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ABSTRACT

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*Invited paper presented during the 52nd American Geophysical Union meeting, 1971, Washington, D.C.

† On leave from the Faculty of Sciences, Marseille, as a National Academy of Sciences - NRC Post Doctoral Associate.

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UPWELLING STUDIES WITH SATELLITES

Many attempts have been made during the last years to determine sea surface temperatures from satellite altitudes (Allison and Kennedy, 1967, LaViolette and Chabot, 1968, 1969, Rao, 1968, Smith, Rao, Koeffler and Curtis, 1970, Warnecke, Allison, McMillin and Szekielda, 1971). However, cloud interference and the absorption of radiation by the atmosphere are still major problems. These two factors limit the use of radiation data for synoptic coverage of the ocean's surface temperature. Therefore, all interpretation of remotely sensed temperature measurements from satellite altitudes has to be done under a few restrictions.

If we measure the radiative sea surface temperature with an airborne radiometer, we have to keep in mind that only behavior of the topmost millimeter of the sea surface will be observed. About 15% of the incoming solar energy is absorbed in this layer and the energy exchange between the atmosphere and the water takes place only over a molecular boundary. In this thin layer, transfer of molecular heat and momentum, rather than eddy, is expected on a smooth ocean surface.

Another effect on the radiative temperature can be predicted from the presence of organic compounds at the surface, because this may change the thickness of the layer of molecular heat transfer. Furthermore, these compounds change the emissivity and may reduce evaporation at the surface. Since surface slicks of organic compounds produce a damping effect on short waves (Garrett and Bultman, 1963), the water would also become less turbulent. Assuming no absorption of the outgoing radiation by the atmosphere we may expect a different ΔT in the presence of organic compounds at the sea surface. If the thickness of the surface slick is monomolecular, then evaporation at the surface layer is reduced and the skin temperature should be very close to the bulk temperature. The influence of atmospheric components on the absorption of the outgoing radiation is well known from theoretical models (Kunde, 1965) and observations, but we don't know so much about the effects of organic surface active compounds on the radiation temperature of a water surface.

The order of magnitude of the influence of organic compounds on the radiation temperature during nighttime can be estimated from the results of an experiment shown in Fig. 1. Different amounts of paraffin oil were placed on a water surface, and the radiative temperature and the bulk temperature were measured. At the beginning of the experiment, a temperature difference of -0.4°C was found between the blackbody temperature and the bulk temperature. The experiment indicated that small amounts of oil on the surface produce a decrease in the difference between bulk and blackbody temperature. It showed the effect of reduced evaporation at the molecular boundary by the oil film. With increasing amounts of oil at the surface, the emissivity decreased and a higher deviation from the surface temperature was observed. In the oceans the concentration of organic compounds at the surface is so small that this would influence the radiation temperature by only a few tenths of a degree or maybe less. However, the accuracy of temperature measurements with recent technology is not better than ±0.5 to ±1.0°. The influence of slicks on the temperature remotely sensed from a satellite will therefore be disregarded in our discussion.

After these remarks, we can state that remote sensing of temperature from a satellite is a significant and accurate tool for investigations in upwelling areas where large horizontal temperature gradients appear. This is true especially for coastal upwelling, where horizontal temperature gradients are in the order of 5°/100 km.

Very detailed information about the upwelling system along the Somali Coast was obtained with three Nimbus satellites during 1966, 1969, and 1970. Upwelling appears along the NE Coast of Africa during the Southwest Monsoon in connection with the Somali Current. During its development the current velocity may exceed 300 $cm \cdot sec^{-1}$, and it is characterized by a strong sloping of the isotherms reaching the surface across the pass of the current. This sloping will be somewhat amplified by wind induced upwelling. Therefore, the discussion of horizontal distribution of isotherms in terms of the geostrophic flow has to be approached with caution.

Two temperature charts for the fully developed upwelling as obtained with the Nimbus 2 satellite are shown in Figure 2.

Upwelling water with minimum temperatures below 18°C is recognizable along the coast. This cold water is transported along the coast by prevailing currents. At about 10°N, the current leaves the coast and turns into an anticyclonic water movement (Bruce, 1968). The two analyses from 3 and 4 July evidently showed the same patterns and temperature gradients. However, a rapid temperature change in the center of the upwelling area was observed during one day. During several orbits separated patches of cold water were detected which are probably caused by change in wind speed and fluctuations in the current velocity. The presence of such separated patches in upwelling areas seems to be a frequent feature because it was also evident in temperature studies along the Northwest Coast of Africa.

The sharp temperature gradient along the coast was used to study the development of upwelling as a function of the prevailing winds (Düing and Szekielda, 1971). Temperature gradients extending from Ras Mabber in an easterly to southeasterly direction were determined over a distance of 150 km while wind data were extracted from the German weather maps. The results from 1966, obtained with the Nimbus 2 High Resolution Infrared Radiometer (HRIR), are given in Figure 3, together with wind data observed by ships in a 5° square bordered by the Somali Coast in the west, the island Socotra in the north and the adjacent region in the south of this island. Both parameters were normalized by dividing through the observed maximum values.

The runs for the 3rd-order polynominal fits were handled separately for the increasing and the decreasing branch. It is obvious that the temperature gradients are directly proportional to the wind speed rather than to the wind stress. It is quite possible that the normally assumed quadratic relationship between wind velocity and stress is not necessarily valid in an upwelling area, where cold water may stabilize the overlaying atmosphere and thus lead to a decrease in the wind stress.

The phase lag between the wind speed and the development of the temperature gradients is surprisingly short during the period from May to July. On the other hand during the decrease of wind speeds by the end of July, the wind speed lagged 14 to 40 days behind the temperature gradients. It is possible that when the wind speed decreases, the Somali Current is still strong enough to slope the isotherms, so that the observed surface gradients may only represent the geostrophic slope of the isotherms. Therefore, we can conclude that at the beginning of the upwelling, geostrophic slope and the wind induced upwelling produce the surface temperature gradients.

In connection with the upwelling along the Somali Coast, processes should be mentioned for obtaining qualitative information about upwelling in that area in realtime. The first process is the study of analog signals which can be obtained from the direct read out of an orbiting radiometer by simple Automatic Picture Transmission (APT) stations in the area of investigation. One example of analog recordings along the N.E. Coast of Africa from June 25, 1970 with the THIR during daytime is shown in Figure 4. It has to be remembered that the field of view of the scanning radiometer rotates through 360 degrees, and views in sequence the earth, the outer space, the housing, and the calibration target. All scan cycles showed clearly lower radiation along the coastline, especially in the center of upwelling. An increase of received energy indicates the warmer offshore water. The second decrease of out-going radiation from the sea surface is a result of limb darkening. The analysis of those data is very fast because one can store the direct read-out data on tape, and play them back on a strip chart recorder. However, some skill is necessary to apply and interpret the data. The second way of analyzing infrared data obtained with an APT station, using the color enhancement of infrared imageries is easier and was discussed by Szekielda and Mitchell (1971).

The investigations showed that temperature differences of 2°C can be observed with this method of analysis. These two methods will certainly be of minor importance for purely scientific purposes, but they can be of considerable use for the fisheries, because of rapid determination of the presence and intensity of upwelling and sharp temperature gradients.

The satellite studies along the Northeast Coast of Africa revealed that separated areas with cold temperatures are present in the area of upwelling.

Similar cold patches were observed aboard the R.V. "Meteor" along the Northwest Coast of Africa (Tomczak*). These separated cold water areas were about 6 miles in diameter with a temperature difference of 5°C between the center of the cold water and the surrounding area. In several studies we tried to determine whether these patches are real, or just an effect produced by the nonsynoptic ship observations along the Northwest Coast of Africa.

During one pass of Nimbus 4 over the Northwest Coast of Africa in April 1971, extremely cloud-free conditions appeared. The photographs taken with the Image Dissector Camera System and the infrared imagery were color enhanced to locate clouds and to analyse the temperature patterns. The color enhanced infrared imagery is given in Figure 5.

The Northwest Coast of Africa, the Canary Islands and the Cape Verde Islands appear black, while the cold water appears light green and blue. It is obvious that a pronounced meandering of the current boundary was observed. An indication of the presence of separated cold zones is given by the light blue, because the television picture showed cloud-free conditions where the meandering and the cooler separated zones appeared. However, the absence of clouds over the upwelling areas is an anomaly rather than a common feature and more specific tests for the absence of clouds must be used to obtain accurate measurements of radiation from the sea surface. One such test is the use of measurements in different spectral regions to determine whether or not the field of view of the radiometer is cloud-contaminated. Shenk and Salomonson (1971) developed a technique which uses the medium resolution infrared radiometer with different

*Personal communication

channels for the discrimination of clouds and high moisture content in the atmosphere. Measurements between 0.2 and 4.0 μm indicate the presence of low clouds, and the channels at 6.4 to 6.9 μm, and 20 to 23 μm, respond to the moisture content of the lower and the higher troposphere respectively. The establishment of thresholds for these channels allows measurements in the window channel at 10 to 11 μm if cloud-free conditions appear.

An example using this three-channel multispectral method along the Southern Coast of Africa is shown in Figure 6. The temperature distribution along the Southeast Coast of Africa is a result of the Agulhas Current which is a part of the large scale circulation in the Southern Indian Ocean. After reaching the East Coast of Africa, the south equatorial current is deflected and flows partly between Madagascar and the continent, and partly east of Madagascar, in a southwest direction. Both parts of this current then feed into the Agulhas Current. Because water is transported from low to high latitudes, the Agulhas Current can be recognized by its temperature distribution. In this analysis the 286°-isotherm reflects the position of the Agulhas Current after it leaves the Coast. The resulting tongue of warm water is a permanent feature. However, the position of its southern end moves as a function of the trade wind belt.

Our analysis from May/June 1966 showed evidently that during this period of the year little or none of the warm water from the Agulhas Current is surrounding the Cape of Good Hope.

At 34°S, where the Agulhas Current leaves the Coast, upwelling appears and is visible in the radiation data analysis. The Benguela Current flowing along the Southwest Coast of Africa is only a weak current, but is important for biological productivity because of very intense upwelling along the Coast (Duncan and Nell, 1969). The cause of the upwelling is certainly the action of the prevailing southerly winds. The satellite study in this area showed the lowest temperatures in connection with the Benguela Current to be at about 32°S, and the area of upwelling to be between the Cape of Good Hope and 30°S.

We have to remember that the ground resolution of the radiometer used was only 30 miles (Goddard Space Flight Center, 1966). Therefore all temperature gradients are smoothed out somewhat. However, future sensors with higher ground resolution will provide much more detailed information about temperature gradients.

A detailed analysis of upwelling along the Southwest Coast of Africa was obtained with the Nimbus 4 THIR during 1970. One example of color enhanced infrared imagery is presented in Fig. 7. It shows the Southwest African Coast between 36°S and 30°S, during a cloud-free period. The indicated patches are a real discontinuity. Three separate upwelling areas were detected in the area of the Benguela Current. Their presence is indicated by the lighter blue. In an offshore direction we again find warmer water, whose temperature is about 5 degrees above that of the coastal water.

From all investigations we can conclude that separate patches of water masses with a different temperature are very commonly in upwelling regions. The behavior of such water masses in a current system are hard to detect with conventional methods aboard research vessels.

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FIGURE CAPTIONS

Figure 1. Influence of an oil film onto the radiation temperature during nighttime.

Figure 2. Temperature distribution along the Somali Coast as recorded with the Nimbus 2 High Resolution Infrared Radiometer during 3 and 4 July 1966.

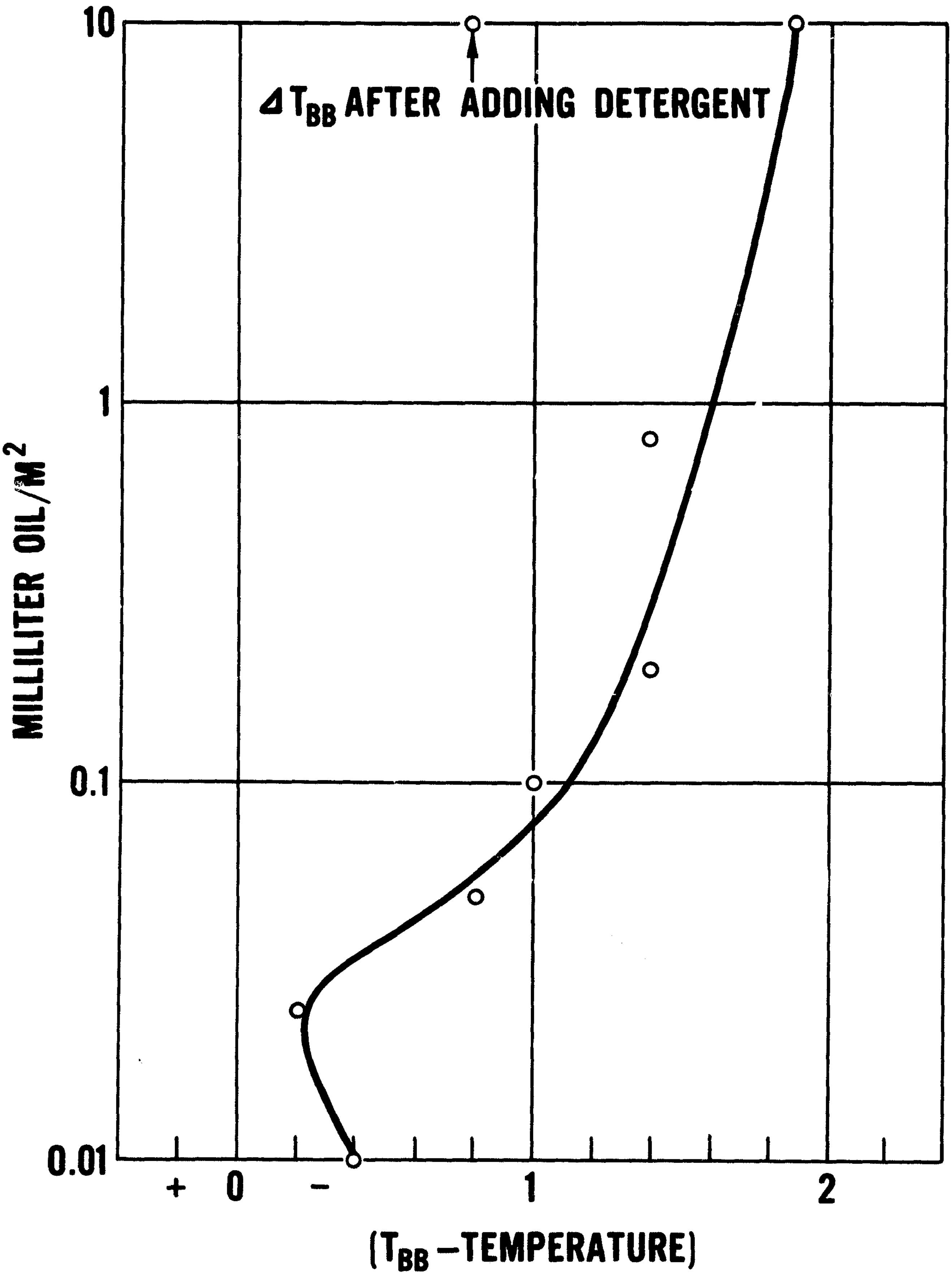
Figure 3. Development of temperature gradients along the Somali Coast as detected with Nimbus 2 High Resolution Infrared Radiometer and wind speed reported by ships.

Figure 4. Analog recordings of the energy obtained aboard the Nimbus 4 satellite along the Somali Coast in the upwelling areas. The three scan cycles show the calibration steps, the outer space and the earth observations. The co-ordinates represent the energy obtained at the radiometer, and the time. The arrows indicate the shoreline between the continent and the adjacent sea.

Figure 5. Color enhanced infrared imagery along the Northwest Coast of Africa as obtained with Nimbus 4 Temperature Humidity Infrared Radiometer in April 1970.

Figure 6. Temperature distribution along the Southern Coasts of Africa. Data are in K and not corrected for the atmospheric influence.

Figure 7. Color enhanced infrared imagery obtained with Nimbus 4 Temperature Humidity Infrared Radiometer (THIR) from the Southwest Coast of Africa.



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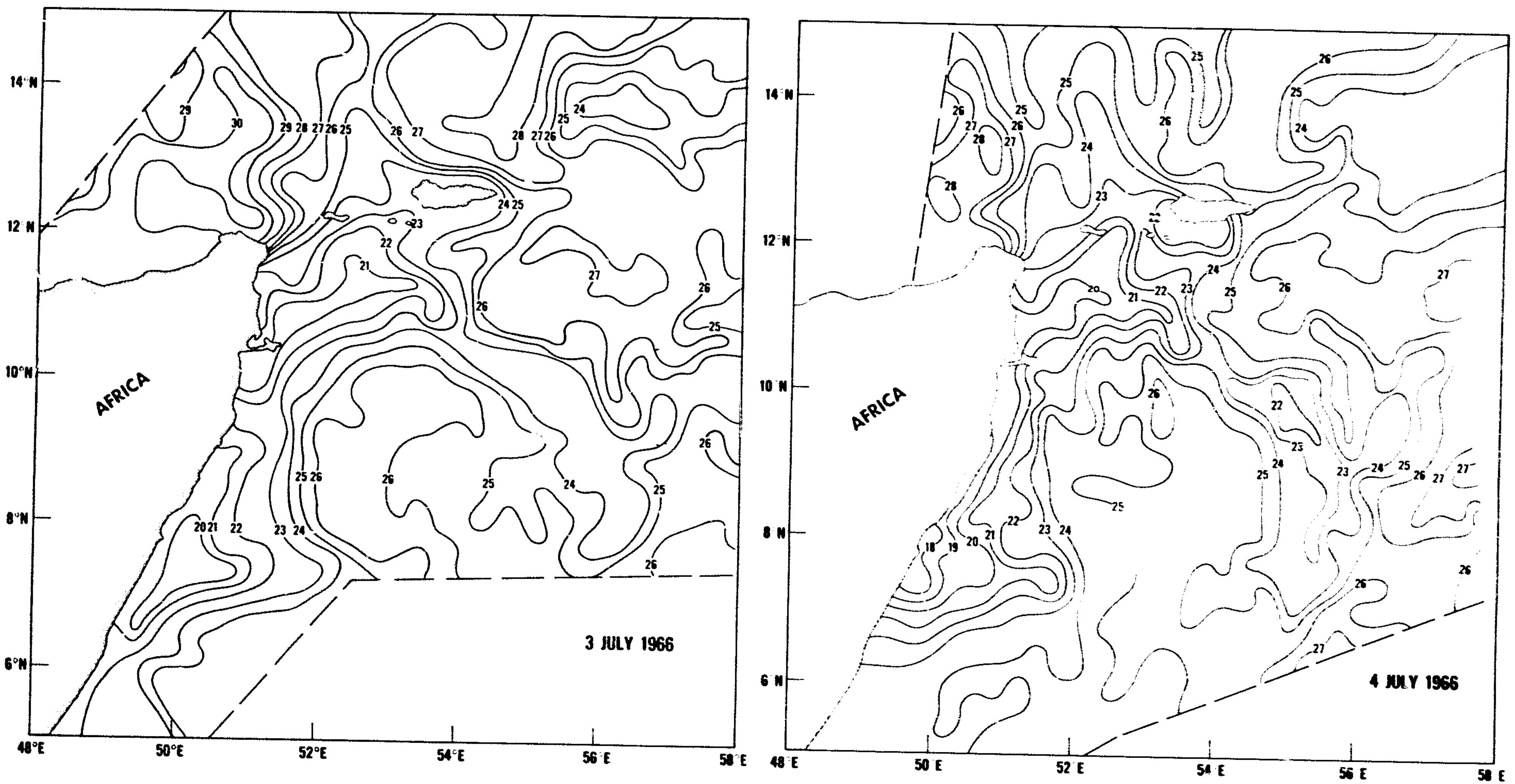

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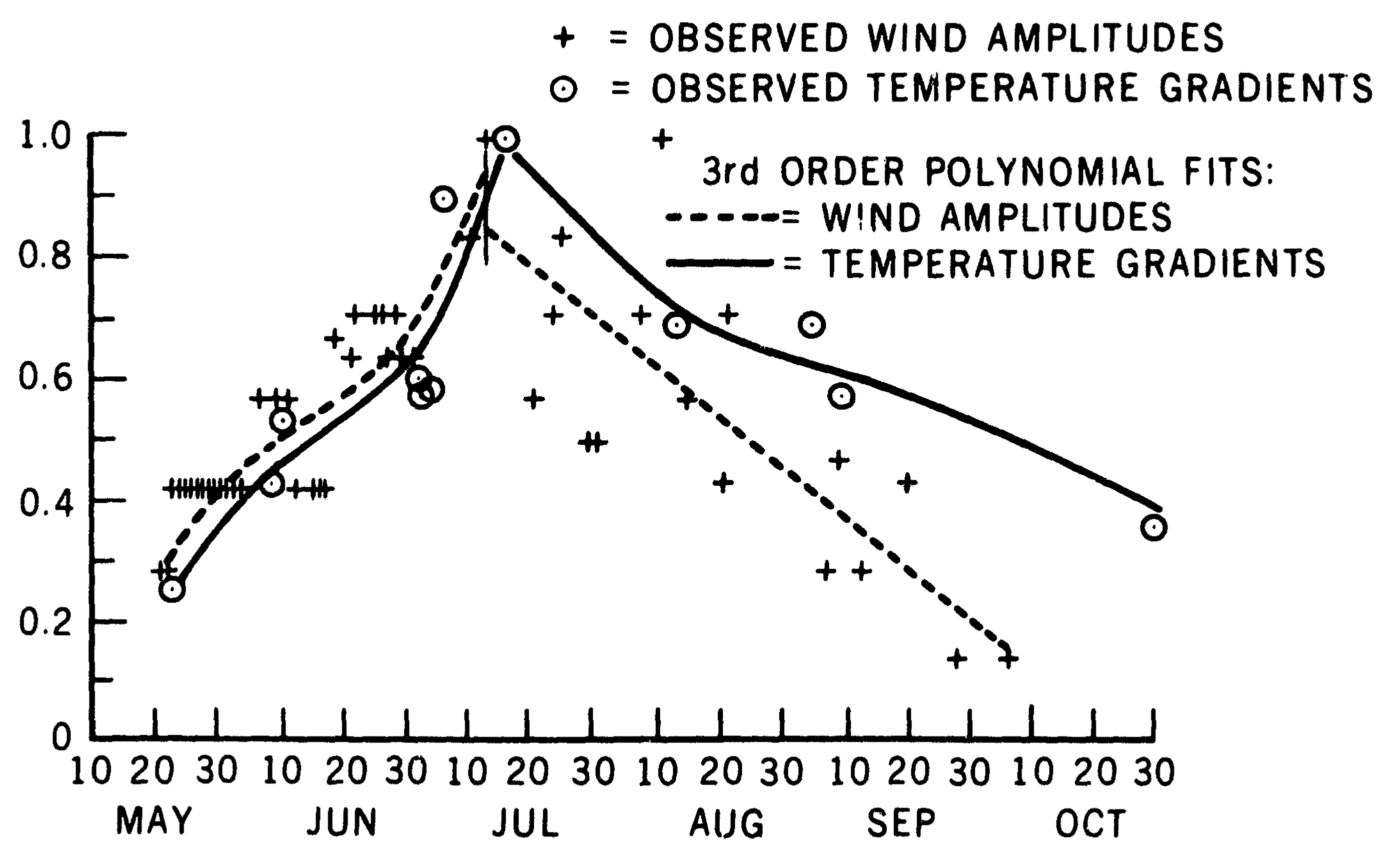

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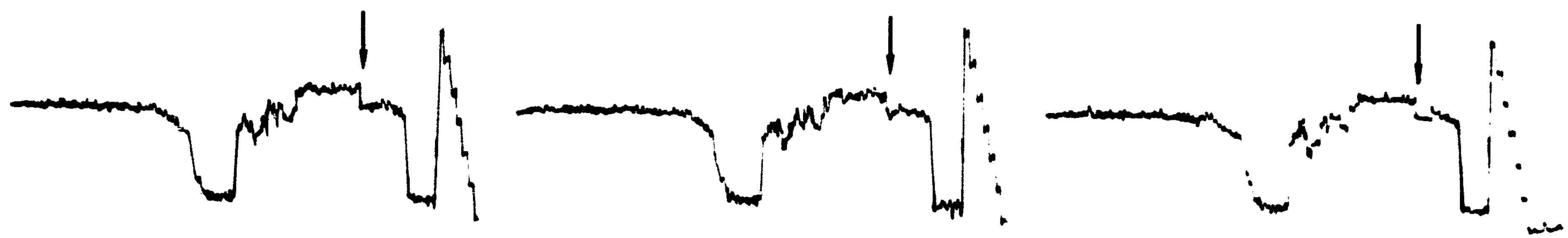

NIMBUS IV DAYTIME THIR 25 JUNE 1970

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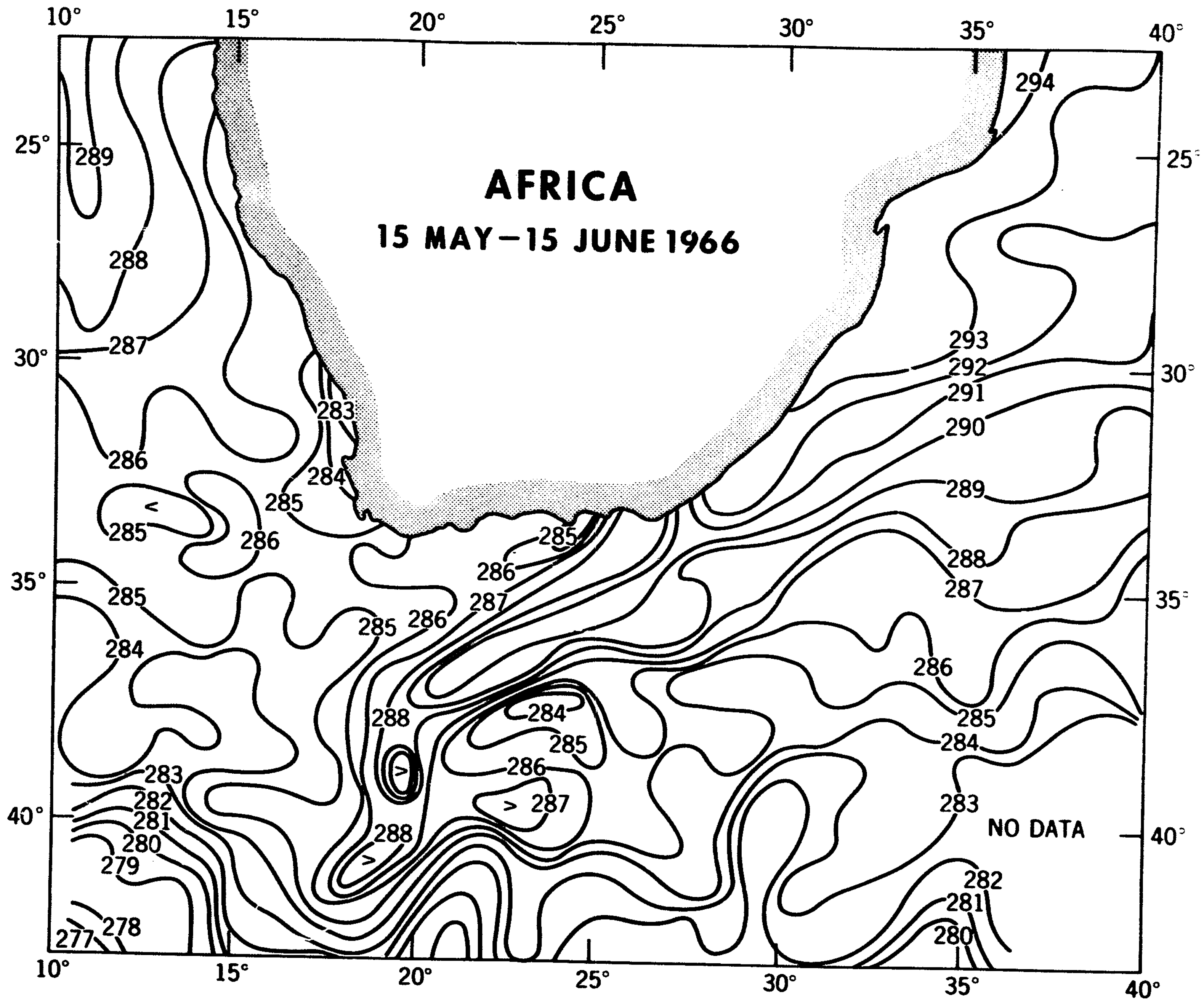

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