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COMPARATIVE PERFORMANCE OF AVHRR-BASED MULTICHANNEL SEA SURFACE TEMPERATURES

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Abstract. A brief outline of the basic concepts of cloud filtering and atmospheric attenuation corrections used in the Multi-channel Sea Surface Temperature (MCSST) method is given. The operational MCSST procedures and products are described in detail. The comparative performance of AVHRR-based MCSST's is discussed via the use of the results of the JPL Satellite-Derived Sea Surface Temperature workshops. For the four data periods there is surprisingly good correspondence in the sign and location of the major monthly mean SST anomaly features derived from MCSST's and those from a screened set of ship-based SST's. With the partial exception of the one data period severely affected in some areas by volcanic aerosol from El Chichon eruptions, global statistical measures of the MCSST anomalies relative to the the ship data are as follows: biases, 0.3-0.4°C (MCSST lower than ship); standard deviations, 0.5-0.6°C; and cross-correlations, +0.3 to +0.7. A refined technique in use with NOAA 9 data in 1985 has yielded consistent biases and rms differences near -0.1°C and 0.5°C, respectively.

1. Introduction

An important part of the influence of the oceans on the atmosphere is through direct radiation and through release of latent heat of evaporation, and both of these processes are directly related to the surface temperature of the ocean. The temperature of the uppermost layer of the ocean determines the heat content there and affects its biological activity, and observed large-scale and persistent anomalies in sea surface temperatures are of great interest in climate monitoring and research. Sea surface temperatures from ships, most of which use the "intake method" of temperature measurement, have long had the reputation of variable quality and usually a positive bias of several tenths of a degree [World Meteorological Organization (WMO), 1972]. Furthermore, for purposes of synoptic, large-scale, or climate studies large areas of the earth's oceans are sampled poorly or not at all, even on a monthly basis.

Polar-orbiting satellites provide the kind of spatial and temporal coverage desired for such investigations. A recent planning document [Joint Oceanographic Institutions, Satellite Planning Committee (JOI/SPC), 1984] tabulates a number of recent national (mostly National Research Council) and international (e.g., International Council of Scientific Unions/Intergovernmental Oceanographic Commission (ICSU/IOC) and WMO/World Climate Research Program (WCRP)) reports identifying needs for satellite measurements in oceanography, including sea surface temperature. Two recent reviews also discuss satellite SST observational requirements for global climate research [Woods, 1983; Harries et al., 1983]. Accuracy goals stated in these various documents range from a desired level of 0.2-0.3°C to an acceptable (usable) level of <0.5°C, generally referenced to monthly means in areas 200-300 km on a side, for climate or other large-scale processes. This article, after outlining the history of sea surface temperatures obtained from NOAA operational polar satellites, briefly discusses the conceptual basis for cloud filtering and atmospheric attenuation corrections using measurements from the advanced very high resolution radiometer (AVHRR). This is followed by a description of operational multichannel sea surface temperature (MCSST) procedures and products. The comparative performance of AHHRR-based MCSST's relative to SST's based on other satellite-borne sensors, and with respect to common sets of in situ SST observations, is covered in the section on the Jet Propulsion Laboratory (JPL) workshop results. Limitations of infrared-based methods such as the AVHRR/MCSST are discussed in the concluding section.

2. History

NOAA has been providing global estimates of sea surface temperature since 1970 with first the Improved TIROS Operational Satellite (ITOS) series and more recently with the TIROS-N generation of operational polar satellites. Before 1973, only one window channel was available on the scanning radiometer (SR) for making these estimates [Schwalb, 1972]. Histogram procedures were developed both for cloud detection and for reducing instrumental noise. Only crude empirical estimates of water vapor could be obtained with this single channel. After the launch of NOAA 2 in the ITOS series in late 1972, satellite sounder data became available from the vertical temperature profile radiometer (VTPR), from which atmospheric temperature and humidity profiles were calculated [McMillin et al., 1973]. Between 1973 and 1976 the atmospheric attenuation in the relatively high-resolution SR window channel was computed from these VTPR profiles [Brower et al., 1976]. However, because the VTPR data were dependent upon the derived sea surface temperature and vice versa (i.e., a feedback mechanism existed) and because the resolution of the profile data (400 km) was much lower than that of the SST data (100 km), the resulting values of the latter exhibited considerable variability in accuracy, particularly in the tropics.

Consequently, in mid-1976 an alternate SST algorithm independent of the derived atmospheric profile data was implemented. This new algorithm

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combined single field-of-view measurements in several of the VTPR channels with coincident SR window data in a regression procedure [Walton et al., 1976]. The new SR/VTPR procedure continued until shortly after the launch of TIROS-N in late 1978, when a similar AVHRR/HIRS (high resolution infrared sounder) technique was implemented. The SST retrievals from this and the other operational algorithms just discussed go by the collective acronym of GOSSTCOMP (global operational sea surface temperature computation). The AVHRR/HIRS technique provided a significant improvement in the accuracy of satellite-derived SST's, but this is the subject of a separate article (C. C. Walton, unpublished manuscript, 1985).

It was not until after the launch of NOAA 7, the third in the TIROS N generation and the first to carry a five-channel, three-window AVHRR, that the multi-channel sea surface temperature (MCSST) method became operational [McClain et al., 1983]. The MCSST procedure has several advantages over the AVHRR/HIRS one: (1) an increase in resolution of the derived SST's from 50 km to 8 km; (2) better corrections for atmospheric attenuation by use of multiwindow measurements; and (3) better cloud detection during the day by day use of the visible-band or reflected-IR data.

The AVHRR provides high-quality digital measurements that have a basic spatial resolution of 1.1 km at nadir in the visible (0.58-0.68 μm) and reflected-infrared (0.725-1.1 μm) bands and in two or three emitted-IR "window" channels (3.55-3.93, 10.3-11.3, and 11.5-12.5 μm). TIROS N, NOAA 6, and NOAA 8 carried AVHRR's equipped with the first two window channels listed, whereas NOAA 7 and NOAA 9 have AVHRR's with all three. The full-resolution measurements are available locally by direct readout (high resolution picture transmission, HRPT) and by means of limited temporary onboard tape storage (local area coverage, LAC). Global area coverage (GAC) data is provided twice daily at a nominal resolution of 4 km (four of every five samples along the scan line are used to compute one average value, and the data from only every third scan line are processed) by means of on-board data reduction and tape recording. There is provision for on-board calibration of the emitted-IR channels.

The noise level has been exceptionally low, <0.1K in the 11- and 12-μm channels. The 3.7-μm window data, however, tend to have an acceptable noise figure ($\leq$0.2 K) during the first 12 months or so after each satellite launch, but then become increasingly contaminated by electrical interference thereafter. Fortunately a so-called "outgassing" procedure was implemented in 1983, and it successfully reduced the complex but coherent noise in the 3.7-μm data to levels comparable to those measured immediately after launch. More recent experience indicates that outgassing must probably be repeated every 6-12 months to control this problem. Details of the AVHRR and HIRS and their calibration are found in Schwalb [1978] and in Lauritson et al. [1979].

3. Basic Concepts of Cloud Filtering

Various combinations of the AVHRR visible and infrared channels are used to detect the presence of clouds in small arrays (e.g., 2 x 2 to 4 x 4) of AVHRR full-resolution or GAC-type data. Only cloudfree data arrays are processed for MCSST's. The various cloud tests can be grouped into three classes:

Visible or IR reflectance tests. The bidirectional reflectance of the cloudfree ocean as measured at a satellite is generally less than 10%, whereas the reflectance of most clouds is greater than 50%. Thus thresholds can be established for the maximum expected AHHRR-measured reflectance in the absence of clouds. These thresholds are a function of solar zenith angle, satellite zenith angle, and the azimuthal angle of the viewed spot. No attempt is made to process SST's in regions of direct specular reflection (glitter) where the ocean reflectance can approach or exceed cloud reflectances.

Uniformity tests. Thresholds of the expected variation of measurement values from adjacent cloudfree fields of view, in either visible-band or infrared channels, are set to be slightly in excess of instrumental noise. With partially cloud-filled fields of view, the variations are generally larger than these thresholds. This test is particularly useful at night, as the instrumental noise in the 11-μm or 12-μm channels is extremely small ($NE\Delta T \leq 0.1$°C), and visible-band data cannot be employed.

Channel intercomparison tests. At night under cloudfree conditions, two or more independent measures of sea surface temperature can be obtained from the three AVHRR window channels with equations of the form $SST = A + B(T_i - T_j) + T_i$. Equating two such equations, one finds the ratio $(T_{3.7} - T_{11})/(T_{11} - T_{12})$ is invariant to changes in atmospheric conditions. Under cloudy conditions, however, this constancy does not apply. With transmissive or subresolution clouds, a measured channel blackbody radiance is a combination of the radiance of the cold cloud and the warmer sea surface. Because the radiance is more sensitive to temperature at 3.7 μm than at 11 or 12 μm, the indicated ratio will increase under these conditions. With thick nontransmissive clouds this radiance effect does not occur; but because the emissivity of such clouds at 3.7 μm is less than at 11 or 12 μm [Hunt, 1973], the ratio will decrease in value. This characteristic is crucial for detecting low-level stratus clouds at night with AVHRR data. Such clouds often have extremely uniform cloud-top temperatures; thus the IR uniformity tests will not detect them.

4. Correcting for Atmospheric Attenuation

The theoretical basis of multiple-window SST techniques was recently reviewed by McMillin and Crosby [1984]. In any spectral interval, thermal radiation emitted by the sea surface is absorbed by atmospheric constituents and reemitted at all levels in the atmosphere. The radiative transfer equation, which describes this process, can be simplified with the mean value theorem of calculus to the form

$$I_i = B_i(T_s)\tau_i + B_i(\overline{T}_i)(1 - \tau_i) \qquad (1)$$

where $\overline{T}_i$ is the radiance at the top of the atmosphere, B(T) is the Planck function at temperature T, and τ_i is the transmittance of the atmosphere. Generally $\overline{T}_i$, which is the atmospheric temperature at some level, will be a function of the spectral interval (i.e., the mean atmosphere altitude varies). The AVHRR on NOAA 7 includes three infrared window channels centered at 3.7 µm, 11 µm, and 12 µm. The atmospheric absorption in these channels occurs primarily at very low levels in the atmosphere. As a result one may assume that the mean atmospheric temperature $\bar{T}$ is the same in these channels [McMillin and Crosby, 1984]. Another result is the that $\bar{T}$ is nearly equal to T_s, the sea surface temperature. Furthermore, atmospheric absorption in these window channels is primarily by water vapor, and the transmittance can be approximated as $\tau_i = e^{-kX} = 1 - k_i X$, where k_i is the absorption coefficient and X is a function of the water vapor amount. With these approximations a Taylor series expansion of (1) in terms of temperature yields

$$T_i - T_s = k_i X(\bar{T} - T_s), \qquad (2)$$

where T_i is the brightness temperature corresponding to I_i. Combining this result at two

$$T_s - T_i = [k_i/(k_j - k_i)](T_i - T_j). \qquad (3)$$

This equation states that the temperature deficit in one channel, T_s-T_i, which results from atmospheric absorption by water vapor, is a linear function of the brightness temperature difference of the two different window channels [see Bernstein, 1982; Barton, 1983].

In actual practice a geographically and seasonally diverse set of actual vertical temperature/humidity profiles from marine atmospheres was used as input to atmospheric transmittance models [Weinreb and Hill, 1980] to generate sets of simulated satellite brightness temperatures corresponding to the band-pass filters of the AVHRR window channels. By regressing (T_s - T_i) against (T_i - T_j) for the several combinations of window channels, synthetic MCSST equations of the form $T_s = T_i + C_1(T_i - T_j) + C_2$, where the C's are constants, were generated. These simulation equations were found to have very small standard errors of prediction, but when used with real data, a significant temperature-dependent bias was found [McClain, 1981]. An effective means of removing this is to use a set of closely matched buoy and satellite measurements, predict the buoy temperature with the simulation equation, then regress the predicted buoy temperature against the measured one to obtain a temperature-dependent bias correction [Strong and McClain, 1984].

Measured radiances in the several window channels decrease with higher values of precipitable water vapor or larger satellite zenith angles (Θ), the brightness temperatures being decreased the most in the least transmissive window. From simulations, which were corroborated in practice, the multichannel equations derived for $\Theta = 0$ give give results for Θ's to about 40°. After experimentation and testing, added terms of the form (sec Θ - 1) and/or (sec Θ - 1) (T_i - T_j) gave the best results for $40° < \Theta < 53°$ when using the nighttime MCSST equations involving the 3.7-µm measurements. The daytime MCSST equation, which uses the 11- and 12-µm measurements (split-window), was found to work well at the larger Θ's with no added terms.

5. Operational MCSST Procedures

Overview of Product Processing

The generation of operational MCSST products is a four step process. First, the raw satellite data are organized into a sensor-level data set containing remotely sensed, earth-view data along with enough information to earth locate and calibrate these data. Next, the earth-view data are processed into measurements of MCSST called "observations." These observations are then analyzed to form MCSST fields. Finally, output products are produced from the observations and fields.

Creation of sensor-level data set. The recorded AVHRR/GAC data are transmitted to the earth each time the satellite passes near a satellite data processing facility of NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) in Suitland, Maryland. Initial ground data processing results in a sensor-level data set called the 1b data set, which consists of the raw sensor data organized as one scan line per record with quality control information, calibration coefficients for each channel, and earth positions for selected data spots appended to each scan line.

Calculation of MCSST observations. The AVHRR GAC 1b data are processed with the MCSST computer algorithms to produce MCSST observations of 8-km resolution. Every 6 hours, all MCSST observations are placed in a user-accessible, geographically organized data base. The MCSST algorithms presented in this section were those in operational use on October 1, 1984. They differ from those in operational use during the three JPL SST workshop data periods [NASA/JPL, 1983] in just two respects: (1) the coefficients of (6) through (9) were updated on September 14, 1982, on the basis of a larger and more seasonally and geographically representative set of close matchups between satellite data and drifting buoy observations [Strong and McClain, 1984]; and (2) in order to eliminate gaps in coverage at low latitudes, the range of Θ used for daytime retrievals was increased from 45° to 53° on March 28, 1984. This latter change for processing of the nighttime MCSST's has been delayed because of lack of resources for adequate testing of the added terms in the MCSST equations (see section 4).

Field analysis. A number of automated, objectively analyzed MCSST fields are produced from the observation data base. These fields have grid points at latitude-longitude intersections, with MCSST and other information (e.g., temperature gradient, climatological temperature, and distance to land) at each grid point.

Product production. Output products, such as isotherm contour charts, archive tapes, and teletype transmisisons on the Global Telecommunications System, are produced regularly from the observation data base and field files.

Orbital Data Preprocessing

As the first step in production of MCSST's the GAC 1b data are organized into "targets" with a nominal spacing of 25 km; these targets are processed one at a time by the MCSST algorithms. A target consists of five 11 x 11 arrays, one corresponding to each of the five instrument channels. The quality flags (such as time or frame synchronization errors and missing or incorrect calibration coefficients) for every scan line in the target are checked, and failure to pass any check on even one scan line is sufficient cause to reject the entire target. Targets completely over land are also discarded. Preprocessing then concludes with selection of the proper processing algorithm. The daytime algorithm is used for targets with solar zenith angles (SZA) <75°, and the nighttime algorithm is used for targets with SZA >90°. When a target has an SZA between 75° and 90°, the nighttime algorithm is used if the reflectance in the 0.9-µm channel is <1.0%; otherwise, the target is not processed.

Nighttime MCSST Algorithm

The following algorithm is used with nighttime AVHRR/GAC data:

1. Satellite zenith angle test. A nighttime target is processed if its satellite zenith angle is less than 45°.

2. Thermal-IR gross cloud test. At least 30 of the 121 target array elements of 11-µm brightness temperature must be >-5.0°C.

3. Low-resolution land/sea test. If any element of the target is within 50 km of land, the target is rejected. Because only one observation is made from each target passing all the tests, the high-resolution (5 km) land/sea tags are not used.

4. Unit array selection. The warmest element of the 11-µm channel target array is located. Four 2 x 2 element subarrays containing the warmest element are then constructed; these are called "unit arrays." If electronic interference or other "noise" becomes significant, the unit array size can be increased to 3 x 3 or 4 x 4. The next four tests are performed on the four unit arrays until one passes all tests. This selection process can yield, at most, one MCSST observation per target, cloud conditions permitting, and thus a nominal observational spacing of 25 km.

5. Thermal-IR uniformity test. All four 11-µm elements of the unit array must agree within 0.2°K (see section 3).

6. Average unit array values. An average of the four unit array elements is calculated for each of the five AVHRR channels. These averages are used in the succeeding cloud tests.

7. Thermal-IR cloud tests. To determine if the three window channels have the interchannel relationships expected in cloud-free conditions, one channel brightness temperature is predicted from a second and then compared with the actual brightness temperature measured in the first channel. There are two tests of this kind:

$$\hat{T}_{3.7} = -25.09 + 1.0916T_{11}$$

$$|\hat{T}_{3.7} - T_{3.7}| < 3°K \qquad (4)$$

$$\hat{T}_{11} = -11.49 + 1.0439T_{12}$$

$$|\hat{T}_{11} - T_{11}| < 1°K \qquad (5)$$

where $T_{3.7}$, T_{11}, and T_{12} are the measured brightness temperatures from the AVHRR; $\hat{T}_{3.7}$ and $\hat{T}_{11}$ are the predicted values (all in degrees Kelvin); and the coefficients were determined by regression using cloudfree data sets.

8. Uniform low stratus test. One final IR channel relationship is used to detect uniform low stratus clouds at night, a type of cloud condition that can often pass the previous cloud tests. The temperature difference between the 11- and 3.7-µm channels must be less than 0.7°K. One of two versions of this test is used. In the first the unit array averages are used, whereas the second employs averages calculated from all 121 target elements. The later version, however, employs a reduced threshold of 0.4°K and is used only when the 3.7-µm channel data are suffering excessive electronic interference.

9. SST calculation. Three separate estimates of MCSST are calculated, as follows:

$$SST_1 = 1.5018T_{3.7} - 0.4930T_{11} - 273.34 \qquad (6)$$

$$SST_2 = 3.6139T_{11} - 2.5789T_{12} - 283.18 \qquad (7)$$

$$SST_3 = 1.0170T_{11} + 0.9694(T_{3.7} - T_{12}) - 276.58 \qquad (8)$$

where $T_{3.7}$, T_{11}, and T_{12} are the brightness temmeasured (in degrees Kelvin) by the AVHRR on the NOAA 7 operational spacecraft; and SST_1, SST_2, and SST_3 are the dual-window, split-window, and triple-window MCSSTs, respectively, in degrees Celsius.

10. SST intercomparison test. The three values of MCSST obtained in step 9 must agree within 1.0°C.

11. Unreasonable SST test. SST_3 is selected for the operational MCSST (except when the 3.7-µm data are too noisy and SST_2 is used instead), and it must fall between -2.0°C and 35.0°C.

12. Climatology test. The operational MCSST must not differ from the monthly climatological value for its location by more than 7.0°C.

13. MCSST output. As the final step the operational MCSST is stored for later incorporation into the observation data base. Stored with it are earth location, time, satellite, algorithm identification, solar and satellite zenith angles, channel brightness temperature or reflectances for all five AVHRR channels, and space-view noise level.

See Table 1 for representative statistics on the failure pattern of the nighttime test sequence for a particular date. It is seen that the thermal-IR uniformity test is the most powerful one for cloud filtering and that the climatology test is needed only to remove a very small fraction of those unit arrays that survive all the other tests.

TABLE 1. Nighttime Cloud Tests: Global MCSST Cloud Test Statistics for April 3, 1982

Test	Number Surviving After Each Successive Test	Percentage of Remainder Failing This Test
Gross cloud	111,812	39.7%
High-resolution land/sea tags	111,812	0.0%
IR uniformity	28,999	74.1%
IR cloud	23,991	17.3%
Uniform low stratus	21,396	10.8%
SST intercomparison	18,010	15.8%
Climatology	17,944	0.4%

Total target arrays available after applica- of low-resolution land/sea tags but before tests above: 185,401. Remaining target arrays with MCSST observations after application of all tests (one MCSST per target): 17,944 (9.7% of total above).

Daytime MCSST Algorithm

The following algorithm is used with daytime AVHRR/GAC data:

1. Satellite zenith angle test. Daytime targets are processed only if the satellite zenith angle is less than 53°.

2. Reflected-IR gross cloud test. The reflectance in the 0.9-μm channel must be less than 10.0% for ten or more target elements. The visible-band channel reflectances at 0.6μm may be used alternatively for this test, but ocean reflectances are virtually zero in the reflective-IR band, making this channel preferable for cloud detection. The purpose of this gross cloud test is to eliminate obviously very cloud-contaminated targets early on so as to decrease the data volume to be processed subsequently.

3. High-resolution land/sea test. The daytime algorithm has the option of making observations as near as 5 km to a coastline in selected aeas of the world. Each element of the target is checked, and any element within 5 km of land is flagged and is not used to calculate an MCSST. As the current earth-location accuracy of AVHRR/GAC data is 4-6 km, any element adjacent to a flagged element is also flagged to prevent a land element being misclassified as a sea element. Effectively, then, only those target elements more than 10 km from land are used to calculate MCSST's.

4. Unit array selection. Multiple MCSST observations can be obtained from each daytime target. The number of observations possible from each target depends upon its geographic location and cloud conditions. Along the coasts of the United States and in selected other regions, observations from contiguous 2 x 2 unit arrays are processed in an attempt to obtain an observational spacing of 8 km. The spacing between observations is increased to about 15 km in open ocean areas adjacent to the U.S. coasts and further increased to about 25 km elsewhere.

5. Reflected-IR uniformity test. All four 0.9-μm channel elements in a unit array must agree to within 0.32% reflectance (see section 3).

6. Reflected-IR cloud threshold. Empirical tables of bidirectional reflectance (for class widths of 5° in SZA, 5° in satellite zenith angle, and 10° in solar/satellite azimuth angle) were generated by building up frequency distributions using many orbital passes of AVHRR reflectance data. For each combination of angles a threshold has been chosen such that the reflectance of a cloudy data element in the 0.9-μm channel will be greater than the threshold. The unit array element of greatest reflectance must be less than the value in the table before a MCSST will be calulated from that unit array.

7. Average unit array elements. An arithmetic mean of the four unit array elements is calculated for each channel and used in the succeeding steps.

8. Calculate MCSST. The MCSST value is calculated as follows:

$$SST_4 = 1.0346T_{11} + 2.5779(T_{11} - T_{12}) - 283.21 \qquad (9)$$

where T_{11} and T_{12} are in degrees Kelvin and SST_4 is in degrees Celsius.

9. Unreasonable MCSST test. The calculated MCSST must be greater than -2.0°C and less than 35°C.

10. Climatology test. The MCSST must not differ from the monthly climatological value at its location by more than 7.0°C.

11. Alternate algorithm mode. If more than one MCSST is to be made from a target, then the algorithm returns to step 4 to find another unit array. If no MCSST's are obtained from a target by the normal daytime algorithm, an MCSST will be attempted by using an alternate algorithm (this was implemented on August 11, 1983). This alternate uses a relaxed reflected-IR cloud threshold test (namely, table values are increased by a factor of 1.5) because the original data set used to establish the tables only included reflectance data from part of the year, and some angle combinations were not sampled adequately. Tests of the relaxed thresholds showed a substantial increase in the number of daytime MCSSTs with no decrease in quality. For those unit arrays passing this relaxed test the alternate daytime algorithm uses the following steps from the nighttime algorithm: unit array selection, thermal-IR uniformity test, and climatology test.

12. MCSST output. All MCSST's made from the target are stored for incorporation in the observation data base.

See Table 2 for representative statistics on the failure pattern of the daytime test sequence on a particular date. It is seen that the reflected-IR uniformity and cloud threshold tests are responsible for removing most of the cloud-contaminated unit arrays.

TABLE 2. Daytime Cloud Tests: Global MCSST Cloud Test Statistics for April 23, 1982

Test	Number Surviving After Each Successive Test	Percentage of Remainder Failing This Test
Gross cloud	1,116,879	23.7%
High-resolution land/sea tags	1,116,879	0.0%
Reflected-IR uniformity	239,982	78.5%
Reflected-IR Cloud threshold	23,355	89.4%
Unreasonable SST	22,179	12.5%

Total unit arrays available after application of low-resolution land/sea tags but before tests above: 1,464,715. Remaining unit arrays with MCSST observations after application of all tests: 22,179 (1.5% of total above).

Field Analysis

In order to produce graphical representations of the SST patterns, the MCSST observations are analyzed objectively to form fields with SST's at regular grid points. The same basic analysis techniue is used at all grid scales (1/8, 1/2, and 1 degree latitude/longitude spacing) and for both compositing intervals (24 hours or 7 days); however, some variations in the search area calculation and weight assignment are necessary. The analysis algorithm is essentially a weighted-average procedure. Grid points are updated, one by one, in the following manner:

1. Define the search area. First, the latitude and longitude boundaries are defined for a rectangular search area enclosing the grid point. The distance between the grid point and boundary of the search area in any cardinal direction varies as a function of the SST gradient in that direction. The higher the gradient, the smaller that dimension of the search area.

2. Obtain MCSST observations. All MCSSTs placed in the observation data base since the last analysis and falling within the search area are selected.

3. Calculate observation weights. Each selected MCSST observation is given a weight that varies inversely with the square of the distance between the observation and the grid point.

4. Average observations. The weighted average of all the MCSST observations in the search area is calculated.

5. Update grid point temperature. The grid point MCSST calculated in the previous field analysis is then replaced with a weighted average of it and the result of step 4. If the sum of the weights of the new observation is higher than the grid point weight assigned during the previous analysis, the previous grid point temperature is given a weight of zero. If no new observations are obtained within the search area, the previous grid point temperature is retained and its weight is halved for purposes of the next updating.

6. Produce contoured fields. Computer-drawn isotherms at a 1°C interval are derived from the the satellite MCSST observations for the seven days prior to the chart date. Dashed isotherms indicate regions in which there were no new observations during the analysis period.

Operational Products

Part 4 of Dismachek et al. [1980] details and gives examples of most of the current NOAA automated operational oceanographic products derived from satellite data. Discussed briefly below are three types of operational MCSST products:

MCSST observations. All observations are stored on disk in a geographic data base for 8 days, where they can be directly accessed by on-line terminal users. One MCSST observation from each 2.5° degree latitude/longitude grid area is sent out twice daily on the Global Telecommunications Systems (GTS). A map of observation locations is displayed daily on film to enable monitoring of observational coverage. Once a week the observations are archived to computer-compatible tape.

Monthly means. MCSST observations are accumulated monthly in 2.5° degree latitude/longitude bins from 70S to 70N. At the end of each month, arithmetic means are calculated for each bin, along with the number of observations and their standard deviation. These monthly mean MCSST's are made available on disk, displayed as isotherms on Mercator charts, and archived to tape.

Analyzed fields. Three scales of analyzed fields are produced:

Global MCSST analysis: This daily analysis covers the world from 70°S to 70°N by using a 1° latitude/longitude grid. On-line terminal users can display sectors of this field at any time. A gray-scale photographic display of the global field is produced daily for monitoring purposes. The basic global display product, however, is a hard-copy Mercator chart produced weekly with isotherms at a 1°C interval (An example can be found in NASA/JPL [1984], part 2, p. 6). The daily global fields are archived to tape twice a month.

Regional MCSST analyses: Weekly composite field analyses are generated on a ½° latitude/longitude grid for five regions: Western North Atlantic, Eastern North Pacific, Hawaii to Alaska, Eastern Equatorial Pacific, and Central Equatorial Pacific. The two equatorial fields are experimental but the other three are operational. Products available from the regional analyses are similar to those for the global analysis [examples can be found in Legeckis et al., 1983].

Local MCSST analyses: Four high-resolution automated analyses are produced weekly on a grid spacing of 1/8°. These analyses, which are experimental, cover the conterminous U.S. coast. The fields on disk are accessible to terminal users, and an isotherm chart of each field at a 1°C interval is produced weekly.

6. JPL SST Workshop Results

Introduction

A series of three Satellite-derived Sea Surface Temperature workshops was held at the Jet Propulsion Laboratory (JPL) between January 1983 and February 1984 [Njoku, 1985]. The SST measurements provided by four space-based sensor systems and their associated retrieval algorithms were compared with one another and with common sets of in situ SST measurements for up to four month-long data periods. The sensor/techniques involved were the scanning multi-channel microwave radiometer (SMMR); the AVHRR; the high resolution infrared sounder/microwave sounding unit (HIRS/MSU); and the visible-infrared spin-scan radiometer (VISSR) atmospheric sounder (VAS) [see NASA/JPL, 1983, appendices A and C through E]. The emphasis of the comparisons was on large-scale (global) quantitative SST measurements with a spatial and temporal resolution of 2 x 2 degrees latitude/longitude and 1 month, respectively. The workshops generated two reports [NASA/JPL, 1983, 1984] and a final report is in the process of publication [NASA/JPL, 1985]. These reports contain details of how the various data sets were processed and then graphically and statistically displayed for evaluation utilizing the Pilot Ocean Data System (PODS) at JPL. It must suffice to state here that a common climatology [Reynolds, 1982] was subtracted from all the monthly mean values (global monthly mean MCSST charts for November 1979, December 1981, and March 1982 can be found in section 1 and appendix C, respectively, of JPL SST workshop 1 [NASA/JPL, 1983] to remove the dominating effect of the strong meridional temperature gradient from equator to poles, and thus all comparisons are with respect to "anomalies," the delineation of which is considered quite important for climate studies. The "Pazan" ship data refers to the set of engine intake temperatures from ships of opportunity that were screened for questionable observations by a special editing method [see NASA/JPL, 1983, section 4; NASA/JPL, 1984, section 2].

In comparison with in situ sensors, particularly those on ships of opportunity, the AVHRR with its nearly continuous on-board calibration generates an internally uniform set of brightness temperature measurements orbit after orbit, day after day. Except for quite unusual circumstances, such as the El Chichon eruptions and the electrical interference problems that have plagued the 3.7-μm data during certain periods (discussed in next section), the operationally derived MCSST's generally comprise a spatially and temporally consistent data base. The few changes that have been made in the operational algorithms have affected the root mean square (rms) differences with respect to drifting buoy temperatures only at the $\leq$0.25C level. Recent drifting buoy spot comparisons over a wide range of temperatures, geographic area, and seasons consistently indicate biases of $\leq$0.1C and rms differences (or scatter) of 0.5°-0.6°C [Strong and McClain, 1984]. Comparisons with screened ship observations, after removal of the common ship-based climatology to derive anomalies, are summarized for the various periods, along with the statistics for the other sensors studied during the several JPL SST workshops, in Table 3.

Table 3 gives the various statistics for each sensor with respect to ship matchups more than 600 km from any land or ice surface. The use of a 600 km mask is necessary in order to equalize the coverage for the AVHRR, HIRS/MSU, and VAS, which can obtain observations near coastlines or ice edges, with those available for the SMMR, which cannot make valid measurements for this purpose unless it is at least 600 km offshore. Furthermore, it should be noted that the "global" statistics include no measurements from the SMMR over the North Atlantic in November 1979 and that VAS coverage is limited to two relatively small areas in March and July of 1982: one about 25° latitude by 30° longitude in the southwestern North Atlantic and the other about 40°latitude by 40° longitude in the extreme northeastern South Pacific.

Table 3 also enables comparison of sensor statistics for ship matchups >600 km from land or ice and those for the same matchups after a 3 x 3 center-weighted smoother is applied. This procedure was used on all available 2° bins >600 km from land or ice. A sharp drop in sample size resulted from application of the smoother, and this was a particularly acute problem in the case of the FGGE buoy set; e.g., the unsmoothed global data set of 400 for the AVHRR matchups was reduced to a sample of one for the smoothed set. The effect of the smoother on the bias is mixed at best, but there is definite (often dramatic) improvement in the scatter (i.e., standard deviation) and cross correlation statistics in nearly every case for every sensor. It is not clear, however, how much of the improvement derives from greater smoothing of the ship observations, whose uneven quality was noted earlier, and how much from the loss of independence that results from the use of overlapping arrays.

Table 4 displays the statistics for AVHRR/ship matchups >600 km from land or ice with various types of in situ data (namely, Pazan ships: >5 and >20 per cell; FGGE buoys; and TRANSPAC XBT's); and Table 5 shows AVHRR/ship matchup statistics separated into day and night. Table 6 enables comparison of two types of in situ observations, namely, Pazan ships and the TRANSPAC XBT's.

Error Characteristics of MCSST's

In addition to the various statistics summarized in Table 3, which all refer to the Pazan set of screened ship data, numerous ship and satellite anomaly fields and associated difference fields were also produced in connection with the workshops. The ship anomaly fields suffer from the traditional lack of observational coverage in the southern hemisphere and some other areas. The TRANSPAC XBT fields are severely constrained by limited geographical coverage. With this in mind, a discussion of each data period follows:

November 1979 data period. This first data period is different from the other three in that no MCSST's were yet available, the NOAA opera-

TABLE 3. Global Statistics for Comparison of Sensor Sea Surface Temperatures with Pazan Screened Ship Temperatures (>5/bin)

	November 1979			December 1981		
	A	S	H	A	S	H
Number of bin matchups	723 (324)	395 (152)	735 (324)	729 (235)	677 (226)	729 (235)
Bias (ship minus satellite)	-0.19 (-0.24)	-0.52 (-0.72)	+0.04 (+0.20)	+0.30 (+0.33)	-0.72 (-0.71)	-0.13 (-0.21)
Standard deviation (scatter)	0.58 (0.35)	1.27 (0.81)	1.01 (0.62)	0.50 (0.28)	1.17 (0.79)	0.88 (0.42)
Cross correlation	0.69 (0.78)	0.34 (0.54)	0.31 (0.41)	0.76 (0.91)	0.21 (0.40)	0.21 (0.45)

	March 1982				July 1982			
	A	S	H	V	A	S	H	V
Number of bin matchups	795 (368)	690 (368)	795 (368)	109 (51)	644 (274)	522 (230)	662 (327)	92 (38)
Bias (ship minus satellite)	+0.36 (+0.44)	+0.21 (+0.17)	-0.30 (-0.29)	-0.90 (-0.91)	+0.48 (+0.35)	+0.43 (+0.69)	+0.07 (-0.09)	-0.48 (-0.55)
Standard deviation (scatter)	0.51 (0.29)	1.11 (0.79)	0.92 (0.41)	0.56 (0.26)	0.79 (0.52)	0.97 (0.60)	0.69 (0.38)	0.46 (0.22)
Cross correlation	0.67 (0.77)	0.24 (0.15)	0.10 (0.40)	0.40 (0.79)	0.62 (0.70)	0.46 (0.55)	0.49 (0.78)	0.49 (0.42)

Values in parentheses are after a 3 x 3 center-weighted smoother was applied: A, AVHRR/MCSST (AVHRR/HIRS GOSSTCOMP in November 1979); S, SMMR; H, HIRS/MSU; V, VAS.

tional products at that time being the AVHRR/HIRS version of the GOSSTCOMP (see section 2). Table 3 indicates that AVHRR biases are comparable to or a bit larger than those for HIRS/MSU but significantly smaller than those for SMMR. AVHRR scatter (correlation) values are much smaller (larger) than for HIRS/MSU and very much smaller (larger) than for SMMR. Table 3 also demonstrates the very substantial improvement in scatter and cross correlation figures for all three sensors that results from the 3 x 3 weighted smoothing procedure. Biases generally worsen somewhat for all sensors when the 3 x 3 smoother is used.

In Table 4 (AVHRR only) there is very little difference in bias from one type of in situ data to another, but scatter values are clearly larger relative to FGGE buoys and a bit larger relative to TRANSPAC XBT's. This was unexpected, as previous studies have found lower bias and scatter relative to buoys than to ships [Strong and McClain, 1984]. Neither the buoys nor the XBT's were given the same kind of extensive screening given the Pazan ships, and an independent study of the FGGE buoy data set for November 1979 for another purpose by a NOAA/NESDIS contractor found that some of the FGGE buoy observations were seriously in error. Cross correlation comparisons are mixed. Scatter and correlation figures improve substantially when the 3 x 3 smoother is used.

December 1981 data period. This was the first full month of operational MCSST processing. As in the November 1979 period, Table 3 indicates that AVHRR biases were comparable to HIRS/MSU ones and significantly smaller than those associated with SMMR, and the AVHRR biases tend to be smaller with the 600 km mask in place. Likewise, scatter magnitudes are much lower for AVHRR than for HIRS/MSU, the latter being significantly lower in turn than for SMMR. Cross correlations are generally comparable for HIRS/MSU and SMMR (0.13-0.33), being much lower than for AVHRR (0.74-0.77). Scatter and cross correlation figures almost always improve substantially when the 3 x 3 smoother is used, but the relative rankings given above still hold.

In Table 4 the bias and cross correlation values are comparable for all the in situ data sets, but scatter is somewhat worse for the

TABLE 4. Global Statistics for Comparison of AVHRR-based SST's with In Situ Temperatures

	November 1979				December 1981		
	P5	P20	F	T	P5	P20	T
Number of bin matchups	723	113	400	457	729	129	286
	(324)	(6)	(1)	(30)	(35)	(2)	(13)
Bias (in situ minus satellite)	0.19	-0.28	-0.24	-0.19	0.30	0.27	+0.30
	(-0.24)	(-0.32)	-	(-0.20)	(+0.33)	-	(+0.63)
Standard deviation (scatter)	0.58	0.50	0.96	0.70	0.50	0.46	0.69
	(0.35)	(0.12)	-	(0.32)	(0.28)	-	(0.33)
Cross correlation	0.69	0.60	0.57	0.72	0.76	0.72	0.73
	(0.78)	(0.87)	-	(0.78)	(0.91)	-	(0.73)

	March 1982			July 1982		
	P5	P20	T	P5	P20	T
Number of bin matchups	795	265	447	644	218	288
	(368)	(23)	(18)	(274)	(7)	(3)
Bias (in situ minus satellite)	+0.36	+0.39	+0.16	+0.48	+0.44	+0.49
	(+0.44)	(+0.60)	(+0.14)	(+0.35)	(+0.45)	(+0.10)
Standard deviation (scatter)	0.51	0.53	0.70	0.79	0.78	1.08
	(0.29)	(0.28)	(0.35)	(0.52)	(0.43)	(0.77)
Cross correlation	0.67	0.64	0.59	0.62	0.71	0.57
	(0.77)	(0.92)	(0.70)	(0.70)	(0.90)	(0.98)

Values in parentheses are after a 3 x 3 center-weighted smoother was applied. P5, Pazan screened ships, >5/bin; P20, Pazan screened ships, >20/bin; F, FGGE buoys; T, TRANSPAC XBT's. November 1979, AVHRR/HIRS GOSSTCOMP; all other months, AVHRR MCSST.

TABLE 5. Global Statistics for Comparison of AVHRR/MCSSTs with Pazan Screened Ship Temperatures (>5/Bin) by Day and by Night

	December 1981		March 1982		July 1982	
	Day	Night	Day	Night	Day	Night
Number of bin matchups	690	729	691	795	374	640
	(232)	(213)	(239)	(368)	(74)	(296)
Bias (ship minus satellite)	+0.32	+0.31	+0.09	+0.49	-0.43	+0.72
	(+0.36)	(+0.83)	(+0.10)	(+0.57)	(-0.79)	(+0.67)
Standard deviation (scatter)	0.57	0.52	0.67	0.46	1.00	0.65
	(0.29	(0.73)	(0.33)	(0.23)	(0.52)	(0.35)
Cross correlation	0.72	0.75	0.56	0.69	0.52	0.70
	(0.89)	(-0.11)	(0.74)	(0.82)	(0.83)	(0.83)

Values in parentheses are after a 3x3 center-weighted smoother was applied.

TABLE 6. Global Statistics for Comparison of Pazan Screened Ship Temperatures (>5/Bin with TRANSPAC XBTs and AVHRR/MCSST's

	Nov 1979		Dec 1981		March 1982		July 1982	
	A	T	A	T	A	T	A	T
Number of bin matchups	723 (324)	232 (29)	729 (235)	158 (8)	795 (368)	242 (18)	644 (274)	154 (2)
Bias (ship minus other)	-0.19 (0.24)	-0.11 (-0.15)	+0.30 (+0.33)	+0.03 (-0.24)	+0.36 (-0.44)	+0.27 (+0.47)	+0.48 (+0.35)	+0.22 (-0.06)
Standard deviation (scatter)	0.58 (0.35)	0.79 (0.34)	0.50 (0.28)	0.84 (0.27)	0.51 (0.29)	0.89 (0.35)	0.79 (0.52)	0.94 (0.28)
Cross correlation	0.69 (0.78)	0.63 (0.68)	0.76 (0.91)	0.63 (0.50)	0.67 (0.77)	0.39 (0.70)	0.62 (0.70)	0.58 (0.99)

Values in parentheses are after a 3 x 3 center-weighted smoother was applied. A, AVHRR; T, TRANSPAC XBTs.

TRANSPAC XBT than the Pazan ships, although even this reverses when the 3 x 3 smoother is used. As before, the 3 x 3 smoother greatly improves the AVHRR/ship comparisons of scatter and cross correlation but generally worsens the biases somewhat.

March 1982 data period. This is the last full month of operational MCSST's prior to the eruption of El Chichon and about the beginning of the period when the 3.7-μm noise level began to climb significantly. The statistics in Table 3 indicate generally lower biases for the AVHRR than for the HIRS/MSU, SMMR, or VAS. The AVHRR scatter values are superior to those of the other sensors, particularly when the 3 x 3 smoother is used. The AVHRR cross correlation values are comparable with those of VAS and substantially higher than those for HIRS/MSU and SMMR; and as with previous periods, those correlations associated with the 3 x 3 smoothing are higher.

Table 4 shows that the AVHRR has somewhat lower bias values for TRANSPAC XBT's than for Pazan ships, and again has about comparable cross correlations and higher scatter values relative to the TRANSPAC XBT's.

July 1982 data period. By this month the El Chichon volcanic aerosol cloud had girdled the earth several times, but generally had remained just north of the equator, and this severely reduced the numbers of daytime AVHRR retrievals in the region of the aerosol cloud. Nighttime MCSST observations in that same zone exhibit large positive biases (AVHRR lower than in situ data because of aerosol attenuation in the high stratosphere). Chief effects of the increased 3.7-μm noise level on the nighttime MCSST's are reduced observational densities and somewhat higher scatter, the latter from occasional erroneous passing of the uniform low stratus test. Table 3 reflects this in the large positive AVHRR bias values. AVHRR scatter is adversely affected also, making it higher than the VAS, comparable to the HIRS/MSU, but still rather lower than the SMMR. AVHRR cross correlations are poorer than in the previous periods but still comparable with or even better than for the other sensors.

Table 4 shows AVHRR statistics are comparable relative to all the in situ data and that all statistical measures are generally worse than for the previous months studied. As with the other periods, scatter and cross-correlation statistics are significantly improved by the 3 x 3 smoothing scheme, whereas the effects of the smoother on the biasing is mixed.

Diurnal variations. Table 5 summarizes the AVHRR/ship comparisons for the three MCSST data periods when both day and night statistics are available. Excluding for the moment the month of July 1982 in which El Chichon had a strong influence that differed by day and night, there appears a systematic diurnal difference in the bias in the March period of 1982, larger positive (ship SST higher than MCSST) at night than in the daytime, that is not evident in December 1981. Standard deviations are somewhat lower and cross correlations somewhat higher at night for all data periods. Both these statistics generally improve substantially when the 3 x 3 weighted smoother is used. The rather drastic change from a moderate to a large negative bias in the daytime to an even larger positive bias at night during July 1982 reflects the impact of El Chichon. Monitoring of drifting buoy/MCSST matchups during the first half of 1982 also detected a nighttime positive bias of about 0.4°C in the NOAA operational product. This bias was effectively removed after mid September 1982 by re-derivation of the temperature-dependent bias correction (see first portion of section 5).

It helps to put the foregoing discussion of the AVHRR/MCSST matchup comparisons with the Pazan ship and TRANSPAC XBT data sets into better perspective if one looks at the statistics for the matchups between the Pazan screened ship observations and the TRANSPAC XBT measurements (see Table 6). The biases associated with the TRANSPAC XBT's tend to be 1 to 3/10 of a degree smaller than those found with the AVHRR, but the standard deviations (cross correlations) of the

AVHRR are consistently and significantly smaller (larger) than those of the XBT's. As has been noted previously, the 3 x 3 weighted smoother has variable results on the bias values for both data sets, generally worsening them somewhat while substantially improving both scatter and cross correlation figures. The XBT standard deviations tend to have larger reductions than the AVHRR when the smoother is applied, thus rendering them quite comparable in magnitude. This was particularly the case in the July 1982 data period when the scatter for the XBT's became smaller than for the AVHRR, presumably because of the adverse effects of El Chichon on the MCSST's. The foregoing once again emphasizes the uncertainties in assessing the "true" accuracy of satellite-derived SSTs when the correlative in situ measurements evidently contain significant but unknown errors of their own. It would be desirable to cross compare the Pazan ship, TRANSPAC XBT, and FGGE buoy data sets in this connection, but the number of ship/buoy and XBT/buoy bin matchups are N = 1 and N = 14, respectively.

Regional AVHRR Error Characteristics

When using the global charts of SST anomalies, or anomaly differences between AVHRR and in situ data sources, valid comparisons can be made only in areas where there is an adequate distribution of both types of observatons. Whereas the density of AVHRR-based SST's was generally good to excellent on a worldwide basis (the exception being the November 1979 GOSSTCOMP distribution, which is poor south of 45°S and in parts of the tropical belt, particularly the zone from 90°E to 180°E), the ship SST distribution (for any of the data periods) is of adquate density only in parts of the North Atlantic and North Pacific and in a few narrow, shiptrack-oriented zones elsewhere. The TRANSPAC XBT data coverage is even poorer than that of the ships, being concentrated along a few heavily travelled shipping lanes, and only a few of the 2° bins have >4-6 observations for a given month. The data for the FGGE buoys (available only in November 1979) are all in the southern hemisphere, but they at least provide some spotty coverage in regions rarely visited by ships. As several of the articles in this issue refer to the global anomaly fields discussed in this section, they are presented once in the appendix of the article by Hilland et al. [this issue].

November 1979 data period. There is general agreement between AVHRR/HIRS and ship-derived anomaly patterns, but some differences in amplitude are evident [Hilland et al., this issue, Plate 20b]. General agreement with the anomalies derived from TRANSPAC XBT's and from the FGGE buoys [see NASA/JPL, 1985] is apparent also, although again not on a bin-by-bin basis. Some of the >3.5°C positive anomalies seem suspect, particularly those on the edge of the AVHRR data void in the southern hemisphere. Parts of the South Atlantic area also appear too warm in the AVHRR.

December 1981 data period. The coverage and density of AVHRR/MCSST in this data period is better than it was with the AVHRR/GOSSTCOMP in November 1979, particularly in the central and western North Pacific, central and eastern South Pacific, and in the high latitudes of the southern hemisphere generally. There is still a paucity of observations in the deep tropics of the western Pacific (Indonesia/Micronesia areas). As in the November 1979 period, if one looks at the larger, more coherent anomaly features, there is good general agreement between the satellite-derived pattern and the ship-derived pattern [Hilland et al.,this issue, Plate 3a, b] although the overall amplitude of the MCSST anomaly field tends to be greater.

The strength of the large positive MCSST anomaly northeast of New Guinea, as well as a weaker one northeast of Madagascar, and a strong ship-based anomaly southeast of the tip of Africa, are all suspect, however.

March 1982 data period. Although MCSST data densities during this period are poorer in the northern and eastern North Pacific than in December 1981, they are higher in the Indian, South Atlantic, and Southern oceans. As previously, the Indonesia/Micronesia area is relatively poorly observed. Once again, the larger-scale patterns generally match, but the amplitude of the MCSST maxima are generally somewhat greater than the ship ones [Hilland et al., this issue, Plate 4a, b]. The positive MCSST anomaly in the Indonesia/Micronesia area and westward appears to have no counterpart in the ship-based pattern.

July 1982 data period. The El Chichon aerosol cloud and the increased 3.7-μm noise had a drastic impact on MCSST observational densities. Excellent coverage remains, however, in the central North Atlantic and in the southern hemisphere down to at least 45°S. If one disregards the "El Chichon negative anomaly" stretching around the globe between roughly 5°N and 30°N, there is yet again reasonably good conformance between the MCSST-based and ship-based anomaly fields [Hilland et al., this issue, Plate 5a, b], although the amplitude of the MCSST negative anomaly in the mid North Pacific appears somewhat too large.

Diurnal effects. Global AVHRR day-minus-night charts [see NASA/JPL, 1985] were produced for the December 1981, March 1982, and July 1982 data periods. Although some systematic difference patterns are evident, their interpretation or explanation is hampered because no separate day and night anomaly charts were produced.

A pronounced positive day-minus-night difference of several degrees extends around the earth between about 25° and 40°S in the December 1981 data period. This positive difference appears in a far weaker, more irregular or interrupted form and generally at somewhat lower latitudes of the southern hemisphere in the March 1982 period. It is absent there altogether in July 1982 but appears in similar latitudes of the northern hemisphere that month. This seasonal behavior, probably associated with the northward shift of the most intense solar heating from the southern hemisphere to the northern hemisphere, is consistent with a widespread "diurnal thermocline" developing in the weak wind regimes of the central subtropical anticyclone belts (see section 7).

The other major day-to-night difference that appears during all three periods is a positive one extending westward from the Indonesia area into the central Indian Ocean near the equator. In December 1981 this is clearly related to making too large an atmosphere correction because of a quadratic term in the original split-window MCSST equation used with daytime data. After January 1982, however, a linear form of the split-window equation was in daytime use, so an alternate explanation must be sought for what appeaars to be a persistent overcorrection for very high moisture. When the coefficients of the operational daytime and nightime equations were adjusted in September 1982 (see section 5), one of the results was to diminish this tendency toward a negative daytime and positive nighttime bias in those regions of the tropics that are extremely moist and thus to lessen diurnal differences of the type noted here.

Errors in the AVHRR-based Anomaly Fields

November 1979. The tendency for a positive anomaly rimming the edge of the data at 45-50S [Hilland et al., this issue, Plate 2a] is probably something peculiar to the GOSSTCOMP method, as it does not appear in any of the three MCSST data periods. On the other hand, the rather scattered 2° bins with ship-based anomalies do tend to support the presence of warmer than normal water in that part of the southern Indian Ocean [Hilland et al., this issue, Plate 2a]. The relatively cooler water extending from near the southwest tip of Africa northwestward into the central South Atlantic is supported in the AVHRR/GOSSTCOMP anommaly field only by a tongue of relatively less warm water. This could be a "diurnal thermocline" effect, as this area of the subtropical Atlantic was characterized by anticyclonic conditions with light winds at the surface and low amounts of cloudiness in November 1979. This information was obtained or inferred from charts of monthly mean pressure at sea level (from National Center for Atmospheric Research), monthly mean SMMR wind speeds (NASA/National Space Flight Center (GSFC)), and of monthly mean albedo and outgoing longwave radiation (from NOAA/NESDIS). There is, however, no obvious explanation for the lack (in the GOSSTCOMP) of the strong negative anomaly evident in the ship data to the east of the southern part of South America.

December 1981. The large positive anomaly northeast of New Guinea, and to a lesser extent the weaker ones just northeast of Madagascar and along the northeast coast of Australia, do not appear to be supported by the ship-based anomaly field [Hilland et al., this issue, Plate 3a, b], although ship data are very scarce in the first area mentioned. The Australian case would seem to be a manifestation of the "diurnal thermocline" in the IR-based SST's. This area was under weak mean monthly pressure gradients near sea level (light winds), and there was a mean monthly albedo of ≤20%, indicating very little cloudiness. The New Guinea and Madagascar cases may also have an element of this effect, but the situation there was aggravated by a quadratic term in the daytime split-window MCSST equation in use at that time. This term was found to produce erroneously high MCSST's, but only in areas where atmospheric water vapor was exceedingly large (i.e., precipitable water ≥5 cm), a characteristic of the region extending westward from Micronesia/Indonesia into the central Indian Ocean. Further confirmation of a moisture maximum there is afforded by an SMMR-derived precipitable water chart for December 1981 provided by NASA/GSFC. The postive anomaly southeast of South Africa seems rather too large in magnitude in the ship-derived field, but there is a large amplitude and equally dubious negative anomaly in the MCSST field just to the south of it in a large region devoid of ship data. There is no obvious explanation of either of these.

March 1982. Aside from the previusly noted tendency for greater amplitude in the MCSST-derived anomalies than in the ship-based ones (see particularly the negative anomaly features in the North Pacific and North Atlantic [Hilland et al., this issue, Plate 4a, b], the only unsupported MCSST feature is the postive anomaly in the far western Pacific and Indian oceans that is centered roughly on the equator. This corresponds climatologically to the moistest portion of the tropics, and this is corroborated by the SMMR-based precipitable water charts supplied by NASA/GSFC. This sort of positive anomaly has not appeared since re-derived bias corrections, based on a much larger and more representative buoy matchup data base, were incorporated in the operational equations in September 1982 (see section 5).

July 1982. The large belt of negative anomaly stretching around the earth from roughly 5-30N is, as discussed previously, predominantly a consequence of the volcanic aerosol from eruptions of El Chichon in Mexico in early April 1982. The bright cold aerosol cloud almost eliminated daytime MCSSTs in this belt and severely attenuated the emitted radiation from the earth's surface. The difference between monthly mean SST's derived solely from satellite MCSST's and those from ship and other in situ measurements has been used by Strong et al. [1983] to track the month-to-month coverage of the volcano cloud during 1982. His charts indicate a southward transport of the aerosol near central West Africa and a northward transport in the west central North Pacific, which is consistent with distortion in the negative anomaly belt in these regions [Hilland et al., this issue, Plate 5b]. The ship-based anomaly field [Hilland et al., Plate 5b] also shows negative anomaly features in these two areas, but the greater extent and amplitude in the AVHRR chart is attributed to the added influence of the volcano cloud. The source of the large negative MCSST anomaly along a large part of the extreme southern edge of the chart, especially southwest of Australia, is suspected to be deficiences in the climatology there (the ship-derived anomaly chart has a data void all through that region). The NOAA/NESDIS anomaly charts, which are based on the Robinson/Baur climatology, show only two small (in area) negative anomalies (maximum of -1.5°C) anywhere in this zonal belt, one southwest of Australia at about 50°-53°S and another southeast of New Zealand near 55°-58°S.

7. Concluding Remarks

Perhaps chief among the limitations of the MCSST, or any other infrared method, is lack of retrievals in areas of persistent cloud cover. The relatively high resolution of the AVHRR, however, does enable more retrievals to be made in patchy cloud cover than can be done with the other sensors.

Severe volcanic eruptions or dust storms can produce extraordinary aerosol loadings in the atmosphere and thereby greatly increase attenuation of the infrared signal reaching the satellite as well as interfere with those cloud detection tests that depend on visible-band measurements. El Chichon, because of the large mass of H_2SO_4 droplets found at very high altitudes in the atmosphere, was particularly severe in its impact on the MCSST's, especially in the northern hemisphere tropics and subtropics. Daytime retrievals were virtually eliminated between 5°N and 30°N for up to 6 months, and nighttime retrievals were biased too low by up to 2°-4°C from April to October 1982 [Strong et al., 1983]. Recent research indicates the very real possibility of using a different formulation of the triple-window MCSST equation, one that appears to be nearly insensitive to the concentration of El Chichon type aerosols [Walton, 1985]. Furthermore, daytime visible-band data from the AVHRR can probably be used to obtain a point-to-point measure of the aerosol loading, thus leading to other possibilities for correction of the retrieval temperatures [Griggs, 1983; L. L. Stowe, personal communication, 1984].

The old problem remains of skin/bulk temperature difference--satellite IR techniques yield skin temperatures at depths of a fraction of a millimeter, and in situ methods of observation give bulk temperatures at depths ranging from a few centimeters (towed thermistors) to 1-2 m (buoys), to 3-10 m (ship intakes). The use in the MCSST method of a temperature-dependent bias correction derived from satellite/buoy matchup data presumably incorporates some sort of average skin versus 1-m depth temperature adjustment, but this effect will always be a source of difference in this type of retrieval. The skin is almost always cool and generally amounts to 0.1°-0.5°C in magnitude [Robinson et al., 1984], although the temperature difference with depth is minimized during well-mixed conditions.

It is not uncommon for the top few tens of centimeters of the water to become heated under low amounts of cloudiness and when very light winds result in little mechanical stirring; this has been termed the "diurnal thermocline" [Robinson et al., 1984]. This is probably the condition associated with the largest satellite/buoy or satellite/ship temperature differences.

Insofar as the JPL SST workshop results go, the following general conclusions are drawn. Despite the difficulty of comparing satellite sensors with differing spatial resolution and geographical coverage and of matching each of these in turn with common in situ data sets that are themselves highly irregular in density of coverage in many regions and are of variable quality (furthermore, they are "spot" measurements at depths of one to several meters, whereas the AVHRR directly senses "skin" temperature (averaged over areas about 8 km on a side for MCSST's)), there is surprisingly good correspondence in the sign and location of the major anomaly features where there is adequate common coverage. In isolated areas there are suspect anomalies during the several data periods, and the amplitude of the AVHRR anomaly field seems somewhat larger overall than the ship field; but generally, there is surprisingly good correspondence in view of the probable errors inherent in both fields. These errors combine in a variable and unknown way in difference fields. The diurnal variations apparent in the global day-minus-night charts are sometimes difficult to account for in the absence of separate day and night anomaly fields, but the prevalence of positive day/night differences can in many instances be attributed to the "diurnal thermocline" effect.

As expressed by the bias, scatter, and cross correlation statistics for the globe (and for the North Pacific, mid-Pacific, South Pacific, and North Atlantic regions, which are given in the final report of the JPL SST workshops), the NOAA/NESDIS operational AVHRR/MCSST product generally compares better with the Pazan screened ship data set than do SST's from any of the other satellite sensors. This is especially true in the case of the standard deviation (scatter) and the cross correlation, with the AVHRR having even lower scatter and higher correlation with respect to the Pazan ships than do the TRANSPAC XBT's. This and the fact that the AVHRR similarly has better statistics relative to the Pazan screened ships than it has relative to either the TRANSPAC XBT's or the FGGE buoys, suggests that the latter two data sets should have had an equally comprehensive screening to delete incorrect observations.

When a modest amount of additional spatial smoothing is done, the AVHRR/MCSST figures for scatter and cross correlation improve significantly. The goodness of the correlations obtained, even before the smoother was applied, are noteworthy in that they refer to anomalies. Unlike the temperatures from which they are derived, anomalies have a much smaller range of values, and the associated correlations are not influenced by the strong and systematic gradients characteristic of the temperature field.

Operational MCSST processing, using AVHRR data from NOAA 9 instead of NOAA 7 began the first part of February 1985. Using the slightly different filter characteristics of the AVHRR on NOAA 9, a new simulation data base was generated, and provisional bias-corrected MCSST equations were derived as described in section 4. A significant refinement introduced at this time was an attempt to further reduce errors in the 11- and 12- μm brightness temperatures stemming from nonlinearity of the detectors. A nonlinearety correction is made over the entire temperature range (205°-315°K) when processing to radiances from counts in the 1b data set and is thus incorporated in the brightness temperatures derived therefrom [Lauritson et al., 1979; Hamilton, 1984, appendix B], but for current MCSST processing, an additional least squares linear fit is made to the 275°-305°K portion of the table of residual errors in appendix B to reduce these residuals to $\lesssim$0.1°K over the normal range of SST. Users of the NOAA operational MCSST equations given in Table 7 are cautioned that input brightness temperatures from the 1b data set should be adjusted accordingly. Increased availability of buoy data in 1985 has enabled several hundred matchups per month with drifters all over the

TABLE 7. NOAA 9 Provisional Bias-Corrected MCSST Equations and Global Statistics From Matchups With Drifting Buoys

	February 1985			March 1985			April 1985		
	N	Bias	RMSD	N	Bias	RMSD	N	Bias	RMSD
Day	268	-0.09	0.55	319	-0.14	0.55	354	-0.11	0.53
Night	220	-0.13	0.50	238	-0.10	0.54	243	-0.14	0.52

Dual-window (night): $SST_1 = 1.5032T_{3.7} - 0.5042T_{11} - 270.59$

Split-window (night): $SST_2 = 3.6535T_{11} - 2.6680T_{12} - 268.41$

Triple-window (night): $SST_3 = 0.9936T_{11} + 0.9825(T_{3.7} - T_{12}) - 269.66$

Split-window (day): $SST_4 = 3.6569T_{11} - 2.6705T_{12} - 268.92$

The bias (buoy-minus-satellite) and RMSD are in degrees Celsius. The equations yield temperatures in degrees Celsius when input temperatures are in degrees Kelvin.

world, and global bias and rms difference have been consistently near -0.1°C and 0.5°C, respectively.

The AVHRR/MCSST technique, which continues to undergo refinement in attempts to handle special situations better, is already providing the beginnings of a long-term, global SST data base of a quality increasingly useful for many purposes, especially climate studies.

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