Comparison of the TIROS-N Satellite and Aircraft Measurements of Gulf Stream Surface Temperatures

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A comparison is made between multi-channel infrared (3.7 and 11 μm) temperatures measured by the TIROS-N satellite and aircraft single channel radiometer and AXBT measurements over the Gulf Stream between Cape Hatteras and Savannah, Georgia, on November 27, 1979. After reducing the noise in the 3.7 μm TIROS-N data, a multi-channel method is used to estimate the sea surface temperatures. For a temperature band of 19 to 26°C, the estimated and AXBT measurements are in agreement within a standard error estimate of 0.5°C. A bias of 1.2°C was found between the aircraft radiometer and the AXBT measurements, and part of this bias is attributed to radiometer calibration errors.

INTRODUCTION

During November 1979, five aircraft surveys of the upper ocean thermal structure were made along the Gulf Stream frontal zone between Savannah, Georgia, and Cape Hatteras, North Carolina, in the region of large-amplitude meander activity downstream of the recurring seaward deflection of the Stream off Charleston, South Carolina. These surveys were conducted as part of the Gulf Stream Meanders Experiment and had the objective of obtaining temperature data over a 400 km by 150 km by 400 m oceanic volume rapidly enough to provide synoptic views of the three-dimensional structure of the Gulf Stream thermal frontal zone. Subsurface temperatures were measured by deploying a grid of Hermes Electronics air-dropped expendable bathythermographs (AXBT's), while simultaneous surface temperature measurements were taken with a Barnes precision radiation thermometer (PRT-5). The aircraft surveys were conducted aboard a P3-Orion research aircraft operated by the U.S. Naval Oceanographic Office and U.S. Navy Squadron VXN-8. *Bane and Brooks* [1981] describe the aircraft temperature measurements and the vertical and horizontal temperature sections made during this survey.

In this paper, a detailed comparison is made between the temperatures measured by AXBT, the aircraft radiometer, and two channels of the Advanced Very High Resolution Radiometer (AVHRR) on the TIROS-N satellite operated by the National Earth Satellite Service (NESS). Although five aircraft surveys were made, sufficiently cloud-free satellite data were obtained only on November 27, 1979. The satellite data were obtained at 0840 GMT, while the aircraft survey on that day was made between 1500 and 1900 GMT. Effectively, satellite data collected at night are compared with aircraft data collected during the following day.

Several major problems had to be resolved to allow the aircraft and satellite data to be compared. The navigation provided with the AVHRR data had to be corrected to allow the geographic position of each sample to be determined to

an accuracy of 1 km. A method had to be found to reduce the excessive noise at the TIROS-N AVHRR 3.7 μm wavelength which introduced intermittent temperature fluctuations of up to 2°C. The satellite and aircraft data had to be then merged to allow precise comparisons. These problems were resolved by using software developed on the IBM-360 at NESS.

Comparisons between the aircraft and satellite measurements have been made by using an equation developed by *McClain* [1981] to estimate sea surface temperatures from the multi-channel AVHRR temperature differences. For temperatures in the range 19°–26°C, the AXBT temperatures at a depth of 1m and the AVHRR measurements coincided to within a scatter of 0.5°C.

SATELLITE AND AIRCRAFT DATA

The polar orbiting TIROS-N satellite provides visible and infrared measurements with a spatial resolution of about 1 km from an altitude of 850 km [*Schwalb*, 1978]. The AVHRR detects the emitted radiation at wavelengths 3.55–3.93 μm and 10.5–11.5 μm. For convenience, these are referred to as AVHRR channels 3 and 4. The gray scale image of channel 4 for orbit 5781 on November 27, 1979, at 0840 GMT is shown in Figure 1. The darker shades of gray represent warmer surface temperatures. The temperature extrema occur in the warmer Gulf Stream waters and the cooler inshore waters, and are about 26°C and 15°C, respectively. A distinctive seaward deflection of the Gulf Stream is evident between latitudes 32°N and 33°N. Several warm water filaments appear landward of the western sea surface temperature (SST) boundary of the Stream.

Although five aircraft surveys were made between November 21 and 29, concurrent cloud free AVHRR data were only recorded on orbits 5781 and 5788 on November 27. Unfortunately, the daytime orbit 5788 at 1900 GMT did not get into the digital archive maintained by the Environment Data and Information Service (EDIS). Therefore, it was not possible to determine the changes that occurred in the satellite data before and after the aircraft survey. The present study compares the AVHRR measurements at 0840 GMT and the aircraft data recorded between 1500 an 1900 GMT on November 27. The aircraft flight track is shown in

Figure 1, and the aircraft data acquisition started at the northwestern end of flight line C. Measurements were only made along the eight cross-stream sections, identified by letters C to Q. The sections are separated by 50 km. The position of the aircraft was recorded by a VLF Omega system with an accuracy of about 1 km.

Fifty-nine AXBT's were dropped at regular intervals during the cross-stream tracks. These provided 50 useable near-surface temperature profiles. AXBT temperatures at a depth of approximately 1 m were matched to the nearest AVHRR and PRT-5 sample for comparison. Owing to the physical design of an AXBT, the shallowest temperatures are measured at about 1 m from the sea surface. Unlike a ship-launched XBT, an AXBT probe stays near the surface for about 1 min before beginning descent and temperature profiling. This allows the AXBT probe to come into thermal equilibrium with the seawater near the surface before descent. With the well-developed mixed layers we observed during the November 27 flight, a 1 m temperature was representative of the bulk near-surface temperature at that AXBT station.

The downward looking PRT-5 radiometer aboard the aircraft recorded the emitted radiation at wavelengths 9.5–11.5 μm. The 2° field of view provided a 10 m diameter circular footprint on the sea surface from an altitude of 300 m. The PRT measurements were digitized at intervals of 0.7 km so that there were about 30% more PRT than AVHRR samples along a given track line. An upward-looking Barnes PRT-4 radiometer was used to monitor the presence of clouds above the aircraft. This 'sky temperature' measure-
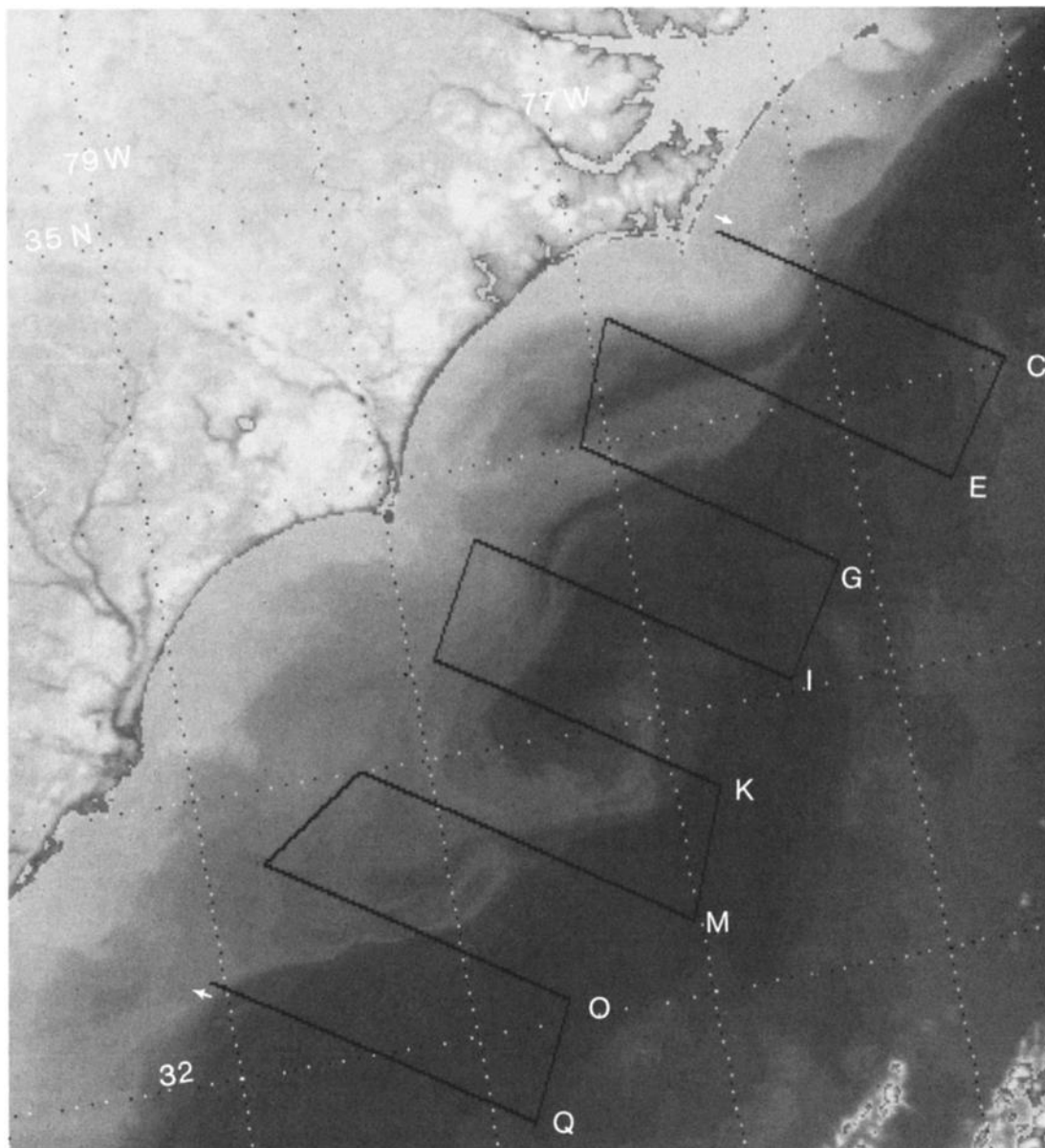

Fig. 1. The infrared AVHRR image from TIROS-N orbit 5781 at 0840 GMT on November 27, 1979. The aircraft flew from the northern end to the southern end of the flight track as indicated. Aircraft radiometer and AXBT measurements were made during the cross-stream tracks C through Q. A 1 degree by 1 degree latitude-longitude grid is generated from the TIROS-N navigation. A seaward deflection of the Gulf Stream is evident between latitudes 32° and 33°N.

ment also gave an indication of the relative moisture content above the aircraft in cloud-free regions.

The AVHRR infrared data were converted to equivalent black body temperatures by using the inverse Plank's radiation equation described by *Kidwell* [1979] at central wave numbers of 2640 and 912 cm^{-1} for AVHRR channels 3 and 4, respectively. Calibration coefficients for converting digital counts to radiance values are computed at NESS and provided on the EDIS digital data tapes. The aircraft PRT-5 radiometer was calibrated during the flight by intermittently exposing the instrument to a stirred water bath. Nine calibrations were performed by using bath temperatures of 20, 24, and 28°C (±0.05°C). A comparison of the radiometer output to the water bath temperatures was used after the flight to adjust the temperatures recorded by the radiometer. With this procedure, the temperatures recorded by the PRT-5 were reduced by an average of 1.4°C. These adjusted values are used in our analysis.

The AVHRR digital data are provided with navigation information that defines the geographic location of every 40th sample along each scan line. To determine the accuracy of the navigation, the AVHRR image in Figure 1 was corrected for earth's curvature and rotation errors by using a stretching method described by *Legeckis and Pritchard* [1976]. The stretched AVHRR image was then displayed at a scale of 1-2 million and compared with an east coast map of similar scale prepared by *Uchupi* [1968]. By aligning land features on the map and the image, it was found that the AVHRR navigation had to be corrected by a northward translation of 6.6 km and an eastward translation of 2 km. This correction allowed all subsequent AVHRR temperature values to be located with an uncertainty of 1 km. Since the aircraft positions are known to an accuracy of about 1 km, the positional uncertainty in comparing the two data sets is about 2 km.

PREDICTED TEMPERATURES AND DATA SMOOTHING

The AVHRR channel 3 (3.7 μm) data on the TIROS-N were very noisy, with random temperature changes of up to 2°C. The AVHRR channel 4 (11 μm) was virtually noise free with a temperature resolution of about 0.1°C in the range of ocean temperatures. To use the difference between channels 3 and 4 to estimate the atmospheric correction, a method of reducing the noise in channel 3 was required.

Fortunately, J. Fahle (personal communication, 1982) determined from spectral analysis that the AVHRR channel 3 data had a coherent high frequency noise component in the cross-scan direction. By using this observation, the channel 3 data for orbit 5781 were smoothed by averaging samples across five scan lines. It was then assumed that the difference between channels 3 and 4 is the sum of the remaining noise and a slowly varying function that depends on the moisture and temperature distribution of the atmosphere in cloud-free areas [*Braun*, 1971]. Inspection of the data suggested that the noise along the tracks in Figure 1 had a wavelength of about 30 samples. Since the study area in Figure 1 appeared cloud free, a running mean of 30 samples of the channel 3 and 4 differences was used to smooth out the remaining noise component. The running mean difference was then used to obtain a mean atmospheric correction for the AVHRR channel 4 data.

The method for using the AVHRR channel 3 and 4 differences to estimate the atmospheric correction in cloud-

free ocean areas is described by *McClain* [1981], who applied the atmospheric transmittance models described by *Weinreb and Hill* [1980] to a set of 59 cloud-free radiosondes. The theoretically estimated temperatures (T_s) were then compared with a set of fixed buoy SST measurements colocated with AVHRR data. *McClain* [1981] found that the estimated temperatures were lower than the in situ observations, and a temperature-dependent bias correction was added to the predicted SST. These bias corrected temperatures are given in degrees Celsius by

$$T_{S+B} = AT_4 + B(T_3 - T_4) + 1.07 \qquad (1)$$

and the bias uncorrected temperatures are

$$T_S = T_4 + B (T_3 - T_4)/A + 1.27 \qquad (2)$$

where

$$T_{S+B} = AT_S - 0.274$$

$$A = 1.0574$$

$$B = 1.5044$$

and T_3 and T_4 are the AVHRR channel 3 and 4 equivalent black body temperatures, respectively, recorded at the satellite. The constants A and B were obtained by linear regression.

RESULTS AND DISCUSSION

The AVHRR channel 4 and the two aircraft radiometer measurements are compared along track line E in Figure 2. There are 173 AVHRR samples and 227 PRT samples in a distance of 150 km. The AVHRR channel 4 temperatures were replaced by a three sample average to smooth out the discreet steps that occur when the track line crosses the AVHRR scan lines. A comparison of the AVHRR channel 4 and PRT-5 measurements in Figure 1 and Figure 2 shows that in the PRT-5 data, the Gulf Stream front is located at sample 88 and the inshore warm streamer at sample 60. There appears to be a westward shift of the AVHRR relative to the PRT data. For example, the maximum temperatures of the warm streamer in the AVHRR channel 4 appears at sample 55. Also, the AVHRR channel 4 temperature decreased to 16.5°C about five samples to the west of the initial PRT-5 measurement. Similar temperature misalignments of 4-6 km observed along the other track lines could be attributed to advection of the surface waters during the 6-10 hour intervals between satellite and aircraft measurements. Since a sequence of satellite images is not available, it is not possible to verify these changes.

In Figure 2 there is also a distinct change in the differences between AVHRR channel 4 and PRT-5 temperatures east and west of the Gulf Stream front. This change is correlated with a corresponding decrease in the sky temperatures east of the front as measured by the upward looking PRT-4 radiometer. This suggests that an atmospheric moisture front is oriented parallel to the sea surface temperature front of the Gulf Stream. Owing to greater absorption by the atmosphere of the emitted radiation eastward of the Gulf Stream front, the AVHRR channel 4 temperatures are decreased. As a result, the temperature gradient at the front detected by the AVHRR channel 4 is about 0.7°C/10 km smaller than measured by the PRT-5.

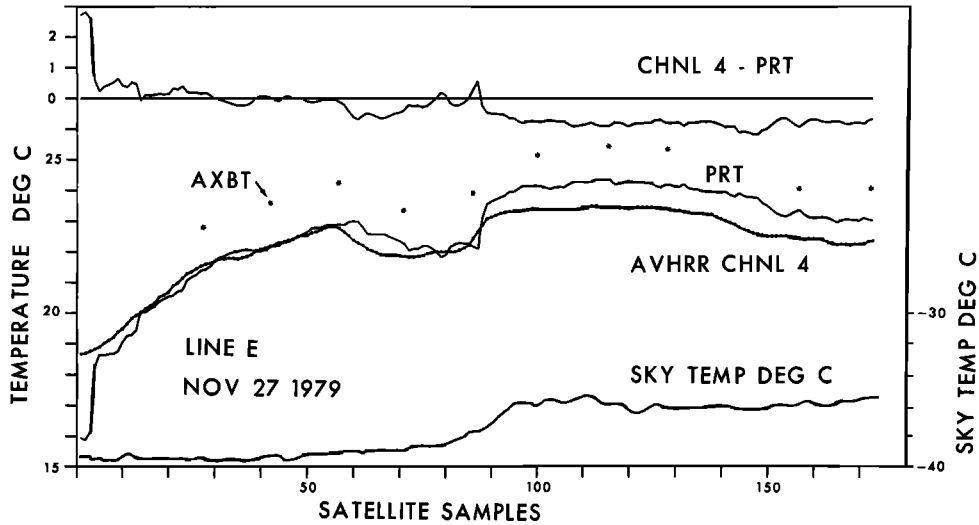The SST estimated by (1) on track line E is shown in

Fig. 2. The aircraft and satellite data are plotted eastward along track line E on November 27, 1979. The PRT-5 downward looking radiometer recorded the sea surface temperature (PRT) and the PRT-4 upward looking radiometer recorded the sky temperature (SKY TEMP) from the aircraft. The AVHRR channel 4 temperatures are recorded at a wavelength of 10.5–11.5 μm. The AXBT data plotted are near-surface temperatures at a depth of 1 m.

Figure 3 along with the AXBT and PRT-5 measurements on that line. The AVHRR channel 3 and 4 differences in (1) are the raw (unsmoothed) data recorded by the satellite. The large amplitude (3°C) oscillations in the predicted SST are due to noise in channel 3. The noise in the temperature predicted by (1) is about 50% larger than in channel 3 due to the constant A in (1). After the noise is reduced by the procedure previously described, the predicted temperatures based on the smoothed data are shown in Figure 4. The nearly constant bias of about 1.2°C in the difference (T-PRT) in Figure 4 between the predicted temperature and the aircraft PRT-5 temperature recorded at 300 m appears in all of the track lines. A comparison of all the track lines shows that the AXBT measurements are scattered about the temperature predicted by (1). Therefore, the apparent bias between the predicted temperature T and the AXBT temperature that appears in Figure 4 is not the usual case.

The SST predicted by (1) is plotted as a function of the AXBT temperature at one meter in Figure 5. With a sample of 50, the linear regression line has a scatter of 0.50°C as measured by the standard error of estimate. The mean bias of the best fit from the perfect fit line is −0.19°C. When the samples at the Gulf Stream front were omitted, 42 samples yielded a scatter of 0.39°C. Although the SST's are limited to a narrow band (19°–26°C), the results in Figure 5 suggest that the smoothed AVHRR channel 3 and 4 differences can provide an excellent estimate of sea surface temperature.

The aircraft PRT-5 temperatures are compared with the AXBT 1 m temperatures in Figure 6. For 50 samples, the linear regression line has a scatter of 0.37°C, and the mean bias of the best fit from the perfect fit line is 1.2°C. Elimination of values in gradient areas reduced the scatter to 0.25°C but left the bias unchanged. Since typical temperature differences across the ocean's cool skin are about 0.2C°
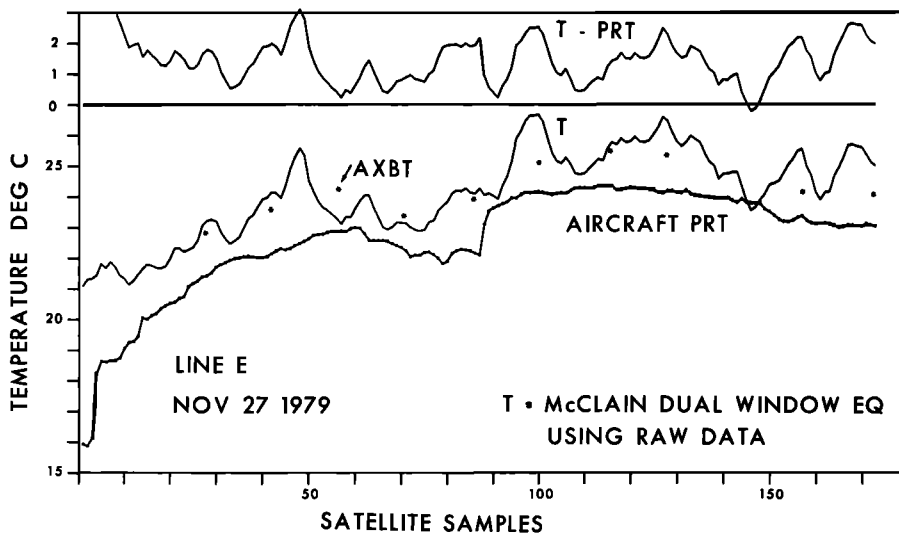

Fig. 3. The sea surface temperature T as predicted by *McClain*'s [1981] dual channel equation defined by (1). The raw (unsmoothed) AVHRR channel 3 and 4 differences are used, and the large oscillations are due to noise in channel 3. The aircraft PRT-5 and AXBT 1 m temperatures are shown for comparison.
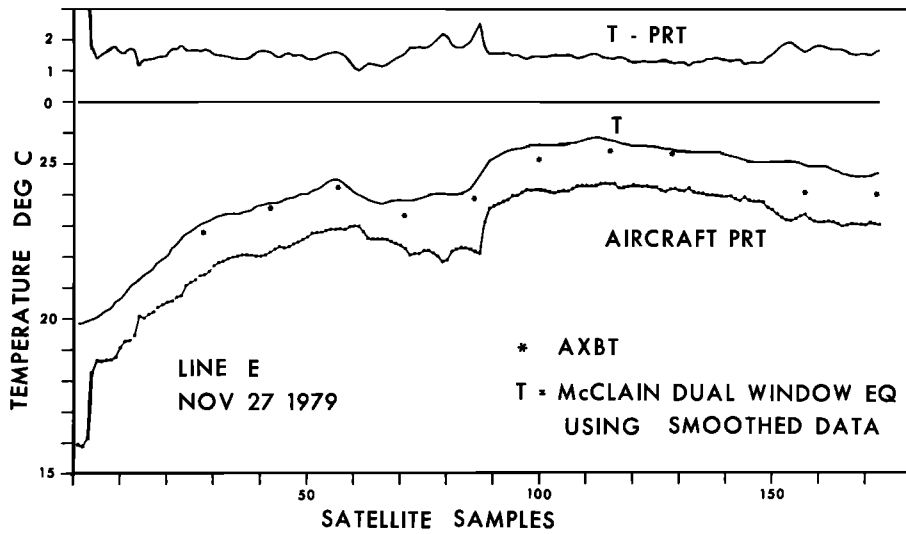
Fig. 4. The sea surface temperature T as predicted by *McClain*'s [1981] dual channel equation defined by (1). The smoothed AVHRR channel 3 and 4 differences are used to compute an average atmospheric correction to AVHRR channel 4. The aircraft PRT-5 and AXBT 1 m temperatures are shown for comparison.

[*Paulson and Simpson*, 1981], the bias of 1.2°C is almost an order of magnitude too high. *Gasparovic* [1982] has shown that atmospheric absorption of the emitted radiation between the surface and the PRT-5 at an altitude of 300 m can account for about 0.5°C of this bias. Therefore, a large part of the bias is probably due to the calibration method used for the PRT-5 radiometer during the flight. As a result of the calibration procedure, the initial PRT-5 temperature measurements were reduced by an average of 1.4°C to force the PRT-5 to agree with the temperature of the water bath used for calibration. Apparently, there is an error in this procedure. Although the exact cause is yet to be determined, it is postulated that energy emitted by the housing of the water bath and the interior of the aircraft are being recorded by the PRT-5 during calibration. We believe that his effect contributes to the bias evident in Figure 6.

In summary, we reflect on several events that allowed this

study to be brought to a conclusion. The first is that, fortuitously, one set of cloud-free digital satellite data was obtained nearly concurrently with one of the aircraft flights. Several earlier attempts at obtaining similar data sets failed due to a combination of hardware and atmospheric causes. The second is the suggestion by J. Fahle (personal communication, 1982) that the noise in the AVHRR channel 3 could be reduced by smoothing in the cross-scan direction. Earlier attempts to reduce the noise in the along-scan direction had left the impression that time could be better spent on other projects. Finally, the sea surface temperatures estimated in (1) by *McClain* [1981] demonstrate the utility of the AVHRR data. It is anticipated that the noise-free, three-channel infrared data from the present TIROS satellites, such as NOAA-7, will provide even more accurate estimates of the sea surface temperature. The noise-free data should allow a variety of new investigations to be conducted.
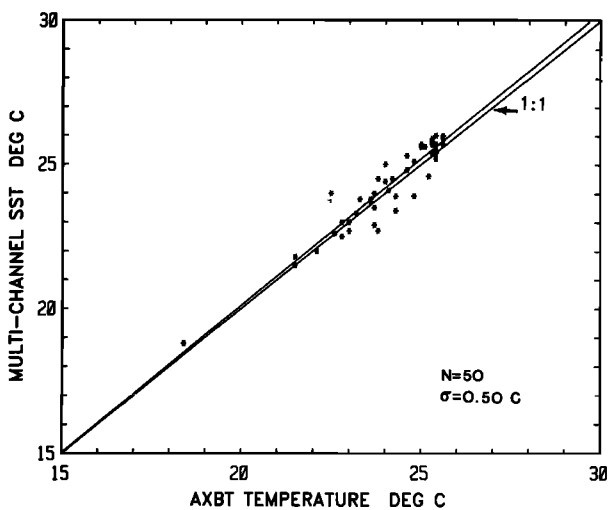

Fig. 5. The AXBT 1 m temperature versus the temperature predicted by McClain's equation defined by (1). The 1:1 line, the linear regression line, and the standard error (σ) of estimate are shown.
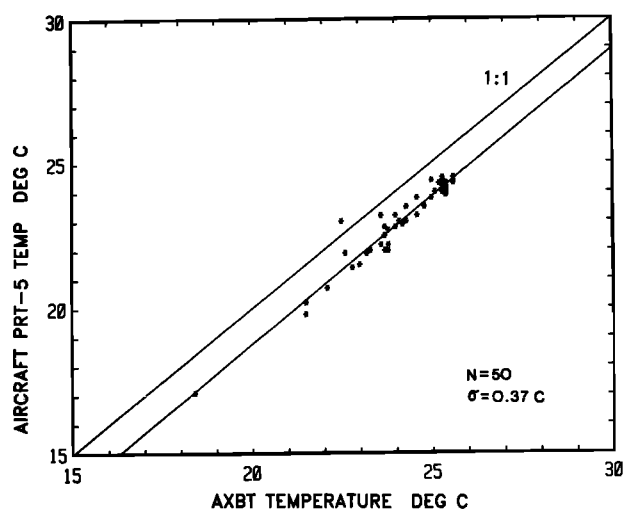

Fig. 6. The AXBT 1 m temperature versus the downward looking PRT-5 radiometer temperature from an altitude of 300 m. The 1:1 line, the linear regression line, and the standard error (σ) of estimate are shown.

For example, diurnal SST changes will become apparent. Likewise, one expects to find sea state and seasonal differences between the skin temperature measured by satellite and the bulk temperature at 1 m measured by AXBT or drifting buoy temperature probes.

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