GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L15603, doi:10.1029/2006GL026356, 2006

Click Here for Full Article

Satellite-based daily SSTs over the global ocean

Charlie N. Barron[1] and A. Birol Kara[1]

Received 20 March 2006; revised 9 June 2006; accepted 21 June 2006; published 3 August 2006.

[1] Daily 1/8° global fields of sea surface temperature (SST), operationally produced by the Modular Ocean Data Assimilation System (MODAS), are presented. Production using a combination of optimal interpolation and climatologically corrected persistence balances eddy-resolving spatial and daily temporal resolution with improved transitions in time and space across cloud-obscured regions to eliminate data voids. Hindcast reanalysis has consistently extended complete MODAS SST coverage from 1993 to the present. In validation analysis using 219 yearlong daily SST time series from both coastal and open ocean buoys over the global ocean, MODAS gives a median root mean squared SST difference of 0.41°C. Whether hindcast or real-time, stand-alone or coupled, MODAS SST is applicable for physical or biological studies and operational applications on regional to global scales. **Citation:** Barron, C. N., and A. B. Kara (2006), Satellite-based daily SSTs over the global ocean, *Geophys. Res. Lett.*, *33*, L15603, doi:10.1029/2006GL026356.

1. Introduction and Motivation

[2] The ocean powerfully influences both daily weather events and global climatic change. One accessible indicator of the ocean's state and potential influence is sea surface temperature (SST). Variability in SST is important not only in studying global climate change on inter-annual and decadal time scales, including El Niño and La Niña events, but it is also essential in investigating shorter time scale oceanic processes, such as frontal dynamics, upwelling and downwelling events, and eddy and plume evolution [*Wang et al.*, 2004].

[3] In light of these factors, a range of climate, biological and other studies generally rely on accurate SST products over the global ocean. However, scattered in situ SST observations from moored buoys, conventional ship-based measurements, drifting buoys, etc., do not provide enough spatial and temporal coverage over the global ocean. Frequent repeat and global coverage of satellite-based observations are essential for creating a global gridded SST with relatively fine spatial and temporal resolution. Satellites are particularly critical for accurately representing spatial and temporal variability of SST. Most of these satellite systems have relied on infrared estimates of SST. Unfortunately, clouds limit the coverage of infrared estimates of SST and bias individual measurements where clouds are not detected. During extended cloudy conditions, reliability of SST estimates is reduced. Coarse-resolution microwave SST estimates may address some of these issues, but this data would only cover the more recent reanalysis years.

[4] The major purposes of this paper are to introduce and evaluate an operational system producing quality-controlled, fine resolution gridded SST fields over the global ocean on time scales ranging from daily to annual from 1993 onward.

2. Processes to Construct Daily SST

[5] Steps in the construction of the Modular Ocean Data Analysis System (MODAS) SST are discussed here and illustrated in a regional application on 6 March 2006 (Figure 1). Each daily MODAS SST is produced by an optimal interpolation (OI) of Advanced Very-High Resolution Radiometer (AVHRR) nonlinear SST (NLSST) observations (Figure 1a). NLSSTs are processed by the Naval Oceanographic Office to estimate subsurface temperature [*May et al.*, 1998]. This subsurface or bulk SST represents conditions in the upper few meters measured by typical in situ instruments, while skin SST reflects conditions at the immediate air-sea interface and is typically 0.0–0.4°C cooler than ≈1 m subsurface conditions [*Castro et al.*, 2003]. The subsurface SST variability may deviate from that of skin SSTs, particularly due to diurnal warming under conditions of high insolation and low wind speed. All operational global AVHRR data from 1993 to the present have been used in the MODAS analyses, reflecting on any given day the collected data from one to three of the NOAA TIROS-N series of polar-orbiting satellites, from NOAA-11 to NOAA-18. While buoy data are used collectively to initially determine and occasionally update NLSST coefficients for aging sensors [*Walton et al.*, 1998], none of the buoy SST data are individually assimilated into the MODAS SST gridded product, allowing the buoy data to serve as an independent validation set (section 3).

[6] The AVHRR sensor is sensitive to the presence of clouds and scattering by aerosols and atmospheric water vapor. Thus, thermal infrared measurements of SST first require atmospheric correction of the retrieved signal and can only be made for cloud-free pixels. The effects of persistent cloud cover on data sampling is evident in the significant data void over the Gulf Stream in the observations 24 hours from 0:00 GMT 6 March 2006 (Figure 1a).

[7] Various approaches may be used to transform the irregularly sampled and cloud-obscured POES AVHRR SST data into a more regular product. For analyses of data in prior years, a suite of global Pathfinder SST products is based on averaging observations within spatial bins from 4 to 54 km and temporal bins from daily to monthly [*Casey and Cornillon*, 1999]. These are often used for climatological studies where the immediate timeliness of the data is not a concern. Real-time global operational fields include 10

[1]Oceanography Division, Naval Research Laboratory, Stennis Space Center, Mississippi, USA.

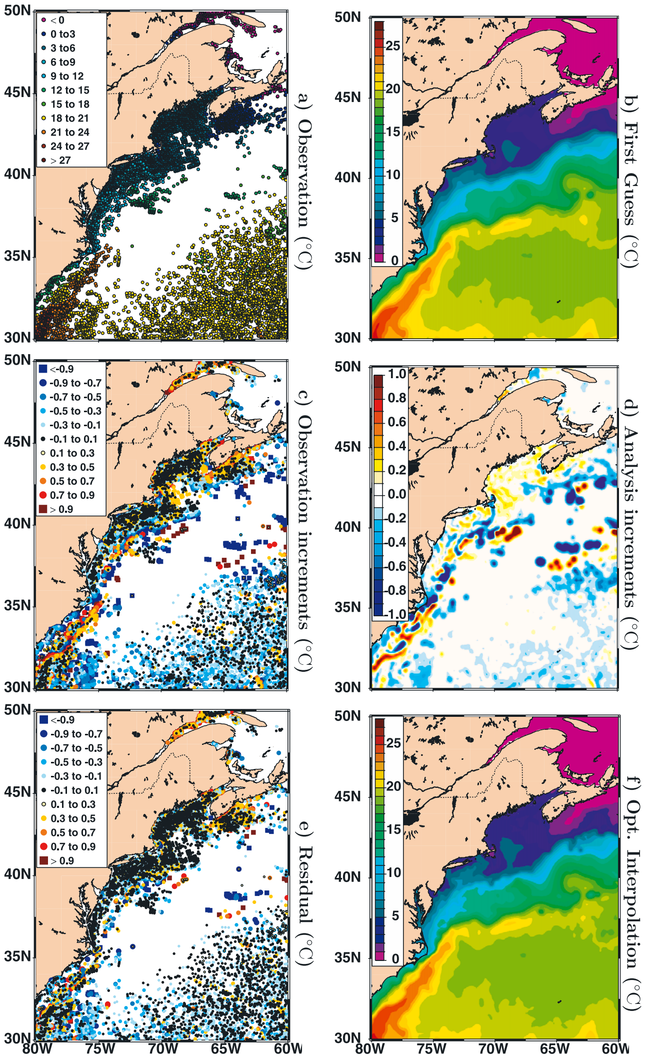

Figure 1. Steps in constructing a daily MODAS SST analysis based on AVHRR data, as described in the text, in detail. Depicted in the northwestern Atlantic on 6 March 2006.

and 100 km daily composites from the Naval Oceanographic Office [*May et al.*, 1998], where bin averages are updated if new observations are available, and the weekly 1° × 1° Reynolds SST [*Reynolds and Smith*, 1994], using OI. Real Time Global (RTG) analysis [*Thiébaux et al.*, 2003] is a two dimensional variational interpolation analysis of in situ and satellite data collected in the 24 hours prior, which is generated once a day. The longer time windows and length scales increase the probability that a sufficient number of cloud-free pixels are captured during the sampling period.

[8] MODAS takes a somewhat different OI approach based on joint emphasis of accurate SST, fidelity in locating and quantifying SST gradients, and avoiding spurious gradients. The daily global MODAS SST analyses are on a 1/8° spherical grid from 80°S to 80°N. The OI mitigates the artificial discontinuities associated with bin edges in composites or data voids in binned averages. It has three components: the observations, the first guess or initial analysis, and the expected covariance of errors in the observations and first guess [*Lorenc*, 1981]. For MODAS, the first guess (Figure 1b) is derived using climatologically corrected persistence, where the MODAS SST analysis and expected errors for the prior day, 5 March 2006, are smoothed and relaxed toward the MODAS bimonthly climatology [*Fox et al.*, 2002] with a 60-day time scale. Expected observation errors are 0.5°C, while expected analysis and first guess errors range approximately over 0.1 to 2.0°C (not shown). Under episodic cloud cover, a lack of recent observations leads to a loss of confidence in the prior analysis and an increase in the expected error of the analysis. For extended cloudy periods, the first guess and its expected error tend toward climatological means and standard deviations.

[9] The OI is performed on the observation increments or innovation vector, (Figure 1c), defined as the SST observations minus the first guess SST. The SST observations used in MODAS are subjected to quality control that excludes data deviating more than 4 standard deviations from climatological SST or the first guess SST analysis.

[10] The character of OI results strongly depends on the error covariance function. If the covariance scales are too long, ocean features will be excessively smoothed, while scales that are too short may lead to artificial fronts and transitions. The MODAS SST OI uses a Gaussian error covariance with 60-hour time and 20-km length scales. These scales were determined subjectively to balance fidelity in representing fronts with mitigation of spurious gradients around data-sparse regions. The OI results in the analysis increments or correction vector (Figure 1d) that reflects a balance between the representativeness and expected errors in the observations with uncertainty in the first guess field. Red areas reveal regions where the OI indicates SST warming; blue designates cooling. Effects from the definition of the error covariance are particularly evident in data-sparse portions of the analysis. Where there is insufficient sampling to better identify the spatial distribution of a temperature mismatch, the analysis will indicate "bulls-eye" features with radius on the order of 20 km. Longer length scales would spread the analysis errors over a larger area, producing a smoother if not more accurate analysis in data sparse regions while reducing less distinct fronts in areas of dense sampling.

[11] The residuals (Figure 1e) quantify the mismatch between the analysis and the observations. A residual indicates the degree to which the OI deems the observation inconsistent with the final solution. The residual is attributed to errors in the measurement and, perhaps more importantly, to errors in the representativeness of an observation to the gridded field. Variability on time and space scales smaller than those represented by the analysis and error covariances contribute to representativeness errors. Adding the correction vector to the first guess produces the SST analysis (Figure 1f). In the present MODAS system, this is the basis for deriving the first guess for the next day.

3. Evaluation of Daily MODAS SST

[12] The application procedure demonstrated for the northwest Atlantic in Figure 1 is applied globally. Figure 2 shows the 6 March 2006 MODAS SST analysis over the global ocean. The same procedure operationally generates

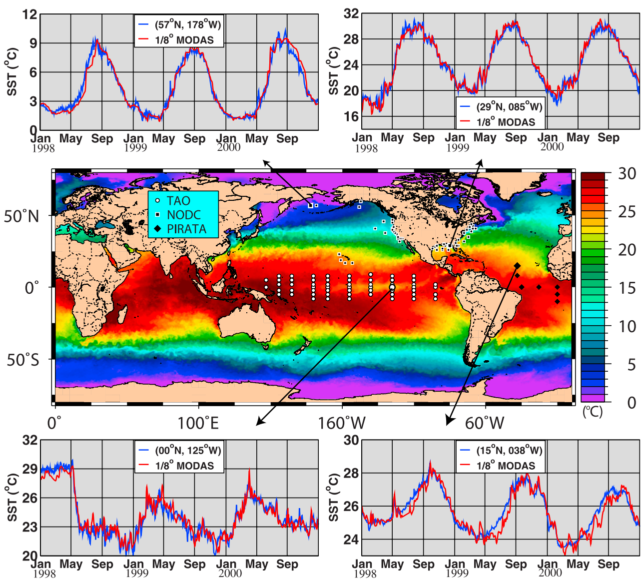

Figure 2. MODAS SST analysis on 6 March 2006 and locations of buoys used for validation. Also included are validations of MODAS SST time series at four buoy locations over the global ocean.

daily SST and has been applied to develop a daily hindcast archive from 1 January 1993 to the present (http://www7320.nrlssc.navy.mil/modas2d).

[13] MODAS SST is validated using daily buoy SST time series reported from three sources: (1) the Tropical Atmosphere-Ocean (TAO) array, (2) the Pilot Research Moored Array (PIRATA), and (3) the National Oceanic Data center (NODC). The time series were divided into one year segments with daily-averaged SSTs. Buoy SSTs are measured at a depth of 1 m below the sea surface, and the MODAS SST represents the subsurface temperature at this depth rather than the skin temperature (see section 2).

[14] As examples to illustrate the MODAS SST assessment procedure, detailed evaluation results are shown for four buoy locations (Figure 2). These buoys are chosen to represent different regions over the global ocean. The time period for MODAS validation is 1998 through 2000, an interval that includes the strong 1998 transition from El Niño to La Niña. Use of a time-centered (1 day before to 1 day after) data window in the reanalysis helps capture the phase of the large SST drop during the transition period from May to June 1998, ≈8°C at (00°N, 125°W). Persistent clouds lead to under sampling and greater reliance on climatology, particularly for the high latitude stations but to a lesser extent at (15°N, 038°W) during June and July.

[15] SST time series from MODAS and buoys are compared using various statistical metrics: mean error (ME), root-mean-square (RMS) difference and correlation coefficient (R). Let X_i (i = 1, 2, $\cdots$, n) be the set of n buoy (observation) values, and let Y_i (i = 1, 2, $\cdots$, n) be the set of corresponding MODAS estimates, where n is equal to 365 (or 366 for leap years) at a given buoy location for a single year. Also let $\overline{X}$ ($\overline{Y}$) and σ_{BUOY} (σ_{MODAS}) be the mean and standard deviations of the observation (estimate) values, respectively. The preceding statistical measures are as follows:

$$\mathrm{ME} = \overline{Y} - \overline{X}, \tag{1}$$

$$\mathrm{RMS} = \left(\frac{1}{n} \sum_{i=1}^{n} (Y_i - X_i)^2 \right)^{1/2}, \tag{2}$$

$$R = \frac{1}{n} \sum_{i=1}^{n} \left(X_i - \overline{X}\right) \left(Y_i - \overline{Y}\right) / (\sigma_{\mathrm{BUOY}}\, \sigma_{\mathrm{MODAS}}). \tag{3}$$

[16] MODAS is able to produce the daily SST variability well at these buoy locations (Table 1). The RMS SST differences are generally ≈0.5°C. As evident from large R values, MODAS reproduces SST seasonal cycle as well.

[17] The comparisons shown in Table 1 are extended to all TAO, PIRATA, and NODC buoys over 1998–2000. Error statistics between the buoy and MODAS SST based on 219 yearlong daily time series give median RMS SST difference of 0.41°C, ME of 0.01°C and R of 0.96. Daily SST variability from MODAS also agrees well with the buoy observations of SST variability, giving median σ_{BUOY} and σ_{MODAS} values of 1.32°C and 1.38°C, respectively.

4. Conclusion

[18] Developed by the Naval Research Laboratory as a real-time transformation of satellite AVHRR observations into a high-resolution SST grid, the daily MODAS SST has been produced operationally since 1999. Each day the operational MODAS conducts consecutive time-centered hindcast analyses for the five prior days before finishing with a one-sided (data from prior 24 hours) nowcast analysis. The hindcasts allow inclusion of any late-arriving

Table 1. Statistical Verification of Daily SST Time Series Between Unassimilated Buoys and MODAS at Four Locations by Year[a]

Year	RMS	ME	σ_{BUOY}	σ_{MODAS}	R
		Buoy Location 00°N, 125°W			
1998	0.61	−0.03	3.31	2.95	0.99
1999	0.54	0.13	1.49	1.60	0.95
2000	0.42	−0.10	1.35	1.40	0.96
		Buoy Location 57°N, 178°E			
1998	0.55	−0.19	2.43	2.43	0.98
1999	0.36	0.04	2.55	2.65	0.99
2000	0.60	0.23	3.01	3.11	0.98
		Buoy Location 29°N, 085°W			
1998	0.70	−0.19	4.39	4.48	0.99
1999	0.47	0.25	3.64	3.70	0.99
2000	0.66	0.30	3.83	3.78	0.99
		Buoy Location 15°N, 038°W			
1998	0.72	−0.43	1.10	0.97	0.79
1999	0.61	−0.45	1.26	1.33	0.95
2000	0.64	−0.47	1.19	1.16	0.93

[a]Approximate water depth is 53 m at the coastal NODC buoy at (29°N, 079°W). Other three buoys at open ocean have water depths of 4,780 m, 3,662 m, and 5,382 m at (00°N, 125°W), (57°N, 178°E), and (15°N, 038°W), respectively. R is dimensionless, other columns are °C.

data to produce the most reliable analyses for archive records, near real-time applications, and use as the first guess for nowcast analysis. Runs are nominally for 0:00 GMT on the day but really represent an time average of the NLSST as sampled from the sun-synchronous polar orbiters each day; the data in the nowcasts are usually complete up to 23:59:59 GMT on the prior day. After intermediate upgrades, a uniform reanalysis has been performed for 1993 to the present.

[19] The primary advancement of MODAS relative to the existing products is its attempt to represent the real-time global SST at higher horizontal resolution through shorter error covariance length scales and a higher resolution background climatology to fill data voids. Such a resolution is important for preserving information on front and eddy location for assimilation into high-resolution dynamic forecast models [*Kara et al.*, 2006]. Eddies of 25–100 km in diameter cannot be adequately represented using a coarser horizontal grid.

[20] The standard gridded MODAS SST has a range of applications, from use in statistical estimation of subsurface conditions [*Fox et al.*, 2002] to assimilation in global ocean nowcast-forecast systems [*Kara et al.*, 2006] to guidance for fisheries management and biological studies [*Ikawa et al.*, 2004].

[21] **Acknowledgments.** Reviewers are thanked for their excellent and constructive comments. This work is a contribution to the Multi-sensor Improved Sea Surface Temperature (MISST) for GODAE. The paper is contribution NRL/JA/7320/06/6196 and has been approved for public release.

References

Casey, K. S., and P. Cornillon (1999), A comparison of satellite and in situ based sea surface temperature climatologies, *J. Clim.*, *12*, 1848–1863.

Castro, S. L., G. A. Wick, and W. J. Emery (2003), Further refinements to models for the bulk-skin sea surface temperature difference, *J. Geophys. Res.*, *108*(C12), 3377, doi:10.1029/2002JC001641.

Fox, D. N., W. J. Teague, C. N. Barron, M. R. Carnes, and C. M. Lee (2002), The modular ocean data assimilation system (MODAS), *J. Atmos. Oceanic Technol.*, *19*, 240–252.

Ikawa, T., H. Okabe, S. Hoshizaki, T. Kamikado, and L. Chen (2004), Distribution of the oceanic insects Halobates (Hemiptera:Gerridae) off the south coast of Japan, *Entomol. Sci.*, *7*, 351–357.

Kara, A. B., C. N. Barron, P. J. Martin, L. F. Smedstad, and R. C. Rhodes (2006), Validation of interannual simulations from the 1/8° global Navy Coastal Ocean Model (NCOM), *Ocean Modell.*, *11*, 376–398.

Lorenc, A. C. (1981), A global three-dimensional multivariate statistical interpolation scheme, *Mon. Weather Rev.*, *109*, 701–721.

May, D. A., M. M. Parmeter, D. S. Olszewski, and B. D. McKenzie (1998), Operational processing of satellite sea surface temperature retrievals at the Naval Oceanographic Office, *Bull. Am. Meteorol. Soc.*, *79*, 397–407.

Reynolds, R. W., and T. M. Smith (1994), Improved global sea surface temperature analyses using optimum interpolation, *J. Clim.*, *6*, 929–948.

Thiébaux, J., E. Rogers, W. Wang, and B. Katz (2003), A new high-resolution blended real-time global sea surface temperature analysis, *Bull. Am. Meteorol. Soc.*, *84*, 645–656.

Walton, C. C., W. G. Pichel, F. J. Sapper, and D. A. May (1998), The development and operational application of nonlinear algorithms for the measurement of sea surface temperatures with NOAA polar-orbiting environmental satellites, *J. Geophys. Res.*, *103*, 27,999–28,002.

Wang, C., S.-P. Xie, and J. A. Carton (Eds.) (2004), *Earth Climate: The Ocean-Atmosphere Interaction*, *Geophys. Monogr. Ser.*, vol. 147, 229 pp., AGU, Washington, D. C.

C. N. Barron and A. B. Kara, Oceanography Division, Naval Research Laboratory, Code 7320, Bldg. 1009, Stennis Space Center, MS 39529, USA. (barron@nrlssc.navy.mil; birol.kara@nrlssc.navy.mil)