# A High-Resolution Global Sea Surface Temperature Climatology

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ABSTRACT

In response to the development of a new higher-resolution sea surface temperature (SST) analysis at the National Meteorological Center (NMC), a new monthly 1° global sea surface temperature climatology was constructed from two intermediate climatologies: the 2° SST climatology presently used at NMC and a 1° SST climatology derived from the new analysis. The 2° SST climatology used a 30-yr 1950–1979 base period between roughly 40°S and 60°N based on in situ (ship and buoy) SST data supplemented by four years (1982–1985) of satellite SST retrievals. The 1° SST climatology was based on monthly analyses using in situ SST data, satellite SST retrievals, and sea-ice coverage data over a 12-yr period (1982–1993). The final climatology was combined from these two products so that a 1° resolution was maintained and the base period was adjusted to the 1950–1979 period wherever possible (approximately between 40°S and 60°N). Compared to the 2° climatology, the 1° climatology resolves equatorial upwelling and fronts much better. This leads to a better matching of the scales of the new analysis and climatology. In addition, because the magnitudes of large-scale features are consistently maintained in both the older 2° and the new 1° climatologies, climate monitoring of large-scale anomalies will be minimally affected by the analysis change. The use of 12 years of satellite SST retrievals makes this new climatology useful for many additional purposes because its effective resolution actually approaches 1° everywhere over the global ocean and because the mean SST values are more accurate south of 40°S than climatologies without these data.

## 1. Introduction

Reynolds (1988) and Reynolds and Marsico (1993) described a sea surface temperature (SST) analysis computed at the National Meteorological Center (NMC) that blended in situ (ship and buoy) SST data, satellite SST retrievals, and sea-ice coverage data. This analysis, henceforth called the blend, was produced monthly from January 1982 to the present on a 2° grid with an effective spatial resolution of 6°. The blended analysis is now being replaced by a higher-resolution optimum interpolation (OI) analysis. The higher-resolution analysis, henceforth called the OI, is done weekly on a 1° grid and uses the same data that were used by the blend. Reynolds and Smith (1994) discuss the OI method and demonstrate that the OI has improved temporal and spatial resolution compared to the blend. The OI has now been computed from November 1981 to the present. November 1981 was selected as the starting point because that is the date when the Advanced Very High Resolution Radiometer (AVHRR), which is used for the satellite retrievals, first became operational. Of course it would be technically possible to compute the OI analysis without satellite data. However, the actual spatial resolution would be degraded.

Because SST varies by more than 30°C from high latitudes to the Tropics and because the annual cycle can exceed 10°C in midlatitudes, a good SST climatology is necessary to monitor interannual climate signals that are typically only a few degrees Celsius. The monthly climatology discussed in Reynolds (1988) was computed on a 2° grid and was developed for use with the blended analysis. The climatology uses in situ (ship and buoy) data from the Comprehensive Ocean–Atmosphere Data Set (COADS, Slutz et al. 1985) for the period 1950–1979, which was supplemented by four years of satellite retrievals (1982–1985) and ten years of sea ice data. Shea et al. (1992) have examined this climatology, pointed out some of its advantages and disadvantages, and developed an improved version. Following the Shea et al. naming convention, the original climatology will be henceforth referred to as the Climate Analysis Center (CAC) climatology and their improved climatology as the Shea–Trenberth–Reynolds (STR) climatology. Shea et al. suggest that the 30-yr period of 1950–1979 is a good base period because it avoids instrumentation errors due to the shift from uninsulated-bucket temperatures to ship injection, which occurred prior to 1943 (Folland et al. 1984), and avoids the recent SST warmings in the Tropics, which began with the 1982–1983 El Niño–Southern Oscillation (ENSO) event (e.g., Smith et al.

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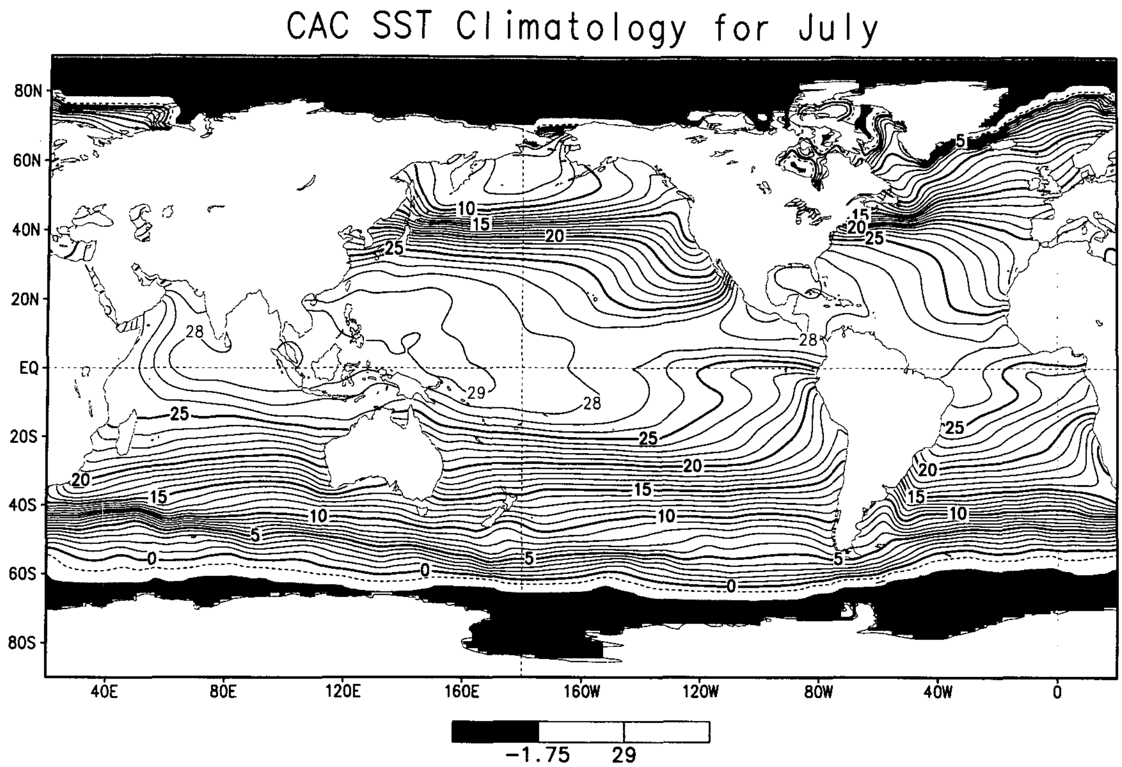


FIG. 1. CAC SST climatology (reference period: 1950–1979, see text) for July. Dark shading shows SST values less than −1.75°C (roughly areas covered by sea ice); light shading shows areas with SST greater than 29°C. The contour interval is 1°C. Negative contours are dashed.

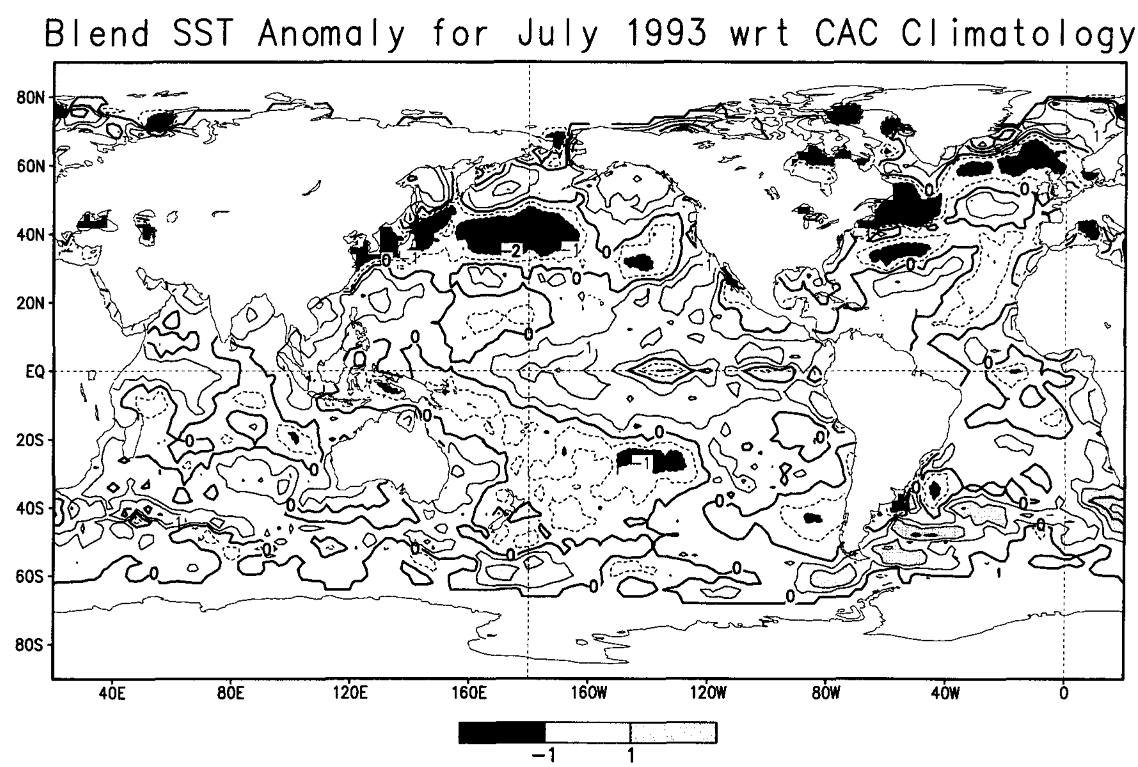


FIG. 2. Blend SST anomaly for July 1993 with respect to the CAC climatology. Dark shading shows anomalies less than −1°C; light shading shows anomalies greater than 1°C. The contour interval is 1°C with two extra contour levels at ±0.5°C. Negative contours are dashed.

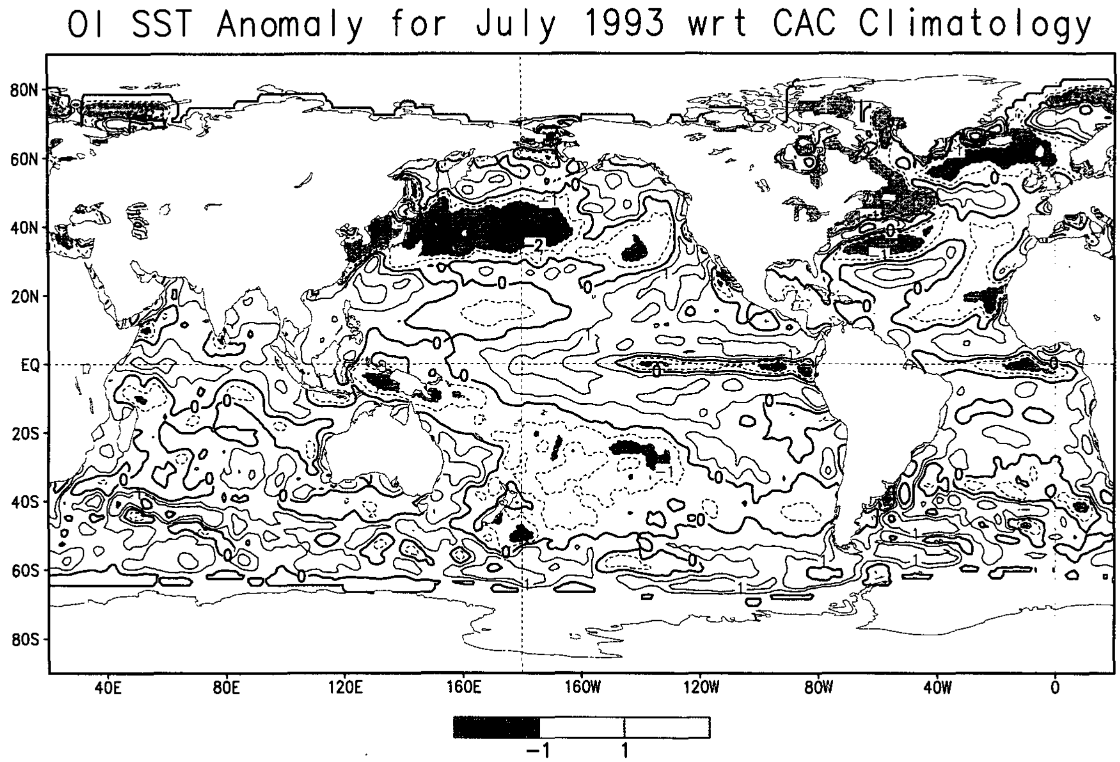


FIG. 3. OI SST anomaly for July 1993 with respect to the CAC climatology. Otherwise as in Fig. 2.

1994). Although the satellite and ice data were not from the same period, their use was essential to give the CAC climatology global coverage. Shea et al. also point out that there were two disadvantages to the CAC climatology: the spatial filtering system degraded the 2° resolution to 6°, and there was no temporal continuity between months. The STR climatology modified the CAC climatology by use of the original 2° resolution COADS values to improve the spatial resolution in the vicinity of the Kuroshio and Gulf Stream and by temporally smoothing the monthly analyses at each grid point by use of a truncated Fourier series (the temporal mean plus the first three Fourier harmonics). Shea et al. also described several additional areas with strong gradients in the Tropics and Southern Hemisphere where the resolution of the CAC climatology should be improved. However, these changes were not made because the COADS data were too sparse for this purpose.

Although the STR climatology has improved the CAC climatology, both climatologies are limited by the 2° spatial grid and are not adequate to display anomalies using the 1° OI fields. To illustrate this point, we first show a sample of the CAC climatology for July in Fig. 1. The STR climatology (not shown) is very similar except for tighter gradients near the Kuroshio and Gulf Stream. We now show the July 1993 monthly SST anomalies for both the blend and the OI with respect to the CAC climatology in Figs. 2 and 3. The monthly OI fields were computed by linearly interpolating the weekly OI fields to produce daily fields and then averaging the appropriate days within a month to produce monthly averages. The figures show very similar large-scale anomaly patterns. However, the higher resolution of the OI results in a stronger negative anomalies than the blend in the equatorial cold tongues of the eastern tropical Atlantic and Pacific. Further, differences in the anomaly patterns are evident in other high gradient areas. One of the most severe areas is the region in the middle and high latitude North Atlantic that is bounded in the south by the Gulf Stream.

There are several older 1° climatologies available (e.g., Alexander and Mobley 1976; Reynolds 1983). However, these are flawed by the use of uncorrected data prior to 1943. This is an especially severe problem at high southern latitudes where a majority of observations came from whaling vessels prior to the 1930s. In addition, the resolution of these climatologies is degraded from 1° in the middle and high latitude Southern Hemisphere because of limited in situ data coupled with a complete lack of satellite data.

The recent 1° climatology of Bottomley et al. (1990) also uses SSTs before 1943. These data have been successfully corrected before they are combined with more recent data. This eliminates one of the data problems discussed above. However, the Bottomley et al. (1990) climatology does not use satellite data to supplement the in situ data in the middle and high latitude Southern

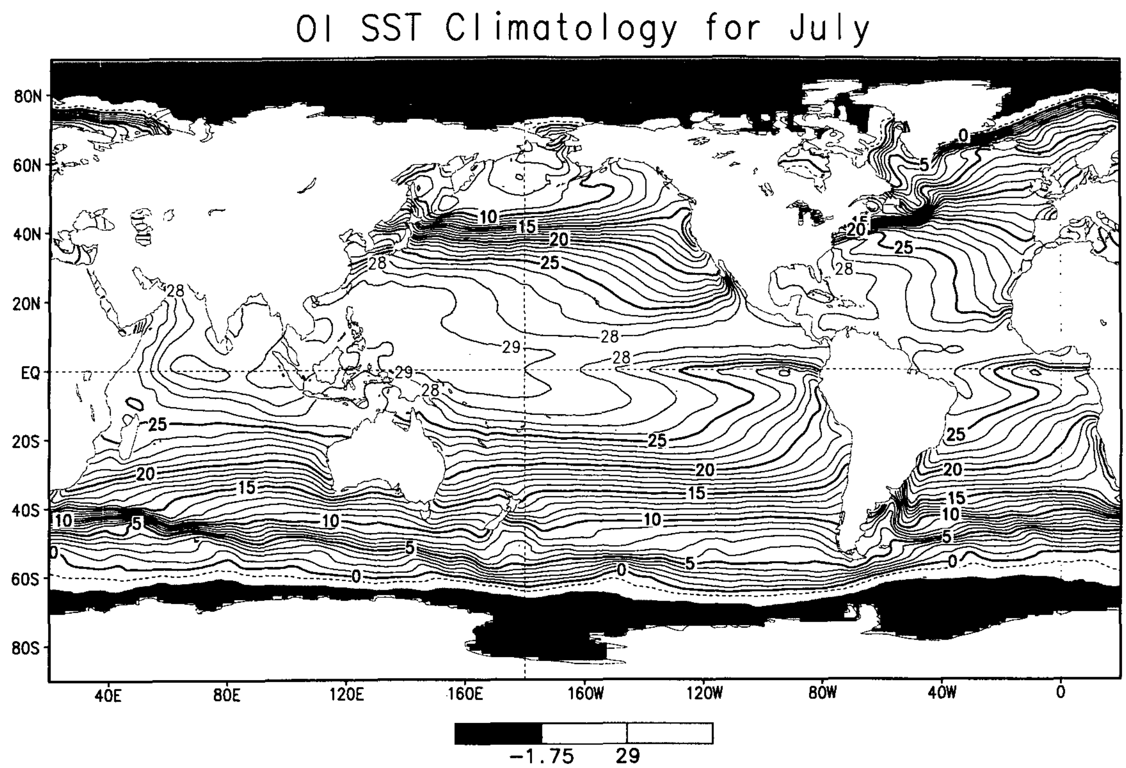


FIG. 4. OI SST climatology (reference period: 1982–1993, see text) for July. Otherwise as in Fig. 1.

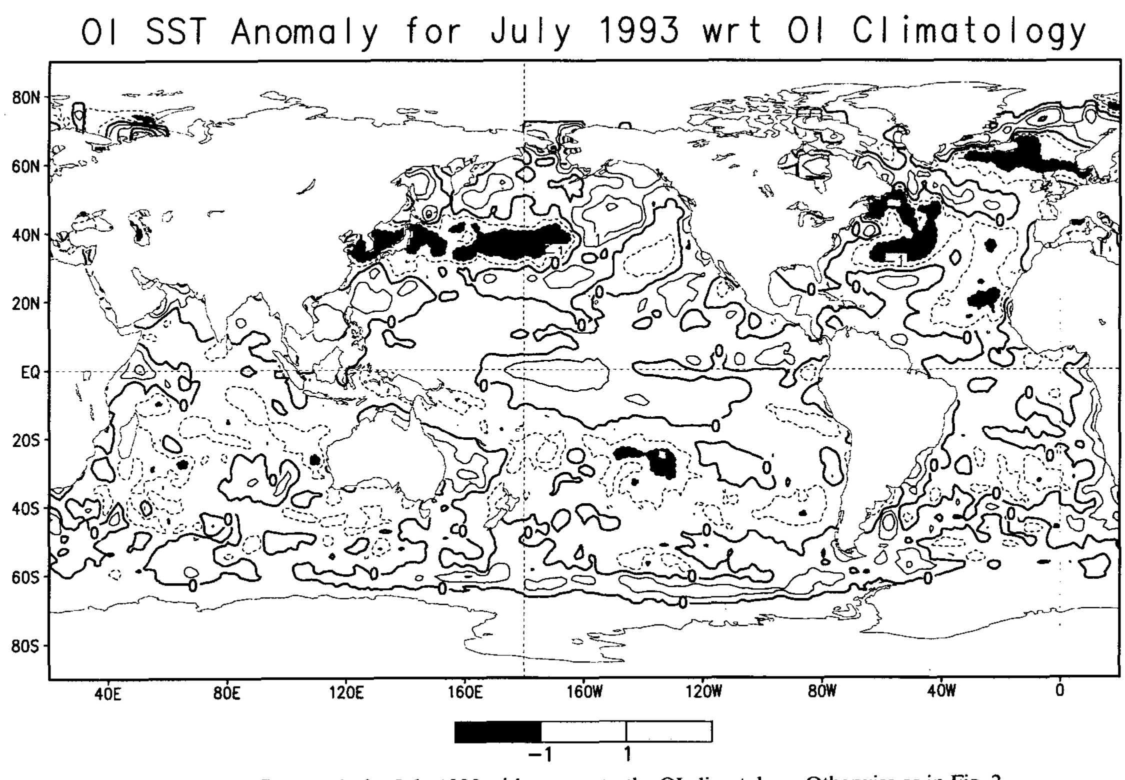


FIG. 5. OI SST anomaly for July 1993 with respect to the OI climatology. Otherwise as in Fig. 2.

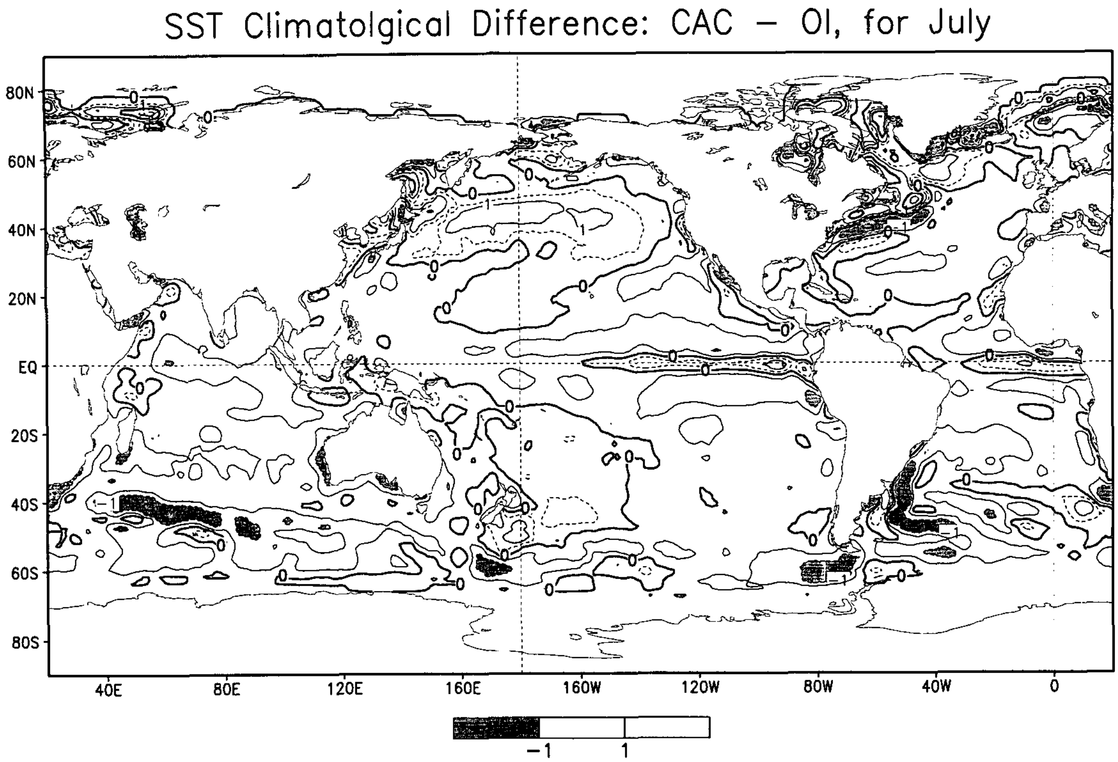


FIG. 6. Difference between the CAC and OI climatology (CAC minus OI). Otherwise as in Fig. 2.

Hemisphere. The result of this neglect of the satellite will be discussed at the end of section 3.

In the sections that follow, we first use the OI analyses to develop a new 1° climatology. We then adjust it, where possible, to have the same base period as the CAC and STR climatologies and discuss the impact of this adjusted climatology on monitoring ENSO events.

## 2. OI climatology

To compute the new climatology we first use the monthly OI fields. At the time this study was begun, the OI analyses existed for the period November 1981 through July 1994. To give equal weight to each month, we selected the 12-yr period from January 1982 through December 1993. To produce a monthly climatology, henceforth called the OI climatology, we simply averaged the OI fields by month. Figure 4 shows the OI climatology for July. As expected, the OI climatology has much tighter gradients than the CAC climatology, especially in the Gulf Stream region. Examples of additional regions include the Kuroshio, the equatorial Pacific cold tongue including the Galapagos Front, the Falkland Current region, and a large region of the subtropical convergence associated with the northern edge of the Antarctic Circumpolar Current near 40°S between 30° and 80°E. The July 1993 SST anomaly relative to the OI climatology is shown in Fig. 5. Here the anomalies are much smoother than those in Fig. 3 because they do not show the noise caused by the difference between the analysis and climatology scales in the high gradient areas.

There are also large-scale differences caused by the shift in the climatological base period from 1950–1979 to 1982–1993. In particular, the positive anomalies in the central and eastern tropical Pacific, obtained using the CAC climatology, are substantially reduced when the OI climatology is used. The difference, presented in Fig. 6, shows that the OI climatology is 0.5°C more positive than the CAC climatology over much of the tropical Pacific. This difference can also be found in the tropical Indian Ocean. In addition, the midlatitude SSTs in the North Pacific in the OI climatology are 1°C more negative than the CAC climatology. These changes in SST have been well documented (e.g., see Parker et al. 1994; Smith et al. 1994). The tropical differences are due to the influence of strong ENSO events of 1982–1983, 1986–1987, and 1991–1992, followed by the weaker and yet persistent ENSO conditions from 1993–1994. Trenberth and Hurrell (1994) describe the changes in the North Pacific SSTs as partially due to atmospheric coupling with tropical Pacific SSTs and partially due to local reinforcement of the anomalous atmospheric circulation.

Smaller-scale differences in Fig. 2 result from the resolution differences between the two climatologies. In particular, the CAC climatology cannot resolve the

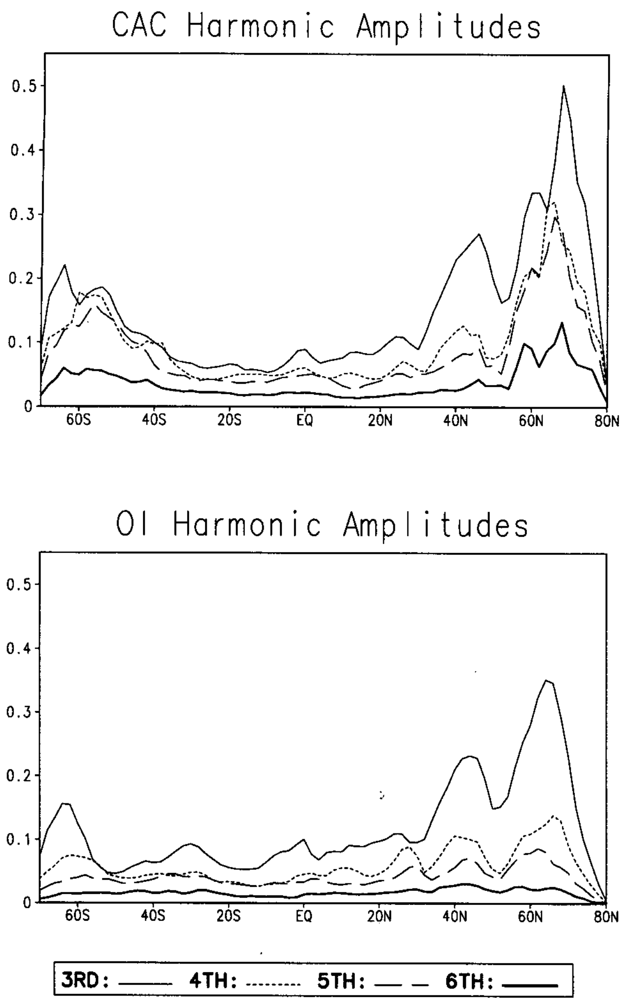


FIG. 7. Magnitude of the zonally averaged third through sixth Fourier harmonics from the CAC climatology (top) and OI climatology (bottom).

cold tongues in the eastern equatorial Pacific and Atlantic as well as the OI climatology. Thus, in these regions the anomalies based on the CAC climatology appear artificially more negative.

The OI climatology uses 12 years of satellite data, while the CAC and STR climatology only used four years. Thus, in the high latitude Northern Hemisphere and in the high and midlatitude Southern Hemisphere, where in situ data are sparse, the climatology should be better represented by the OI. To verify this and to compare the temporal stability, we computed the Fourier components at each grid point for both the OI and CAC climatologies. Because there are 12 months, only six harmonics can be computed. Comparison of the harmonics of the same order from the two climatologies showed that the first two harmonics were very similar. However, the higher harmonics differed. We show the zonally averaged magnitude of the third through sixth harmonics for the two climatologies in Fig. 7. Between 30°S and 50°N, the third and fourth harmonics are very similar. Within this range the CAC fifth and sixth harmonics are slightly larger than the OI fifth and sixth harmonics, respectively. However, outside this range all the CAC harmonics are noticeably larger than the corresponding OI harmonic. If we equate harmonics above three as noise, than the OI is much less noisy than the CAC climatology. Thus, the temporal smoothing used in the STR climatology is not as necessary for the OI climatology as it was for the CAC climatology.

## 3. Adjusted OI climatology

Although the OI climatology is superior to the CAC and STR climatologies in resolution, it is not based on the preferred 1950–1979 period. We will now use the CAC climatology to correct this problem. However, the correction can only be carried out in regions where

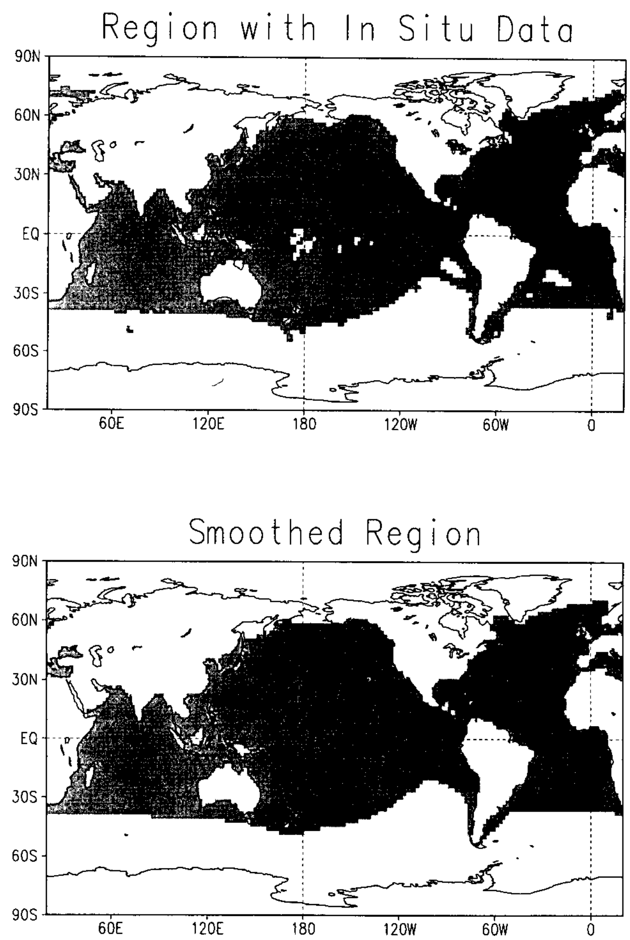


FIG. 8. Shaded region shows where at least 11 out of 12 months were based on in situ data in the CAC climatology (top) and slightly smoothed version (bottom). The shading in the bottom shows ocean areas where $D$ is computed according to (1), in other ocean areas $D$ = 0 (see text).

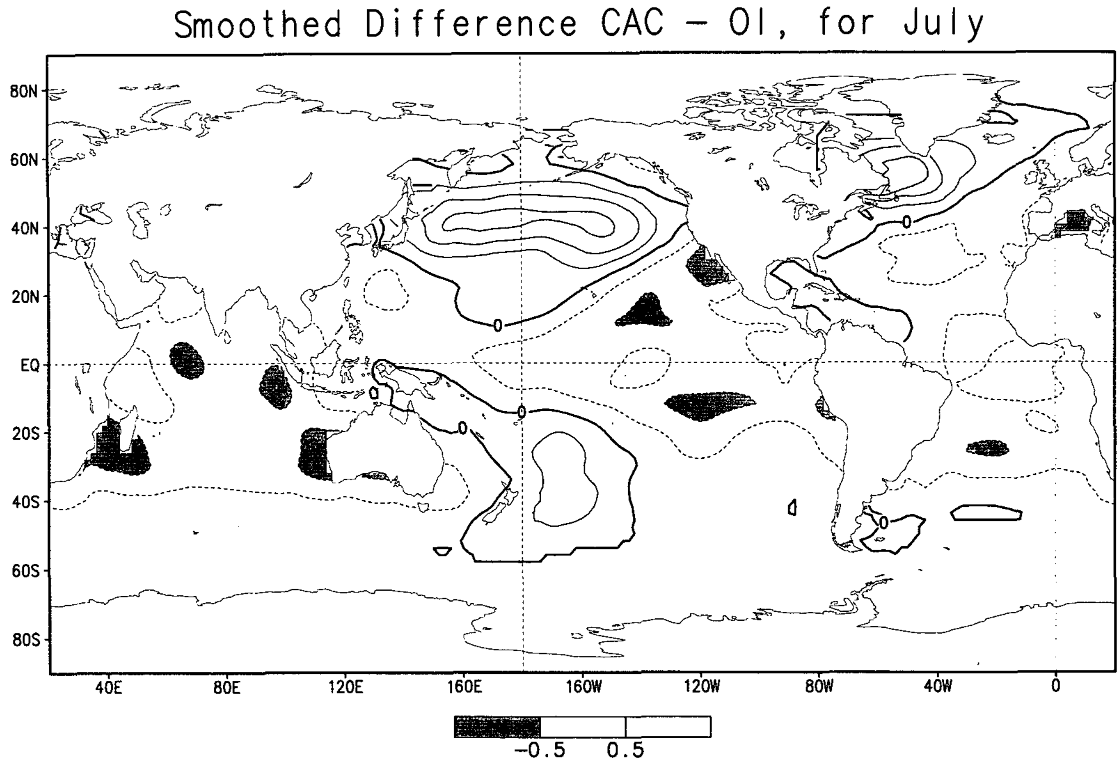


FIG. 9. Smoothed climatological difference S given by (2), CAC minus OI. Dark shading shows differences less than −0.5°C; light shading shows differences greater than 0.5°C. The contour interval is 0.25°C. Negative contours are dashed.

the CAC climatology is defined by in situ data. Outside this region, the CAC climatology uses limited satellite and sea-ice data from a different period, and an SST climatology for the 1950–1979 period is not well defined.

To select the regions that can be adjusted, we use the data flags in the CAC climatology that indicate the grid points that were based on in situ data. In the upper panel of Fig. 8, we have indicated grid points that used in situ data for at least 11 of the 12 months. Because the actual CAC climatology has been smoothed to a resolution of 6°, we manually modified this region slightly, as shown in the bottom panel of Fig. 8, to include the few missing interior regions and lightly smooth the exterior boundaries.

The adjustment method is to first degrade the resolution of both the CAC and OI climatologies to the same level and then use only the grid points in the lower panel of Fig. 8 to provide a monthly smooth difference (CAC − OI). The smooth difference will then be added to the OI to form the adjusted OI (AOI) climatology. This is similar to the way that the satellite SST data are bias-corrected against in situ data before their use in the OI (Reynolds and Smith 1994). To get the large-scale difference for each month, we first compute the difference $D$ at each point

$$D = C - O, \qquad (1)$$

where $C$ is the SST from the CAC climatology and $O$ is the SST from the OI climatology. The smoothed difference $S$ is computed by horizontally smoothing (1) over ocean areas using a moving-area average over a given radius

$$S = \frac{1}{A_r}\int_{A_r} D dA_r, \qquad (2)$$

where $A_r$ is the ocean area within a radius of $r$ of the point being smoothed. We compute $D$ only in regions where there are sufficient in situ data in the CAC climatology as shown by the shading in the lower panel of Fig. 8. In the remaining areas, we assign $D = 0$ before horizontal smoothing with (2). These areas include the Arctic Ocean, the oceans south of about 40°S, and much of the eastern South Pacific. Besides smoothing $D$ in regions where it is computed, (2) also removes abrupt changes in $D$ between areas where it is computed and areas where it is set to zero. There are many other possible filters that could be used in place of (2). However, our purpose is merely to smooth both climatologies in the same way and then determine the relatively small differences between the smoothed climatologies. Any bias in the method should affect both climatologies equally and be eliminated, or at least greatly reduced, in the differences. This technique also has the advantage of not requiring grid points over land.

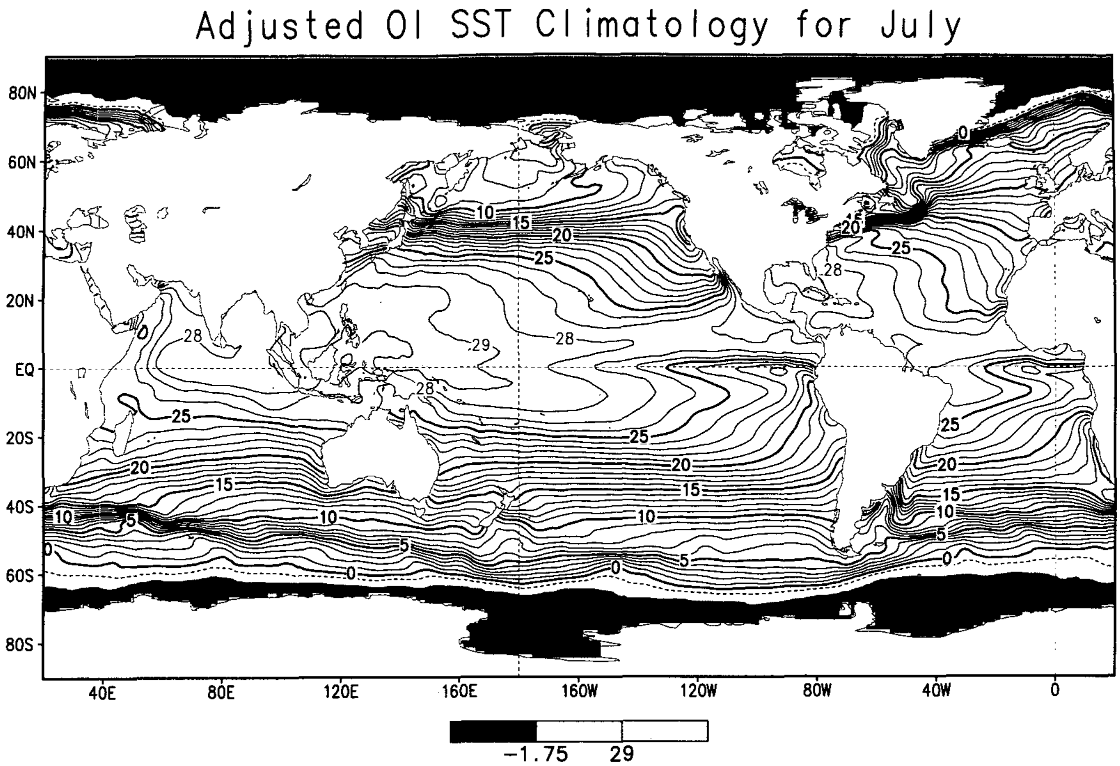


FIG. 10. Adjusted OI (AOI) SST climatology (reference period: 1950–1979, see text) for July. Otherwise as in Fig. 1.

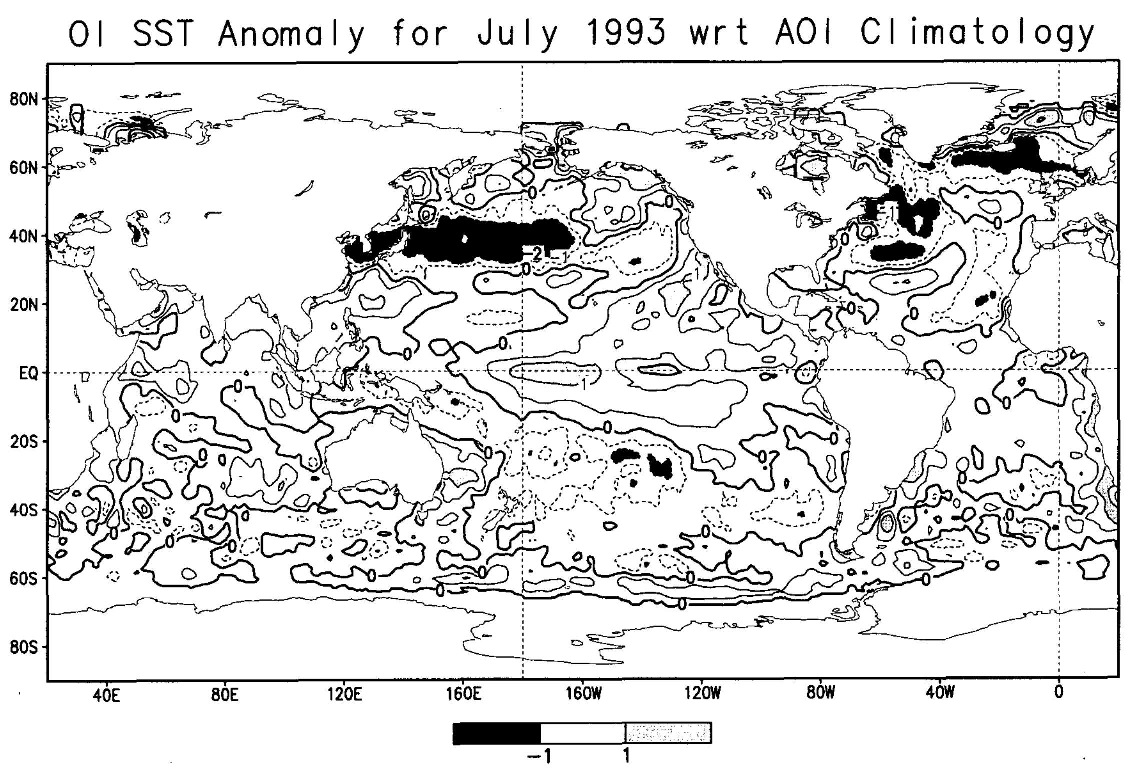


FIG. 11. OI SST anomaly for July 1993 with respect to the AOI climatology. Otherwise as in Fig. 2.

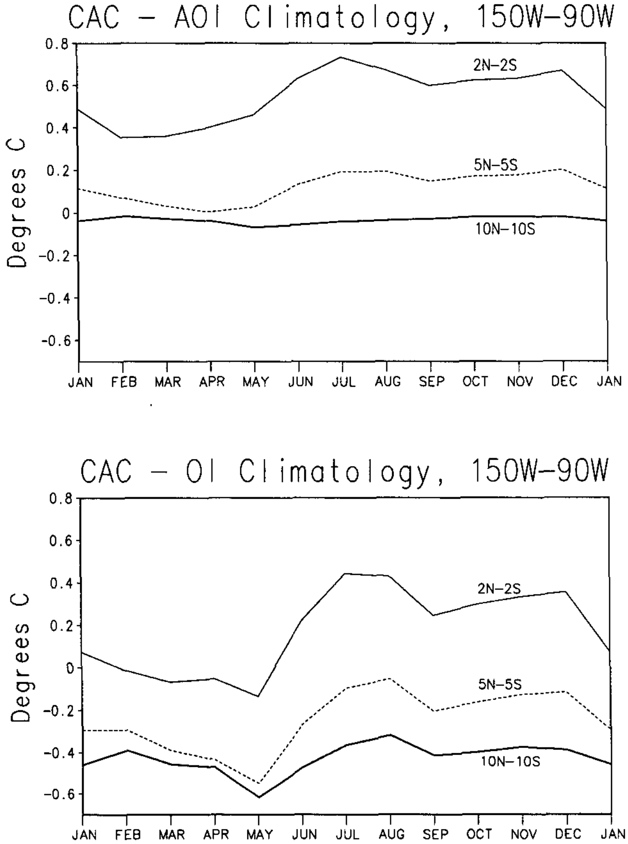


FIG. 12. Difference between the CAC and AOI climatologies (CAC minus AOI) in the upper panel and between the CAC and OI climatologies (CAC minus OI) in the lower panel. All differences are shown over the annual cycle. The differences are averaged between 150°–90°W and between either 2°N–2°S, 5°N–5°S, or 10°N–10°S.

In the definition of (2), we have explicitly assumed that the area $A$ is isotropic and can be given by simply defining the radius $r$ of $A$. We also assumed that $r$ is independent of spatial location. The value of $r$ was estimated by first examining the difference field in Fig. 6. The difference shows that the equatorial upwelling has north–south scales of roughly 500 km. This is also approximately the width of the difference scales near the Gulf Stream. Because we wanted to eliminate these scales while preserving larger scales, we set $r$ equal to 1000 km. When we tried doubling $r$, we found little change in the large-scale pattern of $S$ but noticed that $S$ was reduced in magnitude. However, when $r$ was halved, $S$ began to be influenced by the resolution differences that we wished to eliminate.

We show an example of the smoothed climatology difference for July (Fig. 9). The differences are negative in the Tropics, but positive in the extratropics, especially in the North Pacific. Other months (not shown) show a similar pattern. The smoothing process has eliminated the scale differences between the CAC and OI climatology as shown Fig. 6 while preserving the larger-scale base period change.

To finally compute the AOI climatology for each month, we simply added the smoothed difference to the OI climatology at each grid point, $A = S + O$. Figure 10 shows the AOI climatology for July. Comparison with Figs. 1 and 4 shows that the AOI climatology maintains the stronger gradients of OI climatology that are associated with equatorial upwelling, the Gulf Stream, etc. The July 1993 SST anomaly computed using the AOI climatology (Fig. 11) shows that the large-scale pattern of the anomaly is very similar to the OI SST anomaly using the CAC climatology (Fig. 3) but without the noise due to the resolution differences. In particular, the anomalies based on the OI (Fig. 5) and the AOI climatologies do not show the weak equatorial negative anomalies in the cold tongues in the Pacific and Atlantic that are evident in the OI anomaly pattern derived using the CAC climatology.

In the computation of the smoothed adjustment (2) using (1), we could have substituted the STR climatology for the CAC climatology. However, due to the smoothing in (2), the enhanced resolution areas of the STR in the Gulf Stream and Kuroshio areas would have little effect on the values of $S$. Thus, because there was no compelling justification to use either the STR or CAC climatologies, the CAC climatology was selected. We also considered filtering the smoothed differences $S$ over time as was done in the STR climatology. However, because the magnitudes of $S$, which are used to adjust the OI climatology, are small relative to the OI climatology, the Fourier components of the adjusted OI and the OI were almost identical. Thus, we decided that temporal filtering of $S$ was not needed.

The eastern equatorial Pacific is a region where large SST anomalies develop on interannual timescales and, thus, is a region where anomalies are closely monitored. To examine the difference between the CAC and AOI climatologies, we show area averages of the differences between 150°W and 90°W over several different latitudinal ranges centered on the equator (Fig. 12, top panel). Between 2°N and 2°S, the CAC climatology is between 0.35°C and 0.75°C more positive than the AOI climatology. This difference occurs because the AOI climatology is better able to resolve equatorial upwelling. The difference becomes smaller as the averaging latitudinal band widens. Between 5°N and 5°S, the difference is 0.2°C or less and decreases to less than ±0.1°C for the area between 10°N and 10°S. The difference between the CAC and OI climatologies (Fig. 12, bottom panel) range between −0.13°C and 0.44°C in the band between 2°N and 2°S. In this range, the tendency for the CAC climatology to be more positive than the OI climatology, due to resolution differences in the upwelling area along the equator, is partially offset by the fact that the CAC climatology is generally more negative than the OI climatology over most of the Tropics (see Fig. 6). When wider latitude bands

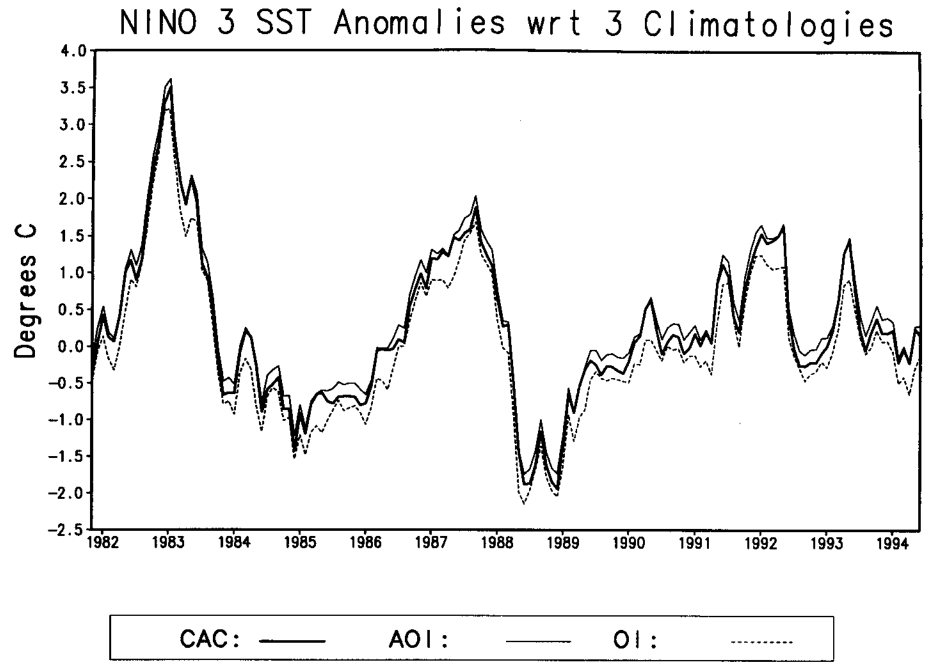


FIG. 13. OI SST anomalies for the Niño 3 region (150°–90°W and 5°N–5°S) with respect to the CAC, OI, and AOI climatologies.

are selected, the large-scale tropical differences overwhelm the equatorial resolution effects and the CAC climatology becomes more negative than the OI climatology.

The time series of the OI anomalies with respect to each of the three climatologies averaged over the Niño 3 region (150°–90°W, 5°N–5°S) is shown in Fig. 13. Each curve shows the same interannual variations, indicating that the choice of climatology will not obscure a moderate to strong warm or cold episode. However, differences between the anomalies based on the CAC and OI climatologies can exceed 0.5°C and lead to confusion about the existence of weak warm or cold ENSO conditions. Differences between anomalies based on the CAC and AOI climatologies are much smaller. Thus, a change from the CAC to AOI climatology will have only a small influence on ENSO monitoring.

To give an indication of the global seasonal cycle, we show the AOI climatology for January in Fig. 14. As expected, the middle and high latitude Northern Hemisphere temperatures are colder compared to the July AOI climatology field (Fig. 10), while the mid- and high latitude Southern Hemisphere temperatures are warmer. This leads to stronger Gulf Stream gradients in January than in July. In the Tropics, the centers of the warmest water (>29°C) have moved southward from July to January. In addition, the tropical upwelling in the eastern Pacific and Atlantic is weaker in January than it was in July.

As mentioned earlier, Bottomley et al. (1990) used all in situ SST data available (1853–1981) to compute monthly climatological and individual monthly mean fields. The in situ data before 1943 were corrected for instrument biases as detailed there. Parker et al. (1994) states that the Bottomley et al. (1990) analysis has been improved by the U.K. Meteorological Office (UKMO) global sea ice and sea surface temperature (GISST) analysis. The individual monthly mean GISST fields are available on a 1° grid, although some intermediate processing is done on a 5° grid. We computed our own monthly GISST climatology by averaging all the individual GISST analyses by month between 1950 and 1979. This period was chosen to match the base period of the AOI climatology as closely as possible.

Figure 15 shows the July GISST climatology for the 1950–1979 base period. A comparison with the AOI climatology for July (Fig. 10) shows good agreement overall. There is some slight additional noise in the tropical isotherms in the GISST climatology compared to the OI. This is a minor problem that may be related to our method of generating the GISST climatology from monthly means and could easily be corrected by light smoothing. However, there are large differences south of 40°S between the two climatologies. The gradients in the region of the Falkland Current and the subtropical convergence region near 40°S between 20°E and 80°E are better resolved in the AOI climatology. In general, the gradients in the GISST July SST field south of 40°S tend to be oriented in the north–south direction with little longitudinal variation. However, the AOI July SST climatology shows stronger perturbations in this orientation. Because vertical oceanic density gradients become weaker with increas-

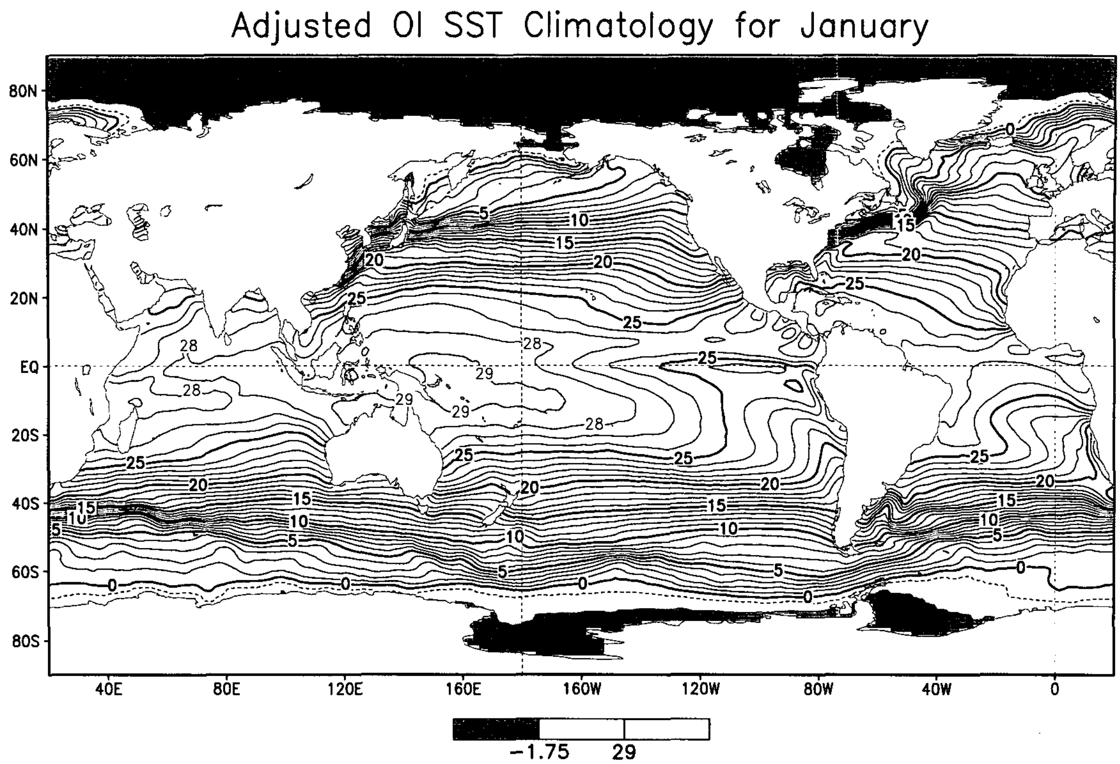


FIG. 14. Adjusted OI (AOI) SST climatology (reference period: 1950–1979, see text) for January. Otherwise as in Fig. 1.

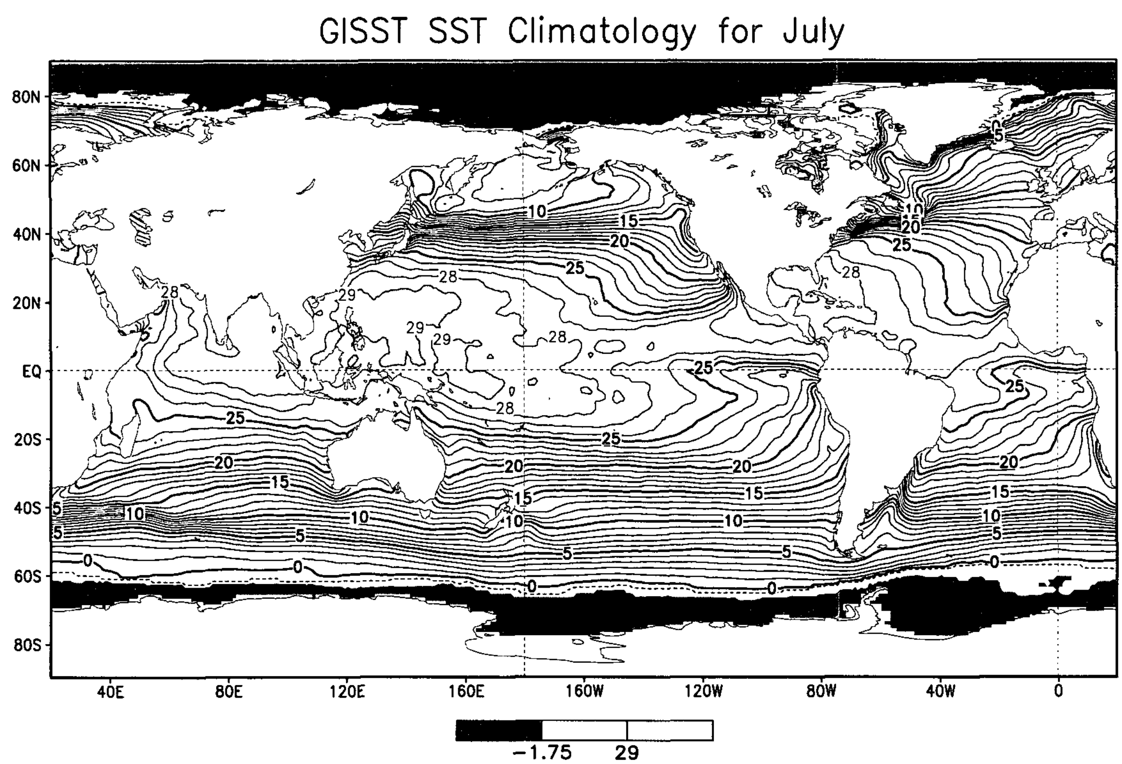


FIG. 15. GISST SST climatology (reference period: 1950–1979, see text) for July. Otherwise as in Fig. 1.

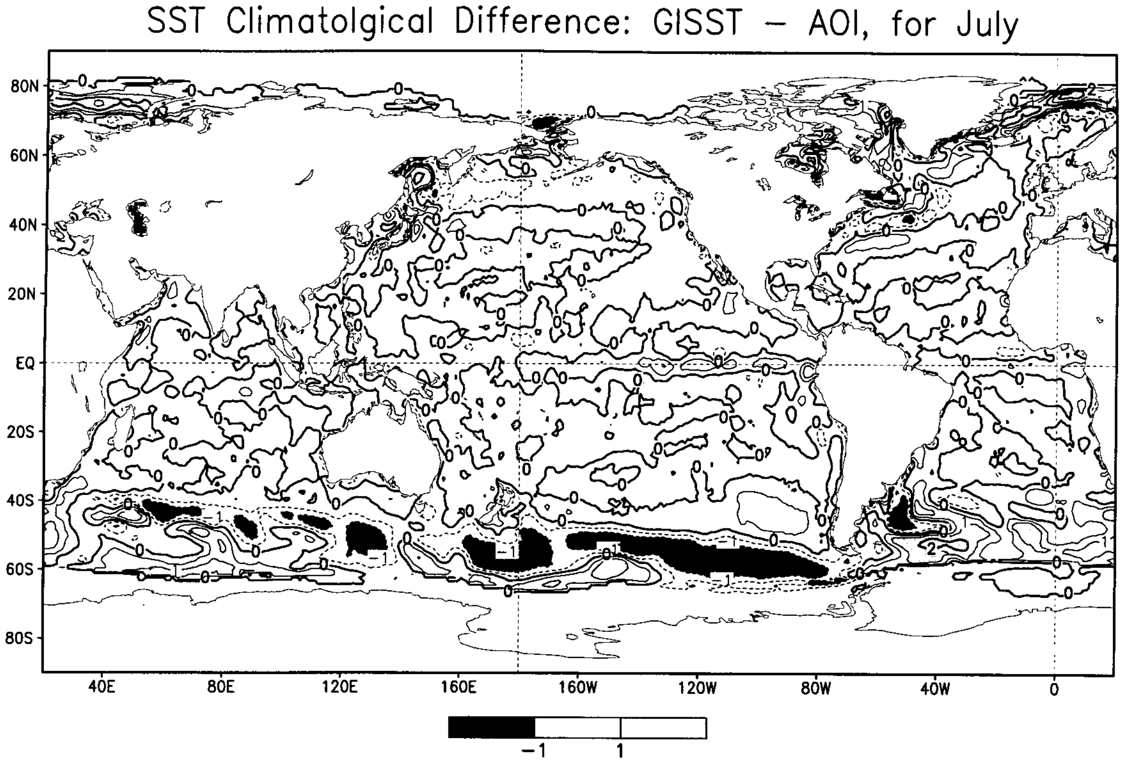


FIG. 16. Difference between the GISST and AOI climatology (GISST minus AOI). Otherwise as in Fig. 2.

ing latitude, topographic steering of surface currents is more evident at high latitudes. This causes some modification of the SST gradients. Comparison of the July and January AOI climatology fields (Figs. 10 and 14) shows that perturbations in the gradient orientation tend to occur at the same locations. This suggests that these perturbations in the AOI climatology are real and fixed in position by topography. The difference between these two climatologies indicates the importance of satellite data in providing more realistic gradients south of 40°S.

The difference between the July AOI and GISST climatologies is shown in Fig. 16. Differences north of 40°S are remarkably small except in some high latitude Northern Hemisphere regions (e.g., Hudson Bay) where data are sparse and the climatological values are uncertain. The 0.5°C positive difference along the equator in the eastern Pacific shows the AOI's superior resolution of the cold tongue. Differences in the western North Atlantic along the path of the Gulf Stream also indicate resolution discrepancies there. Comparison of the two July fields (Figs. 10 and 15) show that Gulf Stream gradients are better resolved in the AOI climatology.

## 4. Summary

We used the 2° resolution CAC SST climatology, which is primarily based on the 1950–1979 period, and the 1° resolution OI SST climatology, which is based on the 1982–1993 period, to construct a 1° resolution climatology with its base period adjusted to the 1950–1979 period. This was done so that the analysis change from blended SST to the OI SST analysis could be accompanied by an associated change in the climatology. This change in both analysis and climatology was designed to minimize jumps in the large-scale anomaly patterns without degrading the OI's spatial resolution. This new climatology, the adjusted OI (AOI) climatology, gives SST anomalies that are coherent over large regions with anomalies computed using the CAC climatology. In high northern latitude regions (roughly north of 60°N) and in mid- and high southern latitudes (roughly south of 40°S) where in situ data for the CAC climatology are limited, adjustments are not possible and the AOI and OI climatologies are equivalent. However, the AOI climatology in these regions is based on 12-yr period that is superior to the CAC and STR climatologies that only used four years of satellite data.

Although the AOI climatology was designed for use with the OI analysis, we feel that it should also have a broader use. To our knowledge, the OI and AOI climatologies are the first to use 12 years of satellite SST data. These data allow the actual resolution of the climatology to approach 1° everywhere. We wish that the AOI climatology could have an overall consistent base period. However, global coverage with a base period of 1950–1979 is not possible. If a consistent base period is required, then the user will either have to be satisfied with the 12-yr OI base period or wait.

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