A COMPUTERIZED METHOD FOR THE MONITORING OF THE CABO FRIO UPWELLING ZONE USING GEOSTATIONARY SATELLITE DATA

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ABSTRACT

Cabo Frio, located in the coastal state of Rio de Janeiro, exhibits the strongest signals of upwelling along the coast of Brazil. The upwelling is sufficiently intense that, in November, offshore water of 19°C found at a depth of 100 m is found at the surface near the coast; 13°C water found at 250 m offshore rises to within only 50 m of the surface on the continental shelf off Cabo Frio. A better understanding of the variability present in the upwelling center can be achieved, in part, through synoptic monitoring of a parameter such as surface temperature. The availability of Visible and Infrared Spin Scan Radiometer (VISSR) data with a spatial resolution of 10 km from the Stationary Meteorological Satellite (SMS-2), combined with the VISSR's 30 minute sampling frequency, offers such a capability. A set of computer programs written to produce sea surface temperature maps of the Brazilian waters was modified to emphasize the Cabo Frio region, and the scale of the machine contoured maps was changed to 4 million: 1 (7.5° X 7.5° geographic coverage), centered near Cabo Frio. The nominal thermal resolution of the VISSR IR sensor is 0.5°C, sufficient to detect a change of several degrees observed from ship data to extend across the upwelling center. Machine contoured maps of the sea surface temperature based on data from several different images suggests that the VISSR instrument appears to offer the capability of observing those thermal changes in features associated with the presence of mesoscale coastal upwelling.

RESUMO

Cabo Frio, localizado na região costeira do estado do Rio de Janeiro, mostra os maiores sinais da ressurgência da costa do Brasil. A ressurgência é tão intensa que, em novembro, a água com uma temperatura de 19°C, normalmente localizada longe da costa a uma profundidade de 100 m, é encontrada na superfície perto da costa; a água de 13°C, localizada longe da costa a 250 m de profundidade, sobe até 50 m da superfície sobre a plataforma continental perto de Cabo Frio. Um maior entendimento da variabilidade presente no centro da ressurgência pode ser obtido parcialmente através do monitoramento sinóptico de um parâmetro tal como a temperatura superficial. A disponibilidade do dados de "Visible and Infrared Spin Scan Radiometer" (VISSR) com uma resolução de 10 km, do Satélite Estacionário Meteorológico (SEM) junto com uma frequência de amostra a cada 30 minutos, pode fornecer tal capacidade. Um conjunto de programas para computador, elaborados para produzir os mapas da temperatura superficial do mar para as águas Brasileiras, foi modificado para dar ênfase à região de Cabo Frio e a escala foi mudada para 4 milhões: 1 (7.5° X 7.5° de cobertura geográfica), localizada no centro, perto de Cabo Frio. A resolução termal nominal do sensor VISSR-IR é 0.5°C, suficiente para detetar uma variação de vários graus que foi observada dos dados dos navios, para estender através do centro da ressurgência. Cartas da temperatura da superfície do mar, obtidas através de computador, baseadas em dados de diferentes imagens, sugerem que o instrumento VISSR parece fornecer a capacidade de observar essas mudanças termais em características associadas com a presença da ressurgência costeira em mesoescala.

1. INTRODUCTION

Coastal upwelling has been of considerable interest to oceanographers over the past decade, as evidenced from the large number of studies made by groups of scientists from all over the world. The studies made off the Northwest coast of the United States, Baja California Mexico, Northwest Africa and Peru are of particular interest because of their multidisciplinary approach. Such concentrated effort is reasonable since coastal upwelling gives rise to much higher biological productivity than found in the surrounding oceanic regions. Because the biota often responds dramatically to changes in the upwelling regimes, the centers of upwelling are best studied using an ecosystems' approach. Underlying such a multidisciplinary approach, however, is the need for physical measurements and analyses.

While the particular features associated with coastal upwelling will vary from location to location, the general characteristics include offshore movement of a surface layer of water near the coast, which is replaced by cooler water from a greater depth that rises to the surface to replace the water advected offshore in the upwelling process. Details of whether the upwelling is primarily a 2-dimensional or 3-dimensional process, whether the upwelling is geographically localized (that is, an upwelling center) or extends as a zone along the coast; how far offshore the upwelling process extends; whether fronts associated with upwelling occur on the shelf or slope; and a number of other specific characteristics appear to vary with the geographic location and coastal and bathymetric geometry. The person interested in information on the dynamics and details of many of the different upwelling areas in the world is referred to the Proceedings of the First International Symposium on Coastal Upwelling. (Richards, 1981).

The objective of this report is to explore and discuss some aspects of monitoring the Cabo Frio upwelling center, site of the most intense upwelling in Brazil. The center is located approximately 125km east of Rio de Janeiro (RJ). A map of the region is contained in Figure 1.

2. CABO FRIO UPWELLING

The surface temperature of the water in the upwelling center often forms a 2-dimensional pattern which generally delineates the locality of stronger vertical velocity and is related to the dynamics of the upwelling center. The coolest surface water in the center has most recently risen to the surface and has not yet had sufficient time to acquire the same temperature as the surrounding surface water. Past oceanographic studies suggest that the thermal patterns appear to change over periods of several days, in response to changes in the wind field (Stevenson et al., 1981). These previous studies observe that the cool surface water may extend in the form of a cool thermal tongue for distances of up to 100 km offshore. The width of this offshore extension of cool water may be half the offshore distance.

A look at actual upwelling conditions in the Cabo Frio center can be appreciated from some measurements collected during the recent CABO FRIO VI Cruise. In this report only a very small portion of the data will be considered, since a more comprehensive and separate report discussing the dynamics of the upwelling center is in preparation by several INPE scientists. The data used in this report were collected along the north/south transect shown in Figure 1.

An example of upwelling observed from the vertical section of temperature is shown in Figure 2. The section began approximately 3 km from Cabo Frio and extended southward for 95 km. The vertical and horizontal variations in temperature are seen to change markedly in passing from the continental shelf to the slope. One of the most important features of interest for this report is the strong thermal gradient ($\delta T/\delta Y = 0.25^{o}C/km$) present between stations 5927 and 5928. By comparison, inshore of station 5927 we observe surface water in the range of $19^{o}C < T < 20^{o}C$; seaward of the surface front we find a zone of water slightly warmer than $23^{o}C$. The surface front and the sharply inclined isotherms beneath and seaward, represent the most intense areas of rising water according to the hydrographic data. If we wish to infer the strength of upwelling from the surface temperature distribution and gradients present within this field, we then need to consider spatial and thermal capabilities of the instruments used to measure these variations. Figure 2 contains information from discrete oceanographic stations (point locations), separated from each other by 30 km or more.

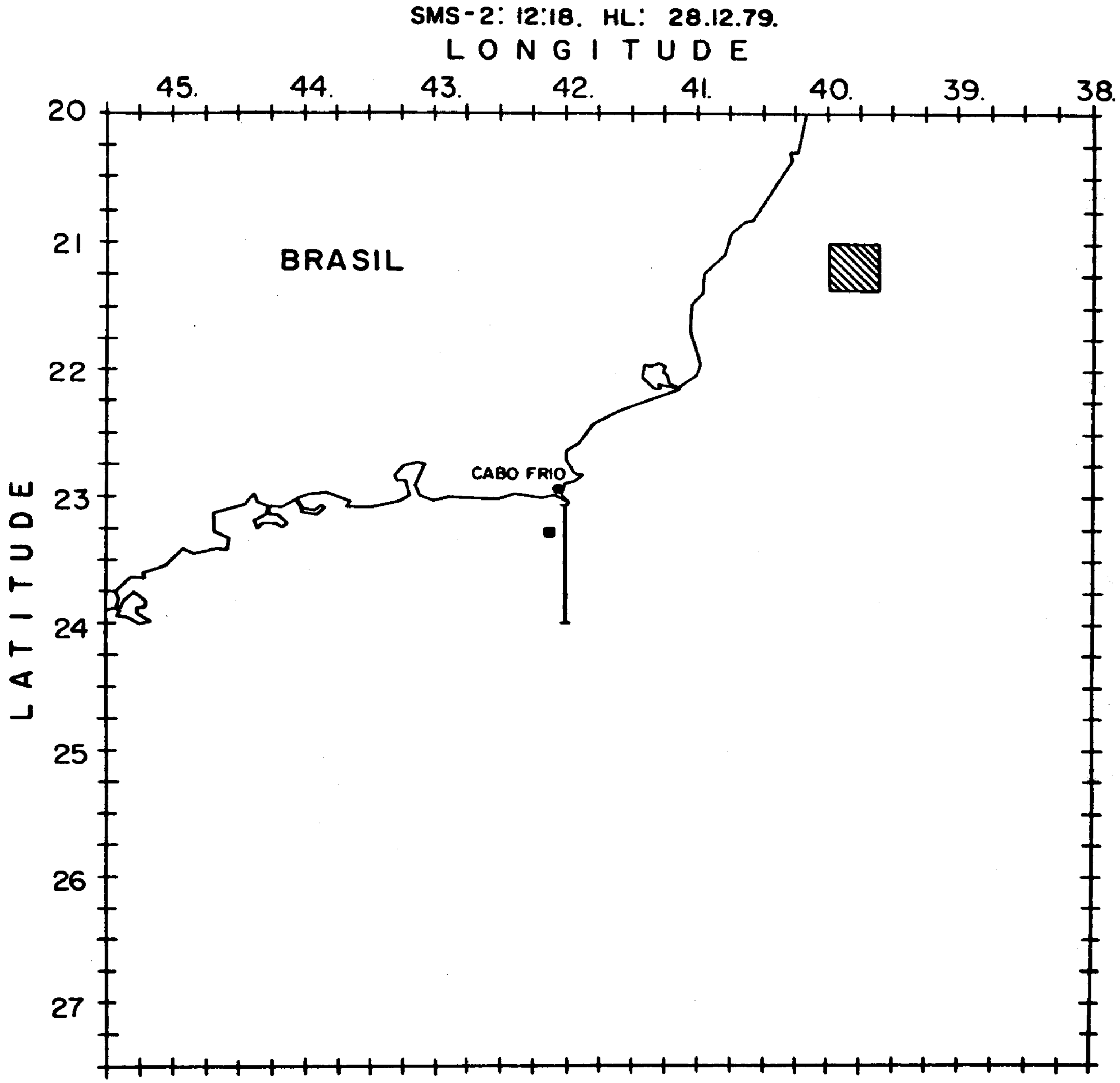

Fig. 1 - Computer drawn map of the Cabo Frio upwelling region showing the size of 1 pixel and a 10 X 10 subarray used in the screening program.

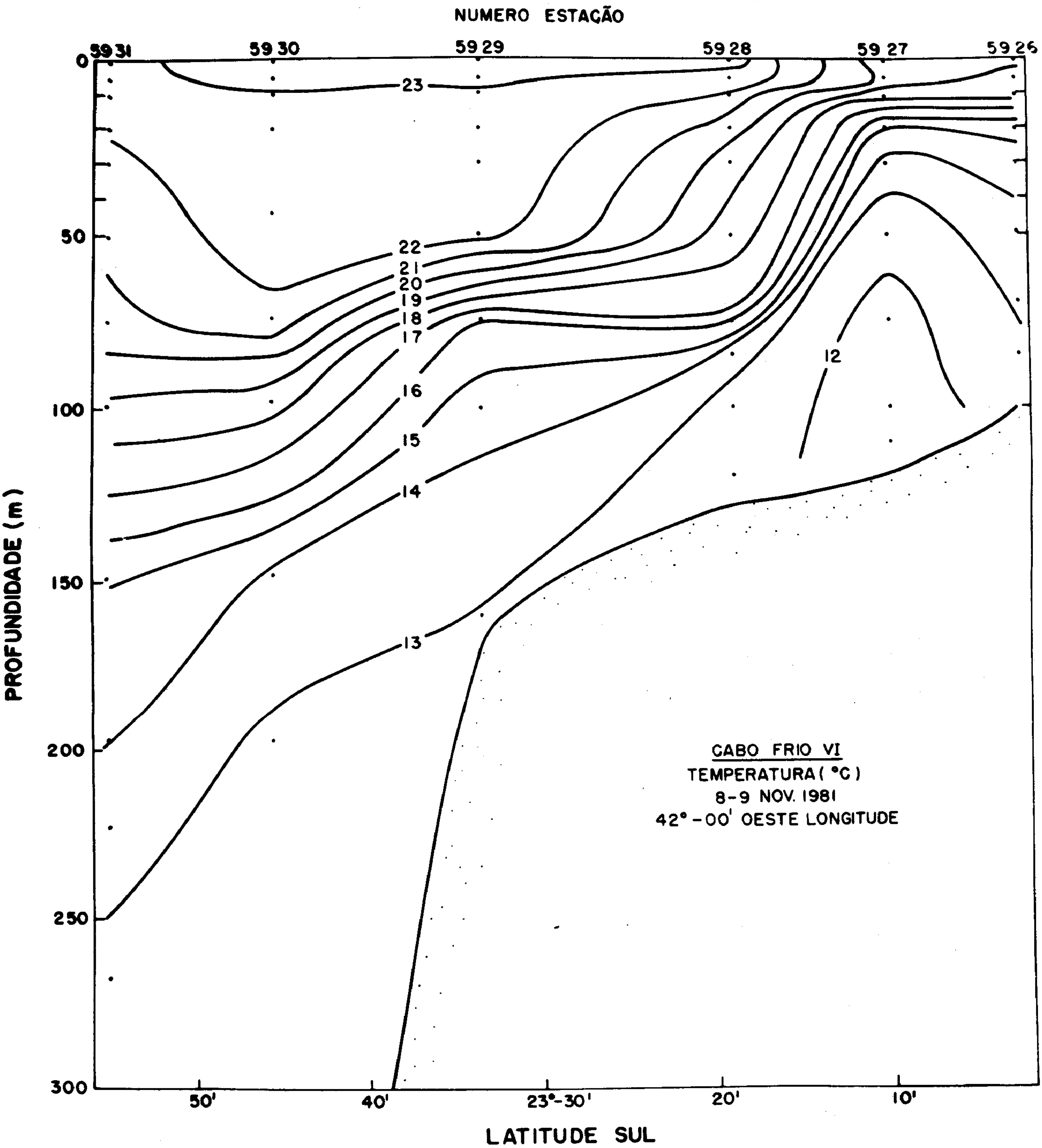

Fig. 2 - Vertical temperature section from the Cabo Frio VI Cruise.

We may get a better idea of the local structure of the surface temperature field if we consider continuously recorded surface measurements. These measurements were made with a Precision Radiation Thermometer (PRT-5) mounted on the ship's bridge, in such a way as to measure the radiometric brightness of the undisturbed water just in front of the vessel. With the graphic recorder the PRT-5 data possesses a thermal resolution of about 0.1°C. The quality and stability of the radiometer data is estimated from the Root Mean Square Error (RMSE), and using the hydrographic stations as the reference the RMSE is only ± 0.2°C.

Figure 3 contains the sea surface temperature profile which was made along the same transect seen in Figure 2. The PRT-5 radiometer data were calibrated using the 6 surface temperature measurements of the hydrographic stations in Figure 2. The most important aspect of the horizontal profile in Figure 3 is the improved resolution possible from the continuously recording instrument. In comparing Figures 2 and 3 we see that the hydrographic station data do not contain the small scale details visible in the PRT-5 record. From Figure 3 we note that the most active upwelling area (evidenced by the coldest water) is just inshore of station 5927. At this location the thermal gradient is 4.2°C/km on the inshore side of the front. Although the offshore side possesses a larger difference in temperature, the gradient is only 0.8°C/km or less than 1/4 as strong as the inshore gradient of the front.

It is apparent that the small scale features of the upwelling area are missed using the hydrographic station spacing, but the station data do retain the general variation of surface temperature seen in Figure 3. From this figure we note that while a thermal resolution of 0.1°C is desirable, a thermal sensitivity of 0.5°C would still provide useful information on the distribution of surface temperatures related to upwelling.

While oceanographic vessels may be used to obtain detailed information on local features of an upwelling system, the high cost of ship operation and maintenance, combined with the complexity of logistical support, makes it difficult to continuously use a ship to monitor the surface temperature field of the Cabo Frio upwelling center. Effective studies of the Cabo Frio center, however, need to provide for flexibility in observing phenomena that can change in several days' time and over a spatial scale of several 10's of kilometers. The monitoring of the continually changing upwelling center requires good synoptic coverage; that is, a reliable basis for continually mapping the region.

A data base obtained from polar orbiting or geostationary satellites offers such an opportunity for repetitive coverage of the Cabo Frio area. In considering the appropriateness of satellite data, one needs to consider the spatial resolution, thermal resolution and frequency of coverage. In a study of time changes of sea surface temperature off the Brazilian coast, Ikeda and Stevenson (1978) found that surface temperatures were somewhat lower near Cabo Frio than in the surrounding area. They used a data base comprised of thermal infrared measurements obtained from the Scanning Radiometer (SR) aboard the NOAA-4 satellite. The ground resolution was about 8-9 km/pixel and the data were averaged to obtain mean temperatures on a $(1/2)^o$ X $(1/2)^o$ geographic grid (GOSSTCOMP). Such resolution was not intended to be used for the Cabo Frio area, nor was it sufficient to delineate the more local thermal gradients present in the upwelling center.

Although they carry Very High Resolution Radiometer (AVHRR) instruments, polar orbiting NOAA - n class satellites are not able to provide daily thermal infrared measurements of consistently high quality due to constantly changing orbital perspective with regard to Cabo Frio. In addition, orbital constraints for the same region preclude more frequent usable coverage than once a day.

Geostationary satellites, on the other hand, provide essentially the same perspective and can obtain repetitive coverage of an area several times a day if needed. Flexibility in data acquisition is also important when an area frequently contains clouds such as the Cabo Frio region. For these reasons then, the Stationary Meteorological Satellite (SMS-2) was selected as the data base for the development of a computerized method for monitoring the sea surface temperature in the Cabo Frio area.

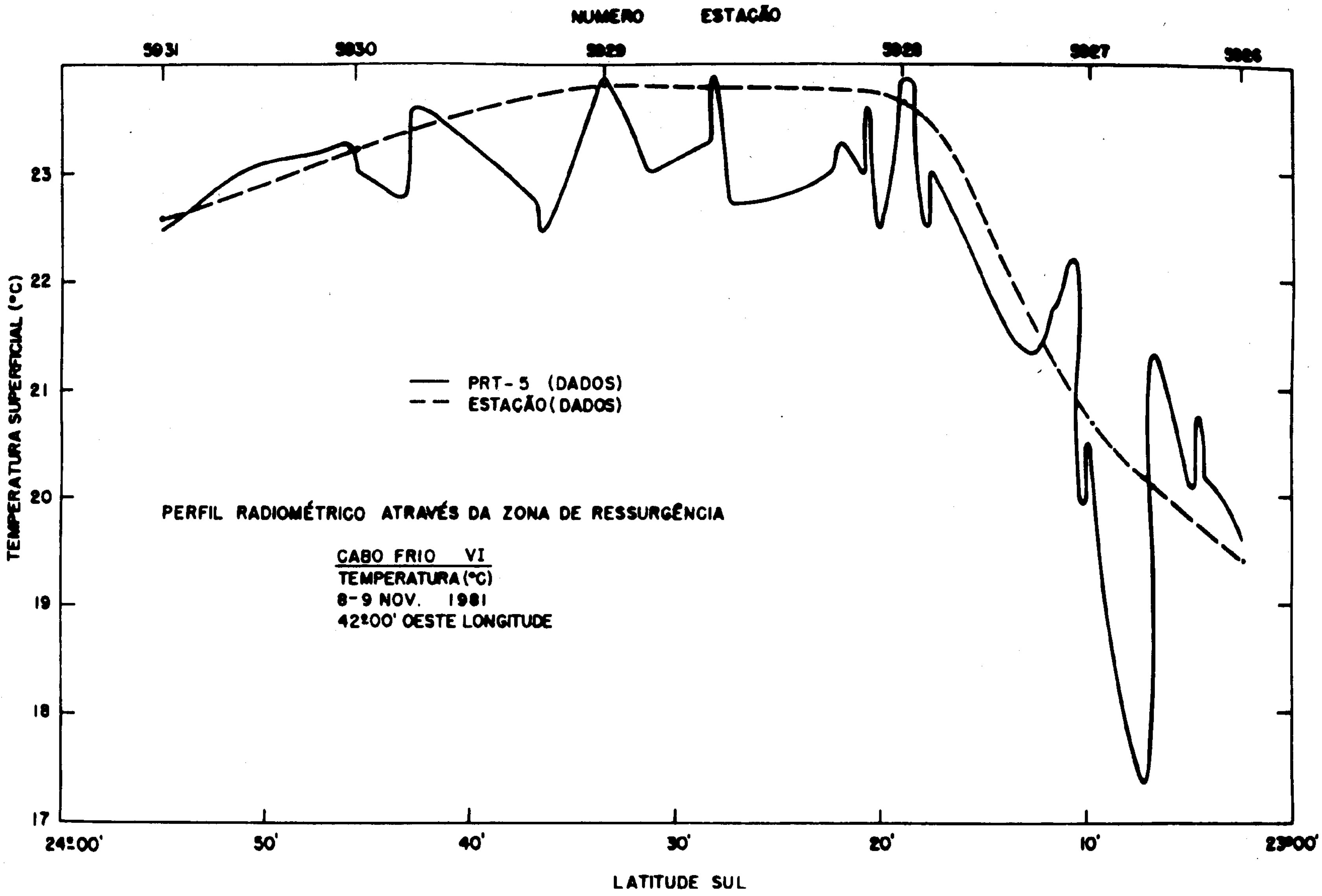

Fig.3 - Offshore surface profile of the sea surface radiometric temperature obtained during the Cabo Frio VI Cruise.

3. METHODOLOGY

Data from the SMS-2 Visible and Infrared Spin Scan Radiometer (VISSR) aboard the SMS-2 is collected and transmitted to earth from 2 channels (Bristor, 1975). The visible (Vis) channel (0.55 - 0.75 μm spectral window) is not presently recorded on digital tape and therefore was not available to this study. The thermal infrared (IR) channel (10.5 - 12.6 μm spectral window) provides the data from which water temperatures may be determined. The ground resolution of the VISSR IR data is about 10 - 12 km/pixel for the latitude and longitude of Cabo Frio. The thermal sensitivity of the IR data is 0.5°C in the temperature range of Brazilian water. Since we have noted that thermal differences across the upwelling center may be 3 - 4°C, the VISSR IR data would appear to be adequate for resolution of general features of the upwelling center at Cabo Frio. In addition, the frequency of data acquisition can be as frequent as once per 30 minutes, more than adequate for monitoring the upwelling center.

When needed, the INPE tracking station located at the São Jose dos Campos (SP) facility can provide computer compatible tapes (CCT's) of 800 BPI density of the thermal infrared channel. The full earth image containing 1821 scanlines is normally recorded at the time of data acquisition. Film images from both Vis and IR channels can also be provided from the SMS-2 telemetry. For the purposes of this study, several digitized VISSR IR images were used from an existing archive at INPE, although a specific sequence of images could be generated at the station on an hourly, daily or weekly basis.

The procedure used in this study was to modify a set of 3 computer programs currently being developed to generate maps of sea surface temperature for the oceanic region off Brazil. The general logic of the programs is seen in the flow diagram in Figure 4.

Upon receipt of a VISSR IR CCT, the first program (SATDAT) searches the tape for the general geographic area (latitude) specified by the user of the program. Since each tape record contains 1 entire scanline (3822 16 bit words), a set of 210 scanlines is read from the tape, decoded into single 8 bit words (0 - 255 counts), stored onto disk file and also written onto a "scratch" tape. The second program (PRSCR) reads the disk file if present in the computer or requests the "scratch" tape. This program performs several operations. The first step is to select the particular 2-dimensional field of pixels corresponding to the region of the longitude of Cabo Frio. The next step is to interpolate between the adjacent scanlines in order to preserve a reasonable aspect ratio in the final map product. Then the program subdivides the 200 pixels by 210 scanline blocks of data (42,000 pixels) into 420 subarrays (10 X 10 pixels each), as shown schematically in Figure 4. The purpose for the subarrays is to screen small areas for the presence of clouds. This procedure is necessary since the presence of clouds blocks the sensor's view and the resulting thermal brightness measurement of the sea surface. Because the visible channel is not available to help screen out the clouds, a more elaborate statistical technique is used as noted in Figure 4. Basically the sample means ($\bar{T}_{i,j}$) and standard deviations ($\sigma_{i,j}$) are computed for each subarray. Those subarrays with mean temperatures lower than a preset temperature are eliminated as heavily contaminated by clouds. Those subarrays possessing mean temperatures greater than the preset value are then checked to see if the $\sigma_{i,j}$ values are less than 2.0. If $\sigma_{i,j} \leq 2.0$ ($\leq 1.0°C$), the entire subarray is utilized. If $\sigma_{i,j} > 2.0$ a second retrieval is used to eliminate those colder pixels responsible for the large value of $\sigma_{i,j}$. If after comparison with a Gaussian function and the elimination of some of the colder pixels the recomputed $\sigma'_{i,j} > 2.0$, the entire subarray is rejected. If after the comparison $\sigma'_{i,j} \leq 2.0$ the partial subarray is used. This method appears to work except for those areas possessing a strong thermal gradient within the same subarray area, in which case the program will interpret the large standard deviation as representing clouds.

The lower part of Figure 4 shows the third program (TESTGRID), which produces the machine contoured map of sea surface temperature. The first modification made in the contouring program was to change the scale of the map. The initial map covered a 15° X 15° geographic area, but the resulting 8 million: 1 scale was too compressed to show any details of the Cabo Frio area. After considering several options, a decision was made to retain the 21 cm by 19.5 cm format, but to reduce the coverage by one half to 7.5° X 7.5° (4 million: 1 scale). This coverage is shown in Figure 1. For reference purposes a single pixel and a 10 X 10 subarray (100 pixels) is included in the figure to give an impression of the size of these elements. To retain the aspect ratio of about 1:1, it was necessary to interpolate between scanlines in the second program.

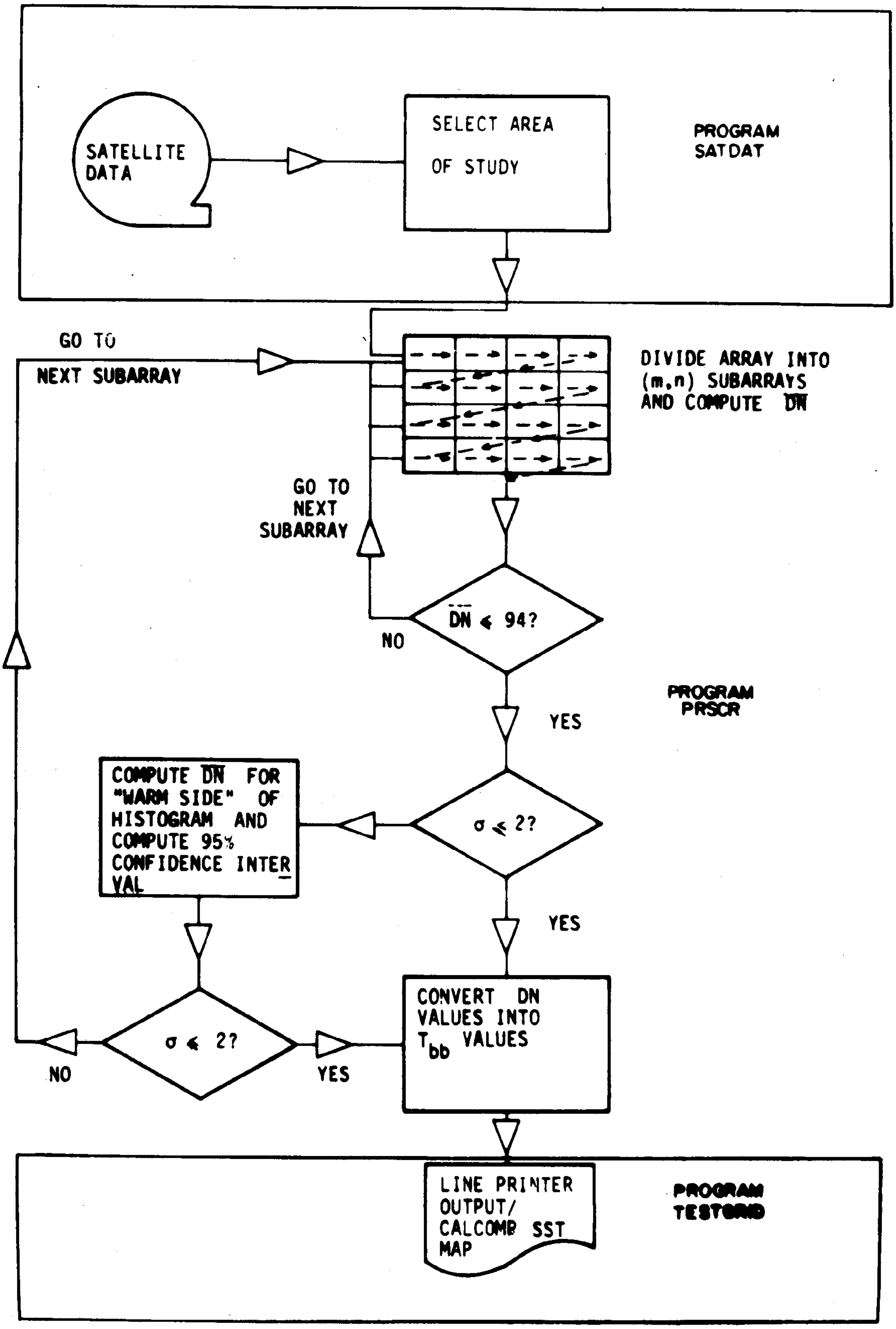

Fig. 4 – Flow diagram of the three program used to produce contoured sea surface temperature charts.

In operation the overall array is scanned to determine the minimum and maximum temperatures. These values become the upper and lower limits for the contours. The contour interval is set within the program at 2°C, although the interval can be easily changed. A smaller interval results in significant changes in running time on the computer, however. The program continues by starting at the lower temperature level and begins to search for the presence of that temperature in one corner of the array. Such an operation is complicated and requires a fairly fast processor and large accessible core storage. The program determines the contoured temperature field, one contour level at a time, over the entire array. In order to produce a realistic contoured field, the spacing between the adjacent data pixels is further divided by interpolation. As a result of this method, it is possible to determine maximum and minimum closed patterns within the 2-dimensional array. Having provided the reader with some background of the operations of the programs, we will now consider some results of the programs.

4. RESULTS

To provide some basis of comparison a VISSR IR image used to generate a sea surface temperature map product is shown in Figure 5. We can note the presence of some clouds in the general area and also some areas relatively free of cloud cover. This image contains the same pixels as used in programs 2 and 3 to extract sea surface temperature (SST) information.

In Figure 6 we see the resulting map of SST based on the data of Figure 5. We observe that the cloudy regions have been effectively removed and the pixel data eliminated from further analysis. The contouring program stops generating the contour line when it encounters geographic extremes of the map, boundaries of clouds or of the coastline. The coastline margin is used to block the use of pixels west of the coastline and the blocking method generally works well even though it represents a separate data source read into the program. Program 3 contains a 2-dimensional smoothing operator that removes the effect of angularities in the contour lines. Occasionally the data from some cloud free areas that lie next to a cloudy region will be lost, depending upon how the 10 X 10 subarrays are spatially defined.

In Figure 7 we see another example of the SST map. Again some clouds are present and give rise to information "voids" in the map. There are two methods to minimize this problem. The first method is to use the visible channel of the VISSR, since it will provide a sharp delineation of those pixels which contain cloud information and those which do not. As a result, it would be possible to recover considerable small areas now lost in the subarray method of analyses. The second method is to collect digital images for several consecutive days and to save the screened areas within the overall region. These are spatially averaged to produce 1 time composited data array from which a map of SST may be generated. If the data are averaged over 4-5 days time, it should be possible to recover 85% or more of the total area.

Our present efforts are to explore both of the above methods to optimize the IR data available to us. We anticipate receiving visible channel VISSR data very soon and will incorporate these data into the PRSCR program. The second method will be implemented using an intermediate archive tape as time permits.

The overall result of the study has shown that while considerable cloudiness exists in the Cabo Frio area, it is possible to use VISSR IR data to generate sea surface temperature maps which include the Cabo Frio upwelling center area. These maps are capable of showing relatively small temperature features.

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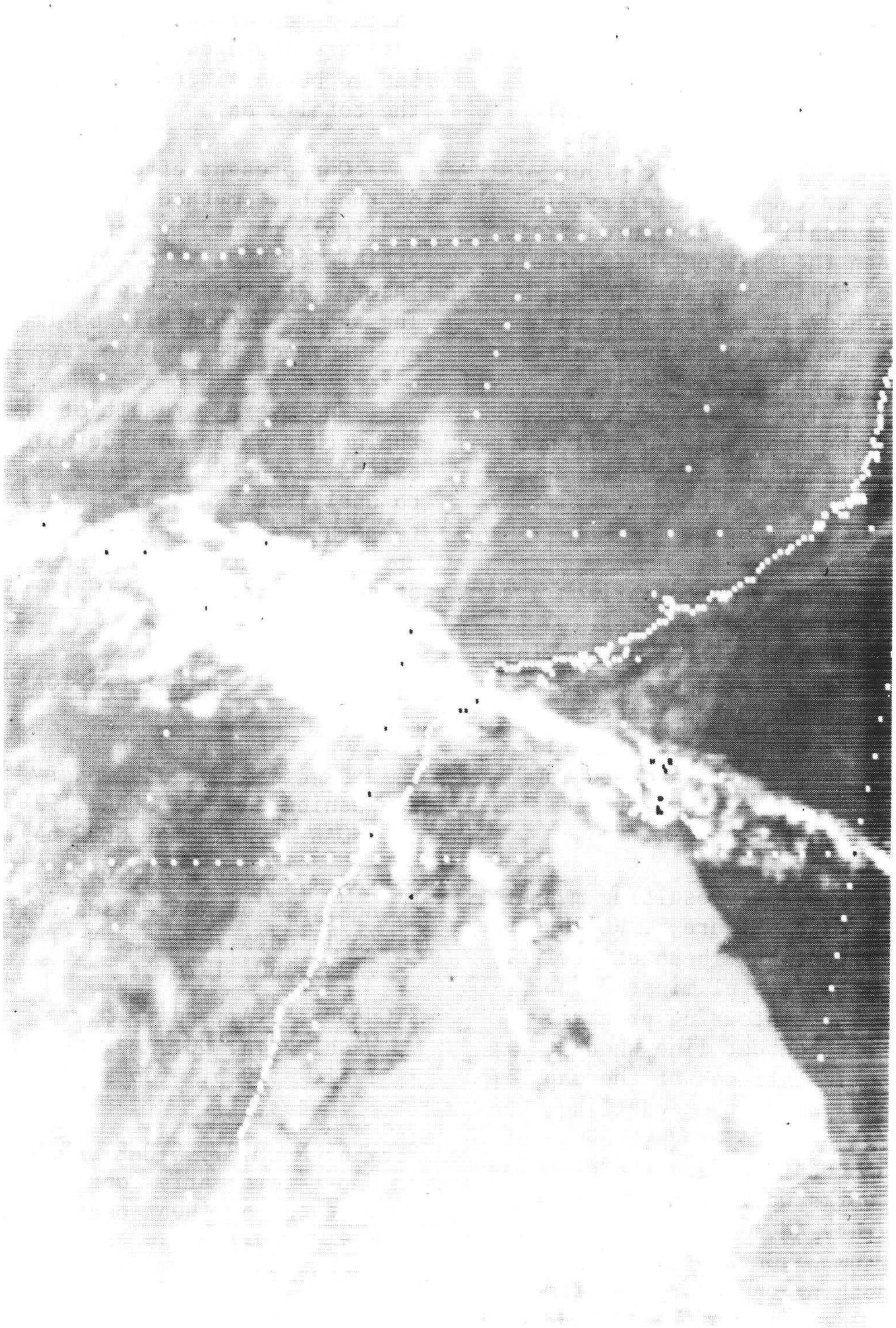

Fig. 5 - SMS-2 satellite VISSR IR image of the Cabo Frio area for June 26, 1981.

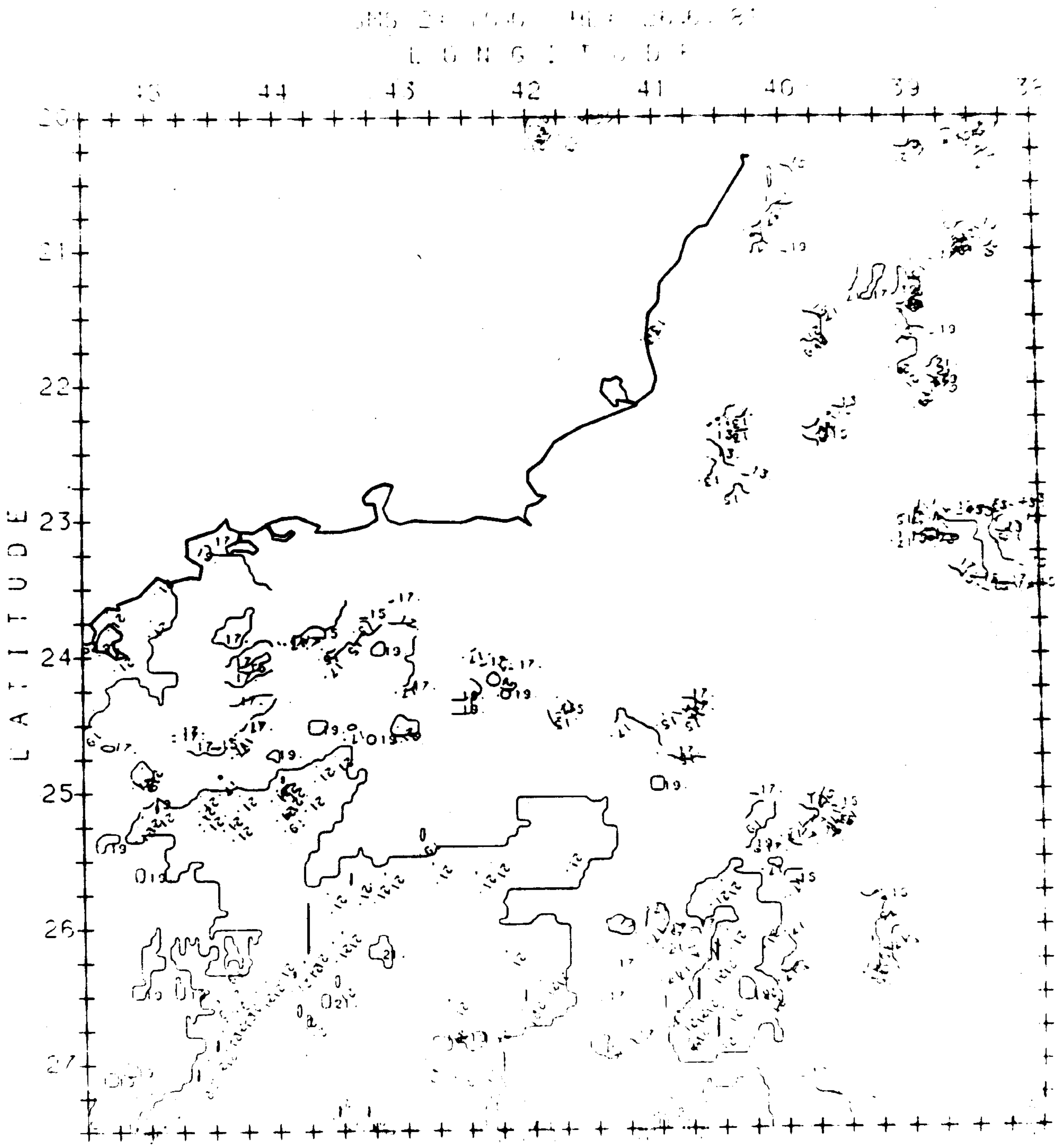

Fig. 6 - Machine contoured map of sea surface temperature based on data from Figure 4.

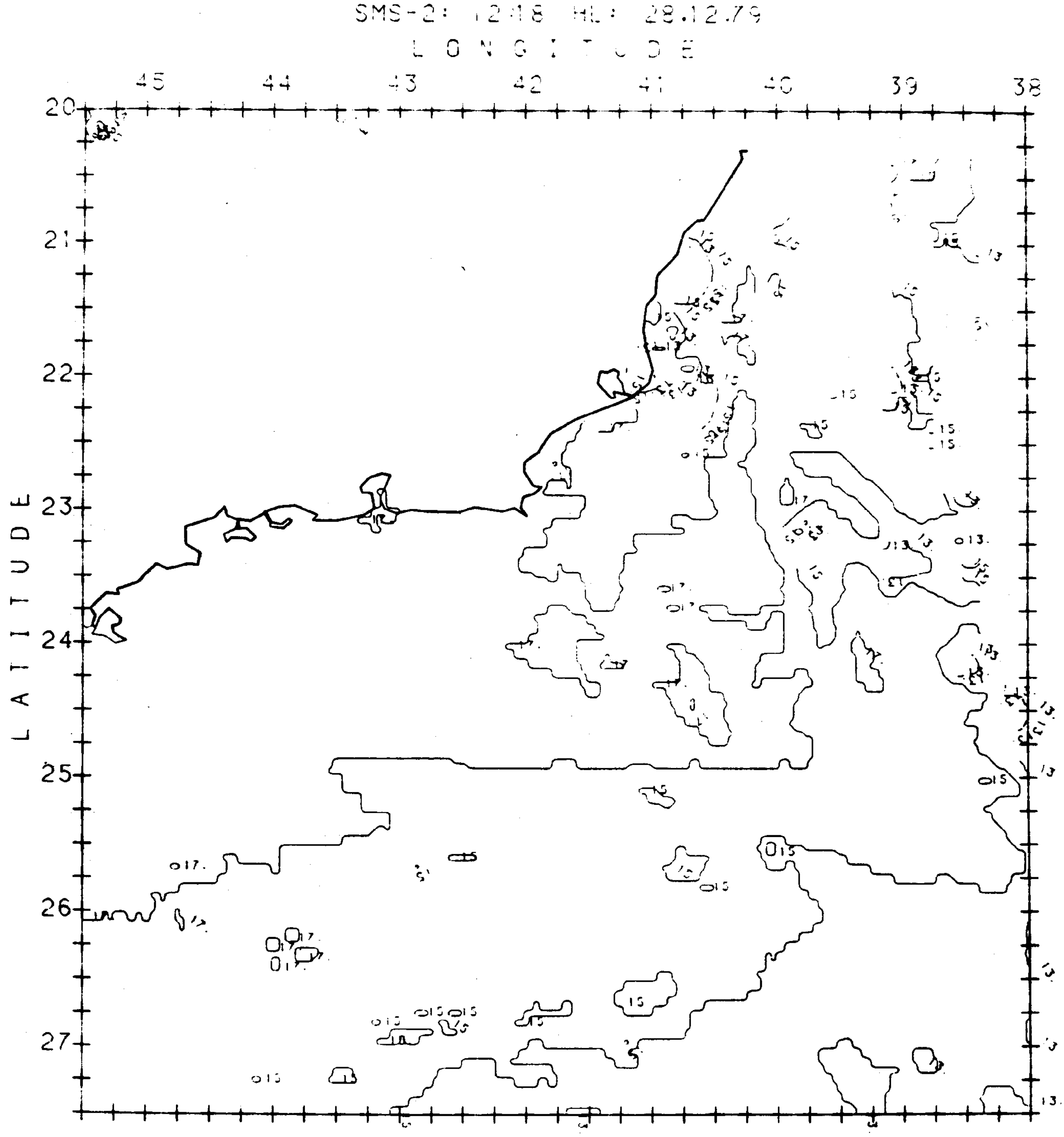

Fig. 7 - Machine contoured map of sea surface temperature for December 12, 1979.