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# THE FEASIBILITY OF SEA SURFACE TEMPERATURE DETERMINATION USING SATELLITE INFRARED DATA

*by James R. Greaves, Raymond Wexler, and Clinton J. Bowley*

Prepared under Contract No. NASw-1157 *by*
ALLIED RESEARCH ASSOCIATES, INC.
Concord, Mass.
*for*

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## ABSTRACT

A first investigation, based on actual infrared data, has been made of the feasibility of observing sea surface temperatures or temperature gradients from a satellite. It has been found that the satellite-measured large-scale patterns are generally persistent, with only limited day-to-day changes, and that the smaller scale features are similar to those observed in intensive conventional measurement programs over relatively restricted areas. These and other evidence suggest that:

1) The satellite data provide good measurements of the gradients of sea surface temperatures.

2) At least one conventional sea surface temperature measurement is required to serve as a benchmark if good absolute values of sea surface temperatures are required. This is due to uncertainties in atmospheric attenuation of infrared radiation and in sensor calibration and degradation for the TIROS radiometer.

3) In many cases, the satellite data appear to be detecting synoptic scale changes which take place over a period of one or more days.

A critical problem is the detection and elimination of data points where clouds prevent an uncontaminated view of the sea surface. It is found that, in daytime, the TIROS Channel 5 data, converted to an albedo, are suitable for detecting cloud contaminated points. No method for reliable cloud detection at night is presently apparent.

It is found that other sources of cloud cover information, such as conventional meteorological observations and satellite TV data, are insufficient for determining all the significant clear areas for satellite observations of sea surface temperature. This suggests that comprehensive studies or operational analyses of sea surface temperatures will require the processing of relatively extensive quantities of satellite radiation data, using these data themselves to determine the daytime cloud-free areas. In this manner maximum use can be made of whatever cloudfree areas do exist both on an individual day basis, and for the averaging of data for short periods of more or less successive days. A single case (for a period of six days) is analyzed using this approach, and strongly substantiates these conclusions. It is recommended that a more extensive set of pilot studies, using the approach of the processing of relatively extensive samples of data, be conducted.

## FOREWORD

This report by the ARACON Geophysics Company, a division of Allied Research Associates, Inc., Concord, Mass., presents the results of a first study of the feasibility of observing sea surface temperatures, or temperature gradients, using satellite data for an infrared window. These studies were performed for the Meteorological Programs Division, Headquarters, National Aeronautics and Space Administration under Contract No. NASW-1157.

Acknowledgement is due to Mr. Richard G. Terwilliger of the Meteorological Programs Division for his continuing interest and assistance during the course of this investigation; and to Messrs. William R. Bandeen and Robert Hite of the Physics Branch, NASA Goddard Space Flight Center, for their cooperation in processing and providing sample cases of the otherwise unavailable TIROS "real time" IR data.

The authors further wish to acknowledge the kind assistance and encouragement offered by Messrs. Joseph Chase and Robert Alexander, and other scientists at the Woods Hole Oceanographic Institute.

Mr. David Chang of ARACON Geophysics Company performed the atmospheric attenuation calculations for most of the cases discussed herein. Dr. William K. Widger also of ARACON provided useful suggestions throughout the study, and assisted in the editing of this report.

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# 1. INTRODUCTION

## 1.1 The Importance of Sea Surface Temperature Data

The need for accurate measurement of the sea surface temperature (hereafter referred to as SST), on a daily basis and for large areas of the world's oceans, is becoming increasingly acute. Nearly all of man's sea-oriented activities (such as fisheries, navigation, marine weather forecasting, and naval operations) rely to some extent upon knowledge of the SST patterns and their variation with time.

Prediction of the spawning grounds of certain varieties of fish can be made using accurate SST information, while good fishing areas frequently occur at the confluence of oceanic currents which can in turn be detected by the packing of sea surface isotherms. Determinations of the probability of icing or fog formation, require SST data. Various investigators [1, 2, 3] have demonstrated direct correlations between the SST and such meteorological phenomena as the growth and travel of hurricanes, and extratropical cyclonic development. The SST can be related to the subsurface temperature structure, which in turn affects the propagation of sound, a significant parameter in submarine warfare.

Despite the importance of SST data, this quantity is generally known only in a gross climatological sense, and even then not adequately over all the oceans of the world. Temperature distributions and their variations on the time and space scales required for the needs outlined above are far less well determined. [4]

## 1.2 Use of Satellite Measurements

As indicated above, the theory and techniques which can make practical use of greatly improved SST information are at hand; what is lacking is an adequate amount of data. A satellite equipped with IR sensors is a world wide observing tool which may be used to considerably close this "data gap". [5] This first study of the feasibility of such an approach employed principally the Channel 2 (8-12 micron) radiometer data from the TIROS VII meteorological satellite. A polar orbiting, sun-synchronous satellite such as Nimbus, which could provide daily coverage of all the earth's oceans, can drastically improve the capabilities demonstrated in this study. While the Nimbus I HRIR (3.7μ) has serious limitations for this application (see Section 3.1), the Nimbus C MRIR should be an improvement over the TIROS data in many respects, including coverage, sensitivity, calibration, and atmospheric attenuation.

It seems significant that when scientists at the Woods Hole Oceanographic Institute were consulted regarding certain aspects of our investigations, they unanimously expressed considerable enthusiasm that such a feasibility study was taking place. They stressed the long standing lack of adequate data of the scale and measurement frequency that only a satellite can practically provide.

### 1.3 Brief Summary of Results of These Studies

These studies have conclusively demonstrated that a satellite can measure pertinent patterns and gradients of SST where cloud cover does not prevent the radiometer from observing the ocean surface. When cases of repeated coverage of a given area within a period of several days were analyzed, large scale temperature patterns were found to have significant persistence. While smaller scale features often changed somewhat from day to day, their patterns were repeatedly similar to those observed in special programs which used conventional measurements.

The absolute temperatures were occasionally uniformly lower or higher from day to day. These discrepencies could not always be completely accounted for in terms of sensor degradation or changing air masses. An occasional conventional temperature measurement is apparently required as a bench mark to properly calibrate the IR measurements, at least until improved techniques for in-flight sensor calibration, and improved knowledge of atmospheric attenuation, are available.

One of the primary deterrents to observations of sea surface temperatures or temperature gradients is the presence of intervening cloud cover. When clouds partially fill the field of the sensor, that data point must be identified and discarded. Our studies have indicated that this problem can usually be solved by establishing a cloud-no cloud threshold value for the Channel 5 (0.5-0.7 micron, visible reflected radiation) albedo listing, and discarding points for which the Channel 5 value exceeds this threshold.

Significant difficulties were encountered in locating even single cases of open mode IR data which simultaneously fulfilled the combined criteria of (1) mostly clear skies, (2) distinct SST patterns or gradients, and (3) adequate conventional ship coverage for comparison. The problems obviously multiplied when attempts were made to find examples of recurrent coverage of a given area for purposes of pattern persistence studies which could serve as one confirmation of the validity of the observations, and particularly for observations of synoptic scale changes in temperature patterns.

A review of these problems has led to the conclusion that the only feasible approach to a comprehensive study of satellite observed SST appears to be the computer processing of FMR tapes without specific prior knowledge as to whether a given pass will contain useful data. In this approach, the Channel 5 albedo data would be the primary source for determining adequately cloud free areas. While this approach is inherently inefficient (since some of the processed data may include not usefully cloud free areas) there would appear to be no alternative.

An initial trial run of this approach was made for an area off the western coast of Australia, averaging clear sky data from six more or less consecutive passes. The average map showed obvious similarity to the mean monthly charts for this area. This case and others will be discussed in greater detail in the following sections.

## 2. DATA SOURCES

The primary sources of data for all cases considered were the Final Meteorological Radiation (FMR) magnetic tapes prepared by NASA. Listings of the available data tapes and descriptions of the data contained therein have been published.[6] Extraction of the actual data from the FMR tapes is accomplished by processing programs developed by NASA for use on the IBM 7094.

The processing can make the data available in any of several formats. The listing program (MS-500) converts the binary FMR data to decimal form and prints it in a convenient tabular format. This tabulation includes data point location information, and values measured by each of the five channels of the TIROS radiometers. Mapping programs are available which map the data to various scales in either a mercator projection (MSC-2) or a polar stereographic projection (MS-501).

## 3. SELECTION OF DATA

### 3.1 Choice of TIROS VII

All of the cases selected for investigation used the TIROS VII data. This satellite was chosen because the degradation of the Channel 2 sensor (8-12 micron) is well known.[7] Moreover, because IR sensor degradation generally increases with time, an attempt was made to the degree feasible to choose cases early in the lifetime of TIROS VII (TIROS VII was launched 19 June 1963).

It was determined that the use of the Nimbus HRIR data during the current study would not be feasible for the following reasons:

1. The availability of these data is extremely limited at the present time, and until the digitization is completed, full documentation of the magnetic tape format (to appear as Nimbus I High Resolution Radiation Catalog and Users' Manual, Volume 2, "Nimbus Meteorological Radiation Tapes - HRIR") is not available.

2. There appears to be no reliable way to discern the presence or absence of cloudiness, other than by abrupt changes in the recorded temperature, which may not detect scattered to broken or low cloudiness. The daylight HRIR cannot be expected to be applicable because of the reflected component. The problems of detecting partial cloud cover at night from infrared data have no apparent solution, as will be discussed in some detail in Section 4.2.2.

3. Those areas which appear clear in the Nimbus I HRIR photofacsimile film strips are of minimum interest insofar as the detection of sea surface temperature patterns are concerned. The probability of finding an area with distinctive patterns which was known to be clear and has presently available digitized Nimbus I HRIR data seemed too small to justify an exhaustive search.

It should be emphasized that the increased resolution capabilities of the Nimbus HRIR data represent a potentially significant advantage over those of the TIROS IR, and any future investigation of sea surface temperature determination should reconsider the Nimbus data when they become available in digitized form. However, the success of such a study will depend on solving the problem of detection of small or low clouds. Because of the HRIR resolution, even very small isolated clouds may be a greater source of error than they would when using the lower resolution TIROS data. One possibility may be a joint use of the digitized data and the analog visicorder record, as discussed in our proposal for this study,[5] but not attempted for the reasons discussed above.

## 3.2 Case Selection Criteria

As has been mentioned previously, much time and effort was spent in attempting to locate cases which simultaneously satisfied the combined criteria of (1) generally clear skies, (2) significant SST gradients, and (3) adequate conventional ship coverage to provide data for comparison. Another significant restriction is that, for all practical purposes, periods of closed mode IR operation must be avoided due to the frequent errors in geographical location of the data. This, of course, is simply a limitation of the measurement device itself.

### 3.2.1 Clear Skies Criterion

In our initial case selections, IR passes were chosen on the basis of generally clear skies as determined from nearly simultaneous TV coverage by TIROS VII or other meteorological satellites. Cases were selected by first examining the nephanalyses contained in the Catalogs of Cloud Photography[8], and then from an examination of the actual satellite pictures for areas that the nephanalyses suggested as promising. This approach, combined with efforts to concentrate on areas with significant SST patterns, led to an obviously insufficient number of usable cases. In particular, it excluded IR passes with no essentially concurrent TV data. Later in the study, attempts were made to use conventional weather maps over the ocean as a means of determining the cloudiness of an area. Since the conventional maps were rarely drawn for the precise time in question, this meant interpolating cloud cover between maps which were already based on sparse information. After reviewing the amount of time required to arrive at some conclusion regarding the cloudiness of an area from conventional data alone, and the undependable nature of the conclusion, this approach was rejected.

The remaining alternative was to determine cloudiness from the IR data themselves. This means, unfortunately, incurring the expense of FMR tape processing before it can be decided whether or not the area scanned includes adequately cloud free portions. The methods of determining cloudiness from the IR data will be discussed in a later section.

This method was used as the sole method for determining cloud cover in only one set of cases, that discussed in Section 6.

### 3.2.2 Temperature Gradient Criterion

The second criterion for case selection in this study, that of significant SST gradients, proved to be generally incompatible with the first. Areas of significant SST gradients (where observable synoptic scale activity seems most likely) usually are areas of persistent or recurring meteorological fronts, and so of obscuring cloud cover. (The comparative locations of the Gulf Stream and of the mean position of the western North Atlantic frontal zone provide one illustration of this problem.) There are several such ocean areas, but only daily observations over a period of several days to a few weeks can be expected to show significant SST changes.

### 3.2.3 Conventional Data Criterion

The third criterion of adequate conventional SST data could not in general be met. (If it could, much of the need for satellite measurement of the world's SST patterns would vanish.) Even in the North Atlantic cases, the number of conventional ship reports proved inadequate. The only area of significant SST gradients where there appear to be sufficient available ship SST measurements is in the vicinity of the Gulf Stream off the east coast of the United States. But it is precisely here that there is seldom readily available IR data.

Most of the data for this area, for the immediate west coast North Pacific waters, and for much of the continental U.S. are the so-called "real time" TIROS IR data and remain in undigitized form. These data are read out in "real time" concurrent with the playback of the IR data for the remainder of the preceding orbit, using a frequency multiplexing technique. The data for the remainder of the orbit are read out at 30 times the record speed and frequency, and the automatic processing system is designed to handle these data. Processing the "real time" data, whose sub-carriers are thus one-thirtieth of those of the majority of the data, require an accelerated rerecording, and considerably more time and manual attention than does the conventional IR data. Moreover, timing errors of the order of seconds are very likely to be introduced because of the manual determination of the "End of Tape" time at the CDA stations. For these reasons, only three cases of "real time" data* were included in our studies. We suggest that the reduction of a sizable sample of

* Made specially available, through the courtesy of Messrs. William R. Bandeen and Robert Hite of GSFC.

the "real time" data on a routine basis would be of significant value to meteorological, geological, and especially oceanographic research; and might well be given serious consideration.

## 4. DATA PROCESSING

### 4.1 General

The data were generally extracted from the FMR tapes using the listing program and were hand plotted onto blank mercator mapping paper. In so far as feasible, these plotted data were corrected for data misplacement errors, following guidelines suggested by Sherr.[9] In his report, Sherr discusses several classes of misplacement errors together with methods for their recognition and correction. In the mapping format, these errors cannot be detected, and hence may introduce some pattern distortion.

Initial analyses were performed without reference to existing maps of mean monthly SST patterns or local currents. Later the analyst consulted maps of mean temperature patterns and currents for the area in question, and used them to guide the analysis, particularly in areas where the plotted data were ambiguous and permitted a choice. In no case was violation of the plotted data permitted. These subsequent re-analyses of previously run cases resulted in a significant improvement in the correlation between IR and conventional temperature patterns without violation of the data.

When scientists at the Woods Hole Oceanographic Institute were consulted regarding the resultant maps, it was noted that the IR temperature patterns were in many ways similar to those seen in intensive conventional measurement programs over relatively restricted areas.

The Woods Hole personnel also suggested that, in cases of particularly noisy data or nearly isothermal areas, averaging over $1^{\circ}$ squares or larger, and possibly over repeated passes, would often be appropriate. Such averaging must be carried out with some care,or small scale features and their changes in time will be quickly lost. The validity of this suggestion will be demonstrated in several of the case studies discussed later in this report.

### 4.2 Elimination of Cloud Contaminated Points

Whenever a cloud or portion thereof falls within the field of view (approximately thirty nautical miles diameter at zero nadir angle) of the TIROS radiometer, it will prevent accurate measurement of the surface temperature. In these cases, the temperature recorded by the radiometer would be intermediate between that of the cloud and that of the sea surface with the relative contributions of the cloud top and surface temperatures depending on the percentage of cloud within the field of view.

### 4.2.1 Daytime Cases

In daytime passes, both Channel 3 (0.2-5 micron) and Channel 5 (0.5-0.7 micron) measure the comparatively intense reflection of solar radiation from the cloud surfaces, and thus can serve as a discriminator between cloudy and clear areas. For the TIROS VII data, Channel 5 exhibits somewhat less noisy characteristics than Channel 3, and was used throughout the study.

Before the Channel 5 data can be used for this purpose, a clear-cloudy threshold value must be determined. Channel 5 data as usually listed represents the irradiance observed by the sensor in the 0.5-0.7 micron (visible) spectral region. This observed value, however, depends on the solar zenith angle as well as the cloud reflectivity and in this form can be used only by noting abrupt changes in its relative value. A more significant parameter is obtained when the Channel 5 value is converted to the albedo. The albedo is determined from the equation

$$A = \frac{I}{I_o \cos \theta}$$

when $\theta$ is the zenith angle of the sun (which is included on the FMRT for each set of data points), I is the radiance measured by Channel 5, and $I_o$ is the radiance that the satellite would measure from a perfectly reflecting isotropic surface illuminated by the sun at its zenith and with no intervening absorption or scattering. The value of $I_o$, which is a constant, may easily be calculated from the solar constant and the known properties of the sensor. In the albedo format, the effect of the solar zenith angle is removed, and thus comparisons from one part of a pass to another can be more easily made. Techniques for the calculation and use of this format were developed midway through the study, and it was used for all subsequent cases.

To determine the required no cloud-cloud threshold, cases were chosen using satellite photographs, in which a distinct cloud edge running nearly perpendicular to the IR swath lines was observed. It was noted that, over clear ocean areas, the measured albedo ranged from 0 to 10 %, while over overcast areas the albedo ranged from 30 to 70 %, or even higher. Threshold values were chosen in the range of from 10 to 20 % (the exact thresholds used in each case are specified in the subsequent case study discussions). Trade-offs must be considered between the greater safety of lower threshold values (which provide greater probability of eliminating all cloud contaminated points), and the improved coverage when higher values are established.

These results are in agreement with the findings of an earlier study by Wexler.[10] Using the early orbits of TIROS III data, Wexler found an uncorrected average Channel 5 albedo of 15 % for the range of concurrent Channel 2 temperatures from 242 to 268°K (clear conditions were assumed for temperatures greater than 268°K, and an overcast was assumed for temperatures less than 242°K). Using the sensor deterioration information presented in the TIROS III and TIROS VII Radiation Catalogues[11,6], this was found to be equivalent, during the early life of TIROS VII, to a 24 % average albedo for approximately 50 % cloudiness. Thus, the 10-20 % threshold values employed for individual data points should eliminate a very large proportion of the seriously cloud contaminated data points.

### 4.2.2 Nighttime Cases

During nighttime passes, no meaningful measurements are available from either Channel 3 or Channel 5. An investigation was made of the difference between Channel 4 and Channel 2 measurements as a cloud detection mechanism. This difference is relatively constant at a given temperature, but should decrease in the presence of high water vapor amounts. Daylight cases were used to attempt to correlate these differences with the presence or absence of clouds. Unfortunately, but not totally unexpectedly, the measured differences showed no detectable changes in the transition from clear to overcast conditions. This seemed due primarily to the high noise level of the Channel 2 minus Channel 4 difference, relative to the peak to peak range of this difference. The estimated short term relative accuracy of these differences was $\pm 3^{\circ}$K, while the entire range of the difference values rarely exceeded 9°K. The failure of this approach may, however, also be due to the lack of sufficient or sufficiently abrupt humidity variations over a partially cloudy area or at a cloud boundary.

Figure 4-1 shows data from a typical daytime swath across a cloud boundary. Channel 5 shows an abrupt change, while the Channel 2 minus Channel 4 difference reveals no obvious breaking point.

It was consequently concluded that the use of nightime IR measurements to eliminate cloud contaminated points from SST data is impractical at the present time. Unfortunately, this result approximately halves the number of usable cases over a given area. There is no reason for believing the Nimbus MRIR data will be significantly better in this regard.

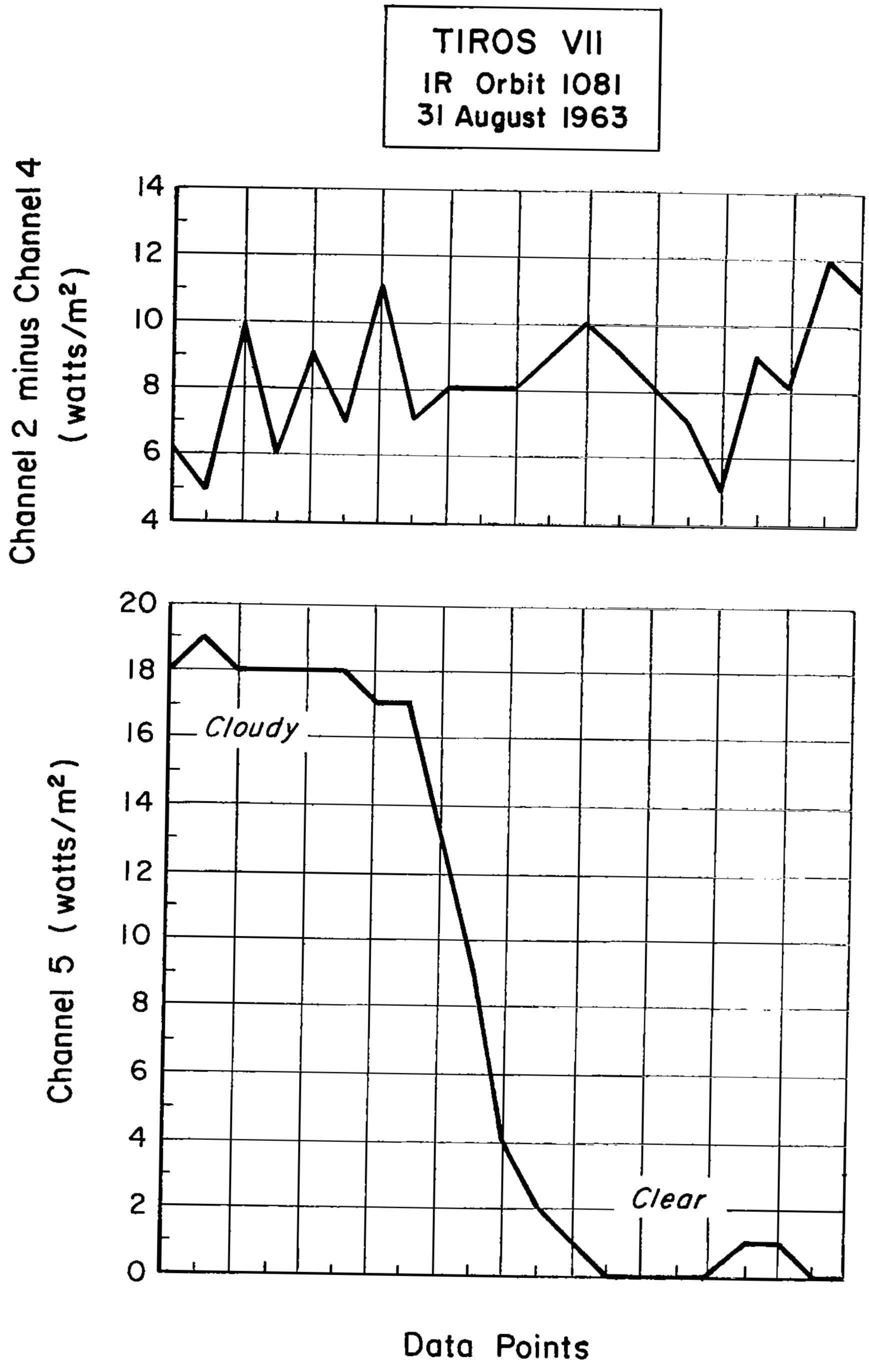


Fig. 4-1 Comparison of Channel 5 and Channel 2-4 Difference at a Cloud Boundary

## 4.3 Atmospheric Attenuation

The radiation emanating from the earth's surface or clouds is attenuated by atmospheric absorption; hence, the satellite sensor measures radiation with an equivalent black body temperature, $T_E$, less than the temperature, T, of the radiating surface. The difference, $\Delta T = T - T_E$, depends on the amount of absorbing gases between the radiating surface and the top of the atmosphere, and so, in general, increases with increasing nadir angle of view of the satellite sensor.

The absorbing gases in the atmosphere which affect the measurement from a satellite of terrestrial radiation are water vapor, carbon dioxide and ozone. Water vapor has a strong vibration-rotation band centered at 6.3μ, and rotation bands beyond 20μ; $CO_2$ has strong bands centered at 4.3μ and at 15μ; $O_3$ has a strong but relatively narrow band centered at 9.6μ. The region 8 to 13μ, to which Channel 2 of the TIROS satellites is sensitive, is termed a "window" region, because of relatively little atmospheric absorption. However, it is a "dirty" window at best because of absorption by $O_3$, and because of the residual absorption by $H_2O$ due to many small bands scattered throughout the region.

It is possible to calculate the amount of atmospheric absorption if the distribution of absorbing gases in the atmosphere is known. The problem is complicated because the absorption varies with pressure and temperature in a non-linear fashion. The calculations utilize experimental measurements of absorption by atmospheric gases. However, because environmental conditions in the experiments are different from those in the atmosphere, theory must be applied. Good results have been obtained by use of the Curtis approximations[12] except in the case of ozone.

Computations of the outgoing radiation for 106 model atmospheres have been made by Wark et al.[13] For clear conditions, water vapor was the primary variable. A correction for an average ozone distribution was made; the error due to different ozone distributions is likely to be relatively small. The results for clear sky conditions are shown in Fig. 4-2 for nadir angles of $0^\circ$ and $45^\circ$. In these diagrams, the ordinates are the amount of precipitable water in the atmosphere. Horizontal lines indicate "average" conditions (w = 2.25 cm) and "moist" conditions (w = 3.9 cm). The nearly vertical lines are labeled $T_E$, the equivalent black body radiation as measured by the Channel 2 sensor. Thus for a $0^\circ$ nadir angle with $T_E = 290^\circ$ the correction to be added to obtain the temperature of the radiating surface is $6.8^\circ C$ for average humidity and $9^\circ C$ for moist conditions; at $45^\circ$ nadir angle the corrections are 9.5 and $12^\circ C$.

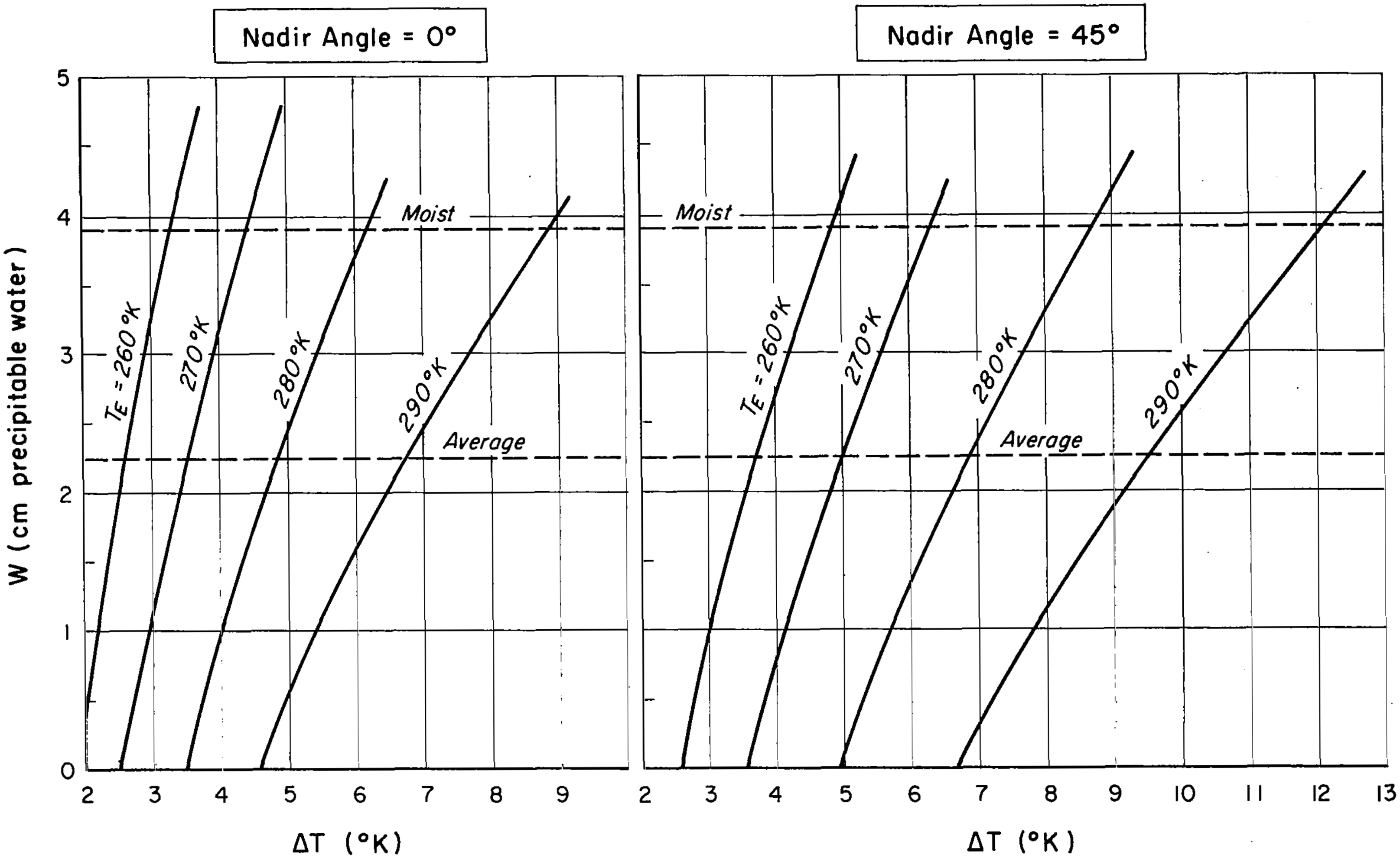


Fig. 4-2 Clear-Sky Temperature Corrections

The humidities should be determined from a nearby, essentially concurrent radiosonde observation. In the absence of such humidity data, approximate corrections can be estimated from synoptic-climatological considerations, or even from climatological data.

In addition, it has been noted that the temperatures measured by Channel 2 and corrected for atmospheric absorption (and also degradation; see Section 4.4) are frequently lower than the actual surface temperature.[14] The discrepancy has been attributed to thin ice crystal clouds or layers of atmospheric particulates not visible from the ground or in the TIROS TV pictures.

### 4.4 Sensor Degradation

It has been recognized that the TIROS sensors have been subject to degradation which increases with time after launch. Corrections for this effect have been provided by NASA in the TIROS VII manuals. These corrections were based on changes in the average signal output with increasing orbit number. For Channel 2, the corrections are shown in Fig. 78 of the TIROS VII manual.[6] For a sensor reading of 300$^{o}$K, the NASA correction is 2$^{o}$K at orbit 780 and 4$^{o}$K at orbit 1500.

An examination of sample printouts of outgoing radiation, as prepared from Channel 2 data by the National Weather Satellite Center of the U.S. Weather Bureau (now of ESSA), was made in order to determine the adequacy of the NASA corrections. The analysis was restricted to clear areas of the tropical Pacific between 5$^{o}$S and 15$^{o}$S, where the ocean temperature was anticipated to remain reasonably constant over the period of interest (June to September 1963). Any change could thus be attributed to degradation. Although there were some discrepancies, it was concluded that, by and large, the NASA corrections were approximately valid.

A periodic degradation of Channel 2 was found by NASA to be related to the orbit-sun phase geometry (Fig. 75 in the TIROS VII manual). The NASA charts showed that, over a 76 day period, errors could be as much as 3$^{o}$K greater or less than those shown in the average degradation curve. A correction for the effect would require determination of the magnitude of the error for individual days during the 76 day period. Corrections to this degree of precision have not as yet been published (the scale in the previously mentioned Fig. 75 is far to gross for this application). It is understood that GSFC is continuing its investigation of the periodic degradation, and that more precise corrections may be available in the future. As a result, no quantitative correction for periodic degradation was attempted in our analyses. The average error due to this effect is estimated to be less than 2°C, which is insufficient to account for the several discrepancies between conventionally observed sea surface temperature and the equivalent Channel 2 temperature corrected for average degradation and atmospheric absorptions, as will become apparent in later sections of this report.

## 5. CASE STUDIES

### 5.1 North Atlantic, Labrador Current

Early in this study, four cases were selected for areas of the North Atlantic. The areas chosen exhibit high climatological SST gradients during summer months, and it was expected that adequate conventional data from ship reports would be available. The selected cases all occurred during late August or early September of 1963. Nearly coincident TV pictures and nephanalyses were used to assure some regions of clear skies within the selected areas.

Of the four cases selected, one was found to be unusable since it included only closed-mode radiometer data. While it was not a criteria for case selection, there were areas of overlap between each of the remaining three cases.

The analysis of the best of these cases is shown in Figure 5-1. These data are taken from Pass 1126 of TIROS VII, on 3 September 1963 between 1234Z and 1238Z. The isotherms shown in this and all subsequent analyses are uncorrected for atmospheric attenuation or sensor degradation. Rather, attenuation and degradation corrections were determined for individual points or areas as required for comparisons with conventional data. The isotherms are drawn at 2-1/2$^{o}$K intervals. The cloud edge shown in Figure 5-1 was determined by using a 10 % albedo threshold and the Channel 5 data. The dashed extensions to the solid isotherms, both into the cloudy area and beyond the edge of the data, are merely extrapolated best estimates. The 267.5$^{o}$K isotherm shown below the edge of the Pass 1126 data was taken from an earlier pass.

Fortunately, the weather ship Bravo was located within the clear area of the analysis, and provided upper air data for use in atmospheric attenuation corrections. These corrections were calculated as discussed in Section 4.3 above. They indicated that, due to atmospheric attenuation, the apparent radiative temperature of the sea surface would be 6$^{o}$K less than the actual sea surface temperature. From the sensor degradation estimates in the TIROS VII Radiation Data Catalog[6], it was found that the measured temperatures would be approximately 2$^{o}$K less than actual for these temperatures and time period. The average temperature of the waters off Labrador in this season is 40$^{o}$F, or 277$^{o}$K.[15] Figure 5-1 suggests that 265$^{o}$K is a good (uncorrected) representative temperature for the area involved. When increased by the 8$^{o}$K combined correction for attenuation and degradation, an average corrected sea surface temperature of 273$^{o}$K is obtained, or 4$^{o}$K less the anticipated value. As discussed at the end of Section 4.3, such a difference between conventionally observed surface temperatures and the corrected Channel 2 data is not unusual.

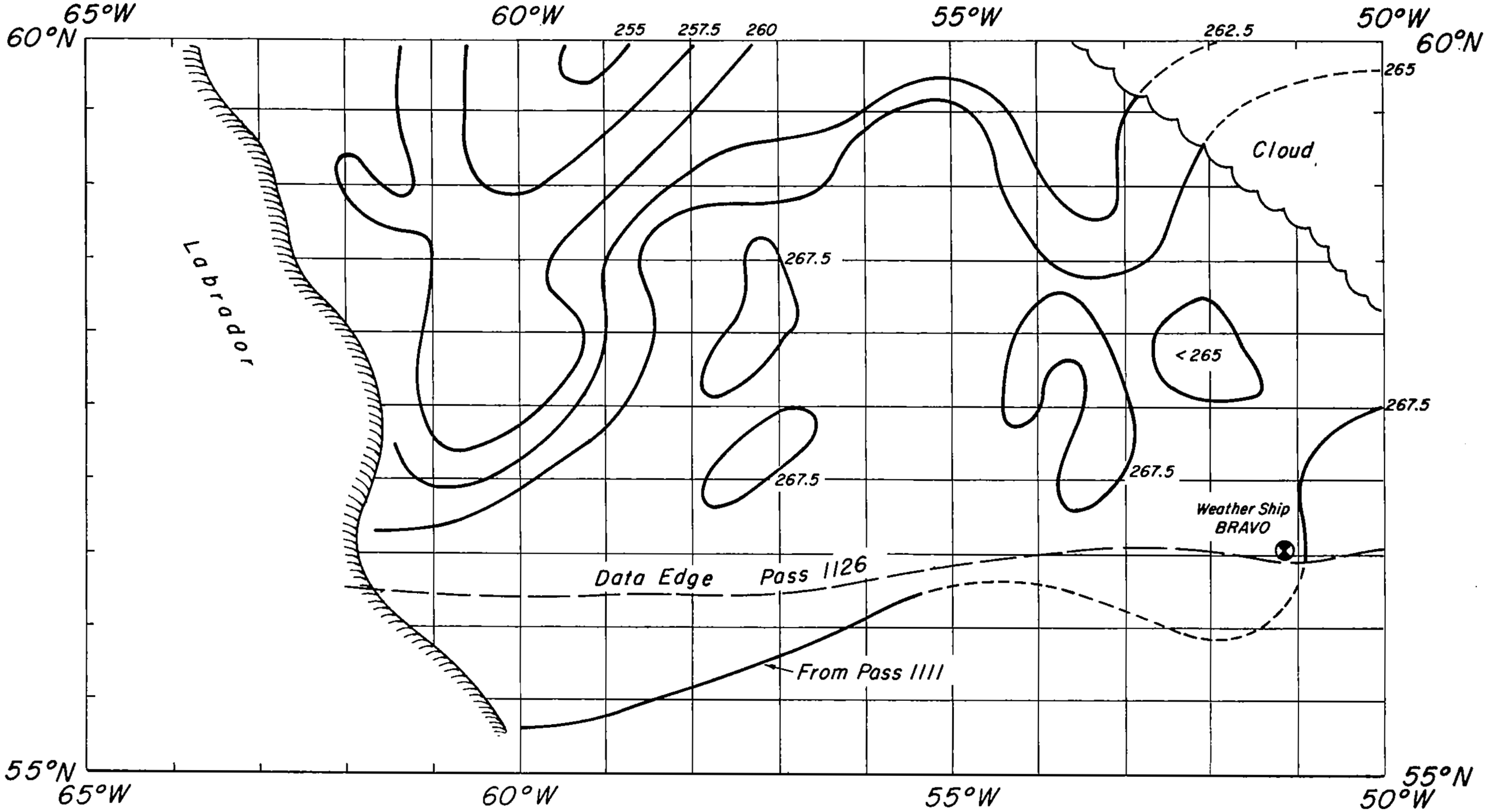


Fig. 5-1 North Atlantic, Passes 1126 (3 September, 1963) and 1111 (2 September, 1963)

Conventional surface ship data concurrent with the selected cases were requested from the National Weather Records Center (NWRC), but unfortunately not a single ship had filed reports for the desired areas during the appropriate time period.

There are several interesting features in the temperature pattern presented in Figure 5-1. There is a strong indication of the cold Labrador Current, which moves southward off the eastern coast of Labrador. To the east of the current there is a nearly isothermal region, probably due to mixing with a warm countercurrent which moves northward along the western coast of Greenland.[16] There is some indication of this warm current in the extreme eastern edge of the analysis, but the significance of the pattern there is speculative.

A pass on the previous day was found to be largely cloud covered (based on a Channel 5 10 % albedo threshold), but a small clear area of the earlier pass did overlap a restricted area in the southwest corner of Pass 1126. This was Pass 1111 of TIROS VII, on 2 September 1963 at 1213Z. The limited SST data from Pass 1111 seemed to fit well with those from Pass 1126 and are included in Figure 5-1.

Figure 5-2 shows the analysis of a still earlier pass over this same area. These data are taken from Pass 1082 of TIROS VII, on 31 August 1963 at approximately 1309Z. The useful SST data were somewhat more restricted by cloudiness in this case, and seemed in general more noisy. When compared with Figure 5-1, Figure 5-2 shows that the detailed structure is considerably changed, but the gross pattern remains the same. Whether or not actual synoptic changes are shown by the difference in detailed structure could not be determined because of the apparent noise in the IR data and the lack of conventional data. There is still an indication of the Labrador current off the east coast of Labrador, with a generally isothermal area east of the current.

The uncorrected Channel 2 values shown in Figure 5-2 average about 2.5°K higher than those for Pass 1126. Because of a decrease in the moisture content of the upper atmosphere, the attenuation correction in this case is only 5°K (1°K less than for Pass 1126) while the correction for sensor degradation remained at 2°K. After these corrections, the approximate average temperature of the field of view in Pass 1082 is 274.5°K, or 1.5°K higher than that seen in Passes 1111 and 1126. There are indications that such an average temperature change over an area of this size is quite reasonable[17], but, without conventional data, the reality of this change could not be substantiated.

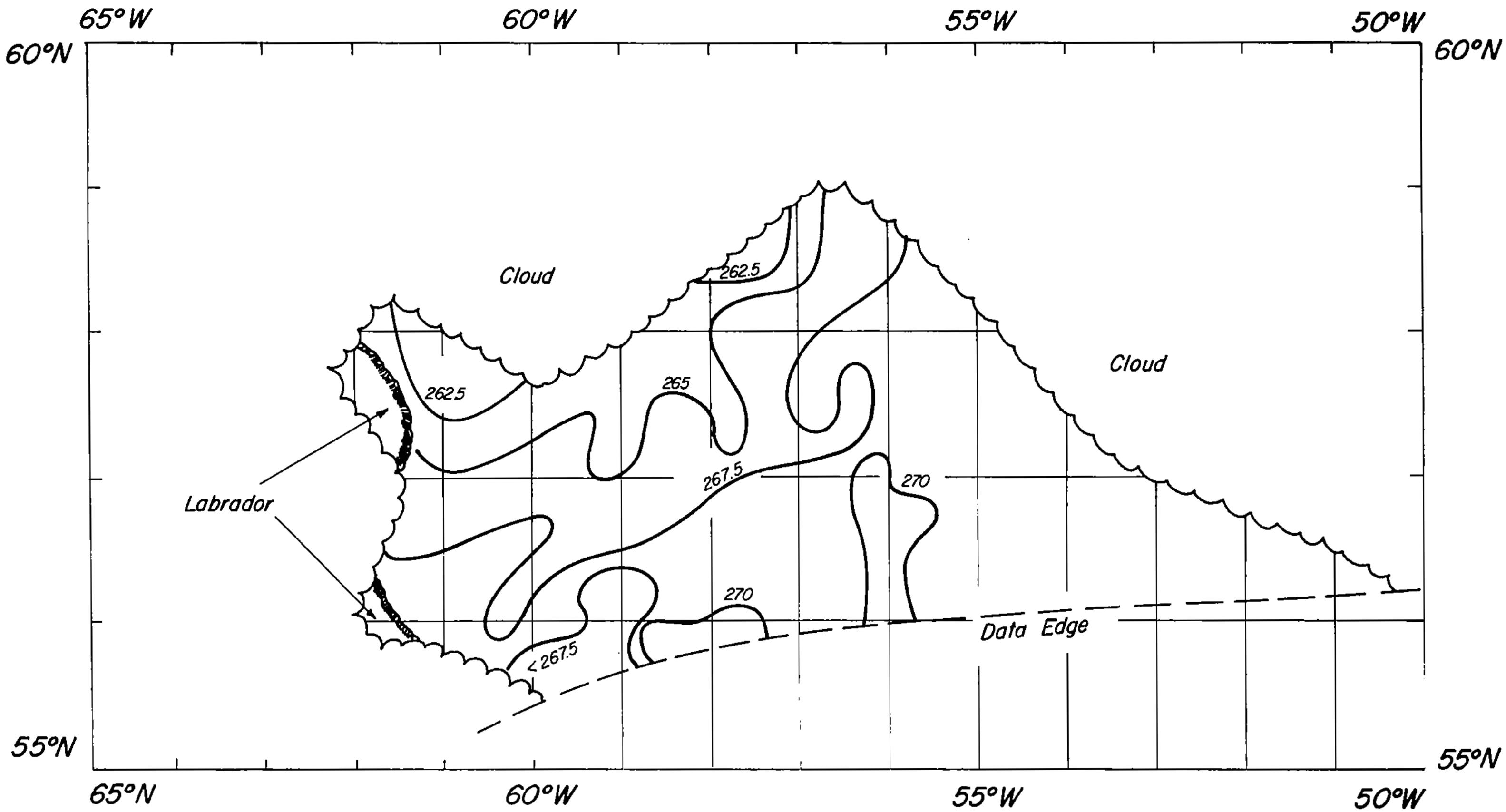


Fig. 5-2 North Atlantic, Pass 1082 (31 AUGUST, 1963)

## 5.2 Western Pacific Cases

Due to the difficulty in finding sufficient cloud-free cases in the high temperature gradient areas of the North Atlantic (due especially to the lack of reduced "real time" data as discussed in Section 3.2.3), it was decided to investigate the relatively cloud-free areas of the Western and mid-Pacific. It was hoped that parts of the Kuroshio or North Pacific Currents could be observed. Three cases were selected for the Western Pacific, and one for the mid-Pacific. Of these four, the mid-Pacific case and one of the Western Pacific cases could not be properly analyzed due to problems associated with near closed-mode conditions. The remaining two cases will be discussed separately:

### 5.2.1 Kuroshio Current Case

The data for this case were run in both the listing and the mapping format. The mapping was done at a scale of 1:2,500,000, but the data proved to be much too noisy for adequate analysis on this scale (adjacent data points at an approximate 20 n. mi separation differed by as much as 20°K). Presumably much of the apparent noise may be attributed to errors in geographical locations due to the near closed-mode conditions. It was decided to hand average the uncorrected data over 1° squares, and to consider abrupt changes in the Channel 5 values as outlining the cloudy areas. (Listings in the albedo format were not available at the time these analyses were prepared.) Since the area was partly cloudy, the nephanalyses were insufficient for precise determination of clear areas.

The analysis is shown in Figure 5-3. The data are from Pass 779 of TIROS VII, on 11 August 1963 at approximately 0238Z . In addition to the problem of the Channel 2 noise, there was occasionally conflicting information as to the cloudiness of an area where individual swaths of the Channel 5 data overlapped each other. As a precaution, all areas indicated as cloudy on any swath were eliminated from the analysis. The resulting cloud pattern, as shown in Figure 5-3 is remarkably similar to that of the nephanalysis[8] from a concurrent TV pass; the nephanalysis showed a series of narrow cloud bands extending westward across a mostly clear area from a larger cloud system.

The gross outlines of the warm Kuroshio current can be seen to the southeast of Japan, although detailed structure was lost in the averaging process. The usual north-south temperature gradient in this region for the month of August is from

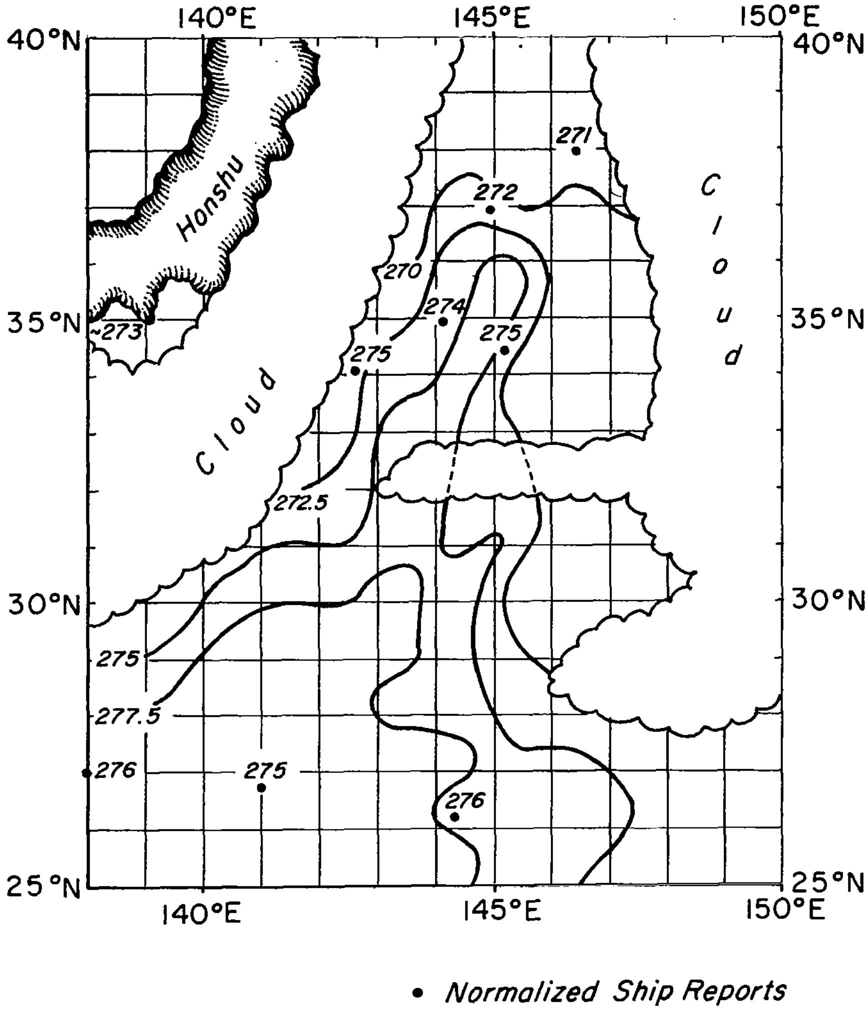


Fig. 5-3 Kuroshio Current, Pass 779 (11 August, 1963)

294 to 301°K [15], or a difference of about 7°K, which is in agreement with the temperature gradient as analyzed from the IR data.

Upper air data from the Japanese station at Tateno indicated a hot and moist troposphere, with a slight subsidence inversion at 820 mb. Taking 275°K as the average temperature of the field, and considering the 20° minimum IR sensor nadir angle of the pass, an approximate atmospheric attenuation correction of 9°K was determined. This, plus a 2°K sensor degradation correction, adjusts the average observed temperature to 286°K, still short of the 300°K indicated in mean monthly charts for this region.

Conventional ship measurements of SST were extracted from the National Meteorological Center (NMC) charts over a five day period centered on the date of this pass (11 August). These conventional measurements were generally in line with the climatological values, leaving the approximately 14° discrepancy in the IR data unexplained. The ship data were converted to degrees Kelvin, and then reduced by 25°K to simplify the comparisons with the IR data. (The conversion of the ship data to a Channel 2 base, rather than vice versa, was used to reduce the amount of data to be modified, since only a very limited amount of conventional data was available.) The modified ship data are plotted in Figure 5-3. Considering the lack of dependability of typical ship reports of SST, and the fact that the ship data cover a five day period, the two types of data correlate quite well. It seems reasonable to infer that, given a suitable conventional observation to serve as a benchmark, absolute temperatures as well as temperature gradients may be deduced from the TIROS IR measurements.

### 5.2.2 Yellow Sea Case

The FMR tapes for this case were processed in the same manner as those for the Kuroshio Current case discussed in the previous section. Again the noise level was such that averaging in 1° squares was necessary. When relative changes in the Channel 5 data were used to eliminate cloud points, only a narrow clear strip remained, running southwestward from the southern tip of Korea to about 25° North.

The data taken from Pass 780 of TIROS VII, at 0417 Z on 11 August 1963, revealed an unpatterned, essentially isothermal field with an average uncorrected temperature of 279°K. Climatological maps [15] reveal a temperature gradient of less than 2.5°K from the tip of Korea to 25° North.

Sparce upper air data from Mosulpo in Korea indicated similar, but slightly drier conditions than reported at Tateno that same day (11 August); the Tateno data were discussed in the previous section. Due to the effect of higher nadir angles, however, the appropriate attenuation correction in this case is $10^{o}$K. The total error is thus approximately $12^{o}$K, raising the corrected average to $291^{o}$K, still $9^{o}$ less than the anticipated value for this region. No ship reports were available to substantiate the finding of isothermal conditions.

## 5.3 Consistency Tests

As can be seen from the previous discussions, the problem of finding conventional data to substantiate the IR observations and analyses is a formidable one. Accordingly, it was decided to apply a series of consistency tests to the IR data. If the IR data from different days can be shown to be consistent over areas where it is expected that day to day temperature changes will be small, then a greater level of credability may be assigned to the day to day small and large scale SST pattern changes observed in the absence of conventional measurements. Three areas were chosen for this part of the study: (1) the Sea of Okhotsk, which is partially sealed off from the North Pacific by the Kamchatka Peninsula and the Kuril Islands; (2) the Gulf of Alaska; and (3) the relatively isothermal waters of the Indian Ocean off the northwest coast of Australia.

### 5.3.1 Sea of Okhotsk Cases

The Sea of Okhotsk is an area of slow SST change. Nephanalyses for 22, 23 and 25 June 1963 indicated largely clear conditions over the area. On all three days the TIROS radiometer was in the alternating-open mode when passing over the Sea of Okhotsk.

The analysis for the first day is shown in Figure 5-4. These data were taken from Pass 51 of TIROS VII, on 22 June 1963. As was to be expected for this remote area of the world, no ship reports were available. Little is known of the local currents, nor even of the climatic temperature trends.

In Figure 5-4, a band of relatively warm water can be seen around the northern coast of Sakhalin, and particularly around the northern entrance to the Tatar Strait, which is between Sakhalin and the Russian mainland. This pattern at first suggested a possible warm current, passing northward from the Sea of Japan. Closer inspection

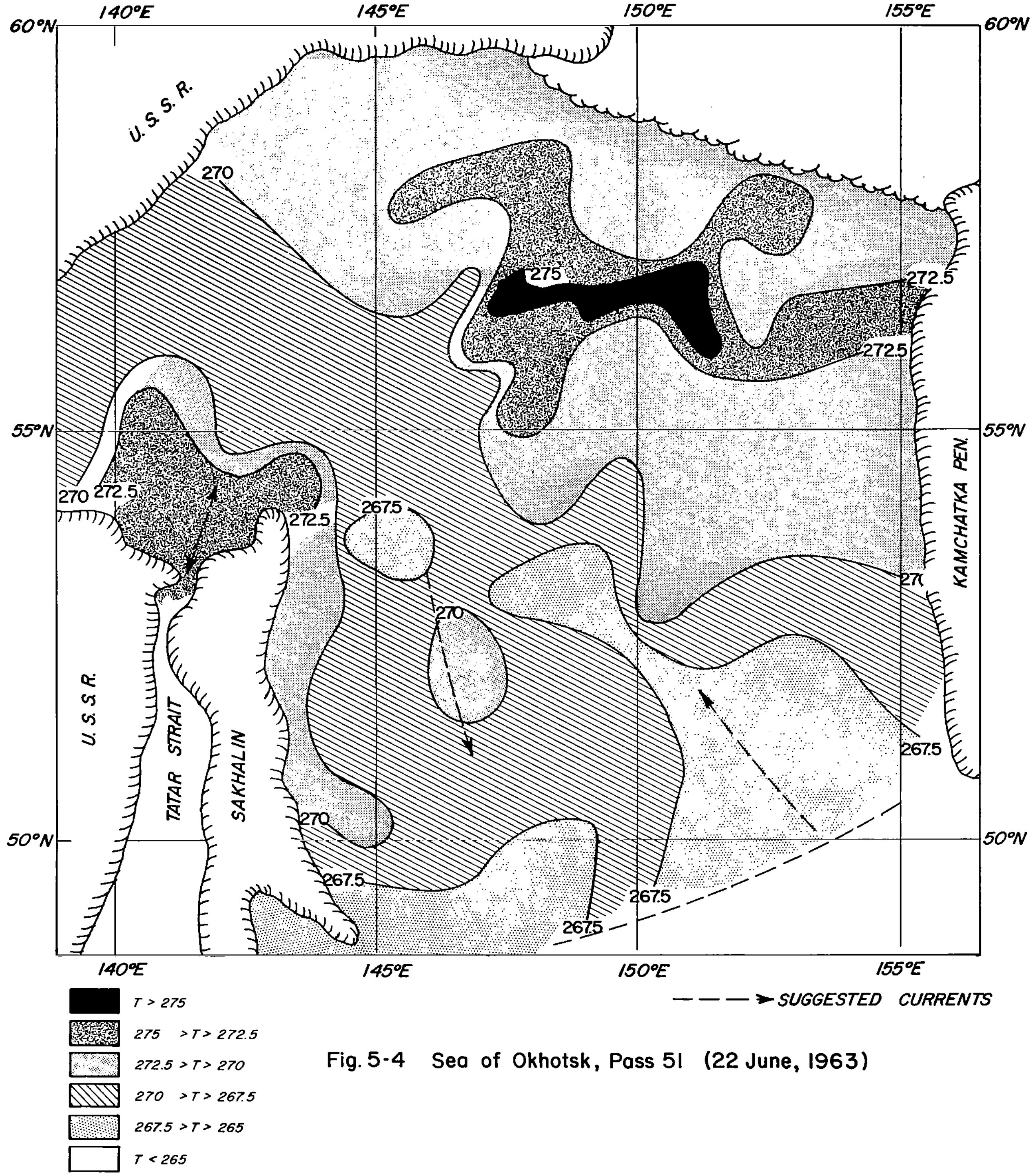


Fig. 5-4 Sea of Okhotsk, Pass 51 (22 June, 1963)

of this and the following days, however, reveals an indentation toward the Strait entrance of the local isotherms, a pattern indicative of a southbound cool current. From these maps alone, no conclusive decision as to current direction could be reached.

Extending northwestward from the southern tip of Kamchatka is a suggestion of a cool current. The cold Oyashio Current is known to flow southwestward along the eastern coast of Kamchatka.[16] The cool current suggested by the IR analysis may be branching from the main Oyashio Current. These suggested currents, and a southbound return current off the east coast of Sakhalin, are indicated in Figure 5-4. It should be noted that both this return current, and a southward current through the Tatar Strait are indicated in standard current maps.

In the northeastern corner of the Sea of Okhotsk is a large area of relatively warm water which does not appear in the analyses of later passes.

Figure 5-5 shows the analysis for this same area one day later, using data from Pass 65 of TIROS VII. Useful coverage here is considerably less than that of the previous day, while the minimum nadir angle is a high $35^{\circ}$, $10^{\circ}$ higher than in Pass 51.

Again Sakhalin is surrounded by a band of relatively warm water, but the warmer water at the northern entrance to the Tatar Strait is no longer evident. The presumed cool branch of the Oyashio Current appears to extend further north, while the warm waters in the northeastern sector of the Sea of Okhotsk can no longer be identified. It is interesting to note that the small scale cold and warm spots, seen in the area to the east of the warm water surrounding Sakhalin, can still be identified. The generally lower temperatures throughout the field of view may be partially attributed to the increased nadir angle. Another possible cause for these lower temperatures is the periodic fluctuation in Channel 2 degradation with the orbit-sun phase geometry. During this period there was a rapid downward excursion in sensor sensitivity (see Fig. 75, Ref. 6) which would have the effect of decreased Channel 2 temperature values. Upper air data from the Alexandrovsk station on Sakhalin indicated no change in air mass between the two days.

The complete disappearance of the northeastern warm waters can not be accounted for. Considering the high level of consistency of the remainder of the map, this disappearance may, at least in part, be real. Other investigators[17] have found, however, that the maximum 24 hour temperature change that one can expect over any extensive region is about $2^{\circ}K$.

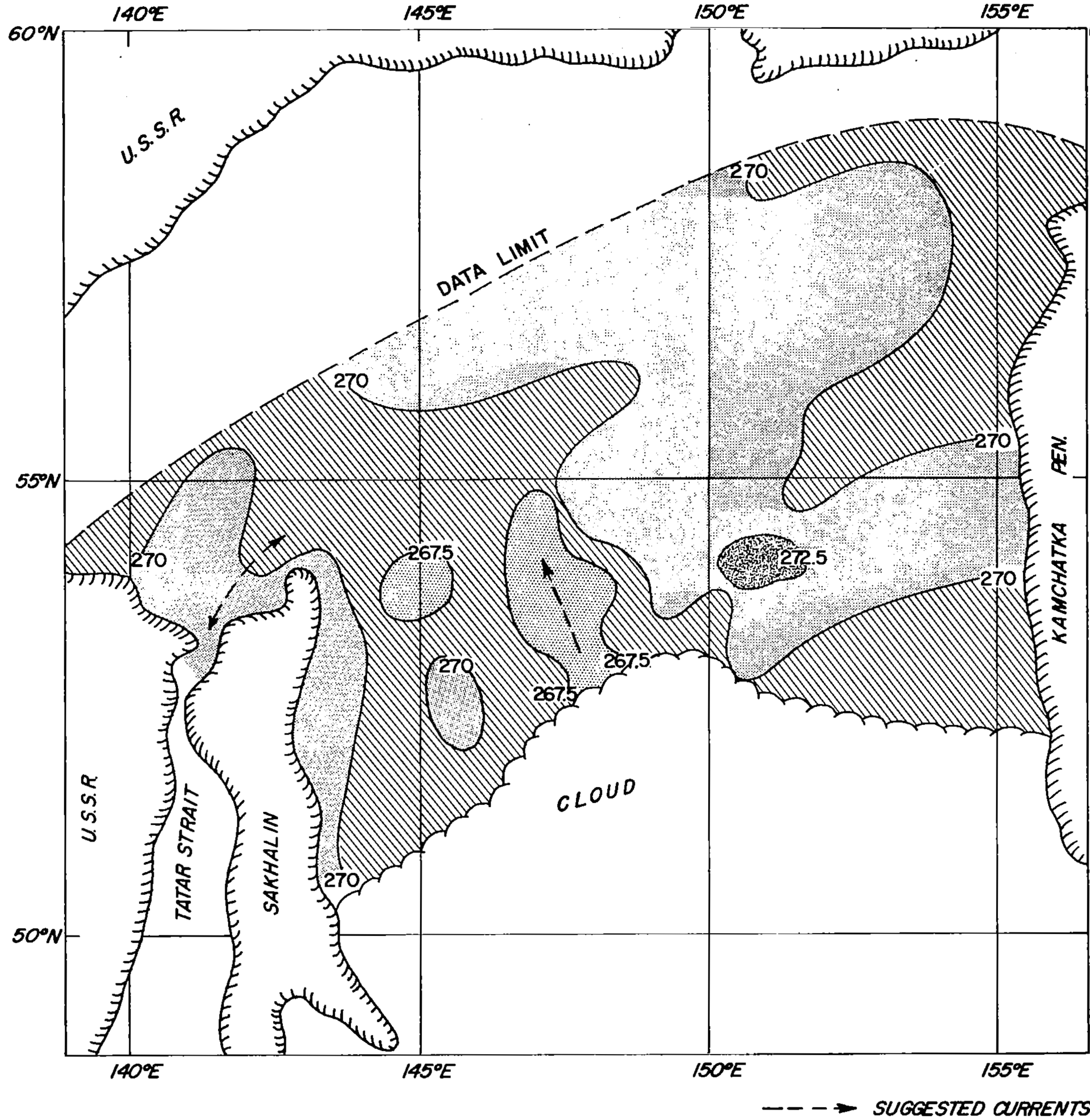


Fig. 5-5 Sea of Okhotsk, Pass 65 (23 June, 1963)

There was no useful IR pass over the area on the 24th of June, but, on the 25th, TIROS Pass 95 again encountered clear skies over the Sea of Okhotsk. By this time, minimum nadir angles were near or above 45°. As a result, the validity of the analysis of this day is questionable, although, as may be seen in Figure 5-6, the fundamental large scale features remained intact. The warm waters in the northeastern part of the Sea of Okhotsk, seen in Pass 51, have not reappeared. Upper air data, again from Alexandrovsk, indicated a net increase in moisture on this day of such an extent that, under similar geometric conditions, the IR recorded temperature would be expected to be from 1/2 to 1 degree lower.

### 5.3.2 Gulf of Alaska Case

The second area selected in the series of consistency tests was the Gulf of Alaska, just southeast of the Alaskan Peninsula. This area appears on mean monthly maps as a large, nearly isothermal region with an average August temperature of about 284°K. Unfortunately there was only a restricted area of cloud free (as determined by relative changes in the Channel 5 data) overlap between the two passes available, and that in an isothermal region devoid of pattern. The data as analyzed in Figure 5-7 were largely taken from Pass 735 of TIROS VII on 8 August 1963 at 0324Z. The dashed line in the southeast corner of the figure represents the northern extent of the overlapping data from Pass 748 on the following day at 0024Z. Pass 748 also showed this region to be isothermal, and at the same absolute temperature as indicated by Pass 735.

Upper air data for both days from the Alaskan King Salmon station indicated a well mixed lower layer with near saturation from the surface to about 800 mb. Because of the relatively cold air temperatures, however, this did not represent a significant amount of precipitable water, and the correction term is only 5°K. Combined with a 2° correction for sensor degradation, the average corrected IR temperature becomes about 280°K. Again, the corrected temperatures are somewhat less than the true values.

In spite of its limited applicability as a consistency test, this case is considered worthwhile because of the suggestion of a warm current moving westward at about 58°N (see Fig. 5-7), which is not analyzed in mean monthly charts. At about 42°N, the North Pacific Current moves due east across the Pacific Ocean toward the American mainland.[16] (It is originally formed to the east of the Asian continent

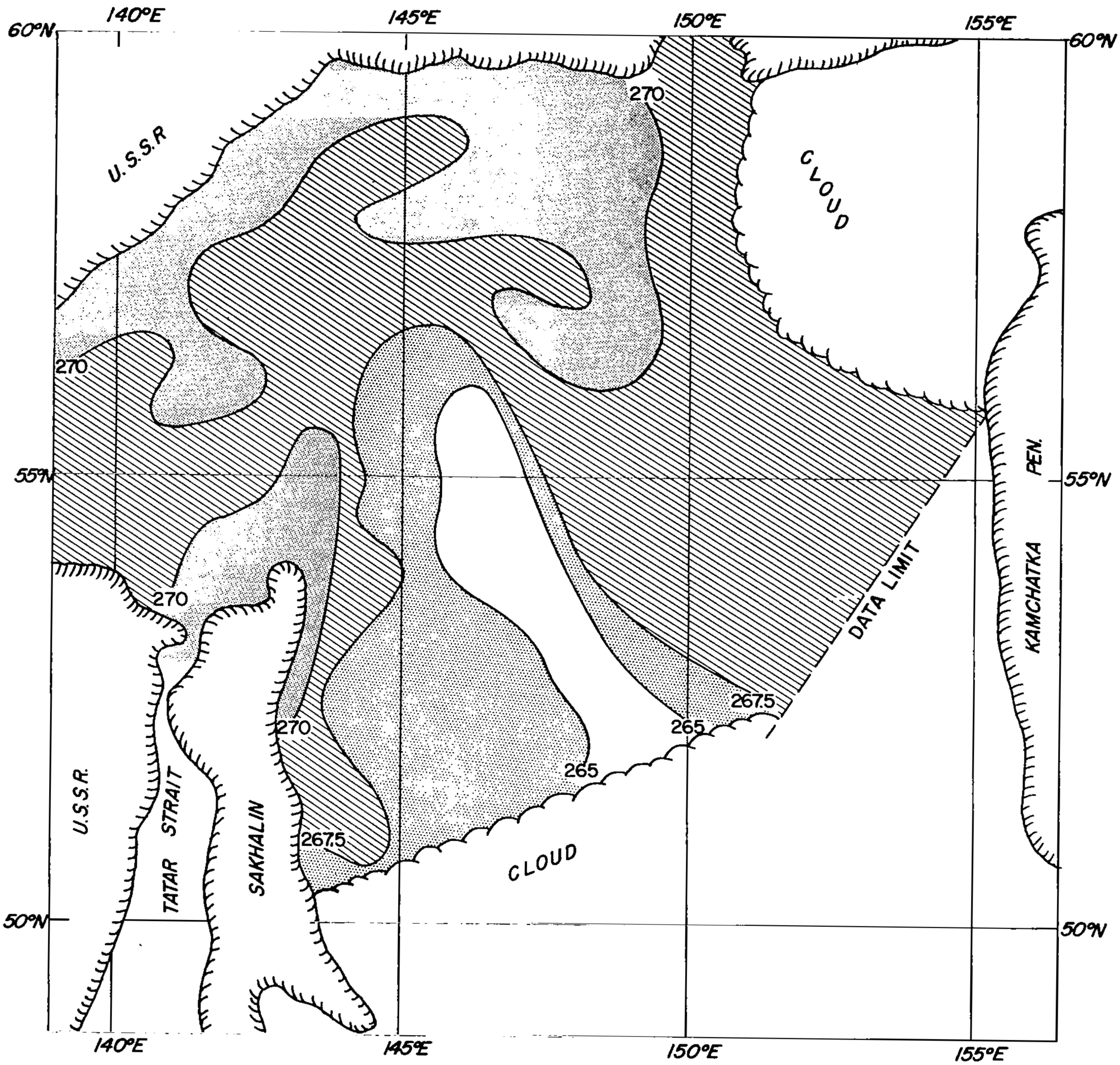


Fig. 5-6 Sea of Okhotsk, Pass 95 (25 June, 1963)

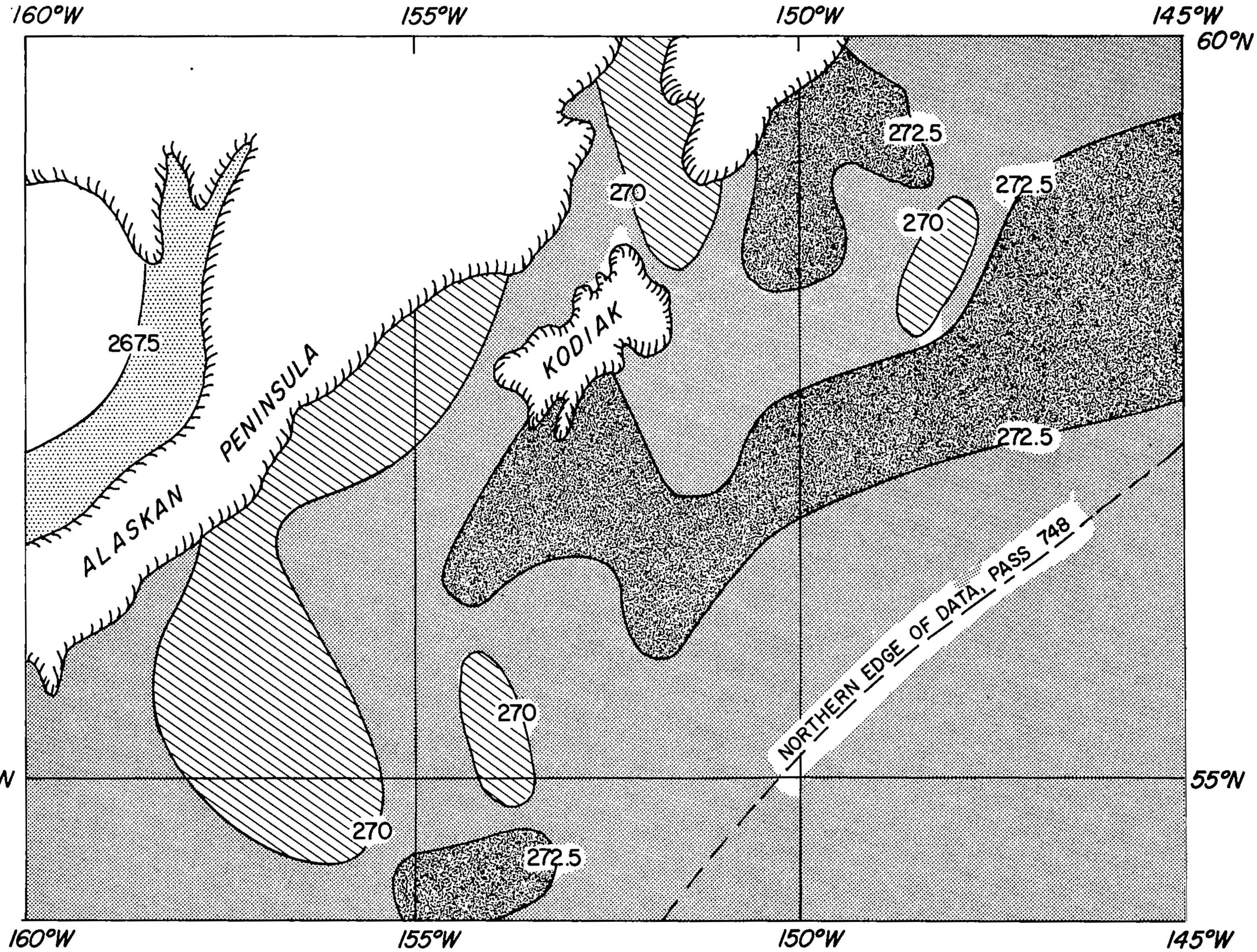


Fig. 5-7 Gulf of Alaska, Passes 735 (8 August, 1963) and 748 (9 August, 1963)

by a confluence of the southward flowing Oyashio Current and the northward flowing Kuroshio Current, both of which have been discussed in connection with previous cases.) Upon reaching the American mainland, it divides into (1) the southward flowing California Current, and (2) the Alaska Current which curves counter-clockwise past the Gulf of Alaska and then follows the Alaskan Peninsula. It is suggested that the elongated warm pattern which, in Figure 5-7, extends across the area from east to west may represent the northern-most branch of the Alaska Current at the longitude where it again recurves southward.

5.3.3 Indian Ocean Case

The third series selected in this set of tests was located in that portion of the Indian Ocean just off the northwest coast of Australia. This area was one of generally clear skies throughout the period 6 August through 8 August 1963, as evidenced by both nephanalyses from TIROS TV passes, and conventional weather maps. This was also one of the few occasions in this investigation when it seemed relatively safe to assume clear skies during a nighttime pass. Two passes were selected for analysis; one from TIROS VII, Pass 706, on the 6th of August 1963 at 0348Z or 1148 local time; and the other 2-1/2 days later from TIROS VII, Pass 744, on 8 August at 1655Z (or 0055 on 9 August local time).

The first of these analyses is shown in Figure 5-8. As indicated previously, the area is largely isothermal, with only a slight increase in temperature toward the north (equatorward). The cloud mass shown in the western portion was determined using a 10 % albedo threshold applied to the Channel 5 listings. The satellite was in alternating-open mode in both cases, so the data as originally plotted were somewhat noisy, particularly in view of the small over-all gradients. Much of this problem disappeared when the data were re-plotted as averages over $1^{\circ}$ squares.

Figure 5-9 shows the corresponding night-time analysis from Pass 744. With the exception of the relatively cool waters along the Australian coast, the pattern looks quite different, although the absolute temperatures are not drastically changed. The area of the warmest waters in Figure 5-9 was largely cloud covered at the time of Pass 706 (Fig. 5-8). The cooler temperatures indicated in the northwest corner of the Pass 744 data seem out of place, and may well be the result of some cloudiness. Of course Channels 3 and 5 provide no information as to the cloudiness of an area in night-time passes. The periodic variation of Channel 2 degradation with the orbit-sun phase geometry is relatively steady during this period, and hence cannot account for the generally warmer temperatures found in the second case.

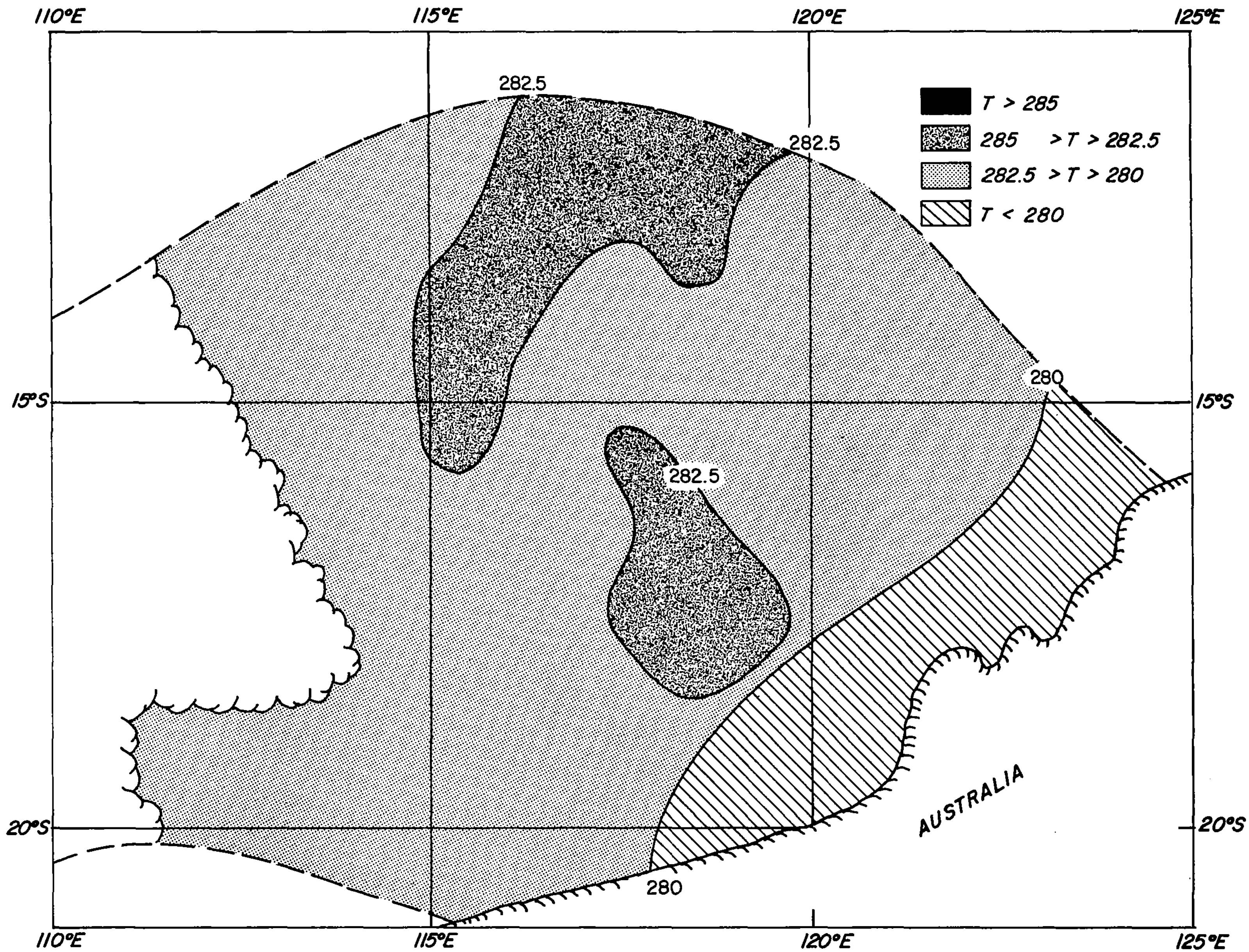


Fig. 5-8 Indian Ocean, Pass 706 (6 August, 1963)

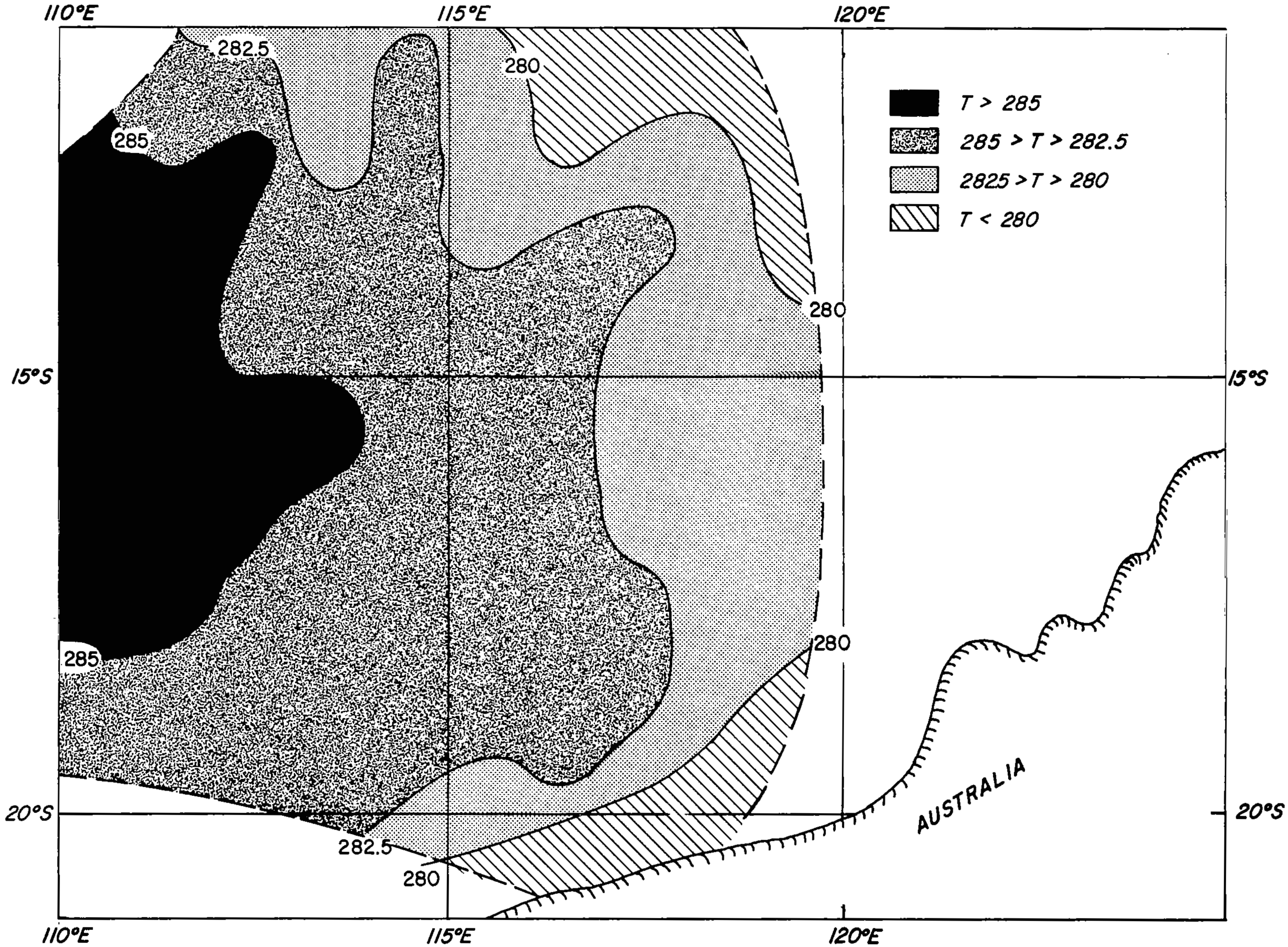


Fig. 5-9 Indian Ocean, Night-time Pass 744 (8 August, 1963)

No upper-air data were available for this area, and of course there were no ship reports. Assuming a large atmospheric attenuation correction of 8°K, and a sensor degradation correction of 2°K, the approximate average temperature of the Pass 706 analysis, 282°K, becomes 292°K. The average August temperature for these waters is 298°K.[15] Part of the discrepancy may be due to the relatively large minimum nadir angle of 30° found in both cases, and part to the presence of invisible ice crystal clouds or atmospheric particulates.

5.3.4 Results of SST Consistency As Compared to Other Studies

As has been the case in all phases of this feasibility investigation, lack of conventional shipboard SST measurements was a major stumbling block. In this particular series of tests, we have taken repeated looks at a given area at intervals of a day or two, and then checked the resultant IR analyses for consistency. Inherent in the procedure is the assumption that there is consistency to be found. Without simultaneous intensive shipboard measurements, the validity of this assumption is always somewhat subject to question.

Numerous investigators have studied both the short and long term fluctuations in SST, and their possible causes. Wolff et al[17] indicate that 48 hour changes in temperature, averaged over relatively large areas, may reach ± 4°K in areas of sharp temperature gradients. On the average, however, these changes are of the order of ± 0.3°K. It is suggested that these changes in SST are caused predominantly by advection patterns which are large in scale, corresponding in area and time scale to atmospheric disturbances at the surface. These findings are substantiated by Chase[18], who found that warming generally occurred in southwest winds prior to the passage of a cold front, while cooling occurred in northerly winds after the frontal passage.

During the discussions which led to the "Recommendations of the Panel on Sea Surface Temperature"[19] of the Conference on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital, and Lunar Laboratories, several of the oceanographers present stated that, over large areas of the oceans, day-to-day changes in SST, and also year-to-year changes for the same calendar month, are considered to be so small that they place greater credence in a climatological value than they do in direct observations from any single ship. It was these opinions that led to the stringent requirements for accuracy of satellite-observed SST, to fractions of a degree C, which are stated in the Recommendations.[19] Our meteorological experience, however, leads us to presently view these opinions with some doubt, feeling that they may result more from lack of adequate data and the consequent necessity of using primarily climatological techniques, rather than any real knowledge, for many areas, of the typical day-to-day and year-to-year variability. Many meteorologists can remember when conditions in both the tropics and the stratosphere were considered to be highly persistent, with little or no departure from climatology to be expected; adequate subsequent observations have since rudely dispelled these illustions. The extent of coverage and the frequency of observations of SST, which only satellites can make practically possible, probably represents our best and perhaps our only chance for determining the real degree of variability of SST.

Some work has been done using airborne IR measurements of SST.[20] Errors at present are of the order of whole degrees. In a study undertaken by the Sandy Hook Marine Laboratory of the U. S. Fish and Wildlife Service, repeated IR measurements of the SST patterns of the middle Atlantic continental shelf were made from heights of 200 to 500 feet at approximate two week intervals. Figure 5-10 shows a successive pair[21] of these measurements for the month of May, 1964. The data are plotted in degrees Farenheit at $1^{o}$ intervals. It should be noted that here also large scale patterns persist, while the smaller scale patterns have changes in the two week interval. The absolute temperature in some areas of the maps have also changed by as much as $10^{o}$F. Of course, this is an area near the western edge of the Gulf Stream where significant SST changes are not unlikely.

Our tests indicate that where there is no general change in the sea surface temperature as averaged over an area of reasonable size, the observed IR patterns within this area also remain relatively constant; this result seems reasonable in terms of scale considerations. This is particularly true of large scale current features such as were seen in the Sea of Okhotsk, and in the Western Atlantic in Section 5. 1. Only in the coastal waters of Australia was there a complete change in pattern, and here there were other influences or possible problems such as a generally isothermal sea, a long 2-1/2 day interval, and the use of a nighttime case in which the presence of scattered or low cloudiness will always remain a possibility. The persistence of the small cold and warm spots off the eastern coast of Sakhalin in the Sea of Okhotsk indicated that even small scale features may at times change only insignificantly. The only really negative result of these tests was the disappearance of the large warm area in the northeastern portion of the Sea of Okhotsk. The high level of consistency in the other portions of this same case suggests that there may have been either an actual change in SST, or, more likely, undetected change in cloudiness or atmospheric absorption. In view of the general

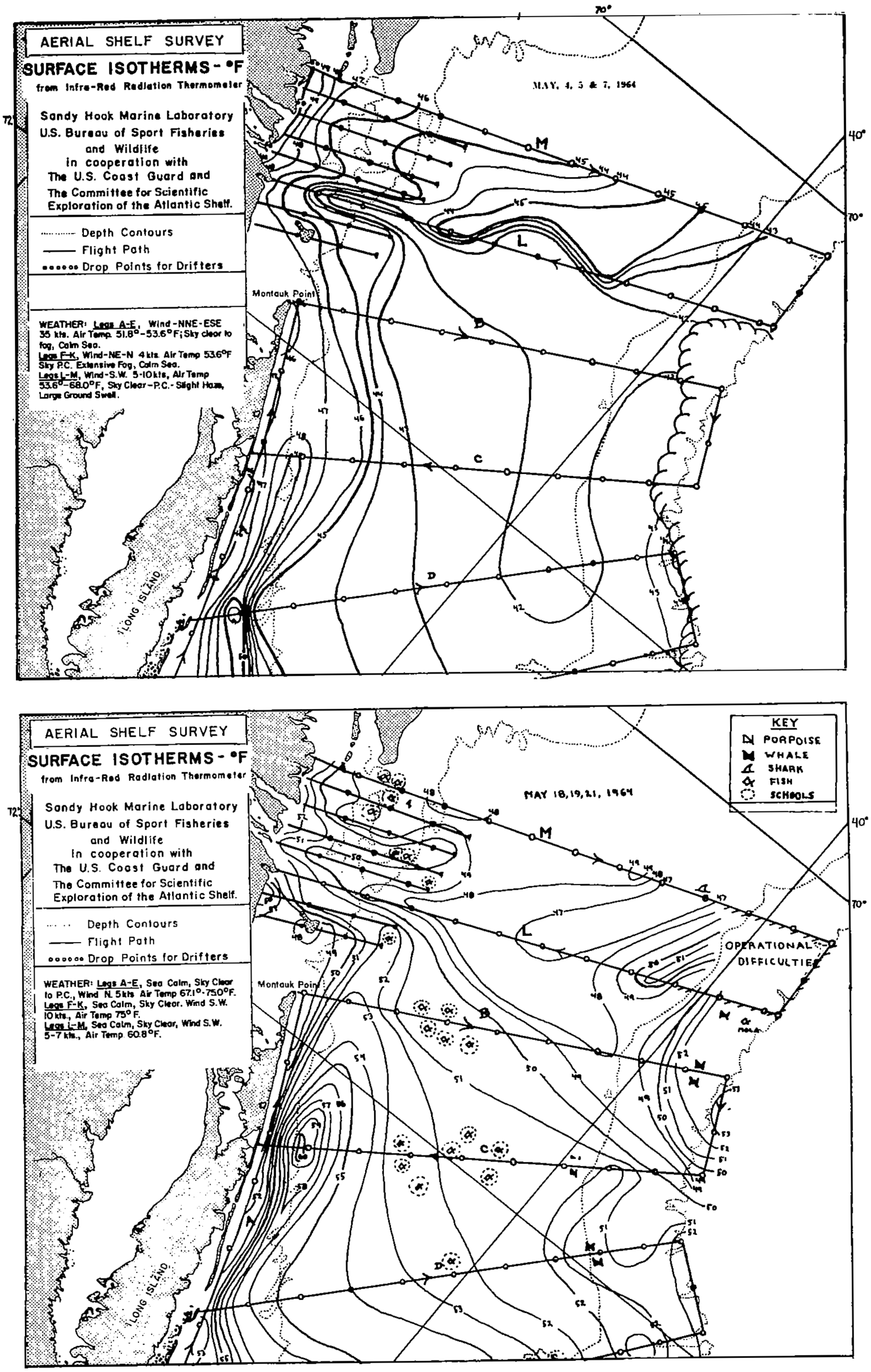


Fig. 5-10 Sandy Hook Marine Laboratory Airborne IR Mappings

pattern consistency revealed in these tests, it is felt that even a single pass over a given area can usually provide an accurate indication of at least the large scale SST gradient patterns. If a conventional measurement is available for a benchmark, reasonably accurate absolute values of SST can be deduced.

## 5.4 Real-Time Studies

As discussed in Section 3.2.3, the greatest density of conventional ship SST reports occurs off the eastern coast of the United States. It is here also that the most investigated of the ocean's major currents, the Gulf Stream, provides an excellent opportunity to observe synoptic scale temperature changes, especially along its edges. Unfortunately, there is very little regularly processed TIROS IR data for this region; most of the IR data for this area are the so-called "real-time" data, which currently require a special, long and laborious conversion to usable form.

For these reasons, only three "real-time" cases for this area were selected and ordered from the Computations Group at NASA's Goddard Space Flight Center. Of these three cases, timing errors caused the rejection of one of them, and were prevalent in a second. The remaining case proved to be satisfactory, although noiser than the usual IR data. The analysis of the first of these cases is presented in Figure 5-11. These data are from Direct Pass 107 of TIROS VII, on 26 June 1963. This is the better of the two usable "real-time" cases, and clearly shows evidence of both the southbound Labrador Current and the Gulf Stream. These patterns show considerable similarity to the most recent mean monthly charts available for this area.[22] The dashed isotherms in Figure 5-11 represent best estimates, used to bridge areas of poor data.

Upper air data from Washington, D. C. for this date revealed a low relative humidity throughout the atmosphere, except very near the surface. Recorded air temperatures were relatively high. Atmospheric attenuation calculations indicated that an approximate $5^{\circ}K$ temperature correction should be added to the recorded Channel 2 values. This pass occurred rather early in the lifetime of TIROS VII, and no sensor degradation correction is required. With these corrections, the recorded temperatures are about $12^{\circ}K$ lower than those indicated for this region in mean monthly charts.

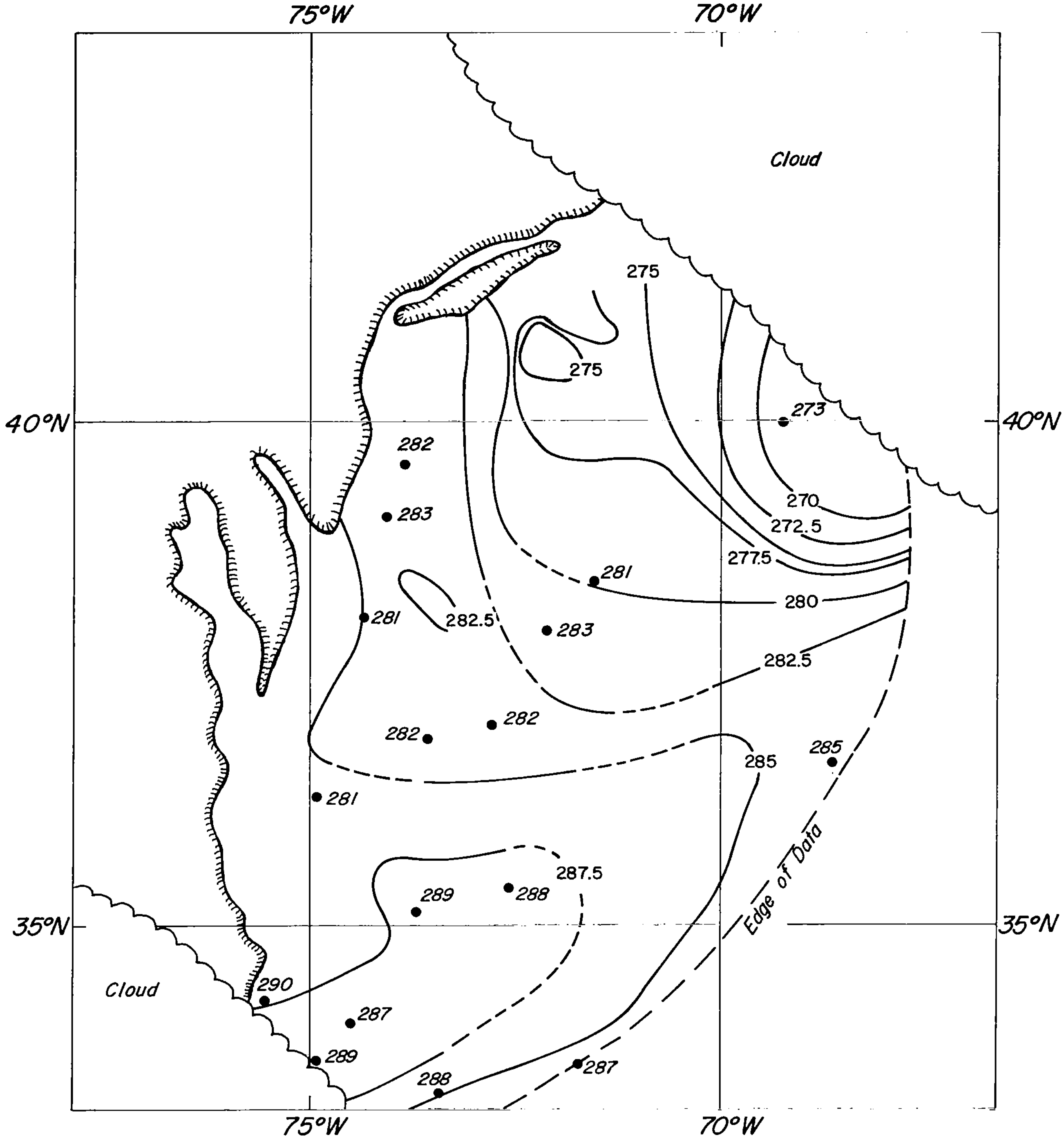


Fig. 5-11 Real-time Data, Pass 107-D (26 June, 1963)

The second usable pass (238-Direct) occurred 9 days later, on 5 July 1963. The data here had considerably more noise, but the basic SST patterns are still visible. (See Fig. 5-12).

Temperatures for this pass were 2.5 to 5°K lower than in Pass 107-D. Upper air data, again from the Washington station, indicated a slightly drier atmosphere for this day, although the calculated correction was still approximately 5°K. As in the previous case, there was no significant correction for sensor degradation indicated by the usual degradation graphs.[6] It should be noted, however, that the periodic orbit-sun phase fluctuation does suggest a rapid degradation during this period. This may account for part of the over-all temperature drop. The minimum nadir angle was 10° higher than in the previous case, but was still a relatively low 20°. Thus, there seemed to be no adequate explanations for the general 2.5 to 5°K temperature drop across the field of view. As this is the time of year when one would expect a gradual warming of the sea surface, it is unlikely that this temperature drop is real.

Conventional surface ship data were extracted from NMC charts for five day periods centered on the dates of each of the selected "real-time" cases. These data indicated no significant change between the two cases, and agreed reasonably well with mean monthly charts. They were converted to °K and uniformly reduced by 12°K for easier comparison with the IR data. The "reduced" data are plotted in both Figure 5-11 and 5-12. In Figure 5-11 it is seen that there is good correlation between the adjusted ship data and the recorded IR data. Good correlation can also be seen in Figure 5-12, if the ship data are reduced another 2.5 to 5°K to compensate for the over-all drop in the IR data.

The first of these two cases is a particularly good demonstration of how a dependable surface temperature measurement may be used as a benchmark to calibrate the recorded IR temperatures. Using this procedure false shifts in the absolute values of a temperature field can be avoided. It may be that only an occasional benchmark (occasional in both space and time) will be required to properly calibrate recurring IR coverage.

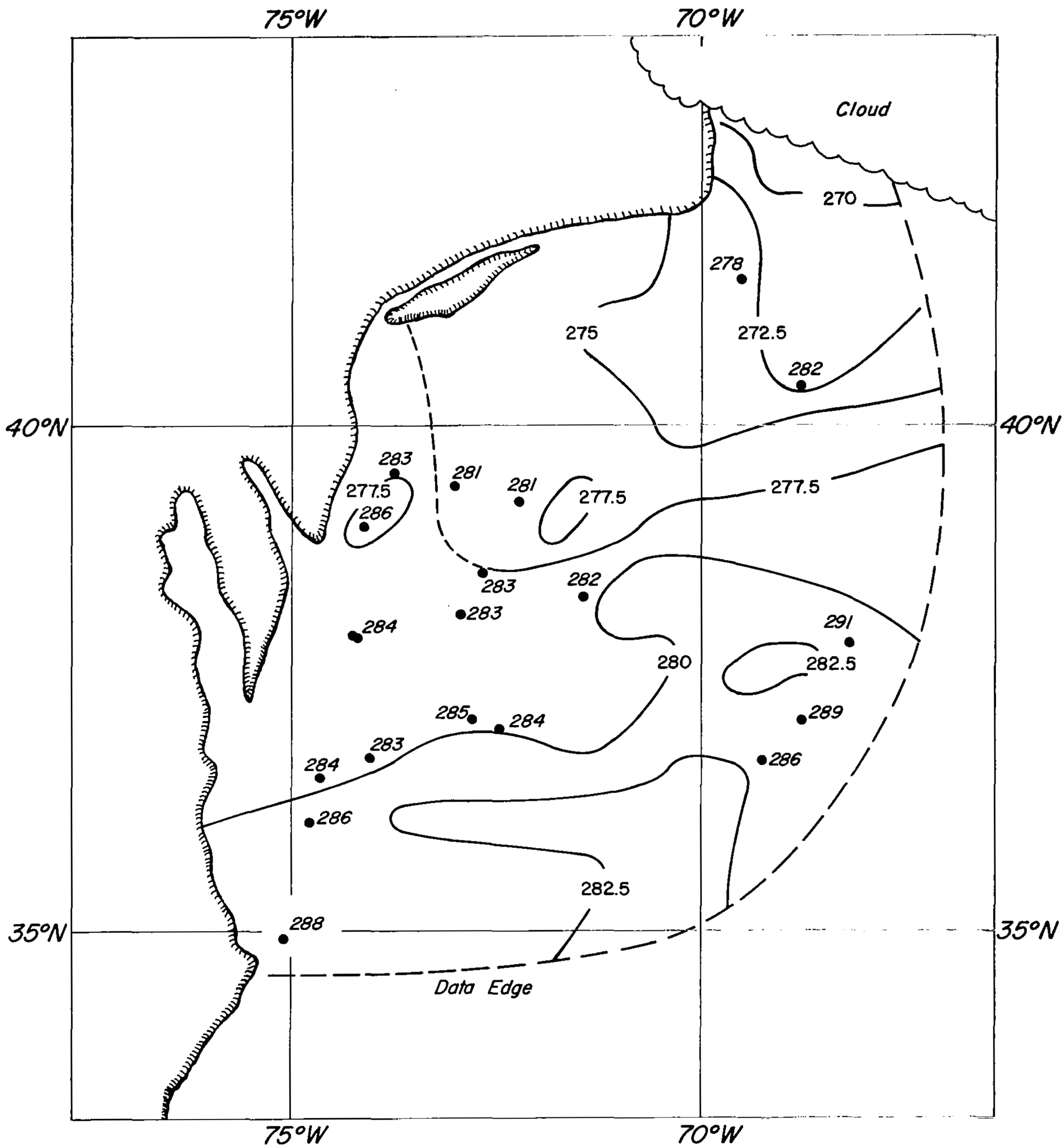


Fig. 5-12 Real-time Data, Pass 238-D (5 July, 1963)

## 6. DISCUSSION OF THE PROPOSED EXTENSIVE DATA PROCESSING APPROACH

The problems encountered in attempting to find suitable cases which simultaneously satisfied the three criteria of clear skies, large SST gradients, and adequate conventional data included the following: (1) frequent absence of usable IR data due to high nadir angle or closed mode conditions; (2) frequent lack of TIROS TV picture data for use in determining whether the area of interest was adequately clear; (3) inadequacy or lack of conventional surface meteorological data over the oceans for determining clear areas; (4) the impossibility of determining the clear areas from the IR data themselves, (using the threshold albedo techniques) until the expenses required for FMRT processing have already been incurred; and (5) the tendency for areas of greatest synoptic interest and change, such as the Gulf Stream, to have frequent and persistent fronts and cloud cover.

Using the currently available (TIROS) IR data, little can be done with regard to Point (1) above; it will be totally alleviated as regards closed mode, and considerably as regards nadir angle, when Nimbus MRIR data becomes available. Points (2) and (3),however, can presently be avoided by facing up to Point (4) and accepting the costs and inefficiencies inherent in FMRT runs without specific prior knowledge as to the presence or absence of adequate clear areas. (Of course, a general examination of any available data, prior to an FMRT run, is desirable to rule out obviously hopeless cases, or to select the more promising of alternative cases.) Rejection of cloud contaminated data on the basis of a Channel 5 albedo threshold value seems feasible, as demonstrated above, and resonable modifications of the existing data reduction programs should permit automatic rejection of these data. Point (5) is really the only condition inherently imposed by nature, and like Point (1) must be lived with. The long and tedious chore of trying to find areas of clear sky over such difficult regions of the oceans, however, can be relegated to a computer when repeated passes over a given area for some specific time period are to be automatically processed. In all probability, the savings in human search, comparison, and decision time will more than compensate for the increased computer costs.

For the initial pilot investigation using these procedures, areas with a reasonable probability of synoptic change should be chosen, and cases would then be run for those periods which, by reference to other readily available meteorological sources (seasonal tendencies, conventional weather charts, TIROS TV data, etc), present the greatest likelihood of having at least minimally adequate periods of clear skies. Analyses for individual days and running averages of the data over several more or less consecutive days should be investigated. These averaged maps should provide a good basis for tracing the gradual changes of large scale SST patterns, while comparisons of the individual days should reveal capabilities as regards smaller scale and more rapid changes and developments.

As a first pilot study to investigate the general feasibility of such an approach, a six day case was run, using both the listing and the mapping formats, for the area off the western coast of Australia. The time span covered by the six days processed was from 29 July to 8 August 1963; and the TIROS VII data used included Passes 589, 647, 662, 691, 706, and 735. For the first few passes, an albedo threshold value of 10% was used with the Channel 5 listings to outline clear areas. This resulted in areas which were too restricted for practical use. By locating abrupt changes in the Channel 2 temperature values, it was determined that a 20 % albedo threshold could be safely used in this case, revealing a much larger apparent clear sky area. All six passes were then processed using the 20 % albedo limit. Of the six passes, only one appeared completely overcast. The outlined clear areas of the several maps were then hand averaged producing the final average analysis in Figure 6-1.

Mean monthly SST maps for this region show isotherms running east-west across the Indian Ocean, and then dipping southward as they reach Australia. From the southern to the northern tip of western Australia the mean monthly SST rises approximately $7^{\circ}K$[15], in agreement with the results in Figure 6-1. No upper air data or ship reports were available for this area, but, even with reasonable attenuation and degradation corrections, the IR observed SST's would again be colder than those anticipated for this region. The individual maps which were used to make up the final analysis in Figure 6-1 were also analyzed, but revealed no obvious continuous or significant change in SST patterns. The individual analyses showed more complex SST patterns than are seen in the averaged mapping. Apparently one advantage of the averaging process is its ability to ferret out the more significant patterns from the background of extraneous noise of both the natural and the sensor produced varieties. The positive results of this trial case have seemed to reaffirm both the utility of the TIROS IR observations as a source of valid SST data, and our feeling that, for extensive studies or operational uses of satellite IR data for SST determinations, the types of extensive processing methods proposed above will have to be employed.

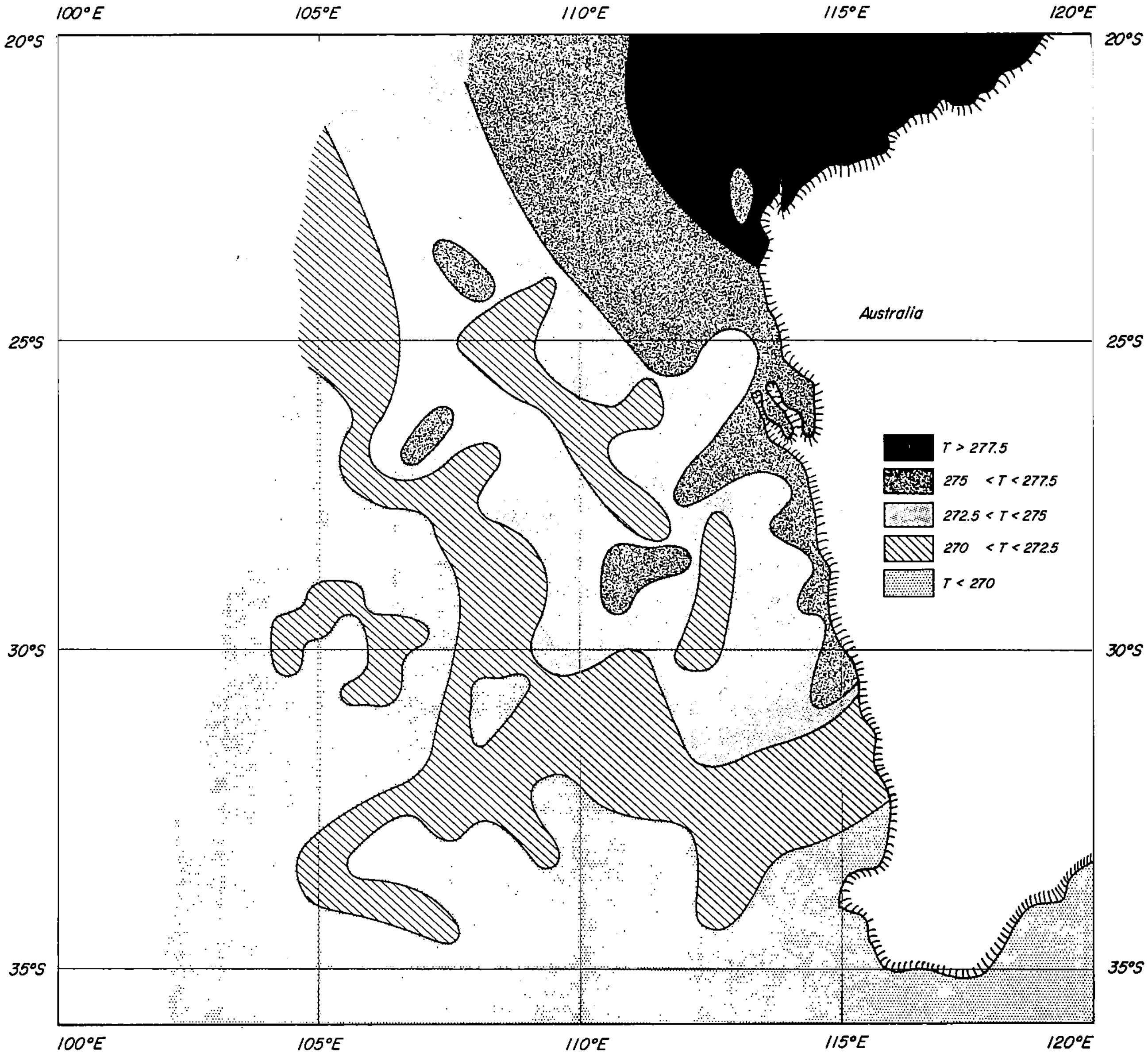


Fig. 6-1 Six Pass Averaged SST Patterns (29 July - 8 August, 1963)

## 7. GENERAL SUMMARY AND CONCLUSIONS

These studies have clearly demonstrated that the satellite IR data provide good measurements of the gradients of sea surface temperatures. This has been confirmed, in part, by consistency of the IR data for areas of known SST persistence, which has given some indication of the validity of the observed SST patterns on single passes. These consistency tests have revealed that larger scale patterns and gradients are easily recognizable and change little from day to day, implying that these patterns are real, and can be accepted without requiring confirmation from conventional measurements (although such conventional substantiating data would still be desirable as we build up further experience regarding these matters). The tests have also revealed that, where there is persistence of small scale patterns, they also can be seen on repeated passes. Whether they will always be seen, and whether observed changes in these small scale patterns are real, remains unanswered. The answers can probably come only from finding adequate samples of satellite SST data with concurrent conventional observations, or from the processing and analysis of statistically significant quantities of satellite observed SST data.

Subsequent investigation aimed at determining the extent of the validity of IR observed small scale patterns will be significantly helped by concurrent ship reports, and it may be that such reports will be indispensable. The Gulf Stream provides an ideal area to observe both mesoscale and synoptic scale changes, and has the greatest density of conventional ship measurements. If significant amounts of "real-time" TIROS IR data were to become available, this would be an obvious area to conduct further studies along these lines; this by itself constitutes a strong justification for routine processing of a full year of such "real-time" data. Otherwise, such investigations will be hampered until the Nimbus C MRIR data become available.

The tendency of the satellite IR temperatures, even when corrected for atmospheric attenuation and sensor degradation, to be significantly cooler than conventionally measured temperatures, indicates the need for an occasional benchmark to calibrate the data. It also re-emphasizes the already existing need for further investigation of these discrepancies, which have been repeatedly noted in various analyses of the TIROS IR data. Even if one of the previously proposed explanations can be shown to be the answer, there will still remain the need for improved methods for estimating the proper corrections.

The determination of clear sky areas from the IR data themselves uses the Channel 5 sensor to distinguish cloudy from clear areas, and has the advantage of reducing or eliminating dependence on satellite TV or conventional meteorological data. Our studies indicate that this can be done for daytime cases for overcast or broken conditions. Areas of small scattered cloud, however, may erroneously decrease the Channel 2 temperature values without being detected by Channel 5. Nighttime detection of cloud points using Channel 2 and 4 differences is not presently possible, and no alternative useful approach to the nighttime cloud detection problem is yet apparent. The use of sharp changes in the Channel 2 values is insufficient, since it may not reveal areas of low or scattered clouds.

The pilot study off the western coast of Australia indicated that methods of extensive data processing can usefully be applied to SST studies. The final map in this study was produced by manually outlining clear areas and then hand averaging point by point. With reasonable modifications of existing computer programs, this tedious process can be automated, and individual or averaged clear sky maps produced as a direct computer output. The human with his experience and knowledge of local currents and mean temperature patterns is still required for the optimum final analysis. We believe that, for comprehensive studies or operational uses of SST, such extensive data processing techniques will be required. The application of these techniques to satellite IR data can significantly increase our knowledge of sea surface temperatures and their patterns, gradients, and variations over the several scales of time and space at which they have significant scientific and practical applications.

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