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The Availability and Limitations of NOAA Satellite-derived Sea Surface Temperature Products

by

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I. INTRODUCTION

The importance of the distribution of sea-surface temperature on local, regional, and hemispheric scales has long been recognized in the marine sciences. Of particular interest to both physical and biological oceanographers have been the time-variant zones of strong horizontal gradients of surface temperature, the so-called thermal fronts, associated with certain major current systems or regions of localized upwelling (World Meteor. Organiz., 1969). Other major thermal features having expression at the ocean surface are huge and persistent warm and cold eddies with anticyclonic and cyclonic circulations, respectively (Richardson et al., 1973).

Sea surface temperature measurements have traditionally been made by either the bucket or intake method (World Meteor. Organiz., 1956), both methods yielding a bulk water temperature from a depth in the mixed layer generally varying from 3 to 9 meters. Both methods also measure the water temperature by direct contact between the water and a thermometer element, i.e. what is measured is the molecular-kinetic temperature. Normally, only research vessels have employed other means of temperature measurements such as thermisters, towed forward or off to one side of the ship, or radiation thermometers (these are not in actual contact with the water and they measure the radiative temperature of the very uppermost fraction of a millimeter, or skin, of the water surface).

Synoptic studies of ocean surface thermal patterns generally have not been successful using surface-based temperature measurements for the simple reason that ship coverage in space and time is inherently totally inadequate to the problem. All synoptic sea surface temperature charts until recently have been climatological in nature, combining ship observations from periods of 25 to 50 years or more (Naval Oceanogr. Office, 1969). It has only been in the past few years, with the advent of modern global communications networks and electronic computer analysis models, that the U.S. Navy has generated routine 10-day composite sea surface temperature charts for the North Atlantic and North Pacific Oceans. These charts, although useful for large-scale meteorological purposes as boundary conditions for numerical weather predictions, are still too generalized for most oceanographic purposes.

Even aircraft radiation thermometer surveys, such as those being made for narrow Atlantic and Pacific coastal strips of the USA are not really adequate for many purposes. The cost of these flights has restricted their frequency to once per month and one aircraft cannot cover the area without flying two or three successive days. The actual coverage is only along the flight track itself, so the contouring of the thermal field requires much interpolation between track lines.

Thus it appears that only polar-orbiting or geosynchronous satellites can provide the capability to measure sea-surface temperatures over large areas on a repetitive basis. The only serious constraint to satellite frequency of coverage in any given area is cloud cover. This limitation and some of the means for partially overcoming it are discussed later. The first good opportunity to explore this capability of deriving sea-surface temperatures from space was provided by some of the early Nimbus meteorological satellites after about 1966. The Nimbus series was the first to carry high-resolution (8 km), scanning infrared (IR) radiometers. Although this early IR data was extremely "noisy", it was possible to detect in a crude way the main features of strong thermal fronts, such as those associated with the Gulf Stream (Curtis and Rao, 1969). This early data also served as a basis for the first attempts to develop statistical methods of spatial and temporal compositing of IR measurements for the purpose of cloud-filtering and hemispheric mapping (Smith et al., 1970).

Later, after better quality, high resolution IR data became routinely available from the NOAA operational environmental satellites in 1970, the feasibility of the histogram method for global mapping of sea surface temperature on an approximately 300 km grid was fully established (Rao et al., 1972). In 1973, experimental operational production of global sea-surface temperature charts (100 km grid) based on a modified histogram method was initiated, and this mapping is presently fully operational on a daily basis (Figure 1).

Beginning in late 1972, the first Very High Resolution Radiometer (VHRR) data became available (1 km spatial resolution) from the NOAA polar-orbiting satellite series. This was followed in 1974 by thermal infrared data (8 km resolution) from the Visible Infrared Spin-Scan Radiometer (VISSR) on board the first of the Synchronous Meteorological Satellites, SMS-1, which are in Earth-stationary orbits at a very high altitude above the Equator.

This paper will discuss currently available sea-surface temperature and temperature gradient products from the NOAA operational environmental satellites. It will also touch briefly on some near-future developments in this area.

II. General Characteristics of the NOAA Operational Satellites and their Infrared Sensors

The NOAA series consists of Improved TIROS Operational Satellites (ITOS), which are placed in circular, near-polar, sun-synchronous orbits above Earth at a nominal altitude of 1450 km (Schwalb, 1972). The Equator-crossing times for the most recent in this series, NOAA-4, are 2040 (northbound) and 0840 (southbound) local time. The data coverage swath on Earth of the radiometers is about 3300 km, providing contiguous coverage as the satellite completes approximately 12.5 circuits of its orbit (passes) each 24 hours. Data swaths overlap increasingly toward either pole.

The ITOS are equipped with dual sets of radiometers for complete redundancy and thus increased sensor reliability and extended operational lifetime of the spacecraft. One type is the Scanning Radiometer (SR), designed primarily to provide daily global coverage and local direct-readout data for general meteorological purposes. The global coverage capability is possible because the data from two to three complete orbital passes can be stored on board the satellite for subsequent transmission to NOAA's Command and Data Acquisition (CDA) Stations, one on the coast of Virginia and the other in central Alaska. Images of that portion of Earth below the satellite can be received on simple and relatively low-cost receivers, whenever the satellite is above the horizon of the receiving station, via direct broadcast from the spacecraft in the VHF band (Automatic Picture Transmission service). APT service has been available worldwide for about 10 years, and there are presently approximately 700 known receiving stations in some 119 countries.

The SR is a dual-channel, line-scanning radiometer that measures reflected solar radiation in the range 0.5-0.7 micrometers (μm) and emitted infrared radiation in the atmospheric "window" region of 10.5-12.5μm. Data are collected from a 3300-km wide swath on Earth by combining the motion of the spacecraft with cross-track scanning through an angle of over 60° by means of a rotating mirror. The instantaneous field-of-view of the visible channel is such that ground resolution of the data at nadir is about 4 km; the corresponding value for the thermal infrared (IR) channel data is about 8 km. Provision was made for the radiometer to view reference-level targets for purposes of sensor calibration.

The second type of radiometer on the ITOS is the Very High Resolution Radiometer (VHRR), which is intended primarily for local direct broadcast of data, and whose chief use has been for non-meteorological purposes, chiefly in the areas of oceanographic and hydrologic applications. Onboard tape recorder capacity permits a maximum of only 10 minutes of stored VHRR data (which covers an area about 3000 km on a side) to be acquired remote from the CDA station. Direct broadcast VHRR data can be acquired by anyone with suitable receiving equipment, but this equipment is much more elaborate and expensive than that needed to receive APT data.

The VHRR is similar in many ways to the SR, being a two-channel, line-scanning radiometer sensitive to energy in the 0.6-0.7μm and 10.5-12.5μm bands. However, the substantially better ground resolution of the VHRR, about 1 km ar nadir for both channels, requires a faster mirror rotation for scanning and an infrared detector cooled to 105°K. Calibration arrangements are similar to those for the SR. Both SR and VHRR data are transmitted in analog form from the spacecraft; digitization, if desired, must be accomplished on the ground.

The SMS, soon to be called GOES (Geostationary Operational Environmental Satellite), is in an orbit that coincides with Earth's equatorial plane (Hussey, 1974). At its altitude of 35,817 km, the spacecraft's west-to-east motion is exactly matched to that of Earth beneath, i.e. it is made to become stationary at whatever longitude is desired. SMS-1 is presently situated at 75°W and SMS-2 is at 115°W. From such a great altitude, the Earth's disk viewed from the satellite extends farther than 60°N and 60°S at the longitude of the spacecraft, as well as 60° in longitude to the west and east. The stationary position of the spacecraft relative to Earth also enables a high frequency of observation, and it is an excellent platform for data collection and relay and for rebroadcast of processed information.

The VISSR onboard the SMS was designed to provide frequent visible and IR images of cloud patterns to the meteorologist. The scanner image is built up line-by-line through a combination of the west-east spin of the spacecraft and a north-south stepping mechanism. The normal mode of operation results in full-disk visible and infrared images every 30 minutes. If special, very high frequency (5-10 minute intervals), coverage is desired, the north-south extent of the images is necessarily greatly reduced. VISSR data are transmitted from the satellite in digital form, and ground resolution at nadir is 1 km for the visible channel data and 8 km for the thermal channel data. The infrared channel makes use of a cooled detector, and provision is made for in-flight calibration.

III. Current Sea-Surface Temperature and Temperature Gradient Products

The normal output data format for all the IR sensors previously described (SR, VHRR, and VISSR) is a black-and-white photographic image whose gray-scale is tuned to general meteorological usage (Figure 2). At three to six hourly intervals the VISSR-IR is currently produced with a gray-scale tuned to the ocean surface temperature range (Figure 3). The SR- and VHRR-IR images can be enhanced similarly by arrangement. Although the SR data are routinely rectified, mapped, and electronically gridded, no VISSR or VHRR data are produced in mapped form at present, although both are gridded in one form or another. VHRR images can be stretched to remove the foreshortening normally present on the western and eastern edges.

As previously mentioned, all the IR radiometers have provision for in-flight calibration, but occasional checking of this calibration against Earth targets of known temperature is advisable. Studies have shown that relative radiative temperature differences (RMS) between ship and satellite temperatures are about 1.5°C for the SR, 1.0°C for the VHRR, and are 0.5°-1.0°C for the VISSR. Absolute temperature accuracy depends strongly on the accuracy of the atmospheric correction. This in turn depends chiefly upon knowledge of the water-vapor content of the atmosphere and whether the radiometer scan-spot was free of clouds. Under the best of conditions the absolute temperature differences between ships and satellites are about 2.0°C for the SR, 1.5°C for the VHRR, and 1.0°C for the VISSR. It should be taken into account, however, that verifying satellite-derived sea surface temperatures is not an easy or straight-forward task. As mentioned earlier, virtually all ship-measured temperatures are molecular-kinetic rather than radiative in type, and are bulk rather than skin temperatures. Studies have shown that the differences between skin and bulk temperatures are generally much smaller than the errors cited above (World Meteor. Organiz., 1972). Another verification difficulty stems from the differing spatial characters of the two types of observations: the data from different ships are essentially independent "spot" or "point" measurements, whereas the satellite measurements are integrated averages over areas one to eight kilometers or larger on a side. In areas of strong horizontal temperature gradients, time differences between ship and satellite observations, or small location errors in either data source can contribute to apparent errors. These considerations, together with the known uncertainties in intake temperatures from ships-of-opportunity (World Meteor. Organiz., 1972), would make it unlikely that routine comparisons would ever yield differences of less than about 1.0°C.

Quantitative IR data are available in a variety of formats on arrangement. Mapped SR data can be presented as alphanumeric printouts or as temperature values at grid-points with computer-produced isotherms (Figure 4). Similar products are available using VHRR and VISSR observations, but in this case the observations are in the form of unmapped scanline data (Figure 5). The SR data are Earth-located with reference to a grid system used routinely in numerical weather prediction models. The VHRR and VISSR data must be located by means of a scanline/scan-spot measurement on the associated image or by cross-reference to common features in the image and print-out. Although access to the special equipment needed is presently limited, it is also possible to produce color-coded quantitative IR temperature displays.

Generally the most useful satellite product, and one that is readily available upon arrangement, is a heavily-enhanced B&W image, gridded and annotated. These can be occasionally supplemented with color-coded or printout-type quantitative charts. These products enable the user or researcher to detect the presence, extent, intensity, and changes in any moderate or stronger thermal feature having expression at the ocean surface.

One operational product based on VHRR-IR images has been produced weekly and distributed by NOAA for nearly two years (Stumpf, 1974). This is the Experimental Gulf Stream Analysis. This chart shows the major thermal fronts separating Gulf Stream, Slope, Shelf, and Sargasso water, together with the locations of cold cyclonic and warm anticyclonic eddies.

VHRR images have enabled researchers to determine the existence, extent, frequency, or intensity of many oceanic thermal phenomena whose characteristics were relatively unknown or only suspected. Two examples: upwelling in the Gulf of Tehuantepec (Stumpf, 1975), and Gulf Stream eddies (Richardson et al., 1973).

IV. Near-Future Improvements in Satellite-Derived Sea Surface Temperatures

The third generation polar-orbiting operational environmental satellite system is in the final planning and initial construction phases, with its first launch tentatively scheduled for 1978 (Ludwig, 1974). The NASA prototype of this series is called TIROS-N, but subsequent NOAA-funded satellites will be called NOAA-(K+1), (K+2), etc., where K is the number of the last in the present ITOS series. The major improvements that TIROS-N will bring include the replacement of the SR and the VHRR by the Advanced Very High Resolution Radiometer (AVHRR) and a conversion to on-board digitizing and direct transmission of data from the satellite. This will be accomplished by an on-board data processor, which also will "degrade" the stored 1-km resolution data to about 4-km resolution for global meteorological coverage. Full-resolution measurements will be available for direct readout service to suitably equipped ground stations and for limited area coverage via the stored data mode. Conventional APT service also will continue.

The AVHRR is to have four channels of 1.1 km resolution data: visible (0.55-0.9μm), reflected IR (0.725-1.1μm), and two emitted (thermal) IR (10.5-11.5 and 3.55-3.93μm). The use of two water-vapor window bands for thermal mapping is expected to greatly improve the accuracy of measuring surface temperatures by enabling a better atmospheric correction. The currently employed methods of correcting the radiative temperatures for attenuation (which is principally from water vapor in the intervening atmosphere) are far from optimum. Such methods use either an assumed water vapor profile implicit in a model atmospheres type of correction; or they use an estimate of total mass of water vapor obtained from an atmospheric sounding radiometer on board the satellite where the IR sounder data are not spatially coincident with the SR or VHRR measurements. The two thermal channels on the AVHRR, however, are in parts of the spectrum in which both the amount of atmospheric attenuation and the functional relation between radiance and radiative temperature are quite different. Since both IR detectors view the same spot on Earth's surface simultaneously through the same atmospheric column, the difference in the measured radiances can be used to determine the proper atmospheric correction to the radiative temperature. There will be problems with the 3.55-3.93μm data during the daytime because of contamination from reflected solar radiation, and methods for handling this situation are unproven. As an answer to this problem and in an effort to improve yet further on the absolute accuracy of the satellite-derived sea surface temperatures, NASA is developing a five-channel version of the AVHRR for incorporation on later TIROS-N flights. The fifth channel is designed to measure emitted thermal radiation in the window region from 11.5 to 12.5μm where solar contamination is no problem.

As mentioned earlier, AVHRR data are to be transmitted digitally from the satellite rather than by analog signal. Analog SR-IR data, and to a lesser extent VHRR-IR data, have been consistently plagued by "noise" problems. The noise is always greater with stored than direct-broadcast data, and a large part of it has been traced to the tape recorders on board the satellite. Recent experience with the VISSR-IR data, which are digitized on board the spacecraft before transmission, and are extremely "clean", i.e. noisefree, lends support to the presumption that the AVHRR-IR data will be very clean also.

Although some improvements in calibration procedures are being developed in connection with VISSR-IR, no changes to the sensor complement of the operational geostationary satellites are planned for the near-future except for the addition of an atmospheric sounder. The only impact of this on the sea-surface temperature measurement capability of GOES will be the availability of atmospheric moisture values for attenuation corrections. Further development of techniques for exploiting the half-hourly observation frequency of GOES to study the dynamics of such phenomena as Gulf Stream waves (Legeckis, 1975) is anticipated.

V. Some Additional Considerations (and Limitations) in the Use of Satellite IR Data for Sea Surface Temperature Mapping

Assuming that atmospheric correction problems will largely disappear with the introduction of multi-spectral AVHRR-IR measurements, the only serious limitation to sea surface temperature mapping from space will be cloud cover. For time scales of the order of a few days to a week or so, most oceanic thermal phenomena are sufficiently conservative in comparison with cloud systems that one or the other of two currently used techniques is generally effective. The first technique is the one used in large-area mapping, and it involves spatial and temporal compositing of the IR data. To reduce the effects of noise in the scan-spots of raw IR data and to use nighttime observations when there are no concurrent measurements from the visible spectrum channel, all scan-spot data falling into small grid squares over a period of several days to a week or more are composited into frequency distributions (i.e. histograms) of radiative temperature. By analyzing the histogram statistically to determine the highest significant modal temperature, cloud-contaminated and noisy data are effectively removed. Of course the larger the grid-box used, the greater is the loss of spatial resolution; also, the longer the compositing period, the greater is the loss of time-changes in the thermal patterns. The higher the resolution in the raw data the better, for two reasons: higher probability of cloudfree scan-spots and higher resolution in the final product. High frequency of observation, as in the case of VISSR, is also advantageous because adequate numbers of cloudfree scan-spots can generally be accumulated over relatively small boxes and/or short compositing periods.

The second technique, which is the one normally used over relatively limited areas and for maximum detail in the delineation of temperature gradients, consists simply of taking advantage of "targets of opportunity", i.e. areas that are intermittently cloudfree or nearly so. In such areas one can use virtually the full-resolution of the raw IR data, although spatial averaging of the IR temperatures over short distances may be desirable to reduce noise in the SR and VHRR measurements that were temporarily stored on tape in the spacecraft. In this technique it is highly desirable, although not always necessary, to use only daytime observations. Daytime measurements enable use of the simultaneous visible spectrum data and thus unambiguous determination of cloudfree ocean areas. The difference between cloud-associated thermal patterns and those associated with sea surface temperature gradients is usually obvious to an experienced interpreter of IR images, especially if the images are of the very high resolution type such as VHRR and they have been enhanced for this type of use. If, on the other hand, the IR image is low resolution, or has poor contrast in the oceanic temperature range, or if the analyst is dealing primarily with alpha-numeric or contoured gridprint type data, use of the simultaneous visible channel data is all but mandatory to prevent confusion or errors related to cloudiness.

Finally, it should be noted that the type of synoptic view of ocean surface thermal patterns afforded by satellites is very new to marine scientists.. Much remains to be learned about the usefulness and limitations of this relatively untried aid to marine environmental analysis. Surface thermal patterns are not always well correlated with those at depth; and the relation between them and dynamic, biological, or chemical processes is often complex, variable, or incompletely understood.

VI. Concluding Remarks

Sea-surface temperature mapping with, or with the aid of, satellite infrared measurements is moving from the experimental stage to being accepted as just another tool for monitoring one important aspect of the atmospheric and marine environment. The U.S. Navy is using satellite-derived sea-surface temperatures to supplement sparse ship observations in generating their temperature charts for the Southern Hemisphere. The U.S. Coast Guard is routinely using VHRR-IR imagery in the Gulf Stream area to improve their air-sea rescue capability. A major oil company is using this same type of information to improve on their ship-routing procedures. Several oceanographic research groups are employing satellite IR imagery to direct their research vessels to the areas of specific oceanic phenomena and thus reduce costly search time (Vukovich, 1975). And, increasing numbers of oceanographic scientists are turning to satellite data in a synergistic sense in the realization that here is an often powerful tool to use in conjunction with conventional instruments and techniques.

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FIGURE LEGENDS

Figure 1 Southern Hemisphere isotherm analysis (6 August 1975) derived from NOAA/NESS global operational sea-surface temperature computation (GOSSTCOMP) on a 100-km grid. Satellite temperature retrievals entering analysis can be several days to several weeks old in areas where unbroken cloudiness is very persistent.

Figure 2 VHRR-IR image enhanced to emphasize the oceanic thermal front extending eastward from Iceland (22 May 1975). By convention the warmer the radiating surface, the darker the tone in the image.

Figure 3 VISSR-IR image enhanced to emphasize the thermal front associated with the Gulf Stream (26 February 1975).

Figure 4 Contoured printout of mapped SR temperatures for 28 June 1973 in NMC grid box number 36-45 (upper left-hand corner of box is at 42.9N, 62.9W). The grid spacing is about 12 km. Onboard calibration was accomplished, and the radiances were normalized to a nadir view before converting to effective blackbody temperatures in deg. K.

Figure 5 Alpha-numeric printout of unmapped VISSR temperatures (25 February 1975). Change from one type character to next (see table at top) corresponds to a 1°C temperature interval. Area shown is Gulf Stream off coast of Carolinas.

GOSSTCOMP SEA SURFACE TEMPERATURE

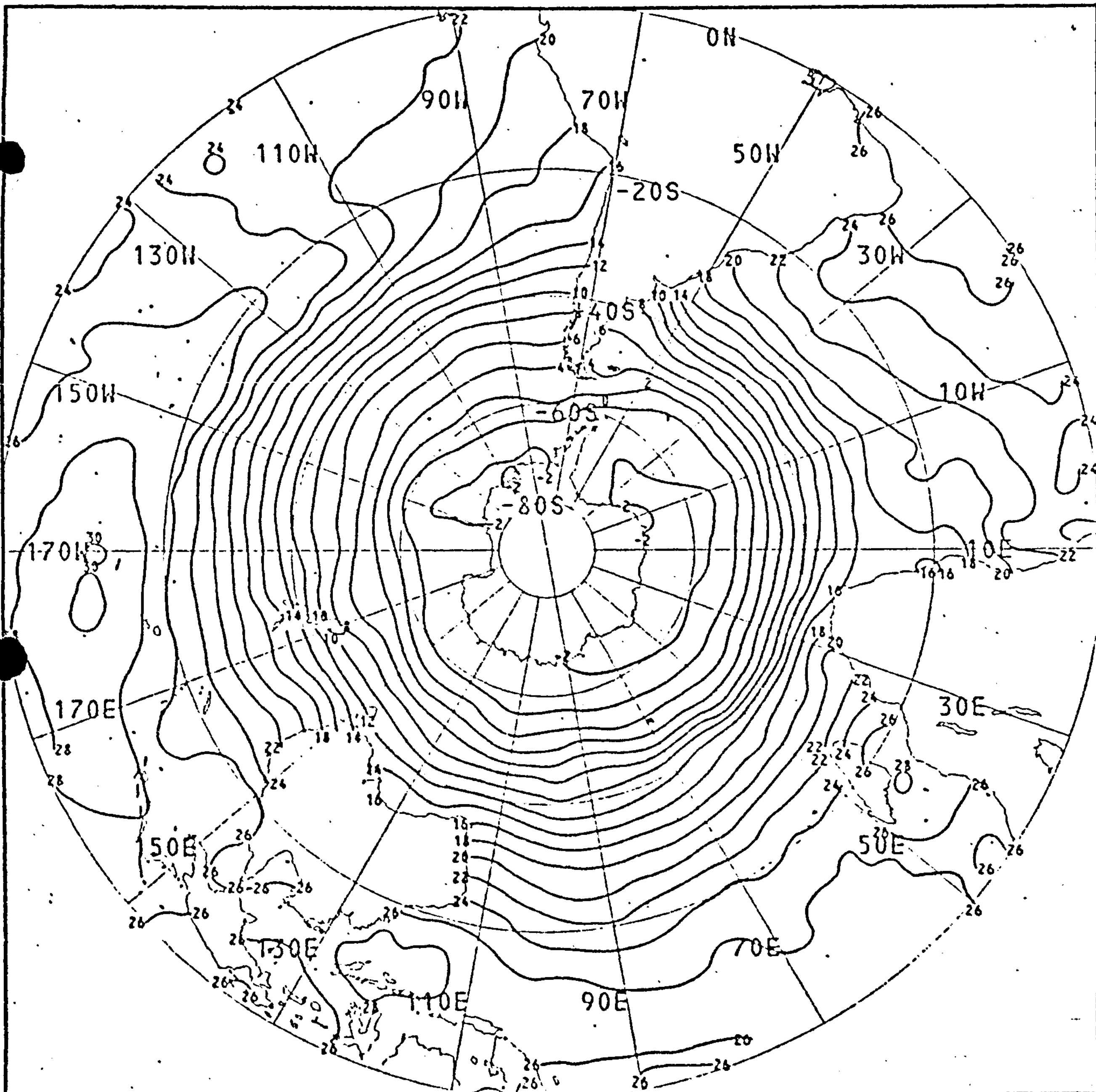

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Figure 1

Figure 2

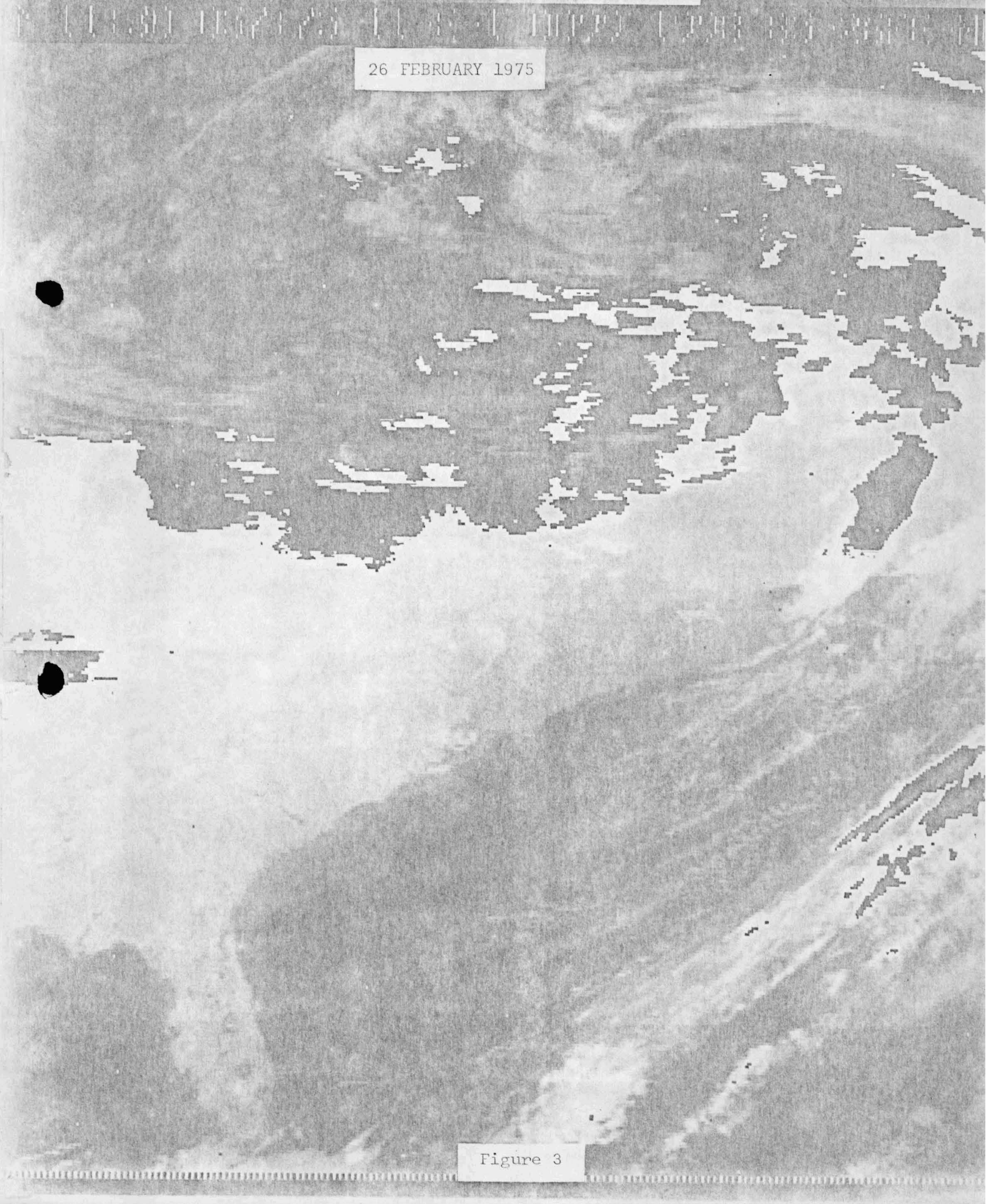
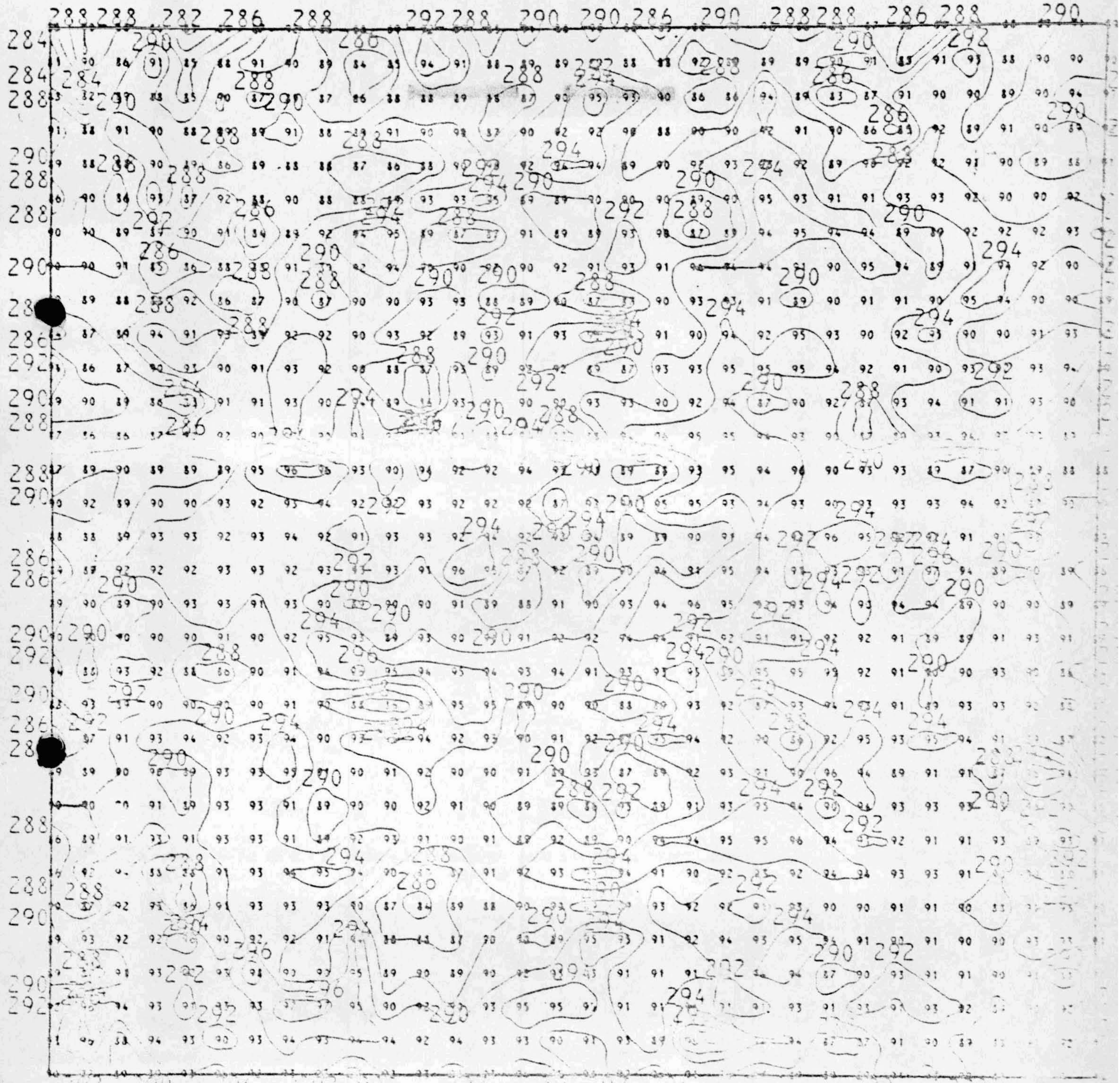


Figure 3

JUN 28 1973



IJ = 36-45 LAT = 42.9N LONG =

Figure 4

DAY 56 1830 Z 2-25-75 N2801

IR DATA EACH LINE IS REPEATED ONCE

TABLE V . R - Y . G / B + 8 . 6 - 4 . 2 / 0 + * BLANK V=COUNT 62 C

1700 WARM COLD

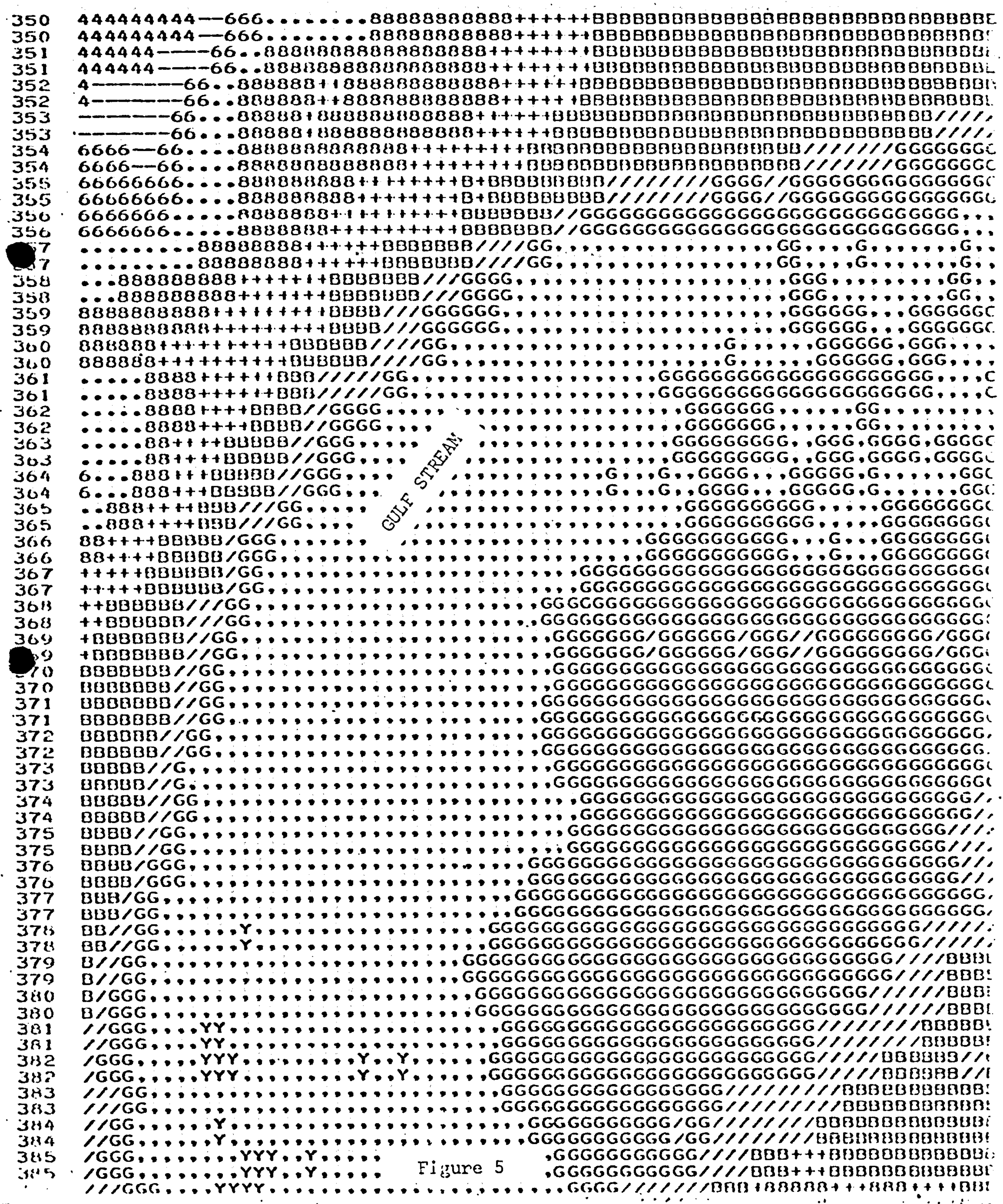


Figure 5