI vs RTG, (d) OI vs MPM for the Gulf Stream region (25°–55°N, 85°–35°W), (e) as in (d) except for RTG vs MPM, and (f) as in (d) except for OI vs RTG. Unit of the gradient amplitude is K (100 km)^{-1}. 
provement to the MPM analysis is a specification of the first guess of the diurnal cycle as a function of local time, surface insulation, and wind speed.

Acknowledgments. The authors gratefully acknowledge the encouragement by Dave Gutzler, Vernon Kousky, Wayne Higgins, Kingtse Mo, and Jae Schemm. The authors wish to thank Diane Stokes and Minguye Chen for their help in extracting and processing observational data. We also greatly appreciate the comments and suggestions by John E. Janowiak, Richard W. Reynolds, Thomas M. Smith, Xiangqian Wu, and Eileen Maturi.

REFERENCES


