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Large-Scale Sea Surface Temperature Variability from Satellite and Shipboard Measurements

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Abstract

A series of satellite sea surface temperature intercomparison workshops were conducted under NASA sponsorship at the Jet Propulsion Laboratory. Three different satellite data sets were compared with each other, with routinely collected ship data, and with climatology, for the months of November 1979, December 1981, March 1982, and July 1982. The three satellite data sets were (i) AVHRR - sea surface temperature estimates produced operationally by the National Oceanic and Atmospheric Administration from the Advanced Very High Resolution Radiometer aboard the NOAA polar-orbiting weather satellites; (ii) HIRS/MSU - estimates produced by a research group at the NASA Goddard Space Flight Center from the 20-channel High Resolution Infrared Sounder and the 4-channel Microwave Sounding Unit, also aboard the same NOAA satellites; and (iii) SMMR - estimates produced by another group at Goddard from the Scanning Multifrequency Microwave Radiometer on the NASA research satellite Nimbus-7. The satellite and ship data were differenced against an accepted climatology to produce anomalies, which in turn were spatially and temporally averaged into two-degree latitude-longitude, one-month bins. Monthly statistics on the satellite and ship bin average temperatures yielded rms differences ranging from 0.58 to 1.37 C, and mean differences ranging from -0.48 to 0.72 C, varying substantially from month to month, and sensor to sensor. The SMMR generally had the largest rms differences and time-dependent biases, while the AVHRR and HIRS/MSU had smaller more comparable values. The monthly bins were further smoothed spatially to correspond to 600 km averages, to further suppress the noise of individual observations, particular for the ship data. When this was done, the monthly ship data standard deviations about climatology varied between 0.35 and 0.63 C. Taking these values as true sea surface temperature signal standard deviation levels, and the satellite-ship rms differences as noise levels, produced signal/noise variance ratios of about 0.25 for SMMR, and 1.0 for AVHRR and HIRS/MSU. Maps of sea surface temperature anomaly reveal a complex pattern of partial agreement and disagreement between ship and satellite data. Maps of satellite-ship and satellite-satellite difference temperatures were often dominated by coherent large-scale patterns of obvious geophysical origin, related to distributions of surface wind speed, atmospheric water vapor, cloudiness, and stratospheric aerosols. Despite such problems, these satellite data sets are beginning to approach levels of useful application, for studies of short-term climate variability and other problems where the signals are large and well-defined. With these satellite data sets, caution must be exercised, however, in relating fluctuations in sea surface temperature to other geophysical variables, because of the correlated nature of the error sources.

Introduction

Infrared and microwave radiometers aboard earth-orbiting spacecraft are natural tools for providing frequent and global coverage of sea surface temperature (SST). For infrared sensing, many research and operational weather satellites have carried instruments which, while designed primarily for meteorological purposes, also could be used to extract some SST information. Thus, infrared instruments intended for either cloud imaging or atmospheric sounding, generally include sensing channels situated in one or more parts of the infrared spectrum of maximum atmospheric transmittance. Clouds are opaque to all infrared radiation, yet even in the absence of cloud cover, and in the so-called spectral "windows" at 3.5 - 4.0 um, and 8 - 13 um, atmospheric water vapor and aerosols absorb and scatter radiation. Small clouds, which cannot be spatially resolved by a given instrument, also cause problems which must be carefully accounted for if SST is to be estimated to some useful accuracy [Bernstein, 1982].

While the ocean radiates very nearly as a blackbody (emissivity close to 1.0) in the thermal infrared, this is not so in the microwave portion of the spectrum. In the latter case, while even a cloudy atmosphere is nearly transparent, the ocean radiates as a graybody, with emissivity varying over the range 0.4 to 0.7, increasing as a function of wind speed. Microwave radiometers with two or more carefully chosen frequencies are thus required to simultaneously determine wind speed and SST [Wilheit et al.,1980].

While earlier weather satellite sensors were of some use, it has only been since the launch of the NASA Seasat and Nimbus-7 satellites [Gloersen and Barath, 1977; Njoku et al.,1980], and the NOAA Tiros-N generation of satellites [Schwalb, 1978], that appropriate radiometers, with sufficient spectral channels, have been available to make quantitative SST estimates from space. In this paper we evaluate the SST data produced by three such instruments over much of the globe, during four selected months in 1979, 1981, and 1982. As part of a NASA-sponsored series of workshops conducted by the Jet Propulsion Laboratory, global data produced by two research groups and one operational center were evaluated, primarily through intercomparison with routinely reported shipboard measurements.

Inherent problems with ship and satellite SST measurements

High quality in situ SST data from ships and buoys tends to be restricted to only a limited number of platforms which may only be operating in localized areas for limited periods of time. The only in situ SST data which begins to approach continuous global coverage comes from the routine surface marine meteorological reports radioed ashore by ships. The great majority of those reports are derived from ship engine room measurements of the temperature of water brought in to cool the engines.

Past work with these data, particularly by James and Fox [1972], Saur [1963], and Tabata [1978], indicates that typical individual observations have one sigma noise levels of about 0.9 C, and that the data on average tend to be biased warm by about 0.3 C, in comparison with adjacent high quality observations. The ship data used in the workshop were carefully screened by Steve Pazan (Scripps Institution of Oceanography) to eliminate obviously erroneous data, much of it due to misreported earth locations which produce unrealistic ship speeds between adjacent reports by a given vessel. Then, all reports deviating by more than 6 C from climatology were also eliminated. Figure 1 is a crossplot of the resulting ship data set, for all possible pairs of observations (where each observation is the SST deviation from climatology) within 6 hours and 100 km of each other, in the North Pacific. The standard deviation of the difference is 1.49 C. Dividing this by the square root of 2 yields a one sigma noise level of 1.06 C for the individual shipboard data used in the workshop, which is consistent with the James and Fox, and other previous findings.

Aside from the problems of measurement noise in the ship data, there is the difficulty of comparing individual point measurements from ships with instantaneous surface average measurements from satellite radiometers. The ship data typically are drawn from a depth of 5 to 10 m. The satellite radiometric measurements are from the upper few millimeters (for microwave radiometers) or the upper few micrometers (for infrared radiometers). True temperature differences of several tenths of a degree C often exist between the very surface "skin" temperature [Grassl, 1976; Paulson and Simpson, 1981] and a bulk thermometric measurement several tens of centimeters below the surface. The skin temperature is normally cooler than such a bulk temperature because of evaporative effects. When meteorological conditions properly combine (low wind speed with cold dry air over warmer water), these evaporative effects can temporarily produce skin - bulk differences of 1 C or more [Katsaros, 1980].

Aside from skin - bulk effects, true differences in bulk temperature often occur within the upper 10 m, especially on afternoons having little cloud cover and light winds with the attendant near-surface solar heating. Such conditions occur often in mid-latitudes during the summer, and at any time of year in the tropics. One example of this "afternoon effect" is illustrated in Figure 2, kindly provided by Patricia Pullen of the Pacific Marine Environmental Laboratory [Pullen, 1985]. Continuous underway temperature measurements, taken from 5 m depth by the R/V Oceanographer, were compared with hourly bucket measurements from the upper meter, for a cruise in the eastern tropical Pacific. When grouped only as a function of local time of day, the mean difference in temperature (Underway minus bucket) at night (7 PM to 7 AM) is -0.06 C, with a standard deviation of 0.12 C. Yet on some afternoons, surface heating can produce differences of 1 to 2 C. The time of maximum differences coincides with the 2:30 PM local time of overpasses of the NOAA-7 satellite, which carries the two infrared radiometers discussed below. Furthermore, such radiometers would tend to provide more observations on days with little cloud cover, when the afternoon effect would be greatest. Since most of the routine ship observations are taken from 5 to 10 m depth, below the depth of the afternoon heating, one would anticipate a positive bias in satellite - ship intercomparisons, which might be at least partly compensated for by the previously noted warm bias in engine room temperature measurements.

Satellite-borne radiometric determinations of SST are characterized by a number of inherent problems. Infrared techniques are limited to areas without excessive cloud cover. In regions of partial cloudiness, infrared radiometer fields-of-view (FOV) which are partially obscured must be properly handled, either to determine which FOV's are completely cloud-free, or to determine the fractional amount of cloud in the FOV and its cloud-top temperature. Microwave techniques are relatively insensitive to cloudcover, but the FOV of the present generation of microwave radiometers tend to be one to two orders of magnitude larger than infrared radiometers. Thus the Scanning Multifrequency Microwave Radiometer (SMMR) on the Seasat and Nimbus-7 satellites produces SST estimates with a spatial resolution of 150 km, while the infrared Advanced Very High Resolution Radiometer (AVHRR) on the NOAA weather satellites has 1 km resolution.

Other problems can occur once a given instrument is in orbit. For example, electrical noise steadily increased in the 3.7 um band of the AVHRR, so that this channel could not be used for the last of the four evaluation months. The Nimbus-7 SMMR suffered from numerous calibration and other problems, due to in-orbit aging of various components. In addition, the instrument was operated with a 24 hour on, 24 hour off cycle, with resultant warm-up problems. Creating an accurate, relatively bias-free long term global SST data set from a single instrument can be very difficult; the problem is compounded if one must deal with a succession of satellite instruments, which may not overlap each other in time.

Aside from instrument difficulties, the volume of satellite data which must be processed once it reaches the ground can be enormous. The global coverage AVHRR data, with an effective resolution of 4 km, constitutes a continuous data stream of 45 kbits/s. Processing algorithms for extracting SST from such a huge dataset may change over time, as new insights or procedures develop. Re-processing of several years of such data may in some cases be completely impractical. Thus, algorithmic changes in such a situation may produce changes in the resulting SST data.

Workshop objectives

Despite the above limitations, various individuals and groups have been working with the new generation of satellites and sensors which were launched in 1978. By 1981 published and unpublished accounts of satellite SST data began to appear, with varying claims of accuracy, generally around 1 C in individual measurements. A series of workshops was instituted by NASA to examine these data and evaluate the present state-of-the-art [Njoku, 1985]. The principal objective was to determine the degree to which the various satellite data sets were consistent with climatology, with each other, and with the routinely available in situ data from ships and buoys. The workshop was quickly focussed by limiting attention mostly to SST variability on large scales.

Three global data sets were examined - - AVHRR, HIRS, and SMMR:

The AVHRR is a visible and infrared radiometer with 1 km resolution in five spectral channels centered at 0.6, 0.9, 3.7, 11, and 12 um, operating on the NOAA polar-orbiting weather satellites. To achieve global area coverage, the data are averaged and subsampled to an effective 4 km resolution. Small 2-by-2 arrays of these 4 km samples are operationally processed by NOAA. Those arrays are subjected to a number of tests designed to identify and eliminate arrays which are cloud-contaminated. The thermal infrared brightness temperatures for cloud-free arrays are then combined as a linear weighted sum which corrects mostly for the absorption of radiation by atmospheric water vapor, to produce an 8 km area estimate of SST. Atmospheric transmittance modeling studies were used to derive the weighting coefficients, which were then slightly modified to insure best agreement of the satellite SST estimates with a set of in situ SST measurements from a large group of drifting buoys. The description of the processing procedure is discussed in detail in McClain et al. [1983]. Unlike the HIRS and SMMR, the AVHRR SST data were produced as part of an ongoing operational system. Thus, any processing errors are only correctable on subseqent data, once the error is noted and the processing algorithms suitably modified.

The HIRS (High Resolution Infrared Sounder), is a twenty-channel instrument which operates in conjunction with the four-channel MSU (Microwave Sounding Unit), aboard the same satellites as the AVHRR. HIRS/MSU data were processed at Goddard Space Flight Center by a group headed by J. Susskind and M. Chahine. The processing is based on a physical relaxation procedure which begins with an initial guess of the vertical profile of moisture and temperature through the atmosphere, and the SST [Susskind et al., 1984]. The vertical profile is derived from a prediction from a global atmospheric model, and SST is from climatology. Since the HIRS is a 30 km resolution instrument, completely cloud-free FOV's occur only rarely. The processing procedures use the multi-spectral data from several adjacent FOV's to estimate the actual percent cloud cover and cloud-top temperature. The resultant SST estimates are for an area 125 km on a side, and are separated by 250 km.

The SMMR is a five-frequency (6.6, 10.7, 18, 21, and 37 gHz) microwave radiometer aboard the Nimbus-7 research satellite. The FOV is frequency dependent, 150 km at 6.6 gHz and proportionately smaller at the higher frequencies. The SST resolution is determined by the lowest frequency. The processing of data was done at Goddard Space Flight Center, under a group headed by T. Wilheit and A. Milman, and is described in Wilheit et al., [1984]. The 6.6 and 10.7 gHz frequencies are used to determine both the wind speed and SST, while the 18 and 21 gHz channels provide total atmospheric column water vapor, which gives a small correction for SST. The 37 gHz frequency is most sensitive to rain, and regions of intense rainfall are thus identified and eliminated, since heavy rain can cause SMMR SST estimates to be in error. If land appears in a sidelobe of the radiometer antenna, significant SST errors can occur in the first few resolution cells. Consequently, no SMMR SST data within 600 km of land (with the exception of small islands) were considered by the workshop.

Each of the above global data sets were provided in four carefully selected months: November 1979, December 1981, March and July 1982. November 1979 was selected because it was near the end of the year-long Global Weather Experiment, a period expected to be particularly rich in ship and buoy intercomparison data. December 1981 was the first month after the introduction of a major change in AVHRR processing procedures at NOAA, and was selected to examine the impact of this change. March 1982 was the last month prior to the El Chichon eruption, which injected large quantities of volcanic aerosols into the stratosphere, that by July 1982 had become well-distributed in a global band just north of the equator. Strong concentrations of aerosol can produce significant errors for infrared SST determination, but microwave determinations should be completely unaffected. These latter two months were thus selected to help examine aerosol effects in the satellite data sets.

The agreed upon ground rules for data submission specified that all data would be produced and delivered to the workshop without any prior examination of the in situ data.

Intercomparison Results - Global Statistics

As a result of the high noise level of individual shipboard observations, any meaningful intercomparison with satellite data first requires some spatial and temporal averaging. The workshop dealt primarily with one-month, 2 degree latitude--longitude averages (hereinafter referred to as bins, and bin averages), since these scales are commensurate with studies of short-term climate variability. When the differences between satellite and ship bin averages are plotted as a function of the number of individual ship observations in the bin, a clear dependence on ship sampling becomes evident (see Figure 3). These results suggest that comparisons be limited to bins containing more than 25 ship observations.

Unfortunately, as Figures 3 and 4 portray, very few bins have more than 25 individual observations. Those that do are mostly confined to a few well-traveled routes in the northern hemisphere midlatitudes. In the southern hemisphere, ship observations are confined to a limited number of routes, with very few bins having 5 or more observations. Even in the well-traveled North Atlantic and North Pacific, most of the ocean areas have less than 15 observations. Consequently, a compromise was made when deriving satellite - ship temperature difference statistics, only to intercompare satellite and ship bin averages for those cases where at least 5 ship observations occur per bin. This compromise broadens the geographic distribution, but only at the expense of inflating the statistics on satellite-ship rms differences because of inadequate averaging of individually noisy ship observations. This is an important point which we will return to later, and must be kept in mind for all further discussion.

The other three panels of Figure 4 give the December 1981 satellite observational densities. Most of the bins contain at least 75 AVHRR observations, and the clearer and drier subtropical bands contain 200 to 300 or more data points, each of which is an 8 km area estimate of SST. The HIRS and SMMR individual observations, which are 125 and 150 km area estimates, respectively, have far fewer data points per bin. The HIRS has at least 5 to 10 points per cell nearly everywhere on the globe, with maxima in the subtropics exceeding 20 points. The SMMR, since it is a microwave instrument unaffected by cloud cover, shows globally uniform coverage of 2 to 6 points per bin, except in regions of overlap caused by orbital and sensor scan geometry, where slightly higher density occurs. Only night data were used, because of problems of instrument heating when the spacecraft was in sunlight. In addition, as noted above, the SMMR was operated on a 24 hour on - 24 hour off cycle. If the instrument had been left on continuously, and if the daytime data could have been used, the data density would have been four times greater. The 600 km land mask to eliminate land contamination in the antenna side lobes is also evident in the figure.

For each individual sea surface temperature observation, both satellite and ship, the time and location of the data point was noted, and used to temporally and spatially interpolate within climatology [Reynolds, 1982], to determine climatological norm for the observation, and hence its departure from this norm. All individual departure temperatures within a given two degree latitude-longitude, one month bin were then averaged to produce a single bin-average temperature departure, or SST anomaly. Use of this procedure helps to minimize the errors associated with observations which might be poorly distributed in space and time within a one-month, two-degree bin. For example, in the mid-latitude North Pacific the climatological gradient across a bin can be 1 to 2 or more degrees C. It was also judged essential to compare fields of anomaly, rather than SST itself, since the true SST field on such scales does not usually depart from climatology by more than 1 C. In order to be truly comparable, the spatial and temporal variations in anomaly from ship and satellite data sets need to agree with each other.

Table 1a summarizes the mean, standard deviation, and root-mean-square deviation (rmsd) of the differences between a given set of satellite and ship binned anomalies, along with the number of bins, for each of the four workshop months. Table 1b is a similar presentation, but in this case gives the statistics on ship data bin average temperatures relative to climatology. This table indicates a slight cooling on average over the entire shipboard data domain over the first three months, followed by 0.37 C of cooling between March and July 1982, for a total decrease of 0.46 C between November 1979 and July 1982. These temporal changes are displayed in Figure 5a, along with similar statistics for the three satellite data sets.

The standard deviations of Table 1b, which may be viewed as the signal level of real variability on scales greater than 200 km and 1 month, but inflated somewhat by ship data noise, decline over the first three workshop months, and then jump by nearly 50 % between March and July 1982. Most of the ship data are from the midlatitude northern hemisphere. The standard deviations are consistent with Cayan [1980], who determined that on climatological scales of 500 km and 1 month, midlatitude SST anomaly variability is lower in winter and spring than it is in summer and fall.

Several observations can be make from Table 1 and Figure 5a. First, the mean difference between the three satellite and ship data sets fluctuates from one month to the next by between a few and seven tenths of a degree, with the SMMR exhibiting the largest such time-dependent biases, and HIRS the least. Note that the SMMR data for November 1979 were limited to the Pacific Ocean. It also should be recalled that the AVHRR processing algorithm was substantially different in November 1979 than in all successive workshop months; a more modest change in algorithm occurred for HIRS between the first two and the last two workshop months. For AVHRR, the standard deviations remain fairly constant between 0.5 and 0.6 C for the first three months, consistent with results previously reported by Strong and McClain [1984], but then climb to nearly 0.8 C in July 1982, when the mean difference drops. This change for July is associated with the occurrence of a large scale stratospheric aerosol cloud produced by the El Chichon volcanic eruption, which caused serious problems for the AVHRR, and will be discussed further below.

In general, inspection of the month to month variation in the mean temperature anomalies of Figure 5a suggests that the three satellite data sets all have time-dependent biases which are sufficiently large to mask out the actual variations measured by the ships. SMMR appears to have the greatest problems of this nature, while HIRS is the least affected. Recalling that the AVHRR data for the first month were produced with a substantially different algorithm, then focussing on the last three workshop months, note that the mean anomalies of Figure 4a for both HIRS and AVHRR change very much like the ship anomaly. Further recalling that the ship data are known to be biased warm by about 0.3 C when compared with higher quality in situ data, we then see that the ship anomalies, adjusted downward by this amount, would agree remarkably well with the AVHRR anomalies. The HIRS data, on the other hand, agree better with the ship data without any such adjustment for ship warm bias. This behavior may well be a reflection of the fact that the HIRS estimates begin with an initial guess for SST of climatology, and the climatology is mostly constructed from ship observations having this warm bias. The AVHRR data, on the other hand, were derived from coefficients applied to infrared brightness temperatures - - coefficients which initially were adjusted to give good agreement with in situ data from drifting buoys which do not have such a warm bias.

On the 200 km and 1 month scales of averaging, intercomparison of Tables 1a and 1b clearly indicates that the rms disagreement between the satellite and ship data is comparable to (for AVHRR and HIRS), or greater than (for SMMR) the rms variability between the ship data and climatology. Since the latter tends to be inflated by insufficient averaging of the noisy ship data, the values shown parenthetically in both tables are those resulting from prior 3 by 3 spatial smoothing of the bins, effectively averaging over 600 km square domains. The smoothing operation tends to reduce the standard deviations of the tables by about 40 %, supporting the previous assertion that the noisy ship data inflates estimates of both the true SST field signal level, and the rms disagreement between satellite and ship observations. The smoothed rms deviations of Table 1a, and the smoothed standard deviations of Table 1b are plotted in Figure 5b. If we take the latter values as reasonable estimates of the true SST signal standard deviation, or at least an upper bound of that level, and the former as the best estimate of satellite SST rms accuracy, the conclusion would be that AVHRR and HIRS have signal-to-noise variance ratios of 1, and for SMMR, 0.25.

While global average statistics are useful in many respects, they also obscure geographically dependent aspects of the satellite SST data. The following two sections thus look at the data, first on an ocean basin scale, and then in even finer detail.

Intercomparison Results - Regional Statistics

As Figure 4 makes clear, the ship data (for bins with at least 5 observations) are mostly confined to the North Pacific north of 20 N, and the North Atlantic north of the equator. Consequently, statistics were computed separately for these two regions and are displayed in Table 2 and Figure 6. The behavior in time of the mean anomaly computed from the ship data is quite similar between the two regions, with little change in the first three workshop months, and then a marked cooling in July 1982. The Atlantic anomalies are 0.2 to 0.3 C warmer than the Pacific anomalies. The SMMR anomalies (note that no SMMR data were available to the workshop for the North Atlantic in November 1979) exhibit the same strong time-dependent biases, being 0.4 to 0.8 C warmer than the ship data in the winter months, and reversing sign to a like negative bias in the spring and summer months. This behavior is consistent with other evidence suggesting that the SMMR algorithm was not properly accounting for the wind speed dependence of the sea surface emissivity, a point we will return to later.

As in the global statistics, for the last three months the HIRS and AVHRR mean anomalies vary in time similarly to the ship anomaly. Also as before, the AVHRR is biased cold in those three months relative to the ships by 0.2 to 0.4 C, while the HIRS is biased warm by 0.0 to 0.3 C.

The sea surface temperature signal level, as estimated by the 3 x 3 smoothed ship standard deviations about climatology, varies between 0.3 and 0.6 C. As in the global case, the satellite - ship rms disagreement (for 3 x 3 smoothing) varies over a similar range for the AVHRR and HIRS cases, yielding signal-to-noise variance ratios of around unity. For SMMR, the large biases drive the rms disagreement values up to the range 0.6 - 1.2 C, for a signal-to-noise ratio of around 0.25. The SMMR standard deviations themselves are in the range 0.5 - 0.8 C, with the higher values in the winter months.

Thematic Maps

A collection of color-coded thematic maps were prepared by the workshop, to portray the relative binned temperature differences between satellite, ship, and climatological temperatures. Since several papers refer to these maps, they are presented once, in the paper by Hilland (this issue), and will be designated here by a prefix H. These maps permit a more detailed inspection of the relative differences in temperature wherever respective pairs of observations are available. These maps will be discussed in sequence.

Figure H-7abcd gives the sea surface temperature anomalies (departures from climatology) for the ship, AVHRR, HIRS, and SMMR, for the four workshop months. Figure H-7a, for November 1979 illustrates the principal limitation for evaluating satellite data: the relative lack of ship data in many parts of the ocean, and its relatively high noise level, even after binning into two degree latitude-longitude quadrangles for a month. The AVHRR data clearly have a much lower bin-to-bin noise level, but in this month provided no retrievals near the equator because of persistent cloudiness in the Intertropical Convergence Zone (ITCZ). The AVHRR data from the last three workshop months does not suffer such a gap. This is attributable to the change in algorithm after November 1981.

The HIRS data are available nearly everywhere, but indicate a ubiquitous zone of warm anomaly near coasts. This was due to a processing algorithm error which was corrected in the last two workshop months. The statistics of Tables 1 and 2 are based on data at least 600 km from land, and are thus uncontaminated by this problem. The bin-to-bin noise of the HIRS data is high, but is in part due to processing of only one fourth of the potentially available data. The July 1982 HIRS data incorporated all available data, and the corresponding thematic map of it is notably smoother in appearance. Similarly, the Table 1 HIRS standard deviation drops substantially in that month compared with the previous three months.

The SMMR data for November 1979 supplied to the workshop were only for the Pacific Ocean between 50 N and 50 S. The 600 km coastal mask to eliminate land contamination in the antenna sidelobes is evident. The SMMR data itself appear on a bin-to-bin basis to be smoother than the HIRS data.

Comparing anomalies between the four maps for November 1979 reveals a number of similar and dissimilar patterns. For example, the arrangement of mid-latitude North Pacific cold and warm anomalies in the ship data is well reflected in the AVHRR map. The same is true for the HIRS map, after taking account of its greater bin-to-bin noise and the coastal warm error. Both the AVHRR and HIRS show similar patterns of warm anomaly in the eastern and central tropical Pacific, a pattern which is only hinted at by the limited amount of ship data there. The SMMR anomaly patterns have little apparent correlation with the ships or other satellite sensors in any geographical region.

In December 1981 (Figure H-7b) the ship and AVHRR anomaly patterns are remarkably similar in the North Atlantic, with a small area of warm anomaly extending east from Newfoundland about halfway across the Atlantic in a narrow band. The eastern Atlantic along Portugal and North Africa as well as the tropical Atlantic have slightly positive anomaly. The western Atlantic near the U.S. east coast has negative anomaly, somewhat more negative for the AVHRR than for the ship maps. Similarly in the mid-latitude North Pacific, negative anomalies are located in the eastern central region, and also just east of Japan, but with the AVHRR biased cold with respect to the ships. This bias was previously established in the statistics of Tables 1 and 2, and Figures 4 and 5. In the western equatorial Pacific an area of quite postive AVHRR anomaly does not occur in the ship data. This is a region of maximum atmospheric water vapor. The tendency for the AVHRR water vapor correction scheme to overestimate sea surface temperature in such situations was noted by NOAA personnel shortly after December 1981, and the algorithm was appropriately adjusted. In the mid-latitude southern hemisphere ship data are sparse. Nonetheless, areas of pattern agreement may be found in the South Atlantic and Indian Oceans.

The HIRS anomaly patterns for December 1981 show agreement with the ship map in the North Atlantic, once the warm coastal error error and the higher bin-to-bin noise level of the HIRS data are accounted for. The eastern mid-latitude North Pacific ship and HIRS anomalies are also similar, with the HIRS appearing biased slightly warm with respect to the ships, as the earlier statistical summaries had shown. The western equatorial Pacific HIRS anomaly shows near normal temperatures there, in agreement with the ships. The mid-latitude South Atlantic HIRS and AVHRR maps are in good agreement. The extreme southern hemisphere HIRS data south of 50 S is consistently cold, both with respect to the AVHRR data, and also to the limited ship data.

As in the previous workshop month, the SMMR anomaly patterns for December 1981 bear little resemblence to the ship, AVHRR, or HIRS maps. Portions of the mid-latitude North Atlantic and North Pacific have strong positive biases, reinforcing the suggestion of a windspeed - emissivity related error in the processing algorithm, which is tending to bias temperatures high in regions of high wind. It is curious to note that the SMMR anomaly pattern in the mid-latitude South Atlantic does resemble that from the AVHRR and HIRS. This region should be experiencing lighter winds at this season, and thus not be so subject to any such windspeed related error in SMMR data. Yet there is virtually no pattern correlation between SMMR and either the AVHRR or HIRS in the tropical Atlantic, or the tropical and mid-latitude South Pacific. For SMMR, large areas of negative anomaly occur in all three southern hemisphere mid-latitude ocean basins, extending in the case of the Atlantic and Pacific in the north west direction into the tropical and subtropical northern hemisphere. These patterns appear in regions where winds would be expected to be weakest, and thus the suggestion remains that windspeed - emissivity effects may be dominating the SMMR algorithm.

Proceeding on to the third workshop month of March 1982 (Figure H-7c), the ship data show temperatures very near normal, with small anomalies over most of the North Atlantic, and similarly for the North Pacific except for some limited areas of cold anomaly. The AVHRR anomaly patterns in both regions are quite different, and biased colder. The western equatorial Pacific and Indian Ocean region continues to show warm AVHRR anomalies not reflected in the ship data. The HIRS does not show this warm bias around Indonesia, and is more in agreement with the ship data in the North Atlantic and North Pacific. As in the previous month, the HIRS data evidences a persistent cold anomaly in the extreme southern hemisphere. The SMMR data appear to be in much better agreement with the AVHRR (but not the ship data) in the mid-latitude North Pacific, South Atlantic, and South Indian Oceans than was the case in previous months, but this does not extend to include the South Pacific.

In both the AVHRR and SMMR data, two narrow bands of warm anomaly extend across the Pacific, beginning near California and Chile respectively, and appearing to end near Indonesia. A similar pattern appears in the South Pacific HIRS map, but not in the ship data, although the latter provides poor geographic coverage there. The positions of these bands coincide with the northern and southern hemisphere tropical convergence zones, areas of persistent high altitude cloudiness, and increased water vapor and rain. We can only speculate that either atmospheric geophysical effects may be acting to produce the same artifact in all three satellites maps, or alternatively, we may be looking at true large scale signals too weak for the noisy and sparse ship data to detect.

The large region of cold anomaly in the subtropical North Atlantic SMMR map for March 1982 occurs also in the July 1982 map (Figure H-7d). This has been identified by those who processed the data as evidence of instrument warm-up problems. The instrument was turned on for 24 hours, then left off for the same period, with the same one day on, one day off cycle continuing throughout its life. The time for turn-on and turn-off are at 00 hours GMT, and the first few hours after turn-on provide the North Atlantic coverage. We again can only speculate that the reason this cold bias does not appear in the first two (wintertime) months is because it is overridden by the warm windspeed-emissivity bias in those periods of higher winds.

The most striking aspect of the July 1982 anomaly maps is the large negative anomaly in the AVHRR data extending globally in a zonal band between roughly 10 N and 30 N. This is the signature of the El Chichon volcanic aerosols mentioned earlier, which were not properly accounted for in the AVHRR processing algorithm. These aerosols remained in the stratosphere, and resulted in serious cold biases in the AVHRR data from April 1982 until late 1982 or early 1983. Procedures are now available for reprocessing the original AVHRR radiance data to determine the aerosol optical thickness and also correct for the aerosol-induced error in sea surface temperature estimates [Griggs, 1984].

Poleward of 30 N and beyond the aerosol contamination, the patterns of AVHRR anomaly are quite similar to those of the ship data, both in the North Atlantic and North Pacific, except that AVHRR anomalies appear to be biased low relative to ships. The same patterns also occur in the HIRS map, which does not appear to be as affected as the AVHRR by the El Chichon effects. Still, some cold biases, most likely from the El Chichon aerosols, do appear in the HIRS. Negative anomalies occur in the eastern Atlantic, near the equator and off North Africa. Also, a large negative anomaly appears in the western subtropical North Pacific. Neither areas have significant cold anomalies in the ship data.

In the South Pacific just northeast of New Zealand a large negative anomaly appears reasonably well defined in the ship data. This region, which is well south of the aerosol contamination band, also appears as a negative anomaly in the AVHRR, HIRS, and SMMR maps. In the mid-latitude North Pacific the SMMR map bears some rough resemblance to the ship map. Finally, we note the tongue of warm anomaly extending along the equator in the eastern tropical Pacific in the SMMR map. The ship data, while sparse there, are sufficient to define a similar feature. Neither the AVHRR nor the HIRS give similar structure there. Over the following few months this anomaly increased steadily as a major El Nino event increased sea surface temperatures in this region.

Other color-coded thematic maps of temperature differences were assembled. They mostly portray aspects which have already been discussed, and will therefore only be commented upon briefly. Figure 8 portrays the relative differences between ship and satellite anomaly fields for the four workshop months. Figure H-8a (November 1979) shows how the noisy ship field is reflected in the AVHRR - ship difference map. Since the HIRS field had considerable bin-to-bin noise as well, the HIRS - ship difference map is particularly noisy. The warm coastal error in the HIRS is clearly displayed. The SMMR - ship difference map for this month manifests a latitude-dependent bias, warm at 50 N and cold at 30 N, in accordance with windspeed as discussed previously. The same pattern is even more evident in December 1981 (Figure H-8b), as would perhaps be anticipated with the normal increase in winds from November to December around 40 to 50 N.

The December 1981 AVHRR - ship and HIRS - ship difference maps also show the respective tendency to cold and warm bias of these two satellite sensors in the mid-latitude northern hemisphere. The HIRS - ship difference map indicates little geographic structure, but the AVHRR - ship difference map suggests that the AVHRR cold bias is concentrated along 40 N in the North Pacific, and along the Gulf Stream in the Atlantic. These are regions of maximum horizontal gradient in sea surface temperature, and perhaps in the development of cloudiness in the overlying atmosphere.

By March 1982 (Figure H-8c) the SMMR - ship differences in the mid-latitude northern hemisphere are much reduced, again as expected with the seasonal relaxation in windspeed. The cold bias over the North Atlantic due to instrument turn-on stands out clearly. The cold and warm biases of the AVHRR and HIRS, respectively, now appear more evenly distributed over the North Atlantic and North Pacific.

In July 1982 (Figure H-8d), the AVHRR - ship difference map gives a clear depiction of the El Chichon aerosol distribution which is also weakly reflected in the HIRS - ship map.

The last sequence of thematic maps (Figure H-9) displays the geographic distribution of the difference between the three satellite data sets. The most disturbing aspect of these differences is that their magnitude and geographic variation so resembles the ship - climatology anomaly maps, i.e. the signal one wishes to study. The differences between the satellite sensors appear to be due to a mixture of large scale geophysical effects, related to such things as windspeed, water vapor, and cloudiness. These maps should serve as a cautioning sign to those who wish to use these satellite sea surface temperature data sets to examine the relation of this parameter to other geophysical variables. Some signals in some regions may be sufficiently strong, or sufficiently error free, to permit such studies. Yet great care should be exercised, and some conclusions must remain conditional.

Conclusions

Since 1978, considerable efforts have been devoted by a number of investigators to improving sea surface temperature (SST) estimation from satellite remote sensing instruments. Steady improvements in algorithms and instrumentation have yielded accuracies that now appear marginally useful for studies of large-scale climatic variability. The most promising techniques utilize infrared, microwave or multi-spectral (both infrared and microwave) measurements of radiation emitted from the sea surface. Individual investigations have reported accuracies better than 1 C by all techniques. The principal instruments are AVHRR, HIRS/MSU and SMMR.

A series of NASA-sponsored workshops were held at the Jet Propulsion Laboratory to intercompare the various techniques and identify relative strengths and weaknesses, with the ultimate goal of further improvements in the SST retrievals. The scope of the workshops was focused by limiting attention to the use of SST for studies of short-term climatic variability (time scales of a month to a few years). Thus, the satellite data were binned into 2 degree latitude-longitude squares and averaged over one month. Four comparison months were selected to span a broad range of environmental conditions: November 1979, December 1981, March 1982 and July 1982. An equally important question that was not addressed by the workshops is the accuracies of satellite SST measurements over shorter space and time scales.

Since all three satellite instruments (AVHRR, SMMR and HIRS/MSU) had purported accuracies better than 1 C, we initially expected that it would be difficult to discern significant differences between sensors. These claimed accuracies were for individual measurements. For the 2 degree quadrangle monthly averages dealt with in the workshops, many individual measurements were averaged in each such 2 degree bin. If the 1 C rms errors were truly random, these errors would be reduced by the square root of the number of observations in each bin. Initially it was thought that some rather involved data analysis techniques might be required to identify problem areas. The actual results of the workshops turned out to be quite different, however. The rms errors in the binned averages appearred to be only slightly improved over those reported for individual measurements. The signal-to-noise variance ratio was about 1 for AVHRR and HIRS/MSU, and about 0.25 for SMMR. The errors in individual measurements must therefore not be entirely random. One of the most productive aspects of the workshops was that a number of candidate causes for the systematic errors were identified. These factors included the effects of water vapor (AVHRR), stratospheric aerosols (AVHRR and, to a lesser extent, HIRS/MSU), cloud cover (AVHRR) and wind speed (SMMR). Improvements in future algorithms for SST retrieval may be

The intercomparison of AVHRR, HIRS/MSU, SMMR, ship and climatological SST for the four selected months revealed a very complex set of relations. The various measuring techniques agreed in some places and at some times, but disagreed in others. The workshops drew attention to some major limitations in the intercomparisons which should be carefully considered in future intercomparison studies. Most important is the lack of geographically well-distributed and high quality in situ data with which to evaluate satellite SST estimates. For the global binned average comparisons of the workshops, routine ship observations were used as "surface truth" data. These ship data are known to be biased high by about 0.3 C and have an rms error in individual measurements of about 1 C (approximately the same magnitude as the signal in SST from variations about the climatological mean). In regions heavily sampled by ships, this rms error can be significantly reduced through appropriate spatial and temporal averaging. Unfortunately, ship observations are quite sparse over most of the world oceans. In the workshops, we were forced to include all 2 degree squares with 5 or more ship samples over a month. Clearly, this is too few to significantly suppress measurement errors. The validation of present and future satellite SST sensors will require a substantial improvement in the quantity and quality of such in situ data over the full range of oceanic and atmospheric conditions.

A final point worth noting is that, in retrospect, the selection of intercomparison months was somewhat less than optimal. Ideally, we would like to choose months with large anomalous SST signals. That was not the case with any of the four selected months. Over the whole world ocean, it appears that SST anomalies as measured by ships rarely differed by more than about 1 C for these four months. If larger SST anomalies had been present during some of the months, it might have been easier to identify strengths and weaknesses of the measuring techniques. Indeed, other factors limiting SST retrievals might have been discovered. Any future intercomparison studies must examine many different months (four was too few to achieve an adequate statistical base) and several of the months examined should be selected specifically on the basis of known large SST anomalies.

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Table 1a. Global binned difference temperature (satellite minus ship) statistics (degrees C). Only bins with five or more ship observations are included. No bins within 600 km of land are included. Values in parentheses are difference statistics for 3 x 3 spatially smoothed bins.

Satellite Sensor		Nov 1979	Dec 1981	Mar 1982	Jul 1982
AVHRR	mean	0.19 (0.24)	-0.30 (-0.33)	-0.36 (-0.44)	-0.48 (-0.35)
	st dev	0.58 (0.35)	0.50 (0.28)	0.51 (0.29)	0.79 (0.52)
	rmsd	0.61 (0.42)	0.58 (0.43)	0.62 (0.53)	0.92 (0.63)
	# obs	723 (324)	729 (235)	795 (368)	644 (274)
HIRS	mean	-0.04 (-0.20)	0.13 (0.21)	0.30 (0.29)	-0.07 (0.09)
	st dev	1.01 (0.62)	0.88 (0.42)	0.92 (0.31)	0.69 (0.38)
	rmsd	1.01 (0.65)	0.89 (0.47)	0.97 (0.42)	0.69 (0.39)
	# obs	735 (324)	729 (235)	795 (368)	662 (327)
SMMR	mean	0.52 (0.72)	0.72 (0.71)	-0.21 (-0.17)	-0.43 (-0.69)
	st dev	1.27 (0.81)	1.17 (0.79)	1.11 (0.79)	0.97 (0.60)
	rmsd	1.37 (1.08)	1.37 (1.06)	1.13 (0.81)	1.06 (0.91)
	# obs	395 (152)	677 (226)	690 (300)	522 (230)

Table 1b. Same as Table 1a except ships minus climatology.

	Nov 1979	Dec 1981	Mar 1982	Jul 1982
mean	0.00 (0.00)	-0.03 (-0.08)	-0.09 (-0.13)	-0.46 (-0.70)
st dev	0.80 (0.54)	0.61 (0.38)	0.52 (0.35)	0.74 (0.63)
# obs	735 (324)	729 (235)	795 (368)	635 (336)

Table 2a-I. Same as Table 1a except for North Pacific between 20 N and 56 N.

		Nov 1979	Dec 1981	Mar 1982	Jul 1982
	mean	0.21 (0.27)	-0.44 (-0.43)	-0.50 (-0.54)	-0.37 (-0.17)
AVHRR	st dev	0.61 (0.33)	0.50 (0.29)	0.48 (0.29)	0.93 (0.62)
	rmsd	0.64 (0.43)	0.66 (0.52)	0.69 (0.61)	1.00 (0.64)
	# obs	397 (176)	376 (127)	434 (210)	320 (117)
	mean	0.06 (-0.06)	0.31 (0.21)	0.47 (0.42)	0.01 (0.14)
HIRS	st dev	1.08 (0.65)	0.89 (0.45)	0.95 (0.41)	0.72 (0.39)
	rmsd	1.08 (0.65)	0.94 (0.50)	1.06 (0.59)	0.72 (0.41)
	# obs	397 (176)	376 (127)	434 (210)	337 (170)
	mean	0.66 (0.76)	1.08 (0.95)	0.05 (0.13)	-0.22 (-0.39)
SMMR	st dev	1.25 (0.78)	1.10 (0.72)	0.99 (0.67)	0.87 (0.48)
	rmsd	1.41 (1.09)	1.54 (1.19)	0.99 (0.68)	0.90 (0.62)
	# obs	353 (148)	361 (126)	392 (200)	278 (127)

Table 2b-I. Same as Table 1b except for North Pacific between 20 N and 56 N.

	Nov 1979	Dec 1981	Mar 1982	Jul 1982
mean	-0.20 (-0.19)	-0.18 (-0.12)	-0.27 (-0.29)	-0.67 (-0.96)
st dev	0.89 (0.61)	0.61 (0.41)	0.48 (0.32)	0.73 (0.50)
# obs	397 (176)	376 (127)	434 (210)	338 (179)

Table 2b-II. Same as Table 1a except for North Atlantic between equator and 56 N.

		Nov 1979	Dec 1981	Mar 1982	Jul 1982
	mean	0.17 (0.20)	-0.15 (-0.19)	-0.29 (-0.30)	-0.57 (-0.48)
AVHRR	st dev	0.57 (0.38)	0.41 (0.18)	0.42 (0.21)	0.60 (0.37)
	rmsd	0.59 (0.43)	0.44 (0.26)	0.51 (0.37)	0.83 (0.61)
	# obs	270 (144)	255 (102)	267 (153)	258 (157)
	mean	-0.13 (-0.35)	0.10 (0.24)	0.16 (0.12)	-0.08 (0.04)
HIRS	st dev	0.95 (0.52)	0.77 (0.39)	0.84 (0.35)	0.62 (0.36)
	rmsd	0.96 (0.63)	0.78 (0.46)	0.85 (0.37)	0.62 (0.36)
	# obs	270 (144)	255 (102)	267 (153)	259 (157)
	mean	-	0.42 (0.47)	-0.76 (-0.77)	-0.88 (-1.07)
SMMR	st dev	-	1.14 (0.76)	1.19 (0.69)	0.93 (0.51)
	rmsd	-	1.21 (0.89)	1.41 (1.03)	1.28 (1.18)
	# obs	-	227 (96)	213 (95)	193 (103)

Table 2b-II. Same as Table 1b except for North Atlantic between equator and 56 N.

	Nov 1979	Dec 1981	Mar 1982	Jul 1982
mean	0.21 (0.23)	0.14 (-0.01)	0.05 (0.10)	-0.26 (-0.40)
st dev	0.59 (0.33)	0.55 (0.35	0.42 (0.27)	0.69 (0.64)
# obs	270 (144)	255 (102)	267 (153)	259 (157)

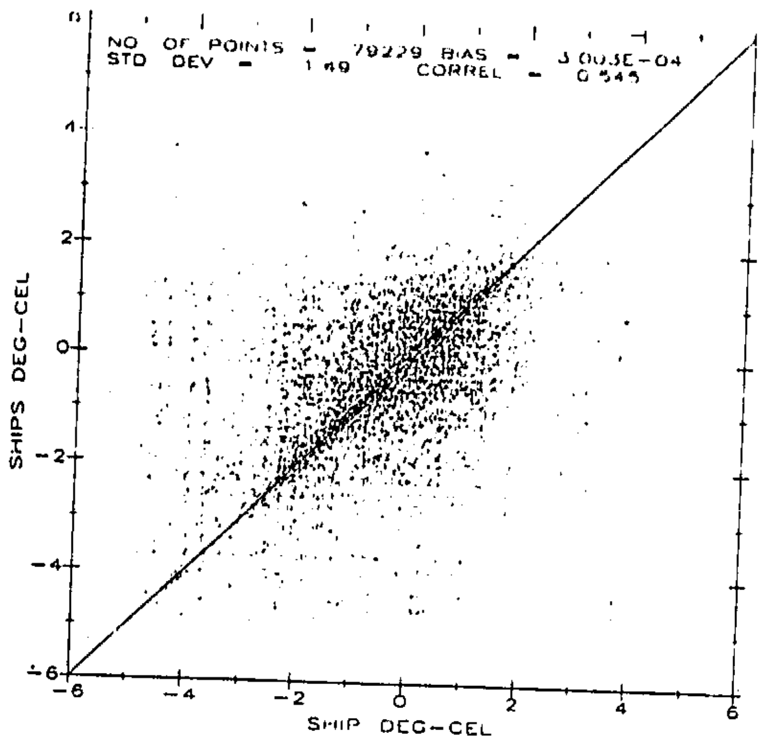

Figure 1. Scatterplot of all pairs of individual ship sea surface temperature observations taken within 6 hours and 100 km of each other during December 1981 in the North Pacific (0 - 55 N, 100 E - 70 W). There are 79,229 such pairs, whose difference in temperature has negligible mean and a standard deviation of 1.49 C.

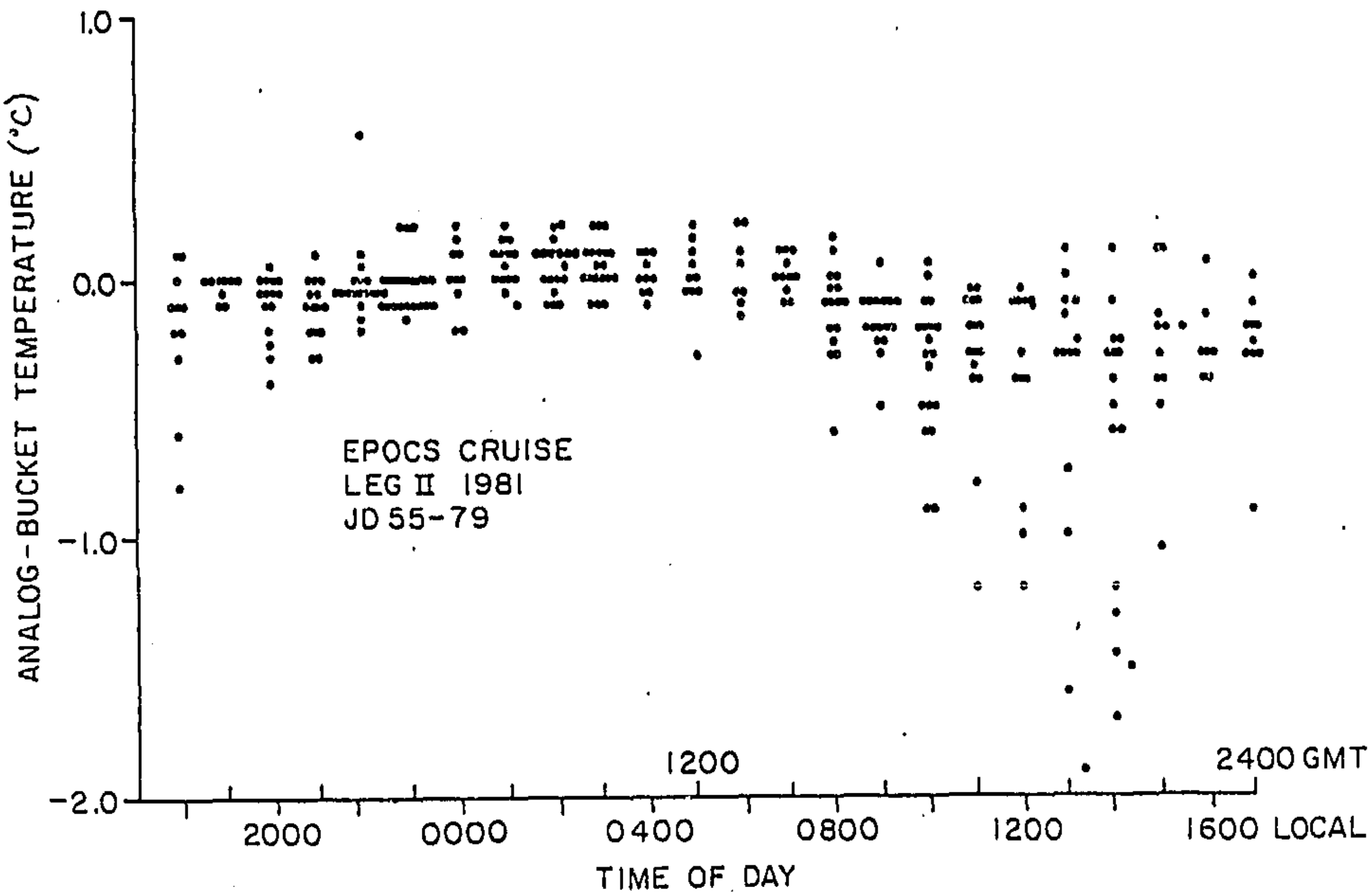

Figure 2. Scatterplot of the temperature differences, continuous underway (5 m depth) minus bucket (<1 m depth), as a function of local time of day for a research cruise in the eastern tropical Pacific, 24 February - 20 March 1981 [P. Pullen, 1985].

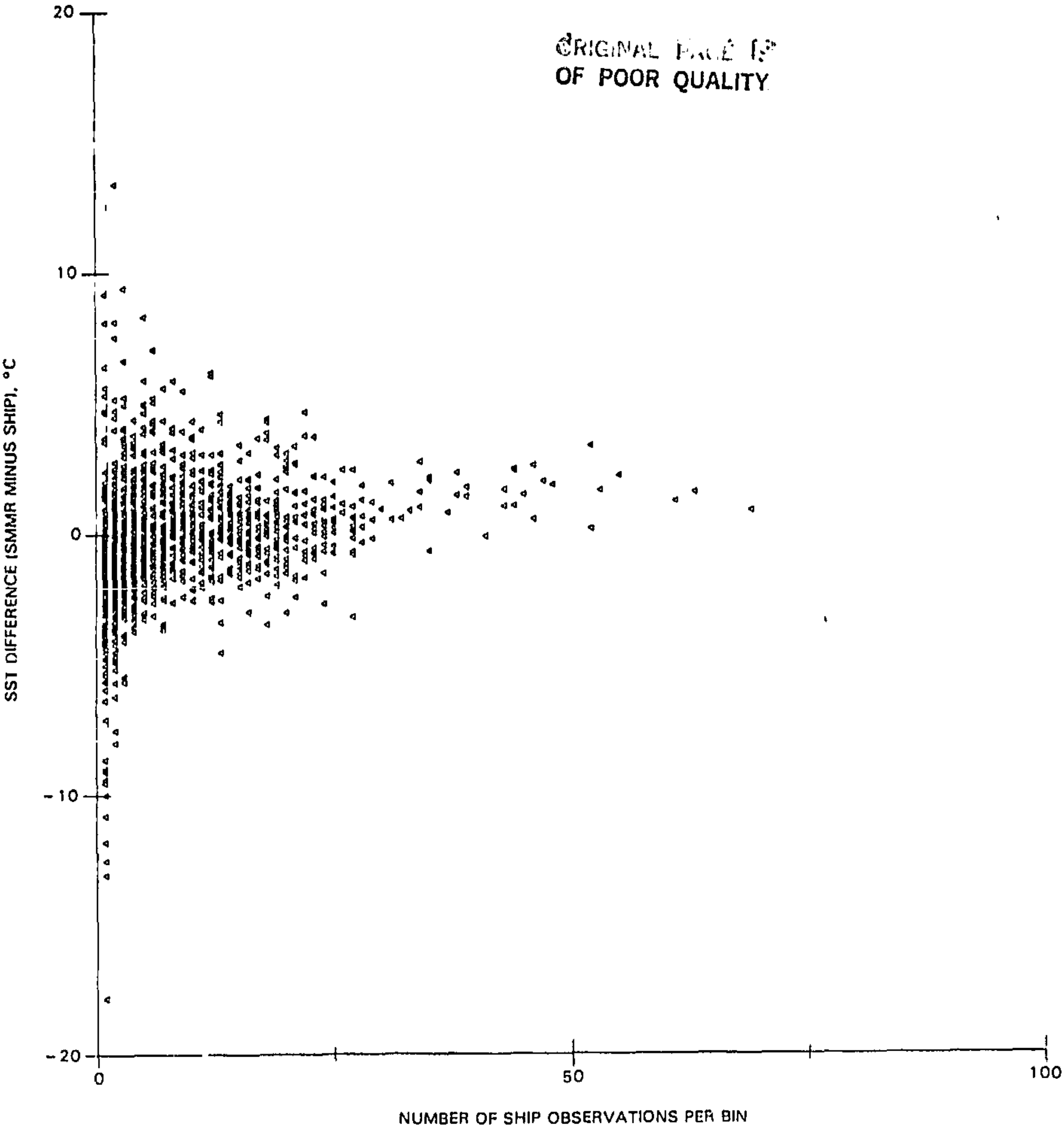

Figure 3. Difference between SMMR and ship binned sea surface temperatures, plotted as a function of the number of ship observations per bin [Jet Propulsion Laboratory, 1983].

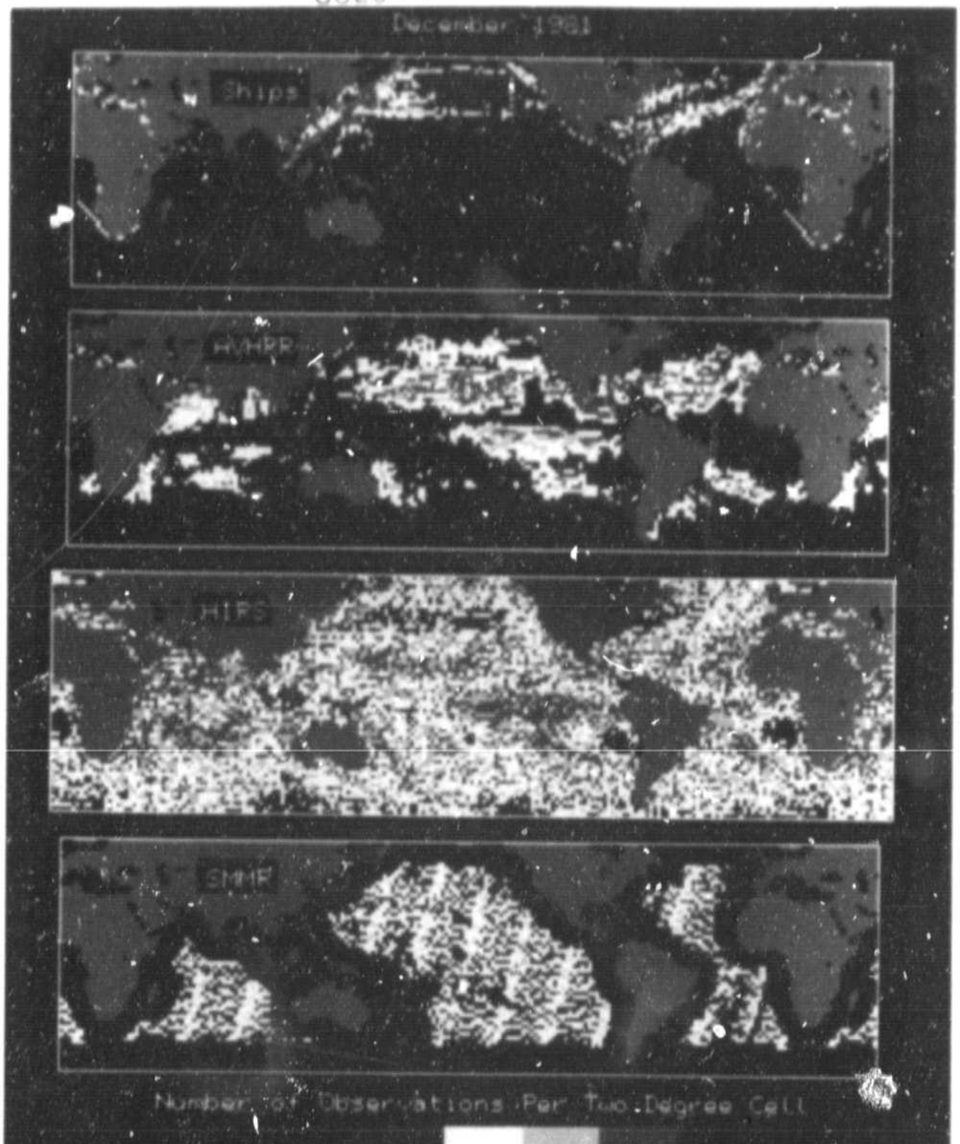

Figure 4. December 1981 distribution of number of individual observations per two degree quadrangle, for ship, AVHRR, HIRS, and SMMR data. Note the different color scale for the four data types.

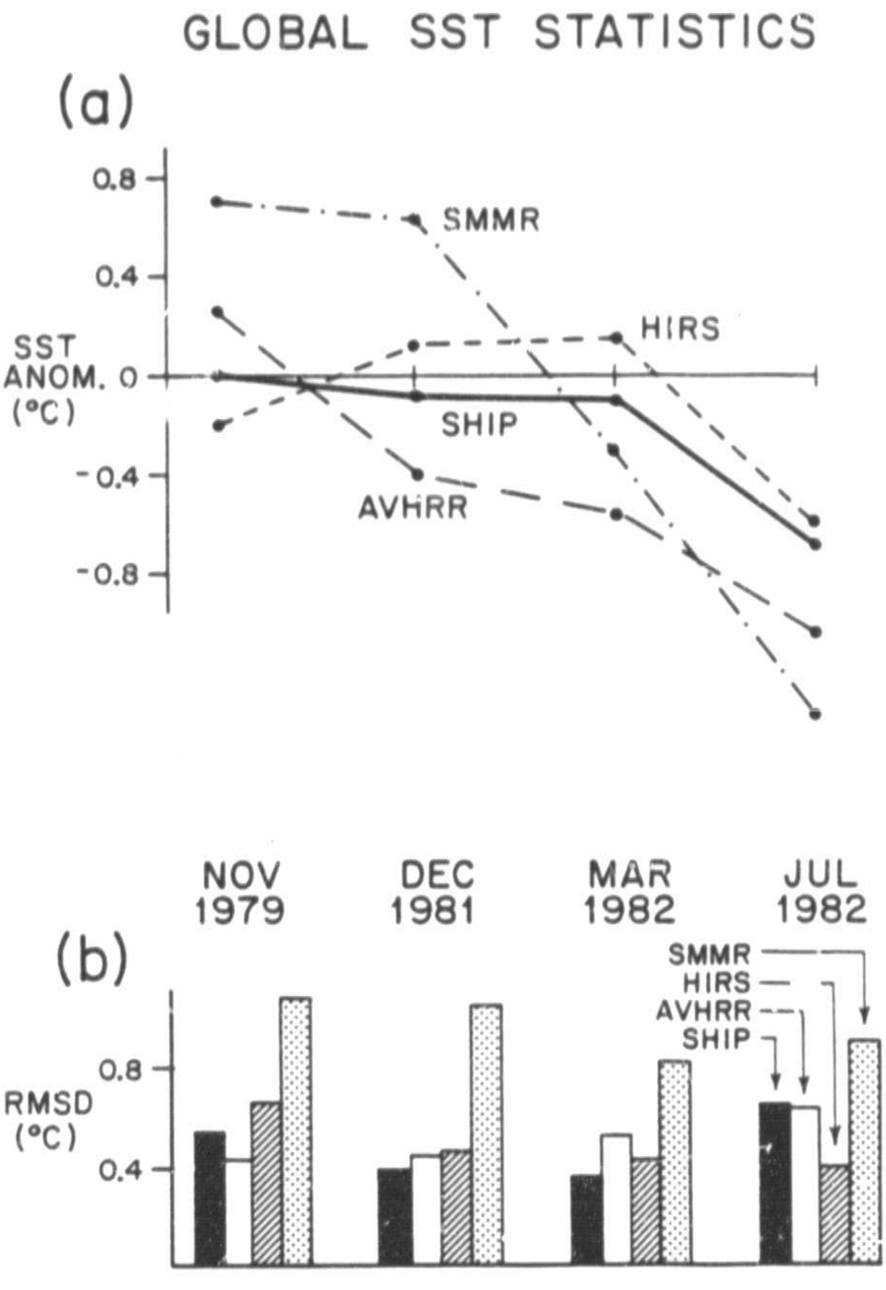

Figure 5. Plot of global sea surface temperature statistics derived from Table 1 (3 x 3 smoothed values): (a) mean difference with respect to climatology, and (b) ship standard deviation, and satellite - ship rms differences, for each of the workshop months.

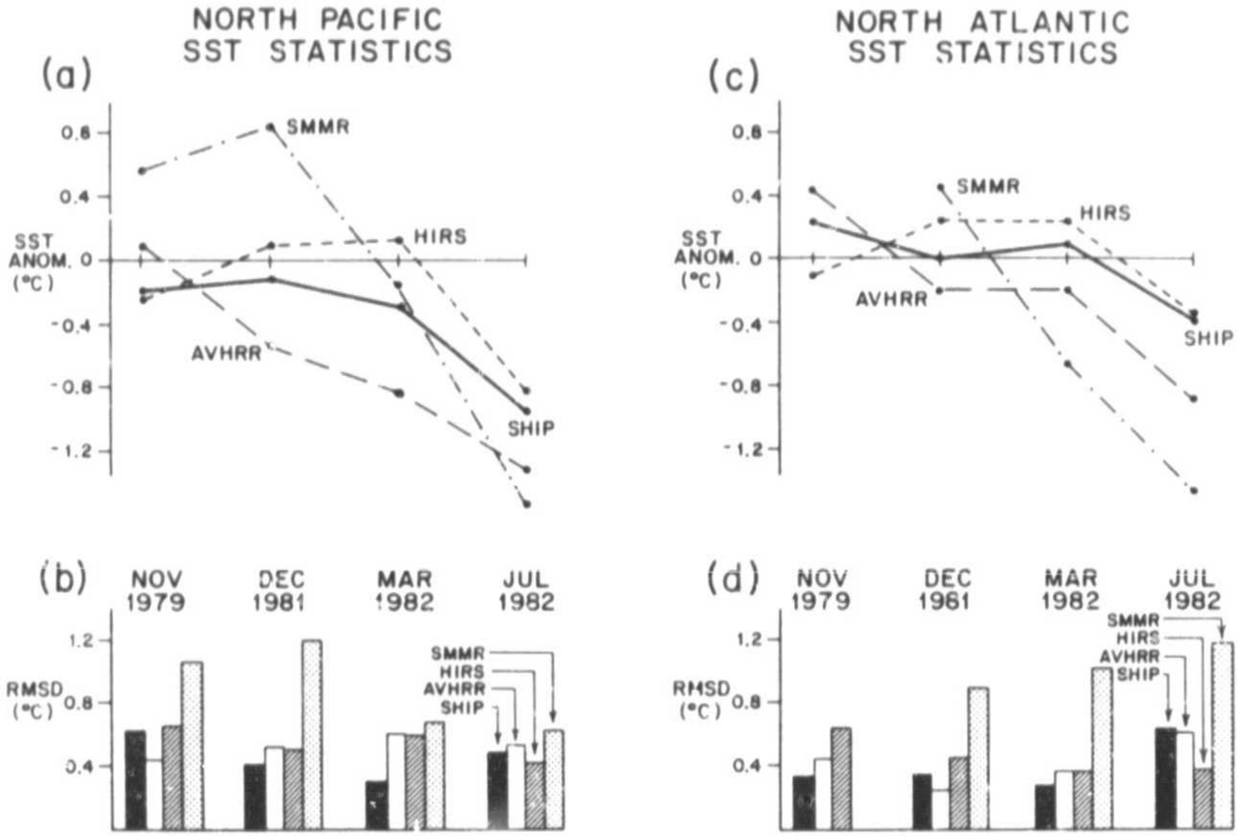

Figure 6. Same as Figure 4, except separately for the North Pacific and North Atlantic, as derived from Table 2 (3 x 3 smoothed values).

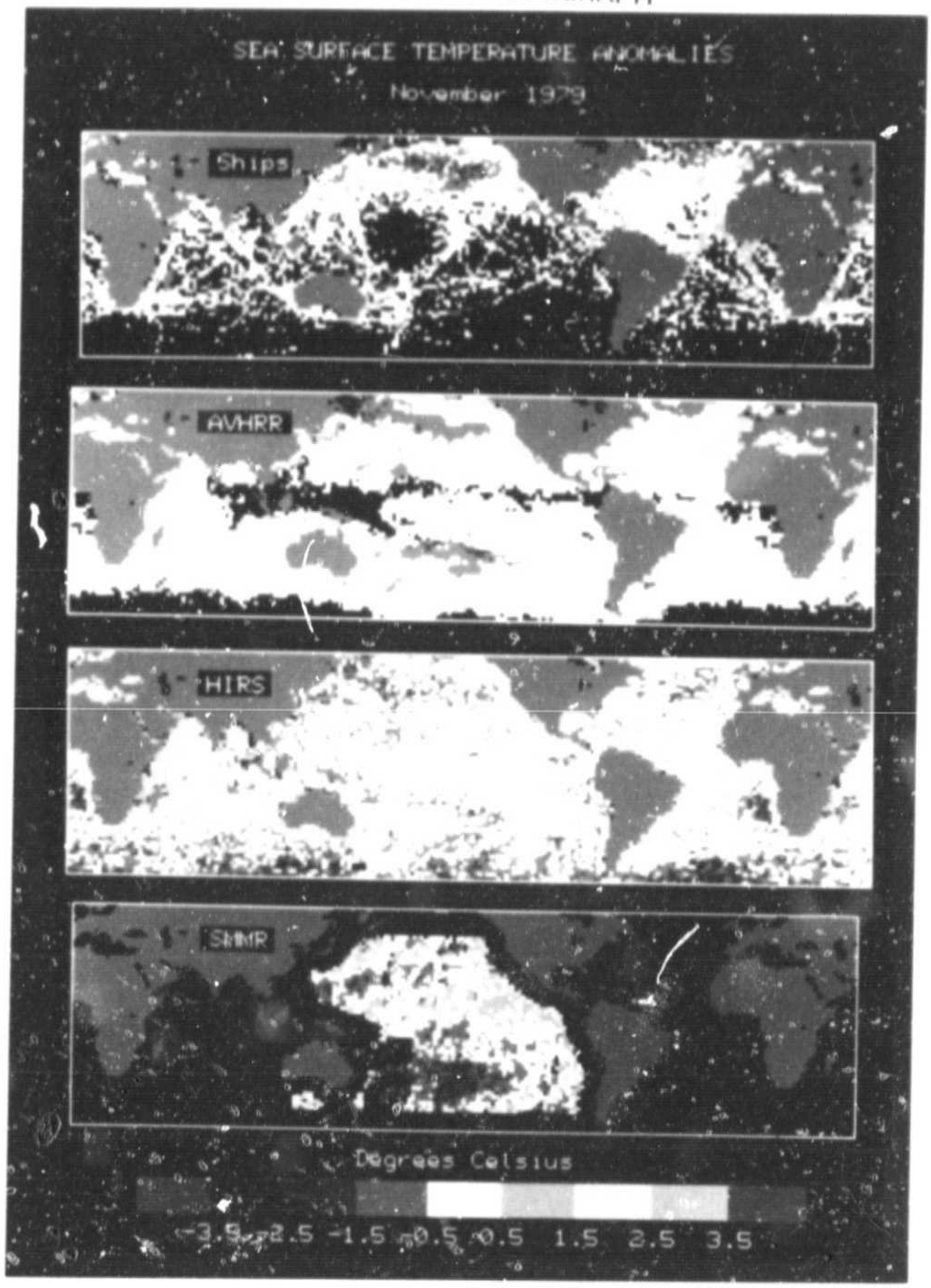

Figure 7a. Sea surface temperature binned anomalies (departure from climatology) for ship, AVHRR, HIRS, and SMMR data, for November 1979.

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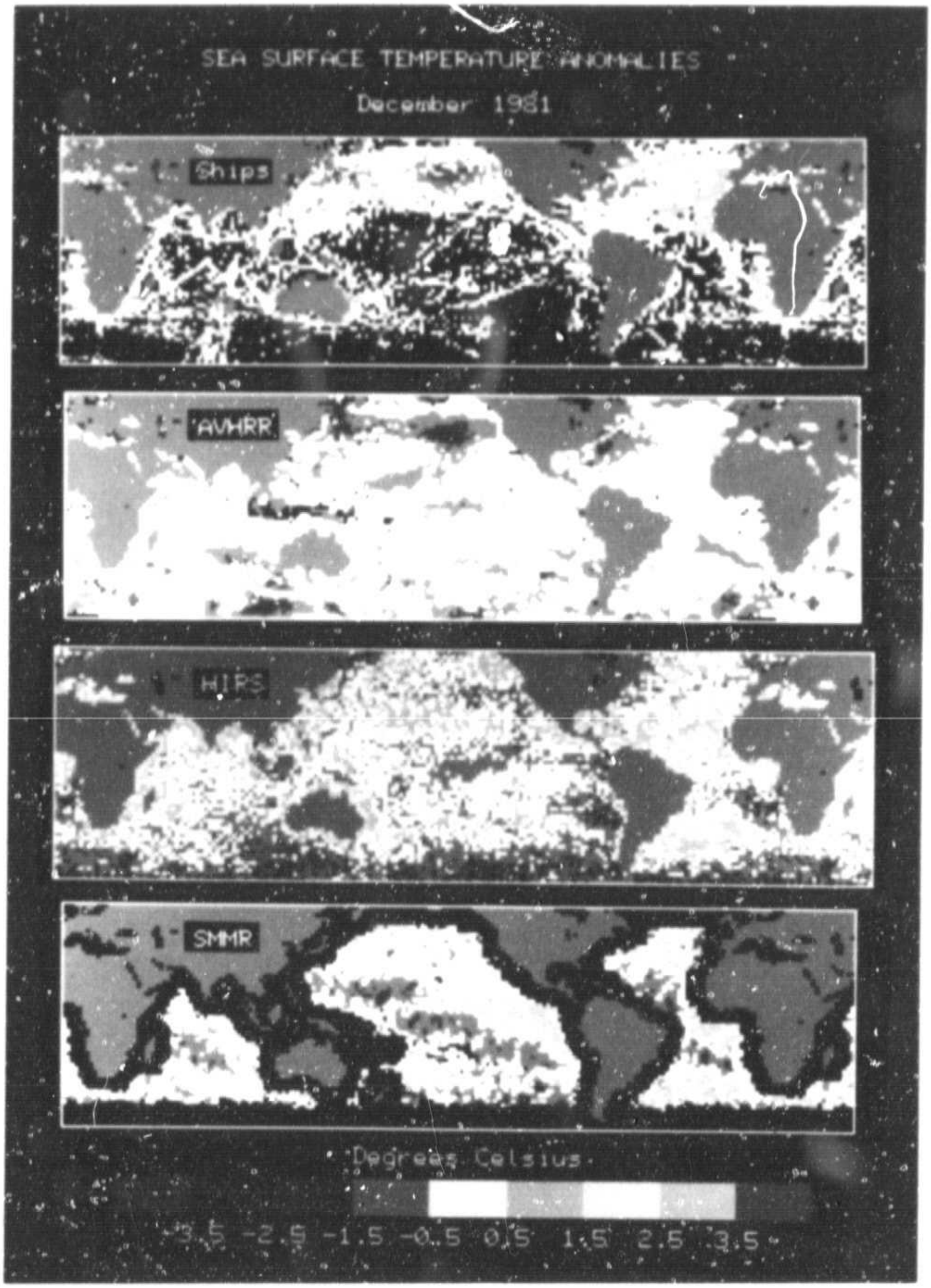

Figure 7b. Sea surface temperature binned anomalies (departure from climatology) for ship, AVHRR, HIRS, and SMMR data, for December 1981.

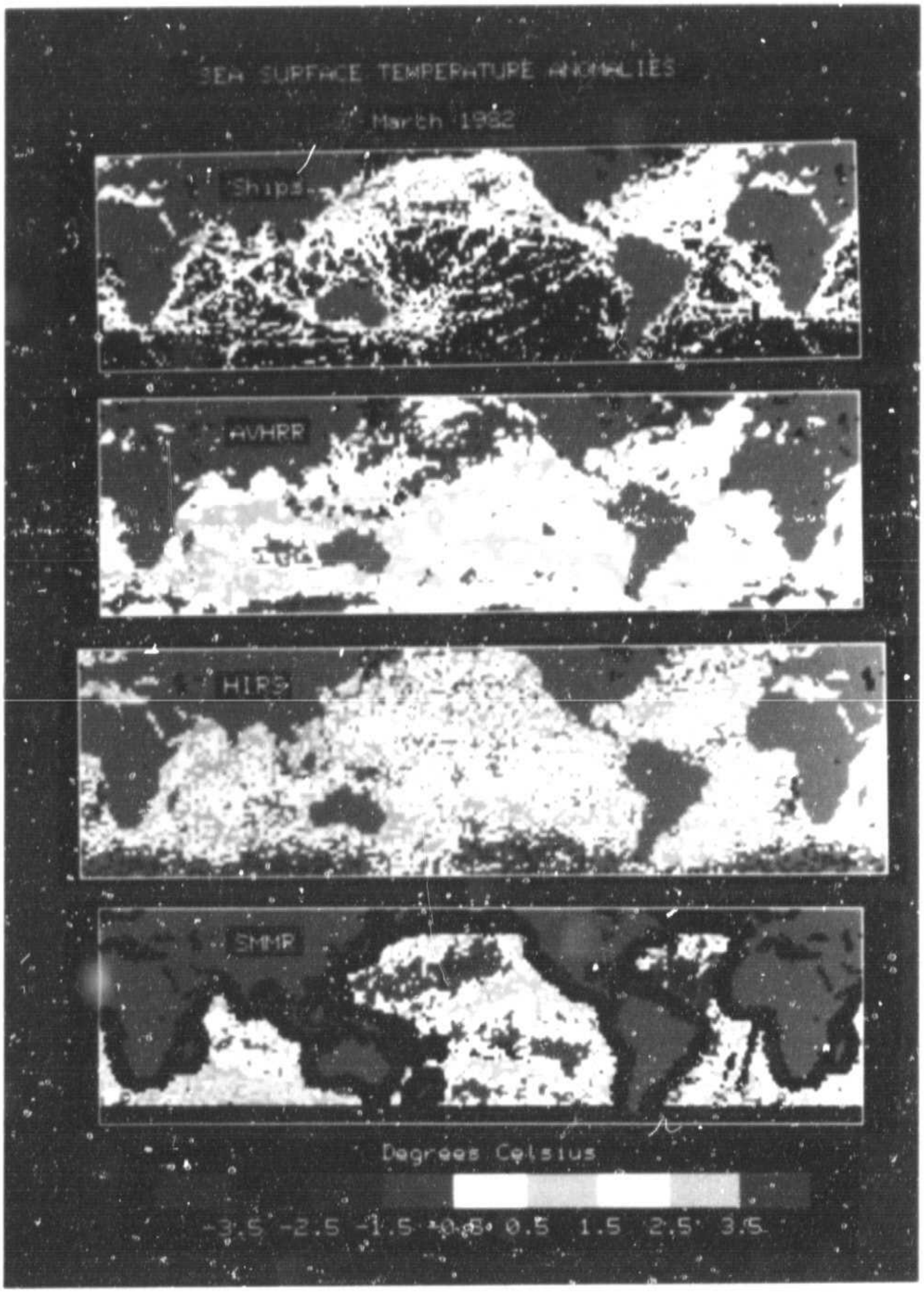

Figure 7c. Sea surface temperature binned anomalies (departure from climatology) for ship, AVHRR, HIRS, and SMMR data, for March 1982.

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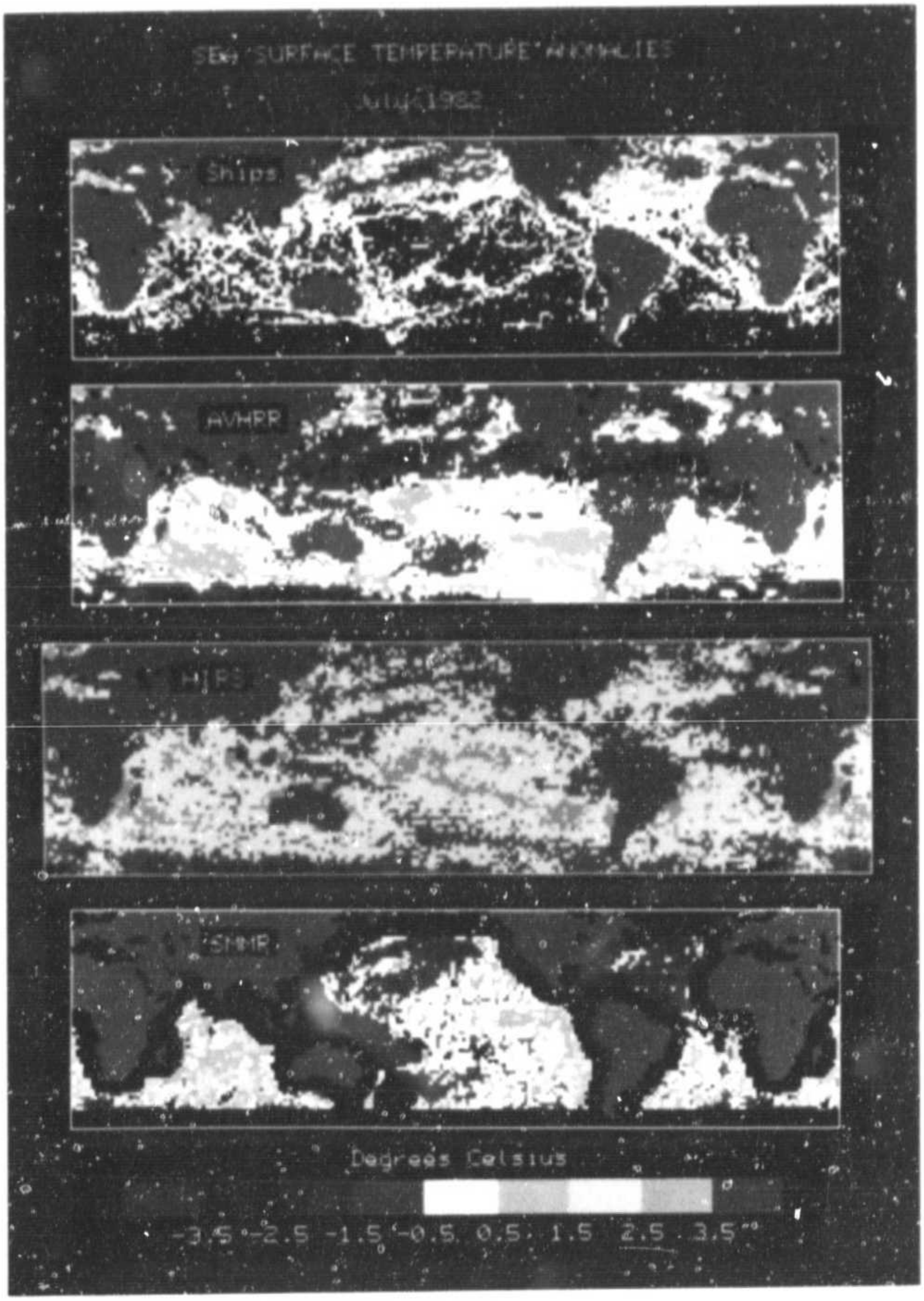

Figure 7d. Sea surface temperature binned anomalies (departure from climatology) for ship, AVHRR, HIRS, and SMMR data, for July 1982.

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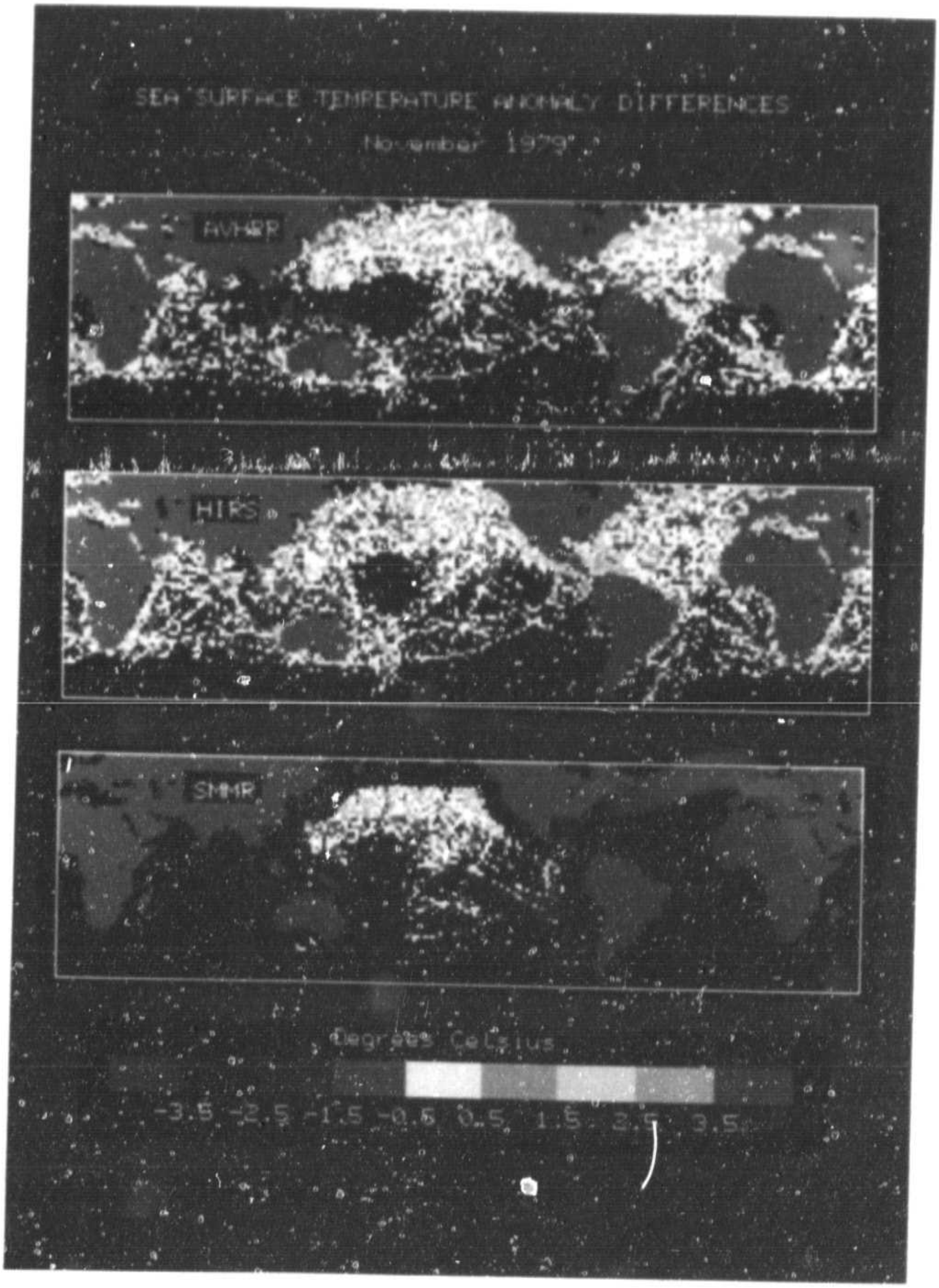

Figure 8a. Difference in binned anomalies, satellite minus ship, for AVHRR, HIRS, and SMMR, for November 1979.

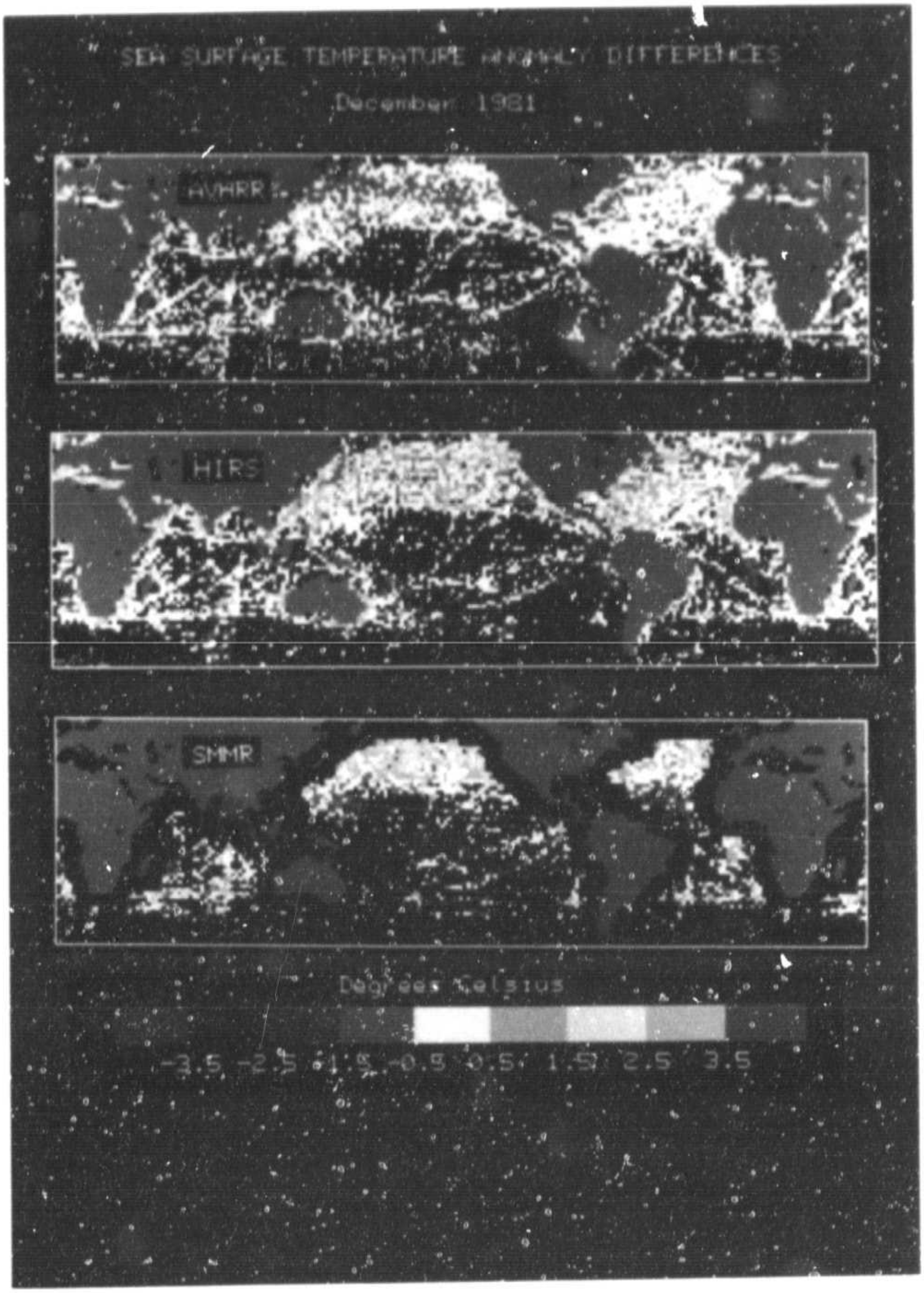

Figure 8b. Difference in binned anomalies, satellite minus ship, for AVHRR, HIRS, and SMMR, for December 1981.

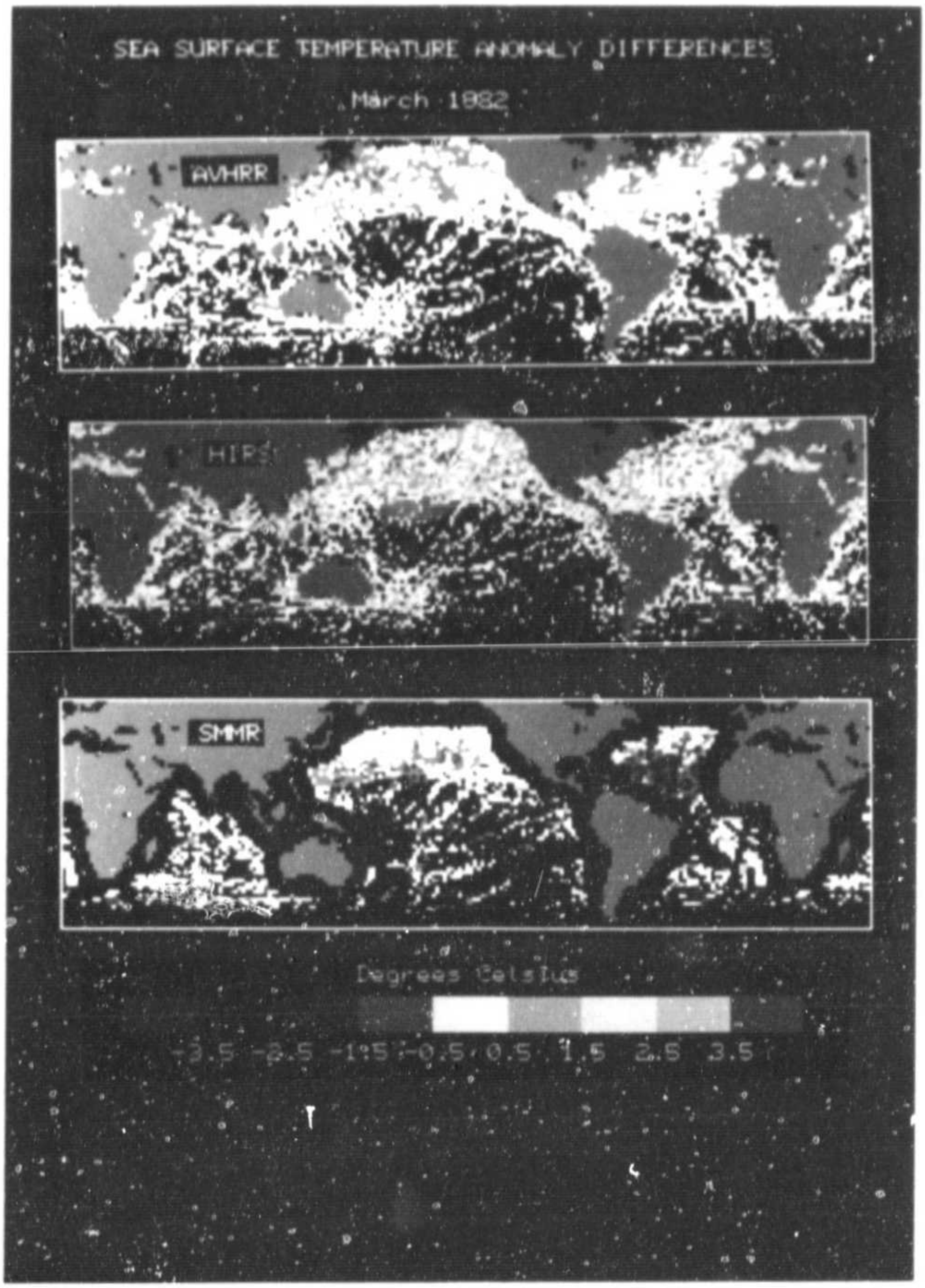

Figure 8c. Difference in binned anomalies, satellite minus ship, for AVHRR, HIRS, and SMMR, for March 1982.

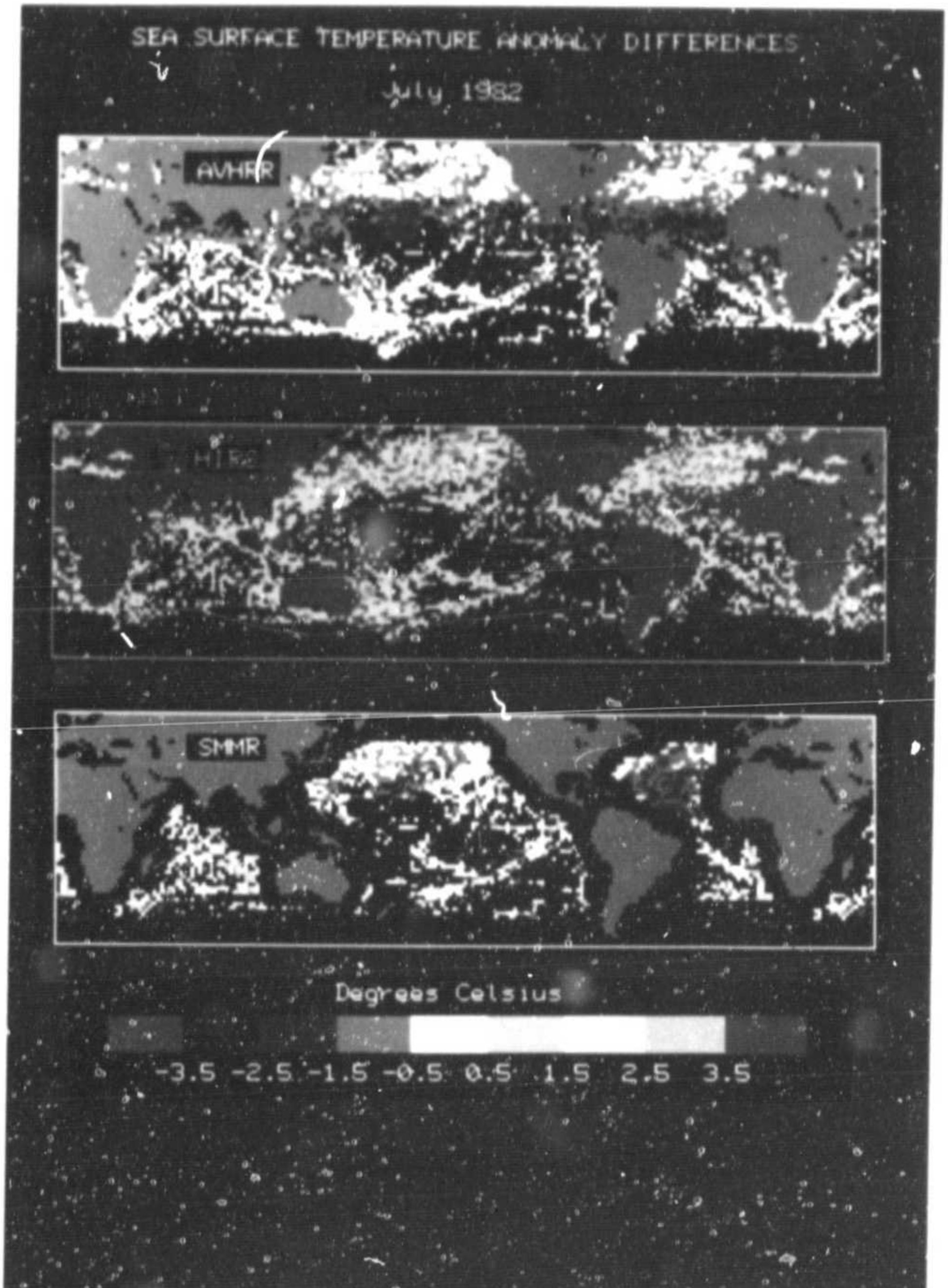

Figure 8d. Difference in binned anomalies, satellite minus ship, for AVHRR, HIRS, and SMMR, for July 1982.

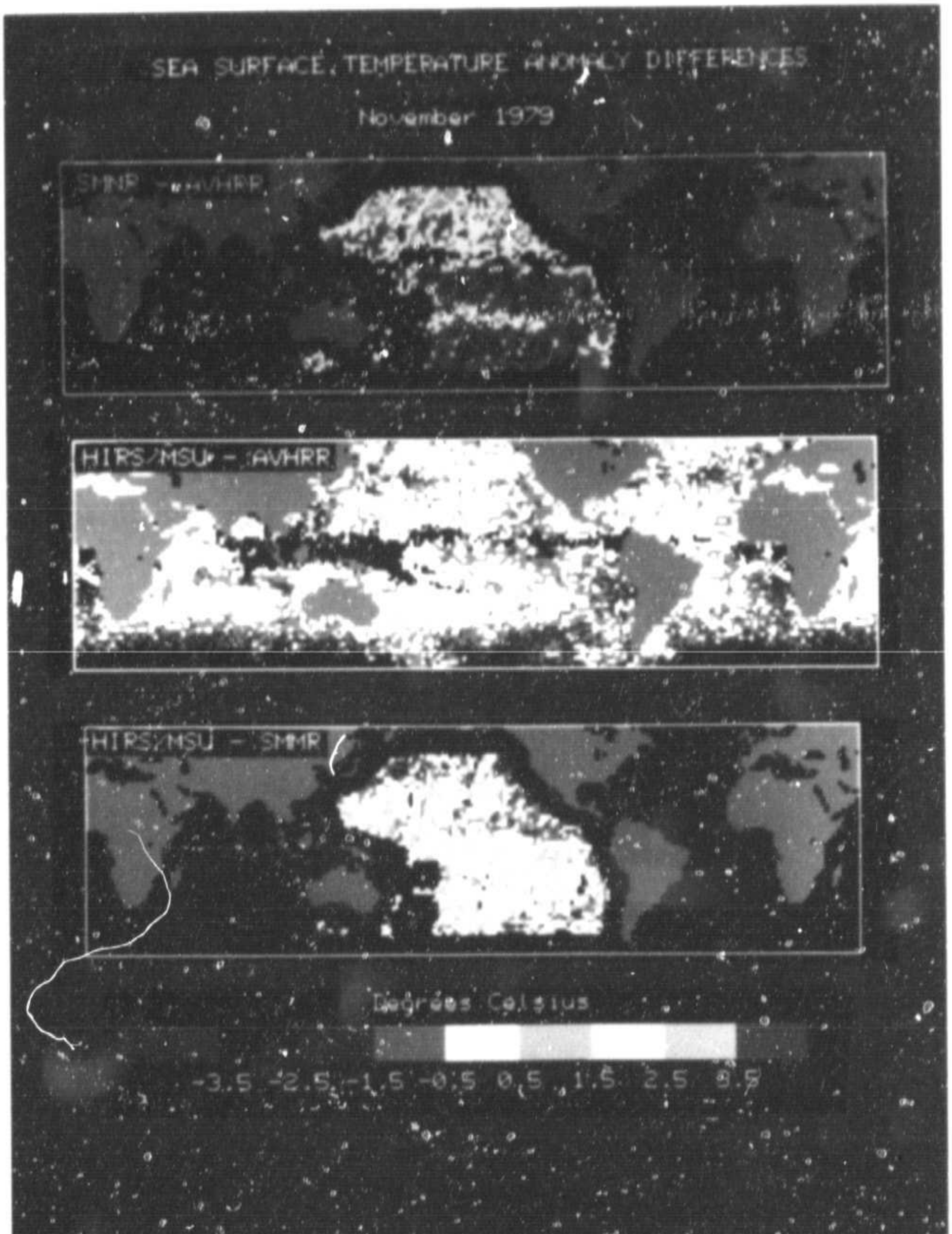

Figure 9a. Difference in binned anomalies, satellite minus satellite, for AVHRR, HIRS, and SMMR, for November 1979.

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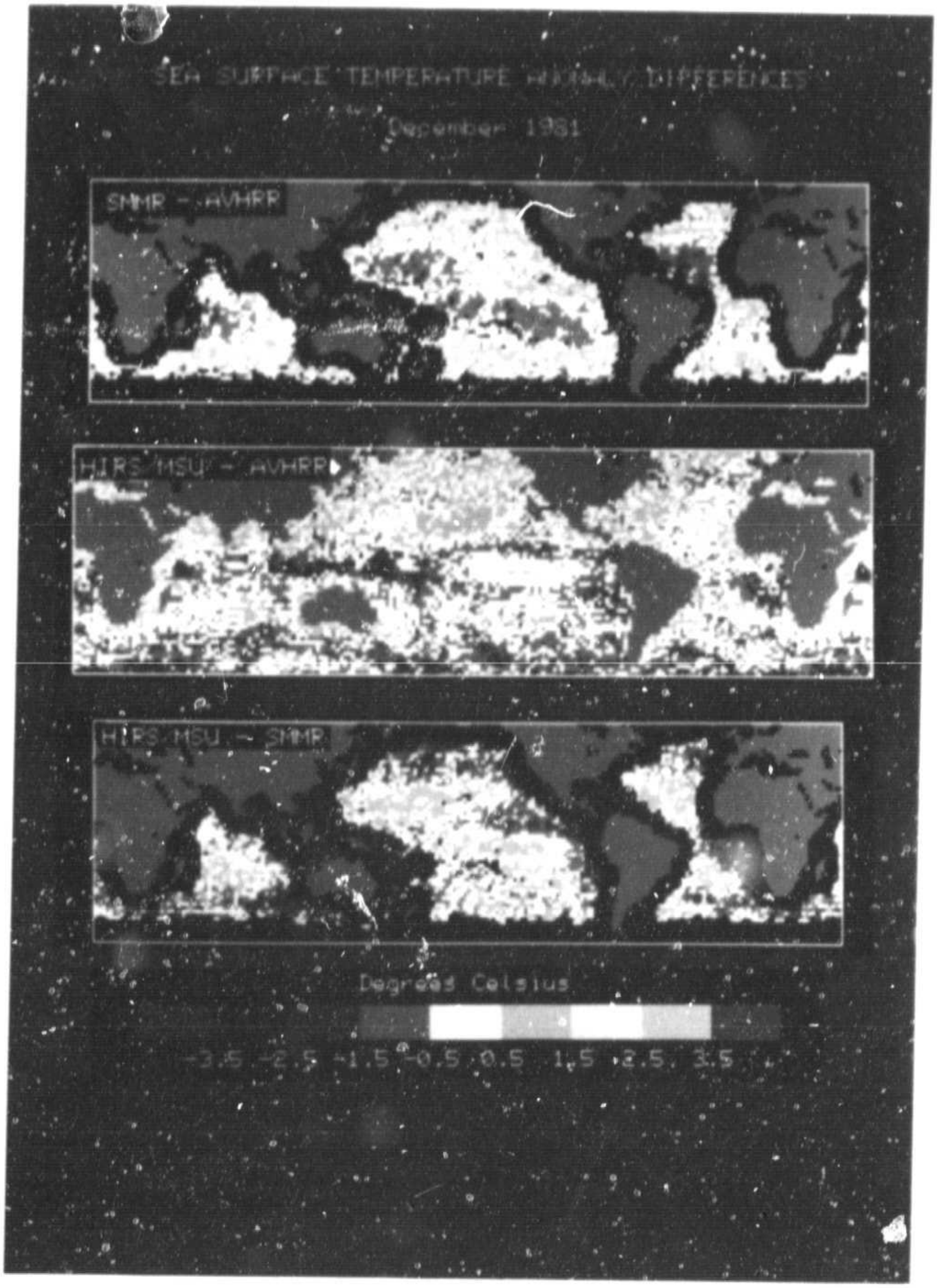

Figure 9b. Difference in binned anomalies, satellite minus satellite, for AVHRR, HIRS, and SMMR, for December 1981.

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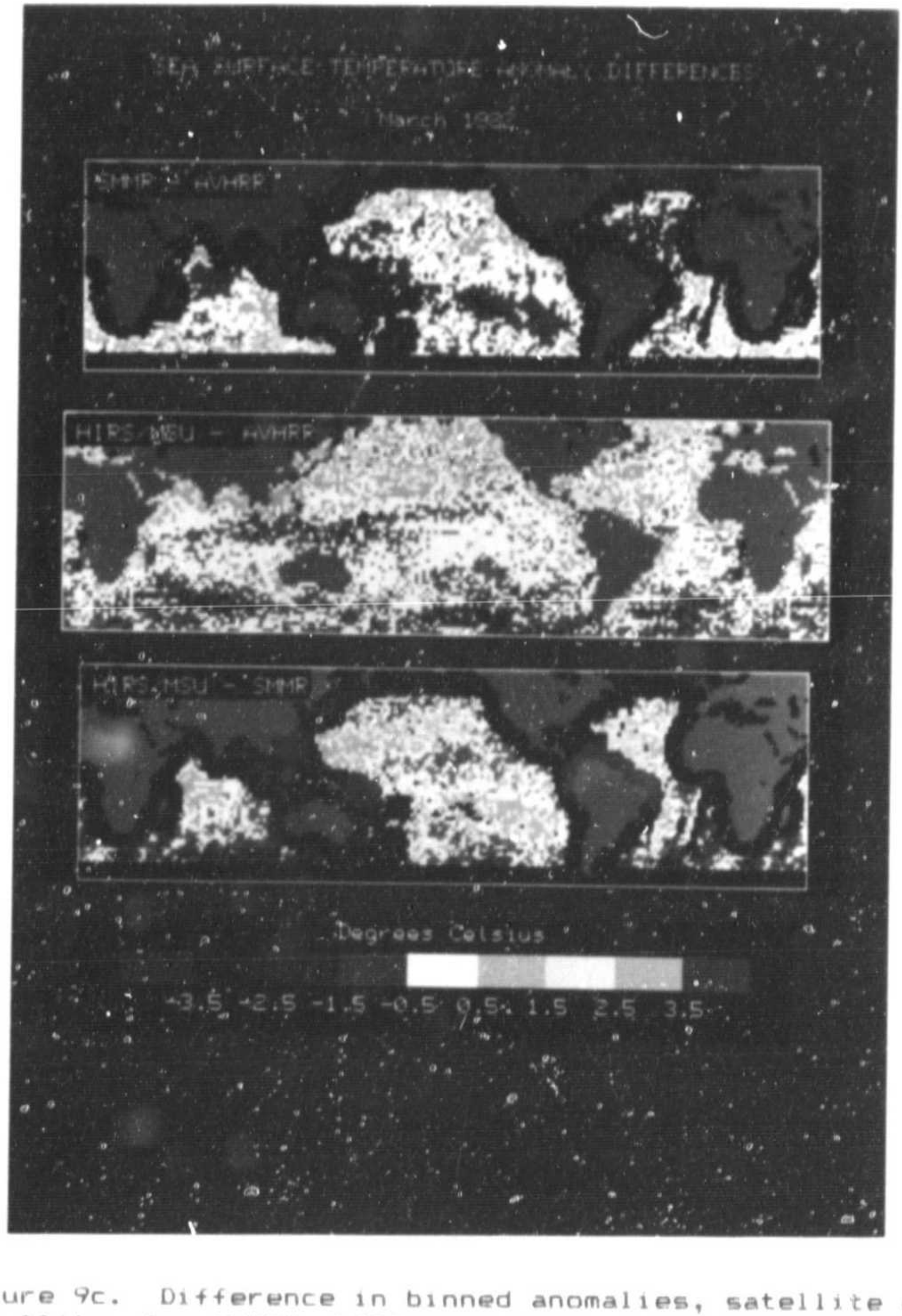

Figure 9c. Difference in binned anomalies, satellite minus satellite, for AVHRR, HIRS, and SMMR, for March 1982.

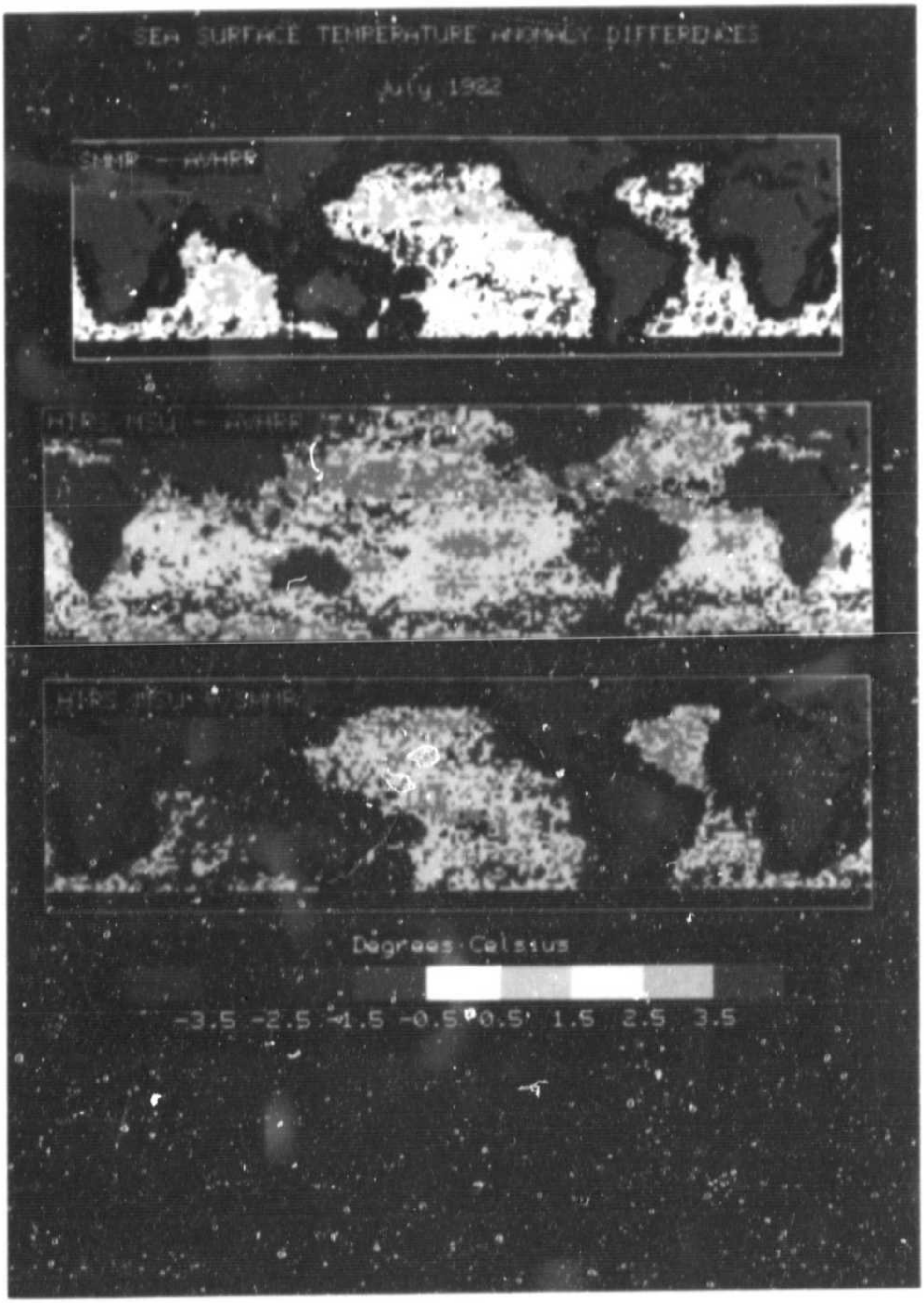

Figure 9d. Difference in binned anomalies, satellite minus satellite, for AVHRR, HIRS, and SMMR, for July 1982.