# A Satellite-Aircraft Thermal Study of the Upwelled Waters off Spanish Sahara

PAUL E. LA VIOLETTE,

*Naval Oceanographic Office, Washington, D. C. 20373*

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## ABSTRACT

During the period 18 through 26 August 1973, a satellite-aircraft oceanographic survey was made of the upwelled waters off the coast of Spanish Sahara. NOAA-2 infrared data received by a field satellite receiver station and computer-enhanced into thermal imagery aided in directing the five flights of a research aircraft over the region's most interesting thermal features. This imagery showed that the upwelling extended from the Canary Islands southward to 20N in the region of Cape Blanc, and that the aircraft survey would best be made along the coast between 26 and 28N. The aircraft used an airborne radiation thermometer to collect data showing the ocean's surface temperature variations, and 300 m airborne expendable bathythermographs to derive the ocean's vertical temperature variation. In addition to aiding the survey operation, the field-collected satellite infrared data were retained in digital form to aid the post-survey analyses. The analyses of the satellite and aircraft data define the region of upwelling and show that during the survey, variable cold and warm eddies extended more than 100 km beyond the upwelling zone. These analyses indicate that the eddies are a result of wind stress and regional topography and may be a periodic dynamic feature of the region.

## 1. General

During the period 18 through 26 August 1973, the survey phase of the Sahara Upwelling Experiment (SUE) was conducted in the upwelling area off the coast of Spanish Sahara. One of the principal purposes of SUE was to explore the operational and post-survey uses of direct-readout satellite data to an oceanographic survey (Maughan *et al.*, 1969; La Violette and Stuart, 1972; La Violette, 1974).

During the survey, visual and infrared data were received from the NOAA-2 satellite by an Automatic Picture Transmission (APT) satellite receiver (Vermillion, 1969). The receiver had been modified to interface with a mini-computer and the computerized APT field station was positioned on Gran Canaria in the Canary Islands. The visual data received by the station provided the SUE scientific and aircraft personnel with daily regional meteorological information. The infrared data transmitted simultaneously with the visible data provided information on the daily position and strength of the surface thermal gradients associated with the upwelling. To optimize this thermal information, the infrared data were digitized immediately upon reception, manipulated by the mini-computer, and then displayed as enhanced thermal imagery of the waters along the Spanish Sahara coast (Fig. 1). This field-collected information was used to modify the aircraft flight tracks to ensure that the most

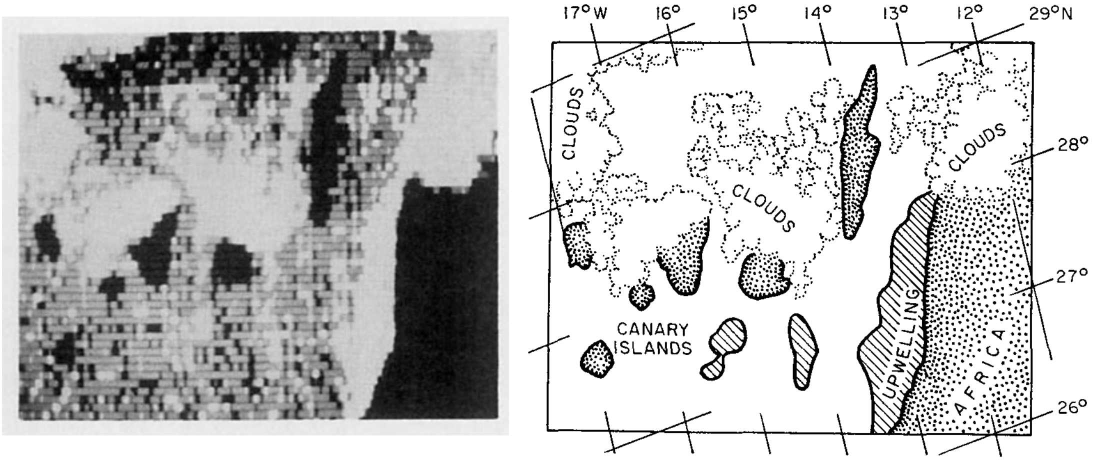

Fig. 1. Field enhanced NOAA-2 infrared imagery (left) and a schematic presentation of the imagery (right) for the morning of 21 August 1973. The data for this imagery were received and processed by a computerized APT field station positioned on Gran Canaria in the Canary Islands. The data were from the 10.5–12.5 μm infrared channel of the NOAA-2 SR sensor. Visible imagery of the same earth scene was received simultaneously with the infrared imagery. This imaging aided in distinguishing clouds (which could be seen in both visible and infrared imagery) from upwelled cold water (which could be seen in the infrared imagery only).

interesting thermal features of the upwelling were examined.

The airborne surveys were made from the U.S. Naval Oceanographic Office Research Aircraft *Arctic Fox* operating out of Gran Canaria and conducted similar to procedures described by Wilkerson (1966). The aircraft made five flights: two morning flights on 18 and 25 August, and three afternoon flights on 21, 22 and 26 August. A flight scheduled for 28 August was cancelled due to insufficient aviation fuel. The basic aircraft track lines as well as a bathymetry chart of the SUE area are shown in Fig. 2.

An airborne APT station (La Violette and Diachok, 1973) was placed aboard the *Arctic Fox* for auxiliary use during flights. Although the satellite thermal imagery obtained by this computerless unit showed the surface distribution of the cold upwelled water, the definition was not as detailed as the computer-enhanced imagery obtained from the ground APT station. The aircraft APT imagery was therefore used mainly to provide meteorological information to the scientific crew of the aircraft during the early morning flights and as a backup for the ground station.

In addition to the meteorological information provided by the APT stations, visual weather observations were made approximately every 15 min from the aircraft. Observations of sea state conditions indicated that the surface winds were steady during the survey period, originated from the north and northeast, and averaged between 15 and 20 kt.

The sea surface temperature data used in this paper were collected by a Barnes 14320 Airborne Radiation Thermometer (ART) operating in the 9.5–11.5 μm spectral range. Pre- and post-survey calibrations showed the radiometer accumulated a drift of −0.1C during the period of SUE.

Information on the vertical temperature distribution of the water was obtained by 300 m airborne expendable bathythermographs (AXBT's). Altogether 57 AXBT's were dropped: nine on 18 August, 23 on 21 August, and 25 on 22 August. In anticipation of the flight planned for 28 August, no AXBT's were dropped on 25 and 26 August. As mentioned earlier, the 28 August flight had to be cancelled; thus, the AXBT data used in this paper are limited to those obtained on 18, 21 and 22 August.

For a variety of reasons, the AXBT's were not calibrated prior to the mission, and adjustments had to be made to their data to make them intercomparable for analysis. Two methods of adjustment were used. Each was made independent of the other, and the resulting corrections for each trace were compared to see if significant differences occurred. The first method consisted of overlaying AXBT profiles dropped at the same location on different days. This resulted in a thermal correction for each trace to produce best fits. (Where possible, each day's AXBT's were dropped at standard locations. Thus, in nine instances AXBT's for 18, 21 and 22 August were dropped at the same locations, and in 14 instances AXBT's for 21 and 22 August were dropped at the same locations.) The second adjustment was to make surface temperatures of each AXBT profile the same, or as close as possible to the ART temperature recorded at the time and place the AXBT was dropped.

No significant differences were found in comparing the corrections obtained by these two methods. It is believed, therefore, that for the purposes of the survey,

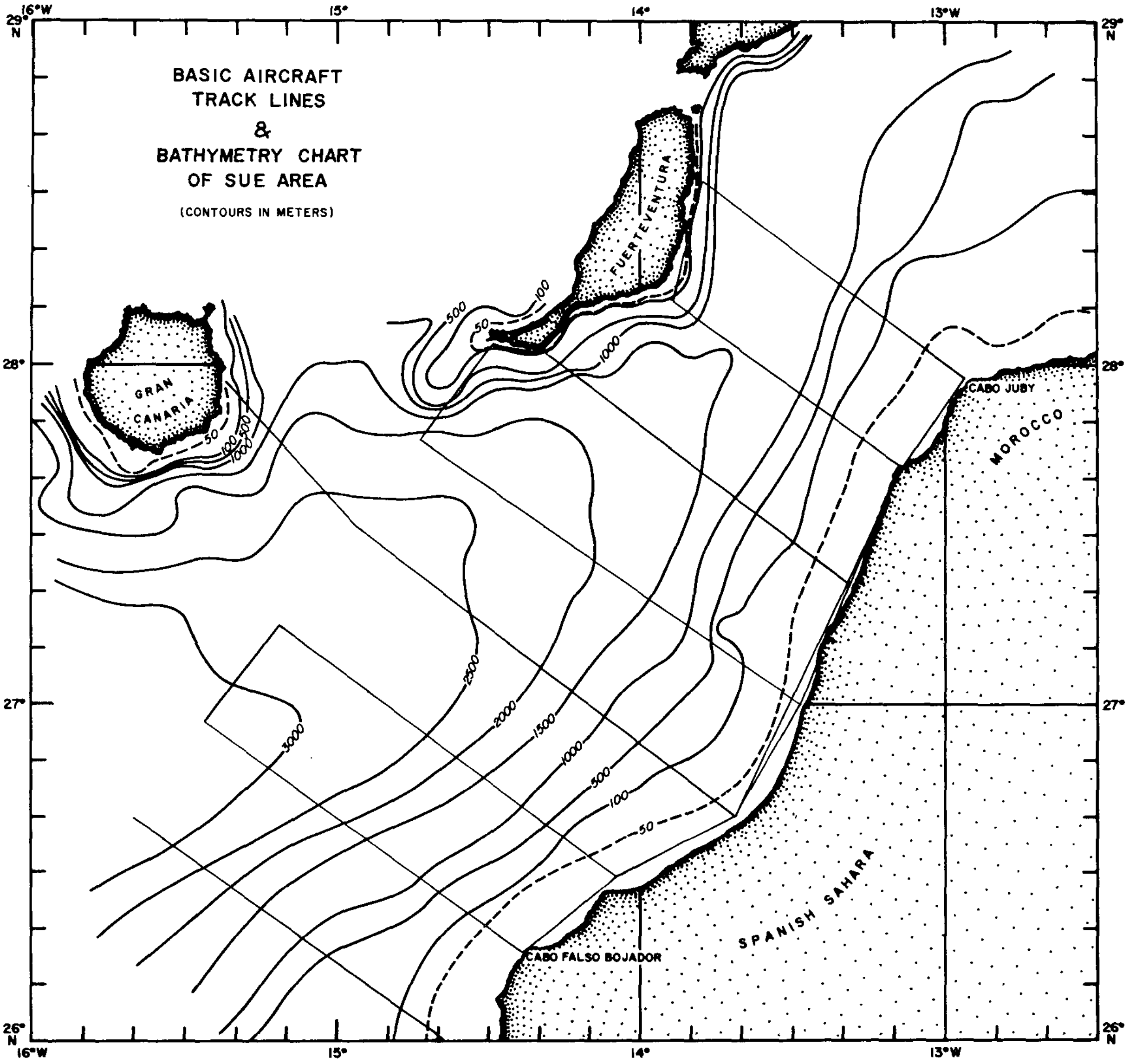

FIG. 2. Basic aircraft tracklines of the R/A *Arctic Fox* and a generalized bathymetry chart of the SUE area.

the AXBT data were adequately corrected and the vertical temperature sections presented in this paper reliably depict the subsurface thermal variation that occurred during SUE.

## 2. Data analysis

NOAA-2 Scanning Radiometer (SR) enhanced infrared imagery received in the field showed that while the upwelling extended as far south as Cape Blanc, the strongest thermal gradients were found in the region 26 to 28N. Based on this information, the aircraft survey was conducted in the upwelling zone between these two latitudes.

During the morning flights of 18 and 25 August, data from the aircraft's hygrometer, visual weather observations, and the cloud distribution present in the satellite visual imagery showed that the early morning distribution of atmospheric moisture in the survey area was highly variable. Since NOAA-2 is a mid-morning satellite, i.e., its optimum overhead pass occurs between 0900 and 1100 local time, infrared data from the satellite's sensors was probably distorted by the variable absorption of the region's atmospheric vapor.

Despite this, a post-survey analysis of the digitized satellite thermal data for the morning pass on 21 August shows close agreement between the horizontal thermal patterns found by these data and the analysis of the data obtained from the 21 August afternoon aircraft survey (Fig. 3).

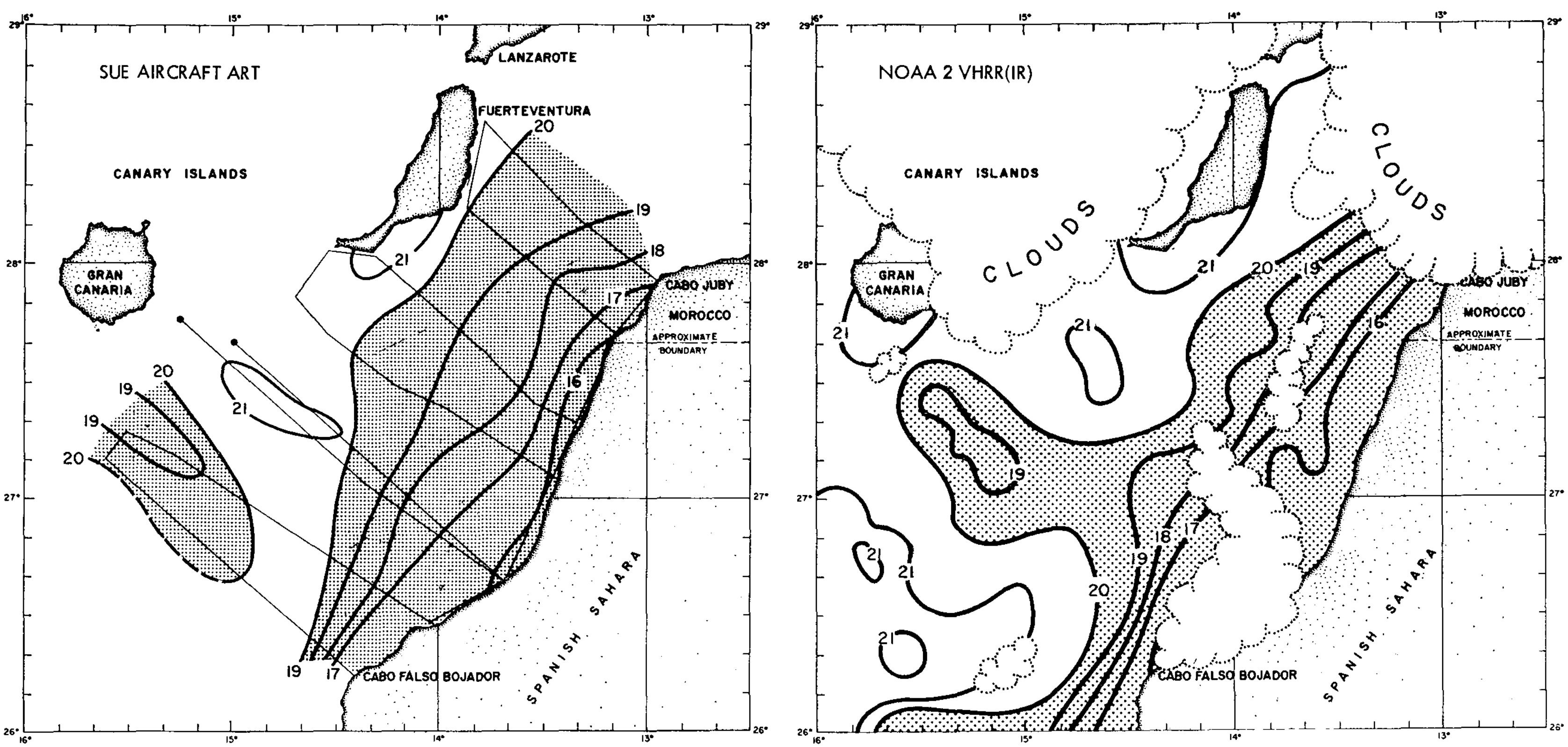

Fig. 3. Comparison of the analyses of aircraft and satellite radiation temperature data (°C) for 21 August 1973. The satellite analysis was made using numerical data obtained from the infrared channel of the NOAA-2 VHRR sensor. NOAA-2 has two types of radiometric sensors capable of furnishing infrared data: the SR, whose infrared channel has a resolution of 7.5 km at the subsatellite point, and the VHRR whose infrared channel has a resolution of ~1.0 km. The NOAA-2 SR sensor provided satellite field data to the R/A *Arctic Fox* and the Gran Canaria APT stations during the period of the survey. The NOAA-2 VHRR sensor collected data simultaneously with the SR sensor. However, the VHRR higher resolution data were stored aboard the satellite and later transmitted to a ground command station at Wallops Island, Va. These data were not available in the field and were used with the SR data to aide the post-survey analyses. A more complete description of the NOAA-2 satellite and its radiometric sensors may be found in Schwalb (1972).

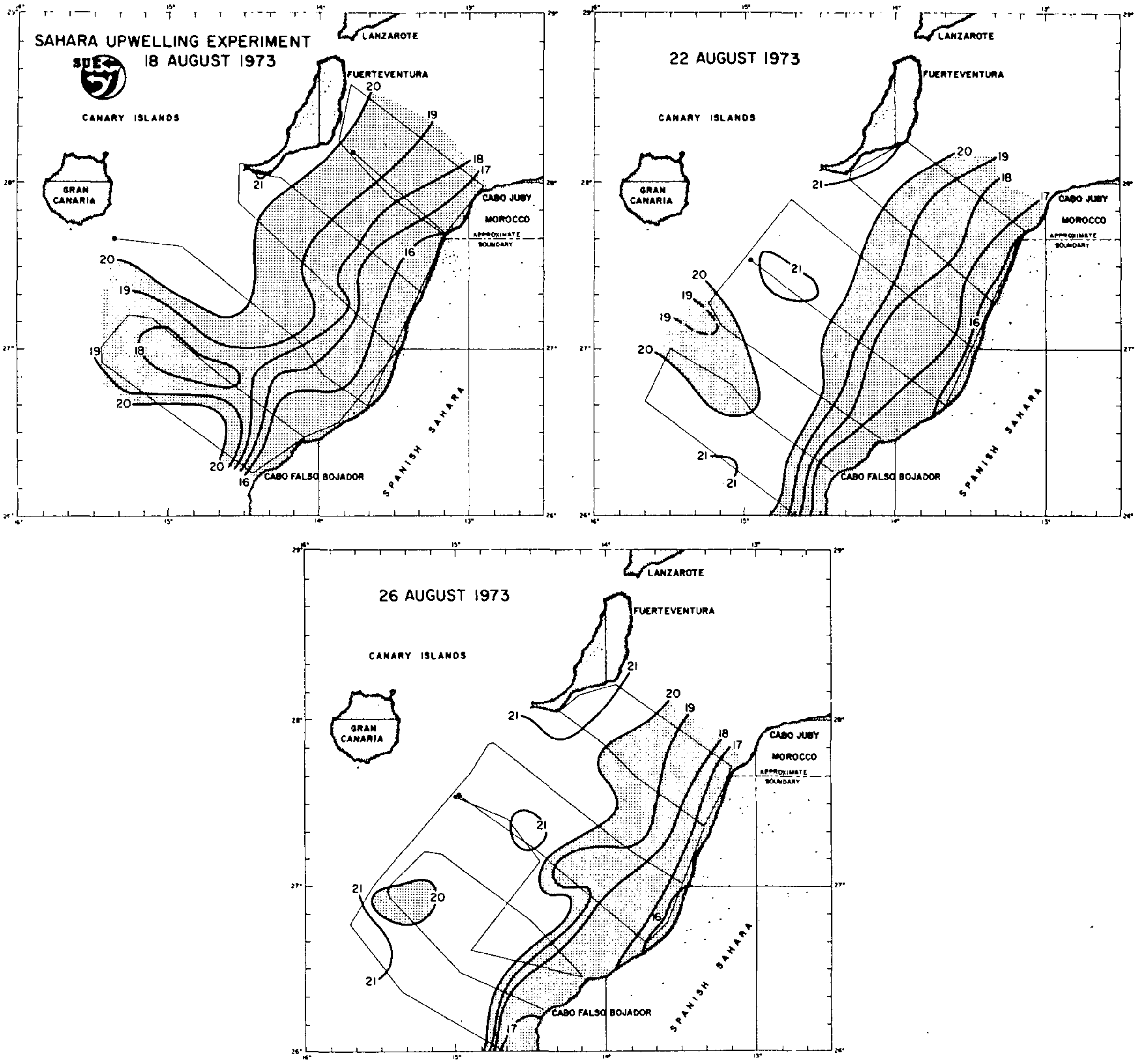

FIG. 4. Analyses of ART data (°C) for 18, 22 and 26 August 1973. The aircraft tracklines have been imposed on the analyses to show the distribution of data used in the analyses.

Analysis of the aircraft data show the furthest seaward extension of the general coastal upwelling occurred on the first flights (18 August) when water of less than 20C surfaced near the coast of Fuerteventura (Fig. 4). By the time of the last flight on 26 August, water of less than 20C was found closer to the coast of Africa.

The ART data show that a plume of water of less than 20C extended north-westward from the coastal upwelling region on 18 August. In the analyses of ART data from the flights that followed, this plume was shown to separate from the coastal zone of upwelled waters, to form a separate surface structure, and gradually diminish in size due to both sinking and surface warming.

The satellite infrared data (Figs. 1 and 5) show that a second cool feature was present on the surface just southwest of Gran Canaria. This structure may have a remnant of an older plume. No aircraft flights were made over this feature. The possible start of a new plume is seen extending from the coastal upwelling zone in the analysis of ART data for 26 August.

An eddy having a water temperature greater than 21C was always present along the lee coast of Fuerteventura. Two other warm eddies—one slightly southwest of the island, and the other barely visible on the southern fringe of the aircraft survey area—were present during most of the flights. The satellite thermal data in Figs. 3 and 5 show the latter of these eddies was part of a large pool of warm water lying just beyond the aircraft survey area. Figs. 3 and 5 show that a warm eddy, similar to that found along the southern coast of Fuerteventura, was present along the lee coast of Gran Canaria.

The regional bathymetry (Fig. 2) indicates that the increased depth south of the islands (from 1500 to 3000 m) and the relaxation of the channeling effect of the island of Fuerteventura and the African coast probably contributed to the formation of the plume and the distribution of gradients of the local upwelling. In addition, the distribution of the warm eddies in the analyses of both the aircraft and satellite infrared data seem to indicate that these may have been created by the intrusion of the island in the prevailing ocean current flow. As these features trail southward from Fuerteventura, they appear to be imposed on the seaward movement of the coastal upwelling. They are best seen in the satellite infrared data analysis shown in Fig. 4. It is interesting to note that cloud formations in the atmospheric wake of the Canary Islands often assume the structure of von Kármán vortices (Chopra, 1973). Cloud formations of this nature occurred several times during the survey (Fig. 6). Barkley (1972) and White (1973) postulate that an analogous oceanic wake may occur downstream from an island. The warm eddies displayed in the infrared data analysis of Fig. 4 may be an example of such an oceanic wake.

Fig. 7 shows the vertical temperature distribution for 21 August. The vertical sections show that the upwelling extended to a depth of at least 300 m (lines 5 and 6), and that water from depths greater than 100 m was being brought to the surface along the African Coast (lines 3 through 6).

The AXBT data show the plume of cold water sank slightly between 21 and 22 August. Comparison of the AXBT's located at standard drop points for 18, 21 and 22 August indicate that some subsurface vertical and horizontal movement occurred in the upwelling zone. Because of the horizontal movement, however, it is impossible to give the rate of sinking. Some idea of the sinking taking place along the spine of the plume may

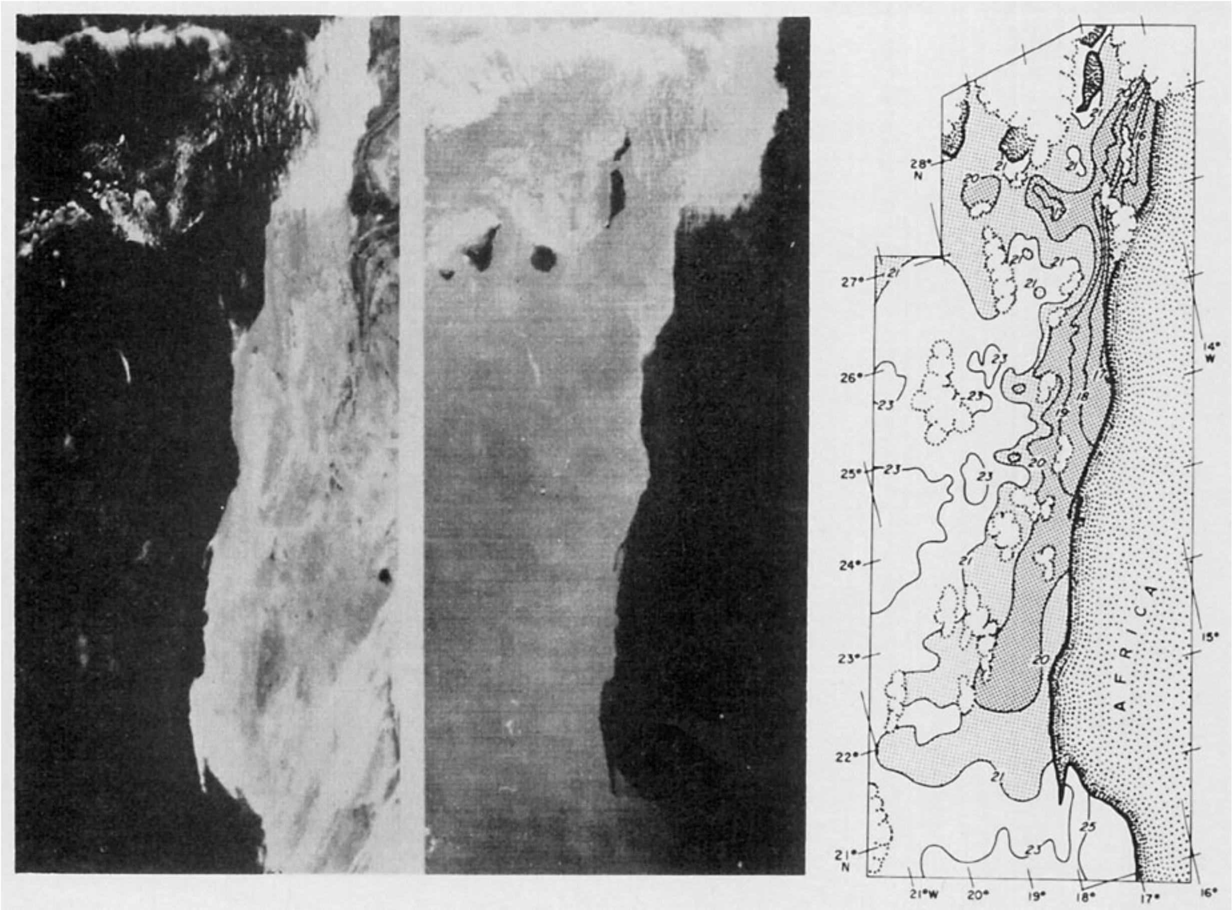

Fig. 5. Imagery and analysis of NOAA-2 VHRR data for 21 August 1973. The visible and infrared imagery are shown on the respective left and center of the figure. An analysis of infrared numerical data obtained from the sensor is shown on the right.

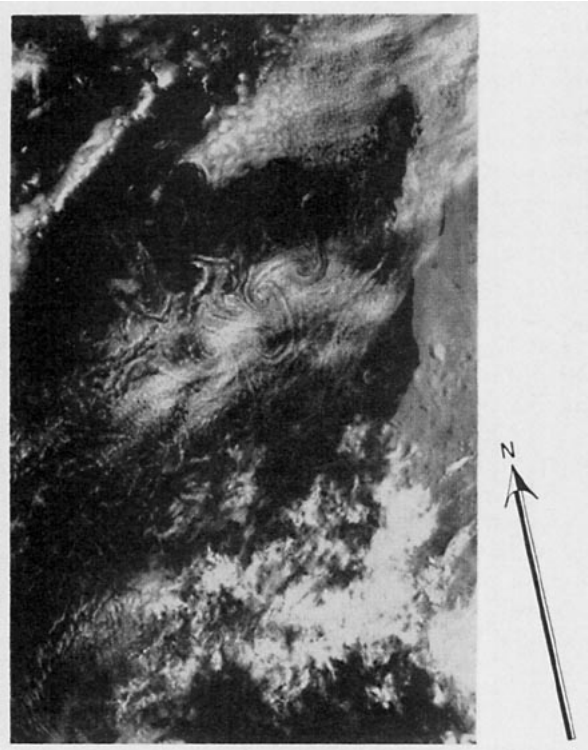

FIG. 6. NOAA-2 VHRR visible imagery showing von Kármán vortices in the clouds downwind of the Canary Islands on 25 August 1973.

be obtained by examining Fig. 8 which shows the vertical sections formed using the data from standard station AXBT's for 21 and 22 August.

Although the subsurface structure of the cool plume is easily discernable in the vertical sections presented in Fig. 7, an unusual feature of these sections is the depth of the warm eddy southwest of Fuerteventura. This is best seen in the vertical sections for line 5 in the figure. Here, 16C water lying deeper than 100 m may be compared to the vertical sections for nearby lines 4 and 6 which show the 16C water to be only slightly deeper than 50 m. This depression of warm water is best seen in Fig. 9 which presents the variation in depth of the 16C water for 21 August.

The surface and subsurface temperature charts for 21 August in Fig. 10 show the effects of the warm eddy extended as deep as 300 m, whereas the upwelling structure related to the plume is absent below 50 m.

## 3. Summary

NOAA-2 SR-enhanced infrared imagery produced by a computerized APT field station during the survey period of the Sahara Upwelling Experiment aided in directing five flights of a research aircraft over the study region's most interesting thermal features. A post-survey examination of the aircraft and satellite data collected during the period (19–26 August 1973) show

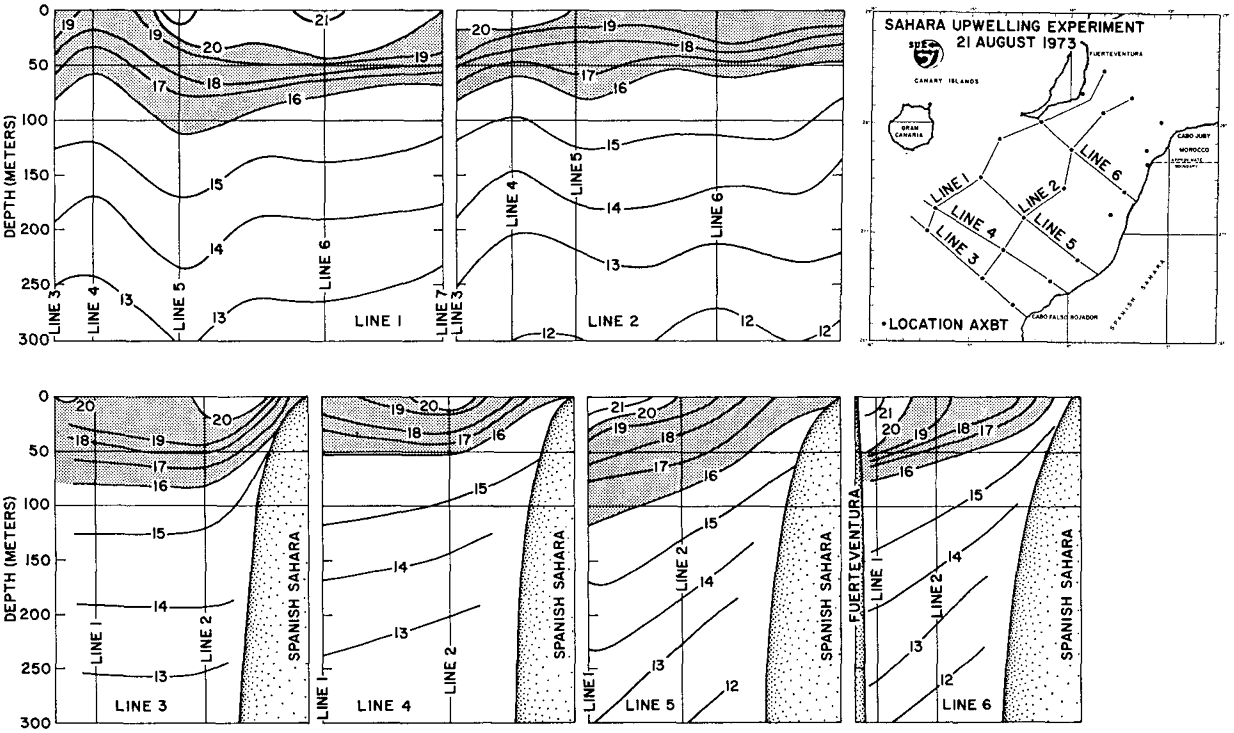

FIG. 7. Vertical temperature sections (°C) for 21 August 1973. These analyses were based on AXBT data.

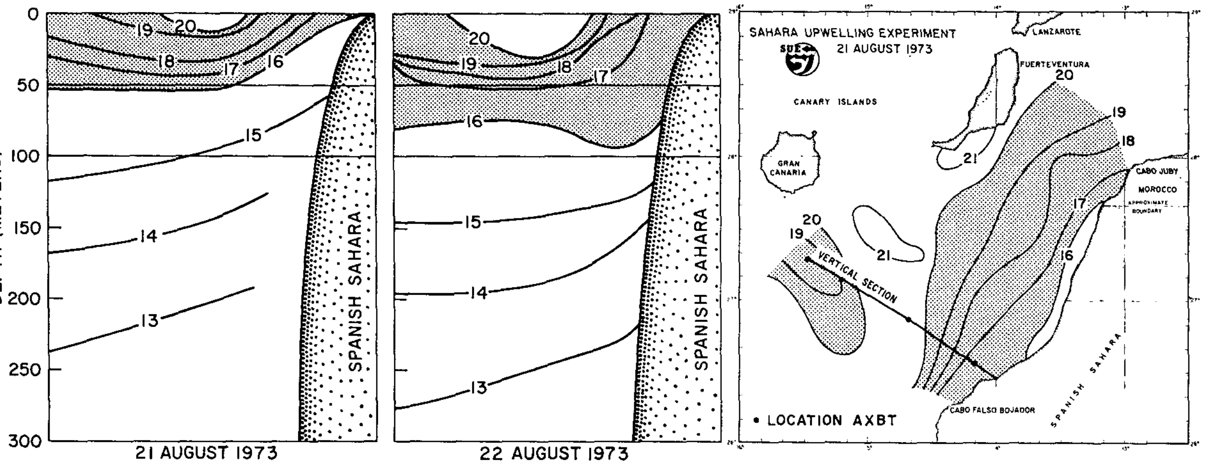

FIG. 8. Selected vertical temperature sections (°C) for 21 and 22 August, and ART surface temperatures for 21 August. These sections demonstrated that some sinking was occurring in the plume structure that extended from the coastal upwelling zone. The sections are analyses of data obtained from AXBT's that were dropped in the same locations on both days. The 21 August section is the same as line 4 in Fig. 7.

the up-welling along the coast of Spanish Sahara, as well as several associated thermal features.

Analyses of the aircraft and satellite radiation data show that these features consisted of variable cool and warm eddies which extended more than 100 km northwest from the coastal upwelling zone. The movement and general appearance of these features during the short period of the survey indicate that they may be a periodic occurrence.

Analyses of AXBT data show that a cool surface plume was part of a large subsurface structure which was probably sinking during that period of the survey when AXBT's were used (18–22 August).

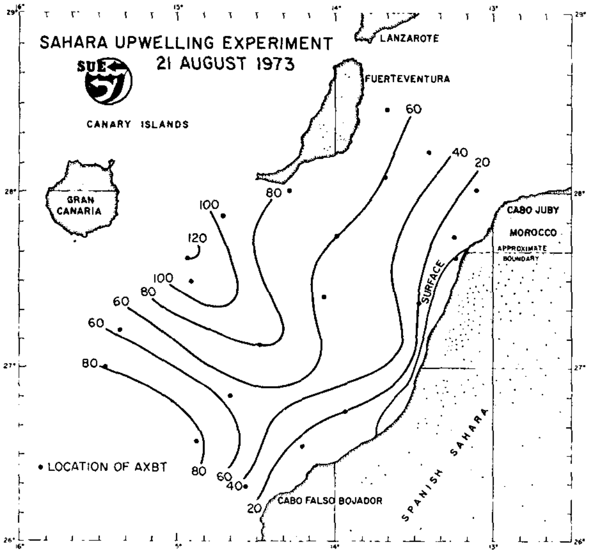

FIG. 9. Depth (m) of the 16C isotherm for 21 August 1973.

The warm eddies south of the island of Gran Canaria and Fuerteventura are well defined in the aircraft and satellite data. In one instance, a warm eddy is shown by AXBT data to have extended to a depth of more than 300 m. The satellite data analyses show these eddies resembled an oceanic wake which intruded into the general upwelling structure south of the Canary Islands.

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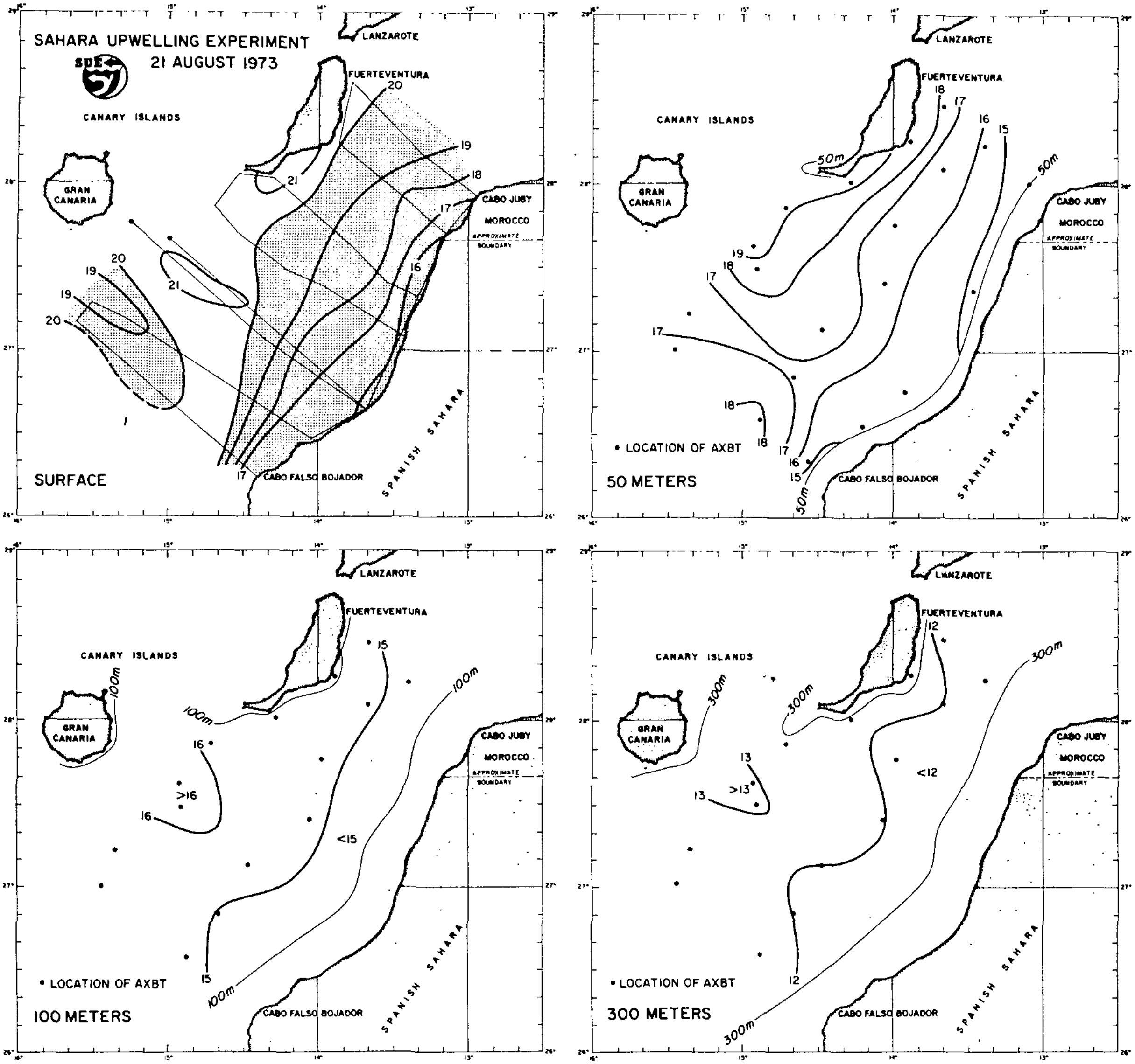

FIG. 10. Surface, 50-, 100- and 300-m temperature distributions for 21 August 1973. These analyses were based on ART and AXBT data.

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