

AN INTEGRATED GLOBAL OBSERVING SYSTEM FOR SEA SURFACE TEMPERATURE USING SATELLITES AND IN SITU DATA

Research to Operations

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An iterative process of cost-benefit conscious design and application helped in the formulation of an efficient, effective operation for this U.S. contribution to the Global Climate Observing System.

In this article, we describe a research-to-operation and decision-making procedure that consists of 1) objective design of an efficient, integrated global sea surface temperature (SST) observing system composed of satellite and in situ observations for maximizing benefits while minimizing cost; 2) transition of the research results into sustained operations; and 3) management applications in the U.S. National Oceanic and Atmospheric Administration's (NOAA) strategic planning and performance monitoring activities. While the presented procedure is specific to the sea surface temperature, the underlying principles may have applicability to other components of the global climate observing systems.

Since the inception and planning of the ocean component of the Global Climate Observing System (GCOS) (e.g., Koblinsky and Smith 2001), the international community has been progressing toward an improved Global Ocean Observing System (GOOS). GOOS consists of several components, including ►

Detail of drifter deployment locations and trajectories. See Fig. 7 for more information.

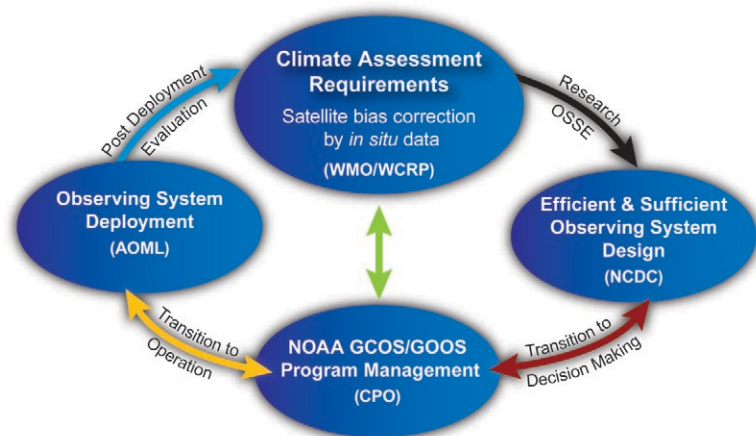


FIG. 1. Conceptual diagram showing the iterative procedure for the design and implementation of a Global Ocean Observing System for climate assessment using SST. The World Climate Research Program (WCRP) under the World Meteorological Organization (WMO) has specifications on the SST accuracy requirement for climate assessment. OSSEs are used by NCDC to design an efficient observing network to maximize benefits while minimizing cost (Fig. 3). Through NOAA/CPO, the observing system is implemented by AOML. The observing system is then evaluated against the SST requirements, and further OSSEs and implementations are carried out when needed. This procedure enables NOAA to strategically target its observing system investments, and as a high-level government performance results act (GPRA) performance measure (Fig. 6), which is reported annually to the U.S. Department of Commerce, the White House, and Congress.

strategic planning, system design and implementation, and effective data integration and dissemination. Efficient management of sustained observing system operations requires continuous monitoring, evaluation, and periodic reviews. Subsequently, these

require the close coordination of many organizations. In this paper, we present such a procedure that encompasses several NOAA offices: the Climate Program Office (CPO) in Silver Spring, Maryland; the National Climatic Data Center (NCDC) in Asheville, North Carolina; and the Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, Florida. This integrated approach, shown schematically in Fig. 1, is an effort to maximize benefits while minimizing the cost in fiscal, physical, and human resources. The procedure involves close collaboration of various NOAA offices and the utilization of the Observing System Simulation Experiments described in NOAA's 5-yr research plan and its 20-yr research vision (www.nrc.noaa.gov/plans.html). The principles we describe here can also be useful to the GOOS community as it prepares for the next decadal review on ocean observations (OceanObs'09; www.oceanobs09.net/).

The rest of this paper details the conceptual processes summarized in Fig. 1: the GCOS climate SST requirements, the observing system design at NCDC for these requirements, the iterative observing system implementation at AOML, and the management and strategic planning applications at CPO. The final discussion contains some concluding remarks.

CLIMATE SST REQUIREMENTS. Climate change indicators include oceanic and atmospheric temperature variability at time scales longer than weather-related fluctuations (typically less than a week). Temperature changes at the Earth's surface (over both land and ocean) have been the prominent indicators in many climate change assessments because surface observations have the longest records and thus provide a historical context for climate change. In this paper, the term "climate assessment" refers to climate trends and variability from observational data, but it does not include attribution of the causes of climate change.

There are several global surface temperature products for climate monitoring and assessment (e.g., Rayner et al 2003; Smith and Reynolds 2005). Because over 70% of the Earth's surface is covered by

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water, accurate SST products are essential for accurate climate assessment and monitoring (see www.wmo.ch/pages/prog/gcos/index.php).

We specifically note that SST products are used for a wide variety of applications, and the required resolution and accuracy may be different for different purposes (e.g., resolving oceanic frontal or eddy features versus climate monitoring and assessment). In this paper, we focus on climate scales for SST. The required accuracy for satellite bias correction given by GCOS is 0.2°–0.5°C on a 500-km grid for weekly time scales (Needler et al. 1999). Denser satellite observations result in lower sampling and random errors (Fig. 2; see also more details in the next section), but satellite observations may have large biases (e.g., Reynolds 1993). In the next section, we review the design of a sea surface in situ observing system to effectively reduce the potential satellite biases as described in Zhang et al (2006a). This review is followed by a description of the transition of the system design into sustained operations through an iterative process.

OBSERVING SYSTEM DESIGN. The modern SST observing system mainly consists of in situ observations (from ships and buoys) and satellite remote sensing. Since the satellite instruments became operational in 1981, satellite observations have provided dramatically improved coverage in time and space. The increased data coverage assures adequately small analysis errors in objectively analyzed SST fields by blending satellite and in situ observations, as shown in Fig. 2. However, adequate in situ observations are still needed to correct systematic biases associated with satellite retrieval algorithms. These biases occur for both infrared and microwave retrievals. Infrared retrievals are impacted by cloud and aerosol contamination, while microwave retrievals are impacted by precipitation and land contamination. Studies of the historical Advanced Very High Resolution Radiometer (AVHRR) SST retrievals show that although globally and annually averaged

AVHRR SST biases are usually small (<0.2°C), regional and seasonal biases may be larger than 0.5°C (Zhang et al. 2004). The disparity occurs because the current AVHRR satellite retrieval algorithms are tuned to the global-mean and time-averaged atmospheric conditions that cannot capture the time-varying components. In addition to seasonal variations, interannual variations in atmospheric conditions can induce further biases, such as the aerosols from volcano eruptions (Reynolds 1993). Note that in situ observations contain errors as well, as discussed in the next section when computing the Equivalent Buoy Density (EBD).

Many of the processes that introduce satellite SST biases cannot be controlled or predicted. Thus, a sufficiently dense in situ network is needed to correct large-scale satellite biases, as detailed in Zhang et al (2006a). In their observing system design, they used Monte Carlo simulations to determine the relationship between the residual satellite bias and in situ data density, as shown in Fig. 3. In these simulations, artificial buoy observations are placed on a regular grid, with varying grid resolutions for the different simulations. (Inclusion of ship observations along with buoys will be discussed in the next section.) In Fig. 3, the Potential Satellite Bias Error (PSBE) is defined as the residual satellite bias that cannot be further reduced at the given buoy density (BD). The BD is represented by the number of independent

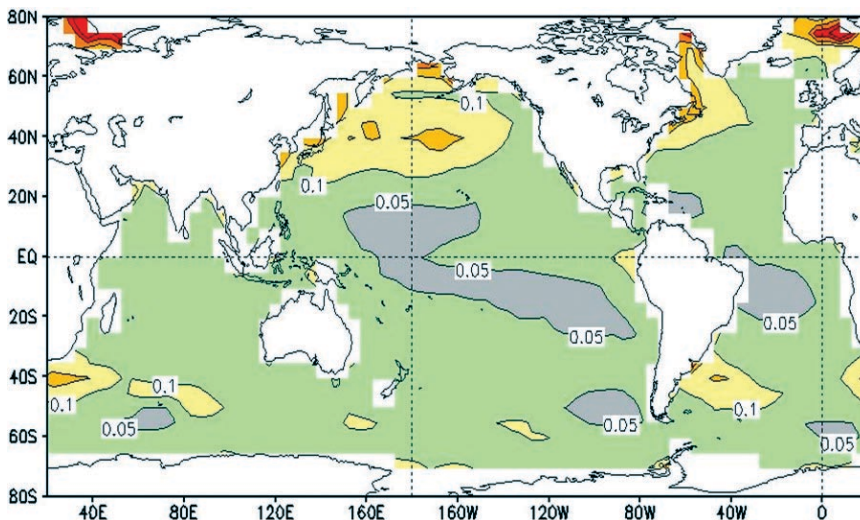


FIG. 2. Monthly and 5° grid Objective Analysis (OA) errors averaged for Jan 1995–Dec 2002. The OA used is the optimal averaging described in Smith et al (1994) and Kagan (1979). The monthly analysis uses data from ships, buoys, and satellite AVHRR SSTs. Cloud cover effects on the AVHRR observations are obvious, in particular over the northwest basins of the North Pacific and North Atlantic. In most areas, the OA errors are less than 0.2°C. Addition of microwave satellite observations will further reduce the OA errors. Warmer colors indicate larger error values, and the contour interval is 0.05°C.

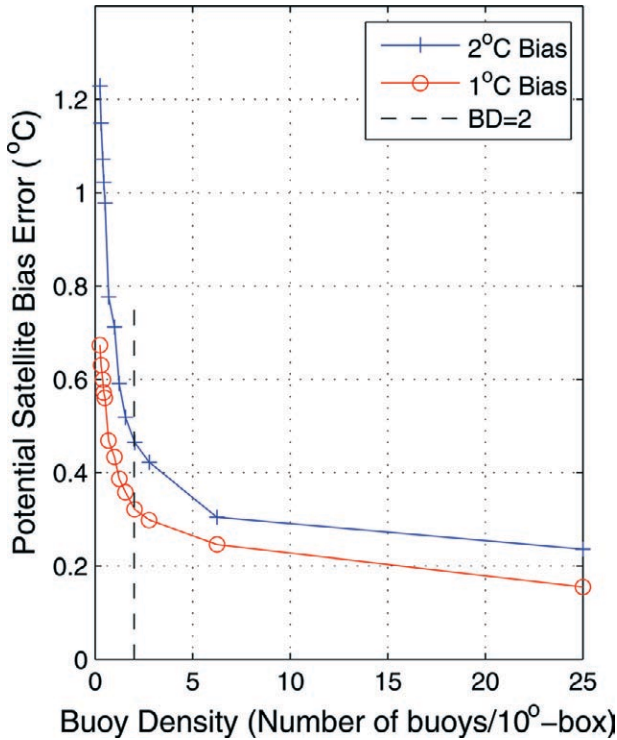


FIG. 3. PSBE vs simulated buoy density (BD) for two cases: the blue (+) curve is for the worst case with a maximum initial uncorrected satellite bias of 2°C (at BD = 0), as after major volcanic eruptions (Reynolds 1993). The red (o) curve represents a more normal case with a maximum initial uncorrected satellite bias of 1°C (at BD = 0). The thin vertical dashed line indicates BD = 2.

buoys in a 10° grid box with sufficiently small errors (e.g., by averaging observations from one buoy in a 10° grid box and within a month; see further discussion in the EBD computations). For the worse-case curve in Fig. 3, we have assumed the PSBE as 2°C when there are no in situ data to correct the satellite biases. The value of 2°C is the typical bias magnitude for the satellite AVHRR instrument (e.g., Reynolds 1993).

Fig. 3 shows the near-exponential PSBE reductions as the BD increases from zero. Rapid error reductions occur when the BD increases from 0 to a BD between 2 and 5; further increase in the BD only results in minimal reductions in the PSBE. Coincidentally, a BD of 2 reduces the maximum bias from 2°C (at BD = 0) to about 0.5°C, which is the upper limit of the GCOS/GOOS requirement. Thus, a BD of 2 is regarded as the minimum acceptable density (dashed vertical line in the figure).

OBSERVING SYSTEM IMPLEMENTATION AS AN ITERATIVE PROCESS. The system design was started as part of a research project to improve

NCDC’s Optimum Interpolation (OI) SST analyses (also referred to as Reynolds SST; Reynolds and Smith 1994; Reynolds et al. 2002, 2007). The project was sponsored by the CPO, which manages the U.S. contribution to the international GCOS and GOOS systems. The goal of the design study was to objectively determine an observing system sampling strategy to reduce satellite bias errors for climate SST analysis. Once the new sampling strategy was completed and reviewed, CPO assisted in transferring the research results into sustained buoy-deployment operations, which are managed by AOML.

The actual in situ SST network is primarily composed of ships and buoys (both moored and surface drifting) as shown in Fig. 4 for June 2002. The buoys are dedicated specifically for ocean observations and provide regular and continuous data streams. The majority of the SST observing ships are from the Voluntary Observing Ship (VOS) fleet of commercial freight vessels, mainly confined to the Northern Hemisphere and between major sea ports (Fig. 4). Various studies indicate that typical random errors are about 0.5° and 1.3°C for buoy and ship observations, respectively (Reynolds and Smith 1994; Reynolds et al. 2002, and references within). The random error differences between ships and buoys show that approximately seven ship observations are equivalent to one buoy observation to achieve the same error

$$\left(\text{i.e., } \frac{1.3}{\sqrt{7}} \approx 0.5\right).$$

A combined ship–buoy density, Equivalent Buoy Density, is thus defined as

$$\text{EBD} = n_b + \frac{n_s}{7}, \quad (1)$$

where n_b and n_s are the independent number of observations from buoys and ships, respectively, within a 10° grid box. Presently, there is insufficient information to accurately compute the integral time and length scales from which to define the number of degrees of freedom and thus the independent number of observations. Here, we take a conservative approach to average the monthly observations within a 10° grid box for each buoy or ship, and we take the average as one independent observation. The monthly average also assures much-reduced random error for the buoy or ship, which is essential to be taken as the ground truth for satellite bias corrections.

The actual EBD of (1) is used in place of the BD in Fig. 3 to determine the PSBE. Our goal is to reduce the PSBE to less than 0.5°C from the maximum satellite

bias of 2°C when no in situ observations are available (upper blue curve in Fig. 3). This requires an EBD of 2 or greater.

Although the GCOS specification on satellite SST bias correction applies to weekly samples, field adjustments over the global ocean on a weekly frequency are difficult to manage at present. Also, the satellite biases do not change greatly from weekly to monthly scales (Zhang et al. 2006a). Thus, we have chosen to compute the EBDs on a monthly basis for each 10° box from actual ship and buoy observations. We then average the monthly values for three months (e.g., January–March) to produce operational quarterly updates. The EBD maps (Fig. 5) are sent to AOML as guidance for new drifter deployments. Note that this guidance is solely for climate SST requirements. Some drifters are also used for other important purposes, such as global surface current monitoring and sea surface pressure measurements useful for weather forecasting. AOML also uses these observational needs when planning drifter deployments.

In Fig. 5, colors are used to indicate where observational samplings are good (green: $EBD \geq 2$), low (yellow: $1 \leq EBD < 2$), and poor (red: $EBD < 1$). There is an improvement (more greens and fewer reds) in 2006 as compared to 2002. Note that the actual areas of the boxes are smaller at high latitudes (a factor of cosine of the latitude). Area averages are used when global means are computed.

We started the operational implementation of this procedure at the beginning of 2003. The spatially averaged PSBE time series (Fig. 6) shows the general improvement over this time period, including the most rapid improvement in 2005. The rapid improvement was due to increased funding in 2005 to achieve the target surface drifter array of 1,250 data buoys in sustained service globally. Present drifting buoy technology yields an average buoy service life of about 450 days at sea, constrained primarily by dry cell battery capacity. Consequently,

the array must be continuously monitored and new buoys deployed to maintain the target drifter population. Since 2006, the surface drifter array has been maintained at ~1,250 buoys and the improvement has generally leveled off (with a small oscillation of a few tenths of 1°C). The EBD maps (Fig. 5) show that the major improvements are in the Southern Hemisphere, exclusively due to increased observations by surface drifters.

While the Southern Ocean region has the greatest improvement, it is still the most challenging region

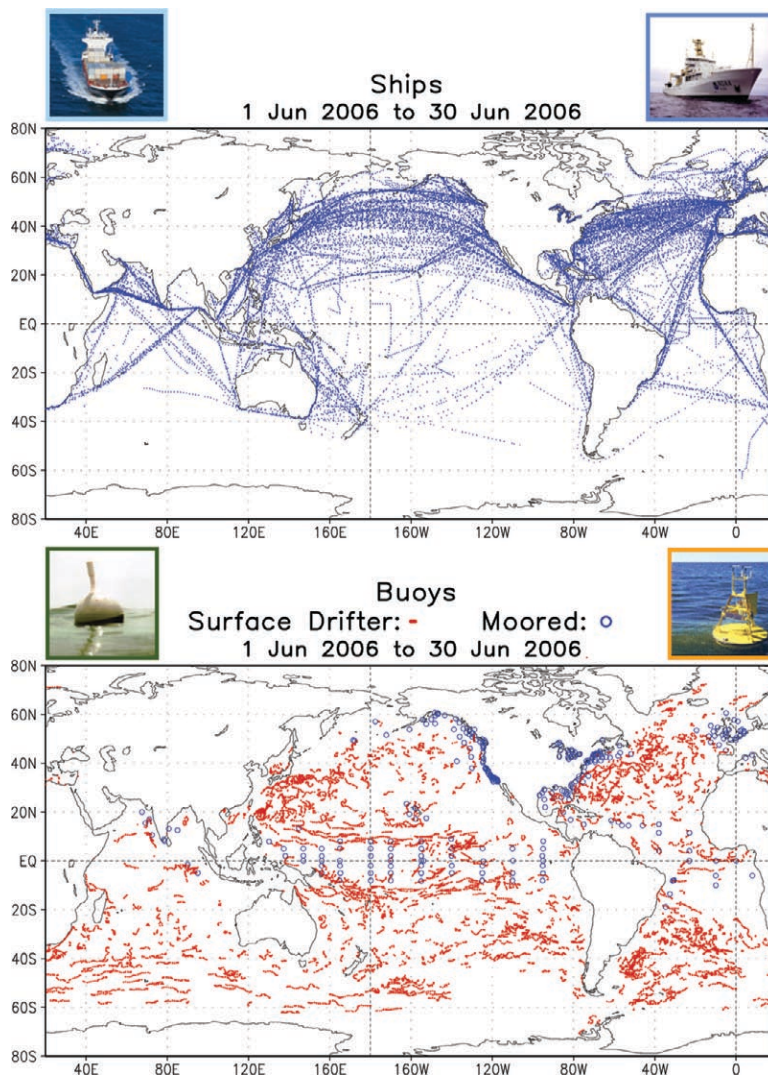


FIG. 4. Locations of major in situ SST observations in Jun 2006. (top) Ship observations, largely from VOS and confined to north of 40°S. (bottom) Moored (blue circles) and drifting (red dots) buoys. The Southern Ocean (40°–60°S) observations were almost exclusively from drifting buoys throughout the year. Also note the complementary observations by the moored and drifting buoys in the vast tropical Pacific Ocean. The tropical moored buoy arrays are also used to monitor the El Niño–Southern Oscillation (ENSO) events that have global climate impacts (drought and flooding, etc).

in which to maintain drifters due to the remote locations for deployment, as well as the tendency for the buoys to drift northward in the Ekman flow out to the Antarctic Circumpolar Current region. Another difficult region in which to maintain drifters is the Indonesia Sea, due to logistical reasons and the complex and shallow topography. Although there have been many drifter deployments in the surrounding regions (Fig. 7), the drifters tend to move away from the Indonesian Sea. There have also been a couple of dozen deployments in the South Sea–South China Sea. However, the drifters that attempt to pass between Sumatra and Borneo encounter shallow bathymetry and thus run aground. This could be a prime spot for moored observations, but the likelihood for instru-

ment vandalism must be evaluated. While this region represents an important climate regime for a densely populated area, its influence is minimal on the globally averaged SST PSBE due to the limited area.

OBSERVING SYSTEM MANAGEMENT APPLICATIONS.

The PSBE is calculated quarterly and provides NOAA with an objective means of systematically evaluating the effectiveness of the network in achieving an integrated global ocean observing system. The Government Performance Results Act of 1993 holds federal agencies accountable for achieving program results, improving program effectiveness, and communicating the relative effectiveness and efficiency of federal programs (GPRA

of 1993). NOAA utilizes the PSBE as a high-level GPRA performance measure that is reported annually to the U.S. Department of Commerce, the White House, and Congress through congressional budget submissions and performance accountability reports. The PSBE has served as an invaluable tool for management of the drifting buoy network, illustrating where improvements have been made and where observing gaps remain. Thus, the PSBE enables NOAA to strategically target its observing system investments. Analyzing the PSBE under varying data-input scenarios (e.g., including only drifters or excluding specific ship deployments) has also enabled NOAA to demonstrate the value of various components of the NOAA fleet and other observing system infrastructure in their contributions to reducing the PSBE.

DISCUSSION. NOAA operates a broad array of observing systems for climate assessment and monitoring, in coordination with

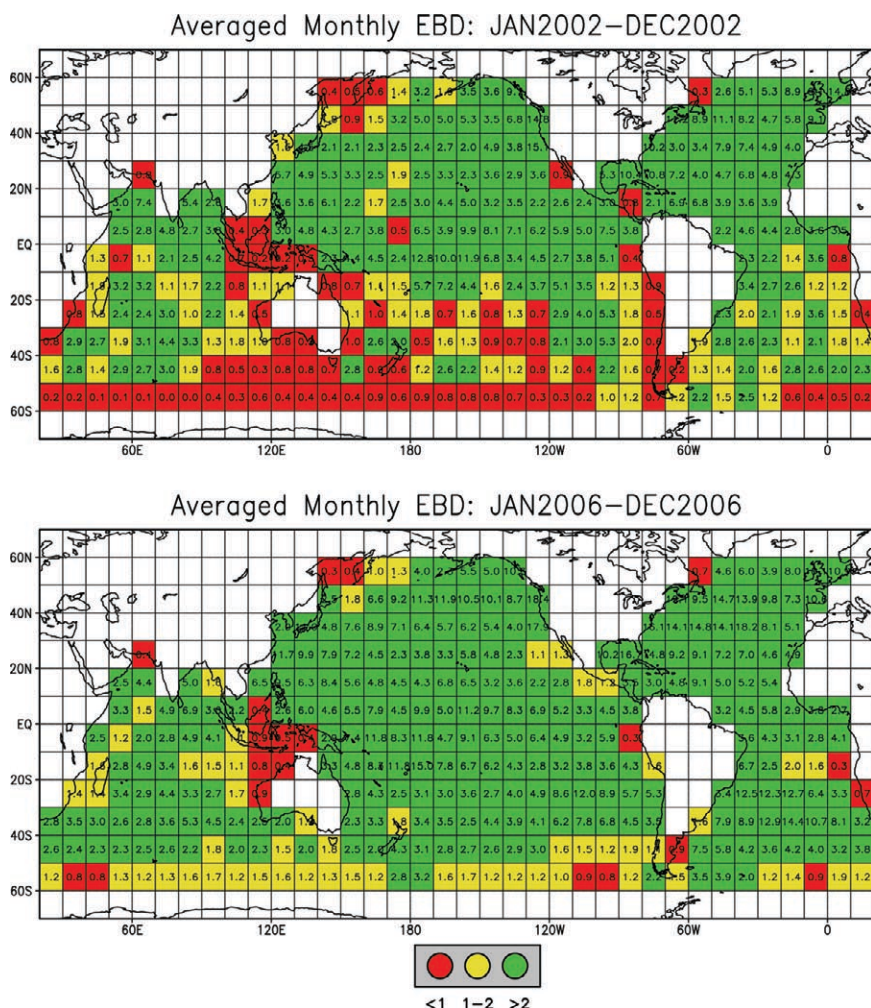


FIG. 5. Averaged monthly EBD in 10° boxes over the global ocean (excluding Hudson Bay, the Mediterranean Sea, and high-latitude oceans). (top) The averages of year 2002; the large number of red and yellow boxes in the Southern Hemisphere indicates the lack of observations from both ships and buoys. (bottom) The averages for year 2006 and the improved observations over 2002, largely due to the increased surface drifter observations in the Southern Hemisphere.

the international community. NOAA is increasingly using Observing System Simulation Experiments (OSSEs) to improve the system design toward an optimal state that minimizes cost while maximizing benefits and to evaluate the potential impacts of proposed observing system changes. OSSEs will prepare for accelerated transition of new observing systems from research to operations (NOAA 5-yr research plan: 2008–12). The climate SST case study we have presented here is such an OSSE example. SST PSBEs have also been calculated for hypothetical observing system scenarios such as the impact on SST analysis of a potential reduction in deployment vessel days at sea. These simulations play an important role in NOAA's planning of future sustained observations.

The present scheme is a nowcast–hindcast system. Future improvements could include a forecast system to determine the optimal drifter deployment locations. Some initial results based on drifter lifetime statistics can be found at AOML (www.aoml.noaa.gov/phod/graphics/dacdata/forecast90d.gif).

If two types of satellite instruments are present with independent error characteristics (e.g., infrared and microwave), the PSBE error could be reduced. In addition to the operational AVHRR SST observations since the early 1980s, microwave observations became available between 38°S and 38°N from the National Aeronautics and Space Administration's (NASA) Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) beginning in December 1997 and globally from NASA's Advanced Microwave Scanning Radiometer (AMSR) beginning in June 2002. Other global microwave satellite SST instruments before 2002 were either poorly calibrated or lacked the low-frequency channels that were needed by the SST retrieval algorithm [e.g., the Special Sensor Microwave Imager (SSM/I)]. Additional microwave SST instruments have recently become available and more are planned. However, due to future uncertainties of these microwave satellite missions, and until these microwave missions become operational at a U.S. agency, we chose to use only the long-term operational AVHRR instrument's error characteristics for the design of the in situ system. This is a conservative approach to ensure a sufficient in situ observing system for long-term climate assessment in the

Potential Satellite Bias Error

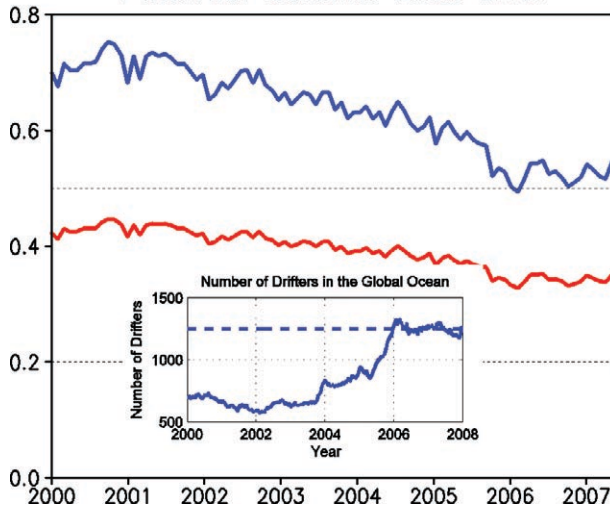


FIG. 6. Globally (60°S–60°N) averaged PSBE as functions of time. Two cases are shown: the worst-case scenario with a maximum uncorrected satellite bias of 2°C (top blue curve) and the more normal scenario with seasonal uncorrected satellite biases of 1°C (bottom red curve). The two thin dashed lines (0.2° and 0.5°C) indicate the targets by WMO–GCOS. The steep decreases in 2005 are due to increased surface drifter deployments (insert), particularly in the Southern Hemisphere (cf. Figs. 4 and 5). The leveling off since then indicates that the number of global surface drifters has reached the sustained number of about 1,250 (dashed line in insert).

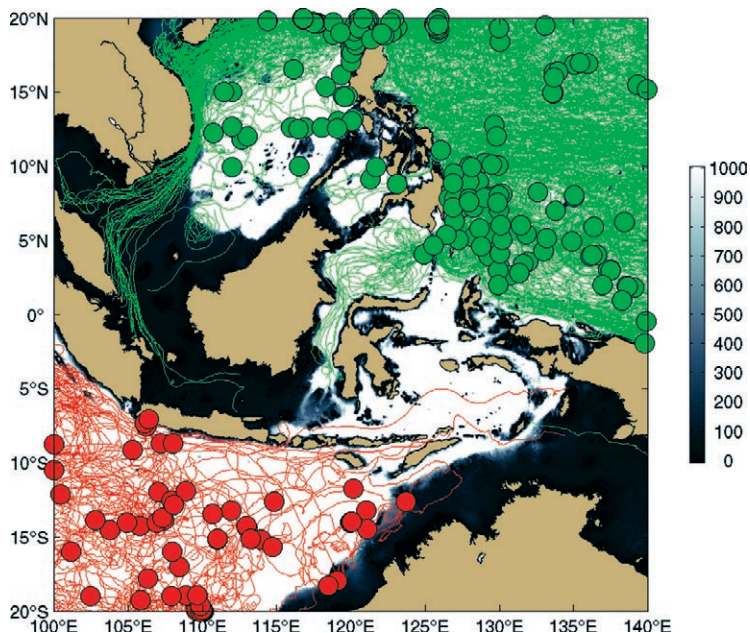


FIG. 7. Complex topography (grayscale shading in meters) in the Indonesian Sea region results in few observations from drifters. Drifter deployment locations (bullets) and trajectories (lines) are shown for drifters deployed in the Pacific Ocean (green) and the Indian Ocean (red) between Aug 1986 and Aug 2007.

lack of microwave observations. Note that NOAA and NASA are working on a research-to-operation transition plan for the creation of long-term climate data records (Bates 2004), according to the principles outlined by the National Research Council (2004) of the United States. Once operational microwave SST satellite missions are launched and the observations are verified, the in situ system requirements will be reexamined.

Finally, we stress that multiple SST products are necessary because different needs require different accuracy and resolutions (e.g., Donlon et al. 2007). For example, many coastal and oceanic frontal dynamic studies need higher resolutions in both time and space. In these studies, long-term (multiple year) consistency may not be as critical as higher resolution. On the other hand, long-term consistency and sufficient sampling coverage are critical for climate applications. This is especially important when creating climate data records on finer (e.g., regional) scales. Sampling studies and error analyses should be an integral part in creating climate data records (e.g., Zhang et al. 2006b).

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REFERENCES

Bates, J. J., 2004: NOAA's Scientific Data Stewardship Program. *AMS 13th Conf. on Satellite Meteorology and Oceanography*, Norfolk, VA, Amer. Meteor. Soc., 5.1. [Available online at <http://ams.confex.com/ams/pdfpapers/79249.pdf>.]

Donlon, C., and Coauthors, 2007: The Global Ocean Data Assimilation Experiment High-Resolution Sea Surface Temperature Pilot Project. *Bull. Amer. Meteor. Soc.*, **88**, 1197–1213, doi:10.1175/BAMS-88-8-1197.

Kagan, R. L., 1979: *Averaging Meteorological Fields* (in Russian). Gidrometeoizdat, 212 pp.

Koblinsky, C. J., and N. R. Smith, Eds., 2001: *Observing the Oceans in the 21st Century*. 2001 GADOE Project Office, Bureau of Meteorology of Australia, 604 pp.

National Research Council, 2004: *Climate Data Records from Environmental Satellites: Interim Report*. National Academies Press, 150 pp.

Needler, G., N. Smith, and A. Villwock, 1999: The action plan for GOOS/GCOS and sustained observations for CLIVAR. *Proc. OceanObs '99*, Saint Raphael, France, CLIVAR, 26 pp. [Available online at www.bom.gov.au/OceanObs99/Papers/Needler.pdf.]

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.*, **108**, 4407, doi:10.1029/2002JD002670.

Reynolds, R. W., 1993: Impact of Mount Pinatubo aerosols on satellite-derived sea surface temperatures. *J. Climate*, **6**, 768–774.

—, and T. M. Smith, 1994: Improved global sea surface temperature analyses using optimum interpolation. *J. Climate*, **7**, 929–948.

—, N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang, 2002: An improved in situ and satellite SST analysis for climate. *J. Climate*, **15**, 1609–1625.

—, C. Liu, T. M. Smith, D. B. Chelton, M. G. Schlax, and K. S. Casey, 2007: Daily high-resolution-blended analyses for sea surface temperature. *J. Climate*, **20**, 5473–5496.

Smith, T. M., and R. W. Reynolds, 2005: A global merged land–air–sea surface temperature reconstruction based on historical observations (1880–1997). *J. Climate*, **18**, 2021–2036.

—, R. W. Reynolds, and C. F. Ropelewski, 1994: Optimal averaging of seasonal sea surface temperatures and associated confidence intervals (1860–1989). *J. Climate*, **7**, 949–964.

Zhang, H.-M., R. W. Reynolds, and T. M. Smith, 2004: Bias characteristics in the AVHRR sea surface temperature. *Geophys. Res. Lett.*, **31**, L01307, doi:10.1029/2003GL018804.

—, —, and —, 2006a: Adequacy of the in situ observing system in the satellite era for climate SST. *J. Atmos. Oceanic Technol.*, **23**, 107–120.

—, J. J. Bates, and R. W. Reynolds, 2006b: Assessment of composite global sampling: Sea surface wind speed. *Geophys. Res. Lett.*, **33**, L17714, doi:10.1029/2006GL027086.