8.1 A DAILY BLENDED ANALYSIS FOR SEA SURFACE TEMPERATURE

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1. INTRODUCTION

The purpose of this paper is to focus on improvements to the climate-scale SST analyses produced at NOAA as described by Reynolds and Smith (1994) and Reynolds et al. (2002). This analysis uses infrared (IR) satellite data from the Advanced Very High Resolution Radiometer (AVHRR) and in situ data from ships and buoys. The analysis is done by optimum interpolation (OI) with a separate step to correct any large scale satellite biases relative to the in situ data. The analysis is performed weekly on a 1^{o} spatial grid from November 1981 to present. This version of the OI will henceforth be referred to as the OI version 2 (OI.v2)

Chelton and Wentz (2005) published an article comparing SST analyses including the OI.v2. In the paper they focused on magnitudes of SST gradients in 6 high gradient regions including the Gulf Stream. These comparisons include intercomparisons of Advanced Microwave Scanning Radiometer - Earth Observing System EOS (AMSR-E) microwave satellite data with the OI.v2 and the National Center for Environmental Prediction (NCEP) daily Real Time Global SST (RTG_SST) analysis produced daily on a 1/2^{o} grid (Thiébaux et al., 2003). The RTG_SST analysis uses the same data used in the OI.v2. However, the RTG_SST has been run daily since 30 January 2001 on a 1/2^{o} grid instead of weekly on a 1^{o} grid and uses smaller spatial error correlation scales than those used in the OI.v2. Chelton and Wentz (2005) showed that the RTG_SST analysis agreed better with AMSR-E than the OI.v2 even though, as will be discussed below, the AVHRR data are often sparse because of cloud cover. Tests with reduced correlation scales showed that the weekly OI.v2 could not reproduce the sharp gradients shown in the AMSR-E data and the RTG_SST. Thus, production of a daily OI analysis on 1/4^{o} grid was given a high priority.

2. BIAS CORRECTION

The OI.v2 analysis used by Reynolds et al. (2002) includes a preliminary correction of the AVHRR satellite data before they are used in the OI. This is necessary because the OI method assumes that the data do not contain long-term biases. The bias correction uses a Poisson technique to remove satellite biases relative to in situ data before the OI analysis is begun. This method has been used successfully. However, a problem with this method is that each correction is performed independently at each time step. Thus, there is no time continuity of the correction. In most cases, the cause of the bias, for example the presence of volcanic aerosols, does persist in time. A new method was developed using an OI bias correction. This was done as an analysis of the difference between in situ data and each type of satellite data. To provide continuity in time, the OI bias analysis uses the preceding OI bias analysis as a first guess. This bias correction was initially computed weekly and compared with the Poisson method. Because the in situ data were noisy, the spatial error correlations and signal to noise ratios were large and had to be assumed isotropic and homogenous. The scales that worked best were a bias noise to signal ratio (standard deviation) of 4 and spatial error correlation scale of 1500 km. Examination of the results showed that differences between the Poisson bias corrections and the OI bias corrections were modest. However, the OI bias correction is superior because of the time continuity and this correction is used in the daily OI.

3. THE DAILY ANALYSIS

To begin the daily analysis, it was first necessary to reacquire the data, since the original data had not been saved because disk space was more limited 10 years ago. The satellite data that had been used were the operational version produced by the US Navy from AVHRR data (May et al., 1998). However, there were also data from the Pathfinder AVHRR reanalysis project (Kilpatrick, et al., 2001). Pathfinder data have the potential of being better than the operational set, because a reanalysis allows corrections to the AVHRR dataset in a delayed mode. It was decided to use both types of AVHRR data. In addition, AMSR-E data were obtained from Remote Sensing Systems (RSS) (http://www.ssmi.com) as gridded data for ascending and descending passes on a daily 1/4^{o} grid. The in situ data were obtained from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS).

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The 1° OI code was modified to run daily on a 1/4° grid and to allow multiple satellite datasets instead of AVHRR alone. However, for this purpose the OI noise to signal and correlation scales had to be modified. These scales had been computed for weekly data. A method was devised to adjust these corrections so they could be used for daily data. The modified spatial scales are similar to the 100-400 km scales used in the RTG_SST. The weekly OI bias correction required little change. It was modified to use the daily SST data files that were used by the daily OI and then computed daily using the most recent 7 days of data.

The daily OI codes were run for both Pathfinder and operational US Navy AVHRR data for January 2002 - December 2003. In addition, the AMSR-E data were obtained from RSS and the daily OI was run from June 2002 (the start of AMSR-E) through the end of 2003. Thus, the following OI daily versions have been completed: AVHRR Pathfinder (January 2002 - December 2003), AVHRR operational Navy (January 2002 - December 2003) and AMSR-E (June 2002 - December 2003). All analyses include the same in situ data and were run with and without satellite bias correction. As can be expected (e.g., Chelton and Wentz, 2005) the coverage of AMSR-E data are dramatically improved over AVHRR because microwave data can be retrieved under cloudy conditions as long as there is no precipitation. In particular, the impact of clouds greatly reduces AVHRR retrievals north of 40°N and south of 40°S compared to AMSR-E.

4. RESULTS

To summarize the results, the monthly average magnitude of the SST gradient in the Gulf Stream region is shown for January 2003 in Fig 1. The RTG_SST and OI.v2 use operational AVHRR data. Thus, the daily OI using operational data and the operational data themselves are shown in the first row. The next row shows the OI.v2 and RTG_SST analyses. The final row shows the daily OI using AMSR-E data and the AMSR-E data themselves. Figure 1 shows that the daily OI using the operational data is very similar to the RTG_SST. However, the gradients in the OI.v2 are strongly smoothed as expected. The operational AVHRR data show the sparseness of these retrievals. The coverage would be better in a summer month when the cloud cover is reduced compared to winter (see Fig. 3, Chelton and Wentz, 2005). The AMSR-E data show much stronger gradients than any of the AVHRR analyses. However, near the coast values are missing because microwave retrievals cannot be made near land. The daily OI using AMSR-E data shows gradients that are almost as strong as the AMSR-E data and stronger than any analysis using AVHRR data. At first it may seem surprising that the OI AVHRR gradients would be as accurate as shown given the sparse AVHRR data. It is necessary to point out that the gradients were computed daily using 4 point centered differences. If any of the four values were missing, the gradient was missing. This tends to exaggerate the impact of any missing data. The results indicate that the daily OI can do a credible job of reproducing SST gradients. Furthermore, a combined analysis using both AVHRR and AMSR-E would produce the best gradients because AVHRR would add coastal values while AMSR-E would improve open ocean coverage over AVHRR alone.

Daily gradients for the 4 western boundary regions (Gulf Stream, Kuroshio, Agulhas and Falkland areas) shown in Chelton and Wentz (2005) have been examined. In these regions the AMSR-E coverage is almost complete over 3 days. The daily OI using AMSR-E shows that much of the gradient is stationary over time due to topography. Thus, the daily OI using AVHRR alone can do a credible job of determining the stationary part of the signal with only limited observations during the month. However, in other high gradient regions, e.g., at the northern boundary of the cold water tongue in the eastern tropical Pacific, the gradients are progressive and cannot be analyzed properly under persistent cloud cover.

Differences between the OI analyses using the different satellite products show that satellite bias corrections are needed for each product. Figure 2 shows the 18 month average difference between the daily OI using Pathfinder and operational AVHRR with and without bias correction. The analysis difference without bias correction (top panel) shows that Pathfinder is cooler in the tropics than the operational Navy product. These differences lie along regions of persistent cloudiness such as the Intertropical Convergence Zone and the South Pacific Convergence Zone. This suggests clouds may contaminate some of the Pathfinder retrievals. Comparisons of the number of observations, not shown here, also indicate an increase in the number of Pathfinder observations compared to the Navy product. The differences along 60°S are due to a problem with the Navy operational product. When the Navy moved from NOAA-16 to NOAA-17 in the spring of 2003, a low stratus cloud test, which worked well for NOAA-15 and NOAA-16, was continued for NOAA-17. However, this test actually limited the coverage and was eliminating too many good SSTs. The test was corrected on August 24, 2004 (Dan Olszewski, personal communication, 2005). The analysis difference with bias correction (bottom panel) shows that almost all the large scale differences have been corrected although a small residual remains in the tropical Pacific along 10°N and in the South Pacific along 60°S.

Figure 3 shows a similar comparison of the 18 month mean difference between the daily OI using Pathfinder AVHRR and using AMSR-E. The tropical differences without bias correction (upper panel) again suggest cloud contamination of the Pathfinder product. However, since the differences are stronger than those shown in Fig. 2 and are spatially similar, this suggests that clouds may contaminate both AVHRR products. In the tropical North Atlantic, dust from the Sahara Desert is blown toward the west and frequently causes negative AVHRR biases particularly in the summer. This appears to be an explanation of some of the differences shown in the Atlantic between the equator and 20^{o}N. Smaller differences of both signs occur north of 40^{o}N and south of 40^{o}S and are difficult to explain. The bias corrected difference (bottom) panel shows that the large-scale tropical differences have been reduced by roughly 1/2 to 1/3 of the uncorrected differences. Similar large scale reductions have occurred with bias correction north of 60^{o}N. However, south of 40^{o}S the bias correction had little impact. This is most likely due to the smaller north/south scales of the differences in Fig. 3 than in Fig. 2. The e-folding scale for the bias corrections is 1500 km or roughly 13.5^o. Thus, corrections on scales smaller than the e-folding scales are difficult. Between 30^{o}N and 40^{o}N, the results are mixed. There is some reduction of the differences with bias correction except off the east coast of the US between Florida and North Carolina where they get worse. This will have to be investigated. However, it may be due to using the lower resolution OI.v2 climatology instead of a higher resolution version before differences were computed. Because there are large gradients in this region (see Fig. 1), SST changes may be large over relatively small distances.

5. FUTURE PLANS

The daily SST analysis shows improved accuracy compared to the OI.v2. In addition, the use of multiple satellite data sources is a tremendous help in diagnosing analysis problems. It is planned to produce an operational version using AVHRR Pathfinder retrievals back to January 1985 which is the present start of the Pathfinder dataset. An initial version of the OI will be available by September 2006 for the entire period and will be updated annually. An operational version using the operational Navy AVHRR retrievals will be available in real time. In addition, another daily OI version will be available by September 2006 using both AVHRR and AMSR-E retrievals for the full AMSR-E period which begins in June 2002. Other satellite datasets will be added in the future.

Before the daily OI can be made operational, there are a number of tuning and other adjustments, which need to be made.

1) The first task is to reexamine the spatial scales and signal to noise ratios for the different datasets.

2) The second major task for development of the daily OI is to retest the constant spatial and signal to noise ratios for the OI bias correction. This will be done by simulating bias differences between Pathfinder and the AMSR-E as suggested by Fig. 3. In this simulation it will be assumed that one of the two products is 'truth' and the other product is 'biased'. The true product will be subsampled at the scales of the actual in situ data with representative random in situ noise. The biased satellite product will be corrected by the OI bias procedure. The root mean square (RMS) difference between the bias corrected product and the true product will be computed.

3) The third task is to reexamine the relative importance of the ship data compared to the buoy data. Recent bias and random errors from ships are summarized by Kent and Taylor (2005). They report that engine intake temperatures are typically biased 0.1-0.2ºC warmer than insulated bucket temperatures due to engine room heating of the intake water and evaporative cooling of the water in the insulated buckets. It is difficult to untangle these biases partly because of limited sampling and partly because the availability of metadata is poor. However, simulations of the impact of ship biases in the daily OI can be used to and determine if there is a better way to combine ship and buoy observations to minimize the bias uncertainty.

4) The fourth task is the implementation of improved error estimates. These estimates include bias, sampling and random errors. The previous weekly OI version, OI.v2, did not include bias errors.

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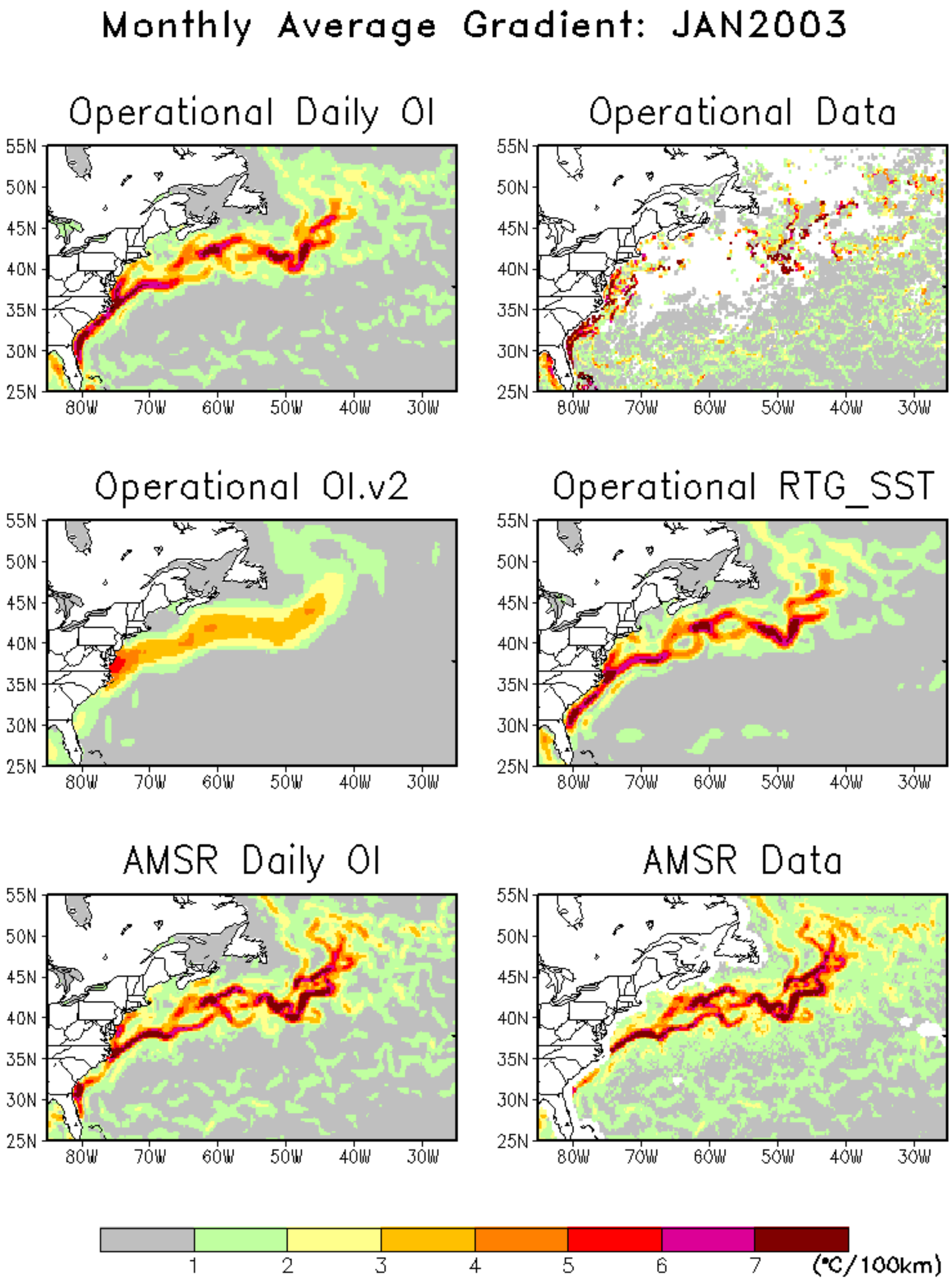

Fig. 1. Monthly averaged SST gradient magnitudes for January 2003. The top left panel shows the 1/4° daily OI gradient using operational AVHRR retrievals; the top right panel shows the gradient from the operational AVHRR retrievals. The middle left panel shows the 1° weekly OI.v2 gradient using operational AVHRR retrievals; middle left panel shows the 1/2° NCEP RTG_SST gradient using operational AVHRR retrievals. The bottom left panel shows the 1/4° daily OI gradient using AMSR-E retrievals; the top right panel shows the gradient from the operational AMSR-E retrievals.

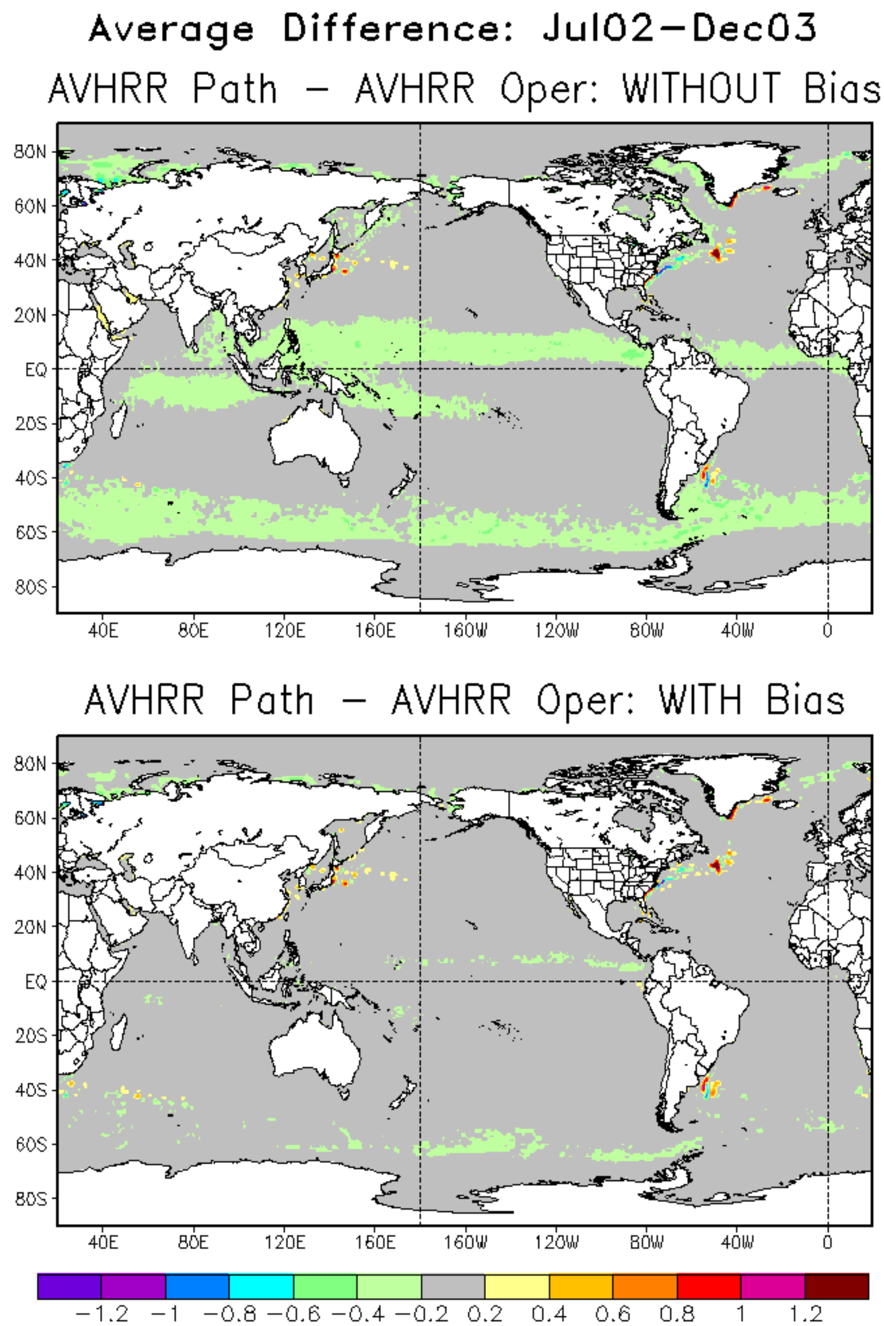

Fig. 2. The average daily 1/4° OI anomaly difference between AVHRR Pathfinder and AVHRR operational for the 18 month period: July 2002 - December 2003. The top panel shows the difference when both sets of satellite retrievals WERE NOT biased corrected before being used in the OI. The bottom panel shows the difference when both sets of satellite retrievals WERE biased corrected before being used in the OI.

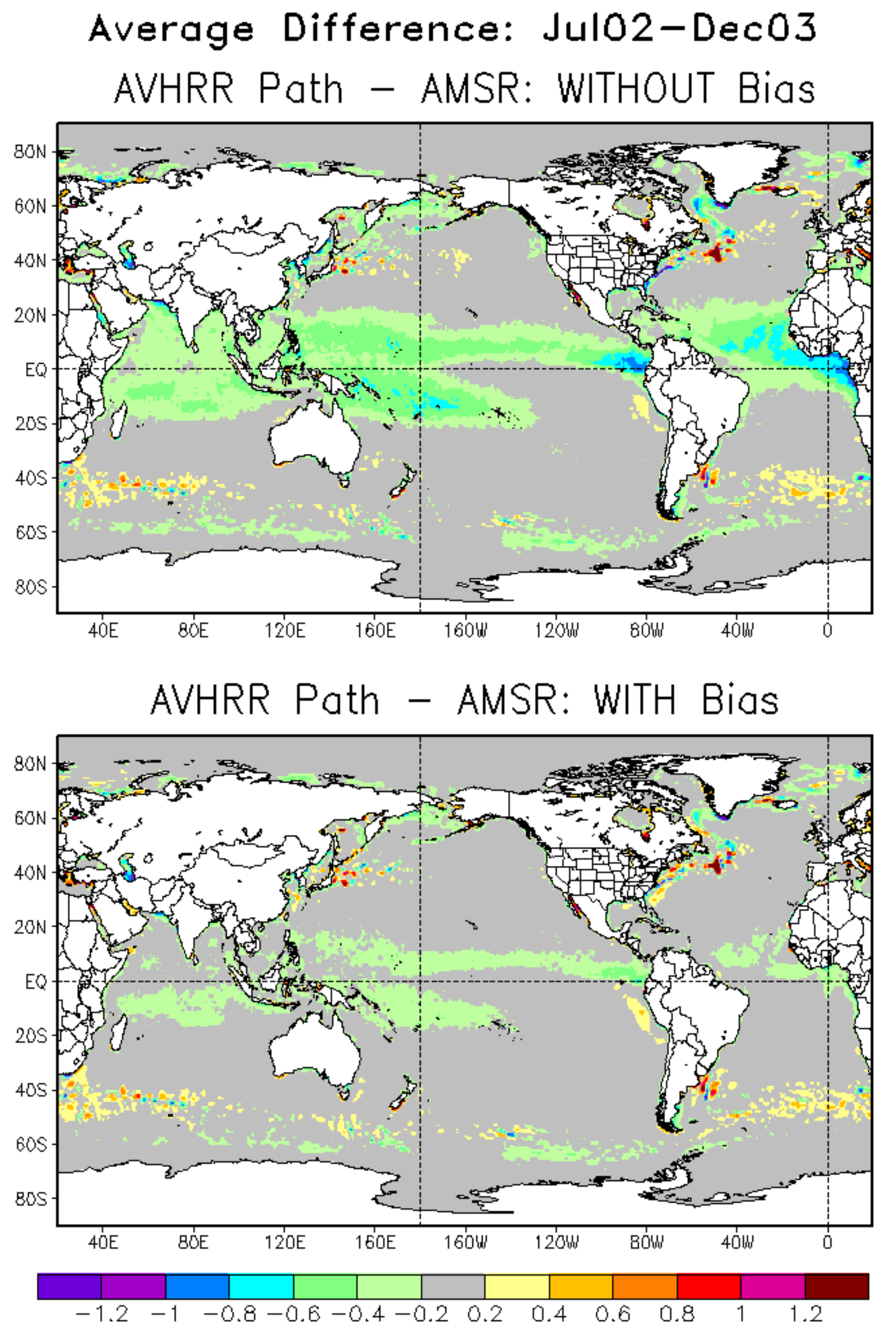

Fig. 3. The average daily 1/4^{o} OI anomaly difference between AVHRR Pathfinder and AMSR-E for the 18 month period: July 2002 - December 2003. The top panel shows the difference when both sets of satellite retrievals WERE NOT biased corrected before being used in the OI. The bottom panel shows the difference when both sets of satellite retrievals WERE biased corrected before being used in the OI.