BIOGRAPHICAL SKETCH

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P. Krishna Rao

1. Introduction

The distribution of sea surface temperature over large areas of this earth is very useful for many earth resources studies and environmental research. A good estimate of this quantity is essential for certain studies of marine activities, but unfortunately a complete and true picture has not been available due to observational difficulties. Many of the presently available sea surface temperature charts are based on commerical ship reports along the routine shipping lanes, and on data from a few research cruises. These data vary widely in space, time and quality and a global distribution cannot be obtained at short intervals of two or three days.

With the launching of several earth orbiting satellites containing radiometers, it is now possible to measure sea surface temperature under relatively clear sky conditions. Before any attempts could be made to process the data in terms of sea surface temperature on a routine basis, an objective method of determining sea surface temperature from the data was required. One such method has been developed and tested and this technique will be discussed in the next section.

2. Surface Temperature Mapping from Satellite Infrared Measurements

The examples presented are based on information obtained from the Improved TIROS Operational Satellite (ITOS). This satellite is equipped with several TV cameras and radiometers. No details of the instrumentation, except a brief description of the radiometer, will be given here. References given at the end will provide additional information on ITOS. ITOS is a three-axis stabilized, earth-oriented spacecraft designed to provide full day and night coverage of the entire surface of the earth on a daily basis. The orbit is circular at 790 nautical miles (1463 kilometers) and near polar in inclination. The scanning radiometer (SR) has two channels: one measures the visible radiation reflected from the earth in the 0.52-0.73 micrometer region during daytime, and the second measures the infrared radiation emitted from the earth in the 10.5-12.5 micrometer region during day and night. If the radiometer looks straight down at Earth's surface, the area instantaneously viewed is about 4 n. mi. (7.4 km) in diameter. The motion of the satellite, together with the action of the scanning mechanism, provides complete coverage without data gaps between successive orbital passes.

The global infrared measurements are stored temporarily on tape on board the satellite for later transmission to the ground and subsequent computer processing. The SR also transmits infrared (SRIR) data in real time directly to Automatic Picture Transmission (APT) stations for local use. These radiation observations are known as the Direct Readout InfraRed (DRIR) data. This information can be displayed on a photo-facsimile recorder and a continuous strip image produced as shown in figure 1. This type of pictorial display is invaluable for qualitative interpretation of the environmental data. The gray scale is arranged such that clouds, snow and ice are shown lighter (less radiant energy reaching the radiometer) and clear and warmer regions are shown darker (more energy reaching the radiometer). A calibrated gray scale wedge can be generated and compared with the picture data to derive quantitative values.

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Figure 1 is an example of nighttime DRIR imagery obtained from the ITOS-1 satellite on 19 October 1970. Some of the prominent features are Cape May, Chesapeake Bay, Delmarva Peninsula, Delaware Bay, warm boundary of the primary Gulf Stream front, a secondary thermal front between the primary one and the coast, and portions of the Great Lakes. Pictures like this obtained at any of the APT stations can be used immediately for many purposes.

For quantitative studies, the digitized IR information is more useful. In quantitative studies the infrared measurements should be corrected for any atmospheric contributions to the observed signal. In the 10.5-12.5 micrometer region, atmospheric water vapor and carbon dioxide are the absorbing constituents. The atmospheric contribution varies most with the viewing angle of observation, cloud conditions, and the amount of water vapor within the atmosphere. All the data presented in this paper are corrected for these factors. One of the outputs obtained over a small region of the Gulf of Mexico on the night of 8 September 1970 (approx. 0300 local time) is shown in figure 2. The information is derived from a computer program and the temperatures are in degrees Kelvin (K). The area covered is approximately 1.25 degrees latitude - 1.25 degrees longitude (or 120.6 x 138.6 km) and each value is a representative temperature for a sub-area of approximately 7.5 x 8.7 km in size, which is essentially the resolution of the present ITOS radiometer. There are about 256 observations over the total area and a detailed analysis can be done. A quick look at the data array shows that in some places the temperature varies as much as 10 K between adjacent sub-areas. Except very near strong current boundaries such large variations in sea surface temperature cannot be accounted for. These variations can be caused by either clouds or instrumental noise. Subjective methods can be used to eliminate such observations, from sea surface temperature analyses, but this is practicable only for small samples. This approach cannot be used for large scale studies, and objective analysis techniques that can be automated should be used. The method that will be presented here can be used in the other areas of the earth resources studies where the cloudfree observations are required to understand a certain phenomenon.

3. Objective Sea Surface Temperature Determination Procedure

The mapping of sea surface temperature from satellite IR observations requires the capability to discriminate the Earth's surface from cloud. With a simple measurement, one might argue that the measurement is either of cloud or of the surface on the basis of only the magnitude of the observed temperature. It is usually impossible to distinguish in this manner the difference between a relatively low opaque or a high thin cloud and the Earth's surface since the associated temperatures may be well within 10 K of one another.

To overcome this problem, a method has been developed to examine a large number of measurements within an area larger than that covered by most cloud masses. From such a sample of measurements, one can determine the surface temperature by making use of the following: (a) the magnitude of the temperature should be highest for the cloudfree observations; and (b) modes dominated by relatively cloudfree observations will be distinct. Since the spatial variability of the sea surface temperature is very small except near the boundaries of major currents and areas of strong upwelling, the statement (b) should hold well over most regions.

The ITOS scans from horizon to horizon in a direction perpendicular to the orbital track and there is data overlap between adjacent orbits. Frequency histograms of these radiation measurements (fig. 3) within a 2.5° latitude/longitude quadrangle (approximately 240 x 280 km) can be generated over large regions. In quadrangles of this size there are 1024 observations. Figure 3 shows one of the computer-produced histograms. The numbers in the left column are coded temperatures (example 120 = 284 K) and run from 89-255. The numbers along the top row, 1-22, identify the various latitude/longitude quadrangles along line 49, section 1 (which gives the location). The numbers in each column from 1-22 specify the number of observations in each box that had the indicated temperature (example: For coded temperature 120 under column 15, the value 159 shows the number (or frequency) of observations having that temperature). The numbers in the bottom row indicate the number of observations that were missing from each quadrangle. The histogram presented here is for a three-day composite (September 6, 7, and 8, 1970), and if no data were available in a particular quadrangle, the number in the bottom row should be 3072 (3 x 1024) as in column 4, for example. In column 20, on the other hand, the last number in the column is zero, which means that none of the 3072 observations is missing from that quadrangle.

If there were relatively few clouds in a quadrangle then the histogram should be compact as in column 7. If there are clouds, but it was not completely overcast, then the distribution will be similar to the one in column 15. By examining such frequency distributions one can select the most probable cloud-free temperatures in the area. One such objective method is described below.

In the absence of cloud-contaminated measurements, it can be assumed that the satellite-observed surface temperature distributions in a small area should be Gaussian with a dispersion produced by noise. The standard deviation, σ, of such distributions is equal to the known standard random error of measurement. For a Gaussian distribution, the temperature $+1\sigma$ from the mean or mode is that temperature on the high temperature wing of the histogram where the change of frequency of observation with temperature is a maximum. When a cloud-contaminated frequency distribution is obtained for an area, it is assumed that this maximum slope, or $+ 1\sigma$, portion associated with the typical cloudfree distribution (clear mode) is identifiable, provided there are sufficient clear spots within the area viewed by the radiometer. Thus, the surface temperature can be defined as the temperature at the point of maximum slope on the high temperature wing of the "clear mode" $T(+ 1\sigma)$, minus the standard error of measurement, σ. This derived value will usually be higher than the observed modal peak temperature because the observed temperature distribution tends to be biased toward lower temperatures when clouds are present.

Figure 4 illustrates the technique by means of two histograms obtained over adjacent quadrangles. Both distributions are skewed toward low temperatures due to cloud contamination. In fact, there were many values below 280°K which are not shown. The dispersion on the high temperature side is mainly due to instrumental noise. The high temperature modes shown are produced by a combination of cloud-contaminated and cloudfree observations. Since the standard error of measurements is about 1.5°K for the SR on ITOS at these temperatures, the most probable surface temperatures are given by $T(+ 1\sigma) - 1.5$°K.

Note that the inferred surface temperature for the more westerly grid square is the same as the modal peak value, indicating that the modal peak is produced predominantly by cloudfree observations. In the other area, however, the modal peak is 3°K lower than the inferred surface temperature, indicating that this peak is produced by cloud-contaminated as well as cloudfree observations (assuming a negligible sea surface temperature gradient over the quadrangle). The observations greater than 301°K are apparently cloudfree, allowing the correct surface temperature to be inferred from the maximum slope of the distribution. The inferred temperatures are in agreement with a nearby ship observation of 301°K.

A complete set of procedures and conditions necessary for reliably specifying sea surface temperatures from histograms of SR temperatures, corrected for atmospheric attenuation, have been devised and put in the form of a computer program. The procedure for specifying the sea surface temperatures is completely objective, and can produce values for a given day over the entire Northern and Southern Hemispheres with a few minutes of computer time. This enables one to bulk process the satellite IR data. The stability of the values increases with the quadrangle size used or through time-compositing because the number of observations that are available for defining the clear modal distribution increases. Also sea surface temperatures for areas where severe cloud contamination exists, or which are not observed due to gaps in satellite coverage, can be inferred through space and time interpolation procedures.

Figure 5 shows the sea surface temperature distribution for the Northern Hemisphere obtained from 3-day composite, 2.5 degree histograms (240 x 280 km) of ITOS nighttime SRIR data. All quadrangles for which temperatures could be specified are indicated by an open circle on the figure. Where these circles are absent, no temperature could be derived because of persistent cloudiness. A few of the cold areas, such as the ones analyzed just west of Baja California and just east of the Philippines, appear to be unrealistic and are evidently due to cloud contamination not adequately handled by the technique. Only with satellites and multiple-day compositing is it possible to cover such large areas and specify temperatures over most of the regions. It is almost impossible to cover such a vast area in a three-day period with conventional observational platforms such as ships or aircraft.

Finally, figure 6 shows a scatter diagram of sea surface temperatures derived from ITOS-SR compared with those reported by the Ocean Station Vessels in the North Atlantic and North Pacific Oceans. Since these vessels take surface temperature measurements at the same depth most of the time, compared to the ships of opportunity, whose reported temperatures correspond to various depths, only the former values were used in the comparison. The root mean square (RMS) difference is about 1.98°K. The difference could be due to a difference between the "skin temperature" and the subsurface temperature measured by ships, or it may be caused by the instrumental calibration of the SR. It has been observed recently that significant noise is introduced by the satellite tape recorder system, which must contribute to the RMS difference noted above. It is also known that ship temperatures vary among themselves with an RMS difference of nearly one degree Kelvin.

Summary

A technique for deriving sea surface temperatures has been developed and tested with a limited amount of independent data. The technique is completely objective and minimizes the influence of atmospheric absorption, cloud contamination, and instrumental noise on the inferred sea surface temperatures.

Clouds and some amount of instrumental noise will be always present in all observations from earth orbiting satellites. The influence of these elements must be minimized to make a meaningful study of the observed quantities. The technique presented here will be useful in solving this problem.

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GLOSSARY

APT: Short name for Automatic Picture Transmission. Certain satellites of the TIROS and Nimbus series have had special camera and transmitter equipment such that television pictures and radiometer data taken while the satellite is within range of a station on Earth's surface can be received and displayed on relatively simple and inexpensive equipment.

Compositing: Here it refers to the use of data taken over the same region but at different times.

Digitization: The process whereby a continuous analog signal received from the satellite is converted to discrete numerical values.

Gaussian: A statistical term that refers to a "normal" distribution.

Modes: A statistical term referring to the most frequently occurring value or values in a sample. When the sample is presented in the form of a frequency distribution, the mode(s) appears as a maximum (maxima).

Photo-facsimile: A method whereby the input voltages from some source are converted to a continuous image by a scanning mechanism that generates gray tones as a function of signal level.

RMS differences: A statistical term meaning Root Mean Square difference. In the example presented it is obtained by taking the differences between the satellite temperatures and the corresponding ships' temperatures, squaring them, taking the average of the squares, and then obtaining the square root of that value.

Skewed: If a frequency distribution is not symmetric about its mode it is called "skewed."

Skin temperature: The temperature of the thin film of the water surface, generally the uppermost fraction of a millimeter.

Sub-surface temperature: The temperature beneath the water surface, and generally refers to a few meters in depth.

Thermal front: Transition zone between the two water masses where there is a strong horizontal temperature gradient.

TIROS: Short name for Television and InfraRed Observation Satellite, a meteorological Earth satellite.

Upwelling: The process whereby water rises from a lower to a higher depth, usually as a result of divergence and offshore currents.

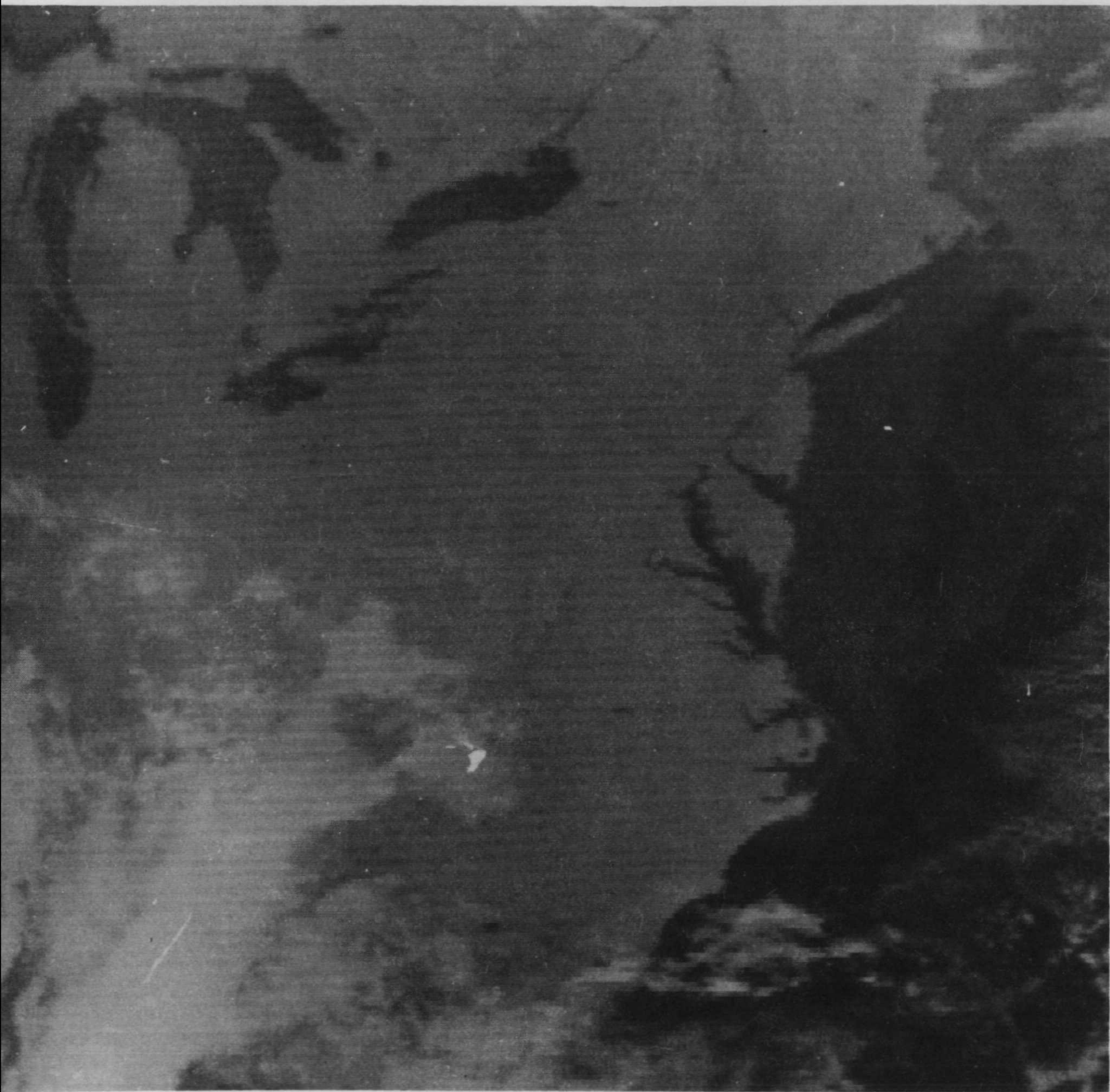

Figure 1.--Direct readout, nighttime infrared imagery obtained from ITOS-1 SHRR on 19 October 1970 in the vicinity of the East Coast. The darker is the tone in an area, the warmer is the radiating surface there.

1.25 DEG. LATITUDE (138.6 km)

+294	+300	+297	+302	+300	+301	+308	+297	+300	+304	+298	+297	+297	+297	+299	+295
+299	+298	+297	+297	+298	+301	+300	+300	+303	+299	+298	+293	+293	+292	+302	+300
+295	+302	+300	+301	+298	+297	+304	+298	+295	+300	+302	+305	+304	+298	+303	+303
+299	+298	+305	+299	+297	+297	+301	+304	+305	+301	+297	+297	+296	+300	+295	+297
+298	+297	+294	+304	+305	+304	+301	+299	+294	+297	+292	+291	+298	+297	+299	+296
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+299	+300	+300	+304	+299	+304	+295	+297	+304	+293	+298	+301	+304	+299	+298	+296
+301	+301	+296	+297	+307	+297	+302	+301	+301	+302	+297	+292	+293	+299	+301	+301
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+298	+306	+302	+301	+301	+303	+301	+298	+295	+302	+302	+305	+301	+295	+293	+294
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+301	+297	+304	+301	+304	+302	+302	+295	+297	+298	+296	+299	+299	+300	+297	+297
+294	+308	+301	+296	+303	+297	+298	+297	+291	+292	+298	+303	+293	+294	+295	+301
+300	+303	+301	+302	+290	+298	+295	+298	+301	+300	+298	+299	+300	+296	+297	+296

1.25 DEG. LONGITUDE (120.6 km)

ITOS 1 SRIR OVER GULF OF MEXICO
TEMP. °K
SEPT. 8, 1970

Figure 2.--Example of computer-generated histograms of ITOS-1 SIRS data.

LINE 49SECTION 1

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
89	0	0	0	0	0	0	0	0	0	0	0	0	0	13	14	1	0	0	0	0	0	1
90	0	0	0	0	0	0	0	0	0	0	0	0	0	11	10	2	0	0	0	0	0	1
91	0	0	0	0	0	0	0	0	0	0	0	0	0	15	12	1	1	0	0	0	0	3
92	0	0	0	0	0	0	0	0	0	0	0	0	0	14	17	1	0	0	0	0	0	3
93	0	0	0	0	0	0	0	0	0	0	0	1	0	12	16	1	0	0	0	0	0	2
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142	0	0	0	0	0	7	5	0	9	9	6	2	0	0	0	4	0	9	0	0	0	2
143	0.	0	0	0	0	0	4	0	3	1	0	0	0	0	0	3	0	3	0	0	0	0
144	0	0	0	0	0	2	2	0	4	0	2	0	0	0	0	0	0	3	0	0	0	2
145	0	0	0	0	0	2	2	0	4	2	0	0	0	0	0	0	0	4	0	0	0	0
146	0	0	0	0	0	2	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0
147	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
148	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
252	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
253	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
254	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
255	3072	3072	3072	3072	3072	2024	1024	1024	1024	1024	1024	1022	708	166	0	0	0	0	0	0	0	0

Figure 3.--Digitized ITOS-1 SRIR data over Gulf of Mexico for 8 September 1970. The temperatures are in degrees Kelvin.

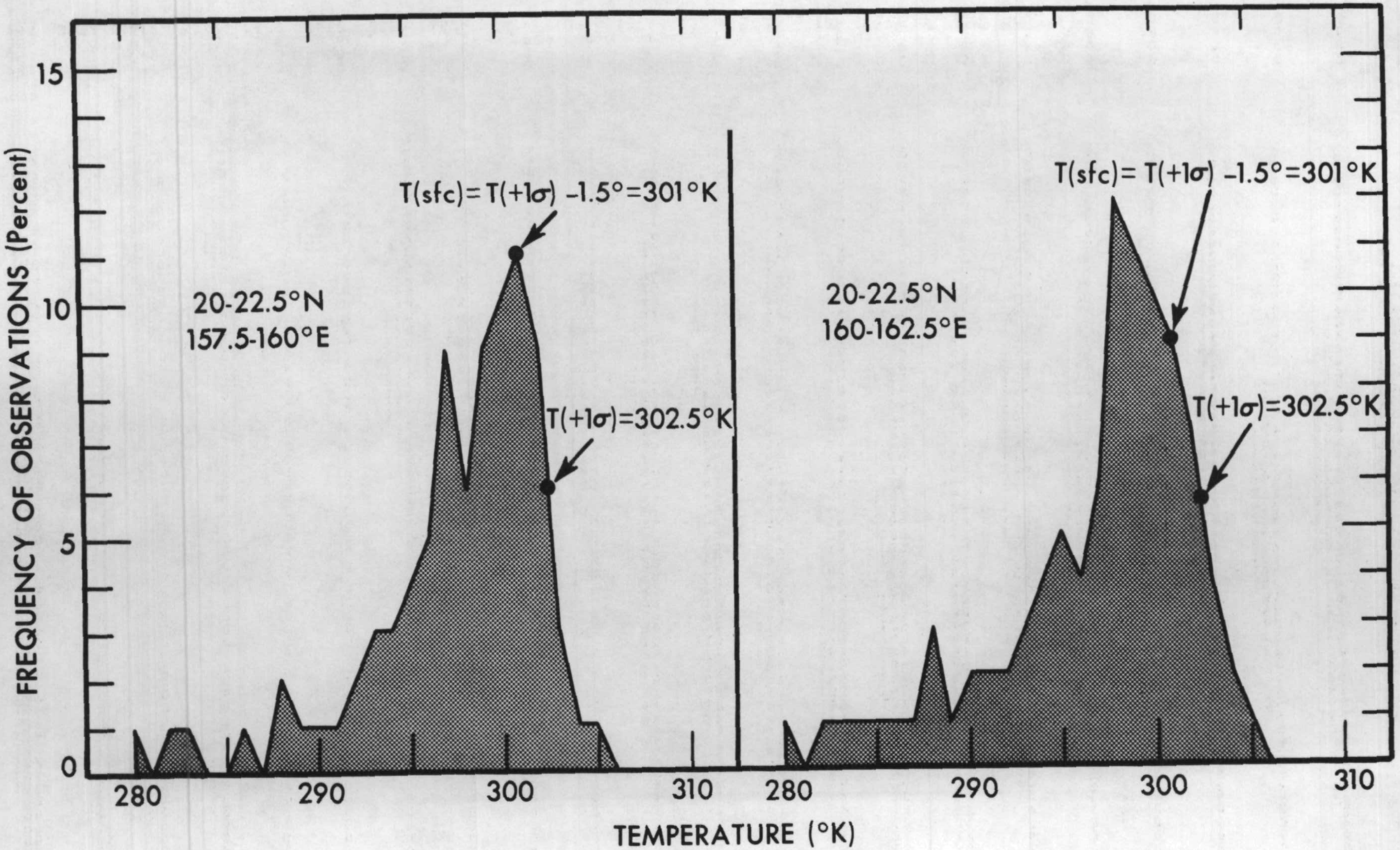

Figure 4.--Sample histograms of corrected ITOS-1 SRIR data showing their relation to sea surface temperature.

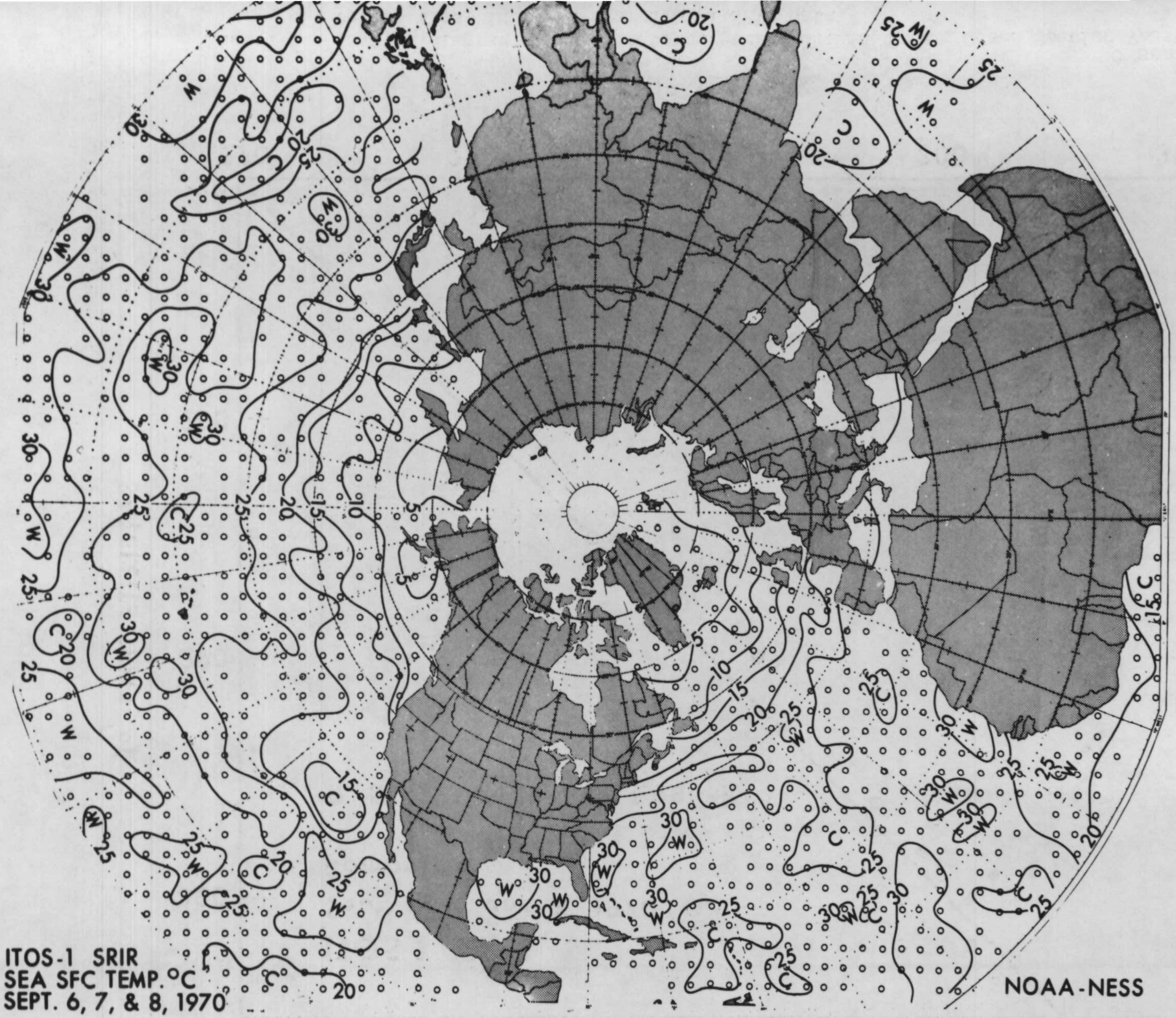

Figure 5.--Three-day (6, 7, and 8 September 1970) composite Northern Hemisphere sea surface temperatures inferred from ITOS-1 SRIR data. The isotherms are labelled in degrees Celsius. Data points are represented by open circles.

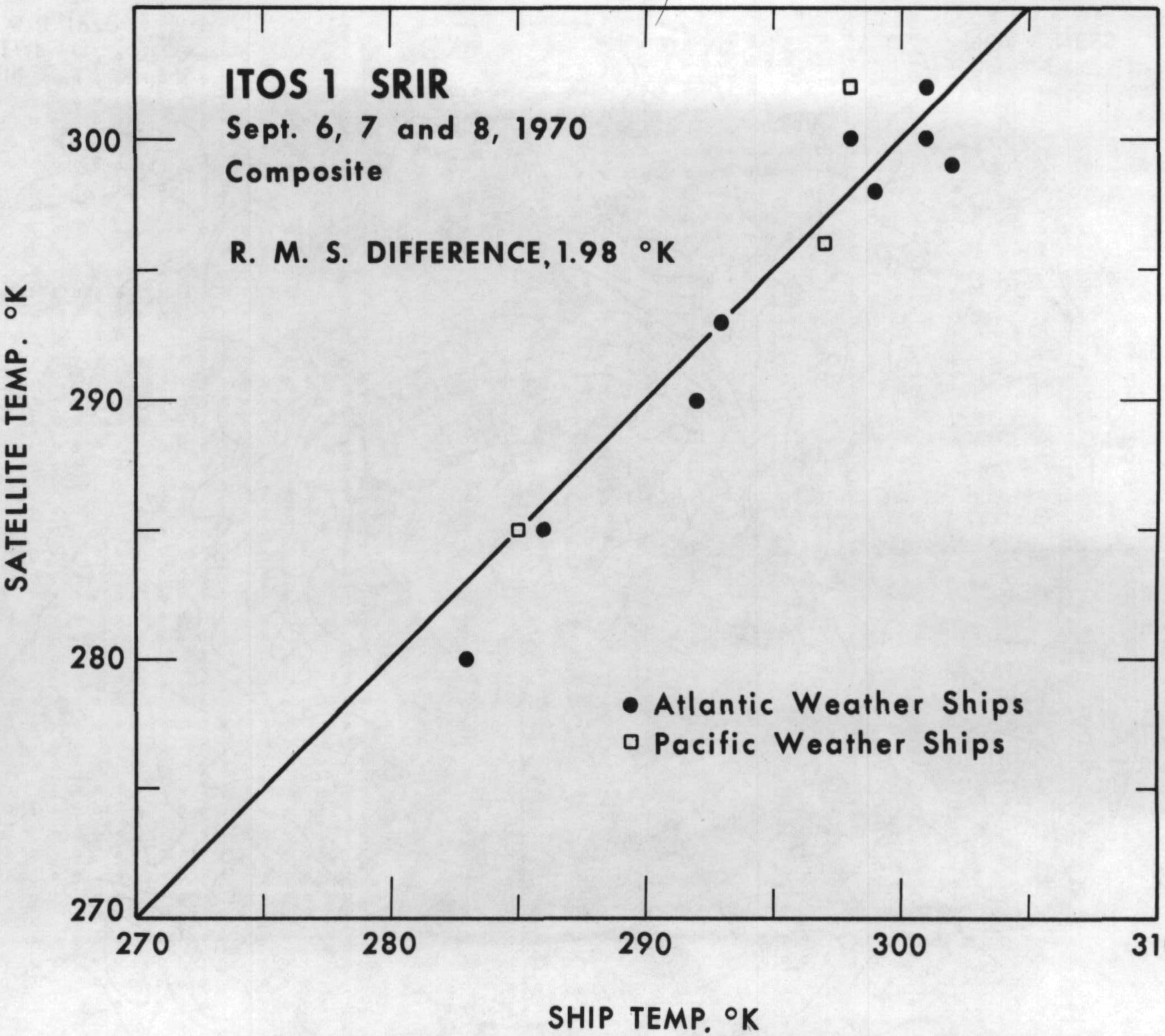

Figure 6.--Scatter diagram of surface temperatures obtained from Ocean Station Vessels versus those inferred from ITOS-1 SRIR data.

* U. S. GOVERNMENT PRINTING OFFICE : 1971 O - 420-976