SECTION 85

OBSERVATIONS OF OCEANIC WHITE CAPS FOR MODERATE TO HIGH WIND SPEEDS

by

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A series of photographs of sea surface whitecap conditions for wind speeds of 10 to 25 m/sec has been obtained and analyzed for areal coverage of white water. The results are in good agreement with the semiempirical calculations of Cardone based on the wind speed and the development of the wave spectrum only when the contribution of thin foam streaks oriented in the direction of the wind is neglected. Since both the actively forming whitecaps and the thin foam streaks contribute significantly, though perhaps to a differing degree, to the microwave emissivity of the sea surface, it is important that the foam streaks be included in the theory but differentiated from large white caps and foam patches. A simple relationship that accounts for the foam streaks based on the rate of energy transfer, the windspeed, and the wave spectrum is proposed herein. By means of empirically derived constant terms for the microwave signatures of white caps and foam streaks, this theory is adapted to the prediction of the increase in brightness temperature due to foam, with reasonable results to windspeeds of 20 m/sec.

INTRODUCTION

Current models for the prediction of the marine environment, both atmospheric and in the surface layers of the ocean, utilize many concepts developed from experimental results which are often contradictory. Roll (1965) stated that the most critical deficiency in most models is due to a serious lack of suitable, reliable, and repeatable measurements. A second inadequacy in current predictions is the data base input to the model which is often inferior in both quality and quantity. Thus, in order to improve our forecasting capabilities we must improve the models by means of improved experiments and improve both the quality and quantity of the data base input to the model.

The purpose of this paper is to present results of some studies designed to improve the theoretical concepts of white cap production. The motivation for this effort is that measurements of the microwave emissivity of the ocean are eminently suitable for space applications. Depending on the microwave band chosen, oceanographic parameters of temperature, roughness (including foam as well as RMS wave slope) and salinity greatly modulate the observed emissivity or brightness temperature (Paris, 1969, and 1971, and others). Williams (1969) first demonstrated experimentally the influence of foam on the measured microwave emissivity of the sea surface. Droppleman (1970) and Porter and Wentz (1971) have modeled this dependence theoretically and others (Ross, et al., 1970, Nordberg, et al., 1971, and Williams, 1971) have obtained quantitative field measurements of this foam dependence. Cardone (1969) utilized the fresh water whitecap observations of Monahan (1969) to develop a semi-empirical theory relating fresh water white cap density to the local wind speed and the wave spectrum. From the results obtained during the course of this study, Cardone's theory has been extended to include salt water white caps and to account for the effects of thin streaks which begin to appear to a wind speed between 10 and 12.5 m/sec.

DATA ANALYSIS

A series of photographs has been obtained of a variety of sea conditions for wind speeds of 10-25 m/sec and significant wave conditions of 2.5-8 meters. These photographs, all vertically oriented and obtained from aircraft, have been analyzed for the percentage of the surface covered by actively forming white caps and new foam patches and thin foam streaks oriented in the direction of the wind. The analysis was accomplished by means of a scanning false color densitometer manufactured by Spatial Data, Inc., of Santa Barbara, Calif. This device scans the photograph and divides the grey scales present into 32 different levels. Each level is assigned a false color and the result is displayed on a color television monitor. This display is then subjectively divided into three categories: (1) actively forming white cap and large new foam patches, (2) thin foam streaks elongated in the direction of the wind, and (3) background foam-free water. Selection of the lines of demarcation between each category is aided by replacing each color in turn with the color black until all white caps and foam patches are blacked out. By means of a planimeter circuit, the coverage of these colors is then obtained. The blacking-out procedure is then continued until the foam streaks are completely filled and the areal coverage of the streaks is obtained. The remaining colors and coverage constitute the background sea conditions. Figure 1 shows a typical photograph along with the enhanced version. Because of deficiencies in the photography, it is not possible to precisely determine the lines of demarcation. In addition, spatial variability in foam conditions is significant. As a result, it is necessary to average a large number of photographs in order to obtain a usefully accurate estimate of the white water coverage.

REFERENCE DATA

As attempt has been made in all instances to suppress the variability in the observations due to windspeed variations with height. This is a necessary procedure, as for example, a 15 m/sec wind measured at an elevation of 10 meters would measure approximately 18 m/sec at 19.5 meters elevation and about 22 m/sec at flight altitudes of 150-400 meters depending on stability criteria (air-sea temperature difference). Therefore, all winds reported here have been adjusted to an anemometer height of 20 meters. For data obtained near ocean station vessels, the winds reported by the weather ship on station are used directly since anemometers on these ships are located at 19.5 meters above mean sea level. Where only flight altitude winds are available, a logarithmic profile was assumed to hold to an altitude of 43.5 meters (see Moskowitz, 1967) and the measured flight level winds were reduced directly to this elevation and then logarithmically to 20 meters. Table I presents the results of this technique for handling winds when measured by means of an inertial navigation system and referenced to surface anemometer winds. It is evident that the technique give reasonable results.

OBSERVATIONS

A tabulation of all foam cover determinations and associated environmental conditions is shown in Table II. According to the measured air-sea temperature differences, all observations are associated with unstable stratification of varying degree. The wind speeds for the data range from 10-25 m/sec so that the low-level Richardson's numbers, a more fundamental measure of stability, indicate only moderately unstable conditions for most observations. Hence, this data set is not as useful for studying the effects of stability on foam cover as other studies of lower wind speeds which cover both positive and negative air sea temperature differences (e.g. Monahan, 1969).

The range of fetches is quite large - the observations in the vicinity of ocean station "I" and southeast of Cape Fear, North Carolina, represent essentially fully developed sea conditions over the wind speed range 10-17 m/sec as observed significant wave heights were close to values given by the Pierson-Moskowitz fully developed sea formulation. The remainder of the high wind observations represent situations in which the fetch was limited by an upwind shoreline and seas were well below the fully developed stage.

The most striking differences between these observations and those at lower wind speeds are the significant contributions of foam streaks to total foam cover for wind speeds above 12 m/sec and the great variability in both streak and whitecap area coverage. The latter characteristic is also indicated in Figure (1), which shows the distribution of whitecap coverage for a typical photograph.

For most cases, histograms of the data depict a weakly bimodal distribution to the whitecap coverage on individual photographs. An examination of each photograph reveals that typically, the large percentage coverage is caused by the presence of a few very large foam patches associated with the relatively infrequent breaking of waves of relatively long wavelengths. For low flight altitudes particularly, the observations are subject to considerable sampling variability, as these large foam patches contribute significantly to average whitecap coverage. It is likely, therefore, that the 24.7 and 22.7 m/sec North Sea data are biased toward low foam coverage as no large foam patches were evident in the small number of photographs analyzed, yet they were observed visually (by the authors) on these flights. On the other hand, the absence of large foam patches for the 20 m/sec limited fetch observations at short fetch is probably related to the fact that wave breaking is restricted to the relatively high frequency components in the wave spectrum,as the extremely short fetches restrict the development and saturation of larger wave components. The higher aircraft altitudes and larger area viewed per photograph may also have contributed to the smaller variability for the first two sets of photographs taken on this flight.

DEPENDENCE OF FOAM COVER ON WIND SPEED

As with most other wind-wave interaction phenomena, a meaningful dependence of foam cover on wind speed can be determined only from a set of observations representing similar stages of wave development. The five observations noted above between 10 m/s and 17 m/sec, which represent nearly fully developed seas, are thus suitable for this purpose and are shown in Figure (2).

The indicated variation of white cap coverage is in good agreement with an extensive set of observations of salt water white cap coverage at speeds below 10 m/sec as analyzed by Monahan (1971). The solid curve shown in the figure, which also provides a good fit to the high wind speed data for total foam, was also found by Monahan (1971) to provide a good description of the highest oceanic white cap coverage values observed below 10 m/sec. This curve is one of the results of the semiempirical theory for white cap coverage, proposed by Cardone (1969), initially to explain the dependence of fresh water white cap coverage on wind speed, stability, fetch and duration, but later simply extended (Ross and Cardone, 1970), to include salt water effects in the manner proposed by Monahan (1969).

The observations indicate that total foam coverage increases with wind speed at a greater rate than predicted by Cardone's model. However, the discrepancy is largely attributable to the contribution to foam cover by the streaks, and a simple way to account for the effect of streaks on total foam cover within the context of Cardone's model is presented below.

The observations of percentage white cap coverage shown in Figure (2) for wind speeds above 20 m/sec lie considerably below what would be expected at these wind speeds for both white cap and total foam cover on the basis of the fully developed sea conditions. This behavior seems to be caused by the fetch limitations associated with these data (as well as a low bias due to sampling) as both Monahan's low-speed white cap data and Cardone's model suggest that for a given wind speed, white cap coverage should increase with increasing fetch and reach a maximum for fully developed seas as seen in Figure (3).

The ratio of streak-to-white-cap coverage for this set of data appears to increase linearly with wind speed. In Figure (4) a simple linear relationship above 9 m/sec is shown to fit the data reasonably well, considering the uncertainty in the observed ratio. A portion of this data was obtained on a flight conducted on 27 January 1971 specifically designed to observe the effect of fetch on the growth of the streak and white cap density and the wave spectrum. The meteorological situation along with the flight track flown are shown in Figure (5). The behavior of the streak and white cap density versus fetch for this flight is shown in Figure (6). It can be seen that the growth of the significant wave height and the white cap and streak density are in reasonable agreement with predictions (solid curves) during the early portion of the flight. However, approximately 120 km offshore, there was a drastic decrease in streak density. Figure (7) is a false color enhancement of the ITOS infrared image of 27 January and shows that the edge of the Gulf Stream lay at approximately this location. Whether this phenomenon is somehow related to the Gulf Stream or perhaps to a mesoscale lull in the wind field is unknown, as the aircraft was not equipped with a navigation system capable of resolving small scale changes in windspeed from the flight altitude flown (the aircraft doppler navigation system is inoperative below 300 meters and the Omega system does not have sufficient sensitivity).

The streak-to-white-cap ratio can be interpreted physically in terms of effective increase in the half-life of whitecaps in surface waters due to the presence of streak producing circulations. The ratio can be employed to extend Cardone's semiempirical theory since, as noted by Monahan, foam coverage is proportional to the product of the whitecap production rate and the half-life of individual whitecaps. Cardone's model calculates, basically, a measure of the whitecap production rate, with the empiricism entering into the model through a description of the effective half-life.

The success of the relationship depends on the assumption that the streak/whitecap ratio is independent of fetch. While this data set is not entirely conclusive in this regard due to the aforementioned anomaly occurring in the vicinity of the Gulf Stream and to unknowns in the wind field, the dominant effect seems to be windspeed. Further efforts, however, must be expended to verify this assumption.

As mentioned earlier, the Cardone model for white cap production is based on the energy dissipated in breaking waves according to the following equation:

$$E = \rho_w \cdot g \cdot \int_0^{\infty} B \cdot S \cdot \delta \cdot df$$

Where E = energy dissipation (ergs/cm^2-sec)
ρ_w = water density
g = gravitational acceleration
B = Miles-Phillips Instability Growth Parameterization
S = Spectral Energy
f = frequency

and $\delta = 1 \quad S \leq S_\infty$
$\delta = 0 \quad S > S_\infty$
S_∞ = Pierson-Moskowitz Fully Developed Spectrum

The empiricism enters in from the data of Monahan and results in the expression for percentage white cap coverage, modified to include salt water effects (Ross and Cardone, 1970), of

$$W_S = .00925 + 1.31 \cdot E$$

Accounting for the streaks by means of the streak/whitecap ratio results in

$$F_T = (1 + R_S)W_S$$

Where F_T = Total Foam Density (% of surface covered by whitecaps plus streaks)
W_S = Salt water whitecap density (%)
$\bar{R}_S$ = Ratio of streaks to white caps = $-1.99 + .06\ \bar{U}_{20}$
$\bar{U}_{20}$ = Average windspeed measured at an altitude of 20 meters (m/sec)

Ross, et al., (1970) and Nordberg, et al., (1971) from data obtained in March, 1969 have shown that K_W, the rate of increase of the brightness temperature with whitecap density at the Nadir viewing angle, amounts to about 1^oK for a 1% change in whitecap density at 19.5 GHZ. Whether this same figure is correct for the thin foam streaks (which may be largely a single-layered phenomena at the surface) is not known exactly, although it would appear to be somewhat less. Williams (1971), investigating the phenomena in a tank, reports that at 3 cm wavelengths, the emissivity of foam covered water is raised from .4 to .9 with a foam thickness of only 3 mm. This would suggest that the streaks might be equally as important as whitecaps, at least at the higher microwave frequencies. However, it is possible that a streak visible on photography is not altogether a surface phenomena, but also includes light scattered from bubbles suspended just below the surface. If this is the case, streaks would contribute less than whitecaps to changes in the microwave emissivity. In either case, the streak contribution may be represented as some constant, K_S, times the ratio of the streaks to the whitecaps, R_S.

If the whitecap and streak sensitivity are represented in this manner, the change in brightness temperature due to foam may be related to the white cap density according to the expression:

$$\Delta T_B = (K_W + K_S R_S)\, W_S$$

Using the observations of ΔT_B K_W, and W_S obtained during the March, 1969 experiment, and the value of R_S determined above, it is possible to solve for K_S. This was done and a value of $K_S = 0.5$ was obtained.

Application of this equation with predicted values of W_S and the empirically-derived constant terms leads, for example, to a ΔT_B of 5.5^oK and 14.5^oK for fully developed conditions associated with winds of 13 and 16 M/sec respectively, compared to observed differences (Nordberg, et al, 1971) of about 7 and 12^oK. For the 20 M/sec case, the calculation leads to a difference of 18^oK vs 18^oK observed, and for 25 M/sec 70^oK calculated vs 22^oK observed. Neglecting foam streaks entirely, calculated values of 4, 8.5, 8.5, and 26^oK vs observed values of 7, 12, 18, and 22^oK are obtained. The following table presents results of calculations of ΔT_B from the above equations and from the photographic observations, compared to observed differences in microwave brightness temperature.

Windspeed (M/s)	ΔT_B Calc. from Ross-Cardone Model (^oK)	ΔT_B Calc. from Obs. of W.Cps.&St's (^oK)	ΔT_B Observed (^oK)
13	5.5	6.0	7.0
16	14.5	10.0	12.0
20	18.0	15.0	18.0
25	70.0	15.0	22.0

While it is recognized that some of the above results may be influenced by invalid atmospheric assumptions, these are judged to be small as the set of observed brightness temperature differences were carefully selected to be from similar atmospheric conditions. Therefore, it would appear that use of the Ross-Cardone model gives reasonable results for windspeeds to 20 M/sec, but may seriously over-estimate ΔT_B for higher winds under fetch-limited conditions. Thus, the thrust of future experiments must be oriented toward the fetch-limited situations and multi-frequency measurements of the microwave signature of foam streaks, and white caps.

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TABLE I

LITTON LTN 51 INERTIAL NAVIGATOR WINDS COMPARED TO SURFACE WINDS

Date	Location	Flight Level Wind Speed (m/sec)	Altitude (feet)	Reduced Flt.Level Wind Speed (m/sec)	Measured Surface Wind Speed (m/sec)	Anemometer Height (meters)	Air-Sea Temp. Difference (°C)	Logarithmic Profile Assumption (meters)
3/14/69	N. Sea	25**	500	22.0**	22.7*	20	-3°	45
3/14/69	N. Sea	27.3**	500	25.2**	24.7*	20	-3°	45
3/14/69	N. Sea	27.8**	500	25.8**	25.4*	20	-3°	45
3/14/69	N. Sea	24.2**	500	22.1**	24.0*	20	-3°	45
3/ 6/69	N. Atlantic (I)	17***	1500	15.5	16	20		
3/10/69	N. Atlantic (I)	16***	500	15	16	20	-4°	45
3/11/69	N. Atlantic (I)	20***	750	18	17	20	-3°	45
3/13/69	N. Atlantic (I)	16***	900	13.5	13	20	-2°	45
	N. Atlantic (I)	13.5***	900	13.0	13	20	-2°	45
	N. Atlantic (I)	16.5***	1100	14.8	13	20	-2°	45
	N. Atlantic (I)	15.0***	500	13.5	13	20	-2°	45
3/13/69	N. Atlantic (J)	9***	600	7	6	20	1°	45
2/ 9/70	Hotel	16.5	150	14.8	15.5	20	-1.5°	45
2/11/70	XERBI	5	150	4.5	4	10	0	45
2/16/71	XERBI	7.5	150	7	6-9	Unknown	-2°	45
2/18/71	Hotel	11	150	10	11	20	0	45

* Reduced Geostropic Winds weighted by Surface Beufort and Anemometer Winds

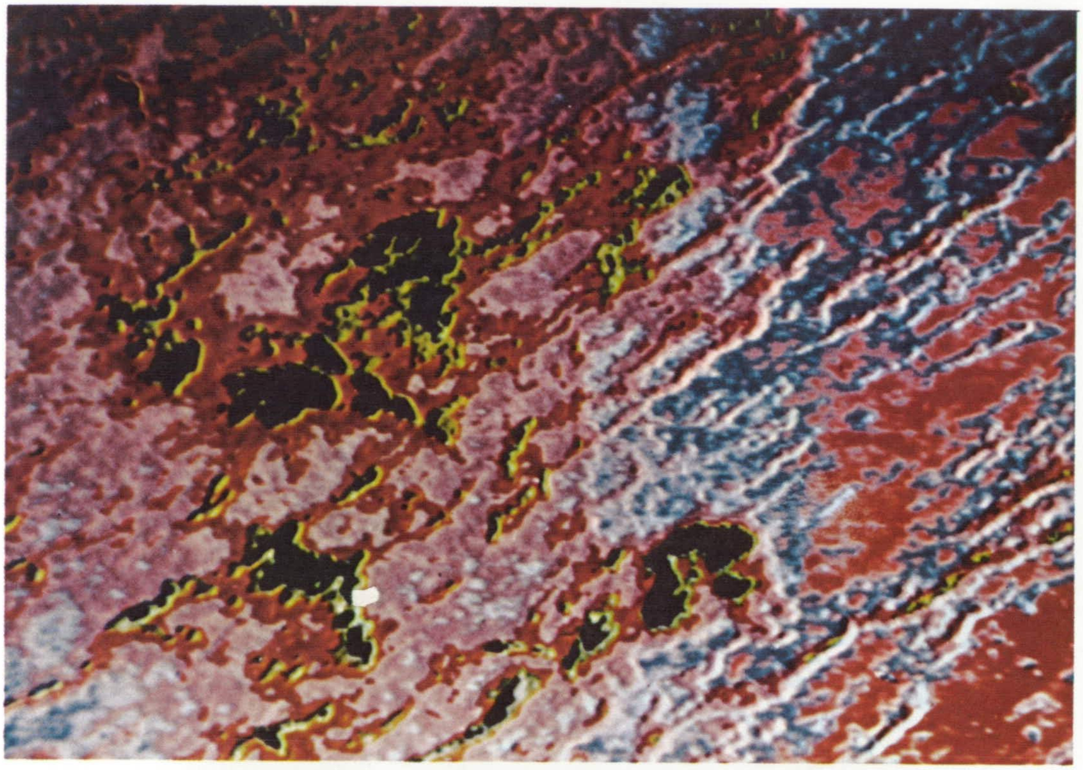
** 20 Minute Average

*** 1 Minute Average

TABLE II - SUMMARY OF OBSERVATIONS

DATE	TIME'	PLACE	FLIGHT LEVEL(m)	FETCH (km)	A-S[5] (°C)	WIND[6] SPEED(m/s)	NUMBER of Photos	WHITECAP COVERAGE(%)	WHITECAP STD Deviation	STREAK COVER(%)	STREAK STD.DEV.	TOTAL FOAM Cvr.	RATIO OF STREAKS TO WHITE CAPS
3/10/69	1426-1439	Atlantic[2]	150	740	- 4	15.5	34	6.7	5.1	7.2	2.8	13.9	1.07
3/11/69	1323-1329	Atlantic[2]	230	740	- 3	17.0	33	9.0	6.3	10.7	6.8	19.7	1.20
3/13/69	1057-1116	Atlantic[2]	270	740	- 2	13.4	27	4.2	4.4	3.5	3.2	7.7	.83
3/14/69	1407-1447	North Sea	140	370	- 3	24.7	10	7.1	8.7	25.3	7.5	32.4	3.56
3/14/69	1510	North Sea	140	> 500	- 3	22.7	8	6.4	3.3	17.0	3.9	23.4	2.66
3/19/69	0947-1038	North Sea	140	340	- 1	20.6	23	6.2	4.6	18.0	7.0	24.2	2.90
11/14/69	1826-1844	Gulf of Mex.	210	140	-20	13.4	6	4.2	1.1	2.9	2.0	6.2	.69
10/3/70		CaribbeanSea[4]	420	>800	- 1	10.3	13	1.4	.3	0	0	1.4	.00
1/27/71	1452-1454	Atlantic[3]	300	6	- 8	20.0	49	4.2	2.3	12.8	4.9	17.0	3.00
1/27/71	1503-1504	Atlantic[3]	300	75	- 8	20.0	13	5.9	2.9	13.9	6.3	19.8	2.36
1/27/71	1513-1515	Atlantic[3]	110	148	<- 8	20.0	82	4.4	7.0	1.9	3.6	6.3	.43
1/27/71	1522-1524	Atlantic[3]	110	204	<- 8	20.0	63	8.4	10.2	13.4	7.8	21.8	1.60
1/27/71	1535-1538	Atlantic[3]	110	296	<- 8	20.0	66	3.8	4.3	14.3	6.4	18.1	3.76

[1]All times in Greenwich Mean Time
[2]In the vicinity of ocean station "I"
[3]Downwind of Cape Fear, North Carolina
[4]Caribbean Sea
[5]Air-Sea temperature difference
[6]Adjusted to 19.5 meter level



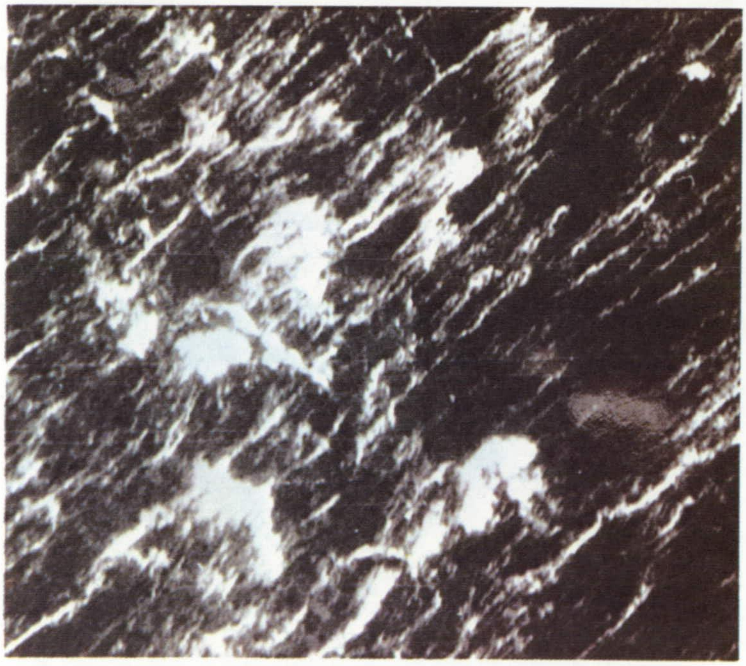


FIGURE 1. False color enhancement of white cap photography for a windspeed of 20 m/s. White caps have been made black while the thin streaks are gold and orange.

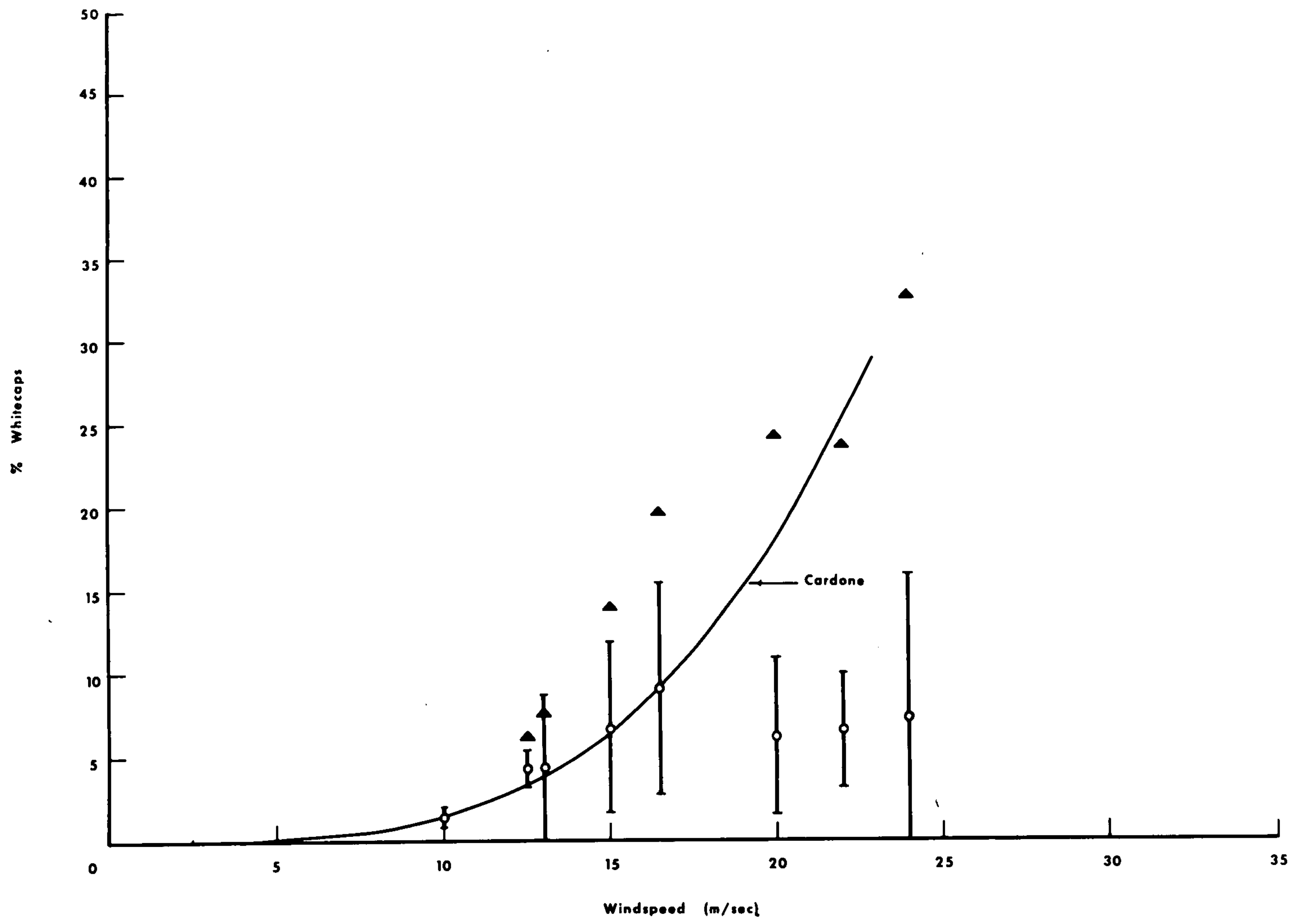


FIGURE 2. Observations of white cap density (open circles) and white caps plus streaks (solid triangles) compared to the predictions of Cardone.

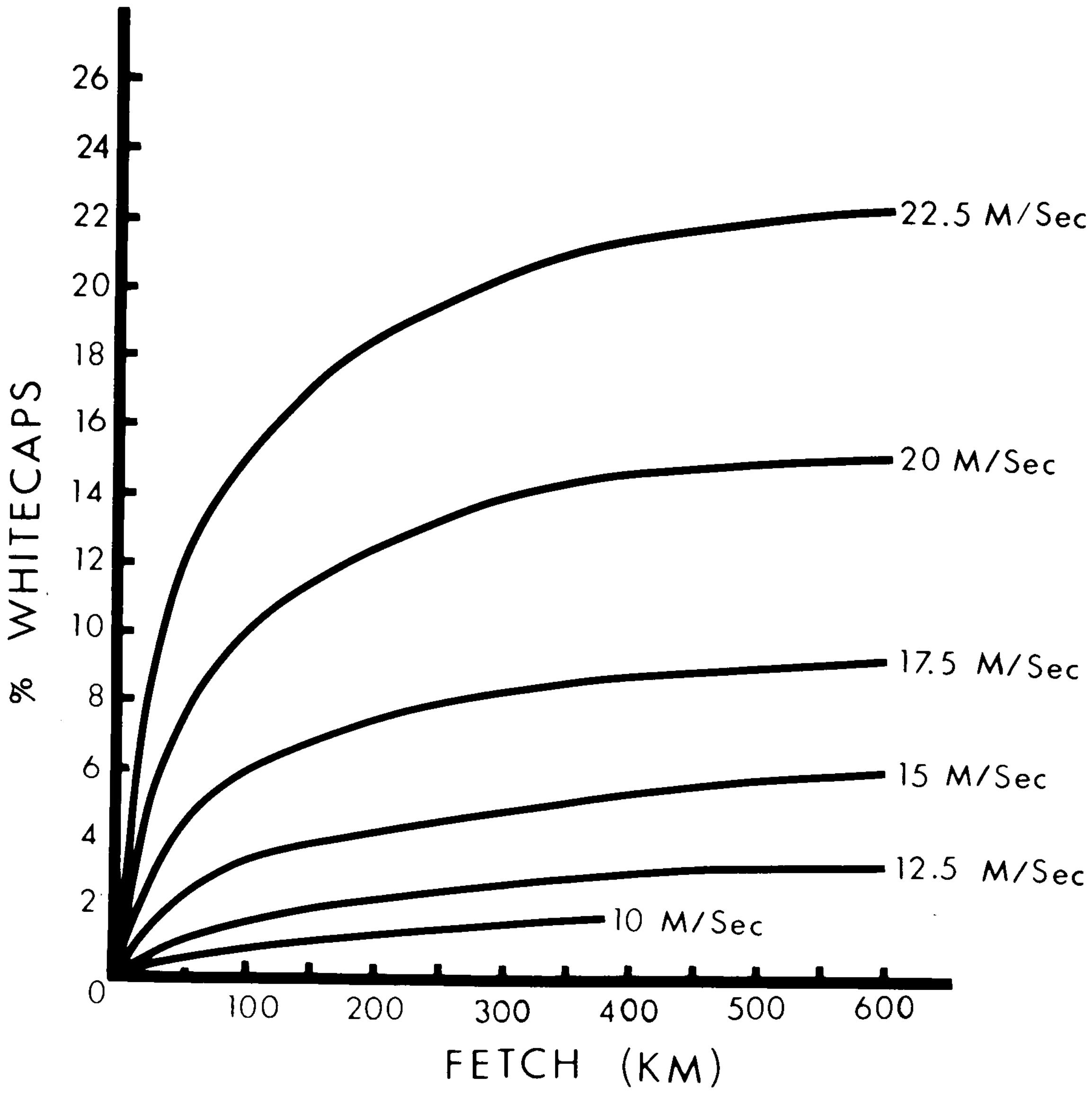


FIGURE 3. Fresh Water White Cap density as a function of fetch according to Cardone (1969).

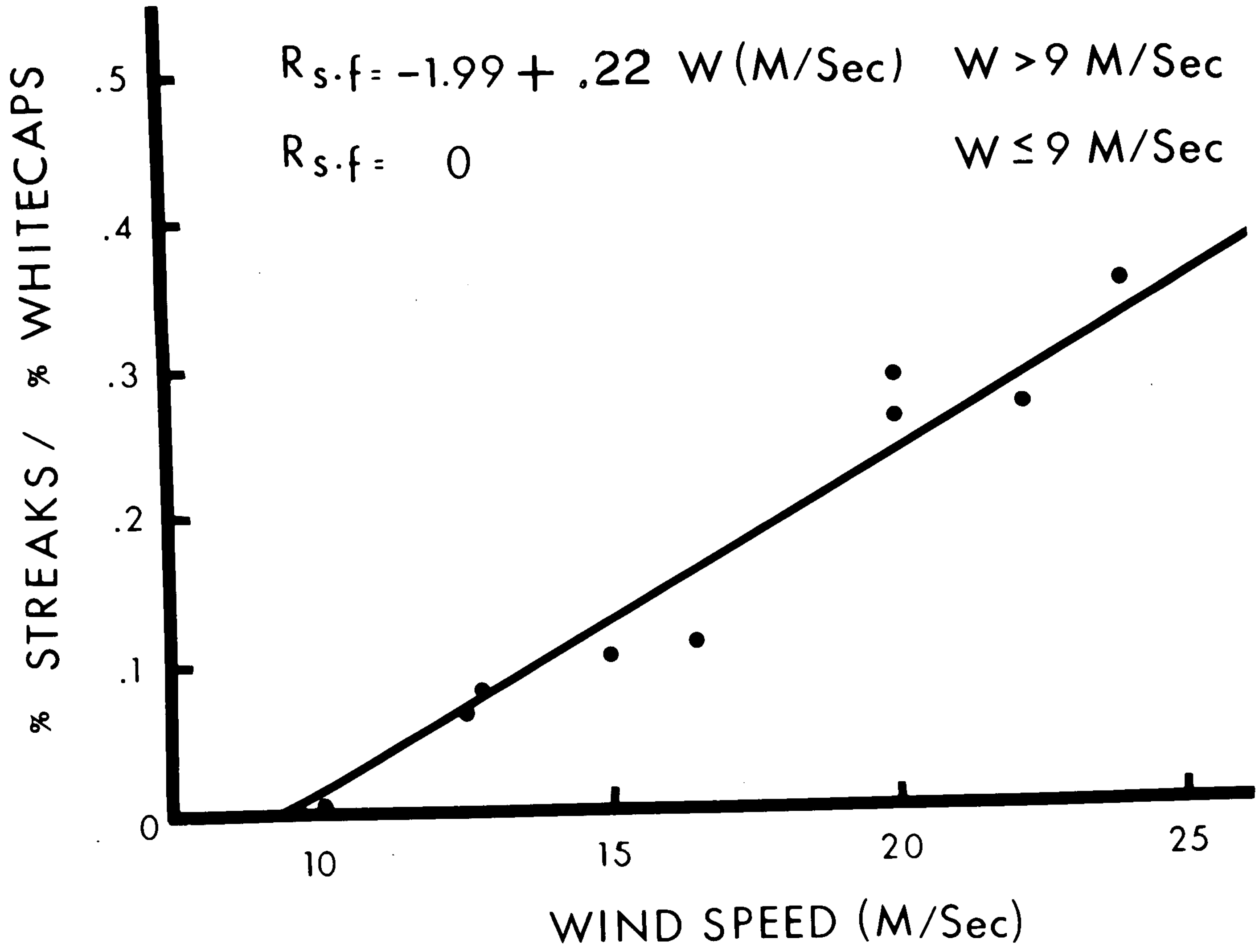
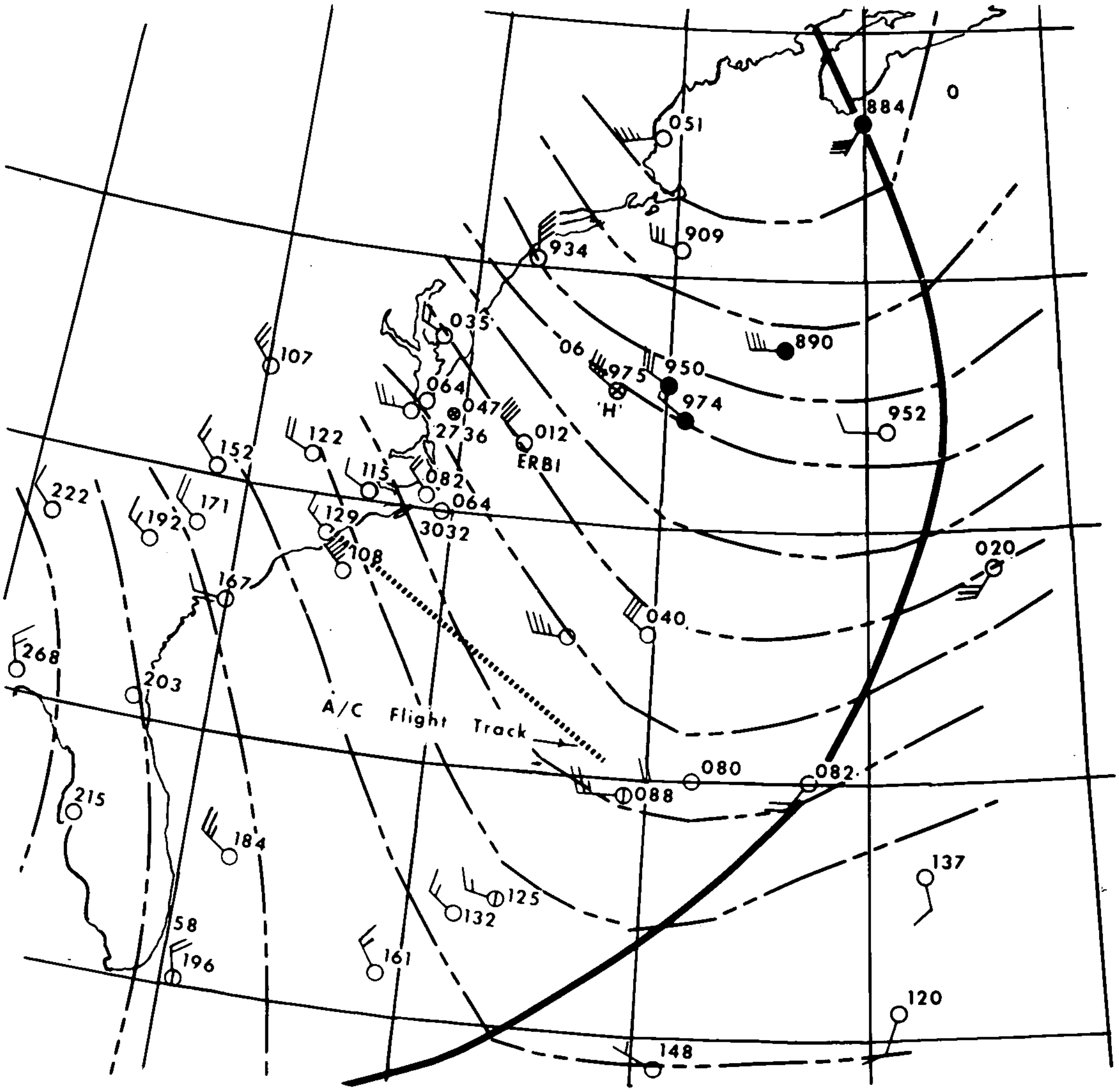


FIGURE 4. Ratio of streaks to white caps vs windspeed.



Surface Analysis 1200 GMT 1/27/71

(isobars drawn at 3 millibar intervals)

FIGURE 5. Meteorology situation for 27 Jan 71 Fetch Limited Experiment.

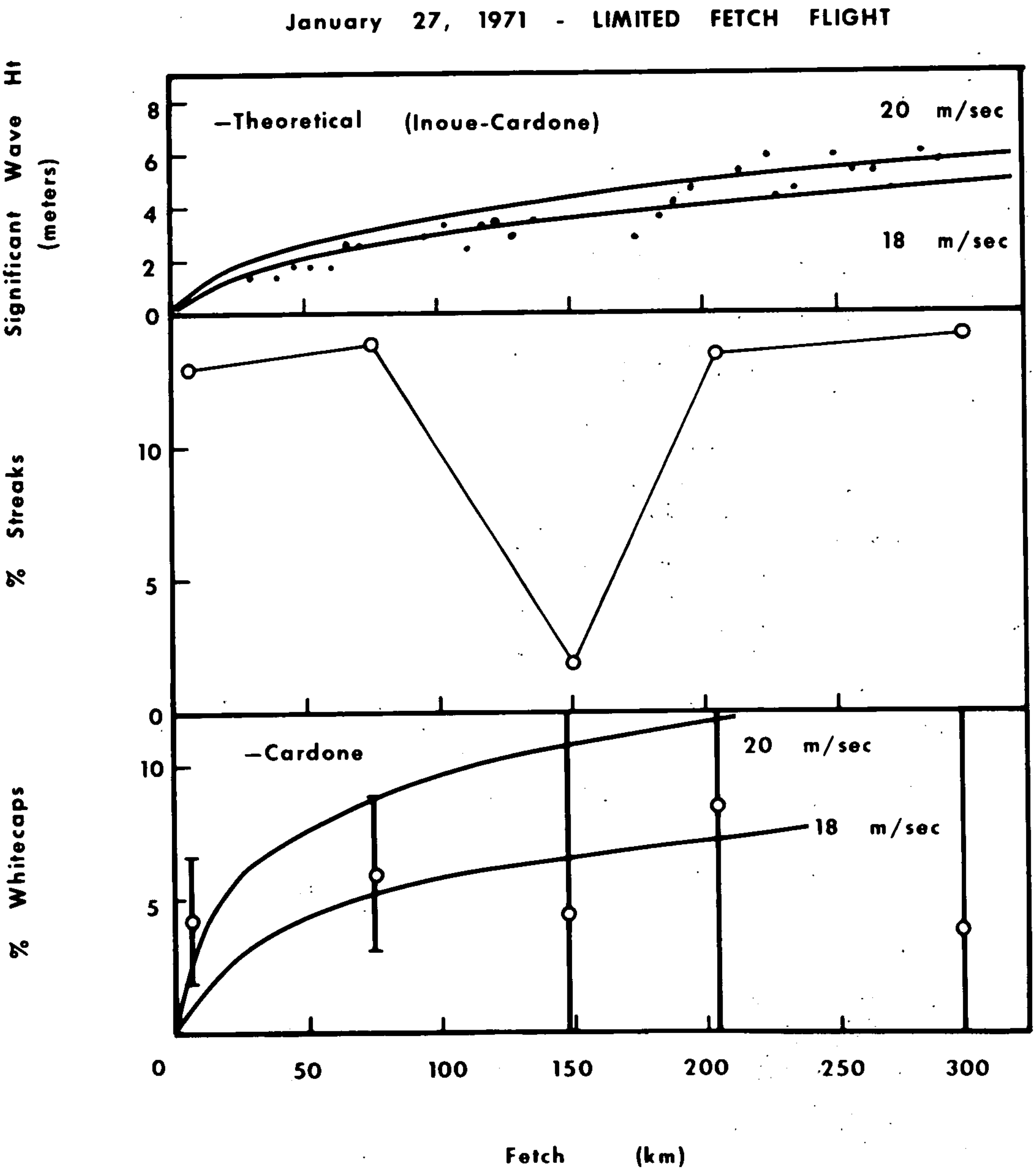


FIGURE 6. Observed behavior of the significant wave height, streak, and white cap density.

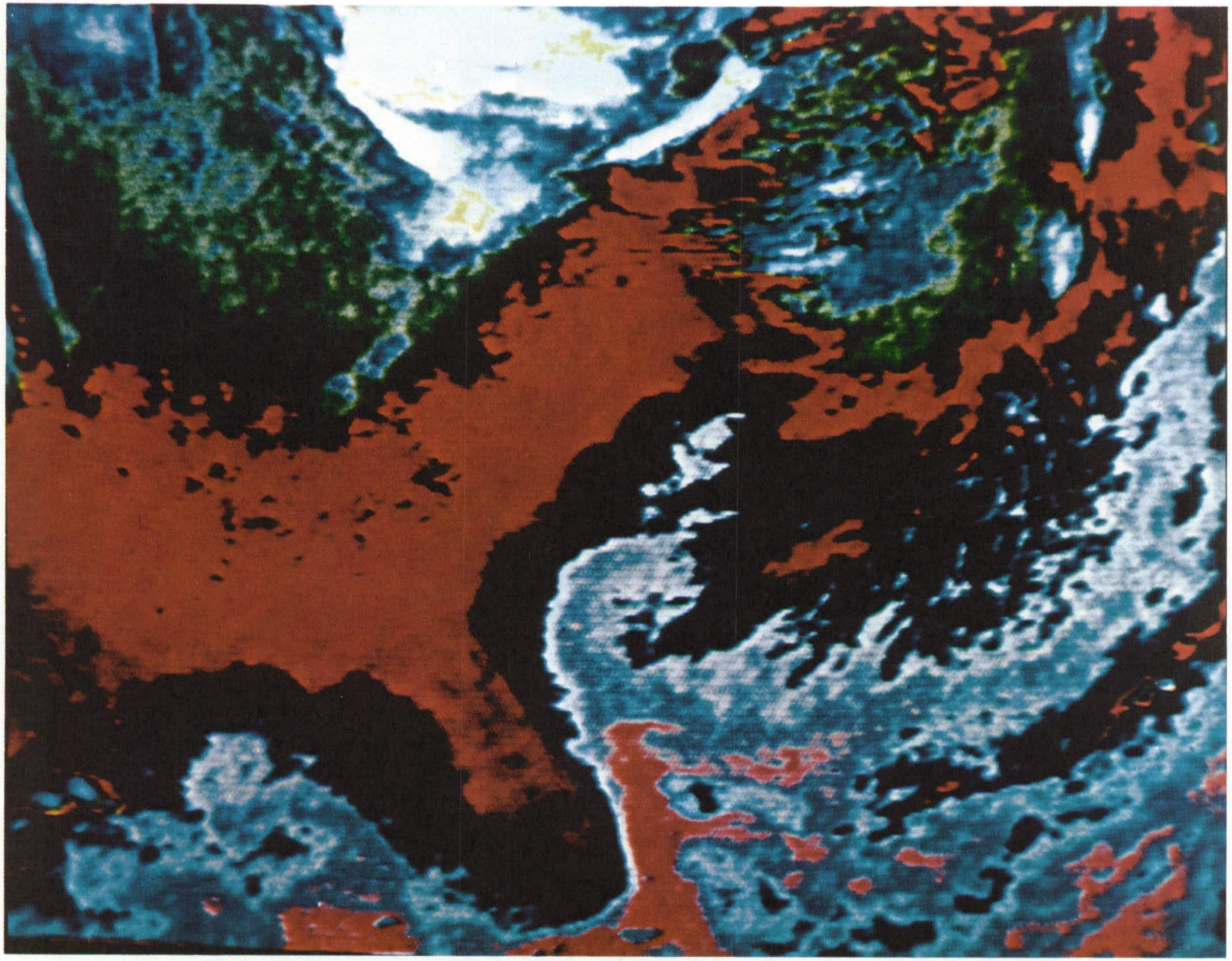


FIGURE 7. 32 level false color enhancement of ITOS HRIR Image of 27 Jan 71 showing warm Gulf Stream in red and light blue and cooler shelf waters in black.