Estimation of Sea Surface Temperatures Using GOES-8/9 Radiance Measurements

Xiangqian Wu,* W. Paul Menzel,*+ and Gary S. Wade*+ 

ABSTRACT

Sea surface temperatures (SSTs) are derived using measurements from the new generation of imaging instruments on the Geostationary Operational Environmental Satellites (GOES). The National Environmental Satellite, Data and Information Service has been producing hourly GOES SST estimates since December 1998. This paper presents the algorithm for cloud detection and atmospheric moisture correction and shows some initial results. Several advantages of GOES SST are evident in comparison with SST from polar orbiting satellites. Frequent sampling by GOES imagers results in a more complete map of SST as clouds move away. Changes in scene temperature over a short period of time help to detect the presence of clouds. The abundance of GOES observations enables stringent screening for cloud-free observations while maintaining good spatial coverage of clear-sky inferences of SST. Diurnal variations of SST over large areas are observed for the first time and their implications for numerical weather prediction and climate monitoring are discussed.

1. Introduction

Sea surface temperature (SST) has been measured from satellites for nearly two decades by the Advanced Very High Resolution Radiometer [AVHRR; May et al. (1998) and references therein] and, more recently, by the Along-Track Scanning Radiometer [Harris and Saunders (1996) and references therein]. Both series of satellites operate from sun-synchronous polar orbits about 850 km above the ground. Compared with in situ measurements by ship and buoy, a great advantage of these satellite SST measurements is their global, nearly uniform coverage (except for clouds) with high spatial resolution (1 km). Significant progress has been made in meteorology, climatology, oceanography, and other branches of geoscience using the AVHRR long-term record of high-quality SST estimates (Walton et al. 1998).

A new series of Geostationary Operational Environmental Satellites (GOES) became operational in 1994, starting with GOES-8. Operated by the National Oceanic and Atmospheric Administration (NOAA), GOES measures the upwelling radiation with significantly improved spatial resolution and signal to noise ratios over that achieved with the previous geostationary satellites (Menzel and Purdom 1994). GOES-8 in the east (75°W) and GOES-9 (now GOES-10) in the west (135°W) take measurements over most of the Western Hemisphere (45°S–60°N, 30°W–180°) every 30 minutes. A unique advantage of SST from GOES is that a location can be observed 48 times a day, compared with twice per day by a polar orbiting satellite. For areas that are sometimes covered by clouds, GOES significantly increases the possibility of measuring SST. For areas that are clear most of the time, GOES offers the first opportunity to study the diurnal variation of SST. The difficulty, however, is that being 36 000 km away from the surface poses significant technical challenges to achieve high radiometric precision with high spatial and temporal resolution.
SST has been estimated from geostationary satellite observations for some time (Maul et al. 1978; Zando et al. 1982). Bates and Smith (1985) derived SST from multiple channel measurements with GOES-5, which had channels similar to those on GOES-8 but with higher noise levels. A limiting factor for GOES-5/6/7, however, was that the instantaneous field of view (IFOV) was 16 km, compared to 4 km for the current GOES. The larger the IFOV, the more difficult it is to ensure that an IFOV is completely cloud free. Recently, Legeckis and Zhu (1997) presented early results of SST derived with GOES-8. This paper presents the algorithm for cloud detection, atmospheric moisture correction, and SST derivation that is being tested for operational implementation by the National Environmental Satellite, Data, and Information Service (NESDIS). The current GOES SST algorithm does not treat explicitly, among other things, the effects of aerosol, a nonblackbody sea surface, and the difference between satellite and buoy measurements (an area estimate of skin SST vs a point estimate of bulk SST). The main purpose of this paper is to demonstrate the capability and special features of GOES in estimating SST. The GOES SST has been produced hourly since December 1998 at NESDIS.

2. Cloud detection

An integral part of the GOES SST algorithm is the detection of cloud contamination with special consideration of the GOES measurement characteristics. A number of cloud detection schemes have been implemented for polar orbiting systems (McClain et al. 1985; Saunders and Kriebel 1988; Simpson et al. 1998; May et al. 1998). These schemes primarily rely on two strategies for cloud detection. 1) The “channel comparison” method (Saunders and Kriebel 1988) uses multispectral measurements for the same IFOV at the same time. The method is based on the differential responses of channel measurements to the presence of various types of clouds. For example, infrared window measurements can detect clouds that decrease scene brightness temperature (e.g., cirrus); visible measurements can detect clouds that increase scene reflection (e.g., low stratocumulus). 2) The “spatial coherence” method (Coakley and Bretherton 1982) uses concurrent satellite measurements over an area, usually a single channel. The method is based on the assumption that SST is homogeneous and warmer than clouds; thus clouds can be identified where the scene brightness temperature has lower mean values or larger variations.

Both of the strategies are used with GOES data to detect clouds. The multispectral measurements by the GOES imager (at 0.52–0.72 μm, 3.78–4.03 μm, 10.2–11.2 μm, and 11.5–12.5 μm) help to detect many clouds. Since the GOES instrument noise (0.2 K) is about twice of that on polar orbiting platforms (typically 0.1 K), the spectral method for cloud detection is sometimes less effective. The disadvantage of GOES in terms of instrument noise also affects the cloud detection based on spatial homogeneity, but other limitations also exist in that test. The IFOV for the GOES imager is 4 km, compared to 1 km for polar systems. It follows that in areas of varying scene brightness temperatures, GOES measurements tend to be smoother than those with higher spatial resolution. On the other hand, the GOES images exhibit “striping” from using two detectors to map a scene (Weinreb et al. 1997). As a result, the measurements over truly homogeneous areas tend to be more variable than those made by polar systems using a single detector. Also, the SST gradient in some parts of the ocean (such as the Gulf Stream and its vicinity) can be so large that the assumption of spatial homogeneity confuses clear scenes for cloudy scenes. Because of these considerations, the GOES SST algorithm restricts spatial tests to the visible data; they are considered of secondary importance.

A third strategy, the “temporal consistency” method, is developed for optimal utilization of information in GOES data. This is based on the assumption that SST variation is small between frequent GOES observations; thus clouds can be identified where scene brightness temperature varies rapidly in time. This additional test greatly compensates for the disadvantages of GOES data in cloud detection.

The GOES SST cloud detection algorithm is outlined in Fig. 1. The input data include brightness temperatures $T_{1\phi}$, $T_{1\lambda}$, and $T_{1\zeta}$ at 4-km resolution, the corresponding 16 measurements of albedo at 1-km resolution (albedo), and $T_{1\lambda}$ at 30 min before and after $(T_{1\lambda} @ \pm30 \text{min})$, all from GOES measurements. In addition, a flag for land (scene; Steinwand 1994) and the most recent SST estimate for the scene and for the time of day (guess) are also used. All scenes first undergo four general tests.

- **Zenith angle of satellite from the scene.** Experience with AVHRR indicates that the quality of retrieved SST decreases at satellite zenith angles larger than
This limits the GOES SST to within approximately 45° latitude from the equator. GOES SSTs at higher latitudes can be produced; the quality, however, is probably less reliable.

- **Surface type of the scene.** Retrieval is attempted only over water surfaces.
- **Window channel brightness temperature of the scene.** The scene is cloudy or frozen if its window channel brightness temperature is too cold.
- **Split-window channels brightness temperature difference.** Absorption and reemission by atmospheric water vapor normally causes $T_{11}$ to be warmer than $T_{12}$. However, if the difference is negative or is too large, it is likely due to the presence of cirrus clouds, calibration errors, or misalignments of the split-window channels' fields of view (Wu et al. 1996).

Further tests may involve either visible (during daytime) or $T_{39}$ (during nighttime) data. If the sun is sufficiently high in the sky, visible data are examined. The scene is clear if it is sufficiently dark and homogeneous. Otherwise, if the scene is not too bright and too inhomogeneous, it is tested further. In fact, even if it is very bright, it will still be tested further if it is close to the coastline or is possibly under the influence of sun glint.

If the sun is below the horizon, the shortwave IR channel can be used for additional tests. These include the comparison of $T_{39}$ and $T_{12}$ to detect subpixel-scale cold clouds or thin cirrus, and the comparison of $T_{11}$ and $T_{39}$ to detect warm stratus or fog (Saunders and Kriebel 1988).

For scenes in the twilight, sun-glint, or coastal areas, and for other scenes still not identified as clear or cloudy at this point, a temporal consistency test checks whether the scene temperature is significantly cooler than 30 min before and after. This test for high temporal resolution measurements by polar orbiting satellites. Both assume that the ocean surface is warmer than the cloud top. In addition, temporal consistency assumes that SST is invariant in a period of time, whereas spatial coherence assumes that SST is invariant in a region.

If a scene survives all these tests, the SST is retrieved. Unless the retrieved SST differs significantly from the guess, it is considered valid and will be used to update the guess.

The cloud detection scheme outlined in Fig. 1 is subject to revision. The threshold values may differ from satellite to satellite and may also change over time. For example, recent study shows that the GOES-10 albedo is 20%–50% higher than the GOES-8 albedo (Schmit 1998), possibly a result of gradual deterioration of GOES-8 mirror reflectance after four years.
for several reasons. In areas such as “A,” temporal consistency assures that these relatively large spatial variations of brightness temperature are due to SST gradient, not clouds. In areas such as “B,” temporal consistency assures that these unusually cool brightness temperatures are due to a cold current intrusion, not clouds. In areas such as “C,” SST is retrieved because Fig. 2b is actually a composite of three SST images within 1 h. As clouds move through a given area, the coverage is further improved.

The spatial coverage of Fig. 2a could be improved by relaxing some or all of the cloud tests, at the expense of somewhat degraded SST quality. This is often a dilemma in designing a cloud detection scheme, as neither the SST with high quality but sparse coverage, nor the SST with good coverage but low quality is highly desirable. The abundance of GOES observations helps maintain an acceptable compromise in this regard.

3. Atmospheric correction

Properly accounting for the absorption and reemission of surface radiation by the overlying atmosphere has always been a crucial step in deriving sea surface temperature from satellite measurements, even when the measurements are available only for a single-window channel (Smith et al. 1970). Modern satellite SST instruments measure radiation in more than one-window channels, based on the “split-window” technique [McMillin and Crosby (1984) and references therein]. This leads to a number of successful operational algorithms for AVHRR (McClain et al. 1985; Walton et al. 1998). The development of these algorithms...
commonly employs empirical regression of satellite-measured radiance against ship- or buoy-measured bulk SST. Since the GOES imager has three infrared window channels similar to those on AVHRR, the current GOES SST algorithm for atmospheric correction relies heavily on the expertise gained in developing AVHRR SST algorithms.

Early studies (McMillin 1975; McClain et al. 1985) suggest that the regression should be of the form

\[
SST = A_0 + A_1 T_{11} + A_2 (T_{11} - T_{12}), \tag{1}
\]

where \(T_{11}\) and \(T_{12}\) are brightness temperatures for the split-window channels, and \(A_0, A_1,\) and \(A_2\) are coefficients determined by regression. Later research and experience (McClain et al. 1985; Walton et al. 1998) showed the benefit of using additional measurements at the shortwave infrared window channel (3.7 \(\mu\)m) at night and using additional parameters such as the view angle and estimate of SST. To investigate the diurnal variation of SST, the algorithm is required to be as consistent as possible during the day and night. For that reason, current GOES SST does not use measurements at the shortwave infrared window \(T_{19}\), which are contaminated by an unknown amount of reflected solar radiation during the daytime. This may affect the accuracy of SST achievable at night (Harris and Saunders 1996); in the future the magnitude of this effect can be compared with the benefit of the day–night continuity of this algorithm. Also, the buoy data collected for this study are concentrated in a handful of locations with view angles between 30° and 50°, making it difficult to use the view angle as an independent variable for regression. A more sophisticated algorithm for atmospheric correction is under study. On the other hand, Fig. 3 shows that Eq. (1) is inadequate; the nonlinearity of water vapor absorption is significant when the range of water vapor content is large. Thus a quadratic term is added to the regression, as suggested by McMillin and Crosby (1984). In summary, the regression equation to correct for atmospheric absorption and reemission has the form

\[
SST = A_0 + A_1 T_{11} + A_2 dT + A_3 dT^2, \tag{2a}
\]

where \(dT = T_{11} - T_{12}\). The regression is performed separately for GOES-8 and GOES-9. This section describes the procedures applied to GOES-8 in some detail; the procedure for GOES-9 is similar.

To determine the regression coefficients in Eq. (2a), buoy reports collocated with GOES imager radiance measurements have been collected from September 1996 to May 1998 for GOES-8 (January 1997 to May 1998 for GOES-9). These include marine reports from the Global Telecommunications System at 3-h intervals between 20°–50°N and 70°–100°W for GOES-8 (10°–40°N and 120°–165°W for GOES-9). Ship reports are excluded because of their nonuniform sampling. For each collocation, a 7×7 array of GOES pixels, with the buoy located in the center pixel, is examined. If any 1 of the 49 pixels is clear, the collocation is recorded. This results in a total of 42,953 collocations.

An important step in regression is to ensure that the sample dataset is fully and solely representative of the population for which the SST is to be derived.

**Fig. 3.** (a) Mean regression residuals as a function of \(T_{11} - T_{12}\). A simple linear regression in the form of Eq. (1) is used. (b) As in (a) but Eq. (2a) is used. The residuals are the root-mean-square of the differences between observations and regression estimates; the mean is found for each range of \(T_{11} - T_{12}\). The residuals of linear regression appear to be a quadratic function of \(T_{11} - T_{12}\), suggesting that a quadratic fit is necessary.
The screening for unfit collocations is summarized in Fig. 4. Since the GOES SST algorithm is mainly intended for ocean application, 9947 collocations in the Great Lakes are removed, as lake environments can be different from those in the open ocean in terms of salinity, turbidity, depth, river discharge, etc. Collocations with gross errors in the buoy reports (1945, mostly missing SST measurements) or in GOES observations (6034, mostly cloud contamination) are also screened out. Another 712 collocations are eliminated for which the buoy SST differs from the AVHRR SST by more than 3 K. This can be caused by errors in either the buoy measurement or the AVHRR estimate, or simply because the buoy measures the temperature at a subsurface point whereas the radiometer measures the radiation from an area of the surface. Regardless, these collocations do not represent the normal relationship between buoy and radiometer measurements and are not used. Finally, 1575 collocations collected between 0400 and 0800 UTC are removed because the GOES calibration sometimes has been unreliable around satellite midnight (Johnson and Weinreb 1996).

The number of clear-sky GOES observations in the vicinity of the buoy appears to relate to the quality of the GOES SST regression fit to the buoy SST. Figure 5 shows that the GOES SST residual of regression decreases with an increasing number of clear-sky pixels around the buoy, particularly when the number of clear

![Quality Control of GOES-Buoy Collocations](image1)

![Quality Control: Cloud Clearing](image2)

![Quality Control: Age of First Guess](image3)

FIG. 4. Summary of quality control for the GOES–buoy collocations. Procedures were applied in the clockwise order starting at the 12 o’clock position.

Fig. 5. Residual of regression as a function of the number of clear pixels in the $3 \times 3$ box with the buoy in the center. Nine regressions were performed with minimum number of clear pixels being 1, 2, ..., 9. Residuals of each regression were then calculated and shown in this plot.

Fig. 6. Residual of regression as a function of the age (in days) of AVHRR SST that was used as first guess.
pixels is less than four. This is consistent with the fact that the more pixels that are identified as clear in an area, the more likely that the area is indeed clear. Since the GOES-buoy collocation dataset provides an ample number of samples, it was possible to require all of the $3 \times 3$ pixels to be clear. This removed 9311 additional collocations.

In constructing the GOES-buoy collocation dataset, the cloud detection algorithm used the most recent AVHRR SST to help identify clouds. Because of clouds or other problems, the most recent AVHRR SST may be several days old. Figure 6 shows that the residual of the GOES SST regression increases with the age of AVHRR SST, apparently because the older AVHRR SST is less representative of the true SST and thus less effective in identifying clouds. Another 2757 collocations were removed for which the AVHRR SST was at least 10 days old.

Wind speed or surface roughness also affects the regression fit. Figure 7 shows that the residual of regression decreases slightly with increasing wind speed from 0 to 5 m s$^{-1}$, then increases with wind speed (especially above 10 m s$^{-1}$). Typically, the GOES-measured skin temperature and the buoy-measured subsurface temperature are better correlated in the presence of a weak disturbance, which can result from light winds that provide adequate mixing in the surface layer of the sea. For calm sea, the skin temperature is more likely to be decoupled from the subsurface temperature. When the sea is too rough, other processes may occur, such as mixing of deep layer water and the formation of foam. Thus 722 collocations for which buoy reports of wind speed were greater than 10 m s$^{-1}$ were rejected. Finally, 53 collocations with residuals greater than 2 K were rejected as anomalies.

Other possible factors that may affect the quality of the regression of GOES radiances to buoy SSTs have been examined. These include the month, hour, latitude, longitude, zenith angle of GOES satellite, zenith angle of the sun, wind direction, wave activity, distance of the buoy location to the shore, SST as estimated from the buoy report or $T_{11}$, and atmospheric moisture as estimated from $T_{11} - T_{12}$. The collocations

![Fig. 7. Residual of regression as a function of wind speed.](image)

![Fig. 8. Residual of regression as a function of split-window brightness temperature differences ($T_{11} - T_{12}$).](image)

![Fig. 9. Residual of regression as a function of the dimension of array from which satellite-measured mean radiance is derived and regressed against buoy-measured SST.](image)
exhibit a reasonable distribution of all values for each factor, which ensures that the final sample properly represents all the situations. Each factor was examined for systematic changes in the residual of the regression and possible physical reasons behind such changes. The conclusion from these examinations is that there is insufficient evidence to reject any collocations based on those factors. This, however, does not necessarily mean that the distribution is uniform and the residual does not change in relation to any of those factors. For example, Fig. 8 shows that the residual tends to increase with $T_{11} - T_{12}$, which suggests that the regression becomes less reliable as the atmospheric water vapor increases. However, if the sample contains no collocations with high atmospheric water vapor, the derived regression would not be applicable to those situations. For the regression to be applicable in the summer season and in tropical regions, those collocations of high atmospheric water vapor content provide valuable information and thus are carefully preserved.

The box size to be used in regression remains an issue. As mentioned before, each collocation records GOES observations in a 7 x 7 array of pixels centered at the buoy location. Regression can therefore be made with an average of GOES observations over an area of various sizes, all centered at the buoy location. After experimenting with different box sizes for the regression, it was found that the 3 x 3 box is optimal (Fig. 9). This is not surprising, since a small box (1 x 1) has larger noise, whereas a large box (7 x 7) is less representative of a buoy measurement in regions of large SST variation.

After the extensive screening described in the preceding paragraphs, the remaining 9897 collocations yield the GOES-8 regression equation as

$$GOES-8\ SST = -6.4110 + 1.0260 T_{11} + 1.1900 d + 0.2017 d^2.$$  (2b)

Similarly, 2389 quality controlled collocations from GOES-9 yield the regression

$$GOES-9\ SST = -6.9510 + 1.0272 T_{11} + 1.7927 d + 0.0756 d^2.$$  (2c)

The coefficients in Eqs. (2b) and (2c) are similar but not identical. Part of the reason for the difference is that the spectral response functions for the split-window channels of the two satellites are different (Schmit 1998). Also contributing is the fact that the GOES-8 regression is based on more buoy reports covering a larger geographic area and greater variety of meteorological conditions for a longer period of time than the GOES-9 regression.

The cloud detection and atmospheric correction are performed for each individual pixel. The resulting GOES SST is smoothed with the pixel in the next line to partially overcome the striping problem, and remapped to 1/20 of a degree of latitude and longitude (approximately 5 km near the equator). It is anticipated that users of GOES SST will perform further manipulation such as averaging, smoothing, and compositing, to tailor it to individual needs. At present the resolution of GOES SST is preserved as high as possible.

4. Verification of the GOES SST

The GOES SST equation is verified in two ways. First, the stability of the GOES SST regression is examined subjectively by dividing the sample in half,
Second, the performance of the regression is verified objectively by comparing the GOES and buoy SST. The verification involves application of Eq. (2b) to three different datasets: a dependent dataset from which the regression coefficients were derived, a semidependent dataset that covers the same geographic region of the dependent dataset but during a different period of time, and an independent dataset that differs from the dependent dataset in both time and space. The standard deviations of difference resulting from the three applications are 0.59, 0.69, and 0.82 K, respectively. The standard deviations of difference between AVHRR and buoy SST is 0.61 K. This can be due to both the more precise signal received by the AVHRR instrument and the more sophisticated algorithm used to derive SST.

5. Diurnal variation

GOES SSTs have been routinely generated every 3 h in the vicinity of the continental United States at the Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin—Madison, since May 1997, and over an extended area at NOAA/NESDIS since February 1998. The diurnal changes in the GOES SST are noticeable. As an example, Fig. 10a shows a 3-day composite of the GOES SST around 1200 UTC (early morning in local time), 20–22 May 1998, and Fig. 10b shows the difference 8 h later. The magnitude of the difference and the spatial distribution of the SST diurnal variation are remarkable. They correspond closely to the surface wind in the area and for the time period, as depicted by Fig. 10c. Variations as large as 3 K are often found near...
Fig. 11. Ascending node equatorial crossing times for NOAA polar orbiting satellites NOAA-6 to NOAA-12 as of the end of 1993 (Bates et al. 1996). The equatorial crossing time for NOAA-11, for example, drifted from 1345 LST in early 1989 to 1630 LST five years later. This could introduce a cooling trend in SST over the years if SST typically cools down from afternoon to evening.

6. Conclusions

The new Geostationary Operational Environmental Satellites (GOES-8/9/10) are capable of producing sea surface temperatures over most of the Western Hemisphere nearly continuously. The spatial resolu-
tion of the current GOES imager (4 km) represents a great improvement over the previous generation of GOES (16 km) but is still not quite as high as those of the polar orbiting platforms (up to 1 km). The noise level for the GOES imager (0.2 K) is slightly higher than that for instruments on polar systems (typically 0.1 K), and the current GOES SST atmospheric correction scheme is not as sophisticated as other SST algorithms. All these factors lead to a GOES SST accuracy of about 0.7 K. Although this accuracy falls somewhat short of the performance from the polar orbiting platforms (0.6 K), GOES has a unique advantage of high sampling frequency. For SST determinations, the frequent sampling by GOES makes possible a more complete map of SST as clouds move through a given area. Cloud detection is enhanced by noting that a change in scene temperature over a short period of time may indicate the presence of clouds. The abundance of GOES observations helps to maintain a balance between high quality cloud-free observations without sacrificing good geographical coverage of SST estimates.

For the first time GOES enables quantification of the diurnal variation of a radiometrically determined SST over large areas and long periods of time. SST diurnal variation may have important implications in both numerical weather prediction and climate monitoring. An algorithm to derive SST from GOES measurements has been implemented at NOAA/NESDIS since December 1998; the derived SST covers much of the Western Hemisphere (Fig. 12). The GOES SSTs, particularly with their capability of identifying SST diurnal variations, are invaluable assets for monitoring and understanding the earth’s environment. Careful analysis of GOES SSTs will greatly enrich our knowledge about SSTs and their application in geoscience.

Acknowledgments. This research is supported by NOAA Grant NA67 EC0100. Figure 10c was produced under NASA Contract NASW-5038.

References


Walton, C. C., W. G. Pichel, J. F. Sapper, and D. A. May, 1998: The development and operational application of nonlinear al-
Second Edition

This quintessential publication in the field of hydrology contains nearly 1800 terms in English, French, Russian, and Spanish, with their definitions, alphabetical indexes, and the Universal Decimal Classification for hydrology. While the title of the publication remains the same as that of the first edition published in 1974, the content has been expanded to include new and scientific developments, such as the greater use of remote sensing. Although its emphasis remains on surface water and groundwater hydrology, this new edition reflects the broader scope of WMO's and UNESCO's programs in hydrology and water resources.

1992: softbound, 413 pp, $67, includes shipping and handling. Please send prepaid orders to: WMO Publications Center, American Meteorological Society, 45 Beacon Street, Boston, MA 02108-3693. (Orders from U.S. and Canada only).

