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REMOTE SENSING OF OCEAN CURRENTS

George A. Maul
National Oceanic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratories
15 Rickenbacker Causeway
Miami, Florida 33149

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Fiscal Report to Accompany Type II Report for Period 11/4/72 – 5/4/73

ERTS Proposal No. 108

Remote Sensing of Ocean Currents
George A. Maul, P.I., GSFCID-CO315

Ship Time:

December:	$ 3200
January:	3500
February:	3100
March:	3100
April/May:	3100
	$16000

Supplies: $3900

Travel: 1400

Support: 2500
                $7800

$23800 – TOTAL

1

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16. Abstract

Monthly field experiments in support of the NOAA investigation of ocean color boundary determination using ERTS data have been conducted since June 1972. The boundary between coastal waters and the Loop Current has been detected by ERTS as a result of sea-state changes as well as color differences. Ocean information is contained in all 24 channels of the Bendix MSS flown on the C-130 in June 1972; this includes UV, visible, reflected IR and emitted IR. Computer enhancement of MSS data are revealing many features not shown in the NDPF product.

17. Key Words (Selected by Author(s)) Detection of the color boundary layer	18. Distribution Statement

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Figure 2. Technical Report Standard Title Page

PREFACE

The objective of this investigation is to locate ocean current boundaries by sensing the color change associated with the cyclonic edge of the zone of maximum horizontal velocity shear. The test site is the eastern Gulf of Mexico where the strongly baroclinic flow from the Yucatan Straits forms into the Loop Current. The research is using ERTS' data in the investigation of ocean color sensing.

A time series of the location of the Loop Current was begun in August 1972. For every other transit of ERTS (i.e., 36 days) the current is located by ship. These data are being used to provide surface measurements in support of the spacecraft observations and to obtain the first time history of the circulation in the eastern Gulf of Mexico.

Further time histories of the variables which allow the use of ocean color as a current detection phenomenon are being made. These research cruises should be continued for at least one year in order to understand the seasonal variability associated with the circulation and detection of the circulation's surface indicators.

3

INTRODUCTION

This interim report covers the second six months of the ocean current detection project using ERTS data. Five field experiments have been conducted in support of the work, all of which are part of a continuing time history of the Loop Current. ERTS images which appear to show the current boundary do so because of either changes in sea-state or ocean color.

FIELD DATA COLLECTION

Ship-satellite experiments were performed in December, January, February, March, and April/May. A time-series of the Loop Current is being obtained by occupying the suborbital track of ERTS that passes into the Yucatan Straits every 36 days. The research vessel is on the suborbital track on the day of satellite transit collecting continuous chlorophyll-a, volume scattering, and radiometric temperature (in conjunction with the NOAA-2 IR sensors); hourly (15 km interval) expendable bathythermograph, surface bucket temperature and salinity samples are being obtained. During daylight, spectra of upwelling and downwelling radiance (400-800 nm) are being measured with $\frac{1}{4}$ meter Ebert scanning spectroradiometer. Upon reaching the Yucatan Straits a temperature/salinity/depth (STD) transect of nine stations is being made in order to determine the geostrophic current and transport fields. After the STD transect, the surface boundary of the Loop Current is being tracked using the same measurements outlined for the subsatellite track. A second STD transect of the Florida Straits from Key West to Havana is made in order to determine the discharge from the basin.

AIRCRAFT EXPERIMENTS

Digital and analog data taken by the Bendix 24 channel multispectral scanner have been received and are being studied. The CCTs can now be read on NOAA's UNIVAC 1108 here at AOML. The analog images supplied by NASA-JSC showed that information was reflected in all channels. In the visible channels these data are color information; in the near IR and UV the data appear to be sea-state (slick bands). The thermal IR

confirmed the ship measurements of a 1°C temperature change across the boundary. The thermal change was coincident with both the color change and the sea-state change.

Plots of the CCT data show a great deal of high frequency noise. The data are being formatted for Fourier Analysis, filter design, and replotting. Even from the unfiltered plots, the radiance levels on each side of the current boundary can be seen to be quite different. Quantification and image enhancement will be attempted after further filtering and frequency space analysis.

A flight aboard NOAA's C-130 was made to study the effect of sea-state on spectra. The data have been observed and are being analyzed to test the hypothesis that sea-state changes spectrally alter the reflection from the surface.
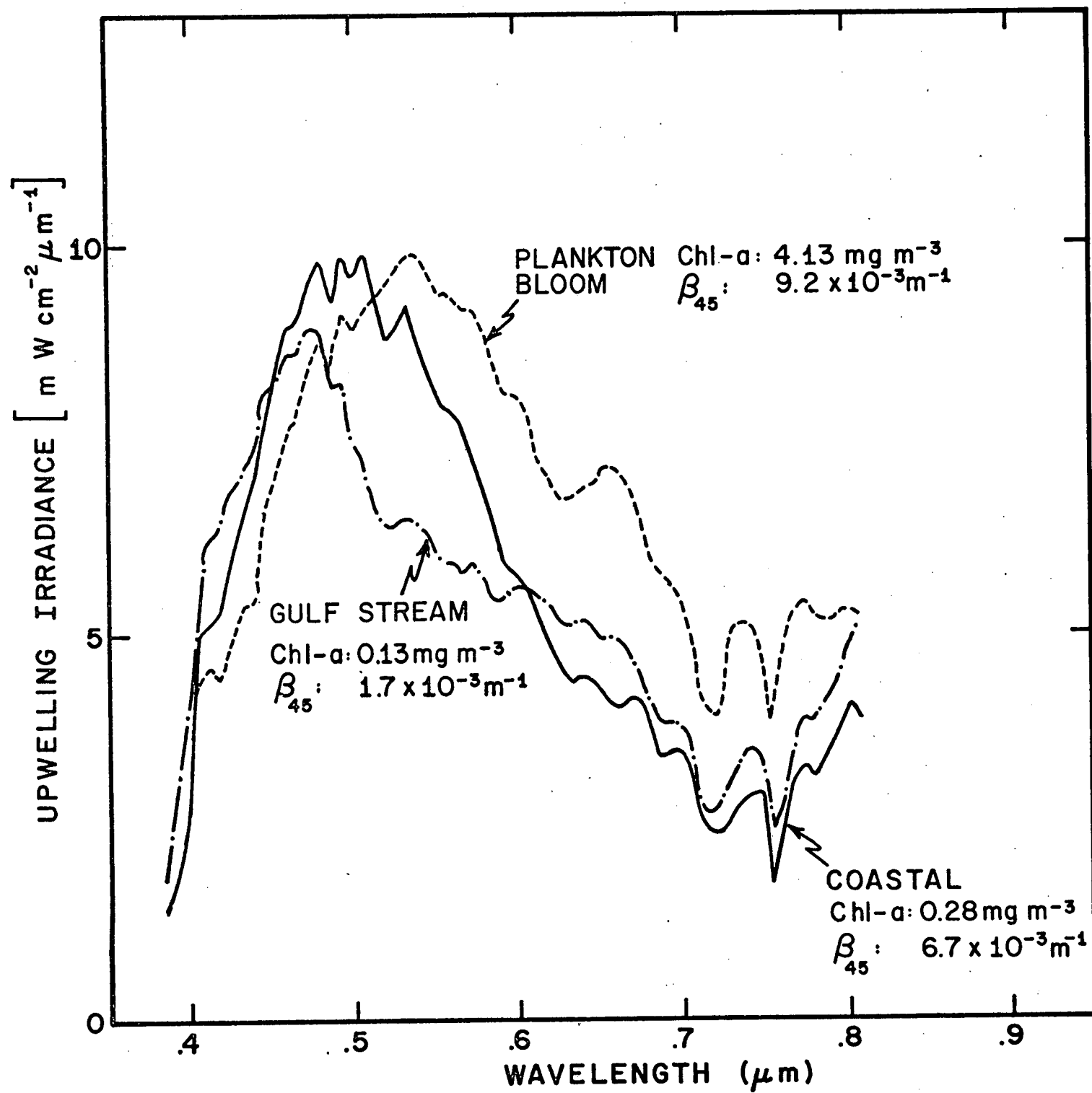
SHIP EXPERIMENT

Location of the Loop Current by ship has been proceeding routinely for ten months. The current was south of the latitude of Dry Tortugas until January, after which it has grown steadily in areal extent and northward penetration. The main body of the Loop Current has been observed to move more than 25 kilometers per day but it appears to be oscillatory rather than translational.

Three spectra, observed four meters above the water from shipboard, in water deeper than 100 meters, with similar environmental conditions and downwelling irradiance, have been taken and analyzed for the ratio of channels approach to chlorophyll-a analysis. From these data (see figure) the energy in MSS 4 and 5 has been been computed. The ratios (MSS 4/MSS 5) are:

Gulf Stream	1.5	(1.1)
Coastal Water	2.1	(0.45)
Plankton Bloom	1.4	(0.44)

Normalized differences [(MSS 4-MSS 5) ÷ MSS 4] are given in parenthesis after the ratios. Neither of these methods, and indeed several other similar manipulations, seem to give useful linear results with these Gulf of Mexico spectra. A theoretical and observational discussion of the nature of spectra was given at the March ERTS symposium (copy of paper attached). The spectra given in this report are in agreement

5

PLANKTON Chl-a: 4.13 mg m^{-3}
BLOOM β_{45}: 9.2×10^{-3}m^{-1}

GULF STREAM
Chl-a: 0.13 mg m^{-3}
β_{45}: 1.7×10^{-3}m^{-1}

COASTAL
Chl-a: 0.28 mg m^{-3}
β_{45}: 6.7×10^{-3}m^{-1}

UPWELLING IRRADIANCE [m W cm^{-2} μm^{-1}]

WAVELENGTH (μm)

with the discussion given at the symposium and are qualitatively
consistent with Monte Carlo calculations being made by H. R.
Gordon (co-investigator). Ratioing and normalized differencing
using MSS 4, 5, and 6 are capable of differentiating between
Gulf Stream waters and coastal waters (useful for ocean current
determination) but were not useful for isolating the plankton
bloom. These considerations do not include the atmospheric ef-
fects which will alter this conclusion somewhat. Further in-
vestigation, using these and many other spectra observed from
shipboard with simultaneous water samples, are being conducted
to explore the utility of multichannel correlations.

The time-series of the Loop Current was reported as oceanogra-
phic observations before the 54th Annual Meeting of the American
Geophysical Union (Trans. A.G.U., 54(4), 1973) in Washington
last April. It is felt that the cruise data extend well beyond
their primary purpose as ERTS ground truth.

ERTS DATA

Several scenes of ERTS data have been computer enhanced to bring
out the oceanographic information. Stretching by the gamma
function approach has been highly fruitful. The test scene was
the 16 August 1972 observation of the New York Bight. Many
features of the plume of the Hudson River are brought out as
well as several features not readily noticeable on the original
data. MSS 5 has been used most successfully because the signal
from the ocean is strong while the atmospheric scattering is
much less than in MSS 4. These techniques are going to be
further explored with the scientists at JPL's Image Processing
Laboratory. Some results of image processing will be reported
to the American Society of Photogrammetry at their annual
meeting in October 1973.

PROGRAM FOR NEXT REPORTING INTERVAL

Cruises every 36 days will continue as before. Biological
analyses continue to supplement the physical observations and
contribute to knowledge of the variations in the plankton and
how they may influence the ratio of scattering to absorbing
materials. Emphasis with CCTs will be placed on adopting pat-
tern recognition algorithms in selected cases. Spectral obser-
vations with bottom reflection will be made for Monte Carlo
comparisons.

7

CONCLUSIONS

The spectral measurements and the computer enhancements are proving to be the most important accomplishments during this reporting period. Much of the credit for these results belongs to R. Charnell, R. Qualset and J. Holmes who have been working with the data as well. Some of these results will be presented to the COSPAR Assembly on 25 May in Konstanz, F.R.G.

8

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
ATLANTIC OCEANOGRAPHIC AND METEOROLOGICAL LABORATORIES
PHYSICAL OCEANOGRAPHY LABORATORY
NASA/GSFC

CRUISE REPORT
R/V VIRGINIA KEY

26 April - 3 May 1973

I.   OBJECTIVES

The purpose of this cruise was to continue a time series
of the location of the Loop Current as part of AOML's
project with the Earth Resources Technology Satellite
(ERTS) and the NOAA-2 Meteorological Satellite. The re-
search is intended to obtain baseline information on the
spectroradiometric properties of the ocean's surface use-
ful for remote sensing and the detection of that informa-
tion at orbital altitudes.

II. SCHEDULE

Date	Time	Activity
April	DST	
26	0800	Depart Miami
27	0430	Commenced STD transect of Florida Straits
28	1600	Commence STD transect of Yucatan Straits
29	0800	Commence tracking current
	1000	Satellite Transit
May		
2	0100	Complete Survey
3	0600	Arrive Miami

9

III. STATION POSITIONS

The northern limit STD transect of the Florida Straits was at the 100-fathom curve south of Marquesa Key Light and terminated 13 n. mi. north of Havana Cuba. The station locations were:

24°21'N	82-14W	Station 1
24°11'N	82-16W	2
24°01'N	82-18W	3
23°51'N	82-21W	4
23°41'N	82-23W	5
23°31'N	82-26W	6
23°21'N	82-28W	7

The station locations for the Yucatan Straits STD transect were:

21°50'N	85 11'W	Station 8
21°48'N	85 21'W	9
21°46'N	85 32'W	10
21°44'N	85 42'W	11
21°42'N	85 53'W	12
21°40'N	86 03'W	13
21°38'N	86 13'W	14
21°36'N	86 24'W	15

The easternmost station was 12 n. mi. west of Cabo San Antonio; the westernmost station was 22 n. mi. northeast of Isla Contoy.

The cruise from Isla Contoy to Dry Tortugas was a saw-toothed path, which crossed the surface boundary layer zone of the current.

IV. PERSONNEL

George Maul, Chief Scientist	NOAA/AOML
Michael Ednoff	FSU
Gary Dingle	NOAA/AOML

V. DESCRIPTION OF OPERATIONS

Data collection commenced with a STD transect of the Florida Straits. After coasting from Havana to Cabo San

Antonio a STD transect of Yucatan Straits was taken. Continuous flow measurements of chlorophyll-a and continuous radiometric sea surface temperature were recorded on a dual channel recorder. While on the track, hourly XBT's surface bucket temperature, surface salinity, and measurements of scattering ratios were taken. Spectra of upwelling and downwelling visible radiation were not observed due to seas. Loran A fixes were made at one hour intervals and at major course, and/or speed changes. One liter samples were filtered for a spectrophotometer calibration of chlorophyll-a every six hours and at major changes in the fluorescence, and for biological samples.

Station 7 was made further offshore of Havana than originally planned due to the presence of a Cuban gunboat. The vessel circled the VIRGINIA KEY while on station and then motored off. At approximately 2100 DST on the 27th the same vessel crossed our bow and shined a searchlight onto the bridge forcing Capt. Hood to stop. After she drifted across our bow and was clear, the VIRGINIA KEY proceeded on her way to station and without further incidence.

The data collection was routine as described in these reports elsewhere. The R/V BELLOWS cooperatively obtained a XBT transect at 28°N across most of the eastern Gulf during this same period. No indication of the Loop was found along their section. A superb IR image of the area was obtained by the NOAA-2 VHRR on 30 April which showed the current boundary. Our tracklines of the 22°C isotherm at 100 meters and the IR image are in remarkable agreement considering the scales involved. ERTS data for this cruise has not arrived at this date.

IV. LOGS

Chief Scientist Log
Deck Log
Track Chart
Loran Log (C&GS 722)
Hydrographic Station Log
Bathythermograph Log

Submitted by: George A. Maul
May 17, 1973

11

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
ATLANTIC OCEANOGRAPHIC AND METEOROLOGICAL LABORATORIES
PHYSICAL OCEANOGRAPHY LABORATORY
NASA/GSFC

CRUISE REPORT
R/V VIRGINIA KEY

22-28 March
1973

I. OBJECTIVES

The purpose of this cruise was to continue a time series
of the location of the Loop Current as part of AOML's
project with the Earth Resources Technology Satellite
(ERTS) and the NOAA-2 Meteorological Satellite. The re-
search is intended to obtain baseline information on the
spectroradiometric properties of the ocean's surface
useful for remote sensing and the detection of that in-
formation at orbital altitudes.

II. SCHEDULE

Date	Time	Activity
March	EST	
22	0800	Depart Miami
23	0330	Commenced XBT transect of Florida Straits
24	0930	Commence XBT transect of Yucatan Straits
	1000	Satellite Transit
	1730	Commence tracking current
26	2200	Complete Survey
27	0900	Arrive Key West; fuel
	1100	Depart Key West
28	0030	Arrive Miami

III. STATION POSITIONS

The northern limit XBT transect of the Florida Straits was at the 100-fathom curve south of Marquesa Key Light and terminated 12 n. mi. north of Havana Cuba. The station locations were:

$24°21'N$	82-14W	Station 10
$24°11'N$	82-16W	11
$24°01'N$	82-18W	12
$23°51'N$	82-21W	13
$23°41'N$	82-23W	14
$23°31'N$	82-26W	15
$23°21'N$	82-28W	16

The station locations for the Yucatan Straits XBT transect were:

$21°50'N$	85 11'W	Station 1
$21°48'N$	85 21'W	2
$21°46'N$	85 32'W	3
$21°44'N$	85 42'W	4
$21°42'N$	85 53'W	5
$21°40'N$	86 03'W	6
$21°38'N$	86 13'W	7
$21°36'N$	86 24'W	8
$21°34'N$	86 34'W	9

The easternmost station was 12 n. mi. west of Cabo San Antonio; the westernmost station was 12 n. mi. east of Isla Contoy.

The cruise from Isla Contoy to Dry Tortugas was a saw-toothed path, which crossed the surface boundary layer zone of the current.

IV. PERSONNEL

George Maul, Chief Scientist	NOAA/AOML
Michael Ednoff	FSU
Gary Dingle	NOAA/AOML

V. DESCRIPTION OF OPERATIONS

Data collection commenced with a T-7 XBT transect of the

Florida Straits; the STD was non-operational. Continuous flow measurements of chlorophyll-a and continuous radiometric sea surface temperature were recorded on a dual channel recorder. While on the track, hourly XBT's, surface bucket temperature, surface salinity, and measurements of scattering ratios were taken. Spectra of upwelling and downwelling visible radiation were not observed. Loran A fixes were made at one hour intervals and at major course, and/or speed changes. One liter samples were filtered for a spectrophotometer calibration of chlorophyll-a every six hours and at major changes in the fluorescence, and for biological samples.

Better weather conditions and the improving laboratory and living spaces aboard the VIRGINIA KEY contributed to a most successful cruise. All observations scheduled were obtained in record time. The deeper penetration of the Loop Current into the Gulf of Mexico as "the spring intrusion" will require longer cruises in the coming months.

LCDR Jimmy Lyons came aboard as skipper on 24-hour notice due to G. Hood being ill; our grateful thanks and a well done to Jimmy for his enthusiasm and cooperation.

VI. LOGS

Chief Scientist Log
Deck Log
Track Chart
Loran Log (C&GS 722)
Hydrographic Station Log
Bathythermograph Log

Submitted by: George A. Maul
                April 4, 1973

14

REMOTE SENSING OF
CURRENTS USING ERTS IMAGERY

George A. Maul

National Oceanic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratories
Miami, Florida

ABSTRACT

Major ocean currents such as the Loop
Current in the eastern Gulf of Mexico have
surface manifestations which can be ex-
ploited for remote sensing. A time series
to study certain aspects of the surface
expression of this current was begun in
August 1972. Surface chlorophyll-a con-
centrations, which contribute to the shift
in color from blue to green in the open
sea, were found to have high spatial varia-
bility; significantly lower concentrations
were observed in the current. The cyclonic
edge of the current is an accumulation zone
which causes a peak in chlorophyll concen-
tration. The dynamics also cause surface
concentrations of algae, which have a high
reflectance in the near infrared. Com-
bining these observations gives rise to an
"edge effect" which can show up as a
bright lineation on multispectral imagery
delimiting the current's boundary under
certain environmental conditions. Frequent-
ly the sea-state in the current is higher
than in surrounding water due to differen-
tial shear. When high seas introduce
bubbles, white caps, and foam, the reflec-
tance is dominated by scattering rather
than absorption. This has been detected
in ERTS imagery and used for current
location.

15

INTRODUCTION

The major circulation feature of the Gulf of Mexico is the so-called Loop Current. This flow enters the basin as a well formed western-boundary current through the Yucatan Straits. It penetrates into the Gulf to a varying latitude before it exits through the Straits of Florida. Transporting vast amounts of heat, salt and momentum, the current significantly affects circulation on the shelf, local fisheries, marine transportation, and is thought to be associated with hurricane intensification.

The current boundary separates two water masses. Across the boundary there is a difference in temperature, salinity, color, velocity, and biomass. These surface manifestations can be used for remote sensing in our efforts to monitor the current's variability. However, surface temperature difference, one of the best indicators, is not usable in the subtropics due to summer insolation which makes the sea surface isothermal. Other surface features, such as ocean color and evidences of horizontal current shear, probably have less seasonal variability.

This paper is a preliminary report on a time series of observations across the surface boundary layer of the Loop Current, and its detection by remote sensing, using several aspects of the surface features. The research is designed to investigate the seasonal variability of the juxtaposed water masses, both temporally and spatially, and the detection by ERTS of their boundary.

FIELD EXPERIMENTS

The field work began in June 1972 with a ship/aircraft experiment designed to detect the color boundary of the Loop Current front south of Dry Tortugas. The NASA C-130 flew over the research vessel track which was oriented in the same azimuth as ERTS suborbital track. Seven altitudes were flown, at 100 mb decrements, over the ship. Aircraft data collection included RC-8 color and color IR photography as well as multispectral photography to simulate the ERTS MSS imagery, PRT-5 sea surface temperature profiles, Bendix 24 channel scanner data, and inflight recordings of atmospheric temperature, pressure and moisture.

Prior to the aircraft overflights the scientific crew aboard R/V BELLOWS located the boundary. Measurements of

16

ocean temperature, chlorophyll-a, volume scattering
function, and salinity were made every ten meters down
to 50 meters; Forel color, and upwelling and downwelling
spectral irradiance were taken at each of the five
stations that bracketed the front. During the over-
flights on the following day, closely spaced surface
measurements of the same variables (except irradiance)
were taken. All measurements were made using standard
oceanographic techniques or analyzed by methods detailed
by Strickland and Parsons (1968).

In August 1972 a time series of the Loop Current by ship
and satellite was begun. The cruise plan is to occupy
the suborbital track of ERTS that crosses the west
Florida shelf approximately 200 kilometers west of
Tampa and terminates in the center of the Yucatan
Straits. Every 36 days, the R/V VIRGINIA KEY is on the
suborbital track. Continuous surface observations of
radiometric temperature (in conjunction with the NOAA-2
IR sensors) and chlorophyll-a (by the fluorometric
method of Lorenzen, 1966) are made; at approximately 12
kilometer intervals XBT's are taken, and samples are
drawn for salinity, bulk temperature, volume scattering
function, and biomass analysis. At appropriate daylight
stations, measurements of upwelling and downwelling
spectral radiance are made using a 1/4 meter Ebert scan-
ning spectro-radiometer. A standard hydrographic sec-
tion of the Yucatan Straits is made in order to estimate
the geostrophic transport relative to 800 db. After the
section, the cyclonic edge of the current is tracked by
following the pathline of the 22° C isotherm at 100
meters; this pathline loops from the western edge of
Yucatan to the Florida Straits south of Dry Tortugas
and is in close proximity to the surface front. Finally
another hydrographic section is observed along the sub-
orbital track of ERTS that passes from Key West to
Havana.

It is planned to continue the cruises to collect one
year of data in order to obtain an evalutaion of the
seasonal variability. The final field experiment,
planned for the autumn, is a SKYLAB/EREP mission in-
volving a ship and an aircraft.

PRELIMINARY RESULTS

The cyclonic edge of the Loop Current tends to concen-
trate flotsam and jetsam. Natural materials, such as
surface marine algae, were seen from the June photo-

graphy to have a pinkish cast on color IR (SO 397) film; this is confirmed in black and white IR photography (type 2424 film and a 89B Wratten Filter). When these algae are present, they appear as a bright lineation marking the edge of the current in ERTS MSS-6 (0.7-0.8μm).

A second consequence of the boundary layer dynamics is to concentrate chlorophyll bearing organisms. A typical profile across the current boundary is given in figure 1. This transect is from Key West harbor, out the channel into the coastal water, and across the front. The feature of interest is the peak in chlorophyll-a concentration just at the boundary. This is a phenomenon noticed in each of the six cruises to date and occurs to a varying degree in the deep sea as well as near shore. Details of the variability will have to await further sampling because of expected seasonal and biological dependence. One would expect however that a shift towards the green would occur and enhance the boundary in MSS-4(0.5-0.6μm). This does indeed happen as will be discussed below.

A third observation is the usual change in sea state across the boundary. When winds and associated waves cross into zones of high current velocity with an opposing set, the seas generally build up rapidly. It is not uncommon for the sea state to increase from 1 to 2 meters when crossing into the current. Thus an increase of white caps, foam, and bubbles is encountered near the edge which increases the reflectance in the current. This raises the reflectance in all channels, but in a non-uniform (wavelength dependent) manner.

The term "edge effect" (Maul, 1972) was coined to describe these phenomena which can be exploited to detect the boundary of major ocean currents. Other streaming events, such as sediments being entrained by the Gulf Stream after passing source regions such as Cape Hatteras (ERTS 1132-15092), can be considered part of this edge effect. It allows a multispectral approach to recognize the boundary of these currents in the absence of sea surface temperature changes.

To understand the physics of reflection from the ocean, consider a simple model of an ocean of semi-infinite depth (Z) with spherical scattering. The spectral reflectance $R(Z,-)$ is defined as the ratio of the

upwelling irradiance $H(Z,+)$, i.e. that from the ocean, to the downwelling irradiance $H(Z,-)$, i.e. that from the sky and sun:

$$R(Z,-) \equiv \frac{H(Z,+)}{H(Z,-)}$$

The reflectance is tacitly assumed to be a function of wavelength. From scattering theory the reflectance at the sea surface $(Z=0)$ can be shown to be

$$R(0,-) = 1-H(\mu)\sqrt{1-\omega_0}$$

where ω_0 is the ratio of the scattering coefficient (b) to the attenuation coefficient (α), $H(\mu)$ is the so-called H-function for various scattering albedos (ω_0) as tabulated by Chandrasekhar (1960) and μ is the cosine of the zenith angle. It should be emphasized that this model does not include multiple scattering or the angular dependence of scattering such as the Monte Carlo calculations of Gordon and Brown (1973). Nevertheless it provides an analytic solution to the radiative transfer equation which illustrates the fundamental variables in reflectance.

An example of calculated reflectance from a plane water surface with the sun in the zenith $[H(\mu_0)]$ is given in figure 2. The curves are based on scattering and atten- uation coefficients given by Jerlov (1968) for natural ocean water bodies; α and b are chosen to exemplify the behavior of reflectance. Curve 1 is the spectral re- flectance for pure water. Curve 2 is generated by changing the attenuation coefficient due to an increased absorption coefficient $(a=\alpha-b)$ due to yellow substance. Note that the reflectance is lower and that the peak has shifted to a longer wavelength. Curve 3 is generated by increasing the scattering coefficient due to isotropic scatters whose b is twenty times the Rayleigh (molecu- lar) scattering at 450 nm.; only the magnitude of the scattering increases, in a wavelength dependent manner, with the peak invariant. Curve 4 combines the effects of absorption and scattering. The reflectance is lower than pure scattering and the wavelength of the peak is shifted to the green.

Curves 1 and 4 can be likened to the change in reflec- tance encountered when crossing an ocean front. An example of an observed reflectance pair is taken from

the June aircraft experiment and given in figure 3. These are uncorrected for the immersion effect and the reflectances are approximately 20% too high. The zenith angle was ~20° in each case. $H(Z,+)$ was measured 1 meter below the surface. The Loop Current water (marked 2) is lower in chlorophyll-a (< 0.1 mg m^{-3}) and lower in volume scattering coefficient ($\beta(45)=2.6 \times 10^{-3}$m^{-1}) than the coastal water (marked 4) with 0.4 mg m^{-3} chlorophyll-a and $\beta(45)=5.4 \times 10^{-3}$m^{-1}. If one assumes that the absorption coefficient is proportional to the chlorophyll-a concentration and the scattering coefficient is proportional to the volume scattering coefficient at 45° (Beardsley et al, 1970) then a qualitative confirmation of reflectance theory is given.

The curves further suggest that changes in ocean color will be reflected in MSS-4. Figures 4a and b are images from ERTS-1 taken over the eastern Gulf of Mexico during times of surface observations. Figure 4a is MSS-4 data showing the higher reflectance of water from Florida Bay pouring over the Keys and being entrained by the Gulf Stream. This image confirms the discussion in the previous paragraph.

Figure 4b is MSS-5 data taken north of the Yucatan Straits during a period of surface observations. The curving discontinuity in the water masses outlines the edge of the current. However, the blue waters of the current are brighter than the adjoining waters in contradiction to the results in figure 3. The explanation must come from figure 2, where we see the effect of increased scatterers. A marked increase in sea state was encountered in the current, which can account for a much higher scattering coefficient due to entrapped air.

An additional explanation of this is offered through consideration of sea state alone. Ross and Cardone (1972) observed that with 15 m s^{-1} winds, 10% of the surface of the sea is covered with white caps, and white caps reflect approximately 90%. If reflectance of the ocean is assumed to be 5% in the absence of white caps and 10% of the sea is covered with white caps, then reflectance is $R=5\%(.9) + 10\%(.9)=13.5\%$ or 270% higher than without white caps.

The spectrum of total upwelling irradiance from above the ocean $H_T(0,+) = [R(0,-) + R_s]H(0,-)$ where R_s is the

reflectance of the surface (both diffuse and direct). For the case R_s = constant and a given $H(0,-)$, H_T depends on ω_0. From figure 2 we estimate that the ratio of $R(0,-)$ at 450 nm to that at 525 nm for pure water is ~ 4.5 (curve 1). The same ratio with scatterers only in the water (curve 3) is 2.0. Quantitative confirmation with realistic scattering phase functions will have to be calculated using the Monte Carlo code. Theoretically, the signal of a differential radiometer (Arvesen, 1972) is subject to such variation in ω_0. If it is fortuitous that ω_0 always varies in the ocean such that $R(0,-)_{523}$ is constant (Duntley, 1972), then a dual channel intrument will work in the absence of sea state changes.

The solar spectrum is fairly flat in the visible region $(H(0,-)_{450}/H(0,-)_{700} \sim 1.3)$. Hence, higher sea states, which reflect high percentages of white light, proportionally add more long wavelength energy to the upwelling irradiance. In terms of a chromaticity diagram, this means that the purity changes but not the dominant wavelength. To correct for sea state a channel in a multispectral scanner near 1 μm appears useful. At this wavelength there is a maximum in the attenuation coefficient of pure water (i.e. $\omega_0 \to 0$), a maximum in atmospheric transmissivity, and the influence of chlorophyll seems low.

CONCLUSIONS

ERTS imagery has been successful in providing information on the ocean in both the nearshore and deep sea environment. As the result of an edge effect the cyclonic side of the Gulf Stream can reflect in several ERTS bands as a prominent feature paralleling the current's edge. It is found however that sea state is a significant variable that can dominate the reflectance and change the spectral signature of surface waters. The prospect is therefore raised that passive remote sensing using ERTS may be used to quantitatively estimate sea state and near surface winds in areas of homogeneous water masses. Further, the sea state problem must be considered a dominant variable in the determination of ocean color from aerospace sensors.

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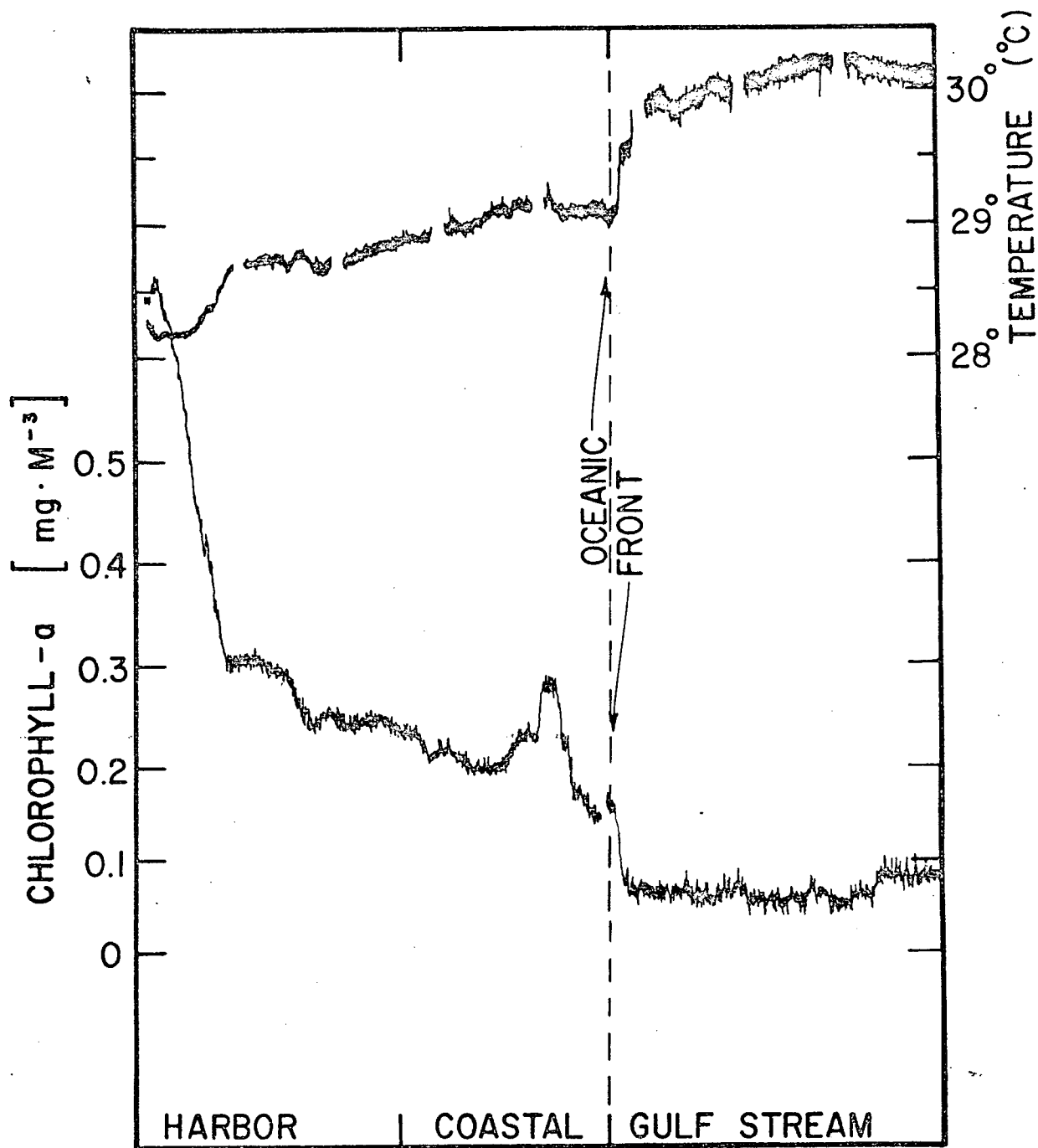
Figure 1: Surface temperature trace (upper) and surface chlorophyll-a profile (lower) across the Loop Current front and into Key West harbor. Horizontal scale across the figure is approximately 75 kilometers.
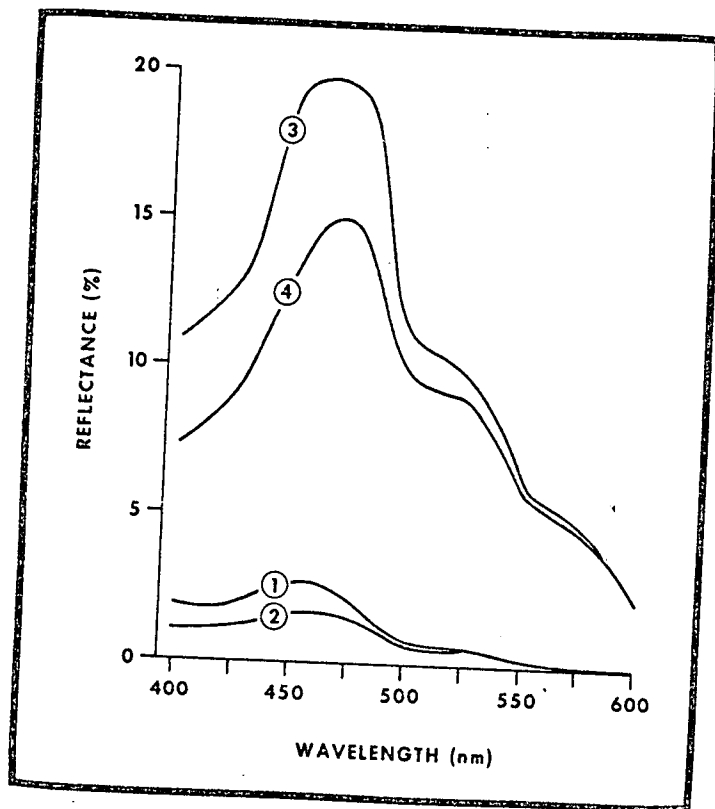
Figure 2: Results of theoretical calculations of reflectance from the water. 1 pure water, 2 pure water plus absorption due to yellow substance, 3 pure water plus isotropic scattering, 4 scattering plus absorption.
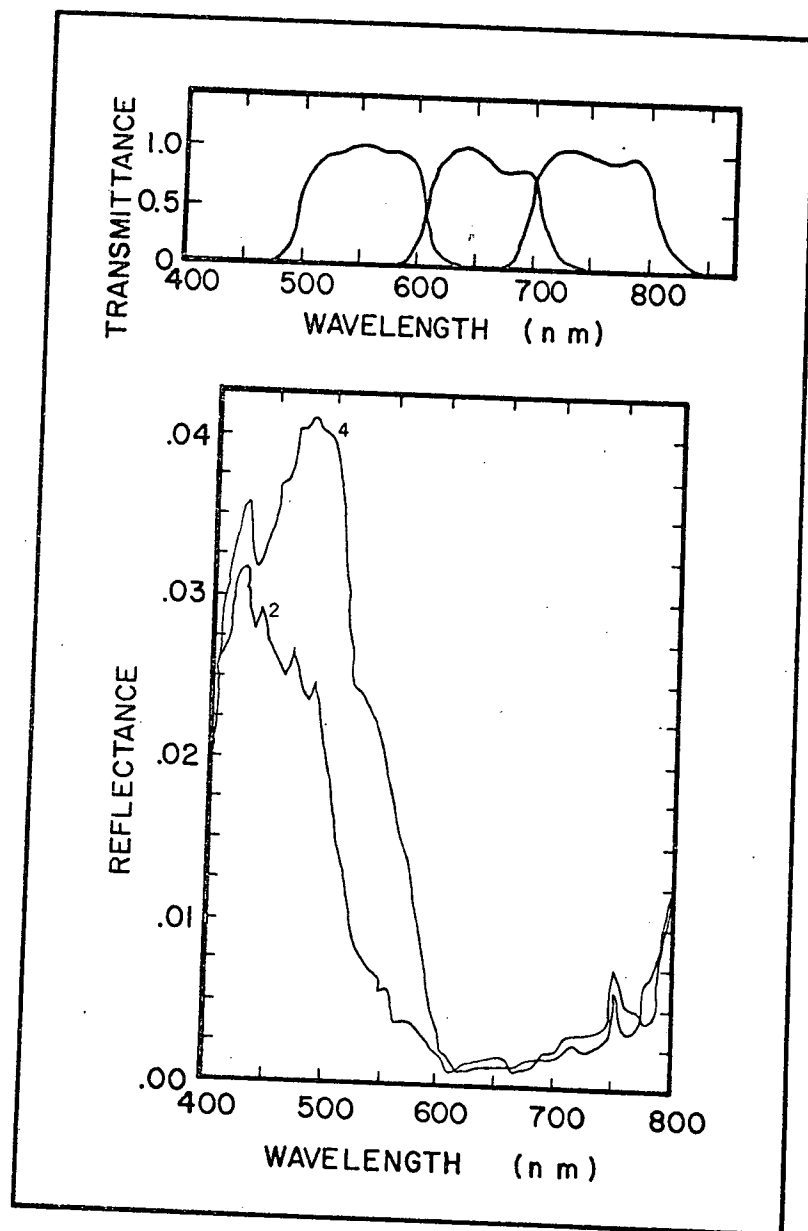

Figure 3: Observed reflectance across the Loop Current boundary. 2 current; 4 coastal water. Bottom depth exceeded 100 meters. Zenith angle about 15° in each case. The upwelling irradiance was measured at 1 meter depth. Upper panel has the spectral response of MSS 4, 5, and 6.
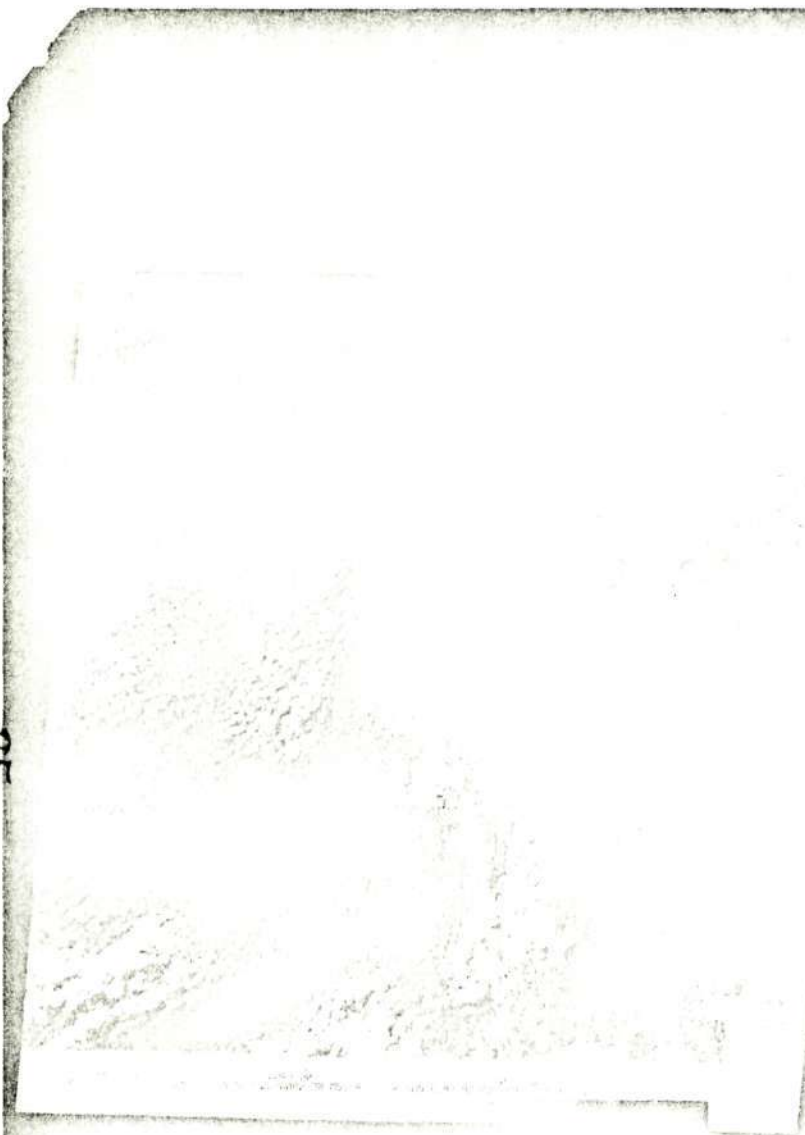
Figure 4a: MSS 4 imagery of the western Florida Keys showing water from Florida Bay being entrained by the Loop Current. The greener water from the bay appears brighter.

Figure 4b: MSS 5 imagery of the Loop Current exiting from the Yucatan Straits into the Gulf of Mexico. The blue water of the current appears brighter due to a higher sea state.