INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **25**: 857–864 (2005)

IMPACTS OF *IN SITU* AND ADDITIONAL SATELLITE DATA ON THE ACCURACY OF A SEA-SURFACE TEMPERATURE ANALYSIS FOR CLIMATE

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Received 11 April 2004
Revised 3 September 2004
Accepted 10 September 2004

ABSTRACT

Additional *in situ* and satellite data improve the accuracy of a blended (*in situ* and satellite) sea-surface temperature (SST) analysis using optimum interpolation (OI). Two studies were conducted to evaluate the impacts of *in situ* and additional satellite data. One study evaluated the adequacy of the recent *in situ* network. Because of the high coverage of satellite data, *in situ* data used in the analysis tends to be overwhelmed by satellite data. Thus, the most important role of the *in situ* data in the analysis is to correct large-scale satellite biases. Simulations with different buoy densities showed the need for at least two buoys on a 10° spatial grid. This will ensure that satellite biases do not exceed 0.5 °C. Using this criterion, regions were identified where additional buoys are needed.

A second study evaluated the impact of satellite SST retrievals from the tropical rainfall measuring mission microwave imager (TMI) on the OI analysis. The present version only uses infrared satellite data from the advanced very high resolution radiometer (AVHRR) instrument. The results of the intercomparisons showed that both AVHRR and TMI data have biases that must be corrected for climate studies. The addition of TMI data clearly improved the OI analysis accuracy without bias correction, but was less significant when bias correction was used. However, there are areas of the ocean with limited *in situ* data and restricted AVHRR coverage due to cloud cover, and the use of both TMI and AVHRR should improve the accuracy of the analysis in those areas. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: SST; buoy; AVHRR; TMI; satellite; optimum interpolation

1. INTRODUCTION

The current sea-surface temperature (SST) observing system consists of *in situ* and satellite observations, as discussed by Reynolds *et al.* (2002). *In situ* observations are made from ships and buoys (both moored and drifting). However, satellite observations have provided dramatically improved coverage in time and space that was not possible with *in situ* data alone. The high satellite data coverage reduces sampling and random errors in SST analyses using combined *in situ* and satellite data. However, satellite retrievals may have large biases, which should be corrected with respect to *in situ* observations.

Reynolds and Smith (1994; Reynolds *et al.*, 2002) produced an optimum interpolation (OI) SST analysis that is widely used for weather forecasting, climate monitoring, climate prediction, and both oceanographic and atmospheric research, as well as for specifying the surface boundary conditions for atmospheric analysis and reanalysis. The analyses appear in many publications and are available to any user via the Internet. The analysis is produced weekly on a 1° spatial grid and uses both *in situ* and satellite data. The OI objectively determines a series of weights for observations at each analysis grid point. The OI method assumes that the

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data do not contain long-term biases. Because satellite biases occur, a preliminary step is carried out prior to the OI analysis that results in a large-scale adjustment of the satellite data relative to the *in situ* data.

When the OI analysis was originally developed in the early 1990s there was only one satellite instrument available to measure SST operationally. This instrument was the infrared (IR) advanced very high resolution radiometer (AVHRR), which was one of the instruments on the National Oceanic and Atmospheric Administration (NOAA) polar orbiting environmental satellites. During the last decade, new IR sensors, such as the moderate resolution imaging spectroradiometer (MODIS), have become available on other satellites, but have yet to be used in the OI analysis. Beginning in December 1997, SSTs began to be available on the tropical rainfall measuring mission (TRMM) satellite. Because of its low inclination orbit, the TRMM microwave imager (TMI) produces SSTs from roughly 38 °S to 38 °N. Additional microwave instruments have become available in 2002 and more are planned. SSTs from microwave instruments have lower spatial resolution than SSTs from IR instruments. However, microwave instruments are able to retrieve SSTs in non-precipitating cloud-covered regions where IR instruments cannot (Wentz *et al.*, 2001).

Our purpose is to improve the accuracy of the OI analysis. The results of this study are presented in two sections. In the first section, the reduction of satellite biases is determined as a function of *in situ* data density. The results will help to determine where and how many additional buoys are needed to augment the current *in situ* observing network to achieve the required climate SST accuracy. In the second section, the usefulness of TMI is examined from the perspective of the OI analysis. In this study, several versions of the OI analysis were computed with different sets of satellite data. For details beyond the brief results reported here, see Zhang *et al.* (in press) and Reynolds *et al.* (2004) for the first and second sections respectively.

Please note that in both sections the satellite data are corrected relative to both ships and buoys. This method does not assume that ship and buoy biases are negligible. However, corrections of these data are not considered here. Differences between ship and buoy observations are discussed in Reynolds *et al.* (2002), where ships were shown to be between 0.1 and 0.2 °C warmer than buoys. In addition, a re-evaluation of ship biases and random error is present in Kent and Taylor (in press).

2. AN *IN SITU* NETWORK FOR SST ANALYSES

To design an *in situ* network to correct potential satellite biases, it is necessary to examine the typical scales and patterns of the biases from historical data. The objective is to extract the major components of the biases so that they can be used to simulate typical bias patterns and scales. This was done by the empirical orthogonal function (EOF) analysis of the satellite biases in the NOAA operational AVHRR SST, which is the longest satellite SST dataset. Ideally, the biases could be computed at collocated positions of satellite and *in situ* data. However, the sparseness of the *in situ* data hinders extracting the spatial scales and patterns. Thus, the OI analysis was used to compute the SSTs with monthly *in situ* and AVHRR satellite data (Zhang *et al.*, 2004). Two versions of the OI SST analyses were computed, one version with and one version without the satellite bias correction procedure. The difference between the two versions defined the satellite SST biases, and the EOF bias patterns were computed from the differences. Figure 1 shows the EOF spatial patterns and time series for modes 1 and 6. Mode 1 reveals biases primarily due to stratospheric aerosols from volcanic eruptions, with large-scale zonal tropical biases. Modes 2 and 3 are seasonal biases (not shown), which are strongly related to local weather phenomena, such as seasonal dust aerosol and cloud cover. Mode 6 shows the strongest loadings in the middle latitude Southern Hemisphere. This is an important mode to include in the simulations below, because *in situ* data are sparse south of roughly 40 °S. Please note that buoy SST data are used to tune the global AVHRR data after the launch of a new satellite and when increasing differences indicate that a new adjustment is needed (Reynolds *et al.*, 2002). This reduces any long-term trends in satellite biases. Taken together, the first six EOFs represent 52.7% of the total variance of the differences between the two OI versions.

To examine the impact of *in situ* data on satellite bias correction, the OI was computed with simulated biased satellite data and simulated unbiased buoy data. Simulations were used because there is no systematic way to predict future satellite biases. The maximum satellite bias error was selected to be 2 °C as the worst

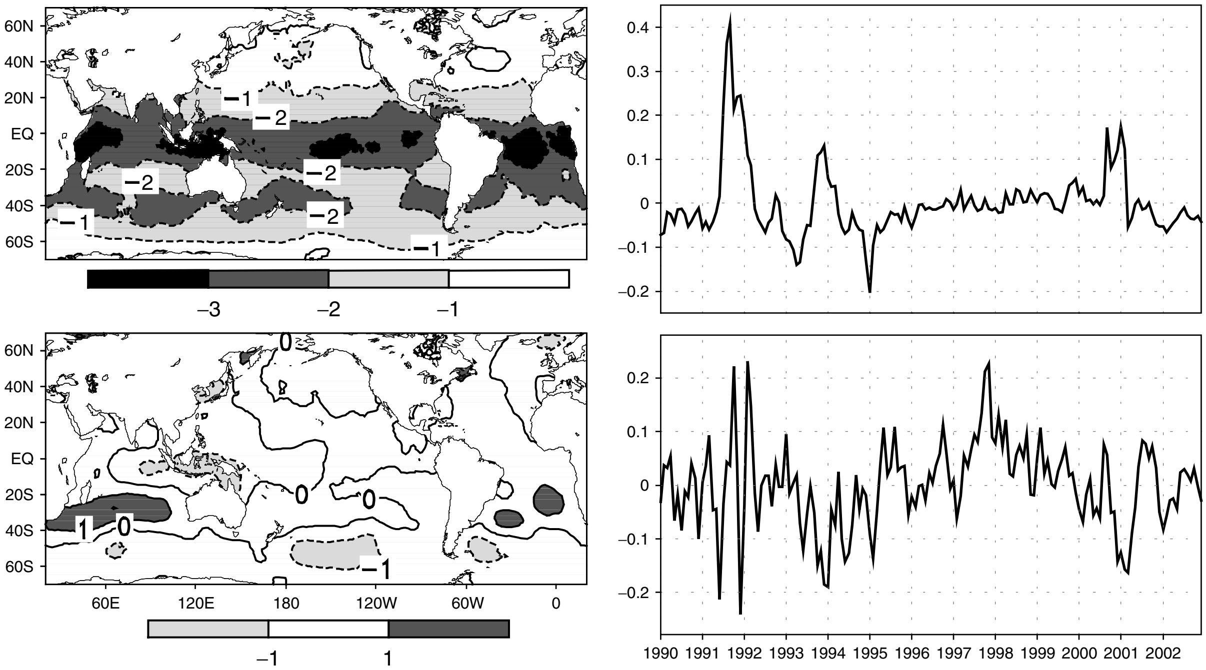

Figure 1. EOF modes 1 and 6 (upper and lower panels respectively) of the AVHRR SST biases for January 1990 through to December 2002. Spatial patterns are on the left and temporal patterns are on the right. Mode 1 represents biases associated with volcano aerosols. Mode 6 represents biases mostly in the Southern Hemisphere and is important because current *in situ* observations are sparser there

case. This will be defined as the 'potential satellite bias error'. Thus, the potential satellite bias error would be 2 °C if there were no *in situ* data to correct the bias. As discussed in Reynolds (1993), the absolute satellite biases from the AVHRR instrument exceeded 2 °C during the eruptions of Mt Pinatubo. Biases on these scales lasted several months, and biases greater than 0.5 °C persisted for almost a year. On climate scales, Needler *et al.* (1999) suggested an SST accuracy of 0.2–0.5 °C for satellite bias correction on a 500 km grid and on a weekly time scale. Because satellite biases do not change greatly from weekly to monthly periods and because a 5° latitude–longitude box is close to a 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 to simplify buoy deployment plans. The simulations were designed to determine the minimum buoy density needed to reduce potential satellite bias errors of 2 °C to below 0.5 °C over the global ocean. In the simulations, satellite biases were defined by the spatial patterns from each of the first six EOF spatial modes multiplied by a random Gaussian-noise temporal function such that the maximum time-averaged root-mean square (RMS) of the bias equals 2 °C in at least one location. Buoy SST values were simulated on different regular spatial grids without biases but with typical random observational errors of 0.5 °C (Reynolds and Smith, 1994).

Monthly OI analyses were computed corresponding to each of the six EOF representations of the satellite biases, using a number of fixed buoy grid resolutions for each EOF for the period, 1990–2002. The simulated monthly buoy and satellite SSTs were the input data to the OI analyses, where the bias correction procedure is used prior to the OI to correct the simulated satellite SST biases. For this effort, the OI first guess is the SST climatology for the month to be analysed. If there were no *in situ* data available, any satellite biases would be uncorrected and the analysis would be equal to the satellite bias plus the first guess. In contrast, if the buoy data were densely distributed over the global ocean, then all the satellite biases would be nearly completely removed with reference to the *in situ* data and the analysis would be nearly equal to the first guess. The RMS difference between the analysis and the first guess is the potential satellite bias error. The objective is to determine the buoy density at which the potential satellite bias error can be reduced to within the required

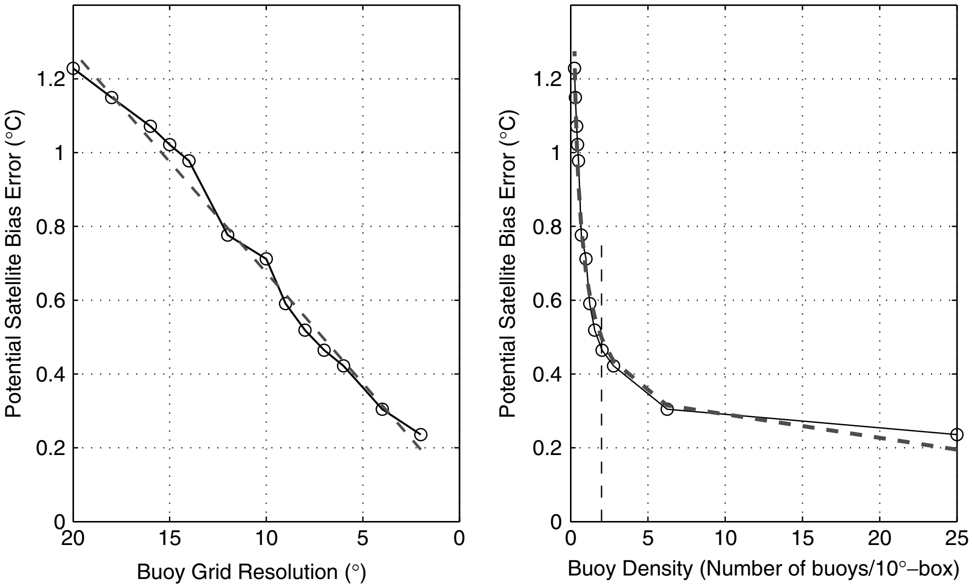

Figure 2. The average of the 'potential satellite bias error' for bias EOF modes 4–6. The left panel shows the averaged potential satellite bias error as a function of the buoy grid resolution (solid line) with a linear fit (dashed line). The right panel shows the averaged potential satellite bias error as a function of the buoy density for a 10° spatial grid with the transformed original linear fit (dashed line). The thin vertical dashed line indicates where the buoy density is equal to two, which is the density needed to reduce a 2 °C bias to below 0.5 °C

accuracy (i.e. below 0.5 °C) over the global ocean. For a number of different buoy grid resolutions and for each bias EOF pattern, the potential satellite bias error was computed over the global ocean for the simulation period. This was done by simulating one buoy on grid resolutions of 20°, 18°, 16°, 15°, 14°, 12°, 10°, 9°, 8°, 7°, 6°, 4°, and 2°. For the first three modes, the potential satellite bias errors were relatively easy to correct because of their larger spatial structures. However, the potential satellite bias errors for modes 4 to 6 were similar to each other owing to their similar spatial scales, even though their individual spatial patterns are different. Because of their similarity, the potential satellite bias error for modes 4, 5 and 6 were averaged and are shown in Figure 2 (left panel) for varying buoy grid resolutions. Overall, the potential satellite bias error and buoy data grid resolution have a nearly linear relationship. In the right panel of Figure 2 the potential satellite bias error is converted to a buoy density on a 10° spatial grid by spatial area weighting. (Thus, one buoy on a 5° grid is equivalent to four buoys on a 10° grid.) The results of the simulations show that average potential satellite bias error was reduced below 0.5 °C with a buoy density of two on a 10° spatial grid.

The data density of the present *in situ* network was evaluated to determine where more buoys are needed. These buoys could be either moored or drifting. However, because of the high cost of moored buoys, they will be assumed to be drifters. To evaluate this requirement using actual observations, it is necessary to determine how to combine ship and buoy data in the results. Because ship observations are noisier (random error of 1.3 °C; Reynolds and Smith, 1994) than buoy observations (random error of 0.5 °C), roughly seven ship observations are required to have the same accuracy of one buoy observation. Therefore, an equivalent buoy density (EBD) is defined:

$$\mathrm{EBD} = n_\mathrm{b} + n_\mathrm{s}/7$$

where n_b and n_s are respectively the number of buoys and number of ships in a 10° box. (Both moored and drifting buoys are used equally in the computation of EBD.)

The EBD was defined for each month, and then averaged seasonally to indicate where additional buoys need to be deployed. An example is shown in Figure 3 for October–December 2003. Boxes poleward of 60 °N and 60 °S were not shown, nor boxes with less than 50% ocean by area or boxes in Hudson Bay and

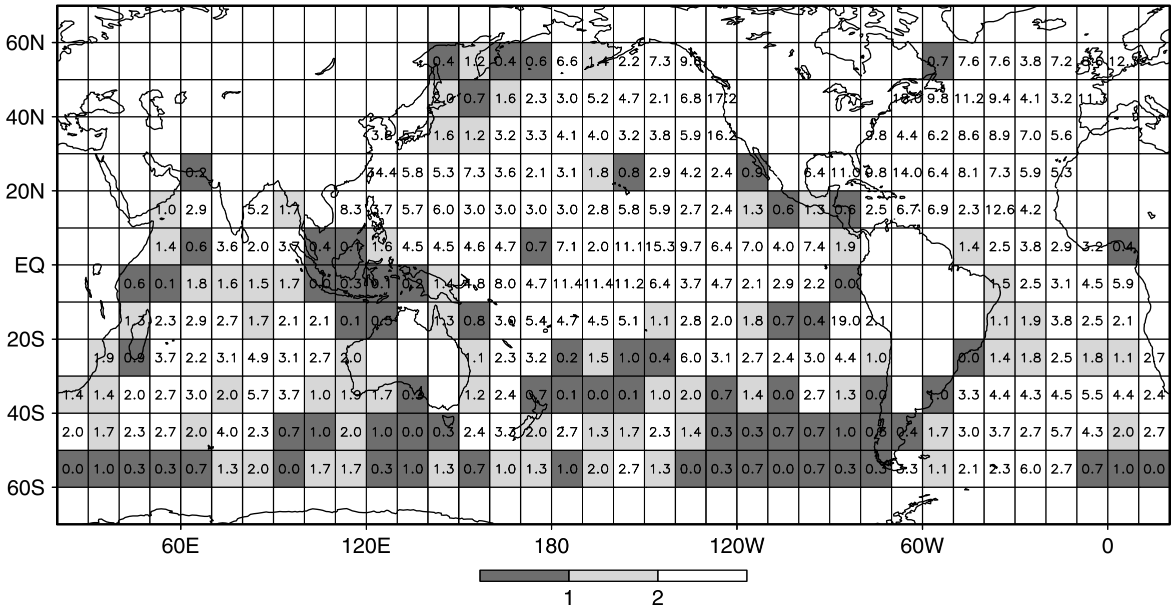

Figure 3. Seasonally (October–December 2003) averaged monthly EBD with respect to a 10° grid. EBD includes contributions from both buoys (drifting and moored) and ships according to their typical observational random errors. Lack of shading indicates where EBD ≥ 2 and where no more buoys are needed. Heavy shading indicates where EBD < 1 and two more buoys are needed in each box. Light shading indicates where $1 \leq$ EBD < 2 and one more buoy is needed in each box

the Mediterranean Sea. Note that this figure is completely defined by the *in situ* data distribution of ships and buoys as given by the EBD. Shading is used in the figure to help indicate where additional buoys are needed, as indicated in the figure caption. The number of additional buoys needed to reach EBD = 2 for all shaded boxes in Figure 3 has been computed. These results show that 189 additional buoys are needed between 60 °N and 60 °S, of which 102 are needed between 60 °S and 20 °S, 65 between 20 °S and 20 °N, and 22 between 20 °N and 60 °N.

The current *in situ* observation network was designed for other purposes and is not necessarily the most efficient network for climate SST. For example, EBD >5 in most of the North Atlantic Ocean (see Figure 3), and EBD <2 in a large number of boxes in the Southern Ocean. For climate purposes alone, the current buoy distribution could be relocated from some regions, especially from the North Atlantic and North Pacific. The results of this study have already had an influence on future buoy deployments. The NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) is using figures like Figure 3 to guide surface drifting buoy deployments.

3. IMPACT OF TMI SSTS ON AN SST ANALYSIS

The second topic was to examine the TMI SSTs from the perspective of the OI analysis (Reynolds *et al.*, 2002). For this study, six different versions of the OI were computed, which can be divided into two groups. One group consisted of analyses with the satellite bias correction step; the second group consisted of analyses without the bias correction step. All analyses used the same *in situ* data. In each group there were three analyses, which each used different satellite data. The first analysis used only AVHRR data (henceforth, AVHRR only). The second analysis used only TMI data (henceforth, TMI only). The third combined both AVHRR and TMI data (henceforth, TMI + AVHRR).

To help define quantitative estimates of analysis differences, some buoy data were withheld from the analysis and used for independent verification. To attempt to make the selection random, buoys (both moored and drifting) were excluded if their ID ended in either 4 or 9. This randomly excluded approximately 20% of the buoy data. The fraction of withheld buoys was selected to exclude enough data for verification while minimizing the impact on the analysis. The six versions of the OI were run weekly from 10 December 1997 to 1 January 2003.

Figure 4 shows time series of the weekly average OI SSTs minus the withheld collocated buoy SSTs between 35 °S and 35 °N, which are smoothed over 11 weeks. The upper panel shows the difference without bias correction; the lower panel shows the difference with bias correction. The upper panel shows that the TMI + AVHRR OI analysis without bias correction tends to have a reduced bias comparable to the other two analyses. This is because the physical causes of errors in microwave and IR instruments are independent and may tend to cancel. Note that there is no guarantee this would happen either globally or locally. However, because the bias errors are independent, it is likely that the overall biases would be reduced when both TMI

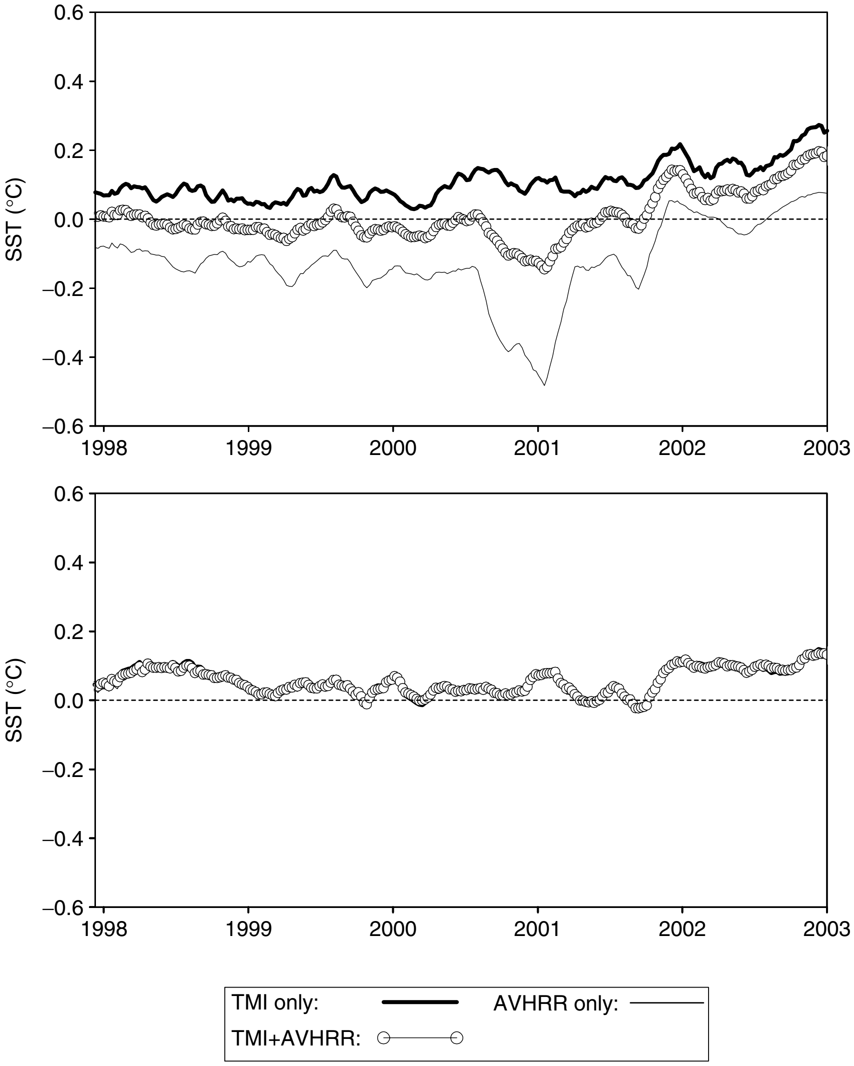

Figure 4. Time series of weekly OI analysis minus buoy average differences for 10 December 1997 to 1 January 2003, 35 °S–35 °N. Only independent drifting and moored buoys are used. The upper panel shows differences with respect to OI analysis without bias correction, and the lower panel with respect to OI analysis with bias correction. Three OI analyses are shown in each panel: AVHRR only, TMI only and TMI + AVHRR. All time series have been smoothed over 11 weeks by a box-car average. In the lower panel the results are almost identical, and it is not possible to distinguish differences among the three curves

and AVHRR data are combined. The lower panel shows that the bias correction results are almost identical for all analyses on these large-scales. In this case it is difficult to show a clear advantage of adding TMI. Although the overall TMI and AVHRR biases are of opposite signs and tend to cancel in the area-averaged combined product, this may not always be the case. Thus, individual bias corrections of both TMI and AVHRR are necessary.

Because bias corrections cannot be made in regions where there are no *in situ* data, the results without bias correction should apply there and indicate that TMI data should be used with AVHRR data in the OI. Furthermore, TMI data can ensure satellite sampling in cloud-covered regions. In addition, the use of more than one satellite product is helpful in diagnosing satellite data problems.

4. SUMMARY AND PLANS FOR FURTHER WORK

Two studies are described to improve the accuracy of the blended (*in situ* and satellite) OI SST analyses. The first study determined the density of *in situ* data required to correct possible satellite biases. This study recommended that there are least two buoy equivalents needed on a 10° spatial grid to ensure that satellite biases do not exceed 0.5 °C. (A buoy equivalent is defined as either one buoy or seven ships.) The second study evaluated the importance of TMI data on the accuracy of the OI. The comparisons using the OI without bias correction showed that a combination of TMI and AVHRR improved the accuracy over TMI and AVHRR alone. Because there are regions with limited *in situ* data where satellite bias correction is not possible, a combination of both TMI and AVHRR should improve the OI analysis even when satellite bias correction is used. The results of the intercomparisons also showed that both AVHRR and TMI data have biases that must be corrected in climate studies.

In the future, it is planned to continue to improve the OI analysis. The plan includes the use of new observations in the OI. The first new dataset that will be used is the advanced microwave scanning radiometer–earth observing system (AMSR-E) SST data, which now provides global retrievals. This should be of particular importance in the Southern Ocean and near the sea-ice margins where other data are sparse. In addition, a careful re-evaluation of the OI spatial error-covariance scales is now being carried out. This improvement is needed to increase the OI resolution without significantly increasing the noise. It is also planned to improve the bias correction step. The correction method was designed when there was only one satellite available for SST. Now that more satellite instruments are available, along with longer records of satellite retrievals, a new study of the bias correction method is needed. This is being done in a cooperative programme with North Carolina State University. In addition, it is also planned to re-examine the error statistics for the *in situ* data. Recent work by Kent and Taylor (in press) has shown that the accuracy of ship observations varies depending on the type of SST measurement. This must be accounted for in both the OI and in the definition of the EBD used in Figure 3.

ACKNOWLEDGEMENTS

The NOAA Office of Global Programs (OGP) and the National Climatic Data Center provided partial support for this work. The graphics were computed using the Grid Analysis and Display System (GrADS; http://grads.iges.org/grads), Center for Ocean–Land–Atmosphere Studies.

REFERENCES

Kent EC, Taylor PK. In press. Towards estimating climatic trends in SST, part 1: methods of measurement. *Journal of Oceanic and Atmosphere Technology*.

Needler G, Smith N, Villwock A. 1999. The action plan for GOOS/GCOS and sustained observations for CLIVAR. In *Ocean Obs '99 Proceedings*, 18–22 October, Saint Raphael, France (available at http://www.bom.gov.au/OceanObs99/Papers/Needler.pdf).

Reynolds RW. 1993. Impact of Mount Pinatubo aerosols on satellite-derived sea surface temperatures. *Journal of Climate* **6**: 768–774.

Reynolds RW, Smith TM. 1994. Improved global sea surface temperature analyses using optimum interpolation. *Journal of Climate* **7**: 929–948.

Reynolds RW, Rayner NA, Smith TM, Stokes DC, Wang W. 2002. An improved *in situ* and satellite SST analysis for climate. *Journal of Climate* **15**: 1609–1625.

Reynolds RW, Gentemann CL, Wentz FJ. 2004. Impact of TRMM SSTs on a climate-scale SST analysis. *Journal of Climate* **17**: 2938–2952.

Wentz FJ, Ashcroft PD, Gentemann CL. 2001. Post-launch calibration of the TMI microwave radiometer. *IEEE Transactions on Geoscience and Remote Sensing* **39**: 415–422.

Zhang HM, Reynolds RW, Smith TM. 2004. Bias characteristics in the AVHRR sea surface temperature. *Geophysical Research Letters* **31**: L01307. DOI: 10.1029/2003GL018804.

Zhang HM, Reynolds RW, Smith TM. In press. Adequacy of *in situ* observing system in the satellite era for climate SST analysis. *Journal of Oceanic and Atmosphere Technology*.