Impact of Mount Pinatubo Aerosols on Satellite-derived Sea Surface Temperatures

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ABSTRACT

The June 1991 eruptions of Mount Pinatubo produced new stratospheric aerosols that were greater than the aerosols from the 1982 eruptions of El Chichón. These new aerosols strongly affected the advanced very high resolution radiometer (AVHRR) retrievals of sea surface temperature in the tropics where negative biases occurred with magnitudes greater than 1°C. The time dependence of these biases are shown. In addition, a method to correct these biases is discussed and integrated into the National Meteorological Center's optimum interpolation sea surface temperature analysis.

1. Introduction

In an attempt to monitor changes in sea surface temperature (SST), Strong (1989) used satellite-derived measurements from the advanced very high resolution radiometer (AVHRR). The satellite data are attractive because of their superior coverage compared to conventional in situ (ship and buoy) data. However, as discussed in Reynolds et al. (1989) and Robock (1989), biases in the satellite data led Strong to erroneous estimates of global warming during the 1982–89 period. Reynolds et al. (1989) showed that the largest biases in the record were due to stratospheric aerosols from the April 1982 volcanic eruptions of El Chichón. Satellite retrievals in aerosol-contaminated regions are biased low because the infrared radiation from the surface is absorbed by the aerosol and then readmitted at the lower temperature of the aerosol. The regular retrieval algorithm accounts for the attenuation by tropospheric water vapor, but it does not account for the different spectral attenuations by the stratospheric aerosols associated with the El Chichón and Mount Pinatubo eruptions (see Walton 1985). Although the El Chichón aerosols and the associated negative biases in satellite-derived SSTs gradually weakened with time, the biases persisted through 1984.

During June 1991, Mount Pinatubo, located in the Philippines (15°N, 120°E), produced new stratospheric aerosols with a volume more than twice that from El Chichón (Stowe et al. 1991). By the middle of July, the aerosols had already encircled the earth. Figure 1 shows the aerosol concentration before and after the volcanic eruptions. The increase of the aerosols following the eruptions is dramatic. Before the eruption (upper panel), most of the aerosols were comprised of tropospheric dust from the Sahara and Saudi Arabian deserts.

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2. Effect of Pinatubo aerosols on SST retrievals

Beginning in July, the presence of the aerosols began to significantly affect the satellite sea surface temperature (SST) retrievals. Because the AVHRR cannot make retrievals in cloud-covered areas, algorithms have been designed to discard retrievals in cloud-covered regions. The algorithms are different for daytime and nighttime as described by McClain et al. (1985). In the daytime, the cloud detection is done using the two AVHRR-visible channels and is based on exceeding thresholds for maximum expected reflectance in cloud-free areas. In the nighttime, the cloud detection is done using the three AVHRR infrared (IR) channels. This detection is more difficult and uses a combination of three different IR tests: a reflectance, a uniformity, and an intercomparison test. The present daytime algorithm detects the aerosols as if they were clouds; the nighttime algorithm does not. Thus, in the aerosol-contaminated regions, the number of daytime retrievals dropped to almost zero while the number of nighttime retrievals was much less affected. This is indicated in Fig. 2 where the number of daytime and nighttime observations between 20°S and 20°N are shown for a 55-week period. The figure shows that the number of daytime observations were above 300 000 per week during May and June 1991. They began to drop in July and reached a minimum of 20 000 per week in September before slowly returning to normal. The number of nighttime observations were almost constant during the period with typical values of 200 000 per week.

In cloud-free regions, the SST retrievals are computed by combining some or all of the three IR bright-

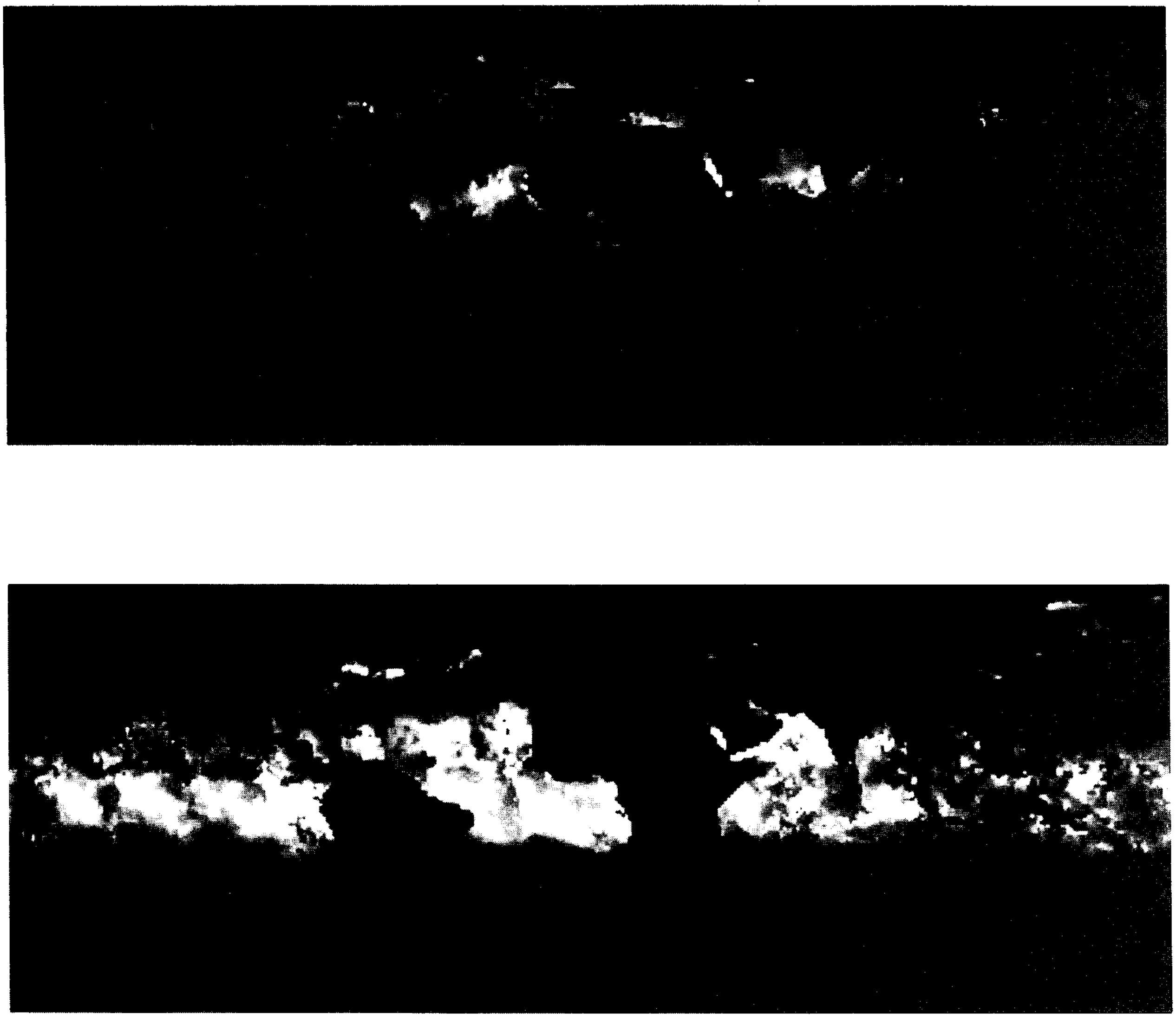

FIG. 1. Two images from *NOAA-11* showing the weekly composite aerosol optical thickness before and after the June eruptions of Mount Pinatubo. The top and bottom images show the aerosols for the weeks ending 6 June 1991 and 25 July 1991, respectively. Land areas are excluded because of their high reflectivity (Courtesy L. Stowe, NOAA/National Environmental Satellite, Data, and Information Service, Satellite Research Laboratory).

ness temperatures (T) from the IR channels. At the onset of the Mount Pinatubo eruption, the linear version of the nighttime satellite algorithm had the form

$$S = aT_{11} + b(T_{3.7} - T_{12}) + c(\sec\phi - 1) + d \quad (1)$$

(Walton 1992, personal communication). Here ϕ is the satellite zenith angle. The subscripts of T refer to the central wavelengths of the three IR channels: 3.7 μm, 11 μm, and 12 μm. The numerical coefficients, a, b, c, and d were determined by regression against SSTs from drifting buoys. The daytime equation was similar in form but did not use the 3.7-μm channel and of course used different numerical coefficients. The tuning of the coefficients is done when a new satellite is launched or when new equations are implemented. The actual operational equations are nonlinear because b is a function of the surface temperature (see Walton 1988). The equations are designed to minimize the effect of water vapor on the retrieved SST.

To examine the effect of the aerosols on the retrieved SSTs, all weekly in situ, daytime, and nighttime satellite observations were separately averaged onto a 1° grid. Gridded values were converted into anomalies by subtracting the climatology as in Reynolds (1988). Weekly averages were then computed between 20°S and 20°N for a 55-week period as shown in Fig. 3. The three curves were tightly grouped during May and June 1991. After this period, the in situ anomaly remained rela-

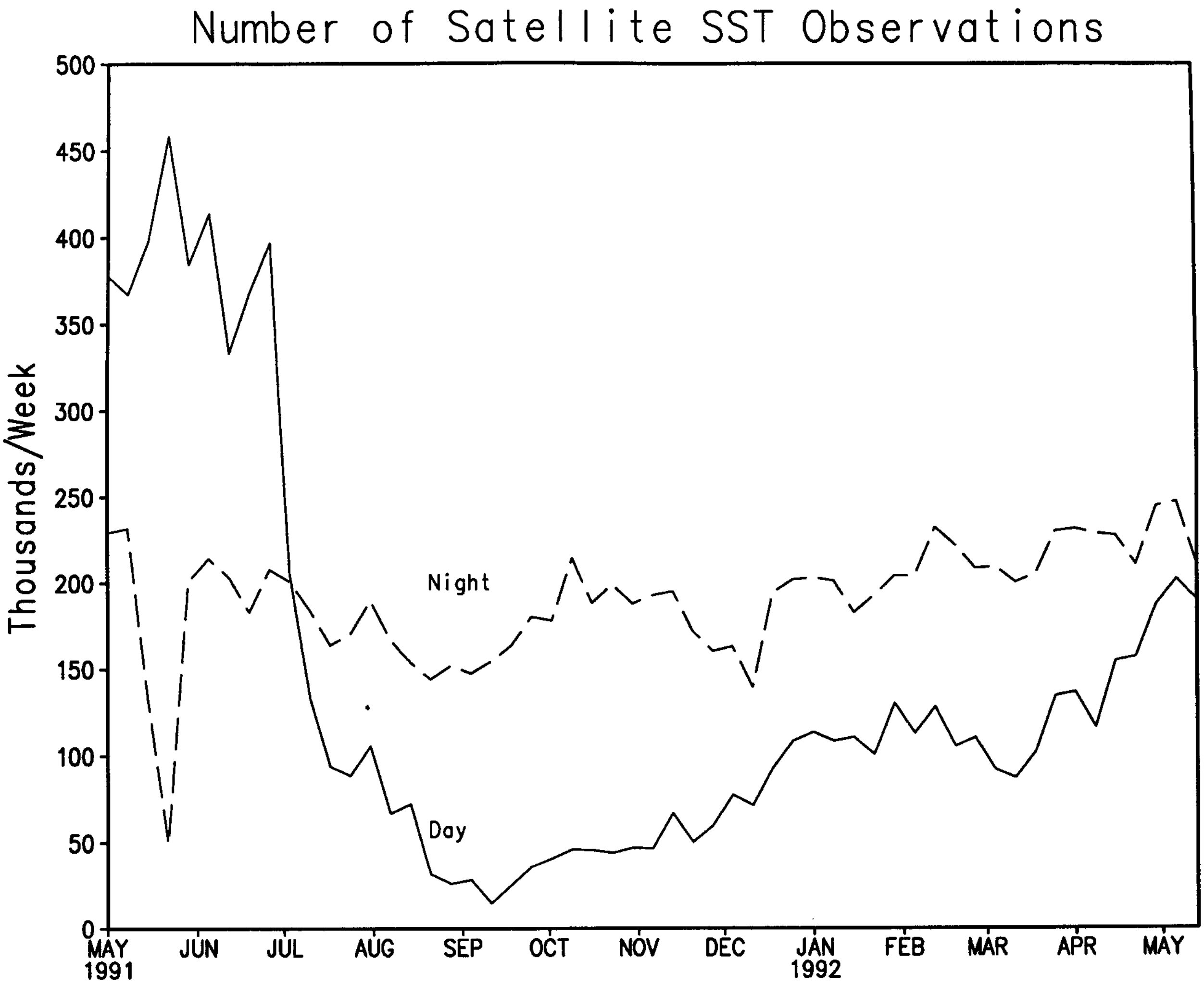

FIG. 2. Time series of the number of daytime and nighttime satellite SST observations between 20°N and 20°S for 55 weeks. The first week is 28 April–4 May 1991; the last week is 10 May–16 May 1992. The daytime curve is a solid line; the nighttime curve is dashed. On the abscissa the dates are labeled at the location of the first day of the month. The ordinate is in thousands of observations per week.

tively constant while the day and night satellite anomalies became more negative. The nighttime anomalies reached a minimum during September. The daytime anomalies reached a minimum during August. However, as shown in Fig. 2, the number of daytime observations were sparse. Thus, some of this change may be due to undersampling of regions with high aerosol concentrations. The difference between the in situ and satellite anomalies show that the satellite observations had average negative biases with magnitudes greater than 1°C in the tropics in August and September 1991.

Walton (1985) discusses the effect of the aerosols on the satellite SST retrievals. He states that the heavier stratospheric volcanic particles drop out with time while the gas (SO_2) is chemically converted to sulfuric acid (H_2SO_4). Although the aerosols have different effects on each of the three IR channels, he found a version of Eq. (1) that eliminated much of the dependence on the concentration of sulfuric acid while decreasing the bias. Because of sparsity of daytime satellite observations, Walton (1992, personal communication) applied this technique to develop a new aerosol-corrected nighttime equation that can be written as

$$S = a'T_{12} + b'(T_{3.7} - T_{11}) + c'(\sec\phi - 1) + d'. \quad (2)$$

The effect of the aerosols was reduced by changing the position of T_{11} and T_{12}. Equation (2) was tuned with July 1991 drifting buoy data to determine the numerical coefficients (a', b', c', and d') and was operationally implemented on 3 October 1991. Although (2) corrects for the effect of aerosols, it is not as effective as equations like (1) in correcting for water vapor (Walton 1985). Thus, in regions uncontaminated by aerosols, (1) would be more accurate. However, the same op-

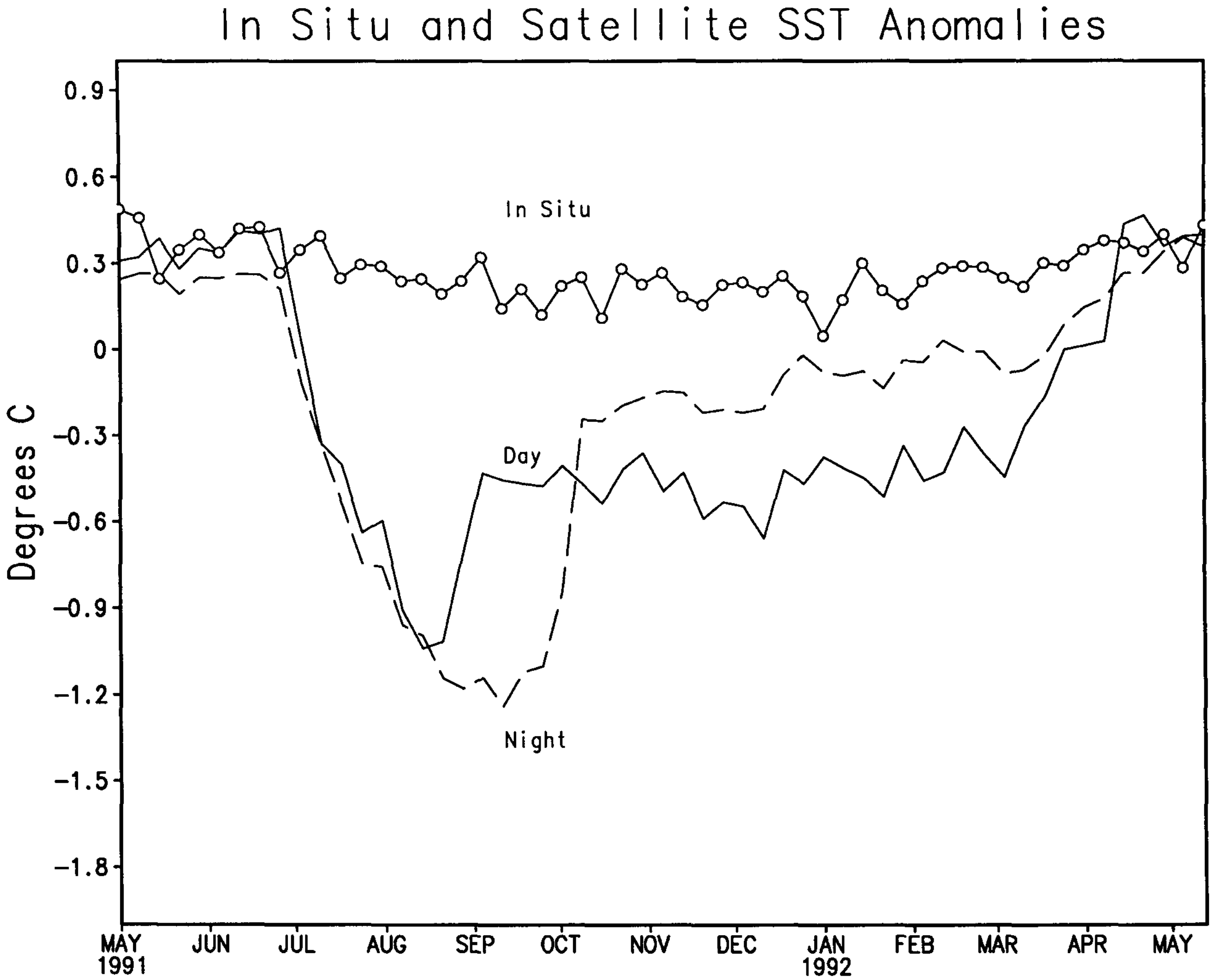

FIG. 3. Time series of the in situ, daytime, and nighttime satellite SST anomalies (see text) between 20°N and 20°S for 55 weeks. The in situ curve is a solid line with circles, the daytime curve is a solid line, the nighttime curve is dashed. The abscissa is as given in Fig. 2. The ordinate is in degrees Celsius.

erational satellite algorithm has always been applied globally.

The impact of the change in the retrieval equation is clearly evident in Fig. 3. The differences between the in situ and the nighttime satellite data change from −1.3°C in September to roughly −0.5°C in October. The figure shows that the magnitude of the difference gradually decreases from October through the end of March. This suggests that the aerosol-corrected equation did not correct all the biases caused by the aerosols and that it may not be completely independent of the aerosol concentration which has spatial and temporal variations. It should be noted that on 9 April 1992 a new operational set of both daytime and nighttime equations was implemented (Walton 1992, personal communication). This change was implemented to adjust for the decrease in Pinatubo aerosols and to remove any remaining daytime and nighttime biases. The change resulted in a further decrease in the residual biases in April, as shown in Fig. 3. This change is particularly evident in the daytime anomalies which had not been corrected after the Pinatubo eruptions.

To examine the latitudinal dependence of the biases, the difference between the zonally averaged in situ and nighttime satellite anomalies is shown in Fig. 4 as a function of time. The figure also shows the effect of the Pinatubo biases. The satellite observations become significantly more negative relative to the in situ observations, showing differences greater than 0.75°C, beginning in July between 20°S to 20°N. These differences exceeded 1.75°C by the end of August and the beginning of September. The effect of the operational change in early October is also evident. From May 1991 through the end of September 1991, the differences shown in Fig. 4 are indications of the strength and location of the Pinatubo aerosols.

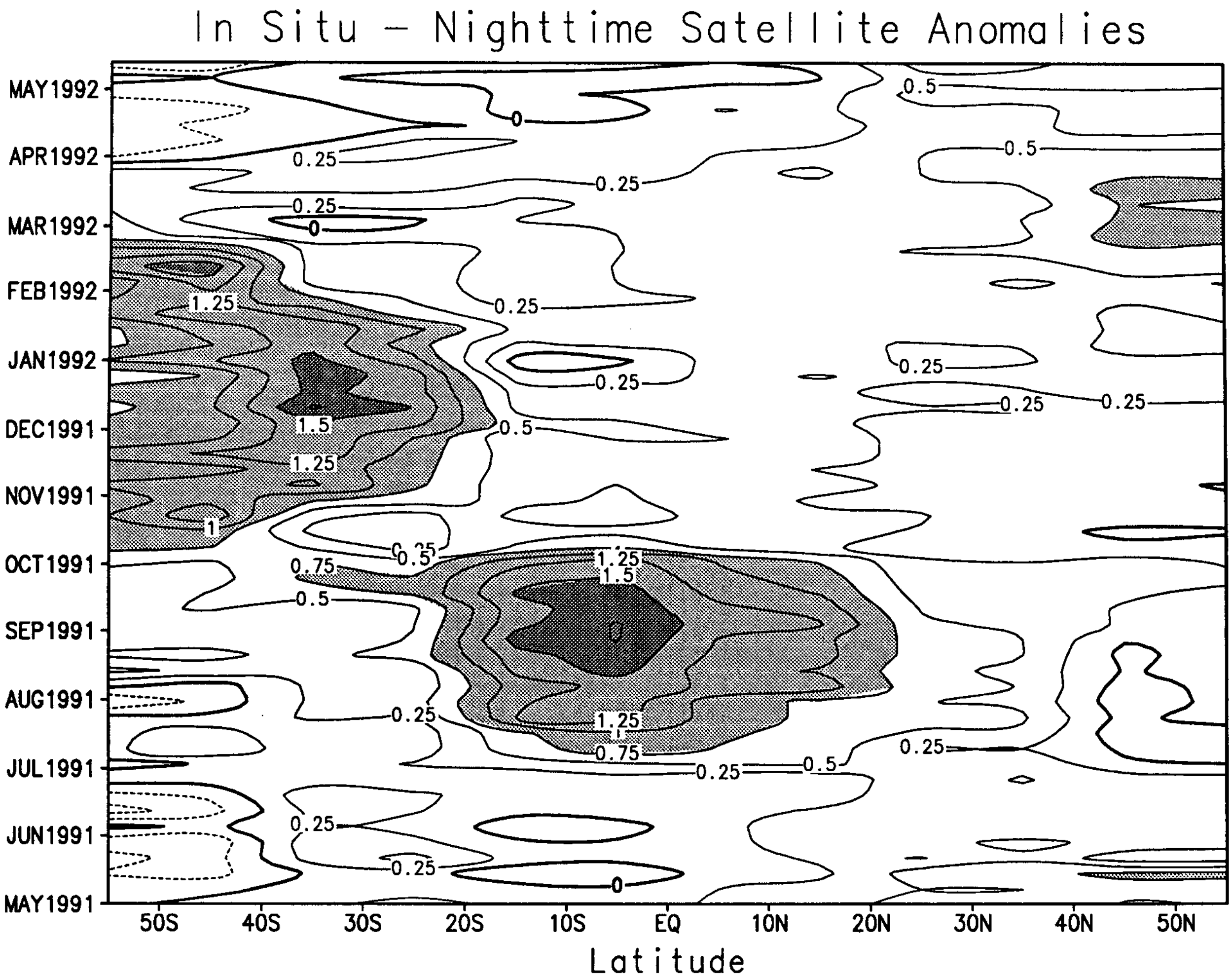

FIG. 4. Zonally averaged difference between the in situ and nighttime satellite anomalies for the 55-week period defined in Fig. 2. The sign of the difference is in situ − satellite. The averages are done over 10°-wide zonal bands. The abscissa is latitude. On the ordinate the dates are labeled at the location of the first day of the month. The contour interval is 0.25°C. Positive contours are solid; negative contours are dashed; the zero contour is a heavy solid line. Light shading indicates values between 0.75°C and 1.5°C; heavy shading indicates values above 1.5°C.

Figure 4 also indicates a new problem which became apparent south of 20°S in mid-October. This bias was partially due to the impact of a new aerosol source, Mount Hudson, which erupted in Chile near 45°S in August 1991 (Stowe 1991, personal communication). However, most of the error resulted from a satellite calibration error (Walton 1992, personal communication). According to Walton, this problem affects one of the IR channels (the 3.7 μm) that is used only in the nighttime algorithms. It occurs at certain solar/satellite geometries when the satellite moves out of the earth's shadow. Unfortunately, the effect of this error was exacerbated by the aerosol-corrected algorithm. The coefficient which multiplied $T_{3.7}$ was approximately doubled by the change. Because of the geometry involved, this type of calibration error is only a problem at mid- and high southern latitudes in local summer. This seasonal dependence is shown in the figure; the Southern Hemisphere bias begins to weaken after the summer solstice from January through April 1992, when it disappears. This problem is expected to be corrected before it reoccurs next year.

3. Effect of Pinatubo aerosols on SST analyses

The U.S. National Meteorological Center (NMC) routinely produces a 1°-gridded SST analysis using optimum interpolation (OI, e.g., see Gandin 1966; and Thiébaux and Pedder 1987). The analysis is produced both daily and weekly following the method of Lorenc (1981). It uses in situ and satellite SST data as well as SSTs estimated from sea ice coverage. In February 1991, the OI replaced a daily version of the analysis discussed by Reynolds (1988) and Reynolds and Marsico (1993), which had a spatial resolution of 6°. The OI was developed to provide a higher-resolution boundary condition for the NMC forecast model. Because of the higher spatial and temporal resolution requirements, the quality-control procedures for the data were improved. Complete documentation for the OI is being prepared. Examples of the two types of analyses can be found in Reynolds (1991).

The OI method assumes that the data are unbiased. Because strong satellite biases are now evident, a preliminary step was added before performing the OI to correct any large-scale satellite biases. This adjustment uses the Poisson technique of Reynolds (1988) to provide a smooth correction field. In this method, preliminary in situ and satellite analyses are produced using spatial median filters. (The median filtering technique is used to eliminate extreme values rather than simply smoothing them into the final analysis.) The in situ analysis uses ship and buoy SSTs as well as SSTs determined from sea ice information. Regions with sufficient in situ observations (presently five per grid box) become internal boundary conditions and regions that are ice covered become external boundary conditions. The SSTs for the remaining grid points are determined by solving Poisson's equation,

$$\nabla^2\Phi = \rho \tag{3}$$

for the SSTs, Φ. The forcing term, ρ, is defined by

$$\rho = \nabla^2 S, \tag{4}$$

where S is the SST field defined by the satellite analysis. This method, henceforth called the blended analysis, adjusts any large-scale satellite biases and gradients relative to the boundary conditions defined by the in situ analysis.

To correct the OI, three preliminary analyses were computed on a weekly 4° grid: the in situ, the daytime satellite, and the nighttime satellite. The median smoothing used in the analyses resulted in a spatial resolution of about 12°. With the use of the Poisson technique, two blended analyses were produced: Φ_D,

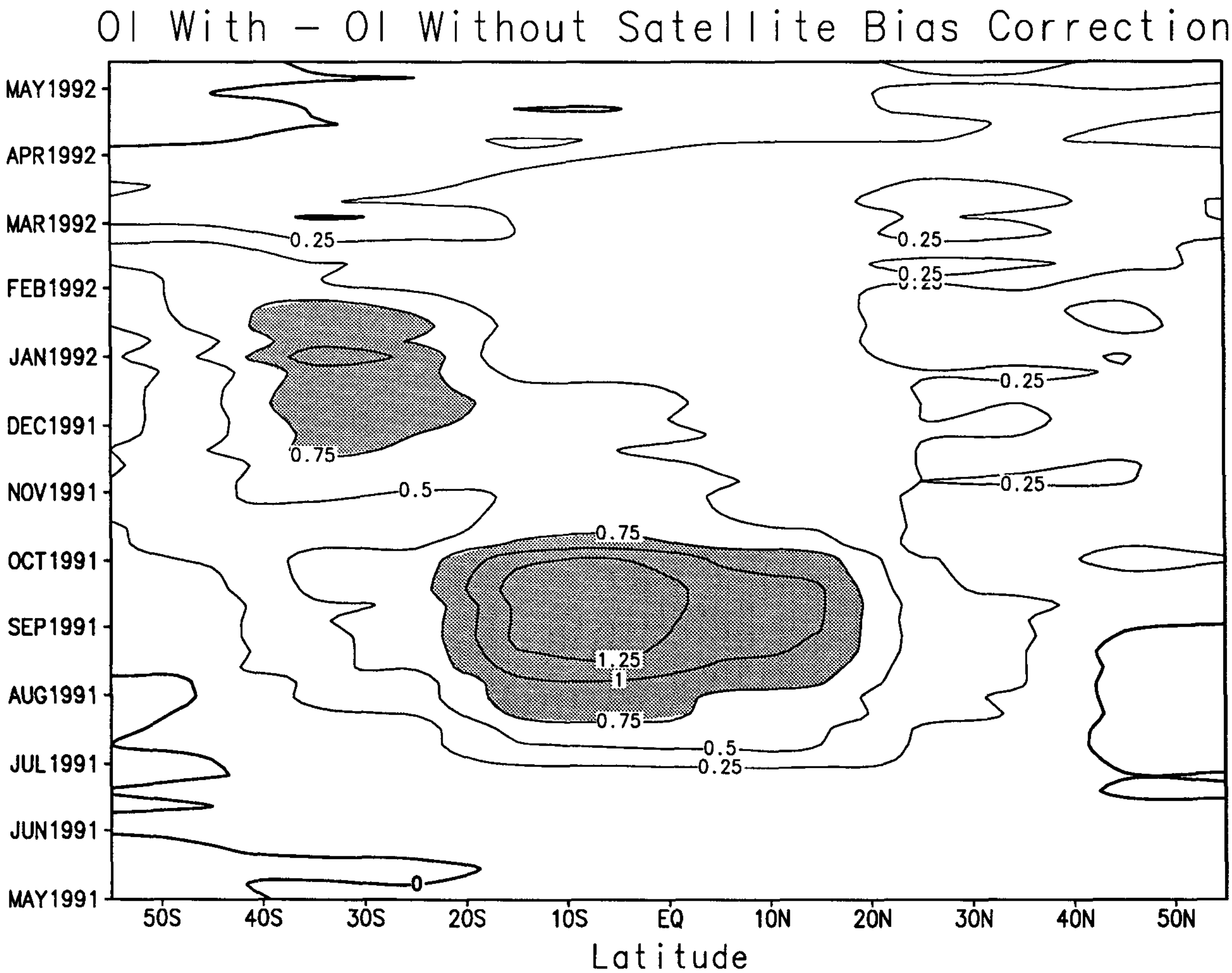

FIG. 5. Zonally averaged difference between the OI with and without the satellite bias correction for the 55-week period defined in Fig. 2. The sign of the difference is with − without satellite correction. Otherwise as in Fig. 4.

by forcing with the Laplacian of the daytime satellite data; $\nabla^2 S_D$, and Φ_N, by forcing with the Laplacian of the nighttime satellite data, $\nabla^2 S_N$. The smoothed daytime and nighttime correction fields were defined by $\Phi_D - S_D$ and $\Phi_N - S_N$, respectively. Both $\Phi_D - S_D$ and $\Phi_N - S_N$ were then spatially interpolated to the location of the daytime and nighttime data, as appropriate, and added to the data to provide the correction. Two versions of the weekly OI were computed: a version with in situ and corrected satellite data, and a version with in situ and uncorrected satellite data.

To examine how the OI is affected by the biases, the OI analyses were zonally averaged for the same period shown in Fig. 4. The difference between the OI with the satellite bias correction and the OI without the correction is shown in Fig. 5. Both periods of the strong negative biases shown in Fig. 4 are also evident in Fig. 5. The differences in Fig. 5 are smaller than the differences in Fig. 4 because both versions of the OI include in situ data which can partially offset any satellite biases. However, as shown in Fig. 5, the negative biases in the OI without the corrected satellite data are large and the magnitudes exceed 1°C in the tropics during August and September 1991. These negative biases in the OI without the corrected satellite data were sufficient to mask the El Niño that was developing in the tropical Pacific at this time.

4. Discussion

The presence of the Mount Pinatubo aerosol cloud can be expected (e.g., see Stowe et al. 1991) to reduce tropical (and global) surface temperatures by reflecting some of the incoming solar radiation back into space. However, any tropical cooling will initially be difficult to distinguish from the natural variability of tropical SSTs. This variability is dominated by aperiodic El Niño/Southern Oscillation events, which cause changes in SSTs of several degrees Celsius and which may persist for several years (e.g., see Rasmusson and Carpenter 1982; and Reynolds et al. 1989).

The results presented here demonstrate that uncorrected satellite SST data should not be used to determine these changes. This is shown by the spurious anomalous cooling that would be inferred from the satellite data in Fig. 3. However, once the satellite data are corrected, they are extremely useful in extending the coverage and increasing the spatial resolution defined by in situ data alone. This is especially true in the Southern Hemisphere where the in situ data are sparse.

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