J8.12 ADEQUACY OF IN SITU OBSERVING SYSTEM IN THE SATELLITE ERA FOR CLIMATE SST ANALYSIS

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ABSTRACT

A method is presented to evaluate the adequacy of the recent in situ network for climate sea surface temperature (SST) analyses which use both in situ and satellite observations. Satellite observations provide superior spatiotemporal coverage but have biases, and in situ data are needed to correct the satellite biases. Recent satellite bias events were analyzed to extract typical bias patterns and scales. Occasional biases of 2^{o}C were found during large volcano eruptions and near the end of the satellite instruments' lifetime. Since future biases could not be predicted, the in situ network was designed to reduce the large biases that have occurred to a required accuracy. Simulations with different buoy density were used to examine their ability to correct the satellite biases and to define the residual bias as a potential satellite bias error (PSBE).

The PSBE and buoy density (BD) relationship was found to be nearly exponential, thus an optimal BD range for efficient PSBE reduction can be defined. The PSBE decreases rapidly as BD on a 10^{o} spatial grid increases from 0 to 3; beyond which the PSBE reduction levels off. To reduce a 2^{o}C maximum bias to below 0.5^{o}C, a BD of about 2 buoys/10º grid is required. The present in situ SST observing system was evaluated to define an equivalent buoy density (EBD), allowing ships to be used along with buoys according to their random errors. Seasonally averaged monthly EBD maps were computed to determine where additional buoys were needed for future buoy deployments. Additionally, a PSBE can be computed from the EBD of the current in situ observing system to assess the system's adequacy to remove potential future satellite biases.

1. INTRODUCTION

Over the last few decades, international groups have begun designing a Global Ocean Observing System (GOOS) as a component of the Global Climate Observing System (GCOS). Sea surface temperature (SST) was one of the important parameters considered. The purpose of this paper is to examine the present in situ and satellite observing system and to recommend how future in situ observing system should be improved to efficiently correct satellite biases for climate SST.

Present SST observing system consists of in situ and satellite observations. In situ observations are made from ships and buoys (both moored and drifting). Kent et al. (1993 and 1999), Parker et al. (1995), and Emery et al. (2001) extensively studied the in situ SST random errors. Reynolds and Smith (1994) and Reynolds et al. (2002) estimated that typical random errors are 0.5 and 1.3°C for buoy and ship observations, respectively. Satellite observations have provided dramatically improved coverage in time and space, expanding from one infrared (IR) instrument to array of multiple IR and microwave instruments over the last two decades. Satellite random error for the AVHRR was discussed by McClain et al. (1985) and May et al. (1998). Reynolds and Smith (1994) and Reynolds et al. (2002) estimated that typical random errors are 0.5 and 0.3°C for daytime and nighttime AVHRR, respectively.

The high satellite data coverage reduces sampling and random errors in SST analyses using combined in situ and satellite data. However, satellite bias error remains significant. Zhang et al. (2004) showed that the AVHRR SST biases have changed over time and can be as large as 2°C. Similar biases can occur with other satellites [e.g., Reynolds et al. (2004) discussed biases in the TRMM Microwave Imager retrievals]. Satellite biases change with time due to orbit changes, aging of satellite instruments, and changes in atmospheric conditions which may differ from those used in the development of the satellite SST retrieval algorithms (e.g., unexpected volcanic aerosols). These biases needed to be corrected to minimize systematic errors in climate SST analyses, which are defined to have temporal resolutions of one week or longer and spatial resolutions of 1^{o} or larger following Reynolds et al. (2002).

In the present study, the optimum interpolation (OI) and bias correction techniques of Reynolds and Smith (1994) and Reynolds et al. (2002) are used to determine the optimal in situ data density for efficient bias reduction. Briefly, the OI objectively determines a series of weights for SST data increments at each grid point. The data increment is the difference between each observation and the analysis first guess. The OI method assumes that the data do not contain long-term biases (e.g., see Lorenc, 1981). Because satellite biases occur, an optional step using a correction based on Poisson's equation can be carried out to remove satellite biases relative to in situ data prior to the OI. This step produces an adjustment of the satellite data, anchoring it to the in situ data and matching the gradients of the two fields. In the OI procedure, various error statistics are assigned that are functions of latitude and longitude. In this work, the analysis was computed on monthly time scales and the first guess was taken as the monthly climatology in the buoy need simulations.

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2. SATELLITE SST BIAS SCALES AND PATTERNS

The in situ data density requirement for satellite bias correction depends on the spatial patterns and scales of the biases. Generally, the more complicated the bias spatial pattern, the more in situ observations are needed. Therefore it is first necessary to examine the typical scales and patterns of historical biases. The objective is to extract the dominant components of the biases, and to use them to simulate future bias regimes. This is done using EOF analysis, which decomposes the multivariate bias into orthogonal modes, where a small number of the modes often contain the major part of the data variance. The AVHRR SST bias analysis was detailed in Zhang et al. (2004) for 1982-2002. Here the bias EOFs for 1990-2002 were recomputed for the design of the in situ network. The 1982-1989 data were not used because the buoy data, which are of critical importance in the tropics and Southern Hemisphere, were sparser in the 1980s, as discussed in Reynolds et al. (2002). However, the major EOF features for the two time periods are very similar. Briefly, mode 1 has a global scale and is attributed to volcano eruptions. The maximum bias can reach 2°C. Modes 2 and 3 are seasonal biases, which are strongly related to local weather phenomena, such as seasonal dust aerosols and cloud covers. Taken together, the first six EOFs represent 52.7% of the total variance. As shown in the next section, the buoy need density for bias correction generally increases as the mode number increases from 1 to 4, and the buoy need density converge for modes 4 through 6, based on which the in situ network will be designed.

3. OPTIMAL BUOY DENSITY FOR EFFICIENT SATELLITE BIAS REDUCTION

This section presents the relationship between the in situ data density and the bias error reduction rate. The relationship was quantified for various bias patterns, represented by the bias EOF modes computed in the previous section. Each of the EOF modes was treated as a typical bias regime that could happen independently, and each bias representation was scaled to a composite bias magnitude to assure that the in situ system can reduce each bias mode as well as composite bias from multiple modes to a required accuracy. The simulations used a maximum bias of 2°C to simulate a worse case as discussed in Zhang et al. (2004).

To study the response of bias correction to changes in buoy density, the satellite SST values were simulated as the monthly climatology (as the assumed ground truth) plus the representative biases (the scaled EOFs) at the locations of actual satellite observations:

$T_{si}(\boldsymbol{x},t) = T_g(\boldsymbol{x},t) + EOF_i(\boldsymbol{x}) * a(t)$,   *for* i=1 *to* 6,

were $T_{si}(\boldsymbol{x},t)$ is the simulated satellite SST, and $T_g(\boldsymbol{x},t)$ is the climatology. $EOF_i(\boldsymbol{x})$ is the EOF spatial mode i with the simulations run for each mode separately. The Gaussian random time amplitude is represented by $a(t)$ which has a zero mean and standard deviation of 1. The variable t is the time in month from t = 1 to 156 (January 1990 to December 2002), and $\boldsymbol{x}$ is the vector location of each satellite observation. Random noise was not added to satellite data because of the high data density, which reduces the random errors to insignificant levels compared to the bias errors.

Buoy SST values were simulated as the ground truth plus typical random buoy SST error:

$T_b(\boldsymbol{x},t) = T_g(\boldsymbol{x},t) + 0.5 * e(t)$,

where $e(t)$ is the Gaussian random time series with a zero mean and standard deviation of 1. To study the response of bias correction to changes in buoy density, the buoy data were placed on regular grids with various grid resolutions for the multiple simulations. For each grid resolution, one buoy was placed at each grid point. For sparser buoy data, data noise becomes important.

The OI analysis with bias correction was then applied on the simulated satellite and buoy data. By design, the monthly climatology would be the expected result of the OI SST if the satellite biases were completely removed. The difference between the OI SST with bias correction and the monthly climatology is the uncorrected residual bias, which is evaluated as a function of buoy density. Residual uncorrected SST biases were computed over the global ocean for each month over the simulation period. The RMS of the residual bias was defined as the potential satellite bias error (PSBE) to reflect that the simulated satellite bias was set to a maximum of 2^{o}C over the global open ocean, which is representative of the larger satellite biases observed over the past satellite period.

Biases of modes 1 to 3 are relatively easy to correct because of their larger spatial structures. The PSBE curves for modes 4 to 6 are similar due to their similar spatial scales, even though their individual spatial patterns are different. Modes 4 to 6 have more stringent requirements because of their smaller spatial scales. The averaged PSBE of modes 4-6 is shown in Fig. 1 as a function of buoy density, defined as number of buoys per 10°x10° box (BD_{10}). The relationship is near exponential. Bias reduction is rapid for BD_{10} < 3, and levels off thereafter. Thus BD_{10} < 3 can be defined as the optimal bias reduction range. The optimal buoy density for bias reduction can be defined between 2 and 3 since it is the buoy density at the end of the rapid bias reduction.

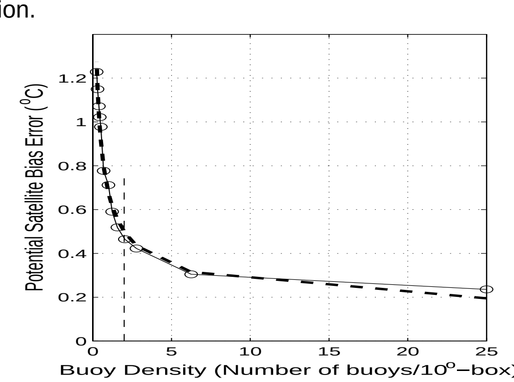

Figure 1. Potential Satellite Bias Error (PSBE) as a function of buoy density. Dashed line is a model fit. Thin vertical dash line indicates where BD=2.

4. EQUIVALENT BUOY DENSITY (EBD) AND NEW BUOY REQUIREMENT

Past and present in situ (ship and buoy) network is evaluated to determine where more buoys are needed to meet a desired SST accuracy. On climate scales, Needler et al. (1999) suggested a SST accuracy of 0.2-0.5°C for satellite bias correction on a 500 km grid and on a weekly time scale, which was endorsed by the WMO (http://www.wmo.ch/web/gcos/gcoshome.html). Because satellite biases do not change greatly from weekly to monthly periods and a 5° latitude-longitude box is close to 500 km box (only 10% larger at the equator), the minimal bias accuracy used here is 0.5°C on a monthly 5° grid. This modification is for the convenience of computation and buoy deployments.

Figure 1 shows that to reduce a 2°C bias to 0.5°C, the needed buoy density is about 2 per 10° grid box. This coincides with the optimal buoy density for bias reduction defined above. The 2°C satellite biases have occurred in the past and it is considered as a worse case scenario. Note that under normal conditions, the magnitudes of satellite SST biases are of 0.5°C to 1°C, thus better than 0.5°C SST accuracy can be achieved under the recommended buoy density of 2 per 10° grid box. For example, the same buoy density would reduce a global maximum bias of 1°C to 0.32°C.

Ship and buoy observations are combined according to their random noise levels as stated in section 1, of 1.3°C for ships and 0.5°C for buoys. Thus roughly 7 ship observations are required to have the same accuracy of one buoy observation. Hence, an equivalent-buoy-density (*EBD*) is defined as

$$EBD = n_b + \frac{n_s}{7}$$

where n_b and n_s are the number of observations from buoys and ships in a 10° box, respectively.

The *EBD* was defined for each month, and then was averaged seasonally for operational buoy deployment. An example is shown in Fig. 2. As the focus is now on the open ocean, boxes poleward of 60°N and 60°S were not shown along with boxes with less than 50% ocean by area and boxes in Hudson Bay and the Mediterranean Sea. Color shading is used in the figure to indicate where and how many additional buoys are needed.

Figures 1 and 2 are combined to obtain the performance of the in situ observational system for SST, as shown in Fig. 3. The impact of additional drifting buoys in the mid 1990s shows a drop in the bias error with time, especially in the middle latitude Southern Hemisphere Ocean (20°S-60°S). In the middle latitude Northern Hemisphere Ocean (60°N -20°N), the equivalent buoy density from the current in situ network is typically dense enough to correct potential satellite SST biases to the required accuracy of 0.5°C. The global (60°S-60°N) and tropical (20°S-20°N) averages of the potential satellite bias error are roughly 0.6°C at the end of our analysis, which are slightly above the required accuracy of 0.5°C.

5. DISCUSSION

The results presented here provide an objective method to determine the minimum in situ network required for SST analyses for climate. For this network, it has been assumed that satellite data are available and that these data provide adequate coverage of the ocean on 5° spatial and monthly time scales. The purpose of the in situ network is to allow large satellite biases to be corrected to the required accuracy.

Simulations showed that the residual potential satellite bias error and in situ data density have a near exponential relationship. Thus once certainty error reduction is achieved, considerably more in situ data are needed to achieve even a small further error reduction. A buoy density of more than 3 in a 10° box does not reduce the bias error significantly. It was also found that about 2 buoy equivalents are needed in 10° boxes to reduce a 2°C satellite bias to below 0.5°C. The required buoy density of 2 is near the end of the rapid error reduction range, thus it may be considered as an optimal buoy density. It is important to point out that under normal conditions, the magnitudes of satellite biases are of 0.5°C to 1°C, and the residual bias error can be reduced to about 0.3°C with the buoy density of 2 per 10° box.

An equivalent buoy density (EBD) has been defined to combine ship and buoy observations according to their typical observational random errors. It is then possible to determine where additional buoys would be needed to bring the EBD to the required 2. A potential satellite bias error (PSBE) can also be defined as a function of EBD to monitor the sufficiency of the current in situ network for SST.

The current in situ observation network was designed for other purposes and is thus not necessarily the most efficient network for climate SST. For example, the EBDs exceeded 5 in most of the North Atlantic Ocean, while the EBDs are less than 2 in a large number of boxes in the Southern Oceans. If it is for climate purposes alone, the current buoy distribution should be redistributed over the global oceans.

These results have already had an influence on future buoy deployments. The NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) is now using seasonal EBD maps to guide surface drifting buoy deployments. The presently designed buoy need network is a nowcast system. It will require reliable information on the global ocean surface circulation to make it a forecast system. This study is a step toward objectively defining requirements for an integrated ocean observing system.

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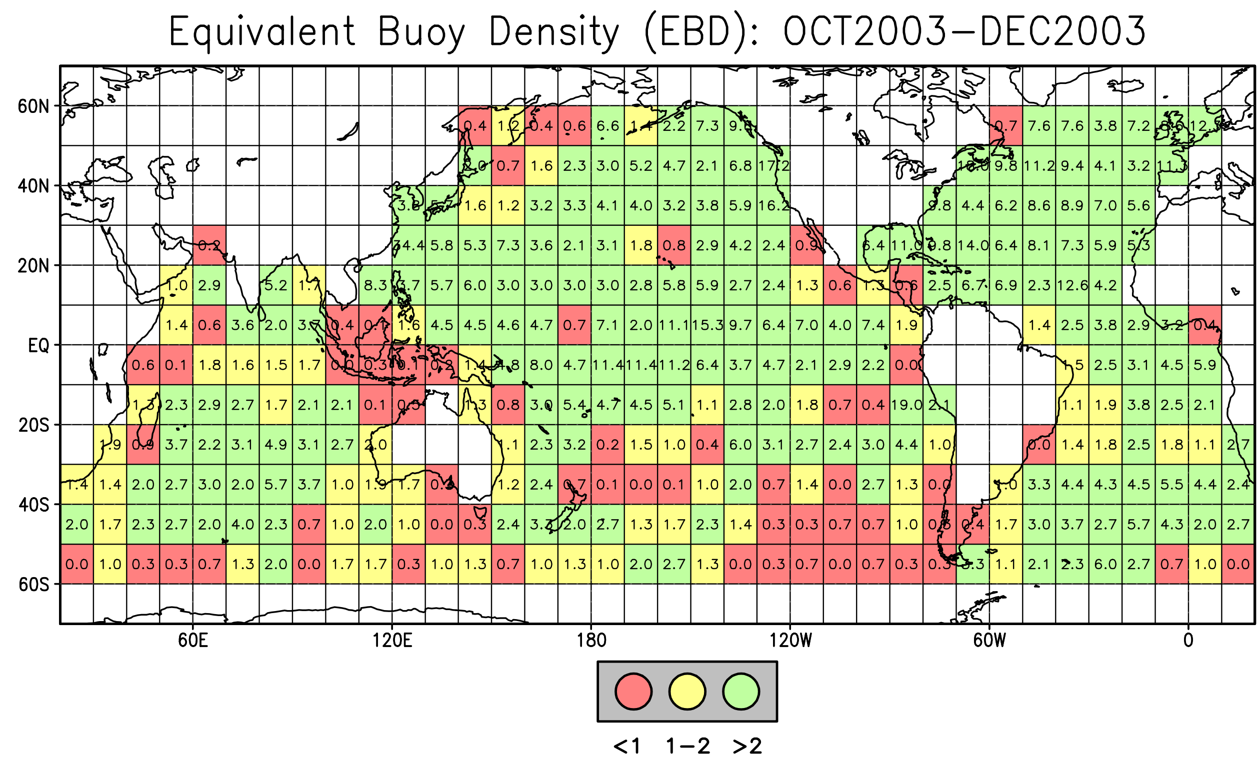

Figure 2. Seasonally (October – December 2003) averaged monthly equivalent buoy density (EBD) on a 10° grid. EBD includes contributions from both buoys and ships, accounting for their typical random errors. Green shading indicates where EBD≥2 and no more buoys are needed. Red shading indicates critical regions where EBD<1 and two more buoys are needed. Yellow shading indicates 1≤EBD<2 and one more buoy is needed.

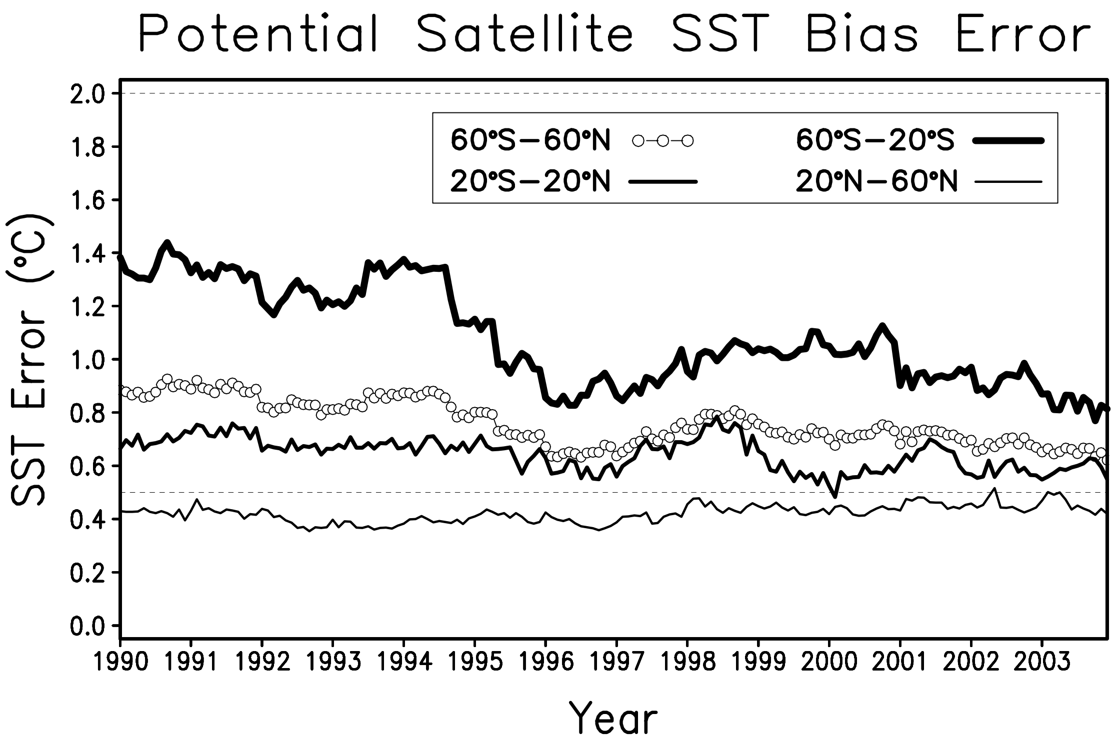

Figure 3. **Simulated potential satellite bias errors (PSBEs). Shown are zonal averages over four latitude bands. The simulated PSBEs are for simulated biases with a global maximum of 2°C. The PSBE is the residual bias error that cannot be removed by the existing in situ observing network. Because the actual biases are often smaller than 2°C, the residual bias errors may be smaller than those shown.**