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25. We thank H. Craig and K. Turekian for helpful discussions, and R. Protsch and R. Berger for providing the Lukenya Hill samples and for the radiocarbon dating of the Muleta Cave bones. We also thank L. Deems for technical assistance. Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, and to the L. S. B. Leakey Foundation for support of this research. Collection of the Muleta Cave bones was funded by National Geographic Society. R.A.S. is a Scripps Industrial Associates predoctoral fellow.

14 June 1973

Ocean Current Monitoring Employing a New Satellite Sensing Technique

Abstract. *The very-high-resolution radiometer on the NOAA-2 (National Oceanic and Atmospheric Administration) satellite has recently obtained imagery in the visible channel containing sunglint over a major portion of the coastal waters off the eastern seaboard of the United States. An abrupt change in surface roughness has been observed at the shoreward edge of the Gulf Stream Current from Florida to Cape Hatteras that results from the opposition of waves propagating against the flow of the Gulf Stream.*

The Gulf Stream has been observed by satellite radiometers under relatively cloud-free conditions since 1966 (*1*). In virtually every case the differentiating signature of this current has been a thermal boundary measured in one of the thermal infrared (IR) water-vapor windows (that is, at wavelengths near 4 or 11 μm). The NOAA-2 (National Oceanic and Atmospheric Administration) environmental satellite obtains global imagery operationally from a scanning radiometer (SR) sensitive in both the visible and IR wavelengths. A very-high-resolution radiometer (VHRR) being developed by NOAA for future operational use is also carried on NOAA-2 (*2*). From the satellite's near-polar, sun-synchronous orbit, the VHRR provides limited coverage of the earth in the IR region with a 1-km resolution; observation times are during daylight at about 0900 local time and at night at about 2100 local time. During daylight, visible imagery with a resolution of 1 km is also provided. The visible and IR detectors are sensitive at 0.6 to 0.7 μm and 10.5 to 12.5 μm, respectively. The VHRR-IR imagery is particularly useful in coastal areas where fine detail is needed to define coastal surface temperatures.

On 29 April 1973, the NOAA-2 satellite obtained imagery of the eastern seaboard of the United States. The simultaneous visible and IR VHRR images are shown in Fig. 1. The IR display (Fig. 1B) shows the relatively cold clouds and land surfaces as light areas (less radiant energy reaches the radiometer) and the warmer regions, such as the Gulf Stream (temperature about 25°C), as darker areas. Landward of the thermal front of this current, the cooler coastal water (about 18°C) contrasts with the warmer land of the southeastern and mid-Atlantic states.

What is truly remarkable, however, is that it is also possible to locate this current boundary in the adjoining visible image (Fig. 1A). The entire front of the Gulf Stream from Florida to Cape Hatteras is delineated by a roughness contrast, highlighted by the solar reflection. Contrasting reflectances have been observed in satellite photography in the past but over very limited areas. For example, it has been shown that anomalous dark patches are indicative of calm surface conditions where short-wavelength capillary waves are absent (*3*). These conditions prevail beneath high pressure ridges and occasionally in conjunction with upwelling. Attempts have been made to relate the size and intensity of the sunglint pattern to surface wind speed (*4, 5*). Under more extreme conditions, brightness contrasts have been observed where local winds are quite strong. This phenomenon results when winds that originate overland, where topography channels the flow offshore, cause rough and choppy seas. Such conditions are well known along the Pacific Ocean shores of Mexico and Central America (for example, the Gulf of Tehuantepec) (*6*).

Scanning radiometer images of sunglint are much different from those obtained by satellite cameras (*7*). The vidicon cameras on the earlier weather satellites obtained approximately 12 essentially instantaneous pictures along the sunlit portion of each pass. In about nine of these photographs, wherever cloud cover permitted and a water surface was being viewed, one nearly circular sunglint would appear at the specular point. On NOAA satellites presently in use a SR obtains data as it scans from left to right through the nadir. An image is built up scan line by scan line in a fashion analogous to that used to generate a television picture. The geometry of the scanning mode of the SR and VHRR and the near-polar orbit of NOAA-2, which moves across the Northern Hemisphere toward the south-southwest during the morning hours, causes the radiometer to "look" in the general direction of the sun over a long segment of each track. Furthermore, the scanner has a greater dynamic range and sensitivity than the cameras of the earlier satellites. The result is that sunglint is detectable over a large region in the Northern Hemisphere during spring and summer. One must conclude that, for sunglint observations from satellites, the scanner has a decided advantage over the single photograph. If we assume that a uniform ocean roughness is caused by wind with a velocity of 10 knots (5 m sec^{-1}) (*4*), a 3 percent or greater reflectance of solar energy (ratio of reflected to incident energy at the surface) would be observed by the NOAA-2 VHRR from an orbital altitude of 1480 km. This area of high reflectance extends over approximately 30 deg of latitude along the nearly north-south image swath (*7*). Cameras on earlier weather satellites photographed this reflectance over less than 5 deg of latitude. As a consequence of the larger contiguous area of sunglint observable and the greater dynamic range of the visible wavelength sensor, a more rigorous analysis can be carried out for that portion of the ocean where roughness variability alters the sunglint pattern.

The surface observations available from ships in the immediate area off the southeast coast indicate that on 29 April 1973 the prevailing winds were northerly to northwesterly with speeds between 10 and 15 knots. Normally, these winds would be expected to produce waves with heights of about 1 m and occasional whitecaps. Over the Gulf Stream, where the wind stress opposes the current moving northward at several knots, a much rougher surface is produced by these winds. This adverse wave condition has been noted in many places (*8*) and is frequently observed by shipboard personnel when crossing the Gulf Stream "wall." The satellites have provided the first opportunity to observe this phenomenon over such a broad area. As these waves, moving southward and eastward with the wind, encounter the northward flow of the Gulf Stream, they are transformed into higher waves with shorter wavelengths and more whitecaps. Although the wave period remains essentially unchanged, the greatly increased roughness (root-mean-square sea slope) increases the diffusion of the sunglint (*5*), thus providing a contrast to the greater reflectance of the smoother inshore waters.

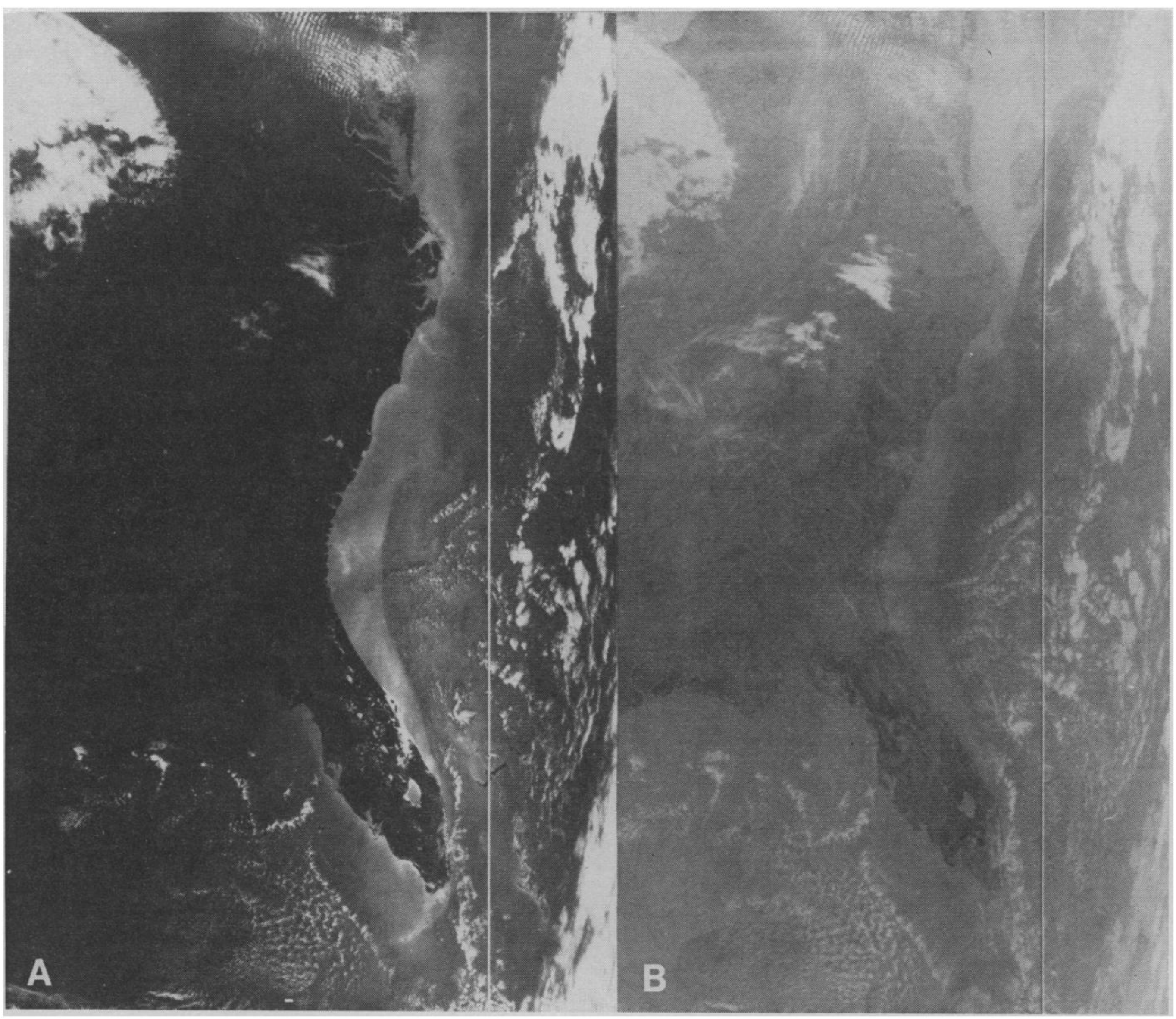

Fig. 1. Very-high-resolution radiometer imagery from NOAA-2 satellite on 29 April 1973 at about 1500 G.M.T. (A) Visible spectrum image; (B) simultaneous thermal IR image. (The white, north-south line is a synchronization line embedded in the image.)

Several other features can be seen in Fig. 1:

1) The greater reflectance along the fetch-limited northern shore of Lake Okeechobee and along the southwestern coast of Florida is indicative of calmer water in those areas. Since northerly winds prevail there, the glitter intensity is highly correlated with fetch.

2) A frequently observed "elbow" appears in the Gulf Stream front off the Charleston, South Carolina (Cape Romain), region (*9*).

3) Scattered cumulus clouds dot the ocean east of the Gulf Stream front; here, because the sea-air temperature differences are greater than those that prevail over the cooler coastal waters, convective activity in the lower atmosphere is stimulated.

Although it is probably of minor significance, the greater atmospheric instability near the sea-air interface over the warmer Gulf Stream (air = 20°C; water = 25°C) is also conducive to greater transport of momentum to the water surface and therefore contributes to increased roughness (*10*).

Another example of this phenomenon was observed on 27 March 1973, in the NOAA-2 VHRR visible image of Fig. 2. Sunglint reveals the lower portion of the Loop Current in the Gulf of Mexico. The current is streaming north out of the Straits of Yucatan into the Gulf of Mexico. Cuba can be seen to the east of this current in the lower right section of the image. Little thermal contrast (less than 4°C) is usually associated with this current. The density difference and, hence, the geostrophic transport is primarily a function of salinity. In this case, 10-knot northerly winds again provided wind stress and wave propagation opposing the northward transport of the Loop Current. The exciting observation in Fig. 2 is the capability of sensing surface currents remotely, regardless of thermal contrast.

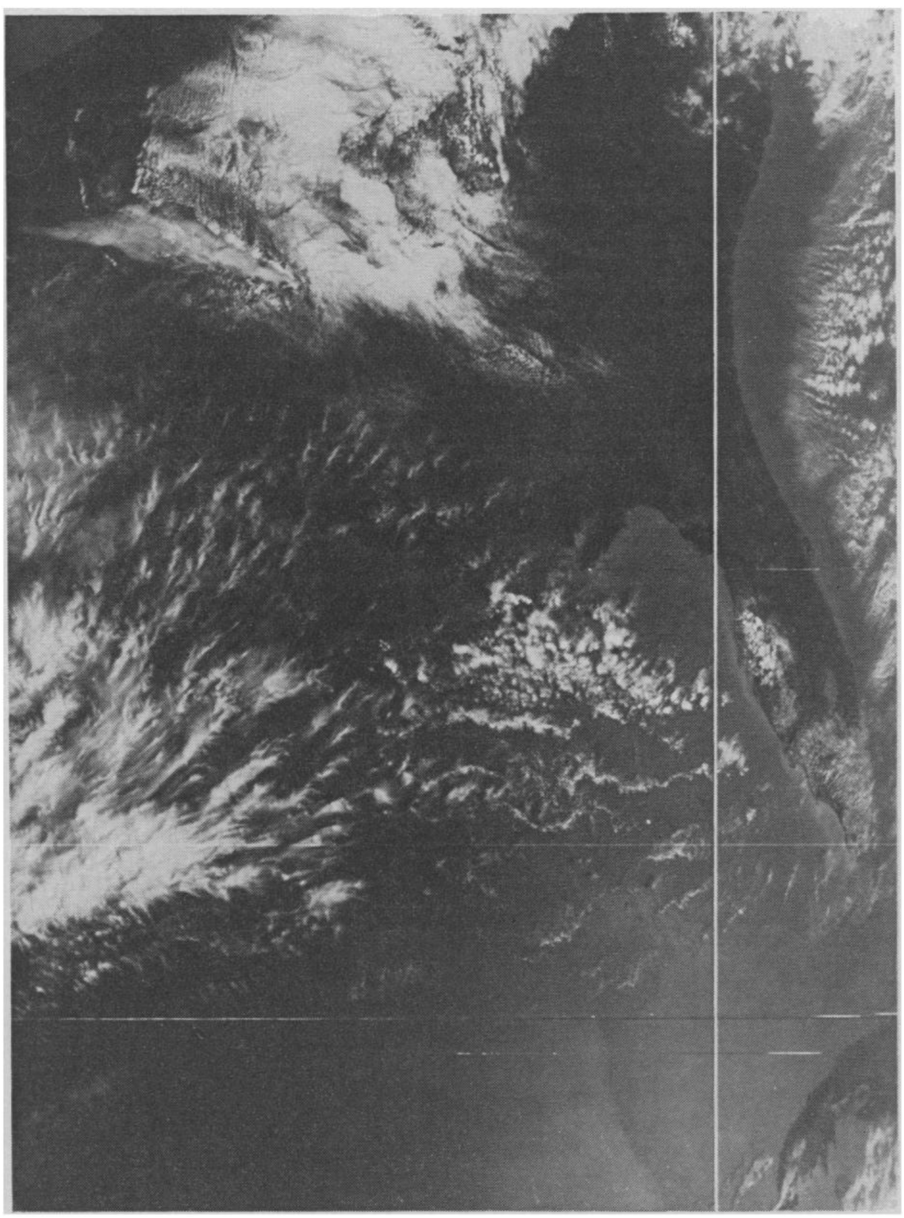

Fig. 2. Very-high-resolution radiometer visible spectrum image from NOAA-2 satellite on 27 March 1973 at about 1600 G.M.T. Cuba and Florida may be seen along the right edge of the image. The Loop Current varies the sunglint to the west of Cuba as this current flows northward into the Gulf of Mexico.

For the first time, major ocean currents have been delineated by means of sunglint variability. One satellite image has confirmed what mariners have known for centuries: the Gulf Stream has atypical waves. The large areas of glitter that often appear in VHRR imagery off the eastern coast of the United States during the 2-month periods preceding and following the summer solstice will assist in the study of ocean surface phenomena.

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2 July 1973