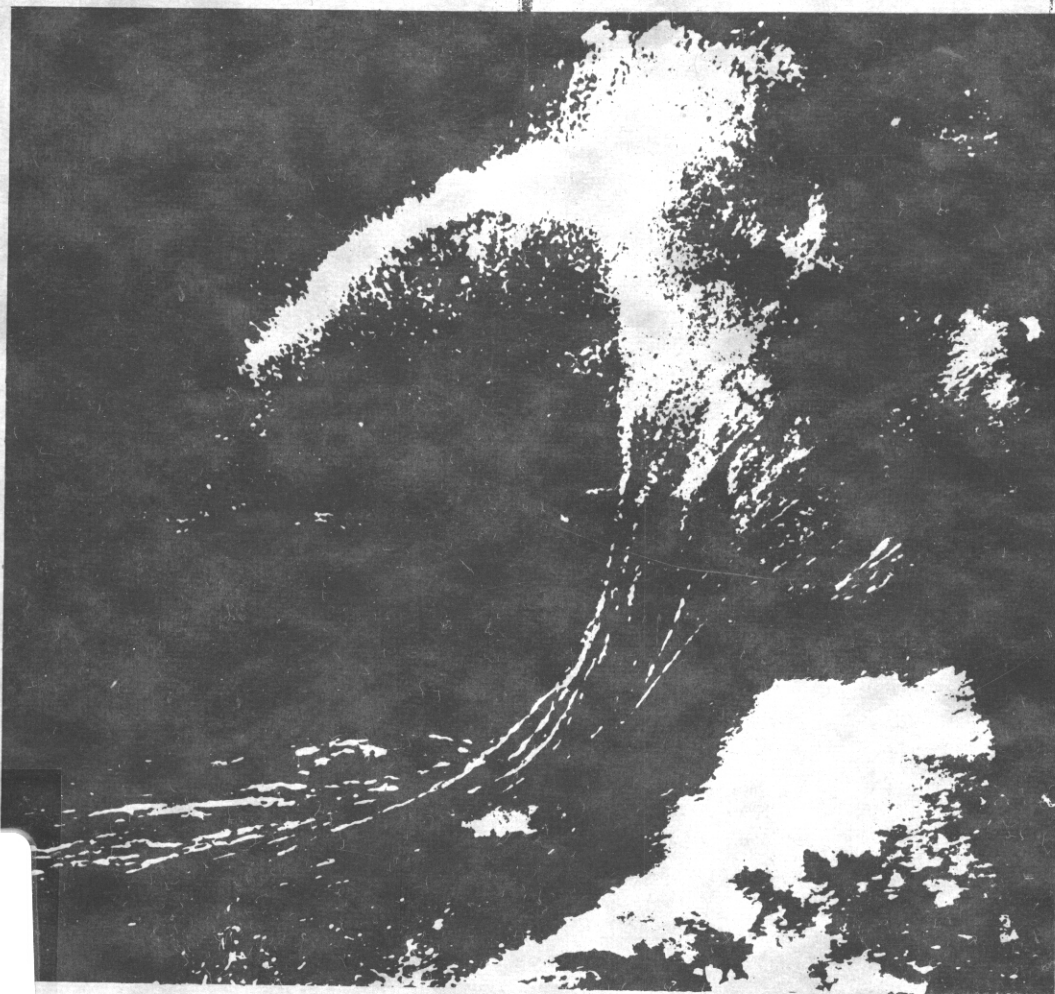


U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration

FEDERAL COORDINATOR FOR METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH



Guidance for Estimating Surface Winds Based on Sea State Observations from Aircraft and Sea State Catalog



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GUIDANCE FOR ESTIMATING SURFACE WINDS BASED ON
SEA STATE OBSERVATIONS FROM AIRCRAFT AND SEA STATE CATALOG

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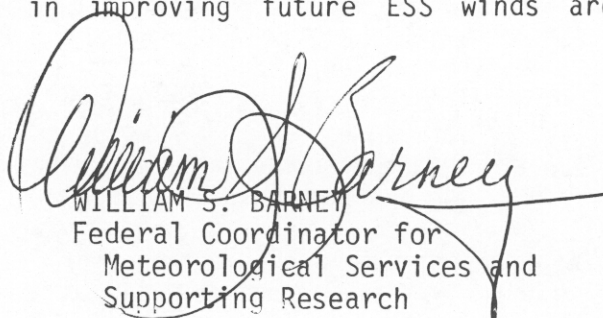
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PREFACE

This guide shows that maximum estimated sea state (ESS) winds from 700 mb western North Pacific typhoon reconnaissance missions are biased low by 8 kt for 20 to 80 kt flight level winds and high by 10 kt for 90 to 110 kt flight level winds. However, ESS winds from 700 mb western North Atlantic hurricane reconnaissance missions are biased 7 to 10 kt low for 20 to 40 kt flight level winds and 12 kt high for 50 to 100 kt flight level winds. Standard deviations about the mean 700 mb ESS wind averaged ± 18 kt. ESS winds from 1500 ft Atlantic missions are biased only 3 kt low for 20 to 40 kt flight level winds and only 3 kt high for 50 to 100 kt flight level winds, with smaller standard deviations of only ± 4 kt. These results suggest that ESS winds are heavily influenced by a knowledge of the flight level winds, that different experience levels exist in the two ocean regions and that different criteria for determining ESS winds are used in the two ocean regions.

In an effort to improve ESS winds, a catalog of vertically pointing sea-state photographs was created. Sea-state photographs were matched with 20-m mean surface winds computed from flight level winds using a hurricane boundary layer model, which were in turn assigned a Beaufort wind force category. A representative sample of 6 photographs per Beaufort category was used to derive a new set of sea-state descriptors for use in low level (~ 1500 ft) tropical cyclone reconnaissance for winds from calm to 100 kt. These descriptors are then extended for use at the 700 mb flight level. Suggested training methods for use of these descriptors and the sea-state catalog in improving future ESS winds are discussed.



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1. INTRODUCTION

Hurricanes and typhoons have been called the greatest storms on earth (Gentry, 1970). Considerable effort has been devoted over the years to forecasting the tracks and intensities of these storms in order to reduce the loss of life and property that they cause (Neumann *et al*, 1981). A major source of initial data for hurricane and typhoon forecasts has been provided by reconnaissance aircraft penetrations ever since Colonel Joseph B. Duckworth, U.S. Army Air Forces, proved that such penetrations were possible by flying an AT-6 trainer aircraft into the eye of the July, 1943 Galveston hurricane. The worth of these missions was tragically emphasized in the following year by the extensive loss of life and destruction of ships and aircraft that were inflicted on Admiral Halsey's Pacific Fleet by a typhoon. Routine reconnaissance was initiated in 1944 and 1945 by both the Navy, flying PB4Y-2 aircraft at 300-1500 ft altitudes, and the Air Force, flying B-25 aircraft at 8,000 to 10,000 ft altitudes.

Since it is the surface winds that cause damage at landfall, either directly, or indirectly by the storm surge, reports of maximum low level winds were very important. After the Navy withdrew from Pacific typhoon reconnaissance in 1971 and from Atlantic hurricane reconnaissance in 1974, low level winds above 50 kts were no longer routinely measured, except during occasional NOAA hurricane research flights. Therefore, during the 1970's and 1980's the responsibility fell to the Air Force to estimate surface winds based on sea-state appearance from their standard reconnaissance altitude of 700 mb. The accuracy of these winds was recently questioned in a Joint Typhoon Warning Center (JTWC) review (personal communication). It is therefore the purpose of this report to review the accuracy of ESS winds, the methods used to derive them and to suggest ways to improve their quality.

This study provides improved documentation for the relationship between the state of the sea, as viewed by aircraft, with the flight level and near surface (20 m level) wind speed. To address the problem of improving surface wind estimation in typhoons and hurricanes, short, intermediate and long term solutions are proposed. The present study represents a short term approach to improving the quality of ESS winds. It involves the analysis of available photographic and digital aircraft data archived at the Hurricane Research Division (HRD) of the Atlantic Oceanographic and Meteorological Laboratory (AOML), formerly the National Hurricane Research Laboratory (NHRL), from hurricane research flights and the creation of a sea state catalog (presented in this report). The intermediate term approach involves improving the quality of sea state photographs through the upgrading of aircraft camera systems together with improved methods of deriving surface wind estimates. Improved high quality, annotated color photographs will be obtained over a 1 to 4 year period which will result in an updated sea state photo catalog. However, the accuracy and consistency of these surface wind estimates will remain limited by the necessity of individual human interpretation of the data and the inability to properly quantify it. Only remote sensing can provide for consistent surface wind estimates. Therefore, the long term solution of the problem involves development of an operational microwave remote sensing instrument that correlates sea surface properties such as radar backscatter cross section or microwave brightness temperature with surface wind speed. Such remote sensing measurements have been obtained from prototype instruments and suggest great promise. Operational use of remote sensing methods is

probably at least 5 to 7 years in the future, assuming that a strong requirement for their need is forthcoming and work on an operational system begins within the next 2 to 3 years.

2. PAST METHODS FOR DERIVING ESTIMATED SEA STATE (ESS) WINDS

The only documentation for deriving ESS winds from airborne sea state photographs consists of two catalogs published in 1952. The Air Force published a catalog (Edwards, 1952) based on photographs taken by Navy Patrol Squadron VP-23, Miami Naval Air Station (NAS), during hurricane reconnaissance flights from 1946 to 1949. After this squadron was moved to Jacksonville NAS and renamed Navy Weather Squadron VJ-2, another catalog was published under the supervision of weather and photo officer, Lt. Charles Neumann¹, based on more extensive photographs obtained during the 1952 hurricane season (Walkinshaw, 1952), primarily in Hurricane Fox, when it was located south of Cuba, Oct. 23-24, 1952. These photographs were reproduced by Kotsch (1970) and by Crutcher and Quayle (1974). Wind equivalents were based on double drift² measurements at altitudes from 400 to 600 ft for wind speeds up to 65 kts and hence represent average wind conditions. Above that, equivalents were based on "estimates by experienced aerologists (ARWO's)". The photographs were taken with a K-20 airborne surveillance camera which used a 4x5 inch format film. The photographs were taken from the open window of a PB4Y-2 aircraft at an oblique angle of about 45° from the horizontal. Exposure settings of f4.5 at 1/500 sec on Tri-X film (ASA 400) were used. The Neumann catalogue also contained a table of descriptors of sea state conditions as a function of wind speed.

This table was later adapted for Air Force use at 1500 ft and 700 mb flight levels. The new descriptors were published by Jordan and Fortner (1960) based upon Hosler (1957) and Ramage (1961). This revised set of descriptors added descriptions of color changes but listed only wind speeds where dramatic changes in sea conditions were first noticed. One conclusion of Hosler (1957) was that there was a lag in observation of key transitions in sea conditions between 1500 ft and 700 mb due to changes in resolution of features that could be resolved by eye. Key sea state transitions at 700 mb were recognized at wind speeds that were 15 to 20% higher than corresponding transitions at 1500 ft. The sea state was perceived differently at 1500 ft than at 700 mb presumably because only coarser resolution features were observable at 700 mb over a wider field of view. Over the years, the descriptors have been modified and an attempt made to estimate the percent of the sea covered by various features as well as the duration of various features. Presumably these changes have been based on impressions gained by the experience of ARWO's over the years. However, no further documentation has been ever published.

It is interesting that these 1952 sea state photographs provided the only documentation for a system of estimating surface winds from aircraft for over 30 years. Furthermore, they provided the basis for the development of early microwave radiometer algorithms used to justify millions of dollars of satellite remote sensing instrumentation. These photographs were used first by Blanchard (1963) and later by Murphy (1968) to compute percent white water

coverage as a function of wind speed. These estimates represented the only high wind data for whitecap and foam coverages available to developers of microwave radiometer algorithms. Since microwave brightness temperature, measured by the radiometers, is a direct function of foam coverage, the results of Murphy (1968) and Blanchard (1964) were widely used to relate white water coverage and hence brightness temperature to wind speed by Rooth and Williams (1971), Ross, et al (1971), Stogryn (1972) and Tang (1974).

A summary of past and present descriptors and their wind speed equivalents is given in table A1. For comparison, Beaufort sea state descriptors, Beaufort force number and the equivalent nautical term for each category, and the equivalent 10-m level mean wind as well as the revised 20-m wind equivalents (see Cardone, 1969 or Kaufeld, 1981) are listed in table A2. These descriptors and the 10 m equivalents were adopted by the WMO International Meteorological Committee Meeting in Paris, 1946 and can be found in various publications such as: World Meteorological Organization (1975), List (1963), Meteorological Office (1939), Atmospheric Environment Service (1975), Crutcher and Quayle (1974), Kotsch (1970) and Bowditch (1977). The revised 20-m equivalents were adopted by the WMO Commission on Marine Meteorology (CMM) at the CMM IV meeting in 1964. It should be emphasized that these wind equivalents refer to 10 to 30 minute average winds, not sustained 1 minute winds or peak gusts. The differences between winds averaged over different time intervals are discussed in detail by Black and Adams (1983).

A list of sea state transition events was compiled from the descriptors in tables A1 and A2. The wind speeds at each flight level and from shipboard at which the various sea state features first appear are listed in table A3. The low wind events at 1500 ft are detected at slightly lower winds than the 20-m shipboard reference. At winds above 30 kt, agreement between first detection of events from 1500 ft and 20 m is good. For winds above 25 kt, a given sea state event corresponded to a wind at 700 mb which is 30-40% higher than the wind for that event at 1500 ft, according to the 1982 Air Force descriptors listed in table A1.

There are numerous shortcomings in the set of descriptors in table A1 and the manner in which they have been used operationally. Some of these shortcomings are ordered below relative to their importance:

1. High variability of estimates between observers due to differences in observer experience.
2. Inappropriate influence of extraneous inputs, such as the observer's knowledge of the flight-level winds.
3. Inadequate and insufficient descriptive information, particularly between certain wind intervals where sea-state characteristics evolve subtly.
4. Inadequate training aids, such as poor quality black and white photographs.

5. Inadequate documentation of previous studies with regard to the methods used in establishing descriptors and matching them with questionable ground truth, which has resulted in the usability of such aids in only a general way.

6. Lack of a formal training program.

7. Availability of only broad descriptors for large wind ranges at the higher wind speeds for observations from the 700-mb observation altitude.

8. Unavailability of color sea-state photography as a training aid when much of the descriptive phenomena are based on color interpretation.

9. Other limiting factors to absolute accuracy and consistency, such as adjustments of estimated surface wind for fetch, duration of wind, wind speed trends, interaction of sea with swell, and the angle of view and lighting available.

Of course, a degree of subjectiveness will always be present in the estimation of surface winds from sea state, since this method does not easily lend itself to quantification. In addition, although correction factors may be determinable to a degree for fetch, duration, sea-state lag and the many other variables, these correctors will always be limited in accuracy. Nevertheless, the resulting final wind estimates should be more accurate if these correctors are applied. An adequate determination of these factors remains to be accomplished. Most of the shortcomings, however, with the current descriptors and techniques that contribute to the large scatter of ESS values, can be objectively approached through a formal training program and with improved descriptive information and reliable ground truth.

3. ACCURACY OF ESS WINDS DETERMINATIONS IN WESTERN NORTH PACIFIC TYPHOONS AND WESTERN NORTH ATLANTIC HURRICANES

Previous estimated sea-state surface winds, or ESS winds as suggested by Jordan and Fortner (1960), have been based primarily on correlations between sea-state and winds derived from aircraft navigational systems that were in use during the 1940's and 1950's. These systems contained large random errors or poor calibrations. The correlations have been based on unknown averaging times and on unknown relationships between the flight level and surface winds (previous relationships generally assumed they were equal). Therefore, the primary objective of this work has been to improve the accuracy of ESS winds by correlating sea state photographs with concurrent, near surface (20-m) wind estimates. These surface winds were based on highly accurate flight-level winds from state-of-the-art inertial navigation systems (INS) which were averaged over a precisely defined time period and reduced to the surface with a well documented planetary boundary layer (PBL) model.

This study was motivated by a request from the Joint Typhoon Warning Center (JTWC), Guam, to improve the ESS winds. The request was based on a review of maximum typhoon winds derived from four different methods for 35 aircraft reconnaissance missions during the 1979 typhoon season. These methods were: 1) maximum wind derived from minimum surface pressure (PMIN) based on the relationship proposed by Atkinson and Holliday (1977), 2) the

maximum wind derived from satellite cloud morphology based on the method proposed by Dvorak (1975), 3) the maximum wind measured at flight level, and 4) the maximum surface wind estimate based on state-of-the-sea observations (ESS winds). The results from this review concluded that in all but two cases, the ESS wind was higher than winds derived from the pressure-wind relations and satellite methods and in all but nine cases was higher than measured flight level winds, even though PBL models suggest that 20-m level winds should be less than cloud base and 700 mb winds in typhoons and hurricanes by about 20% (Bates, 1977; Powell, 1980). The conclusions of the JTWC review were in agreement with earlier results presented in Jordan and Fortner (1960) and discussed later in Bell (1961).

Therefore, over the past 20 years it has been suggested that in the Pacific region, maximum ESS wind values were significantly greater than maximum surface wind estimates derived from other techniques and greater, in a majority of cases, than maximum flight level aircraft winds. It has also been suggested during this period that, in the Atlantic region, ESS winds were lower than flight level winds. In fact, after comparing all available data between the mid-seventies and early-eighties (see appendix B), it is now evident that the opposite situation exists in both oceanic regions and that the JTWC review represents a somewhat biased subset of the 1979 data in appendix B.

The original motivation for this study was the perceived problem with ESS values in the Pacific region. Yet, the data in appendix B indicates that, in the mean, ESS winds in the Pacific seem much more reasonable now than in the past (Jordan and Fortner, 1960) while ESS values in the Atlantic region appear questionable. However, the scatter about the means are intolerable. In both the Atlantic and Pacific data sets a large random error exists of ± 18 kts for observations from the 700-mb level. At the 1500 foot observational altitude the scatter is much smaller in both oceans, although the mean values are so similar to flight-level recorded winds that no special meaning should be assigned them as they do not appear to be independent determinations.

Since no new documentation of ESS winds occurred during the 1960's, there apparently has been a change in interpretation of sea-state as a function of wind speed which has produced the dichotomy between the two regions. As pointed out in appendix B, the comparison of the data analyzed in 1960 with more recent data suggests several major problems. First, it is possible that different subjective criteria are being used to derive ESS winds in the Pacific than in the Atlantic, even though a standardization of techniques between the two regions has long been recommended. Second the experience level of a given observer within a year is much greater in the Pacific than in the Atlantic due to the larger number of storms. Third, the comparison points in appendix B cluster along or parallel to the line of perfect agreement between ESS and flight level measurements. This is readily apparent at the 1500 ft observational level. Surface winds, according to planetary boundary layer models (Powell, 1980), should be about 80% of 1500 ft flight level wind values. Since ESS winds cluster close to the line of perfect agreement with flight level winds, possibly the observers awareness of the flight-level wind has influenced his ESS determinations or flight level rather than surface winds, were used to derive the training aids for ESS wind determinations. Therefore, present practices for deriving ESS winds seem to result in no new information beyond what is measured at flight level, reported differences being a result of random errors in estimation based on flight-level winds.

4. USE OF VERTICAL PHOTOGRAPHY FROM LOW LEVEL HURRICANE RESEARCH FLIGHTS TO IMPROVE THE CORRELATION OF SEA-STATE APPEARANCE WITH WIND SPEED

About 86 low-level black and white sea-state photographs were culled from several thousand frames taken from NOAA aircraft flights in hurricanes in the 1970's. The sea-state photographs are shown in appendix C. Table 1 summarizes the sea-state descriptors that were derived for these photographs grouped according to Beaufort categories. The 20-m wind equivalent and estimated sustained wind corresponding to each Beaufort number is also listed.

These descriptors are the result of a combination of inputs, including information from the current Air Force descriptors adjusted for the surface wind speeds at which they should appear based on our more accurate ground truth derivation. The improved descriptors also carry over much of the color descriptive information (i.e., green) from the previous Air Force descriptors, although much of this information is based only on real-time "naked-eye" interpretations and cannot be verified.

The essence of the improved descriptors in Table 1 is based on a survey of several experienced and a few relatively inexperienced observers at the HRD (formerly NHRL) and the Research Facilities Center (RFC) in Miami, Florida. Approximately one-half of the 86 sea-state photographs over the entire Beaufort range between B3 and B17 were distributed to 12 individuals. Each photograph was described in writing by each of the survey participants. Thus, with about 3 photographs for each Beaufort category and 12 descriptions for each photograph, approximately 36 descriptive sets were obtained for each Beaufort category in addition to the descriptive information obtained from the adjusted Air Force descriptors. All of this descriptive information for each Beaufort category was then sorted for commonality to provide the improved descriptors in Table 1.

In addition to the new descriptive information provided by this survey an attempt was made to determine the potential benefits of a training program. Therefore, after ordering the photographs relative to increasing sea-state severity and then describing each photograph, the survey participant was then asked to reorder the photographs without any reference to his previous ordering and without the written descriptive information in hand. On average the second ordering showed a 15 to 20% improvement. This implies that an intensive training program could result in a significant improvement in sea-state observation accuracy. However, a more extensive survey is recommended both to improve the descriptive sets and verify an improvement as a function of training.

4.1 Use of the catalog

The 86 available photographs cover a range of Beaufort numbers from B3 to B19, or a mean surface wind velocity between 9 and 102 kts. The mean wind equivalents for the Beaufort numbers are based upon the 20-m values adopted by the WMO at the CMM IV meeting in 1964 and recently verified by Cardone (1969) and Kaufeld (1981). Each Beaufort category contains up to six photographs with about two photographs per page defining the low-end range of a Beaufort number, two for the middle range and two for the upper range. Each sea-state

photograph was classified by Beaufort number according to its 20-m derived surface wind. The 20-m mean surface wind was derived by inputting 30-s average flight level winds together with estimated surface air-sea temperature differences into a planetary boundary layer model (Powell, 1980).

Each photograph in the catalog is labeled with a figure number and is identified with its flight number (year, month, day, aircraft), storm name, radar altitude (RA) in feet and the flight-level wind in meters per second. Between this information and the appropriate Beaufort descriptor at the bottom of the page is the 20-m mean surface wind in meters per second, the Beaufort-scale number, the 20-m mean surface wind in knots and the 20-m sustained 1 minute wind in knots. The mean and sustained wind speed ranges for each Beaufort category are indicated together with the Beaufort descriptor. The phrase which indicates the most outstanding characteristic of the sea for each Beaufort category is underlined. Below and between the two photographs on each page is a compass rose indicating the location at which the observation was made relative to the storm center and storm motion vector, which is at the top of the compass rose. Each radial circle on the compass rose represents 50 nmi. The compass rose is divided into right-front, right-rear, left-rear and left-front quadrants. The photographs are oriented so that the top of the page (bound edge) points approximately in the direction of the storm motion (S.M.) vector. The sustained wind is estimated by multiplying the 20-m mean wind by 1.13, a factor derived from hurricane surface wind measurements over water and discussed further in Black and Adams (1983).

The field of view shown in the photographs is approximately 1.3 times the aircraft altitude. Most photographs were taken at altitudes within ± 100 ft of 550 ft, 900 ft, 1500 ft and 2300-3600 ft. These represent fields of view of about 650, 1150, 2000 and 3900 ft on a side, respectively.

The Beaufort categories where warnings of various types are first raised are indicated in the catalog. These warnings were first defined by the WMO in 1946 as the lower end of the 10-m mean wind equivalent range for the Beaufort number defining the warning (see table A2). Thus, small craft, gale, storm and hurricane warnings were to be raised at Beaufort 5, 8, 10 and 12, respectively. According to the original WMO definition, this corresponded to mean winds of 18, 34, 48 and 64 kt, respectively. These wind equivalents were later interpreted as sustained (1 minute average) winds rather than 20-30 minute means. In addition, the mean wind equivalents were subsequently redefined for 20-m in 1964. However, the lower end of the range of estimated sustained winds at 20 m for the various Beaufort numbers corresponds reasonably closely to the 10-m sustained wind equivalent and for all practical purposes can be considered the same. Therefore, warnings can be defined by either a 10-m or 20-m sustained wind equivalent. It is therefore recommended that the sustained wind equivalent be reported by observers. Other users of the observation who are interested in mean wind equivalents could then reduce the observed sustained value by 12% to obtain 20-m mean winds, or by 18% to obtain 10-m mean winds for near neutral stability conditions.

4.2 Discussion of the catalog

The appearance of the sea corresponding to a given surface wind may vary according to a number of factors such as aircraft flight altitude, sunlight or

overcast conditions, previous sea conditions, fetch, sea surface temperature and viewing angle. For a number of Beaufort categories, efforts were made to illustrate some of these problems.

In this catalog, the effect of viewing angle on the appearance of the sea has been removed by using only photographs taken at a vertical (straight down) orientation. Observers should be aware that the sea can take considerably different appearances for a given wind speed when viewing the sea at an oblique angle rather than vertically. The sea may appear rougher and whiter when viewing the sea in an upwind direction than in a downwind direction. An intermediate state may be observed in the cross wind direction. Therefore, when using this catalog as a guide, an effort should be made to view the sea as nearly vertically as possible.

The problem of changing resolution and field of view with flight altitude is illustrated by figs. 1a and 1b for Beaufort 3 conditions, by figs. 2a and 2b for Beaufort 4 conditions, by figs. 3c and 3f for Beaufort 5 conditions, by figs. 5c and 5d for Beaufort 7 conditions, by figs. 6a, 6b and 6f for Beaufort 8 conditions and by figs. 10c and 10d for Beaufort 12 conditions. One can see that many more details are visible at the lower 500 ft altitude than at the 1500 ft and 5000 ft altitude.

In a similar manner, the sea appears differently when illuminated by the sun, especially in a region of sun glint, than when the sky is cloudy above the aircraft. Examples of this difference can be seen in figs. 2e and 2f for Beaufort 4 conditions, in figs. 4c and 4d for Beaufort 6 conditions and in figs. 7c and 7d for Beaufort 9 conditions. In regions of full sun or sun-glint, the contrast of small scale features on the sea is enhanced. However, the contrast between the background and whitecaps or streaks is reduced. In some cases, whitecaps in a sunglint region may appear black against the bright glint. The tilting angle of wave facets, the capillary wave activity and the general textured appearance of the sea are very prominent in full sunlight and contribute to an almost three dimensional appearance to the sea. There is much less contrast between features under cloudy conditions and the sea appears somewhat flatter.

The effects of fetch (radial distance from the storm center) and of prior sea conditions, which would be a function of quadrant of the storm, were more difficult to ascertain. Comparisons of photos taken at similar winds speeds and in different quadrants or at different radial distance were difficult to obtain. The effects may be well within the range of error of the boundary layer model used to estimate the surface winds.

Use of buoy surface wind measurements and improved photographs in the future may allow this effect to be measured and compensated. Only one photograph, fig. 9d, could be correlated directly with a buoy surface wind measurement.

The effect of changing sea surface temperature (SST) could not be assessed in this study since most of the photographs were taken over a limited range of SSTs between 27°C and 29°C. Atmospheric stability conditions were either neutral or slightly unstable.

Table 1. Surface wind estimates (kts) from state-of-the-sea observations at 1500 ft. Both mean and sustained (in parenthesis) wind equivalents are indicated.

Beaufort Number	Descriptor	Wind (20 m) Equivalent	
		Range	Average
0	Sea glassy. Appearance of being covered by oil.	Calm	1
1	Slight ripple.	2-5 (2-6)	3 (4)
2	Slight ripple. Isolated brief whitecaps. Unable to determine direction.	5-9 (6-10)	7 (8)
3	Surface like wrinkled paper. Small well defined whitecaps of uniform size but few in number. White crests disappear quickly. First able to tell direction but with difficulty.	9-14 (10-16)	12 (14)
4	Small foam patches. Number of breaking crests increase slightly and are a little larger. First able to tell direction with confidence. Wrinkled texture of surface is very evident.	14-18 (16-20)	16 (18)
5	<u>Small craft warning.</u> Size and number of whitecaps and foam patches increase significantly. White caps on most wave crests. Very short streaks may appear in foam patches.	18-23 (20-26)	21 (23)
6	Well defined short streaks in foam patches. Small whitecaps on most wave crests. Occasional medium size foam patch or breaker. Isolated green patches of short duration. Foam patches, short streaks and whitecaps (white water) cover 5-7% of sea surface.	23-28 (26-32)	26 (29)
7	Medium size breaking crests. Dense foam patches and accompanying short streaks are numerous. Average length of streaks equal to diameter of average foam patch. Small green patches occasionally visible.	28-33 (32-37)	31 (34)
8	<u>Gale warning-tropical storm.</u> Streaks more numerous and occasionally longer. Some streaks may appear unassociated with breaking waves or foam patches. Area covered by whitecaps stabilizes at 7-10%. Occasional large foam patch. Small green patches continually visible with occasional moderate sized green patch.	33-39 (37-44)	36 (40)
9	Streaks readily apparent between foam patches. Streak length varies from patch size to occasional regions of long, nearly continual streaking. Streaks patches and breaking waves cover 15 to 20% of sea. 50% of foam patches are green.	39-44 (44-50)	41 (47)

Table 1 (Continued). Surface wind estimates (kts) from state-of-the-sea observations at 1500 ft. Both mean and sustained (in parenthesis) wind equivalents are indicated.

Beaufort Number	Descriptor	Wind (20 m) Equivalent	
		Range	Average
10	<u>Storm warning.</u> Wind streaks become the most obvious surface feature and are continuous or nearly so. Well-defined, thinly breaking waves form on long crestlines often preceded by short breaking wavelets giving a step-like appearance. Occasional large foam patches are quickly fragmented and elongated into streaks. Sea covered 20-25% by white water.	44-49 (50-55)	47 (52)
11	Streaks are well-defined, parallel, thin, close together and continuous with very short capillary wavelets cutting across and perpendicular to streaks, giving sea surface a "shattered glass" effect in certain areas. Some large breaking crests may take on "rolling" or "tumbling" appearance. Sea covered 30-40% by white water.	49-55 (55-62)	52 (58)
12	<u>Hurricane warning.</u> Sea may occasionally be obscured by spray and take on a murky appearance. Large, curved, breaking crests have undulating effect on streaks giving churning appearance. Streaks appear to thicken and become milky or pale greenish.	55-61 (62-69)	58 (65)
13	Surface features generally become murky. Streaks and foam patches begin to lose their sharp definition and appear to smudge, thicken or merge together. Frequent, extremely large, almost semicircular crests outlined by thinly breaking waves with occasional groups of large foam patches after entire crest breaks.	61-66 (69-75)	64 (72)
14	Quantity of spray increases. Streaks thicken and appear to have more depth. Previous crisp, shattered glass appearance now appears blurred. Most features appear to be submerged rather than surface phenomenon due to obscuration. Very short capillary wavelets which cut across streaks give surface a stressful appearance as though undergoing compression. Sea surface 50% white.	66-72 (75-81)	69 (78)
15	Sea appears flatter and entire surface takes on a whiteish/grayish cast. Streaks organize somewhat into broader, diffuse bands. All features lose some definition and appear submerged. Surface 50-55% white.	72-78 (81-88)	75 (84)

Table 1 (Continued). Surface wind estimates (kts) from state-of-the-sea observations at 1500 ft. Both mean and sustained (in parenthesis) wind equivalents are indicated.

Beaufort Number	Descriptor	Wind (20 m) Equivalent	
		Range	Average
16	Many thin streaks are partially obscured and those which can be seen may appear as bands spaced farther apart. Occasional cloud below aircraft blots out or obscures surface. Sea appears almost flat. Whiteish cast covers 60-65% of surface.	78-84 (88-95)	81 (91)
17	Breaking waves and foam patches appear as diffuse, white, puffy areas. Streaks become fuzzy bands. Surface 70-80% white.	84-90 (95-102)	87 (98)
18	Cloud, spray and foam patches merge into large, white, undefineable areas historically referred to as "white sheets." Surface features have only rough boundary definition.	90-96 (102-108)	93 (105)
19	Isolated large, white puffs. Only strongest features of previously seen thick streaks remain to be observed and result gives impression of only a very few widely scattered and non-parallel streaks or wide bands. Whiteish and greenish cast cover 100% of surface.	96-102 (108-115)	99 (112)

5. EXTENSION OF THE IMPROVED SEA-STATE DESCRIPTORS TO THE 700-mb OBSERVATIONAL LEVEL

Unfortunately, the Air Force does not fly into typhoons and hurricanes at low altitudes, frequently. The most common operational altitude is 700 mb. Yet, there exists little in the way of descriptive documentation of sea state as observed from this flight level. On the contrary, the available descriptive information has presumably been derived from "impressions" gained by the experience of aircraft reconnaissance weather officers (ARWO's) over the years and by application of Jordan and Fortner's (1960) conclusion that there is a lag in observations of key transitions in sea conditions between the 1500-ft and 700-mb observation levels. Jordan and Fortner's data indicate that key sea-state transitions at 700 mb were thought to be recognized at wind speeds that are 15 to 20% higher than similar transitions observed at 1500 ft presumably because only coarser resolution features are observable at 700 mb over a wider field of view.

In addition, it would appear that larger breaking waves inject more air bubbles deeper into the ocean than the smaller waves at lower winds. This deep air injection creates a color change in the resulting foam patches. Injection of air bubbles deeper into the ocean near the surface layer will have the effect of enhancing the green or turquoise appearance in the foam patches. Therefore, the color of the sea is probably a more sensitive indicator of the surface wind speed than the percent coverage of whitecaps. Also, at higher altitudes, such as the 700-mb level, the eye cannot resolve many of the small-scale features on the ocean surface. Therefore, from this level, winds at the low wind speeds will be difficult to estimate accurately. Wind estimates will have to be tuned more to changes in surface color and overall "whiteness" of the ocean rather than to percent coverage of small-scale features.

Yet, until adequate color photography and high quality surface-photographs are available for the 700-mb observation level, the best that can be accomplished is application of a lag factor to the new, improved, low-level descriptors. Although Jordan and Fortner's data indicate a 15 to 20% lag in the recognition of key sea-state transitions between the 1500-ft and 700-mb observation levels, the current Air Force descriptors indicate a much higher lag on the order of 30 to 40%, as suggested in table A3. In the absence of documentation to confirm either of these values, an average lag of two Beaufort categories will be applied until adequate documentation is available. For example, the improved descriptors in table 1 indicate that the onset of continuous streaking occurs at a surface wind speed of about 45 kt, or B10. Hence, the onset of the same feature should be observed from 700 mb at about 60 kt, or B12. However, the onset of many features such as "non-continuous streaking", may not be observed at all. When streaking is first observed from the 700 mb level, it may already appear continuous as the observer merely sees continuous streaks that have thickened or merged together. Similarly, descriptive features such as "sea heaps up", "wind carries along wave crests" and "waves have overhanging crests" are less likely to be observed from the 700-mb level. With due consideration given to these factors, the improved sea-state descriptors for 700-mb observations are listed in Table 2.

Table 2. Surface wind estimates (kts) from state-of-the-sea observations at 700 mb.
Both mean and sustained (in parenthesis) wind equivalents are indicated.

Beaufort Number	Descriptor	Wind (20 m) Equivalent	
		Range	Mean
0-1	Sea has glassy, smooth appearance.	Calm -5	3
2	Sea rippled. Wave crests appear smooth.	5-9 (6-10)	7 (8)
3	Isolated, small whitecaps appear like white dots. Wind direction not obvious. Tightly compacted surface texture. May be able to see long underlying swell.	9-14 (10-16)	12 (14)
4	Wind direction detectable with difficulty by down-wind elongation of whitecaps. Whitecap "dots" are slightly larger and more uniformly distributed over the sea.	14-18 (16-20)	16 (18)
5	<u>Small craft warning.</u> Diffuse, scattered foam patches detectable with difficulty. Wind direction somewhat detectable by more pronounced downwind elongation of whitecaps and foam patches. Whitecaps are more numerous and cover 1-2% of the sea surface. Foam patches plus whitecaps cover 5% of the sea.	18-23 (20-26)	21 (23)
6	Wind direction easily detectable. Short, thin and diffuse looking streaks may be apparent under good lighting. Large, well defined foam patches and whitecaps are evident.	23-28 (26-33)	26 (29)
7	Foam patches occasionally take on a faint green cast. Short streaks may be more apparent under ideal conditions. Whitecaps cover 5% of the sea surface. Dense foam patches, short streaks and whitecaps cover 7% of the sea.	28-33 (32-37)	31 (34)
8-9	<u>Gale warning-tropical storm.</u> Green patches become distinct and somewhat elongated. Whitecaps and short streaks are more numerous. Whitecaps cover 10% of the sea surface.	33-44 (37-50)	38 (43)
10-11	<u>Storm warning.</u> Edges of whitecaps become less distinct. Some streaks have greenish cast. Sea appears 10% greenish. Sea mostly covered by streaks of medium length and takes on a faint overall whitish cast. Dense white water in whitecaps, foam patches and streaks cover 30% of the sea.	44-55 (50-62)	50 (56)

Table 2. Surface wind estimates (kts) from state-of-the-sea observations at 700 mb.
Both mean and sustained (in parenthesis) wind equivalents are indicated.

Beaufort Number	Descriptor	Wind (20 m) Equivalent	
		Range	Mean
12	<u>Hurricane warning.</u> Churning or rolling appearance of the sea first noticed. Streaks appear broader and somewhat meandering.	55-61 (62-69)	(65)
13	Wind streaks become continuous or nearly so and broader to form bands. Sea appears 30% green. Dense whitewater areas cover 50% of the sea.	61-66 (69-75)	(72)
14-15	Streaks are continuous. Sea takes on a milky appearance. Streaks, patches and whitecaps more diffuse looking at their edges. Breakers have large, curved crests and have more distinct undulating effect on streaks giving a more pronounced churning effect. Whiteish cast becomes tinged with green.	66-78 (75-88)	(81)
16-17	Blowing spray reduces visibility and increases obscuration of surface features. May see small white crescents and only thickest streaks. Sea takes on a flat appearance. Large, milky foam patches are apparent. Broad, continuous bands of indistinct white and green foam are evident. Sea 50% greenish.	78-90 (88-102)	84 (90)
18-19	Sea covered by a white cast. Only small, white spotty areas and occasional thick band can be seen on a generally whiteish/greenish background. Sea takes on a confused appearance. Surface appears 85% white and green.	90-102 (102-115)	99 (109)
20-21	Foam patches, bands and whitecaps merge into large undefinable areas or white sheets. Variations in brightness are less distinct but still result in churning appearance.	102-116 (115-129)	110 (122)
22-23	Sea 100% white and green. Only slight variation in whiteness is apparent.	116-132 (129-145)	125 (137)

6. TRAINING METHODS SUGGESTED FOR APPLYING SEA-STATE DESCRIPTORS TO DETERMINATION OF ESTIMATED SEA-STATE WINDS

Estimated surface winds from sea-state characteristics are, by definition, rigidly based on sea-state observations alone. Thus, it is imperative that the very best sea-state descriptors be available to observers (ARWO's) for each observational altitude. With the descriptive material in hand, it becomes equally important to use trained observers who will make these sea-state determinations as consistently and accurately as possible, given the subjective nature of such observations. There is no evidence to support the assumption that a "experienced observer", without adequate descriptors matched with ground truth, and without continuing training with positive feedback, can make such judgments more accurately than a relatively inexperienced observer, although he may be more consistent in such determinations. Experience without training and valid feedback will not improve accuracy.

A formal training program is motivated by the large scatter about the means of the ESS values throughout the observed sea-state ranges within a given storm or group of storms. Therefore, it is recommended that a training program be established to "fine-tune" the ability of observers to make such judgments. This training program would include sea-state descriptive information matched with high quality sea-state photographs and the highest available quality "surface truth." The published sea-state catalog should be used as a guide to make sea-state determinations for operational and training purposes. A useful training program, however, would include additional sets* of sea-state photographs for each possible observational level (1500 ft and 700 mb). Currently, there are available only black and white photographs taken from about the 1500-ft altitude level over a surface wind speed range of approximately 14 to 102 knots or Beaufort 4 to 19. Each black and white sea-state photograph for the 1500-ft observational level has been matched to a Beaufort number based on a derived 20-m surface wind from the known flight-level wind. Additional sets of photographs would be needed to conduct a "flash card" type training program. An intensified training program using these visual and descriptive aids should familiarize observers with instant pattern recognition of sea state for each Beaufort category. Through an intensified training program of this type, consistent and accurate estimates of surface wind speeds could be accomplished. With the new 70-mm automatic aperture Hasselblad camera system with controller for frame annotation, improved quality color photographs matched with ground truth for both the 700-mb and 1500-ft levels can be obtained.

At a selected time before the beginning of the tropical cyclone reconnaissance season, the intensive training program should begin, using combinations of the photographic training sets. A training session of perhaps 1 hour is recommended to take place each week throughout the field season. In addition, there should be a control group of observers who will not take the training, but who will be tested at least once with the trainees. However, the control group should not see the test results and should not have access

*There should be enough sets to minimize trainee recognition of previous photographs.

to the training aids. Statistics should be kept for each individual and group to compare levels of improvement. Furthermore, similar statistics should be recorded in the field for analysis at the end of the field season.

In conclusion, we believe that analysis of the results of the training program in future field seasons with the interim improvement of the quality of the photographs of sea-state matched with ground truth, and added descriptive information for each Beaufort category which until now has not been documented, will result in the reduction of the scatter of estimates that presently exists and should, over the long term, produce more realistic mean surface wind estimates.

7. CONCLUSIONS AND RECOMMENDATIONS

This study has provided the first documentation in 30 years for use as guidance in estimating surface winds over the ocean from aircraft. The study has utilized representative sea state photography in tropical cyclones to construct a sea state catalog ranging from Beaufort category 3 to Beaufort category 19, which is representative of mean 20-m winds from 9 to 102 kt.

It has been concluded that a training program can be conducted whereby observers can consistently recognize sea state characteristics over a wide range of sea conditions to estimate surface winds to within one Beaufort category or about ± 6 kt. A new set of descriptors applicable to aircraft viewing of the sea has been developed based on low level flights near cloud base and extrapolated for use at the 700 mb (10,000 ft) flight altitude.

A study of previous estimated sea state (ESS) winds suggested that prior knowledge of flight level winds biased the estimates toward that value in the mean. Estimates by weather observers in the western North Pacific showed smaller overall biases than less experienced observers in the western North Atlantic. The former tended to underestimate winds below 80 kt and overestimate those above 80 kt while the latter overestimated winds above 40 kt. The standard deviation of differences between the maximum ESS winds and maximum flight level or minimum pressure estimated winds averaged ± 20 kt for the 700 mb flight level, but only about ± 4 kt for the 1500 ft flight level. These values may reflect, in part, the natural variability in real vertical wind shear within tropical cyclones.

It is therefore recommended that a series of short term, intermediate term and long term steps be taken to improve the quality of surface wind estimates. An immediate step that can be taken is to establish an ongoing training program for airborne weather observers and one or two other flight crew members. It is suggested that an initial workshop be organized in which observers are taught to recognize key sea state characteristics, guided initially by sea state descriptors but ultimately by pattern recognition whereby repeated exposure to sea state photographs are matched cognitively with proper wind speed estimates. Follow-on, periodic sessions throughout the year, as flight experience in real storms is gained, should be scheduled at 2-3 month intervals and the observers tested on their skills.

It is also recommended that a practice be established whereby an aircrew member, or a consensus of aircrew members, with no knowledge of the flight

level wind be designated as those responsible for estimating the surface wind. In this way, a truly independent surface wind estimate could be obtained.

In the intermediate range, over the next 2-4 years, it is recommended that steps be taken to improve the documentation of sea conditions with simultaneous high quality, color photography and reliable surface wind estimates either from additional low level aircraft, prototype airborne remote sensors or from surface buoys. A special effort should be made to obtain photographs from 700 mb concurrent with some form of reliable surface wind measurement.

Since the sea state estimation method is ultimately limited by its subjectivity, the long term solution to the problem of reliable and consistent surface wind measurement over the ocean lies in the use of remote sensors to measure surface winds. Several techniques using active and passive airborne microwave sensors have already been tested. A commitment to develop an operational passive microwave sensor should be made as soon as possible to provide the capability for routinely measuring surface winds within 5-7 years. The technology exists. Therefore if there is a sufficient national need for surface wind estimates over the ocean for use in forecasts and warnings of damaging winds, storm surge or ocean wave heights, it is recommended that planning be undertaken as soon as possible to transfer existing technology to the operational arena.

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Footnote List

1. Current affiliation: National Hurricane Center, Miami, Florida.
2. "Double drift" was a technique of estimating the wind vector by flying along two or more different headings for several minutes on each heading, on the assumption that the mean wind did not change over the course flown. An average drift angle was determined along each heading by estimating the angle between the heading of the aircraft and the course made good (or aircraft track) with reference to identifiable features on the sea surface. Furthermore, care was taken to maintain a constant true airspeed along both headings. Optimum results could be obtained by flying three headings along a zig-zag pattern involving 45° to 90° turns. A wind solution could then be computed graphically with a dead reckoning (DR) slide rule computer, as outlined in the U.S. Air Force training manual, AFM 51-40, NAVAIR 00-80v-49 (1973), or it could be computed directly from :

$$\begin{aligned}X^2 &= 1 + 2[1 - \cos \Delta H - \cos \delta 2 + \cos (\Delta H + \delta 2)] \\Y^2 &= X^2 - 2X \cos \delta 1 + 1 \\W &= AY \\WD &= H1 + \cos^{-1} (X^2 - Y^2 + 2Y - 1)\end{aligned}$$

where $\Delta H = H1 - H2$ is the heading change, $\delta 1$ and $\delta 2$ are the two drift angles (right drift is positive), A is the airspeed, W is the wind speed and WD is the wind direction.

APPENDIX A
PREVIOUS SEA STATE DESCRIPTORS

Table A1. Past and present sea state descriptors as a function of wind speed

Beaufort Number	ESS wind speed (kt)		1500 ft		700 MB	
	VJ-2 (1952)		Hosler (1957)		AWS 105-25 (1982)	
	Navy Range	Air Force Mean				
1-2	<6	0	No whitecaps visible; small occasional ripples	-	Sea glassy; appearance of being covered with oil	Sea like a mirror, glassy.
3	7-9	5-9	Occasional ripples	First detectable whitecaps	Sea rippled; isolated, brief whitecaps; unable to determine direction	Sea rippled; crests have a glassy appearance and do not break.
	10-12	10	Whitecaps become more frequent; occasional small whitecaps are elongated perpendicular to wind direction and carry down-wind a short distance	-	Small, well defined whitecaps of uniform size; white crests disappear quickly; first able to detect direction	First detect isolated brief whitecaps; may be difficult to discern direction
4	13-15	14	Whitecaps become larger and more frequent; occasional small patches of foam remain from breaking wavelets	-	Whitecaps closer together, and some longer than others; may detect slight wind streaks of short duration	Frequent, small whitecaps; easy to determine wind direction.
	16-18	17	Slight traces of wind streaks parallel to wind direction begin to appear; white-caps and small patches of foam cover entire sea	-	-	-
					First detectable whitecaps	
					-	

Table A1. (continued) Past and present sea state descriptors as a function of wind speed

Beaufort Number	ESS wind speed (kt)		1500 ft		700 MB	
	VJ-2 (1952)		Hosler (1957)		AWS 105-25 (1982)	
	Navy Range	Air Force Mean				
5	19-22	20	20	Wind streaks become more noticeable; secondary wavelets appear on swell crests	-	Whitecaps on 75-100% of crests; all whitecaps produce some wind streaks
6	23-28	25	25	Larger, elongated waves form; numerous patches of white foam remain from breaking waves; wind streaks become still more noticeable	-	Isolated green patches of short duration visible in all directions close to aircraft; occasional wave crests carried by wind
7	29-35	32	30	Larger and more frequent patches of white foam from breaking waves; occasional very large waves "mush" or flare out downwind while breaking and produce large patches of white foam; light spray blowing off breaking waves is carried downwind	-	Small green patches occasionally seen at a distance; 50% of wave crests picked up by wind; some wind streaks form broad bands; sea heaps up
					-	First detect small green patches lasting about 3-5 sec; sea heaps up and definite wave height discernible.
					-	Green patches last approximately 10-15 sec.

Table A1. (continued) Past and present sea state descriptors as a function of wind speed

Beaufort Number	ESS wind speed (kt)		1500 ft		700 MB	
	VJ-2 (1952)		Hosler (1957)		AWS 105-25 (1982)	
	Navy Range	Air Force Mean				
8	36-42	39	40	Blowing spray becomes more pronounced; wind streaks appear very prominent, but are not continuous	Green patches cover 50% of sea; waves have overhanging crests; wind streaks appear very prominent but are not continuous	Some green patches persist after wave front breaks; white streaking increases, with some streaks forming broad bands.
9	43-48	45	45	Wind streaks become continuous	Green patches cover 50% of sea. Wind streaks become continuous.	First detectable green patches
			50	-	Green patches cover 50% of sea; waves appear to be pushed by the wind; streaks of foam become patchy	Sea appears 10-20% green in color. Areas not green are mostly streaked. Spray carried ahead of larger waves, and rolling motion of larger waves first detected.
10	49-59	54	55	Wind streaks continue to increase and cover entire sea; visibility of sea surface affected by blowing spray	-	-
11			60	-	Wind streaks cover entire sea; visibility of sea surface affected by blowing spray; churning effect evident.	-

Table A1. (continued) Past and present sea state descriptors as a function of wind speed

Beaufort Number	ESS wind speed (kt)		VJ-2 (1952)		1500 ft Hosler (1957)		AWS 105-25 (1982)		700 MB Hosler (1957)		AWS 105-25 (1982)	
	Navy Range		Air Force Mean									
12	60-75	67	65	Whole sea takes on whitish-green cast; large individual patches of white foam and breaking waves are still visible; blowing spray covers entire sea	Many large green patches; white spray appears	Surface 75% green and white; individual patches of white foam and breaking waves are still visible; blowing spray covers entire sea.	Green patches become numerous	Sea appears 25-40% green; broad streak bands seen everywhere; churning effect evident in small areas.				
	76-100	88	80	Sea becomes whiter and whiter from blowing spray and foam	-	Surface 90% green and white	-	Sea 60% green with slight white sheet				
			100	-	Entire surface green and white, but spray still distinguished	-	Many large green patches; white spray appears.	Surface 75% green and white. Surface features indistinct with areas frequently appearing as large white sheets.				
	>100		130	Sea completely white with blowing spray and foam; assume tumbling, cascading appearance.	Solid white-green, churning appearance	-	-	Entire surface green and white				
			>130			-		Entire surface white and green with churning but spray still distinguishable.				

Table A2. Current 10-m Beaufort wind speed equivalents and sea state descriptors.

B	Wind Speed (kt) Range	Mean	Nautical Term	Revised 20-m Wind Speed Equivalents (kt)	Descriptor
0	< 1	0.5	calm	1.6	Sea like a mirror.
1	1-3	2	light air	4.0	Ripples with the appearance of scales are formed, but without foam crests.
2	4-6	5	light breeze	7.0	Small wavelets, still short, but more pronounced; crests have a glassy appearance and do not break.
3	7-10	9	gentle breeze	11.0	Large wavelets; crests begin to break, foam has glassy appearance; scattered whitecaps.
4	11-16	13	moderate breeze	15.0	Small waves, becoming longer; fairly frequent whitecaps.
5	17-21	19	fresh breeze	20.0	Moderate waves, taking a more pronounced long form; many whitecaps; some spray.
6	22-27	24	strong breeze	24.5	Large waves begin to form; whitecaps everywhere; more spray
7	28-33	30	near gale	29.3	Sea heaps up, white foam from breaking waves begin to be blown in streaks.
8	34-40	37	gale	34.5	Moderately high waves of greater length; edges of crests begin to break into spindrift; foam is blown in well marked streaks.
9	41-47	44	strong gale	40.3	High waves; dense streaks of foam; wave crests begin to roll; spray may reduce visibility.
10	48-55	52	whole gale or storm	47.0	Very high waves with long overhanging crests; foam patches blown in dense white streaks; sea takes on white appearance; rolling of the sea is heavy; visibility reduced.
11	56-63	60	violent storm	54.3	Exceptionally high waves; sea covered with white foam patches; edges of wave crests blown into froth; visibility still more reduced.
12	64-71	68	hurricane	58.0	Air filled with spray; sea completely white with foam and driving spray; visibility greatly reduced.

Table A3. First detection of ocean surface features based on past and present descriptors.

No.	Event	Wind Speed of first detection (kt)			
		700 MB	1500 ft	ships old 10 m	new 20 m
A	Ripples on the sea	7	3	2	4
B	Whitecaps	10	8	9	12
C	Wind direction from elongated whitcaps	15	11	-	15
D	White foam patches	-	14	13	17
E	Wind streaks	25	17	30	30
F	Green patches	30	25	-	-
G	Spray blowing off breaking waves (spindrift)	50	35	37	36
H	Wind streaks become continuous	-	45	37	36
I	Spray begins to reduce visibility	80	55	44	42
J	Churning appearance of sea	55	60	47	44
K	Visibility of sea surface features severely hampered by blowing spray	100	65	60	54
L	Sea completely green and white	130	100	68	59

APPENDIX B

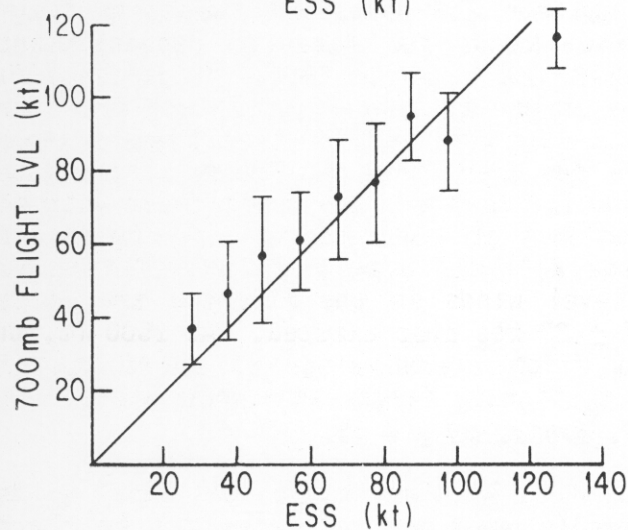
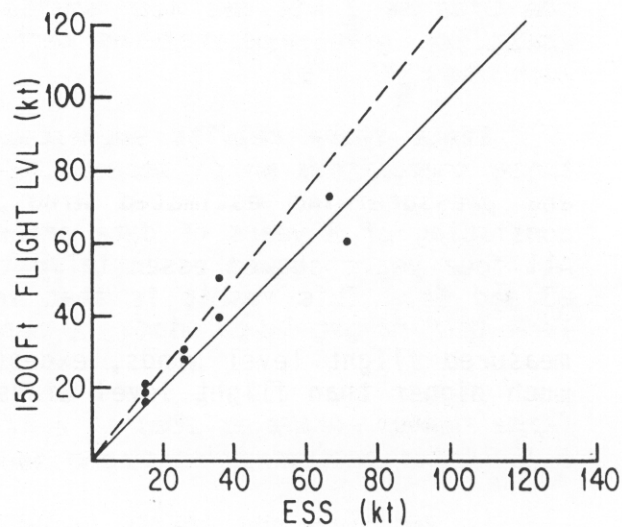
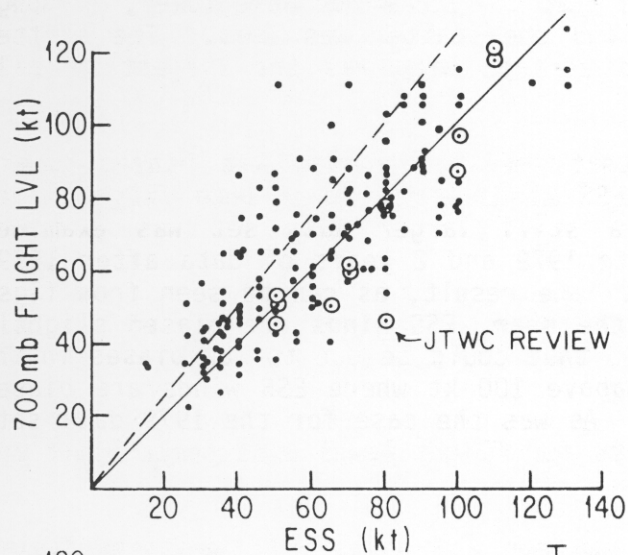
ESS WINDS AS A FUNCTION OF INDEPENDENT WIND DETERMINATIONS FOR THE
WESTERN NORTH ATLANTIC AND WESTERN NORTH PACIFIC TROPICAL CYCLONE REGIONS

Maximum ESS winds were compared with measured flight level and pressure/wind estimated maximum winds for the entire 1979 typhoon season, rather than the limited subset described in the JTWC review (personal communication). These results are shown in figs. B1 and B2 with the JTWC points circled. The larger comparison data set for the entire 1979 season suggested that in the mean, the ESS winds were slightly less than flight level winds by a mean bias of 8 kts. The scatter about the mean flight level wind, as measured by the standard deviation, was large, averaging ± 18 kts. The comparison of ESS winds with 1500 ft winds also revealed that the ESS winds were lower, although the bias of 3 kts was much smaller and the scatter was less. The scatter about the mean pressure/wind derived surface wind was the largest of all, averaging ± 25 kts.

Since these results suggested that the JTWC review was biased toward those comparisons which showed that ESS winds were higher than flight level and pressure/wind estimated winds, a still larger data set was examined consisting of 2 years of data prior to 1979 and 2 years of data after 1979. All four years showed essentially the same result, as can be seen from figs. B3 and B4. This result is that in the mean, ESS winds are biased slightly less than flight level winds, a result that could be due to low biases in the measured flight level winds, except above 100 kt where ESS winds are biased much higher than flight level winds. As was the case for the 1979 data set, large random errors existed of ± 17 kts for flight level wind comparisons and ± 25 kt for pressure/wind comparison.

It was also decided to compare maximum ESS winds with measured flight level and pressure/wind derived maximum winds for Atlantic reconnaissance missions in 1979 as well as for 1976-1978, 1979 and for 1980. Comparisons for 1979 are shown in Fig. B5 and for the other years in Figs. B6 and B7. Surprisingly, the Atlantic data set for 1979 as well as the other 5 years showed that the ESS winds were much larger, in the mean, than the 700 mb flight level winds, exhibiting a bias of nearly 20 kts. However, the comparisons with the pressure/wind estimates showed the same sort of low biases as did the Pacific data. This suggested that either the Atlantic pressure/wind relation was biased high or the measured flight level winds in the Atlantic are biased low. The same large random errors of ± 20 kts also existed. At 1500 ft, the ESS winds were slightly smaller than flight level winds up to 40 kts, in agreement with Pacific comparisons, but slightly larger at higher winds. The scatter is much smaller than at 700 mb, averaging ± 4 kt.

In the comparisons of maximum ESS winds with maximum flight level winds, it was possible that the two measurements were not colocated due to clouds obscuring the sea at the time of maximum flight level wind measurement. Therefore reconnaissance reports from flight logs of simultaneous flight level and ESS winds were compared for Atlantic missions flown in 1979. This spot comparison for 1500 ft and 700 mb flight levels is shown in Fig. B8. It essentially confirms the results of previous maximum wind comparisons, i.e., that 1500 ft ESS winds agree with flight level winds and that 700 mb ESS winds are biased low compared to flight level measurements.



1979 ANNUAL TYPHOON REPORT

Fig. B1. Comparison of maximum estimated sea state (ESS) winds with flight level maximum winds for western North Pacific typhoons during 1979 based on data published in Joint Typhoon Warning Center (JTWC) Annual Typhoon Report. Cases referenced in JTWC review are circled in upper left panel. Averages and standard deviations (indicated by error bars) in 10 kt categories are plotted in lower left panel for the 700 mb flight level.

ANNUAL TYPHOON REPORT (1979)

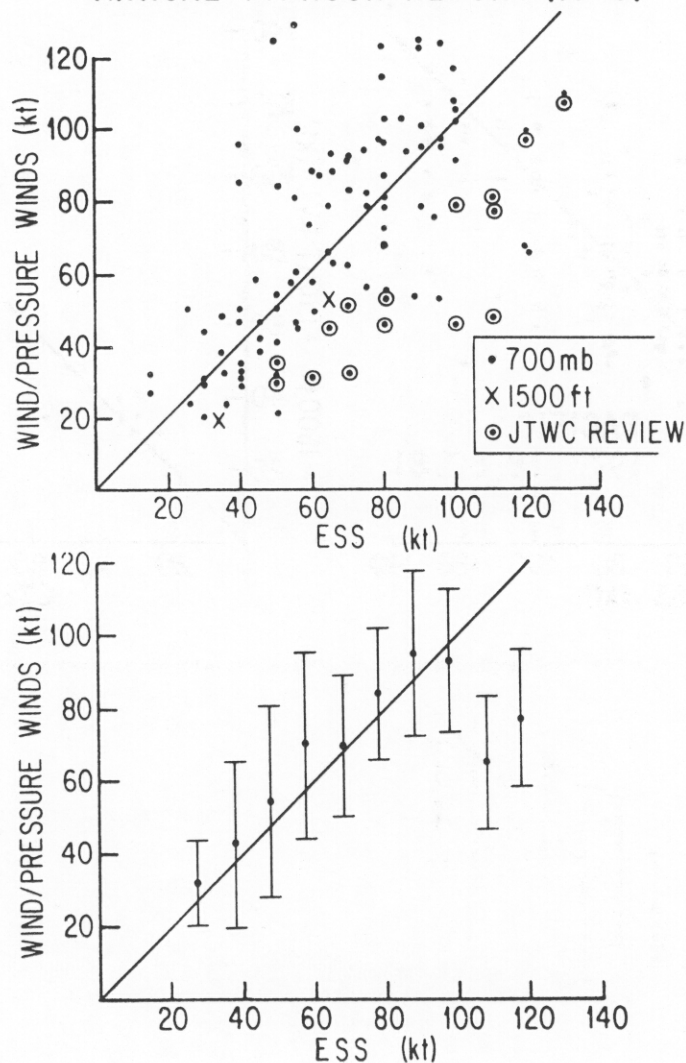


Fig. B2. Same as Fig. B1, except comparisons are made of maximum ESS winds with 1 minute maximum sustained surface wind estimates derived from application of the Atkinson and Holiday (1977) relationship to measurements of the minimum surface pressure.



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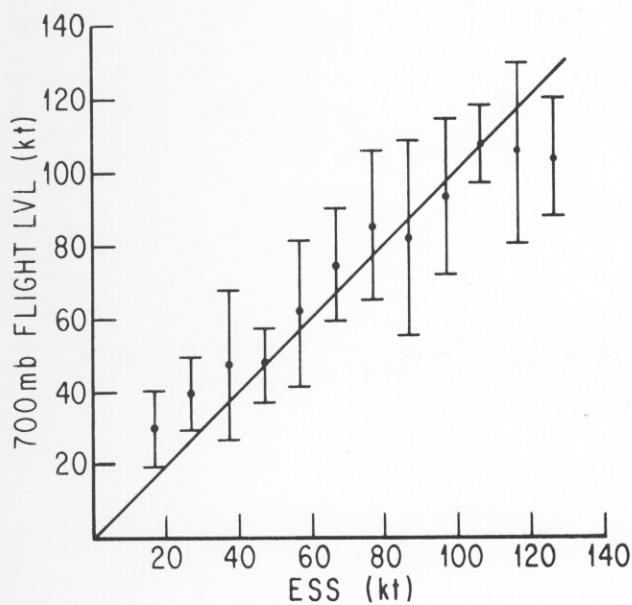
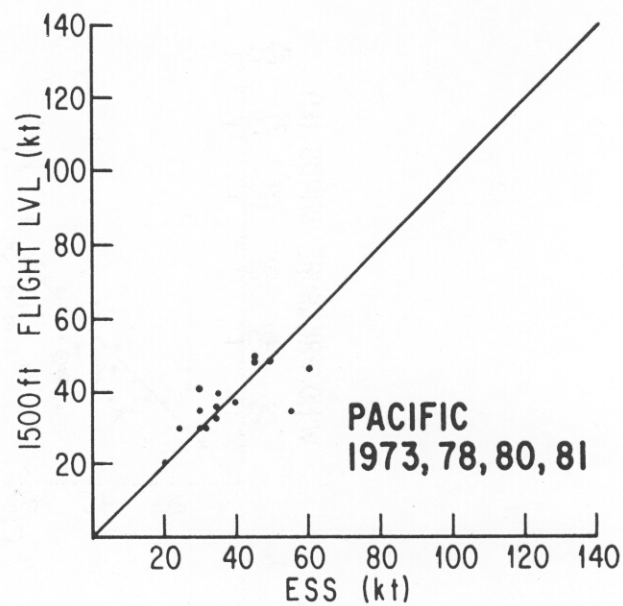
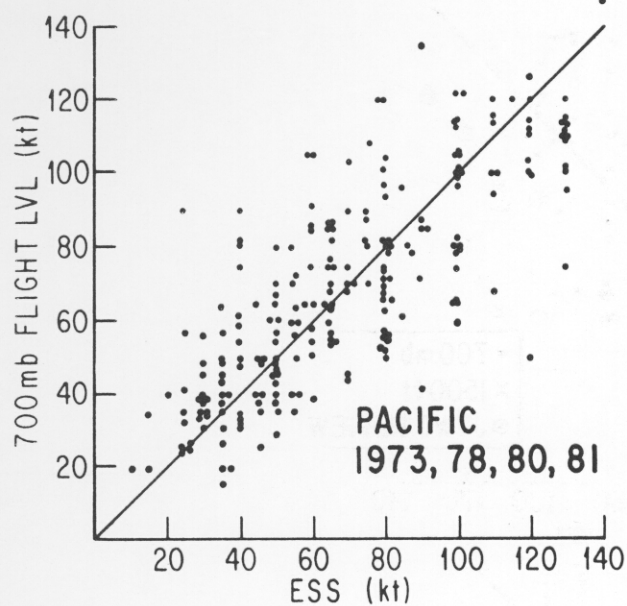


Fig. B3. Same as Fig. B1, except that comparisons are based on data published in JTWC Annual Typhoon Reports for 1973, 1978, 1980 and 1981.

ANNUAL TYPHOON REPORT 1973, 1978, 1980, 1981

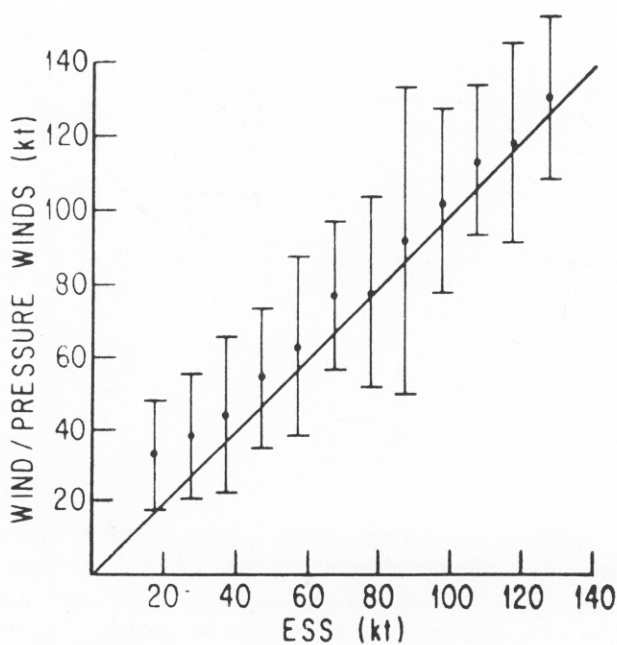
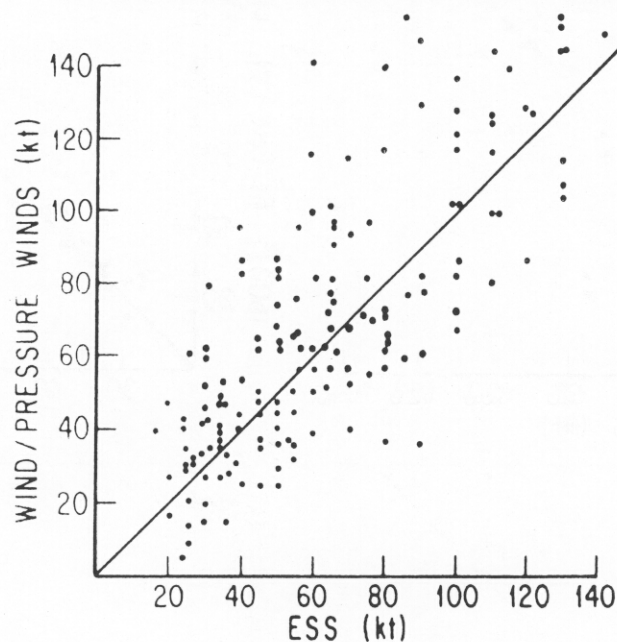


Fig. B4. Same as Fig B2, except that comparisons are based on data published in JTWC, Annual Typhoon Reports for 1973, 1978, 1980 and 1981.

ANNUAL DATA & VERIFICATION TABULATION ATLANTIC TROPICAL CYCLONES 1979

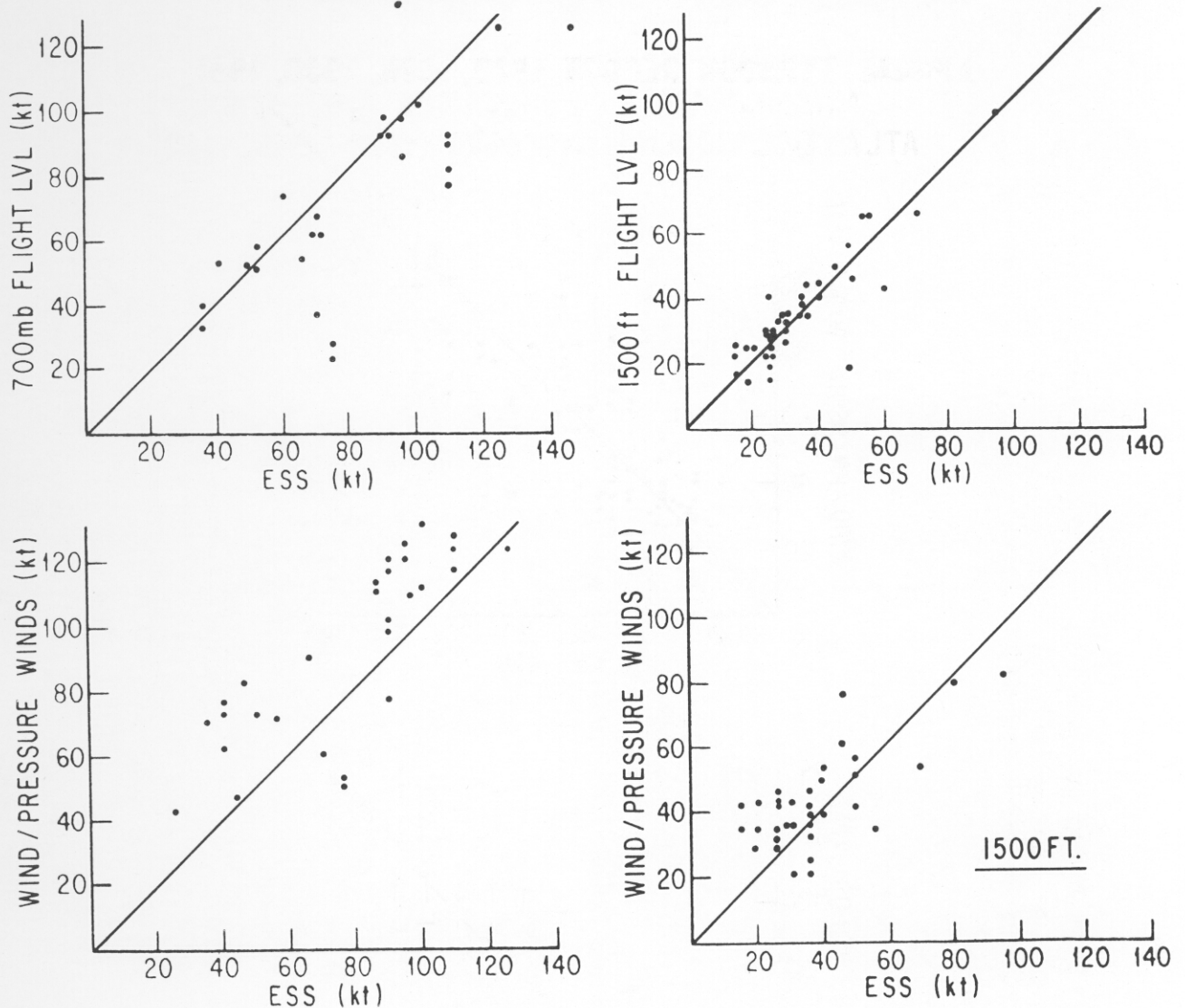


Fig. B5. Comparison of maximum ESS winds with flight level maximum winds (top two panels) for western North Atlantic hurricanes during 1979 based on data published in National Hurricane Center (NHC) Annual Data and Verification Tabulation, Atlantic Tropical Cyclones (Hebert, P. J. and staff) for 1979. Bottom two panels show comparisons of maximum ESS winds with 1 minute maximum sustained surface wind estimates derived from application of the Kraft (1961) relationship to measurements of the minimum surface pressure.

ANNUAL DATA & VERIFICATION TABULATION ATLANTIC TROPICAL CYCLONES (1975-1978, 1980)

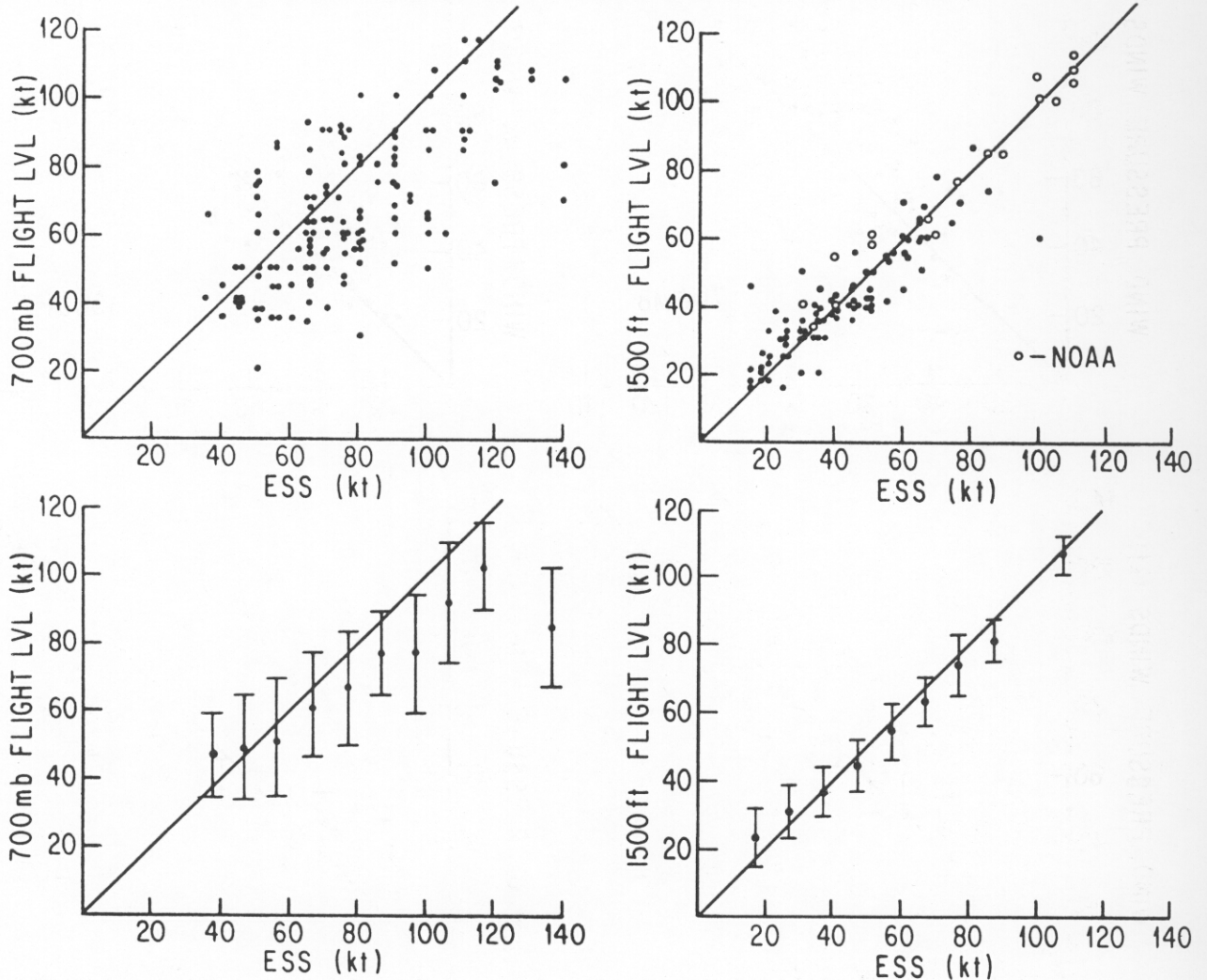


Fig. B6. Comparison of maximum ESS winds with flight level maximum winds for western North Atlantic hurricanes based on data published in NHC Annual Data and Verification Tabulation, Atlantic Tropic Cyclones for 1975-1978 and 1980. Averages and standard deviations (indicated by error bars) in 10 kt categories are plotted in lower two panels.

ANNUAL DATA & VERIFICATION TABULATION ATLANTIC TROPICAL CYCLONES (1976-1978, 1980)

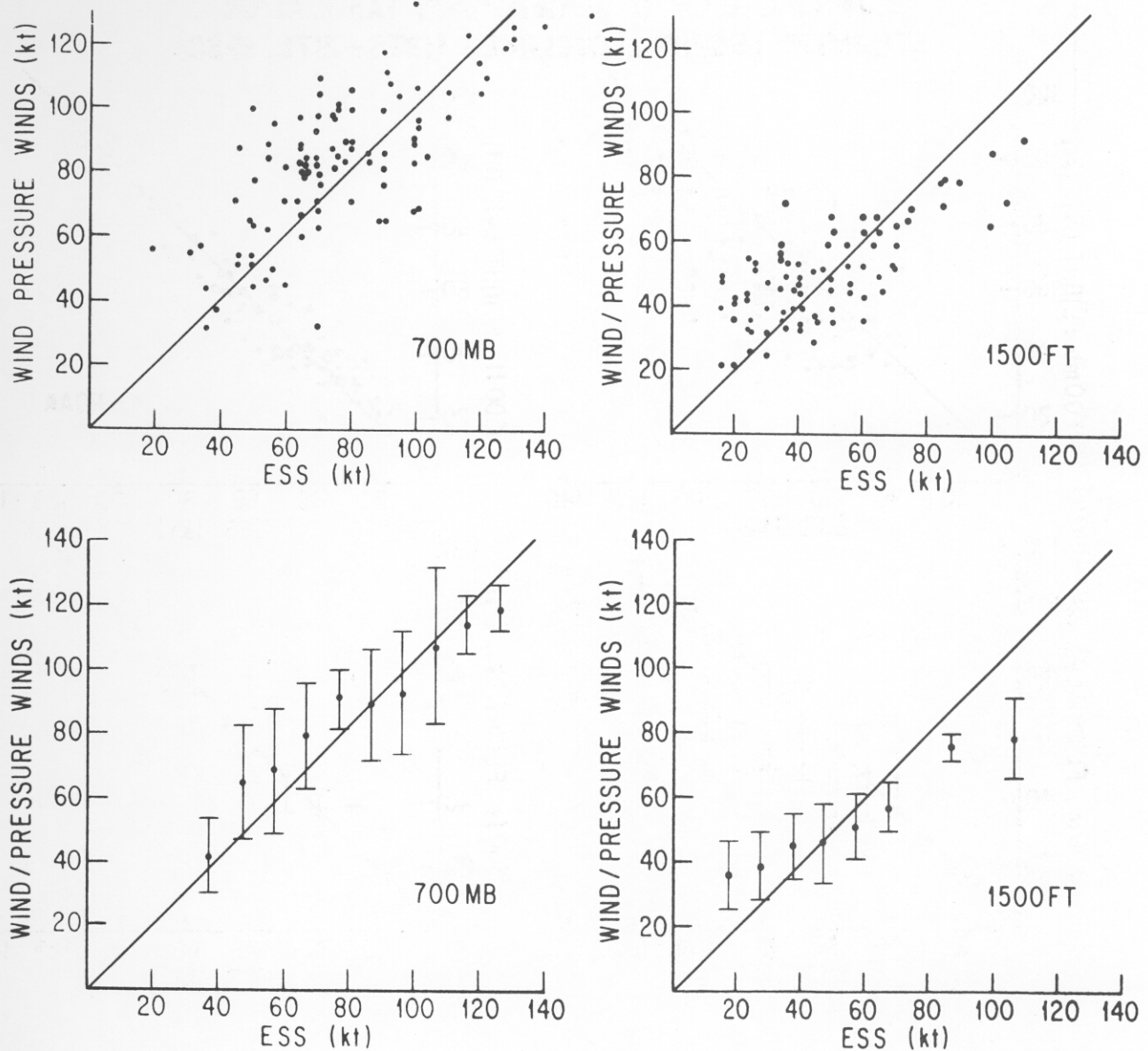


Fig. B7. Same as Fig. B6, except comparisons are made of maximum ESS winds with 1 minute maximum sustained surface wind estimates derived from application of the Kraft (1961) relationship to measurements of the minimum surface pressure.

1979 ATLANTIC SPOT DATA

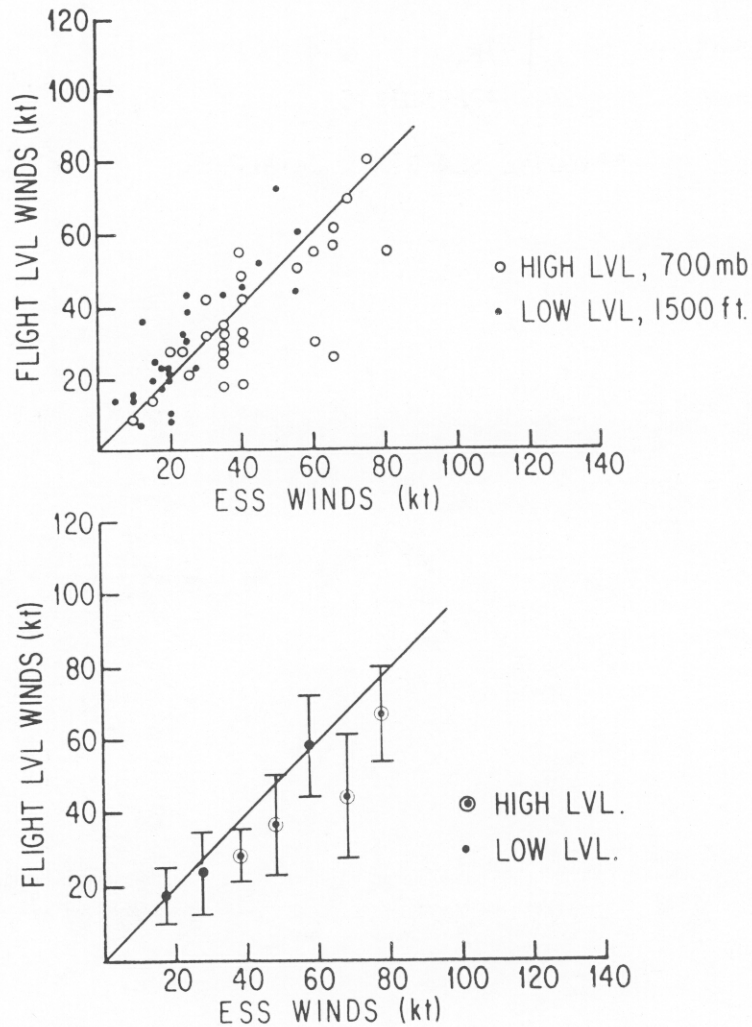


Fig. B8. Comparison of spot ESS winds with flight level winds observed at the same geographical location for western North Atlantic hurricanes for 1979 based upon recco message logs on file at NHC. Bottom panel shows averages and standard deviations. Open circles indicate comparisons with 700 mb observations and solid circles indicate comparisons with 1500 ft observations.

APPENDIX C
AIRBORNE SEA STATE CATALOG

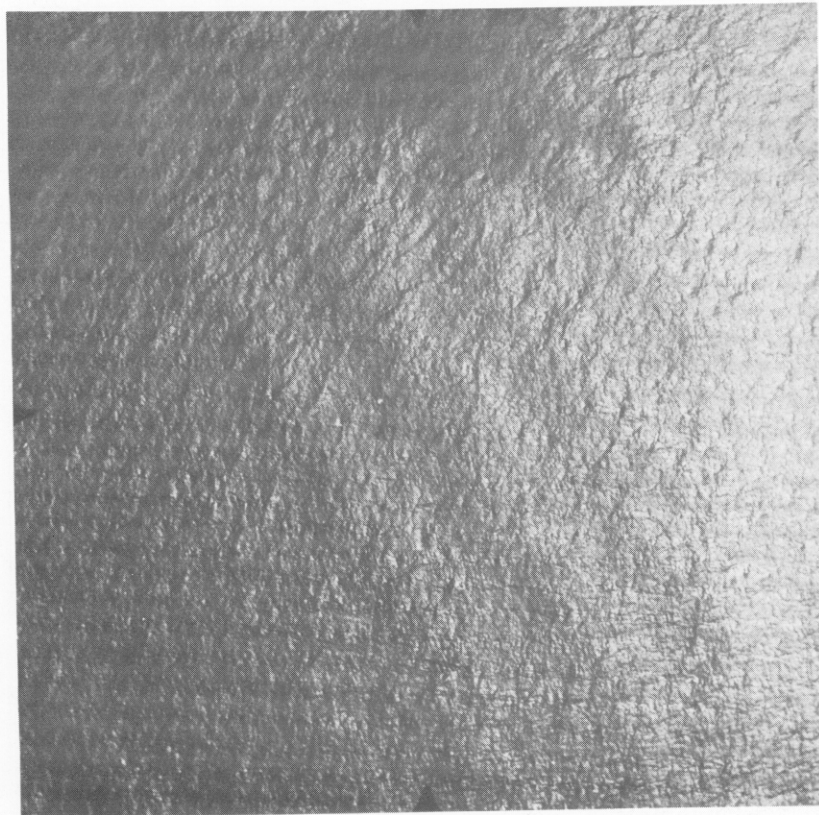


Figure 1a. Flight 750916A, Eloise.
RA = 5276 ft. Flight level wind 6.9 m s^{-1}

7 m s^{-1} B3 13 kt (14 kt)

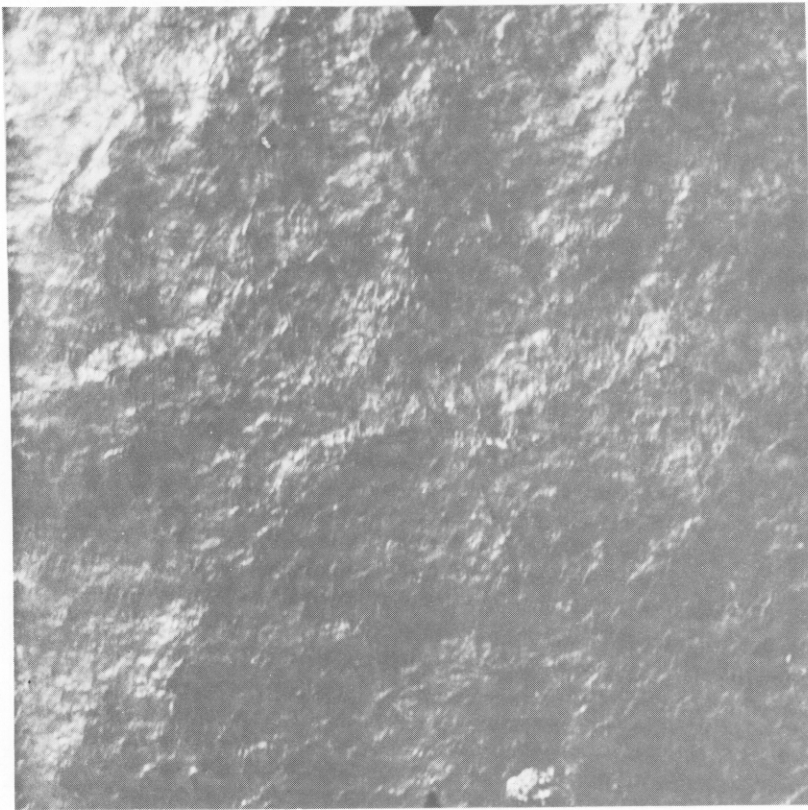
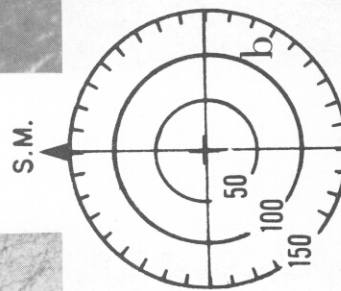


Figure 1b. Flight 750929A, Gladys.
RA = 515 ft. Flight level wind 7.7 m s^{-1}

7 m s^{-1} B3 14 kt (16 kt)



Beaufort 3 (9-14 kt mean; 10-16 kt sustained). Surface like wrinkled paper. Small well defined whitecaps of uniform size but few in number. White crests disappear quickly. First able to tell direction but with difficulty.

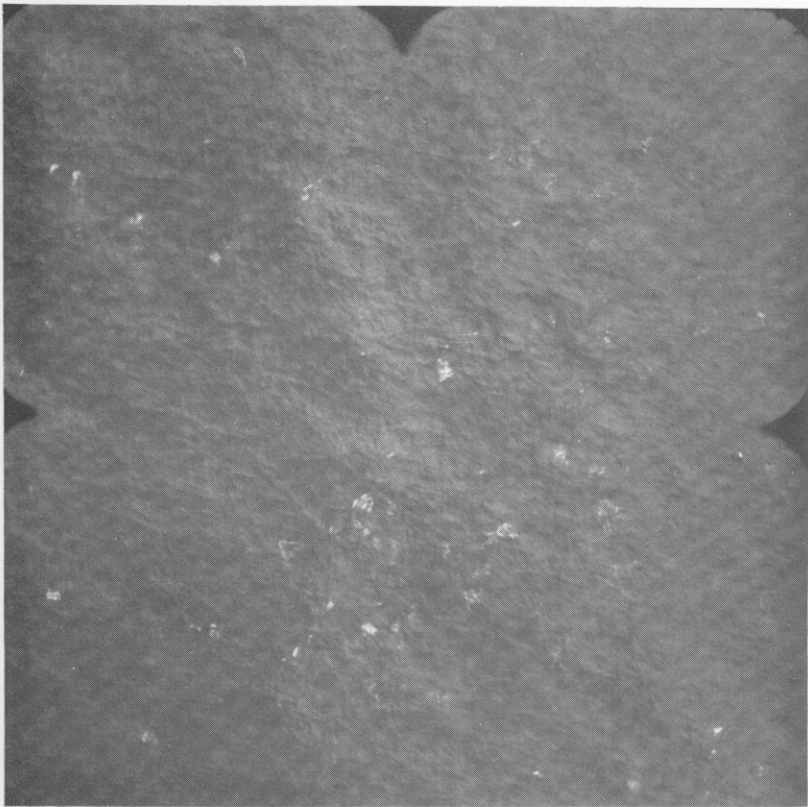


Figure 2a. Flight 750917A, Eloise.
RA = 1542 ft. Flight level wind 8.3 m s^{-1}

8 m s^{-1} B4 15 kt (17 kt)

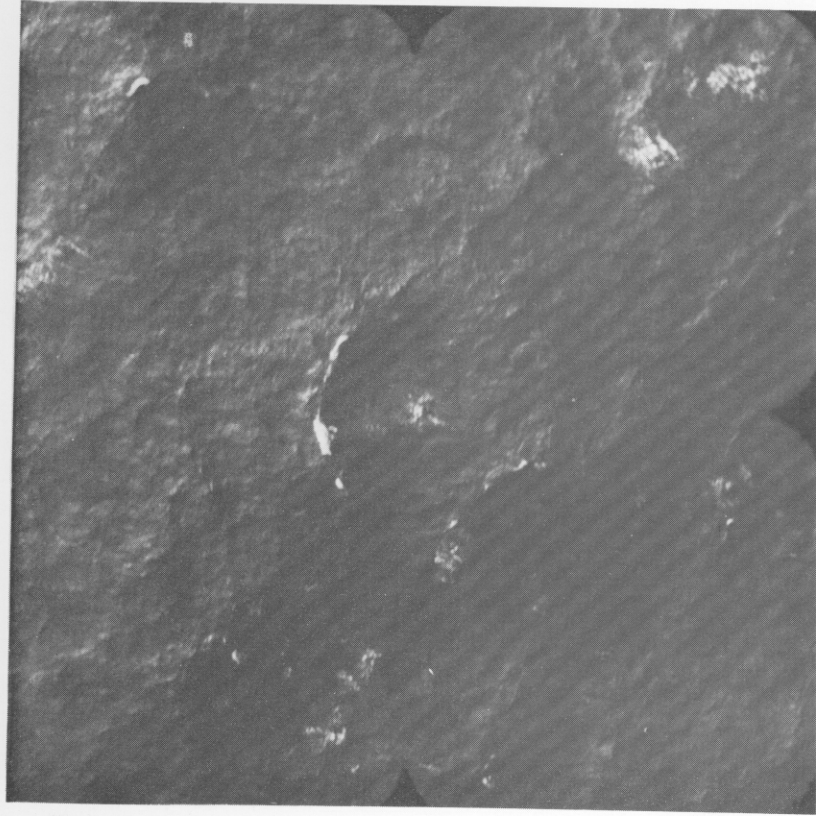
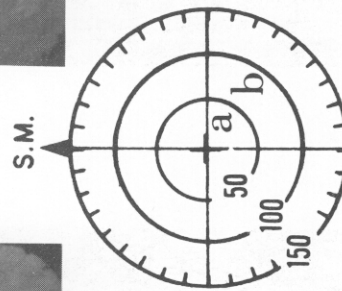


Figure 2b. Flight 750929A, Gladys.
RA = 509 ft. Flight level wind 8.6 m s^{-1}

8 m s^{-1} B4 15 kt (17 kt)



Beaufort 4(14-18 kt mean; 16-20 kt sustained). Small foam patches. Number of breaking crests increase slightly and are a little larger. First able to tell direction with confidence. Wrinkled texture of surface is very evident.

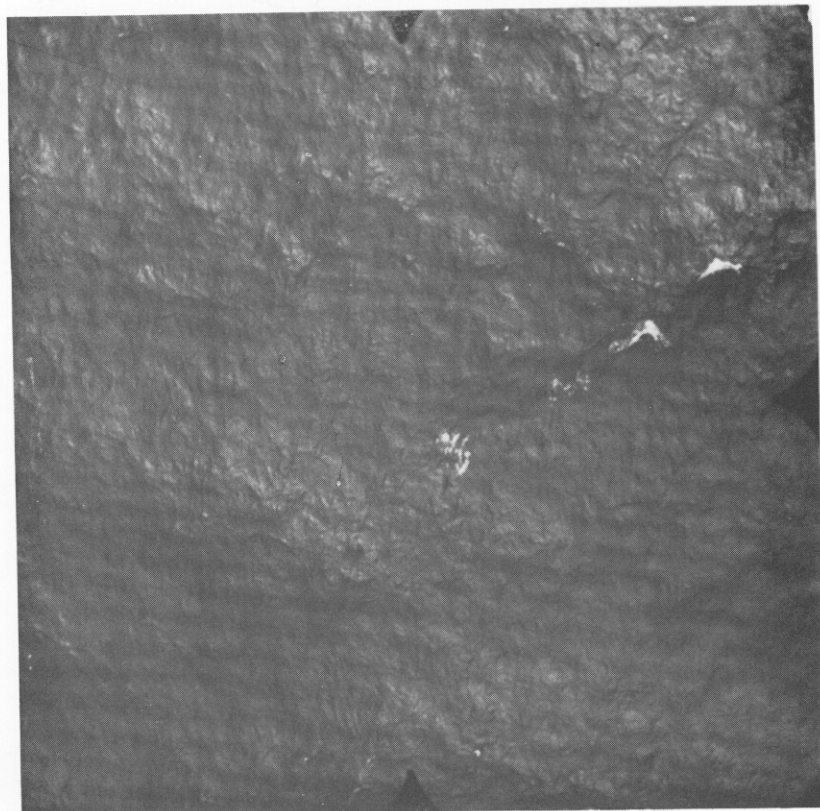


Figure 2c. Flight 750916A, Eloise.
RA = 454 ft. Flight level wind 8.5 m s^{-1}

8 m s^{-1} B4 15 kt (17 kt)

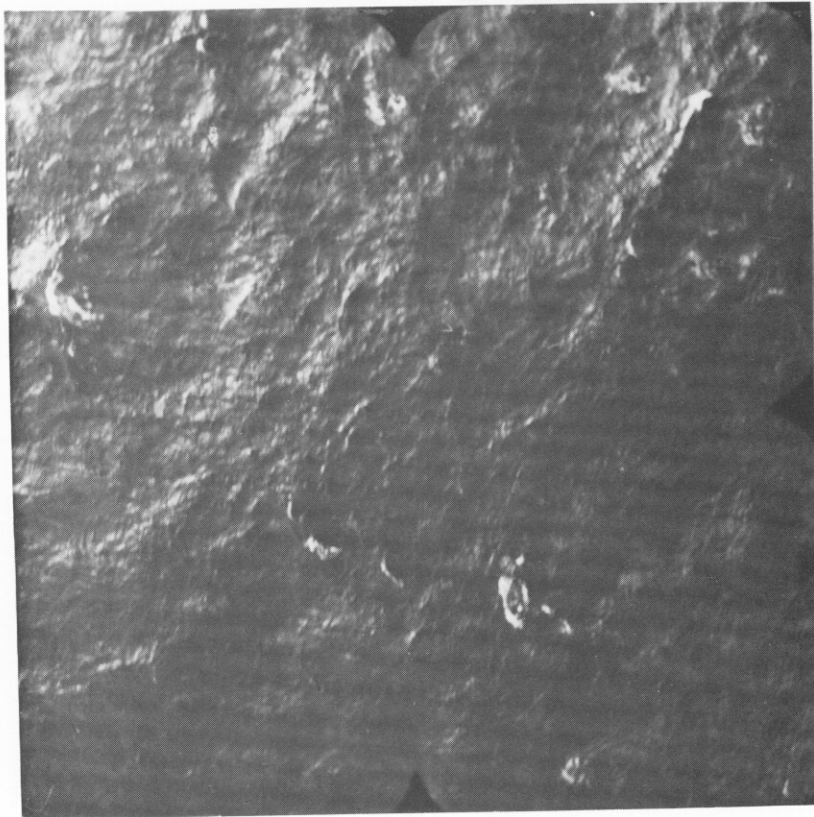
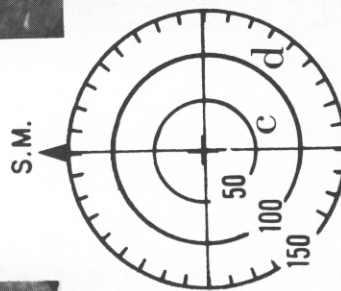


Figure 2d. Flight 750929A, Gladys.
RA = 502 ft. Flight level wind 8.8 m s^{-1}

8 m s^{-1} B4 15 kt (17 kt)



Beaufort 4 (14-18 kt mean; 16-20 kt sustained). Small foam patches. Number of breaking crests increase slightly and are a little larger. First able to tell direction with confidence. Wrinkled texture of surface is very evident.

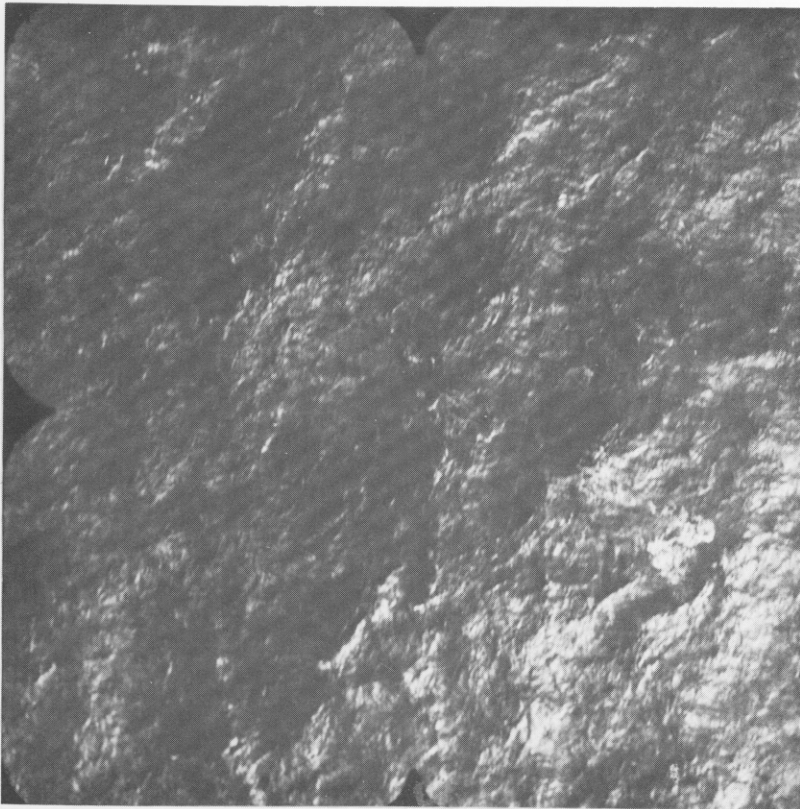


Figure 2e. Flight 750929A, Gladys.
RA = 502 ft. Flight level wind 9.5 m s^{-1}

9 m s^{-1} B4H 17 kt (19 kt)

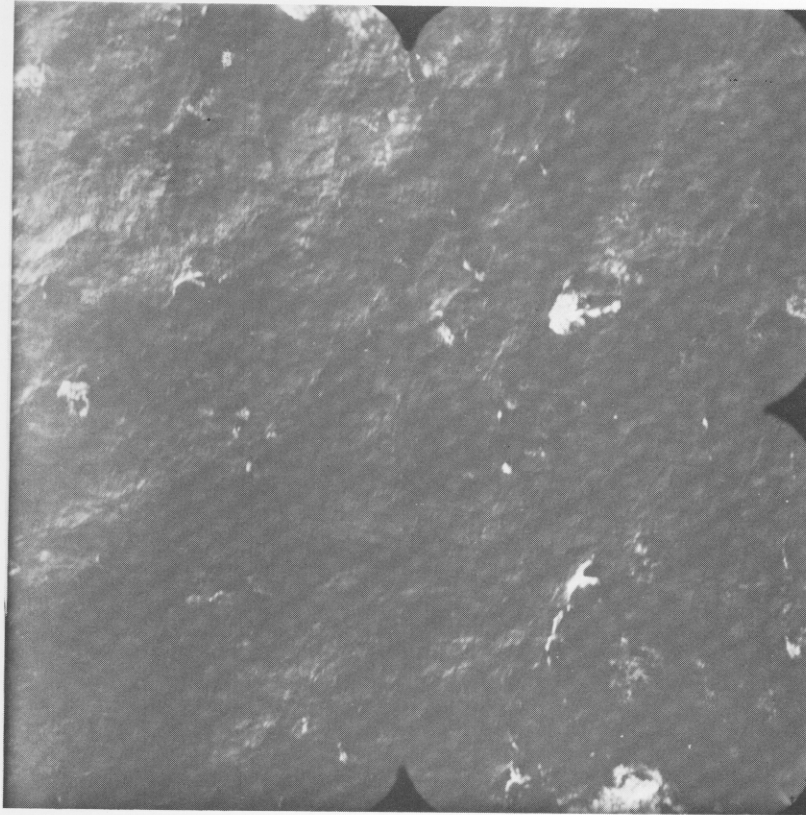
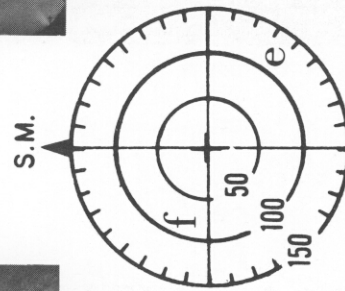


Figure 2f. Flight 750929A, Gladys.
RA = 528 ft. Flight level wind 9.8 m s^{-1}

9 m s^{-1} B4H 17 kt (19 kt)

Beaufort 4(14-18 kt mean; 16-20 kt sustained). Small foam patches. Number of breaking crests increase slightly and are a little larger. First able to tell direction with confidence. Wrinkled texture of surface is very evident.

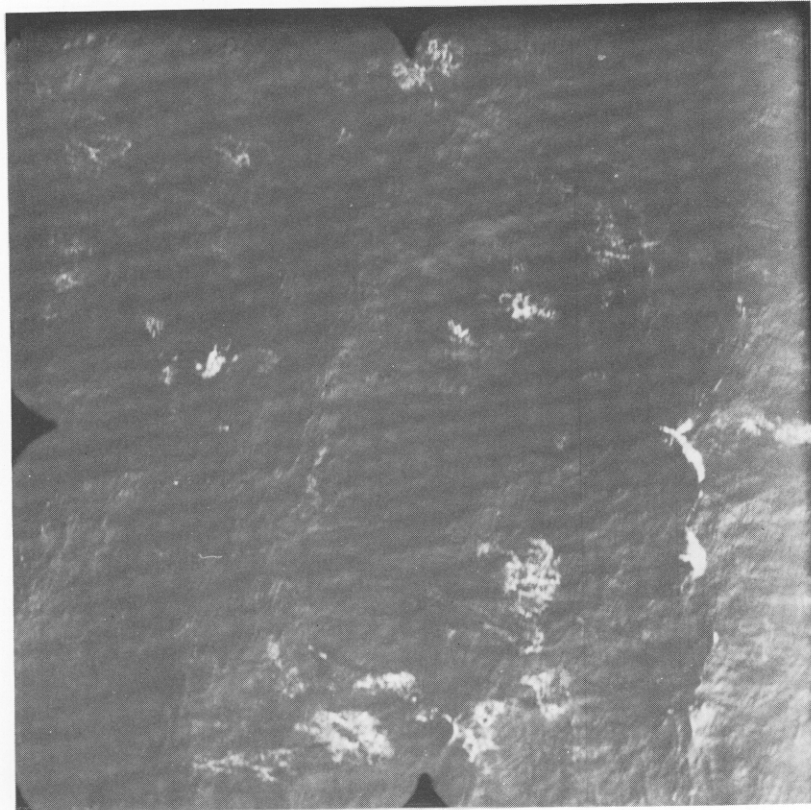


Figure 3a. Flight 750929A, Gladys.
RA = 508 ft. Flight level wind 10.8 m s⁻¹

10 m s⁻¹ B5 18 kt (21 kt.)

SMALL CRAFT WARNING

Beaufort 5(18-23 kt mean; 20-26 kt sustained). Whitecaps on many wave crests. significantly.

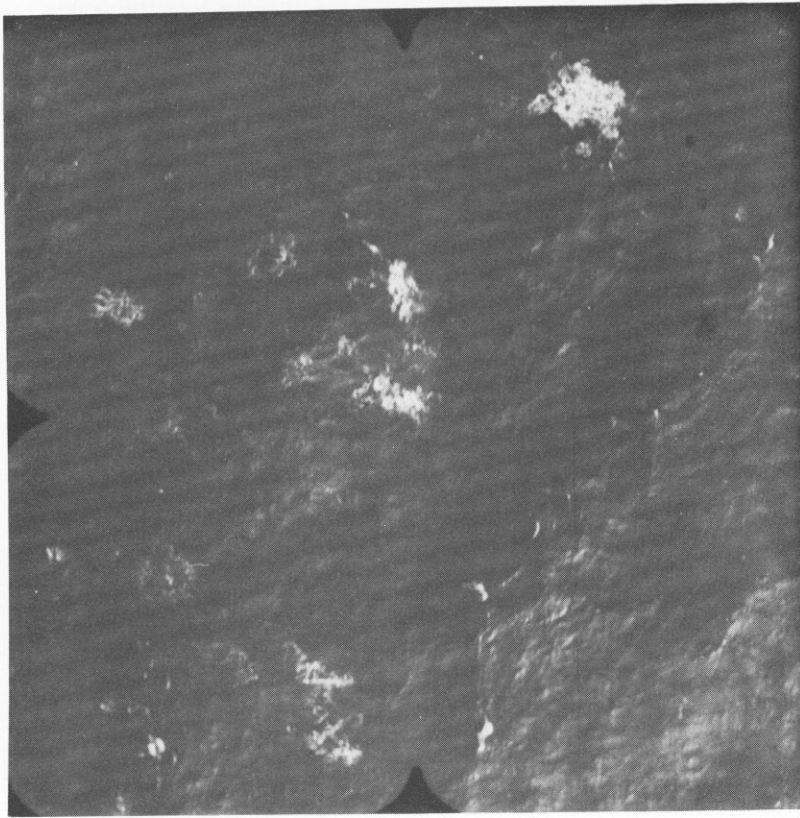
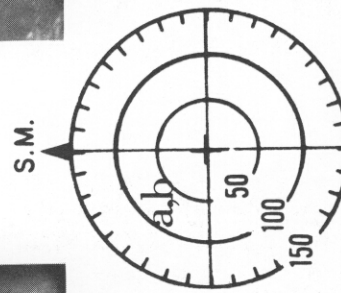


Figure 3b. Flight 750929A, Gladys.
RA = 502 ft. Flight level wind 11.1 m s⁻¹

10 m s⁻¹ B5 19 kt (21 kt.)

SMALL CRAFT WARNING

Size and number of whitecaps and foam patches increase
Very short streaks may appear in foam patches.



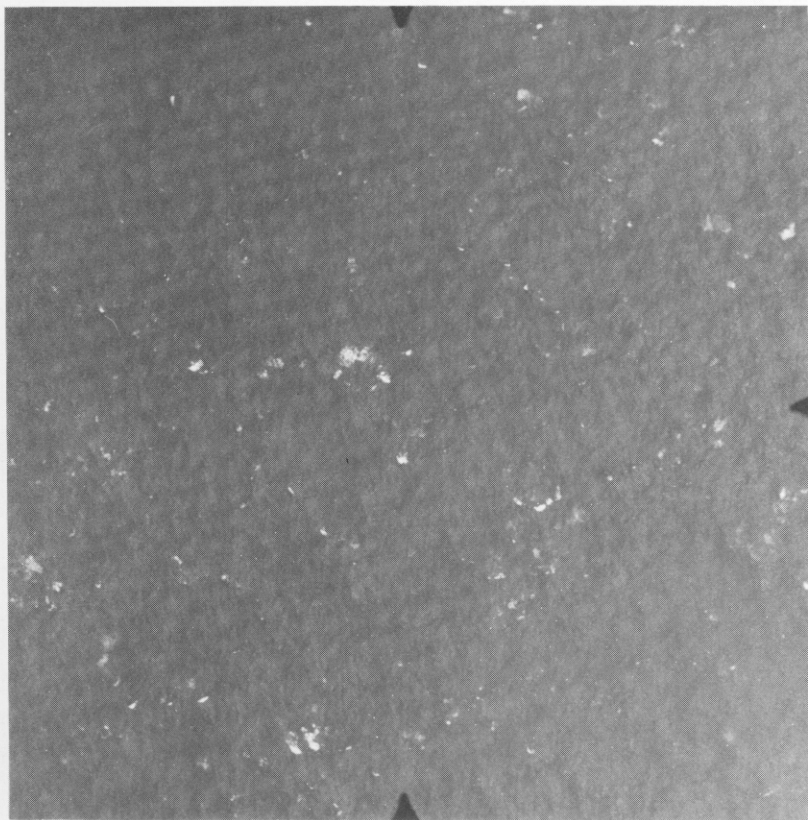


Figure 3c. Flight 750917A, Eloise.
RA = 3182 ft. Flight level wind 14.0 m s^{-1}

10 m s^{-1} B5 20 kt (22 kt)

SMALL CRAFT WARNING

Beaufort 5 (18-23 kt mean; 20-26 kt sustained). Size and number of whitecaps and foam patches increase significantly. Whitecaps on many wave crests. Very short streaks may appear in foam patches.

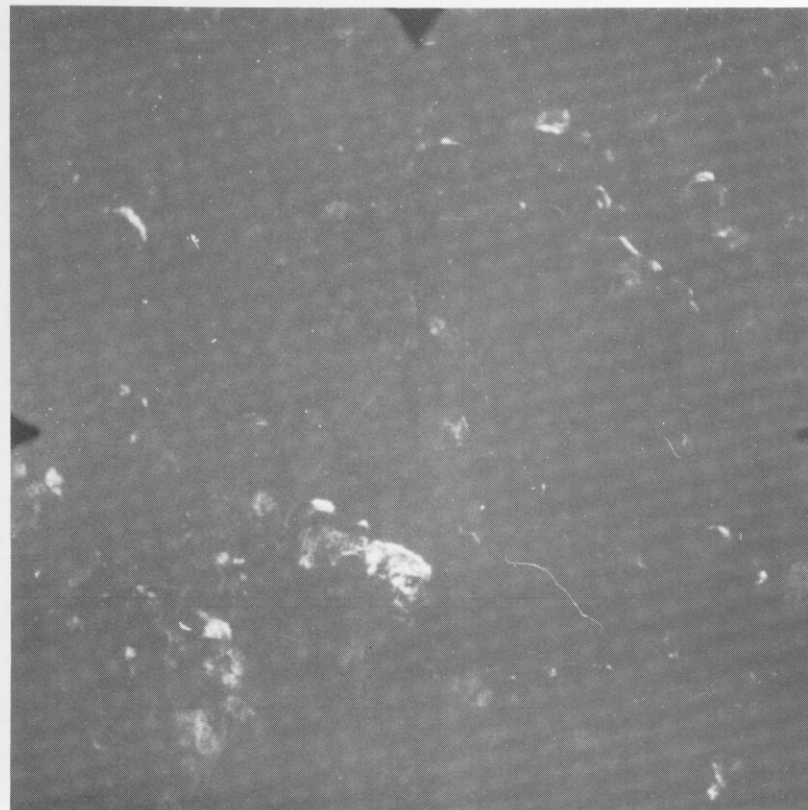
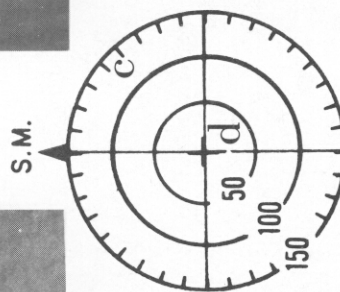


Figure 3d. Flight 750929A, Gladys.
RA = 839 ft. Flight level wind 10.5 m s^{-1}

10 m s^{-1} B5 19 kt (22 kt)

SMALL CRAFT WARNING

Size and number of whitecaps and foam patches increase significantly. Very short streaks may appear in foam patches.



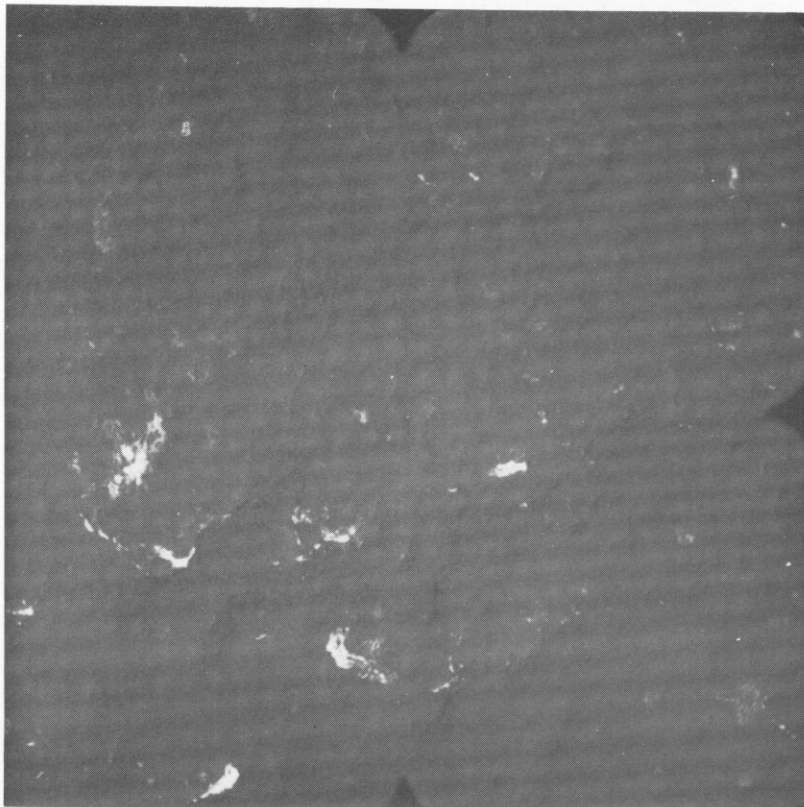


Figure 3e. Flight 750917A, Eloise.
RA = 859 ft. Flight level wind 13.2 m s^{-1}

12 m s^{-1} B5H 23 kt (25 kt)

SMALL CRAFT WARNING

Beaufort 5(18-23 kt mean; 20-26 kt sustained). Size and number of whitecaps and foam patches increase significantly. Whitecaps on many wave crests. Very short streaks may appear in foam patches.

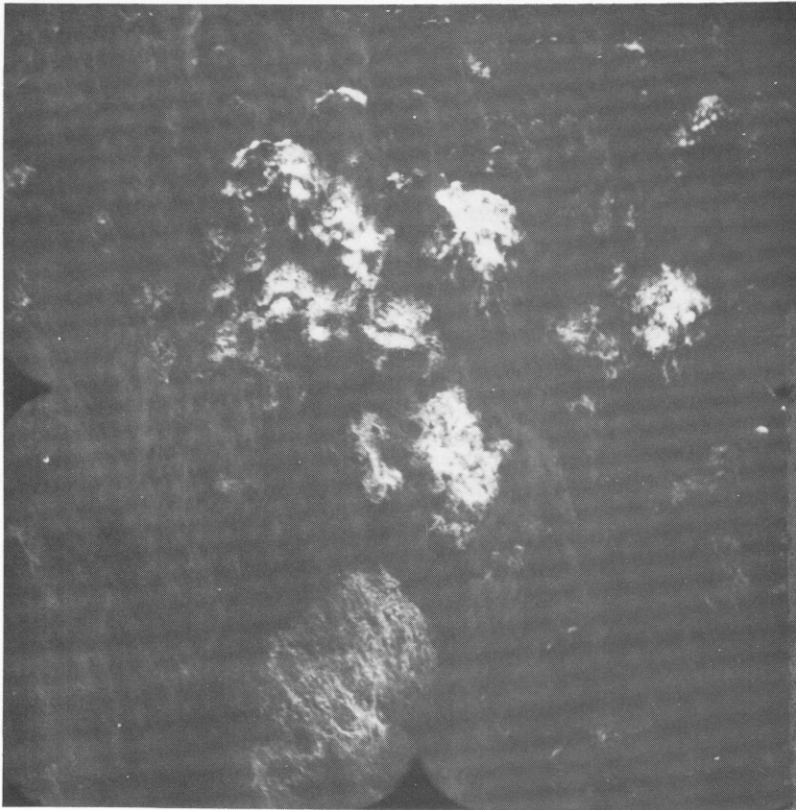
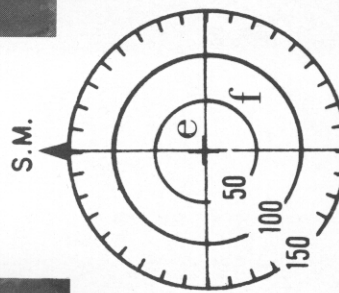


Figure 3f. Flight 750916A, Eloise.
RA = 525 ft. Flight level wind 13.0 m s^{-1}

12 m s^{-1} B5H 23 kt (26 kt)

SMALL CRAFT WARNING

Size and number of whitecaps and foam patches increase significantly. Very short streaks may appear in foam patches.



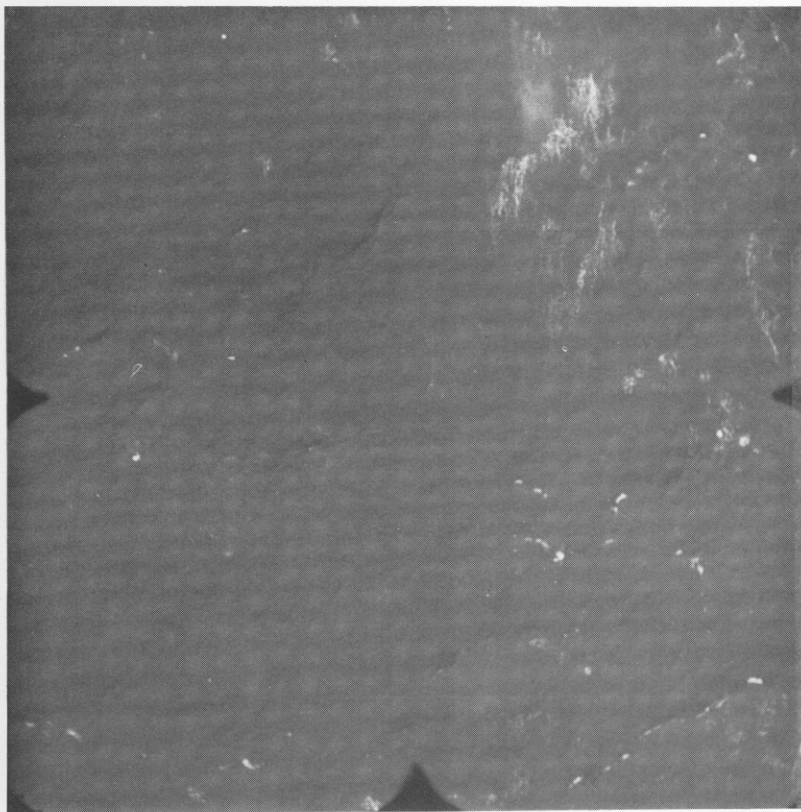


Figure 4a. Flight 750916A, Eloise.
RA = 506 ft. Flight level wind 13.9 m s^{-1}

13 m s^{-1} B6L 25 kt (28 kt)

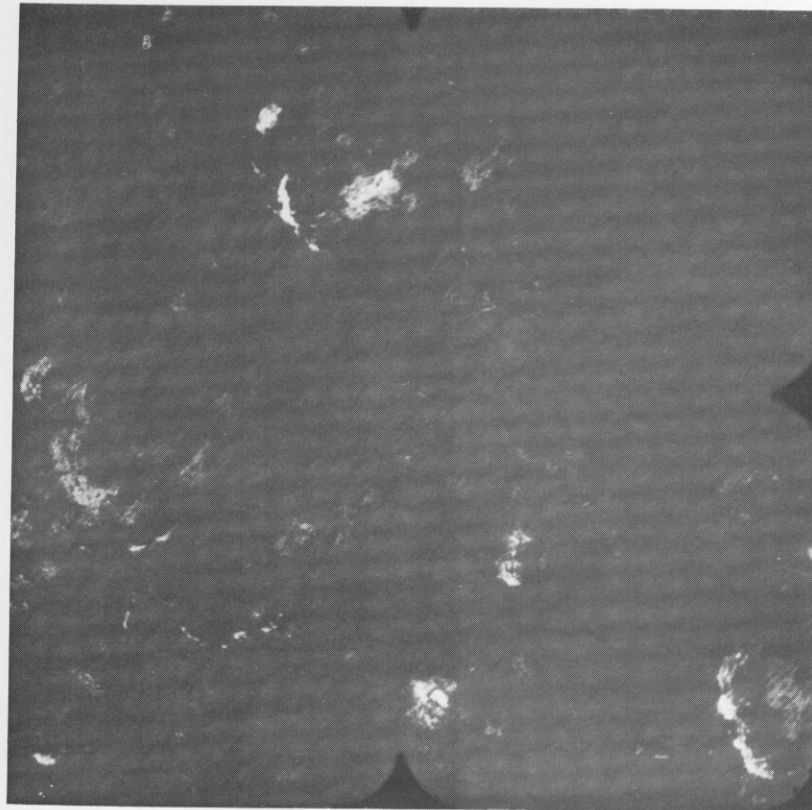
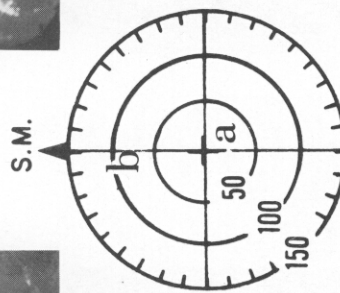


Figure 4b. Flight 750917A, Eloise.
RA = 817 ft. Flight level wind 15.5 m s^{-1}

14 m s^{-1} B6 26 kt (29 kt)

Beaufort 6 (23-28 kt mean; 26-32 kt sustained). Well defined of short streaks in foam patches. Small white-caps on most wave crests. Occasional medium size foam patch or breaker. Isolated green patches of short duration. Foam patches, short streaks, and whitecaps (white water) cover 5-7% of surface.

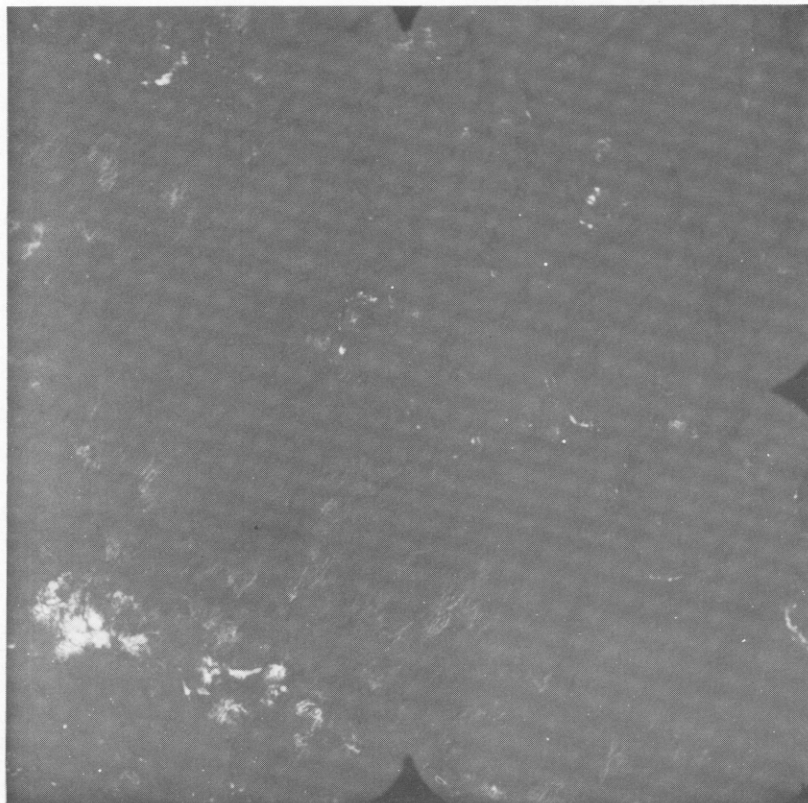


Figure 4c. Flight 750917A, Eloise.
RA = 810 ft. Flight level wind 15.7 m s^{-1}

14 m s^{-1} B6 26 kt (29 kt)

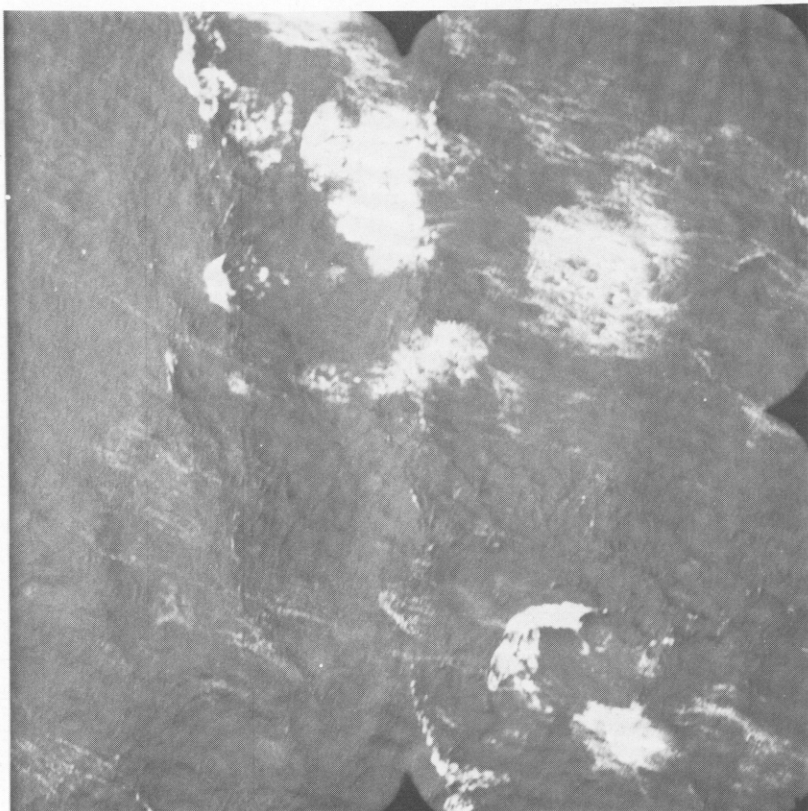
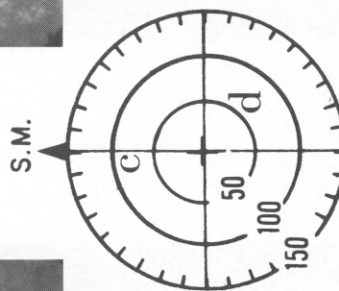


Figure 4d. Flight 750929A, Gladys.
RA = 508 ft. Flight level wind 16.0 m s^{-1}

14 m s^{-1} B6 27 kt (30 kt)



Beaufort 6 (23-28 kt mean; 26-32 kt sustained). Well defined of short streaks in foam patches. Small white-caps on most wave crests. Occasional medium size foam patch or breaker. Isolated green patches of short duration. Foam patches, short streaks, and whitecaps (white water) cover 5-7% of surface.

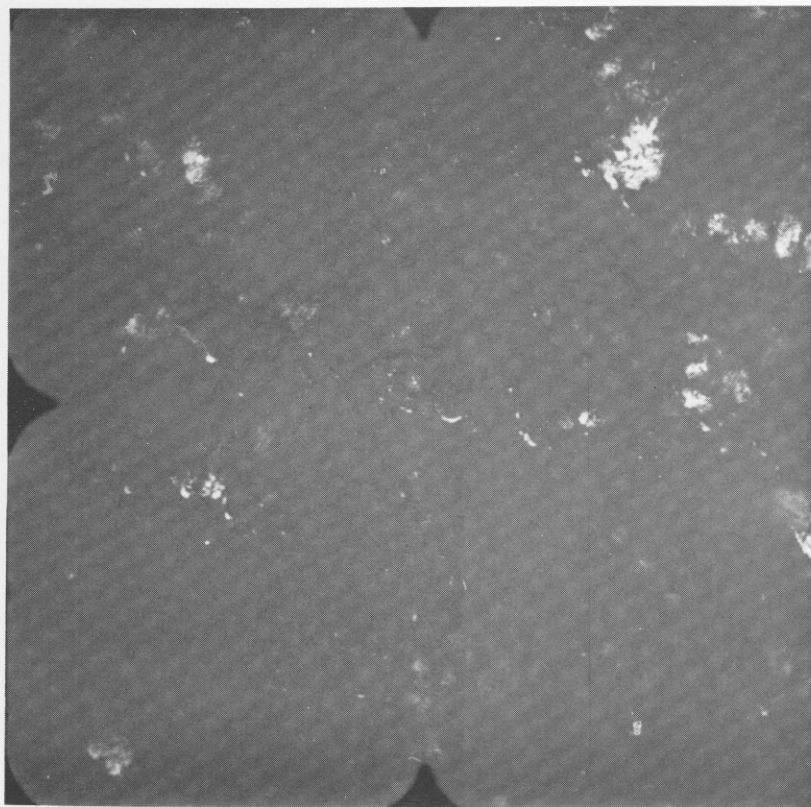


Figure 4e. Flight 750917A, Eloise.
RA = 794 ft. Flight level wind 15.5 m s^{-1}

14 m s^{-1} B6 27 kt (30 kt)

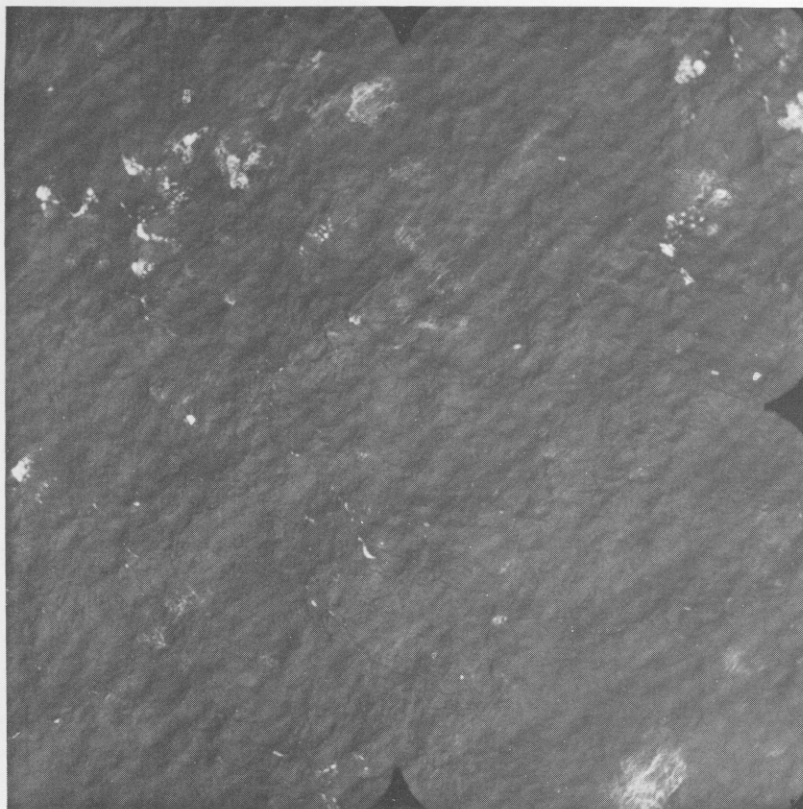
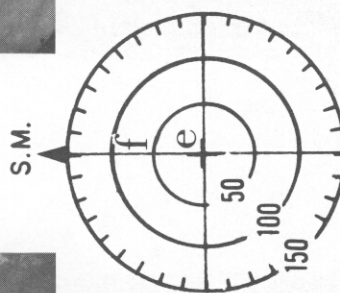


Figure 4f. Flight 750917A Eloise.
RA = 863 ft. Flight level wind
 16.6 m s^{-1}

14 m s^{-1} B6 28 kt (31 kt)



Beaufort 6 (23-28 kt mean; 26-32 kt sustained). Well defined of short streaks in foam patches. Small whitecaps on most wave crests. Occasional medium size foam patch or breaker. Isolated green patches of short duration. Foam patches, short streaks, and whitecaps (white water) cover 5-7% of surface.



Figure 5a. Flight 750917A, Eloise.
RA = 813 ft. Flight level wind 17.6 m s^{-1}

15 m s^{-1} B7L 29 kt (33 kt)

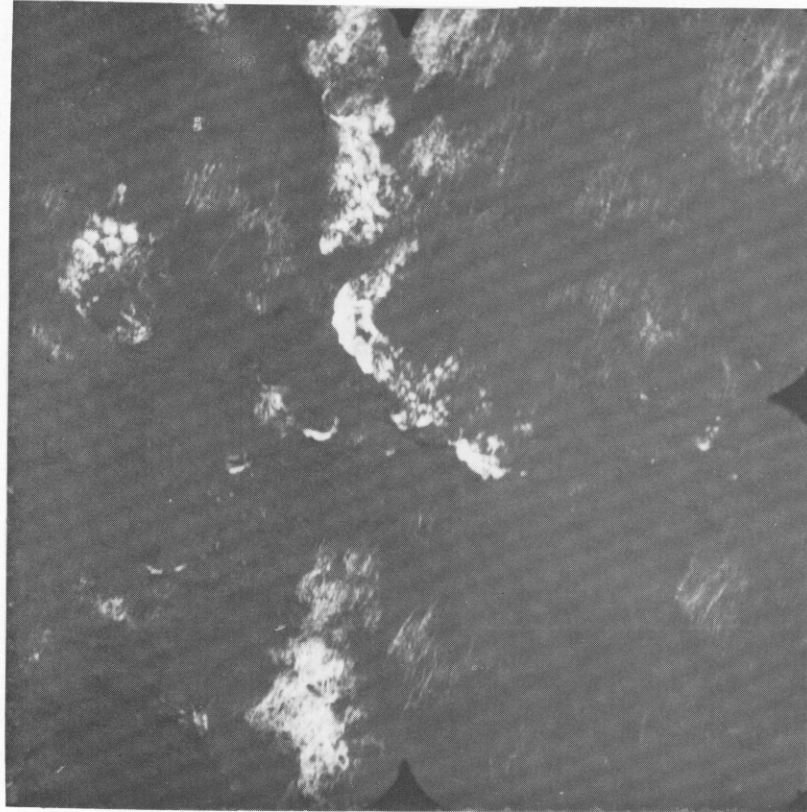
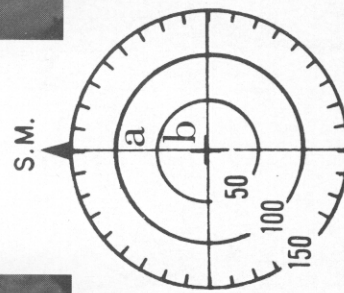


Figure 5b. Flight 750917A, Eloise.
RA = 361 ft. Flight level wind 17.0 m s^{-1}

15 m s^{-1} B7M 29 kt (33 kt)



Beaufort 7 (28-33 kt mean; 32-37 kt sustained). Medium size breaking crests. Dense foam patches and accompanying short streaks are numerous. Average length of streaks equal to diameter of average foam patch. Small green patches occasionally visible.

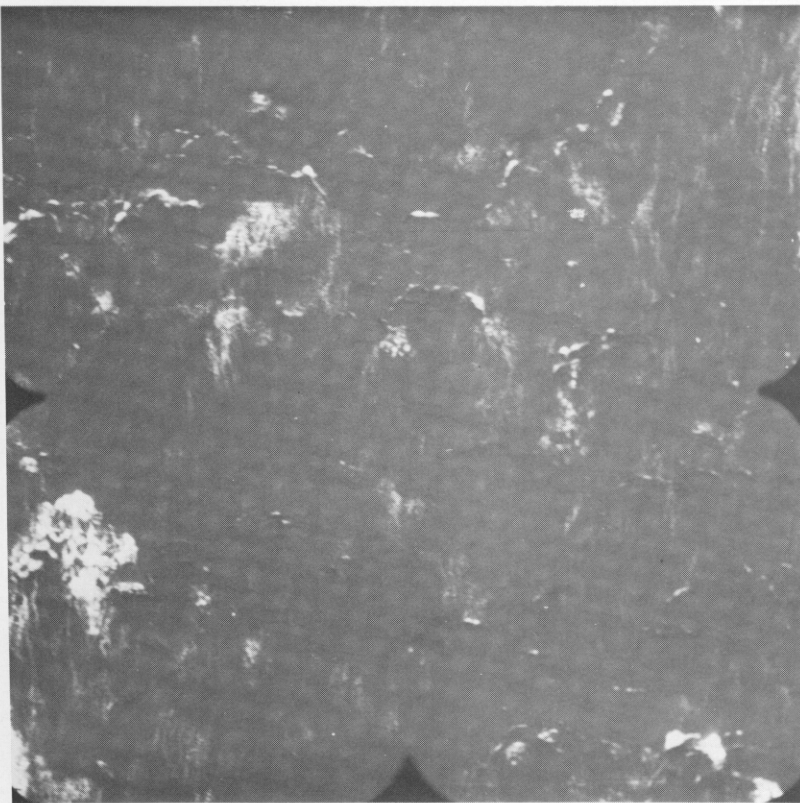


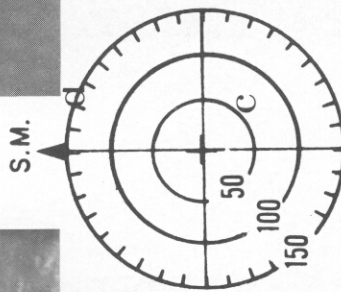
Figure 5c. Flight 750929A, Gladys.
RA = 521 ft. Flight level wind 17.0 m s^{-1}

15 m s^{-1} B7M 29 kt (33 kt)



Figure 5d. Flight 750922A, Eloise.
RA = 4134 ft. Flight level wind 17.6 m s^{-1}

16 m s^{-1} B7M 31 kt (34 kt)



Beaufort 7 (28-33 kt mean; 32-37 kt sustained). Medium size breaking crests. Dense foam patches and accompanying short streaks are numerous. Average length of streaks equal to diameter of average foam patch. Small green patches occasionally visible.

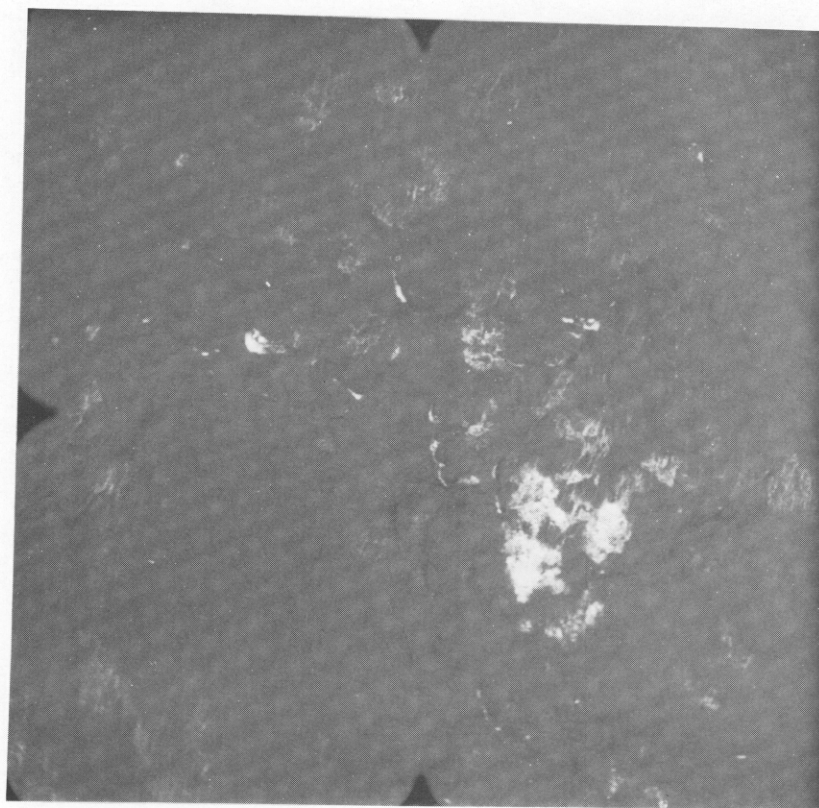


Figure 5e. Flight 750917A, Eloise.
RA = 828 ft. Flight level wind 18.1 m s^{-1}

16 m s^{-1} B7M 31 kt (34 kt)

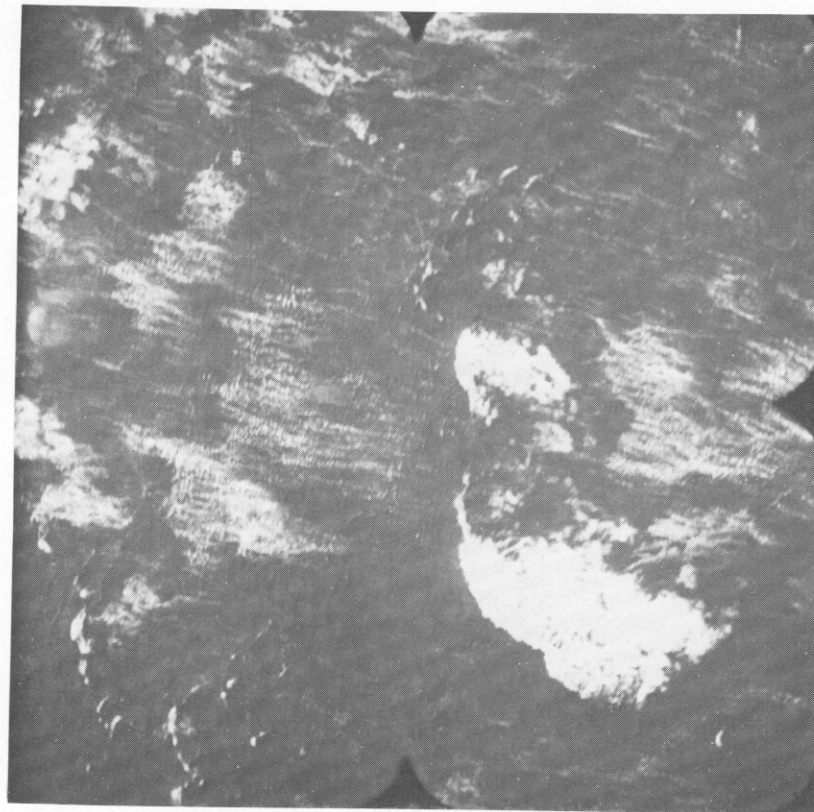
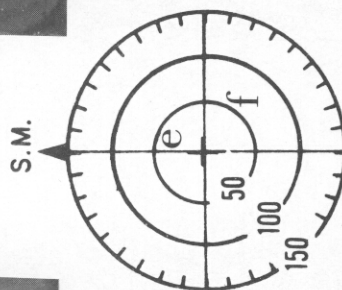


Figure 5f. Flight 750929A, Gladys.
RA = 495 ft. Flight level wind 19.9 m s^{-1}

17 m s^{-1} B7H . 33 kt (37 kt)

Beaufort 7 (28-33 kt mean; 32-37 kt sustained). Medium size breaking crests. Dense foam patches and accompanying short streaks are numerous. Average length of streaks equal to diameter of average foam patch. Small green patches occasionally visible.

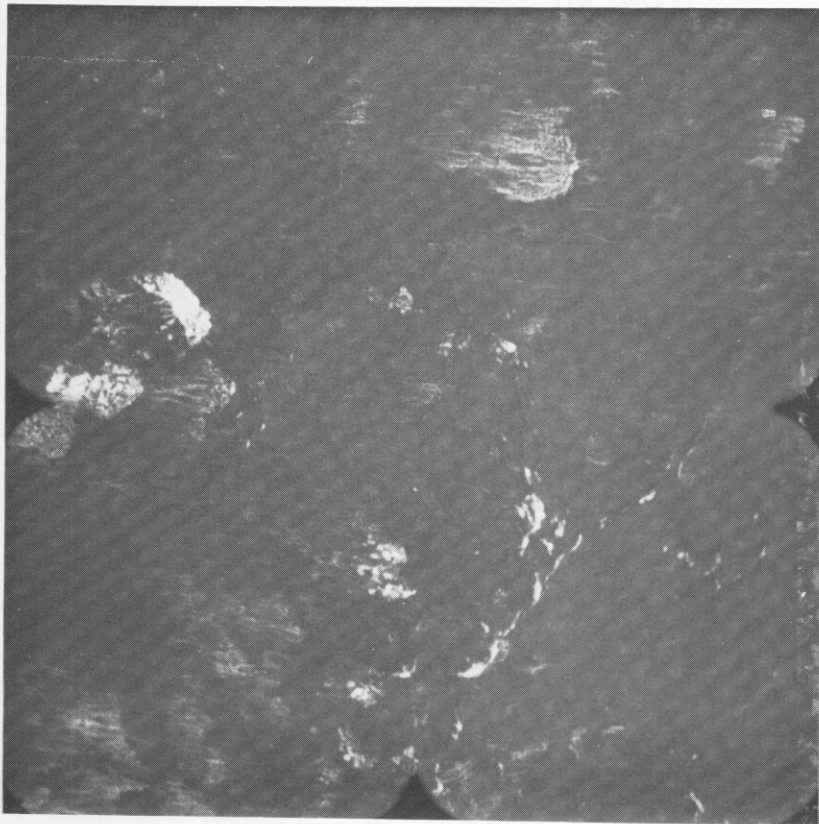


Figure 6a. Flight 750917A, Eloise.
RA = 502 ft. Flight level wind 21.0 m s^{-1}

18 m s^{-1} B8L 35 kt (39 kt)

GALE WARNING - TROPICAL STORM

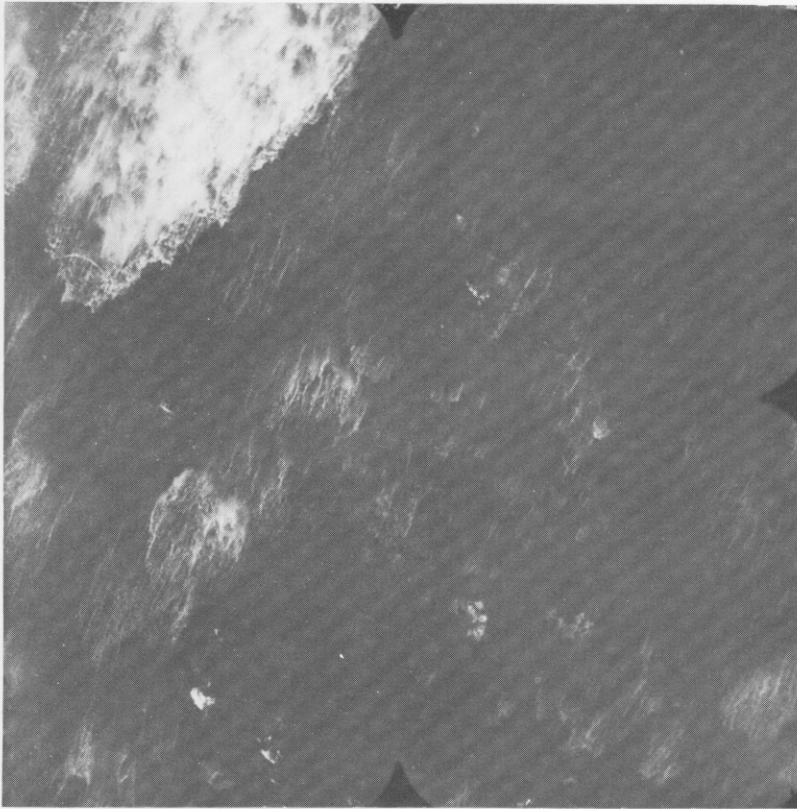
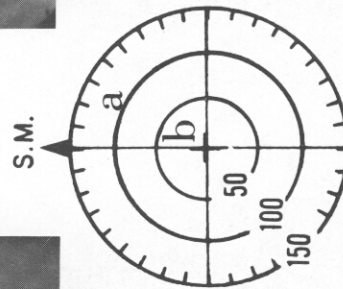


Figure 6b. Flight 750917A, Eloise.
RA = 541 ft. Flight level wind 20.5 m s^{-1}

18 m s^{-1} B8M 35 kt (39 kt)

GALE WARNING - TROPICAL STORM

Beaufort 8(33-39 kt mean; 37-44 kt sustained). Streaks more numerous and occasionally longer. Some streaks may appear between breaking waves or foam patches. Area covered by whitecaps stabilizes at 7-10%. Occasional large foam patch. Small green patches continually visible with occasional moderate size green patch.

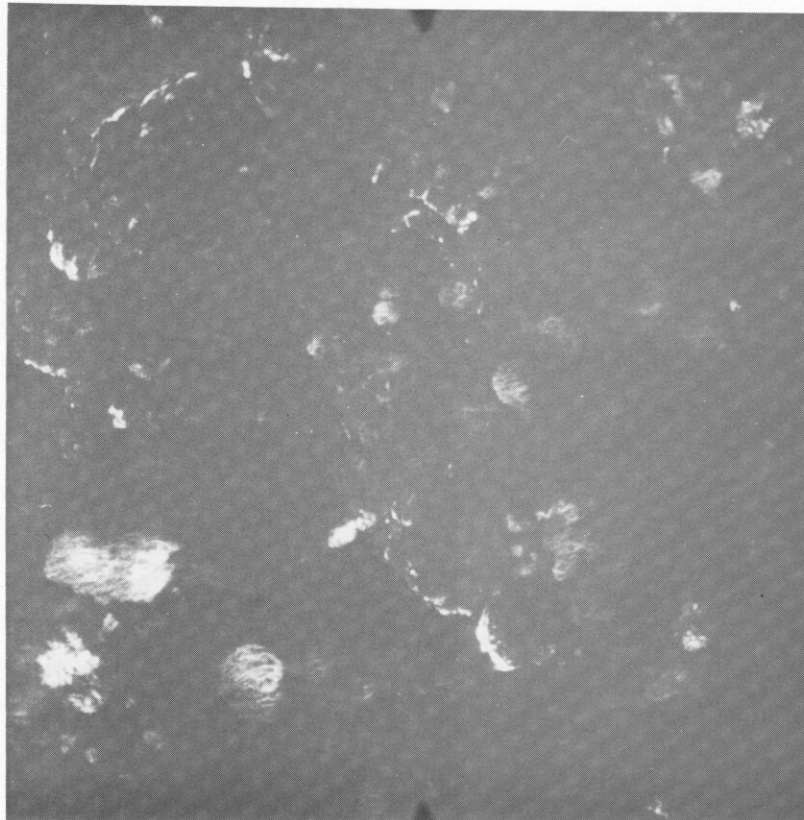


Figure 6c. Flight 750922A, Eloise.
RA = 1499 ft. Flight level wind 21.5 m s^{-1}

18 m s^{-1} B8M 36 kt (40 kt)

GALE WARNING - TROPICAL STORM

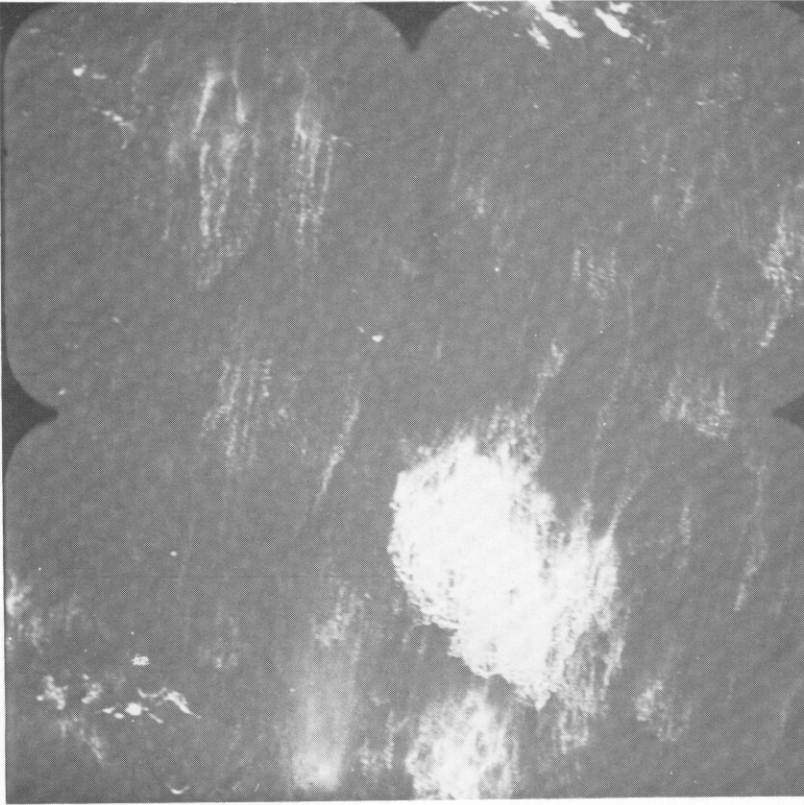
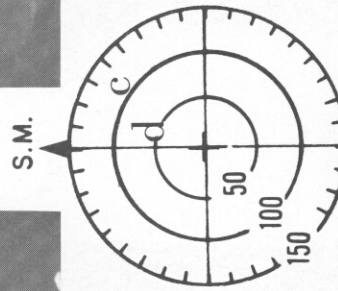


Figure 6d. Flight 750929A, Gladys.
RA = 502 ft. Flight level wind 21.5 m s^{-1}

19 m s^{-1} B8M 37 kt (41 kt)

GALE WARNING - TROPICAL STORM



Beaufort 8(33-39 kt mean; 37-44 kt sustained). Streaks more numerous and occasionally longer. Some streaks may appear between breaking waves or foam patches. Area covered by whitecaps stabilizes at 7-10%. Occasional large foam patch. Small green patches continually visible with occasional moderate size green patch.

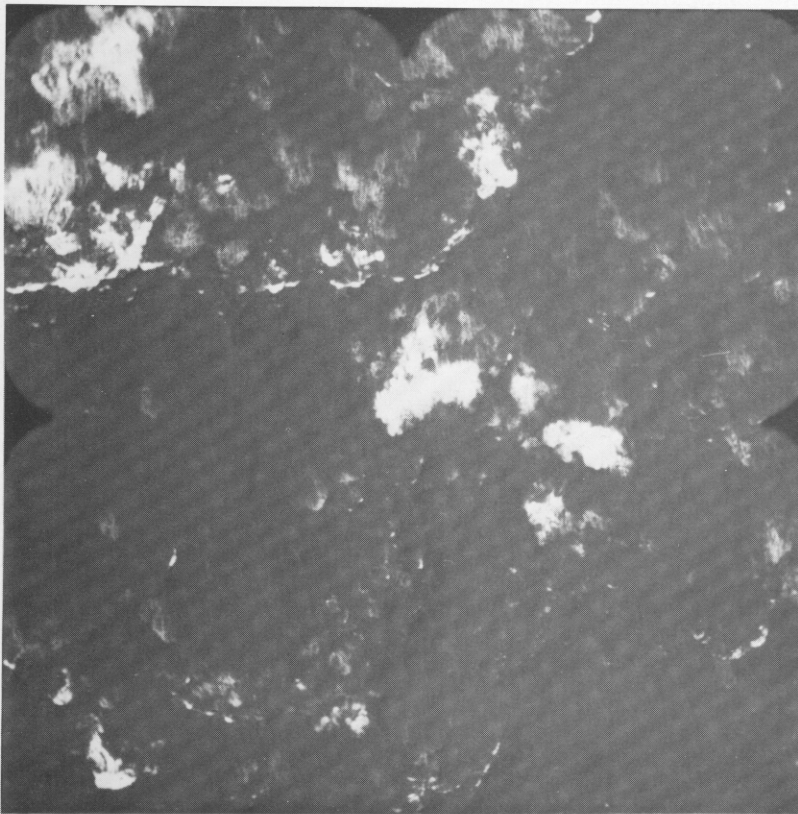


Figure 6e. Flight 750922A, Eloise.
RA = 1535 ft. Flight level wind 23.2 m s^{-1}

20 m s^{-1} B8H 38 kt (43 kt)

GALE WARNING - TROPICAL STORM

Beaufort 8 (33-39 kt mean; 37-44 kt sustained). Streaks more numerous and occasionally longer. Some streaks may appear between breaking waves or foam patches. Area covered by whitecaps stabilizes at 7-10%. Occasional large foam patch. Small green patches continually visible with occasional moderate size green patch.

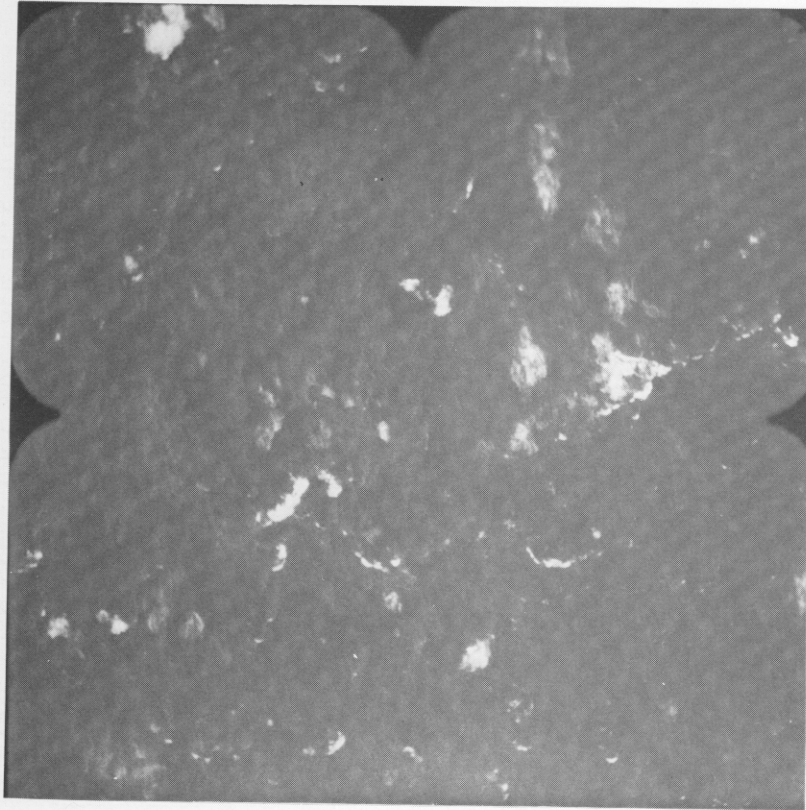


Figure 6f. Flight 750922A, Eloise.
RA = 2296 ft. Flight level wind 23.8 m s^{-1}

20 m s^{-1} B8H 38 kt (43 kt)

GALE WARNING - TROPICAL STORM

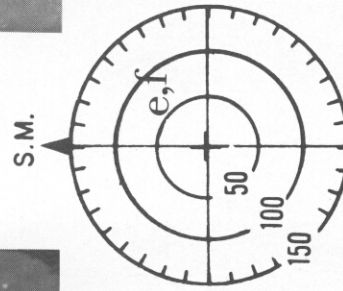




Figure 7a. Flight 750922A, Eloise.
RA = 1519 ft. Flight level wind 23.8 m s^{-1}

20 m s^{-1} B9L 39 kt (44 kt)

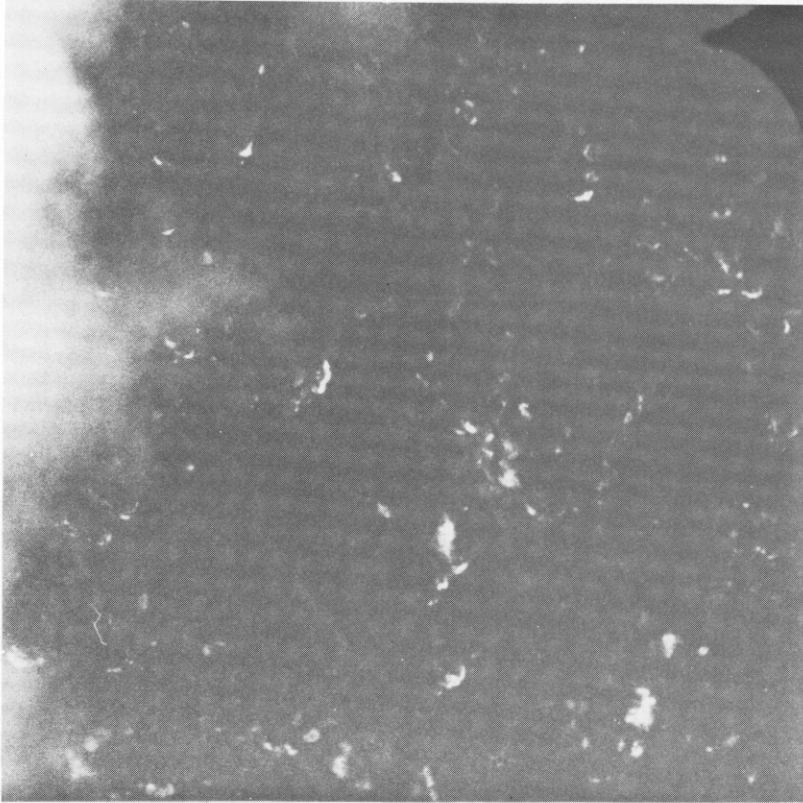
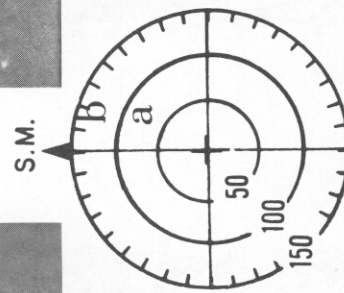


Figure 7b. Flight 750922A, Eloise.
RA = 3904 ft. Flight level wind 23.3 m s^{-1}

20 m s^{-1} B9L 39 kt (44 kt)



Beaufort 9 (39-44. kt mean; 44-50 kt sustained). Streaks readily apparent between foam patches. Streak length varies from patch size to occasional regions of long, nearly continuous streaking. Streaks, patches and breaking waves cover 15-20% of sea. 50% of foam patches are green.

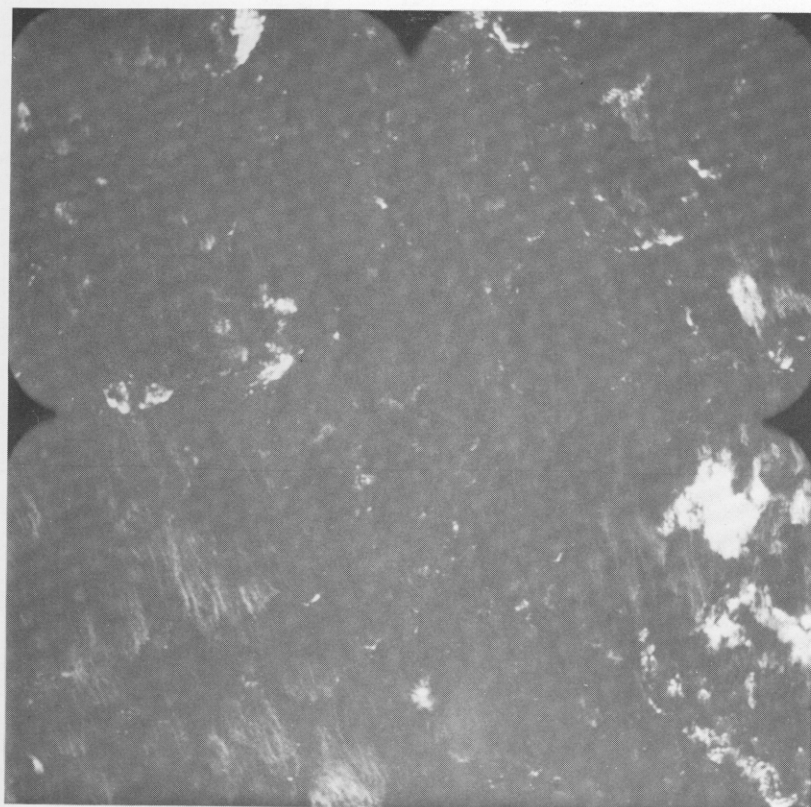


Figure 7c. Flight 750922A, Eloise
RA = 1440 ft. Flight level wind 23.7 m s^{-1}

21 m s^{-1} B9L 40 kt (45 kt)

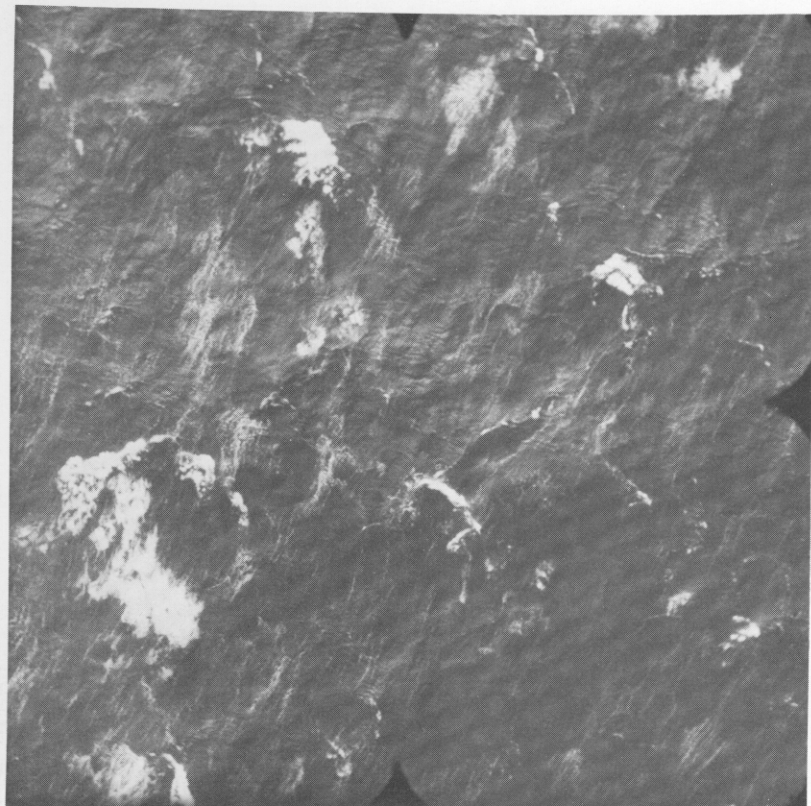
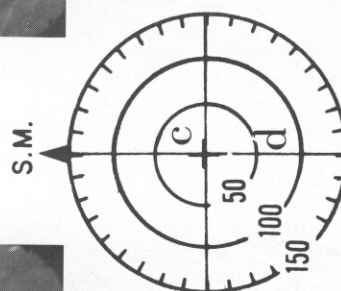


Figure 7d. Flight 750917A, Eloise.
RA = 823 ft. Flight level wind
 24.4 m s^{-1}

21 m s^{-1} B9L 40 kt (45 kt)

Beaufort 9 (39-44 kt mean; 44-50 kt sustained). Streaks readily apparent between foam patches. Streak length varies from patch size to occasional regions of long, nearly continuous streaking. Streaks, patches and breaking waves cover 15-20% of sea. 50% of foam patches are green.

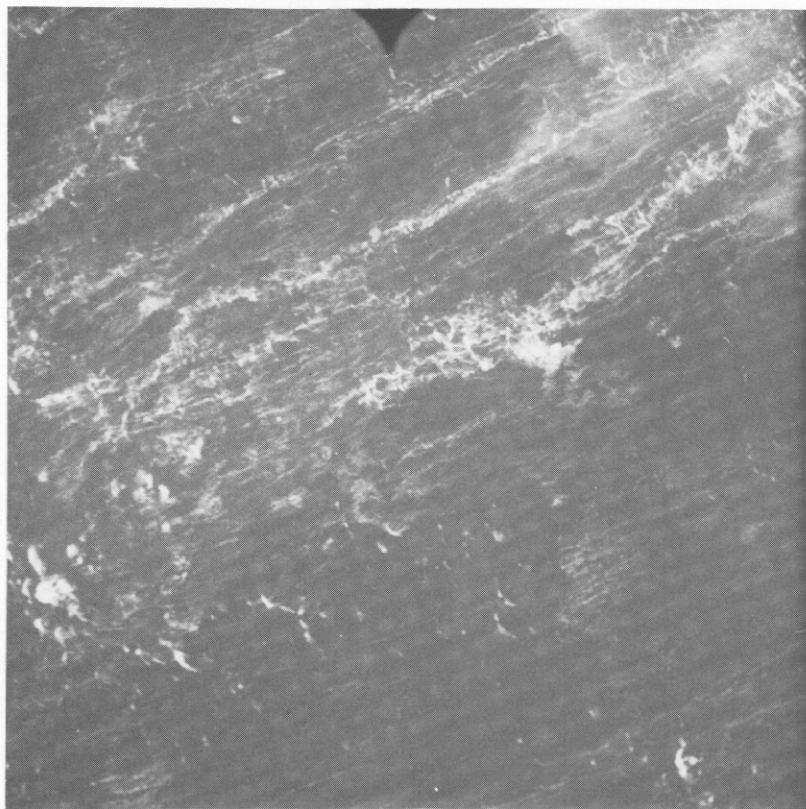


Figure 7e. Flight 750916A, Eloise
RA = 1040 ft. Flight level wind 26.3 m s^{-1}

22 m s^{-1} B9H 43 kt (47 kt)

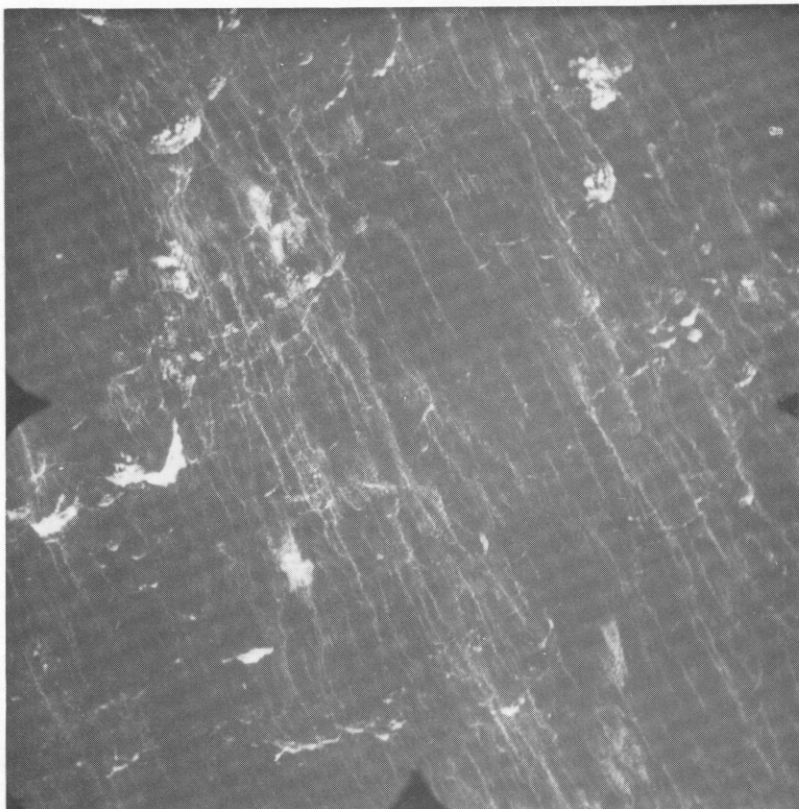
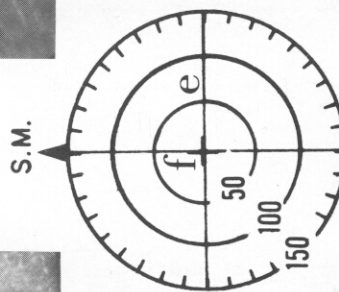


Figure 7f. Flight 750916A, Eloise.
RA = 1036 ft. Flight level wind 26.6 m s^{-1}

22 m s^{-1} B9H 44 kt (49 kt)



Beaufort 9 (39-44. kt mean; 44-50 kt sustained). Streaks readily apparent between foam patches. Streak length varies from patch size to occasional regions of long, nearly continuous streaking. Streaks, patches and breaking waves cover 15-20% of sea. 50% of foam patches are green.

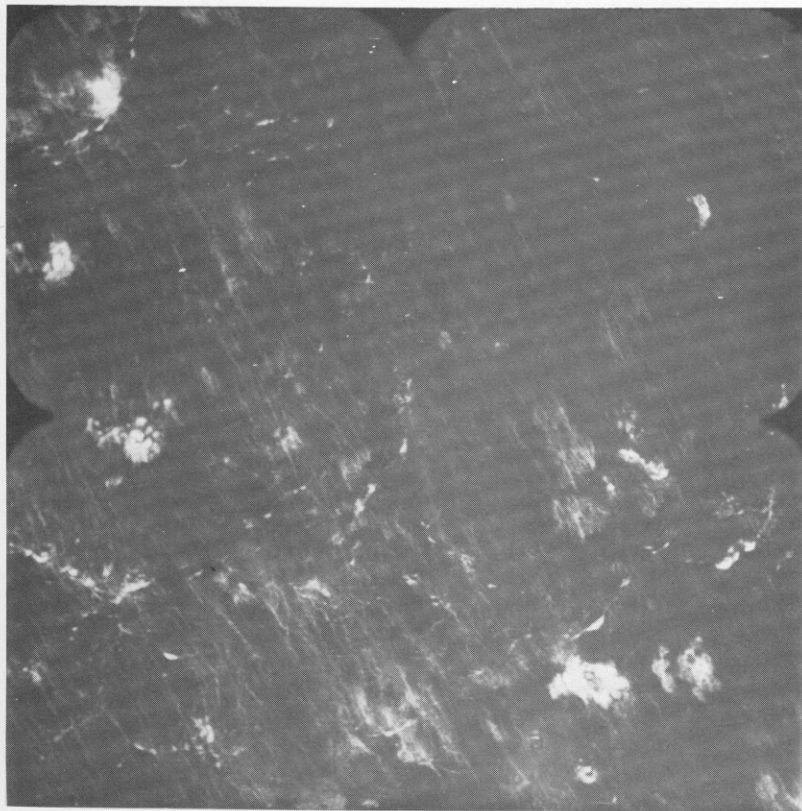


Figure 8a. Flight 750922A, Eloise.
RA = 1007 ft. Flight level wind 26.7 m s^{-1}

23 m s^{-1} B10L 45 kt (50 kt)

STORM WARNING

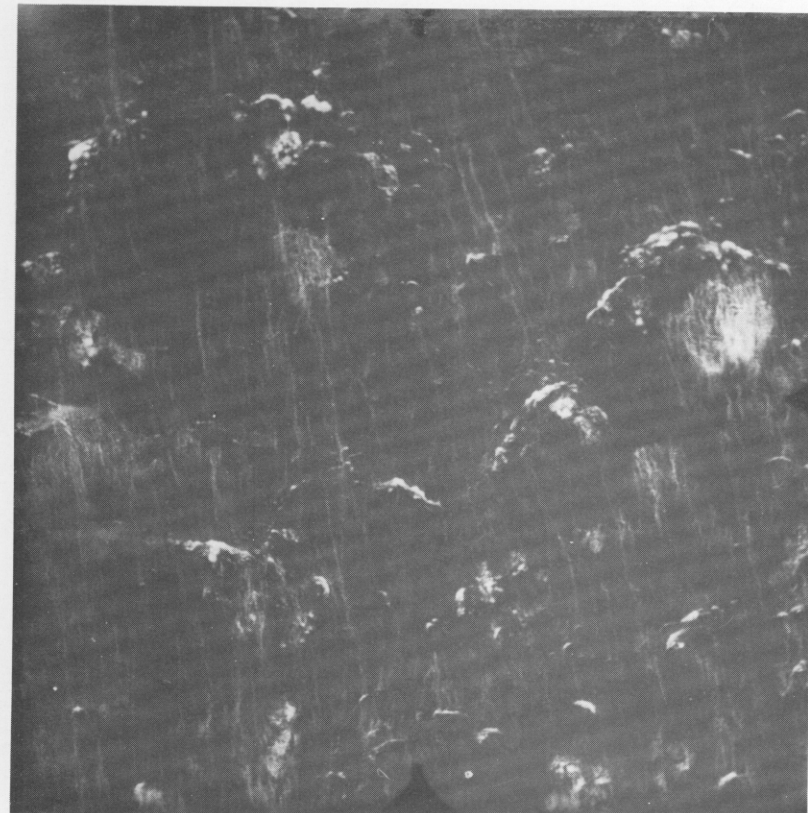
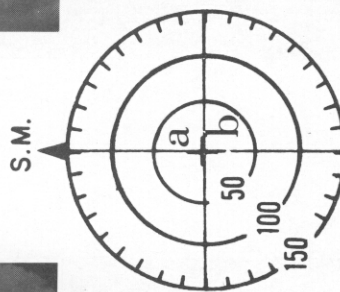


Figure 8b. Flight 750916A, Eloise.
RA = 799 ft. Flight level wind 26.8 m s^{-1}

23 m s^{-1} B10L 45 kt (50 kt)

STORM WARNING

Beaufort 10(44-49 kt mean; 50-55 kt sustained). Wind streaks become the most obvious surface feature and are continuous or nearly so. Well-defined, thinly breaking waves form on long crestlines often preceded by short breaking wavelets giving a step-like appearance. Occasional large foam patches are quickly fragmented and elongated into streaks. Sea covered 20-25% by white water.

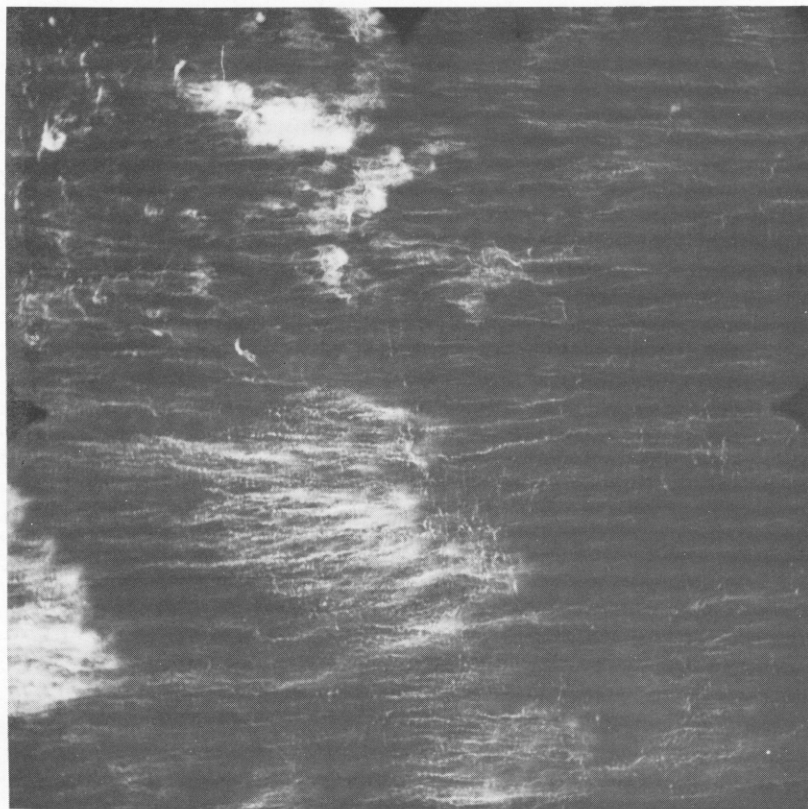


Figure 8c. Flight 750916A, Eloise.
RA = 830 ft. Flight level wind 28.0 m s^{-1}

24 m s^{-1} B10M 47 kt (53 kt)

STORM WARNING

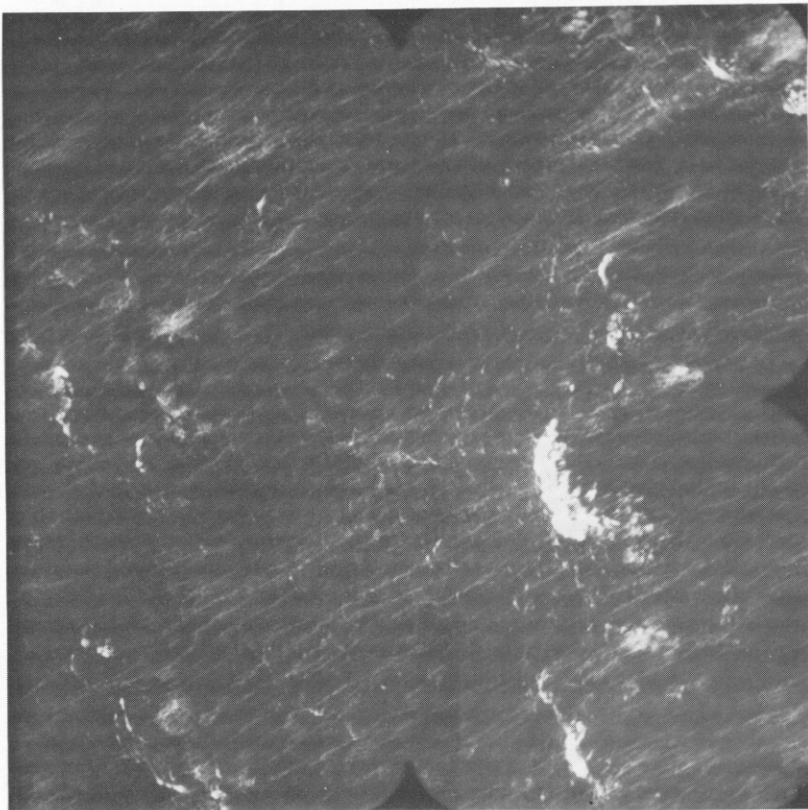
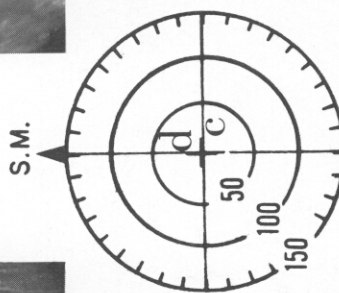


Figure 8d. Flight 750922A, Eloise.
RA = 1017 ft. Flight level wind 29.0 m s^{-1}

24 m s^{-1} B10M 47 kt (53 kt)

STORM WARNING



Beaufort 10(44-49 kt mean; 50-55 kt sustained). Wind streaks become the most obvious surface feature and are continuous or nearly so. Well-defined, thinly breaking waves form on long crestlines often preceded by short breaking wavelets giving a step-like appearance. Occasional large foam patches are quickly fragmented and elongated into streaks. Sea covered 20-25% by white water.

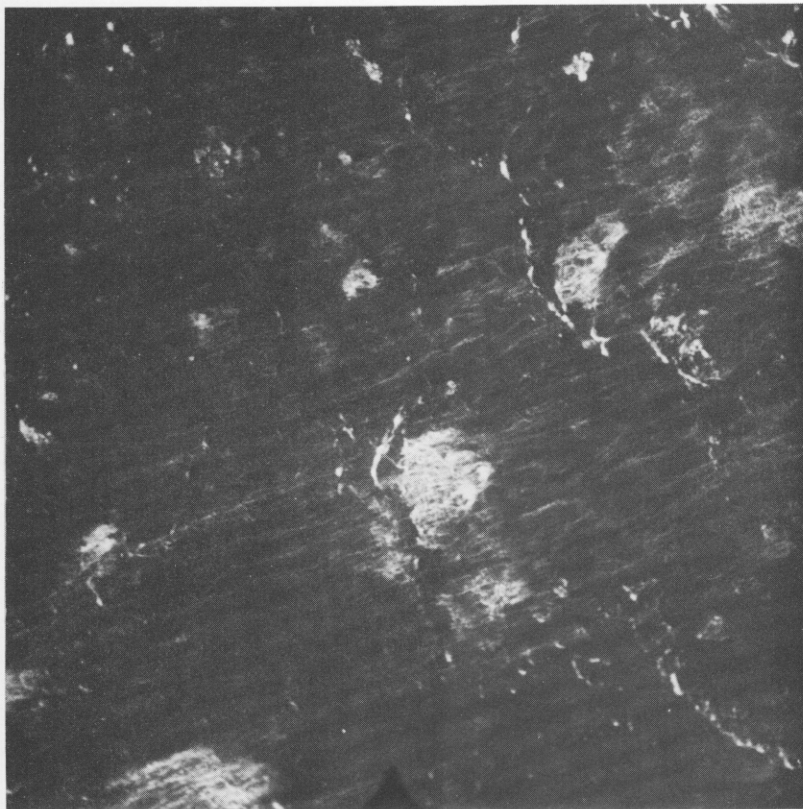


Figure 8e. Flight 750916A, Eloise.
RA = 988 ft. Flight level wind 29.2 m s^{-1}

25 m s^{-1} B10H 48 kt (54 kt)

STORM WARNING

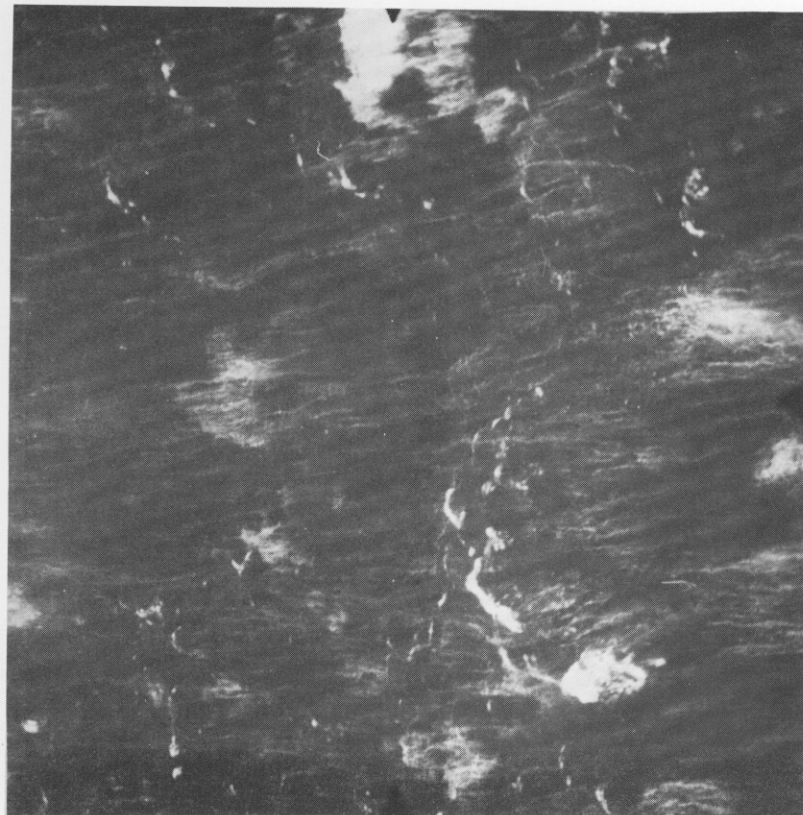
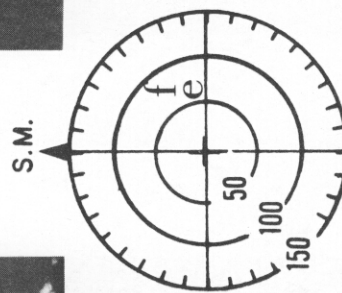


Figure 8f. Flight 750922A, Eloise.
RA = 1001 ft. Flight level wind 29.8 m s^{-1}

25 m s^{-1} B10H 48 kt (54 kt)

STORM WARNING



Beaufort 10(44-49 kt mean; 50-55 kt sustained). Wind streaks become the most obvious surface feature and are continuous or nearly so. Well-defined, thinly breaking waves form on long crestlines often preceded by short breaking wavelets giving a step-like appearance. Occasional large foam patches are quickly fragmented and elongated into streaks. Sea covered 20-25% by white water.

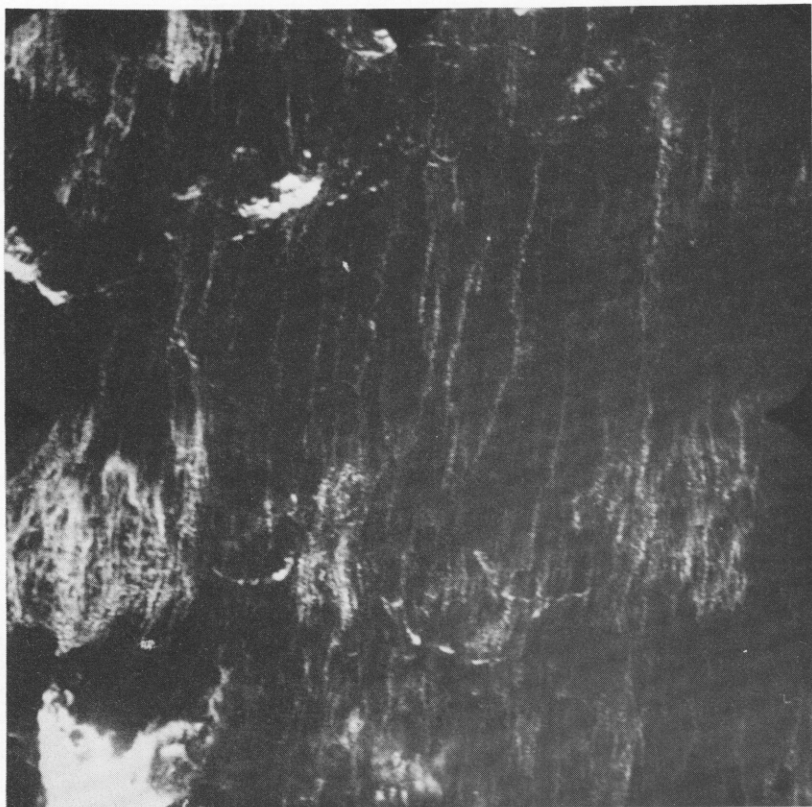


Figure 9a. Flight 750929A, Gladys.
RA = 538 ft. Flight level wind 29.0 m s^{-1}

26 m s^{-1} B11L 50 kt (56 kt)

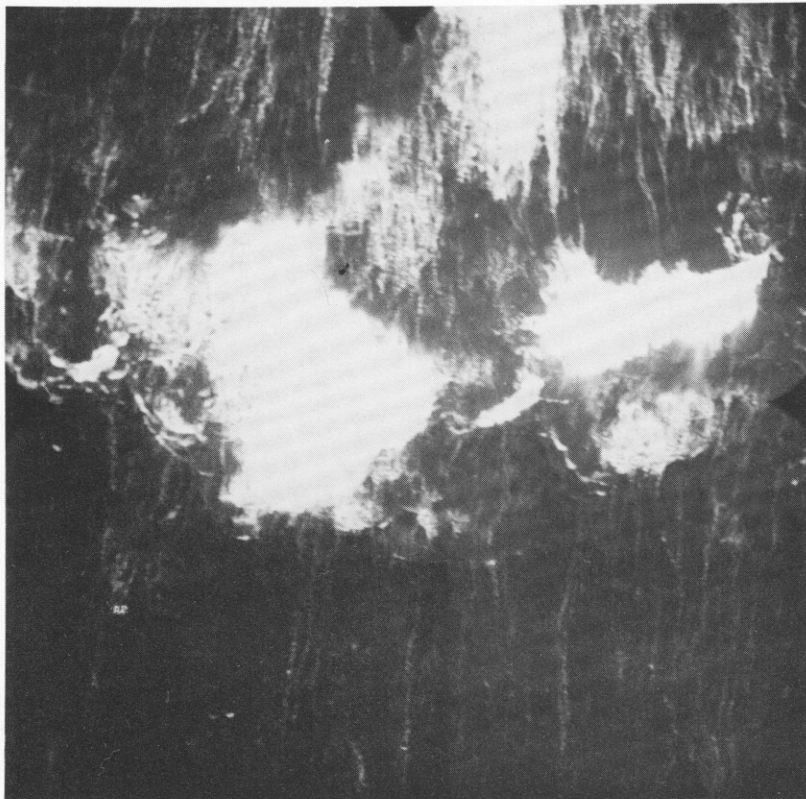
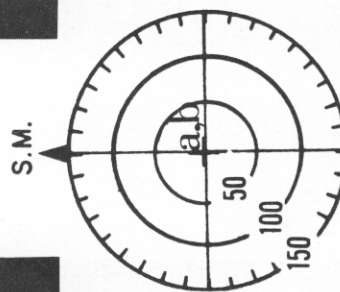


Figure 9b. Flight 750929A, Gladys.
RA = 548 ft. Flight level wind 29.7 m s^{-1}

26 m s^{-1} B11L 51 kt (57 kt)

Beaufort 11(49-55 kt mean; 55-62 kt sustained). Streaks are well-defined, parallel, thin, close together and continuous with very short capillary wavelets cutting across and perpendicular to streaks, giving sea surface a "shattered glass" effect in certain areas. Some large breaking crests may take on "rolling" or "tumbling" appearance. Sea covered 30-40% by white water.

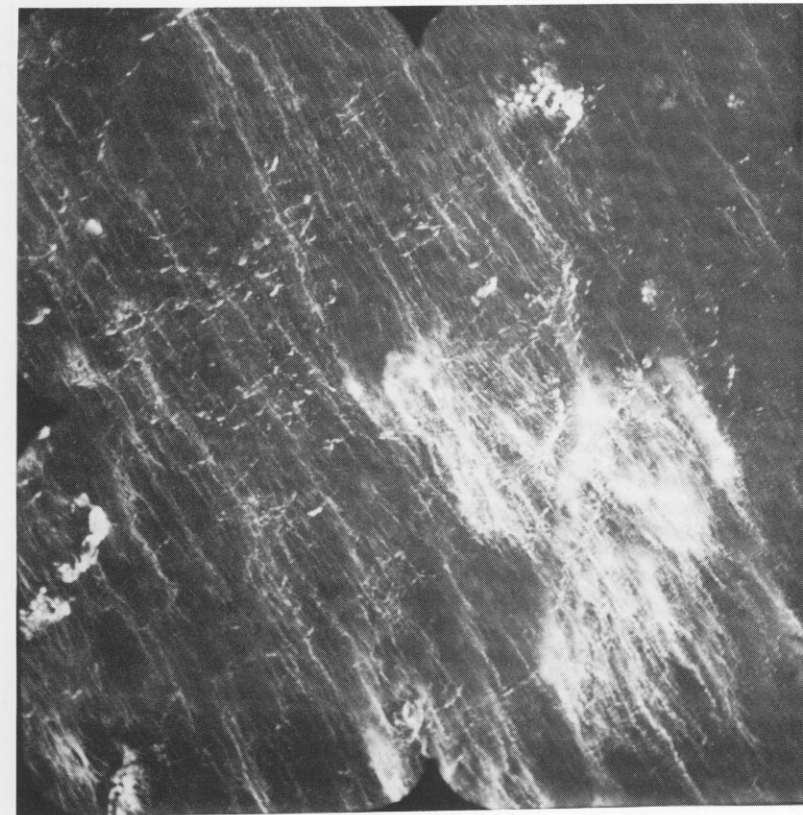


Figure 9c. Flight 750922A, Eloise.
RA = 981 ft. Flight level wind 32.0 m s^{-1}

27 m s^{-1} B11M 52 kt (58 kt)

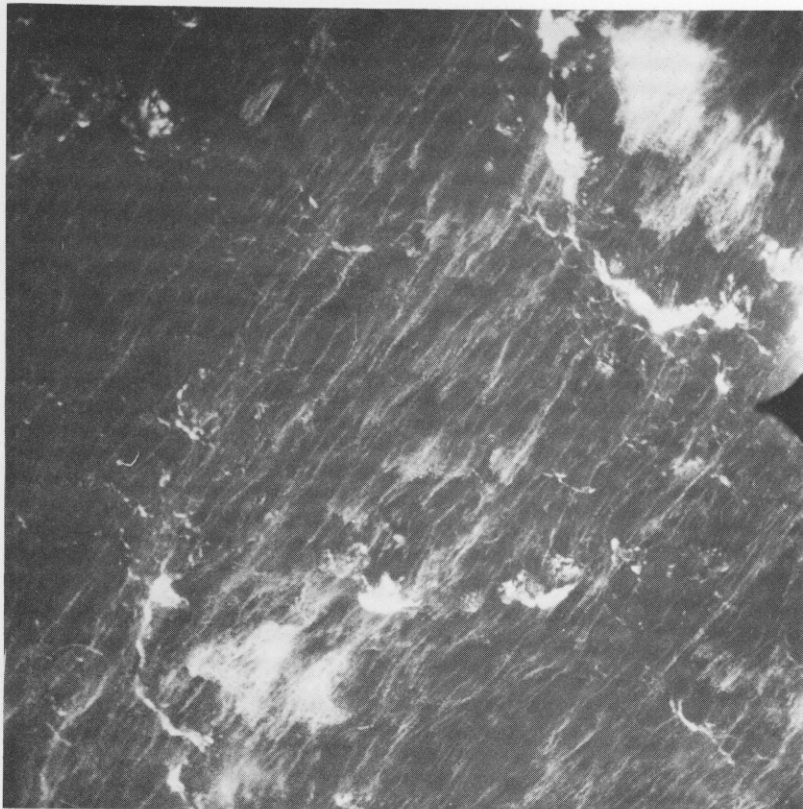
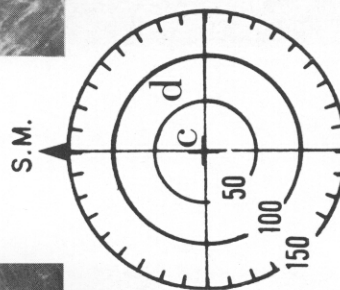


Figure 9d. Flight 750922A, Eloise.
RA = 1024 ft. Flight level wind 32.7 m s^{-1} . Buoy 10-m wind 25 m s^{-1} (EB-10)

27 m s^{-1} B11M 52 kt (58 kt)

Beaufort 11(49-55 kt mean; 55-62 kt sustained). Streaks are well-defined, parallel, thin, close together and continuous with very short capillary wavelets cutting across and perpendicular to streaks, giving sea surface a "shattered glass" effect in certain areas. Some large breaking crests may take on "rolling" or "tumbling" appearance. Sea covered 30-40% by white water.

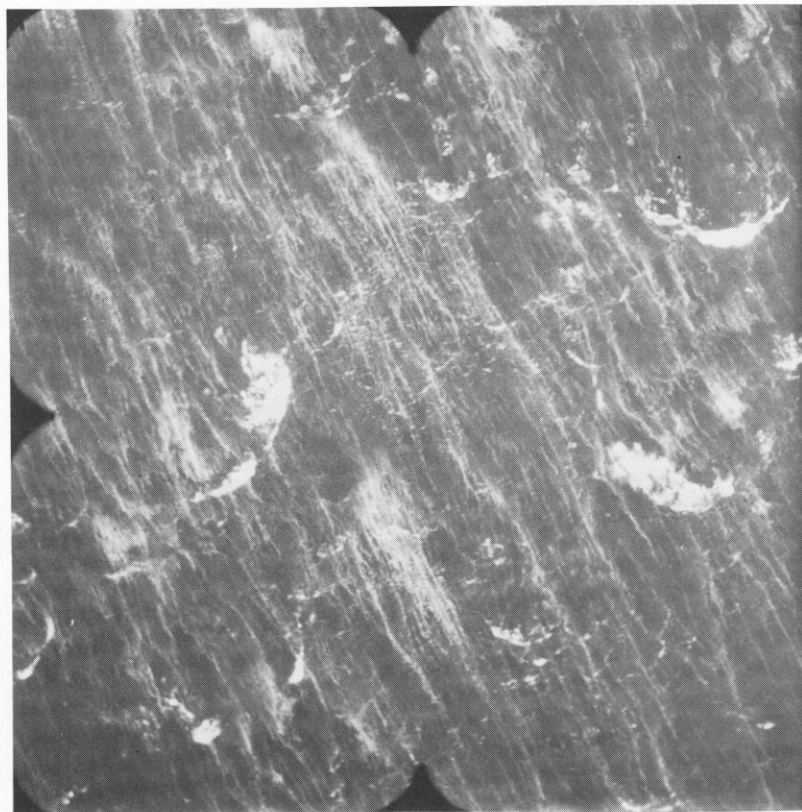


Figure 9e. Flight 750922A, Eloise.
RA = 1050 ft. Flight level wind 33.3 m s^{-1}

28 m s^{-1} B11H 54 kt (61 kt)

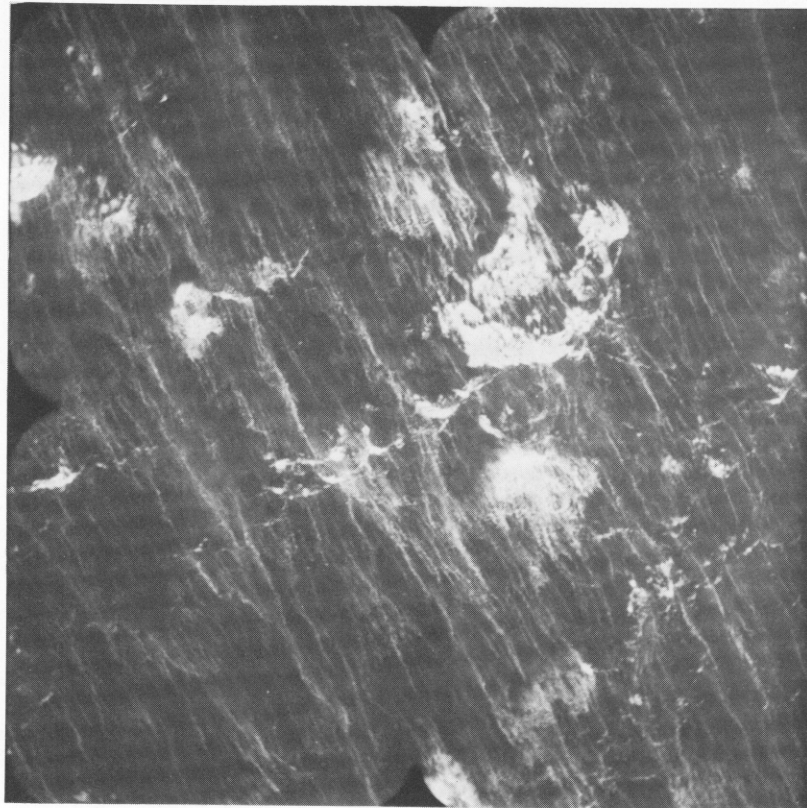
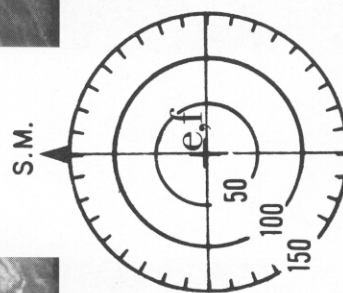


Figure 9f. Flight 750922A, Eloise.
RA = 1010 ft. Flight level wind 34.2 m s^{-1}

28 m s^{-1} B11H 55 kt (62 kt)



Beaufort 11(49-55 kt mean; 55-62 kt sustained). Streaks are well-defined, parallel, thin, close together and continuous with very short capillary wavelets cutting across and perpendicular to streaks, giving sea surface a "shattered glass" effect in certain areas. Some large breaking crests may take on "rolling" or "tumbling" appearance. Sea covered 30-40% by white water.

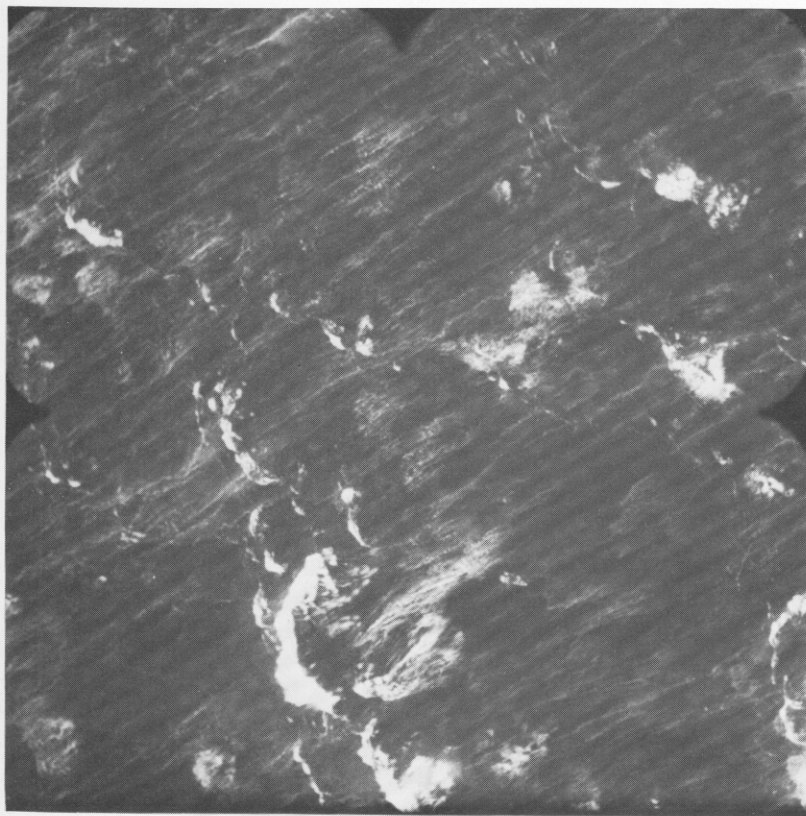


Figure 10a. Flight 750922A, Eloise.
RA = 1004 ft. Flight level wind 34.3 m s^{-1}

28 m s^{-1} B12L 55 kt (63 kt)

HURRICANE WARNING

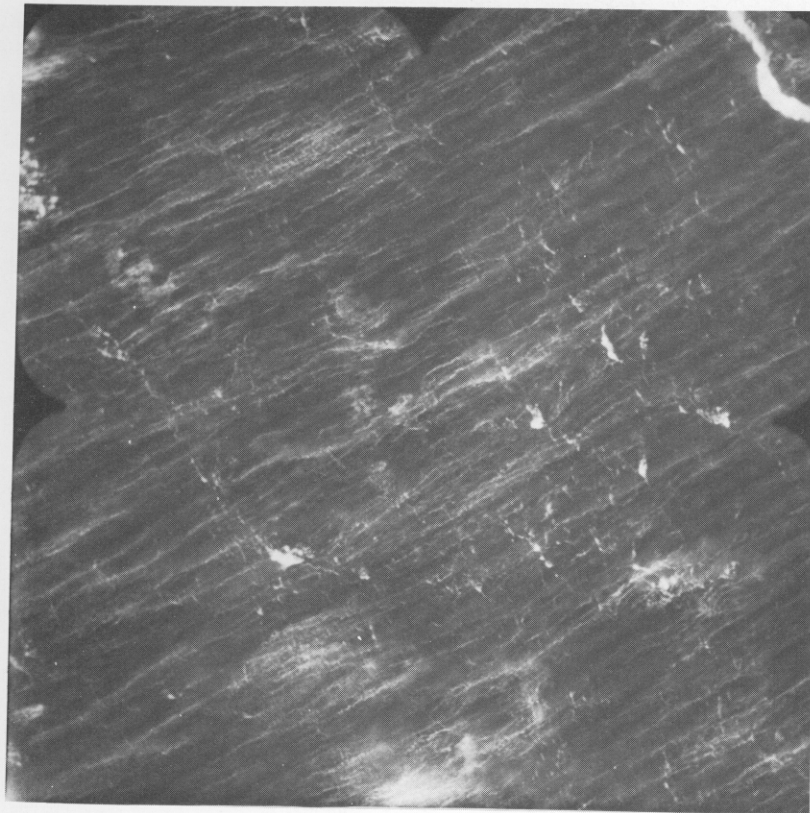
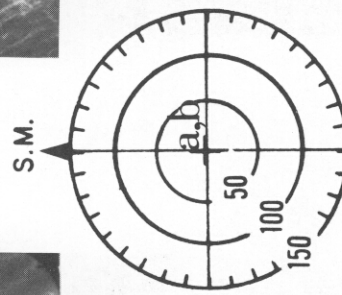


Figure 10b. Flight 750922A, Eloise.
RA = 1010 ft. Flight level wind 34.4 m s^{-1}

28 m s^{-1} B12L 55 kt (62 kt)

HURRICANE WARNING



Beaufort 12(55-61 kt mean; 62-69 kt sustained). Sea may be occasionally obscured by spray and take on a slightly murky appearance. Large, curved breaking crests have undulating effect on streaks giving churning appearance. Some streaks appear to thicken and become milky or pale greenish.

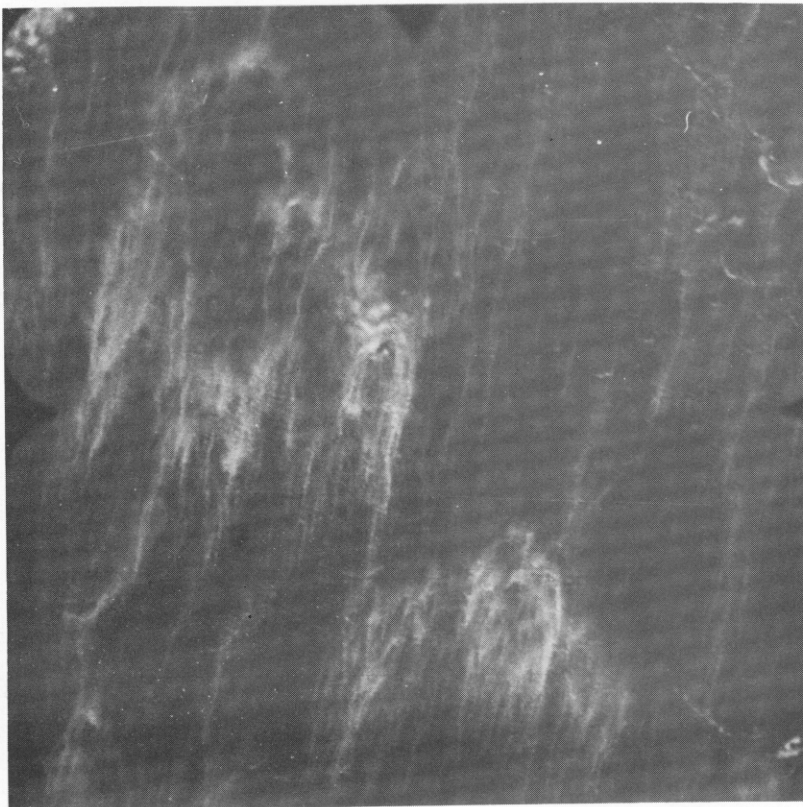


Figure 10c. Flight 750929A, Gladys.
RA = 502 ft. Flight level wind 31.5 m s^{-1}

29 m s^{-1} B12L 55 kt (62 kt)

HURRICANE WARNING

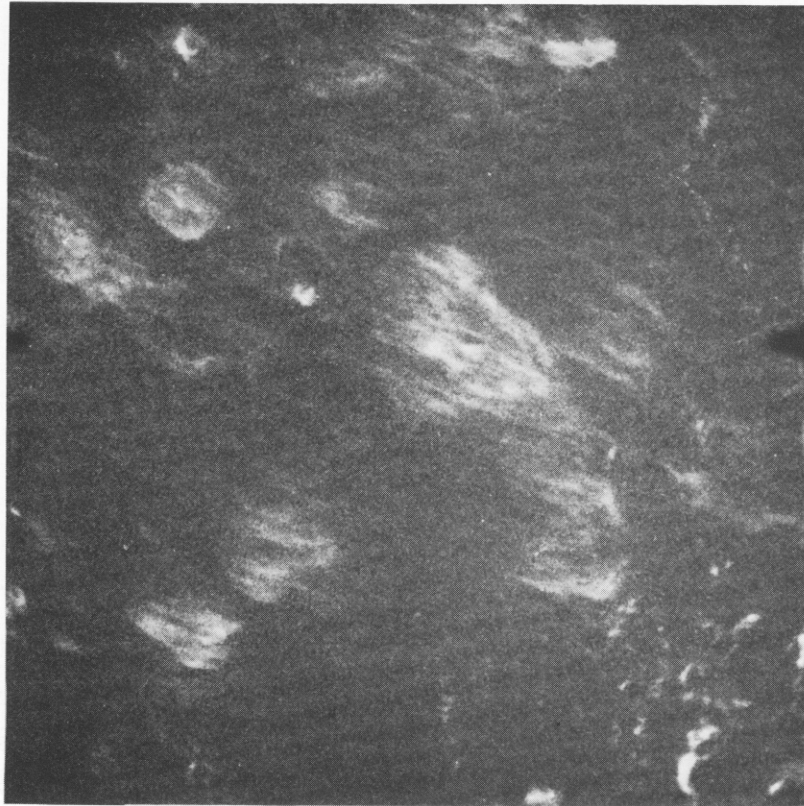
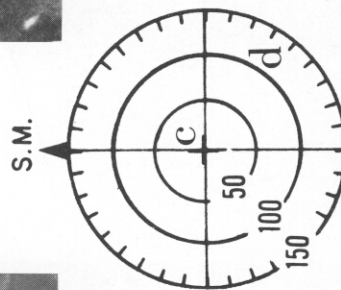


Figure 10d. Flight 800805I, Allen.
RA = 1394 ft. Flight level wind 36.7 m s^{-1}

30 m s^{-1} B12L 57 kt (64 kt)

HURRICANE WARNING



Beaufort 12(55-61 kt mean; 62-69 kt sustained). Sea may be occasionally obscured by spray and take on a slightly murky appearance. Large, curved breaking crests have undulating effect on streaks giving churning appearance. Some streaks appear to thicken and become milky or pale greenish.



Figure 10e. Flight 750929A, Gladys.
RA = 768 ft. Flight level wind 34.2 m s^{-1}

30 m s^{-1} B12H 59 kt (66 kt)

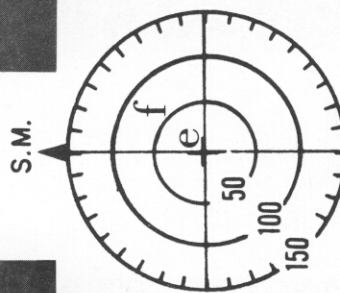
HURRICANE WARNING



Figure 10f. Flight 750922A, Eloise.
RA = 1027 ft. Flight level wind 37.4 m s^{-1}

31 m s^{-1} B12H 60 kt (68 kt)

HURRICANE WARNING



Beaufort 12(55-61 kt mean; 62-69 kt sustained). Sea may be occasionally obscured by spray and take on a slightly murky appearance. Large, curved breaking crests have undulating effect on streaks giving churning appearance. Some streaks appear to thicken and become milky or pale greenish.

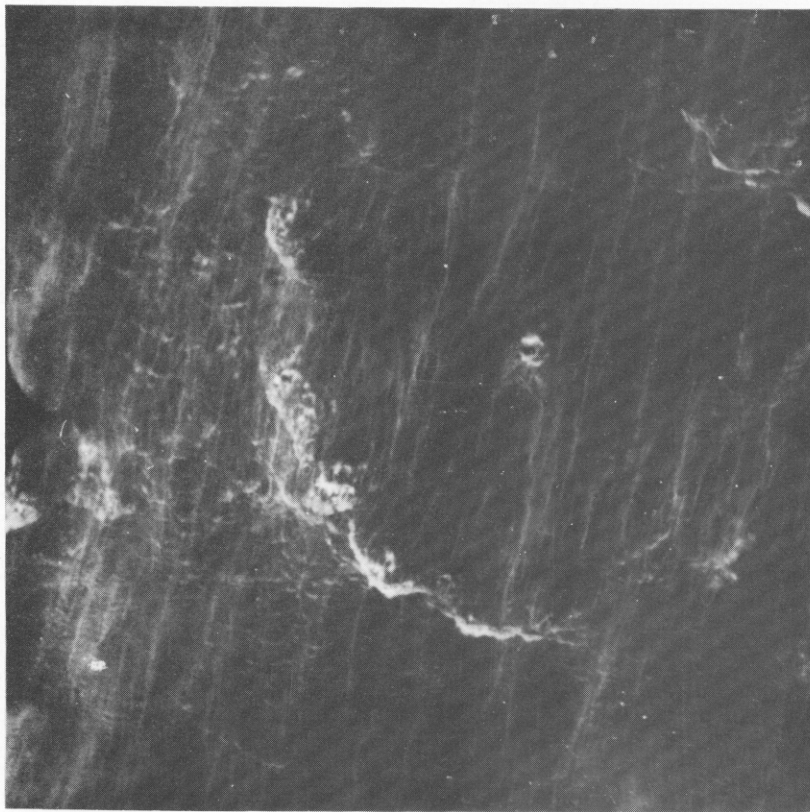


Figure 11a. Flight 750929A, Gladys.
RA = 761 ft. Flight level wind 35.7 m s^{-1}

31 m s^{-1} B13L 61 kt (69 kt)

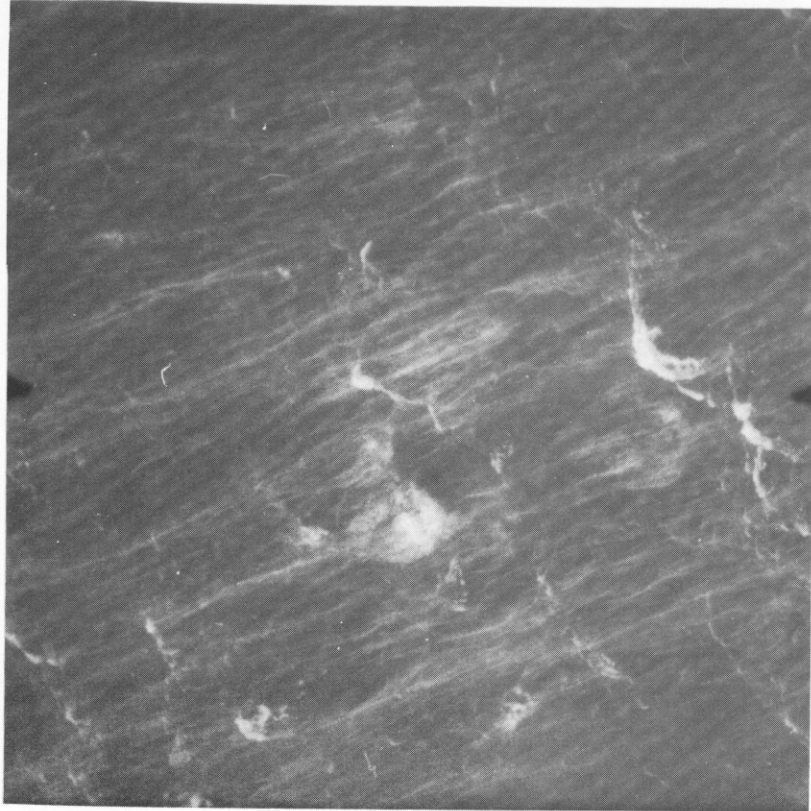
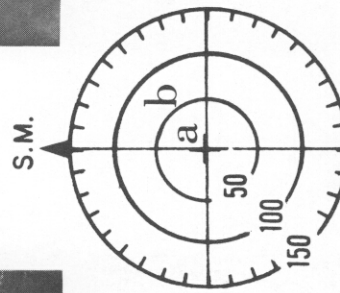


Figure 11b. Flight 750922A, Eloise.
RA = 1010 ft. Flight level wind 38.8 m s^{-1}

32 m s^{-1} B13M 63 kt (71 kt)



Beaufort 13(61-66 kt mean; 69-75 kt sustained). Surface features generally become murky. Streaks and foam patches begin to lose their sharp definition and appear to smudge, thicken or merge together. Frequent, extremely large, almost semi-circular crests outlined by thinly breaking waves with occasional groups of large foam patches after entire crest breaks.

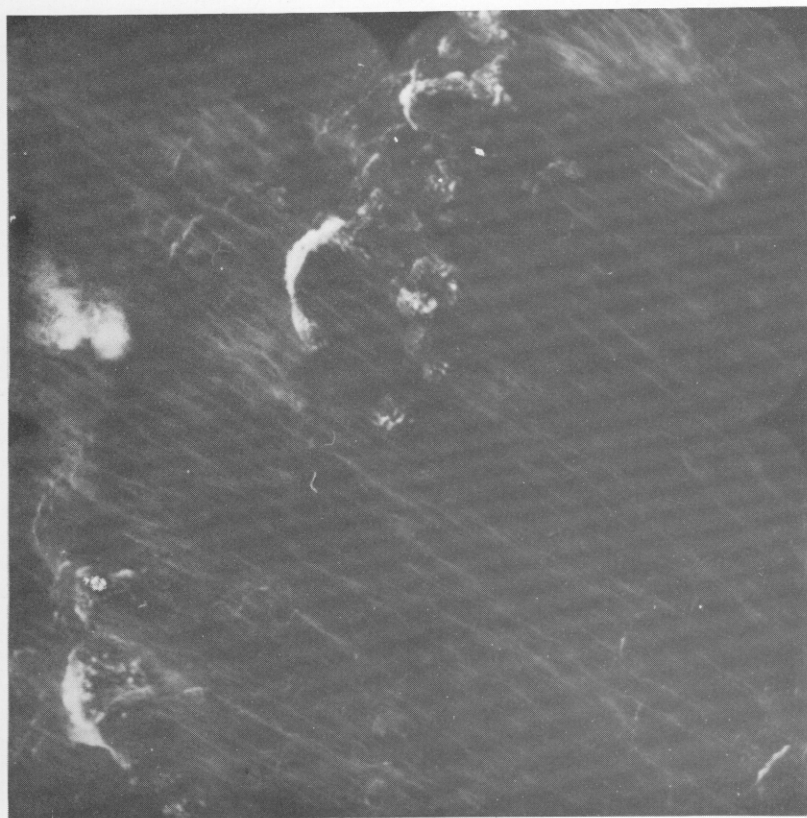


Figure 11c. Flight 750929A, Gladys.
RA = 987 ft. Flight level wind 38.8 m s^{-1}

33 m s^{-1} B13M 64 kt (72 kt)

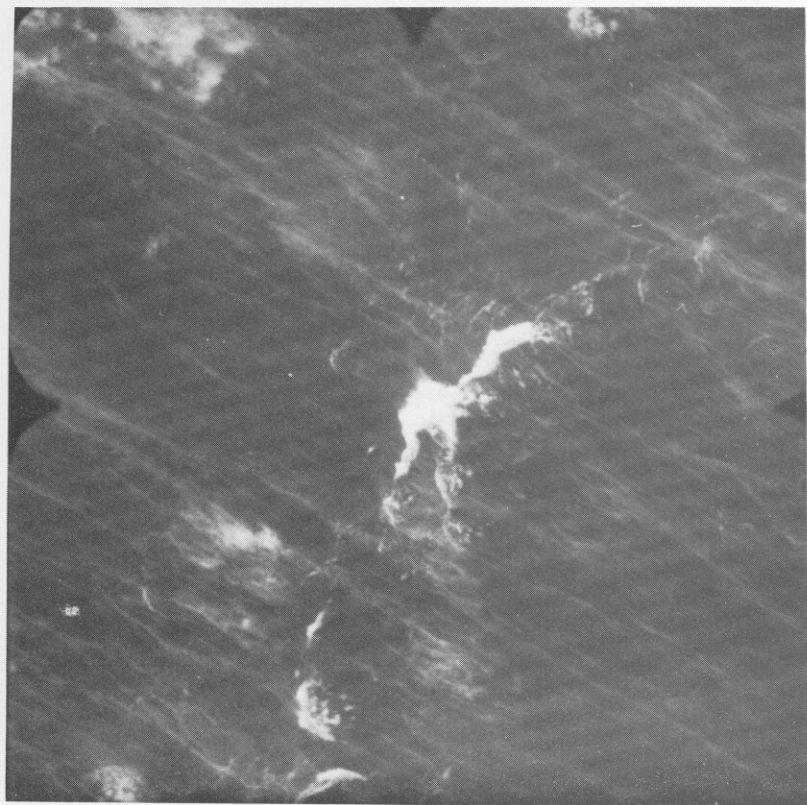
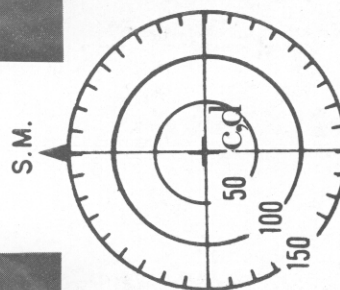


Figure 11d. Flight 750929A, Gladys.
RA = 1086 ft. Flight level wind 39.5 m s^{-1}

33 m s^{-1} B13M 64 kt (72 kt)

Beaufort 13(61-66 kt mean; 69-75 kt sustained). Surface features generally become murky. Streaks and foam patches begin to lose their sharp definition and appear to smudge, thicken or merge together. Frequent, extremely large, almost semi-circular crests outlined by thinly breaking waves with occasional groups of large foam patches after entire crest breaks.



Figure 11e. Flight 750929A, Gladys.
RA = 1043 ft. Flight level wind 39.4 m s^{-1}

33 m s^{-1} B13H 65 kt (73 kt)

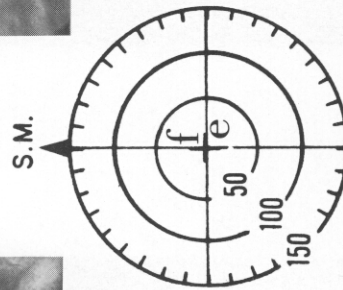


Figure 11f. Flight 750929A, Gladys.
RA = 640 ft. Flight level wind 39.2 m s^{-1} .

33 m s^{-1} B13H 65 kt (73 kt)

Beaufort 13(61-66 kt mean; 69-75 kt sustained). Surface features generally become murky. Streaks and foam patches begin to lose their sharp definition and appear to smudge, thicken or merge together. Frequent, extremely large, almost semi-circular crests outlined by thinly breaking waves with occasional groups of large foam patches after entire crest breaks.

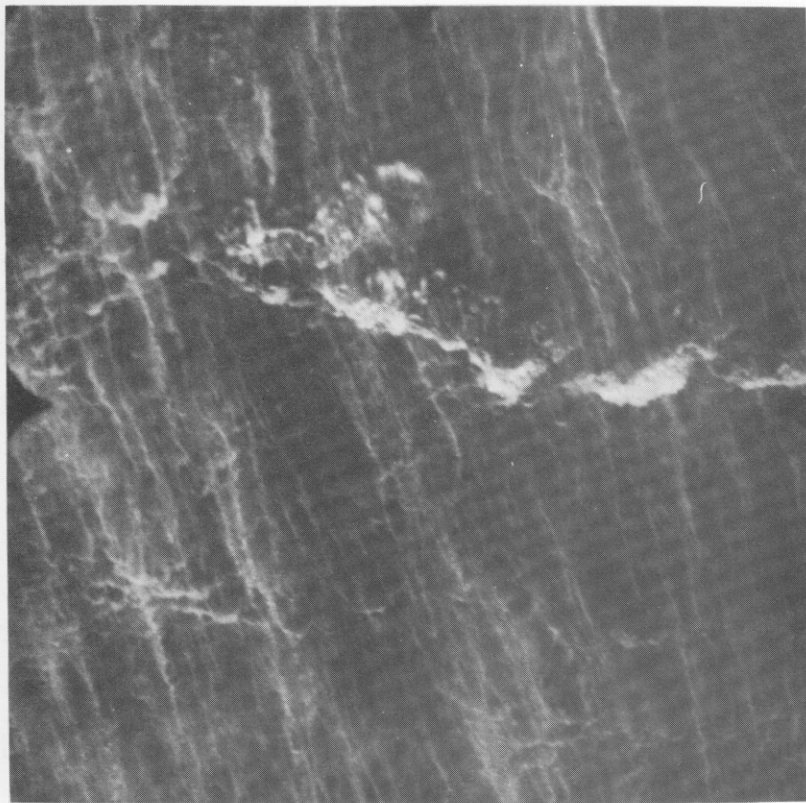


Figure 12a. Flight 750929A, Gladys.
RA = 656 ft. Flight level wind 40.5 m s⁻¹

34 m s⁻¹ B14L 67 kt (75 kt)

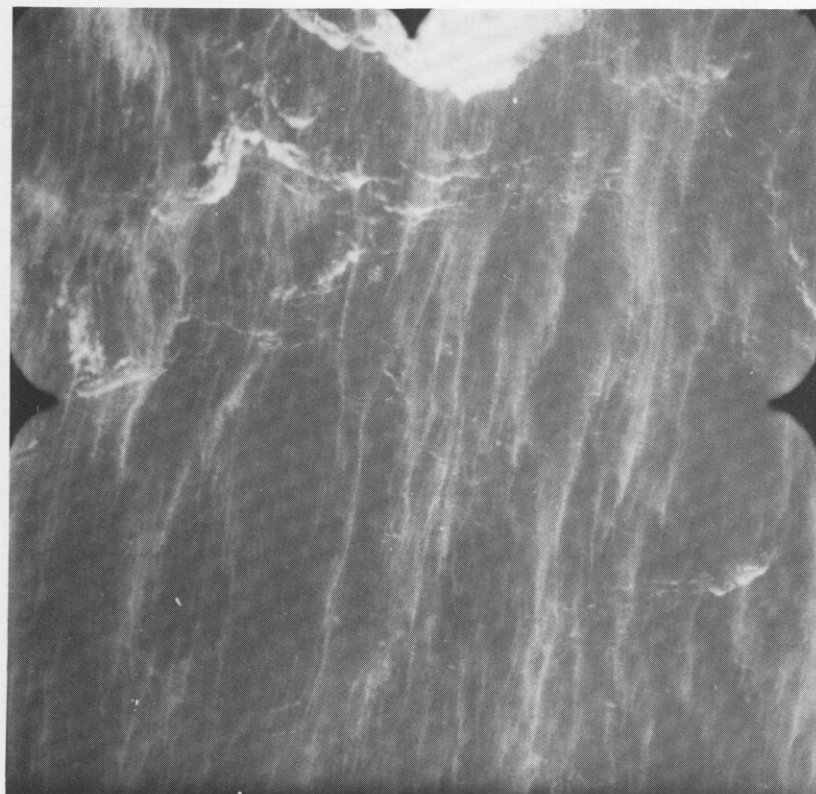
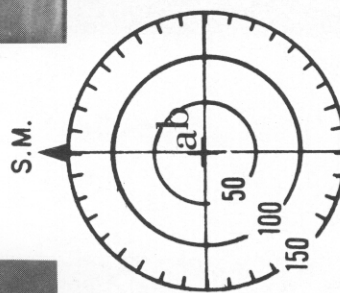


Figure 12b. Flight 750922A, Eloise.
RA = 968 ft. Flight level wind 42.1 m s⁻¹

35 m s⁻¹ B14M 68 kt (77 kt)

Beaufort 14(66-72 kt mean; 75-81 kt sustained). Quantity of spray increases. Streaks thicken and appear to have more depth. Previous crisp, shattered glass appearance now appears blurred. Most features appear to be submerged rather than surface phenomena due to obscuration. Very short capillary wavelets which cut across streaks give surface a stressful appearance as though undergoing compression. Sea surface 50% white.

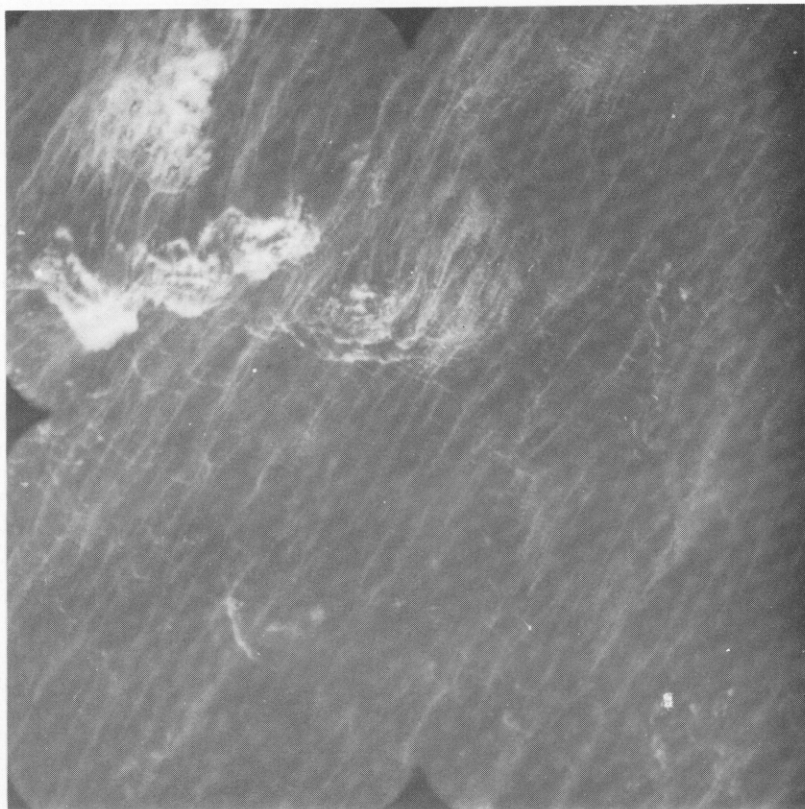


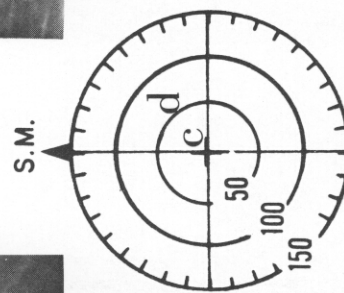
Figure 12c. Flight 750929A, Gladys.
RA = 928 ft. Flight level wind 41.5 m s⁻¹

35 m s⁻¹ B14M 68 kt (77 kt)



Figure 12d. Flight 750922A Eloise
RA = 1148 ft. Flight level wind 43.2 m s⁻¹

36 m s⁻¹ B14M 69 kt (78 kt)



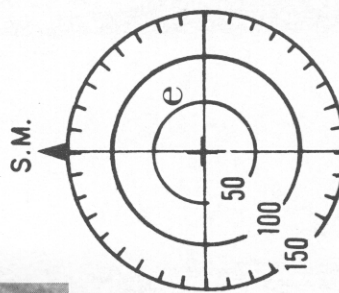
Beaufort 14(66-72 kt mean; 75-81 kt sustained). Quantity of spray increases. Streaks thicken and appear to have more depth. Previous crisp, shattered glass appearance now appears blurred. Most features appear to be submerged rather than surface phenomena, due to obscuration. Very short capillary wavelets which cut across streaks give surface a stressful appearance as though undergoing compression. Sea surface 50% white.

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Figure 12e. Flight 750922A, Eloise.
RA = 1017 ft. Flight level wind 43.5 m s^{-1}

36 m s^{-1} B14H 70 kt (79 kt)



Beaufort 14 (66-72 kt; 75-81 kt sustained). Quantity of spray increases. Streaks thicken and appear to have more depth. Previous crisp, shattered glass appearance now appears blurred. Most features appear to be submerged rather than surface phenomena due to obscuration. Very short capillary wavelets which cut across streaks give surface a stressful appearance as though undergoing compression. Sea surface 50% white.

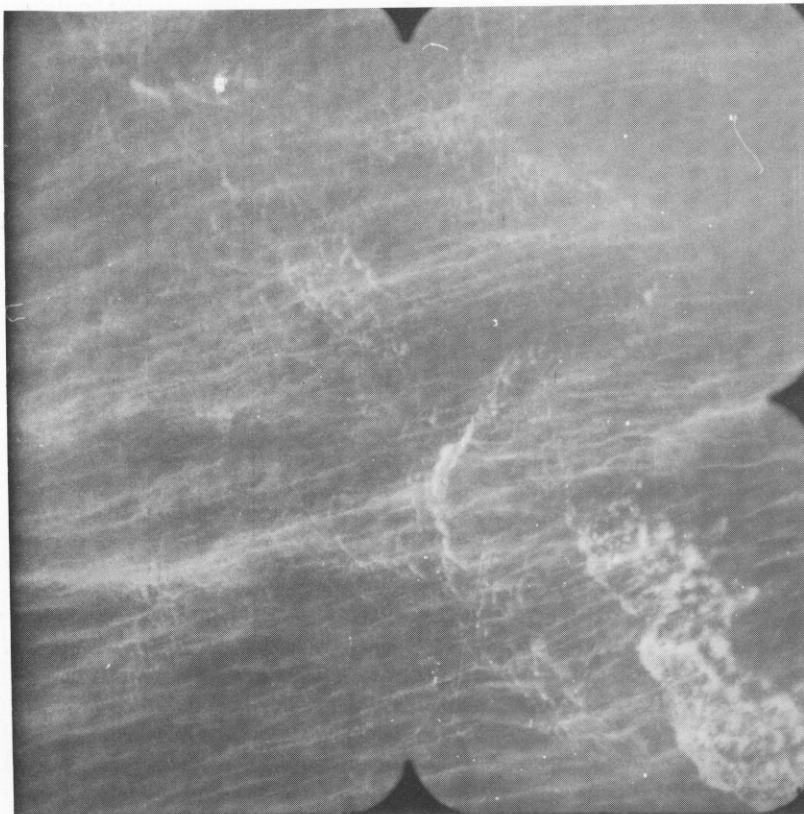


Figure 13a. Flight 750929A, Gladys.
RA = 689 ft. Flight level wind 43.4 m s^{-1}

37 m s^{-1} B15L 72 kt (82 kt)

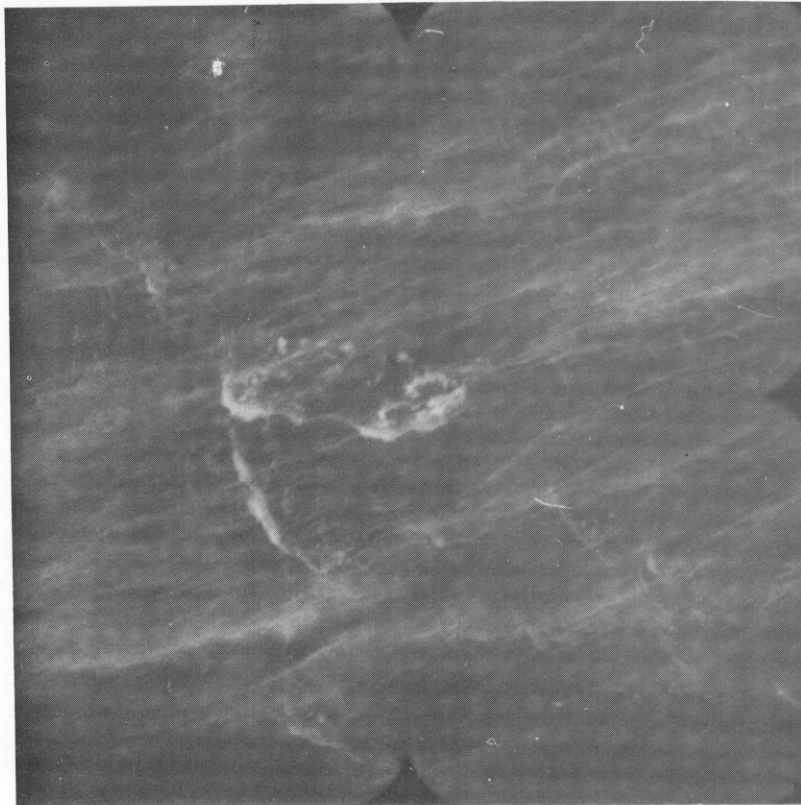
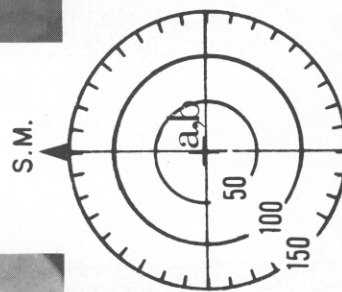


Figure 13b. Flight 750929A, Gladys.
RA = 597 ft. Flight level wind 43.0 m s^{-1}

38 m s^{-1} B15M 74 kt (83 kt)

Beaufort 15 (72-78 kt mean; 81-88 kt sustained). Sea appears flatter and entire surface takes on a whiteish/grayish cast. Streaks organize somewhat into broader, diffuse bands. All features lose some definition and appear submerged. Surface 50-55% white.



Figure 13c. Flight 750922A, Eloise.
RA = 935 ft. Flight level wind 45.5 m s^{-1}

38 m s^{-1} B15M 74 kt (83 kt)

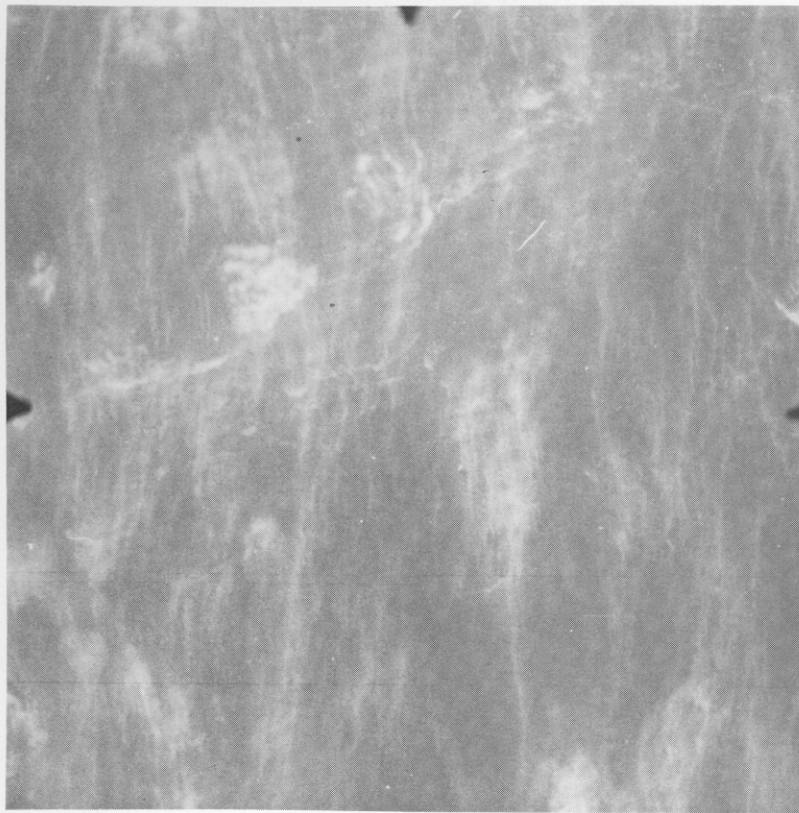
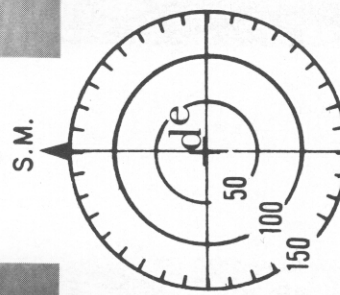


Figure 13d. Flight 750929A, Gladys.
RA = 1020 ft. Flight level wind 45.0 m s^{-1}

38 m s^{-1} B15M 75 kt (84 kt)

Beaufort 15(72-78 kt mean; 81-88 kt sustained). Sea appears flatter and entire surface takes on a whiteish/grayish cast. Streaks organize somewhat into broader, diffuse bands. All features lose some definition and appear submerged. Surface 50-55% white.

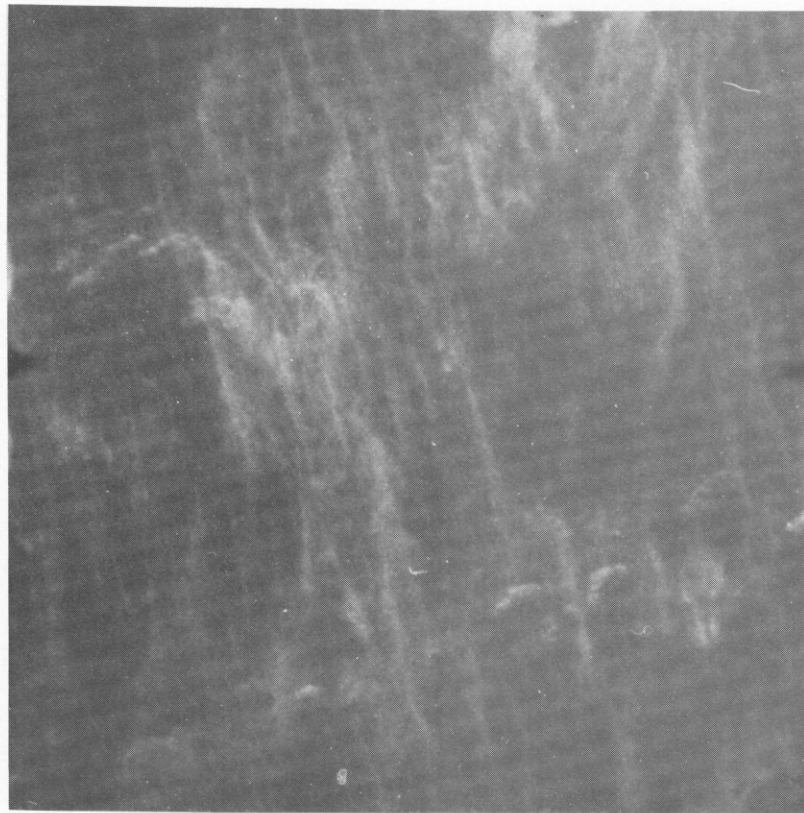


Figure 14a. Flight 790830I, David.
RA = 1528 ft. Flight level wind 50.7 m s^{-1}

41 m s^{-1} B16L 79 kt (89 kt)

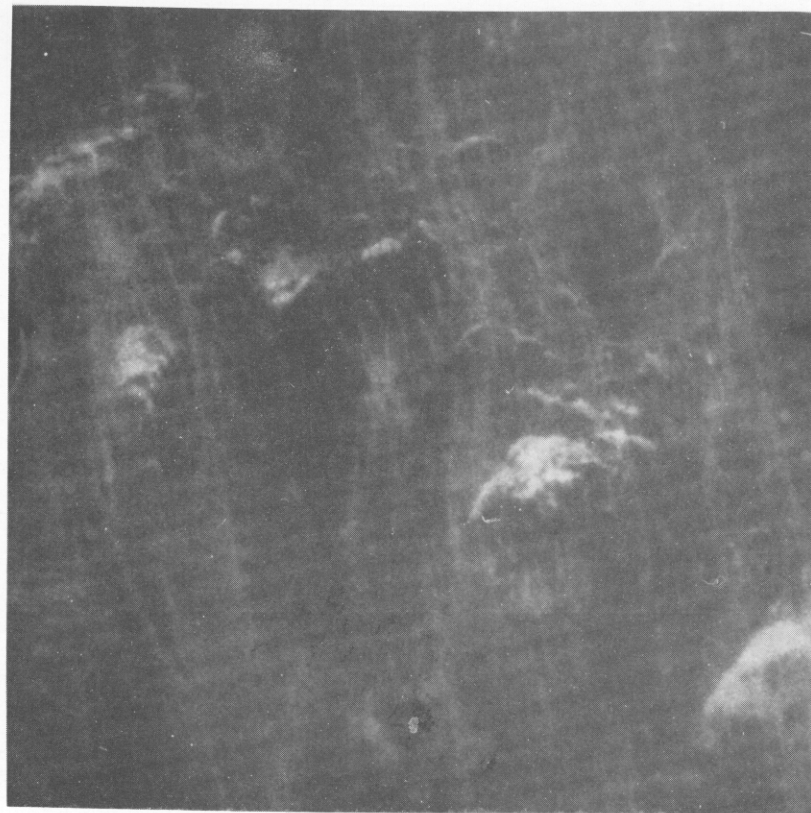
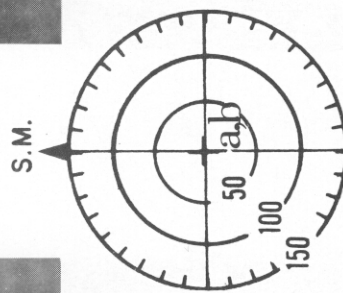


Figure 14b. Flight 790830I, David.
RA = 1542 ft. Flight level wind 50.7 m s^{-1}

41 m s^{-1} B16L 79 kt (89 kt)

Beaufort 16 (78-84 kt mean; 88-95 kt sustained). Many thin streaks are partially obscured and those which can be seen may appear as bands spaced further apart. Occasional cloud below aircraft blots out or obscures surface. Sea appears almost flat. Whiteish cast covers 60-65% of surface.



Figure 14c. Flight 750922A, Eloise.
RA = 991 ft. Flight level wind 49.1 m s^{-1}

41 m s^{-1} B16L 79 kt (89 kt)

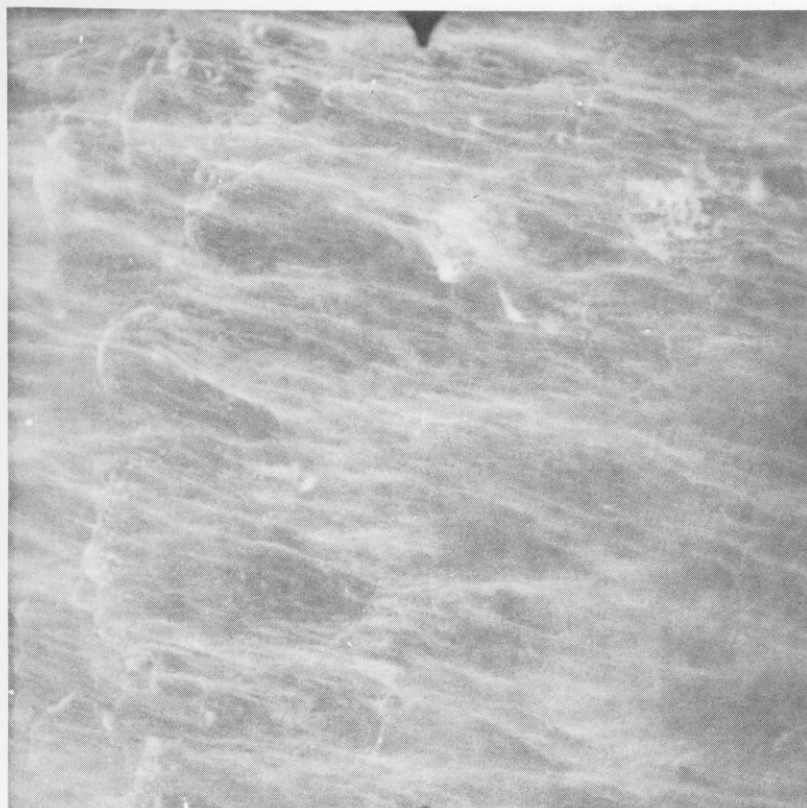
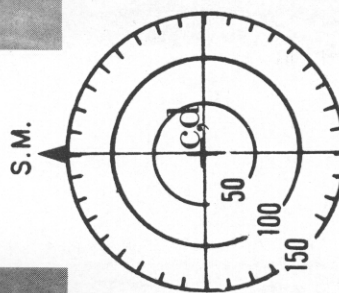


Figure 14d. Flight 750922A, Eloise.
RA = 1004 ft. Flight level wind 49.4 m s^{-1}

41 m s^{-1} B16M 80 kt (90 kt)

Beaufort 16 (78-84 kt mean; 88-95 kt sustained). Many thin streaks are partially obscured and those which can be seen may appear as bands spaced further apart. Occasional cloud below aircraft blots out or obscures surface. Sea appears almost flat. Whiteish cast covers 60-65% of surface.



Figure 14e. Flight 750922A, Eloise.
RA = 1014 ft. Flight level wind 50.1 m s^{-1}

42 m s^{-1} B16H 81 kt (91 kt)

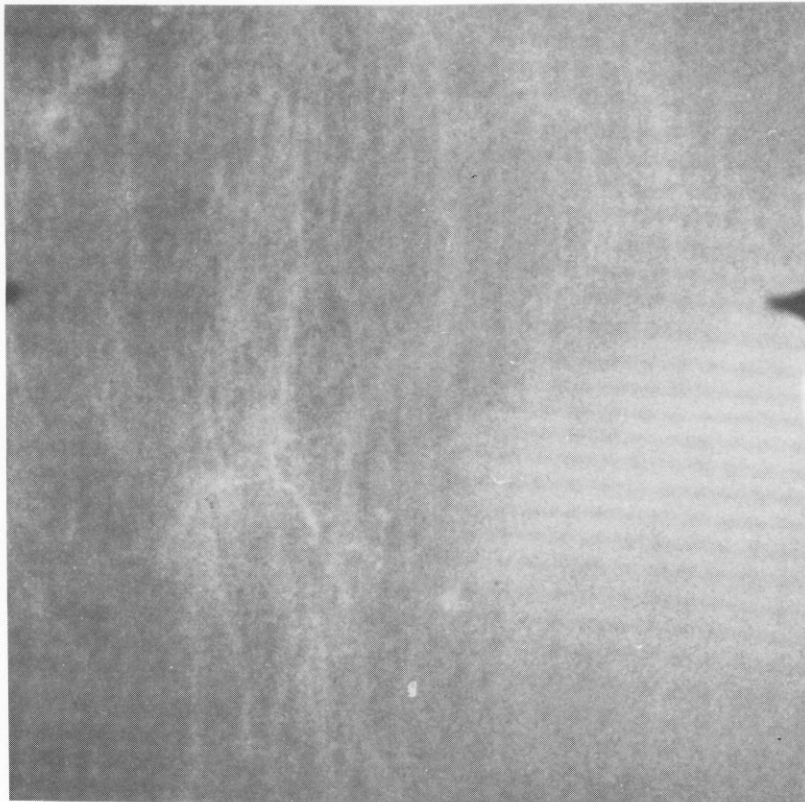
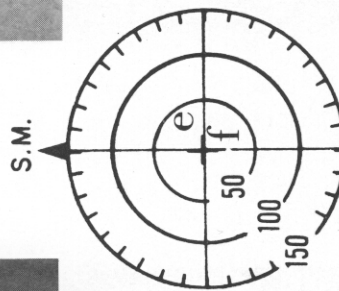


Figure 14f. Flight 790830I, David.
RA = 1558 ft. Flight level wind 53.8 m s^{-1}

43 m s^{-1} B16H 83 kt (93 kt)

Beaufort 16 (78-84 kt mean; 88-95 kt sustained). Many thin streaks are partially obscured and those which can be seen may appear as bands spaced further apart. Occasional cloud below aircraft blots out or obscures surface. Sea appears almost flat. Whiteish cast covers 60-65% of surface.

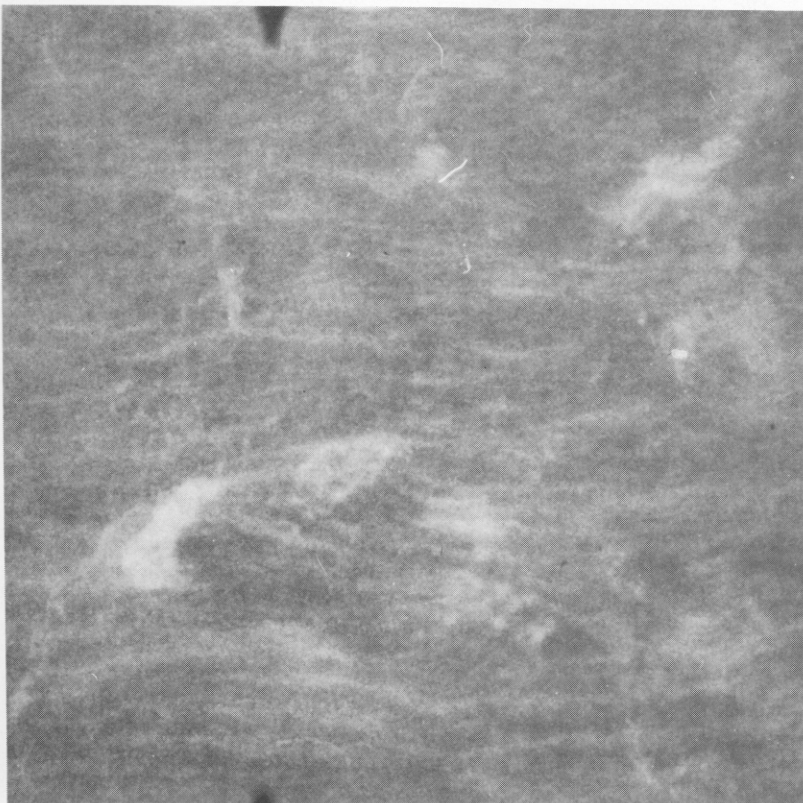


Figure 15a. Flight 790830I, David.
RA = 1542 ft. Flight level wind 56.0 m s^{-1}

44 m s^{-1} B17L 85 kt (96 kt)

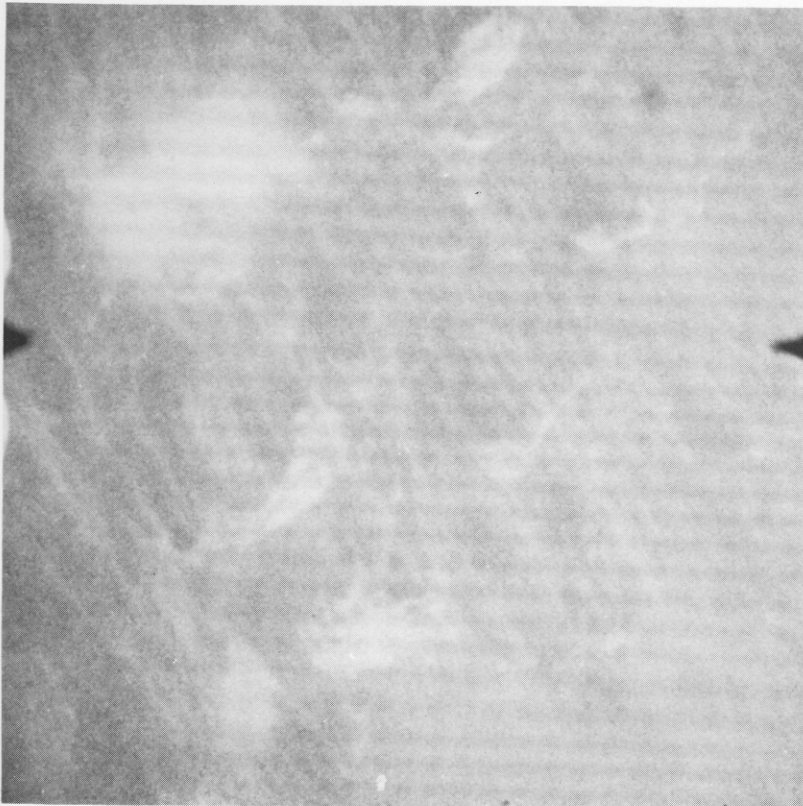
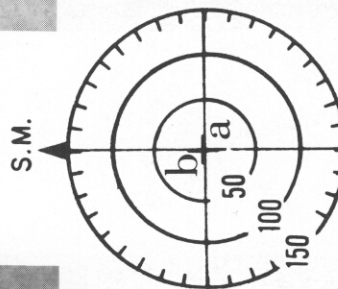


Figure 15b. Flight 790830I, David.
RA = 1709 ft. Flight level wind 57.0 m s^{-1}

45 m s^{-1} B17M 86 kt (97 kt)

Beaufort 17 (84-90 kt mean; 95-102 kt sustained). Breaking waves and foam patches appear as diffuse, white, puffy areas. Streaks become fuzzy bands. Surface 70-80% white.

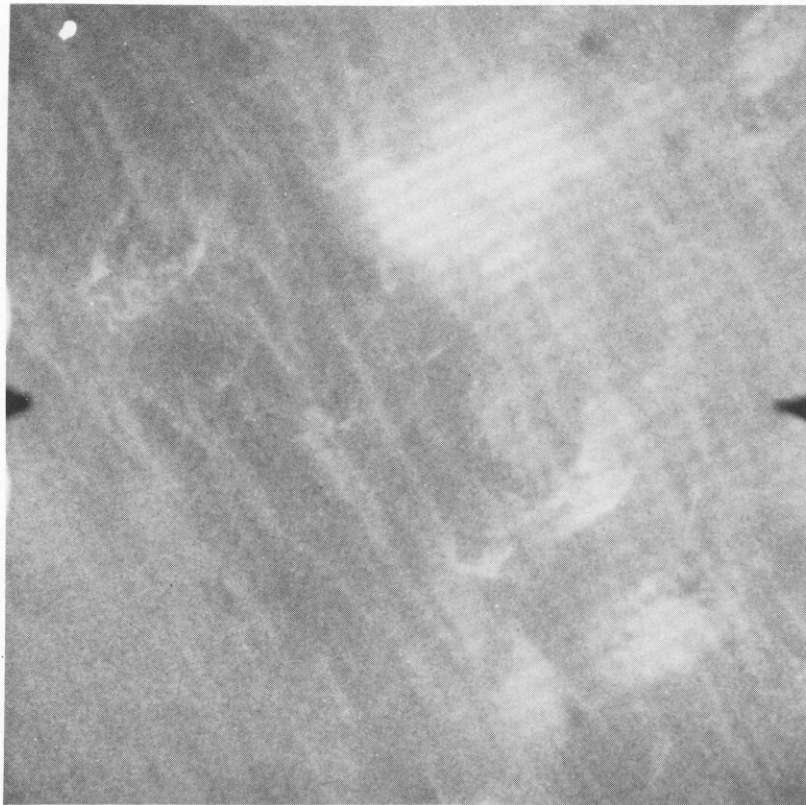


Figure 15c. Flight 790830I David
RA = 1709 ft. Flight level wind 57.1 m s^{-1}

45 m s^{-1} B17M 86 kt (97 kt)

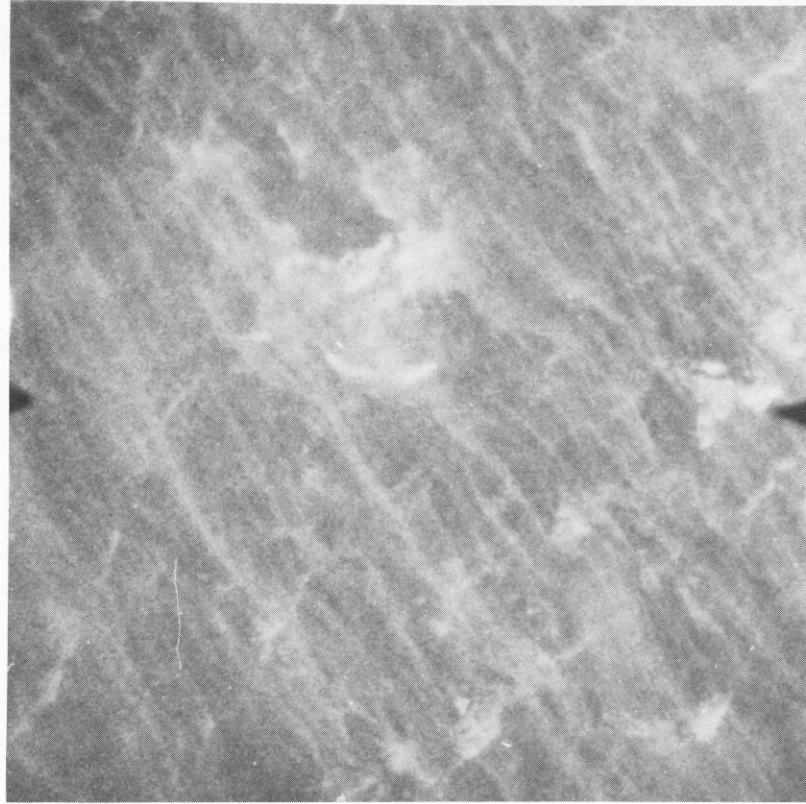
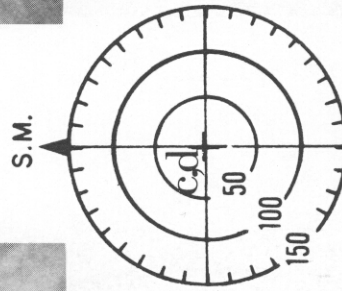


Figure 15d. Flight 790830I David
RA = 1643 ft. Flight level wind
 58.8 m s^{-1}

46 m s^{-1} B17H 89 kt (101 kt)

Beaufort 17 (84-90 kt mean; 95-102 kt sustained). Breaking waves and foam patches appear as diffuse, white, puffy areas. Streaks become fuzzy bands. Surface 70-80% white.

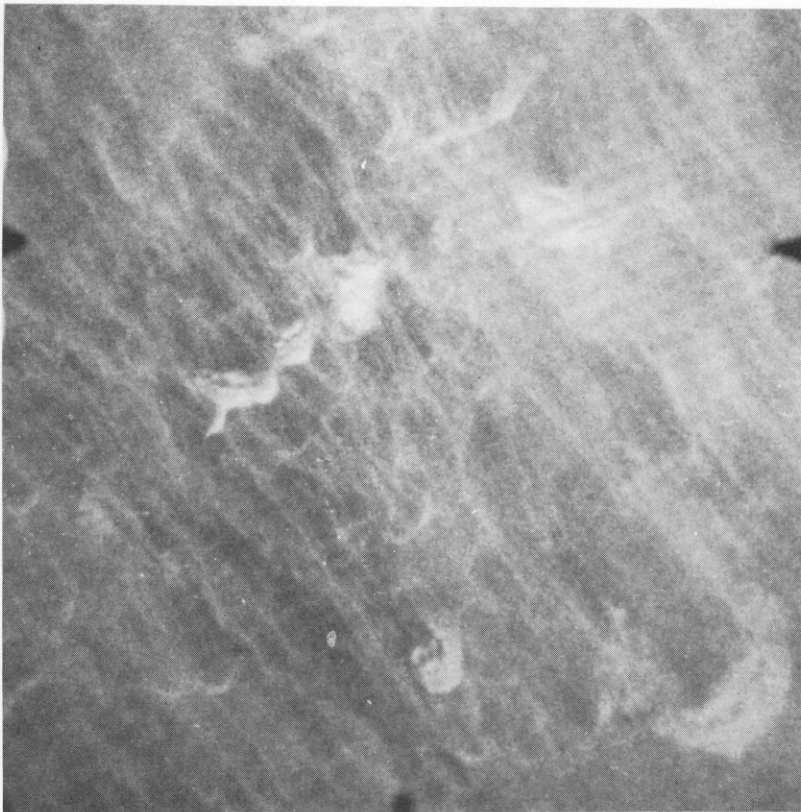


Figure 15e. Flight 790830I, David.
RA = 1647 ft. Flight level wind 58.8 m s^{-1}

46 m s^{-1} B17H 89 kt (101 kt)

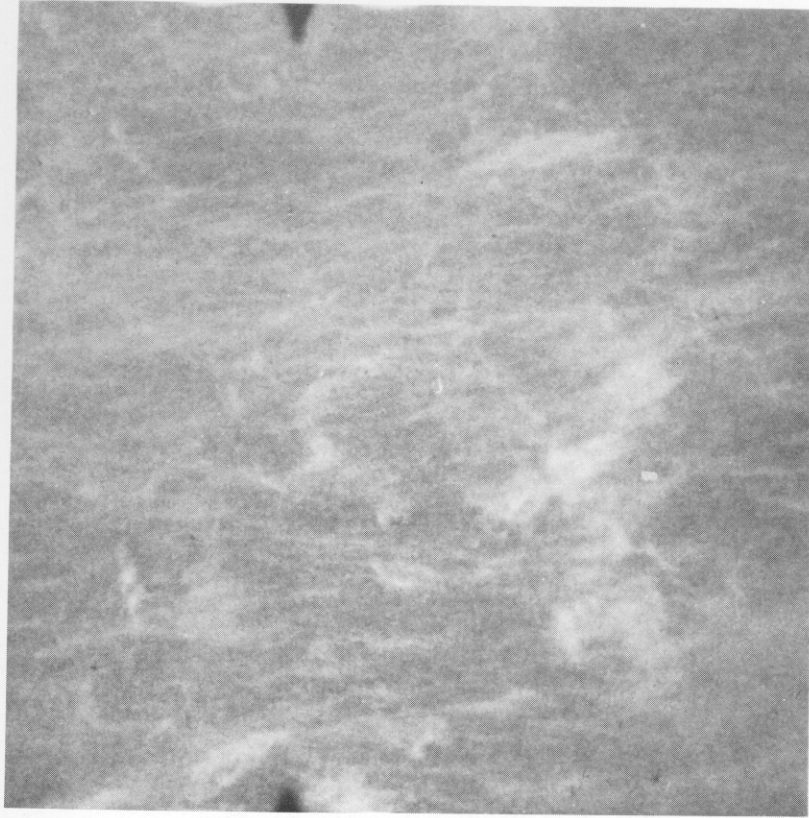
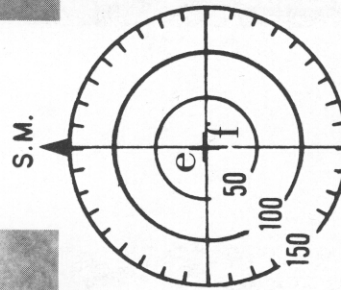


Figure 15f. Flight 790830I, David.
RA = 1542 ft. Flight level wind 58.3 m s^{-1} .

46 m s^{-1} B17H 89 kt (101 kt)

Beaufort 17 (84-90 kt mean; 95-102 kt sustained). Breaking waves and foam patches appear as diffuse, white, puffy areas. Streaks become fuzzy bands. Surface 70-80% white.

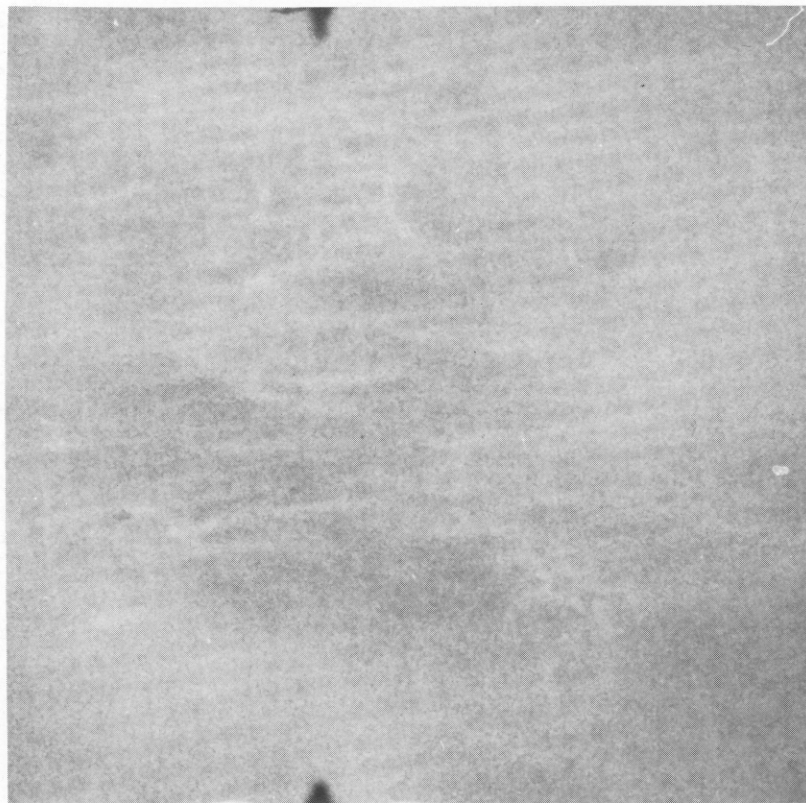


Figure 16a. Flight 790830I, David.
RA = 1486 ft. Flight level wind 61.7 m s^{-1}

49 m s^{-1} B18H 95 kt (107 kt)

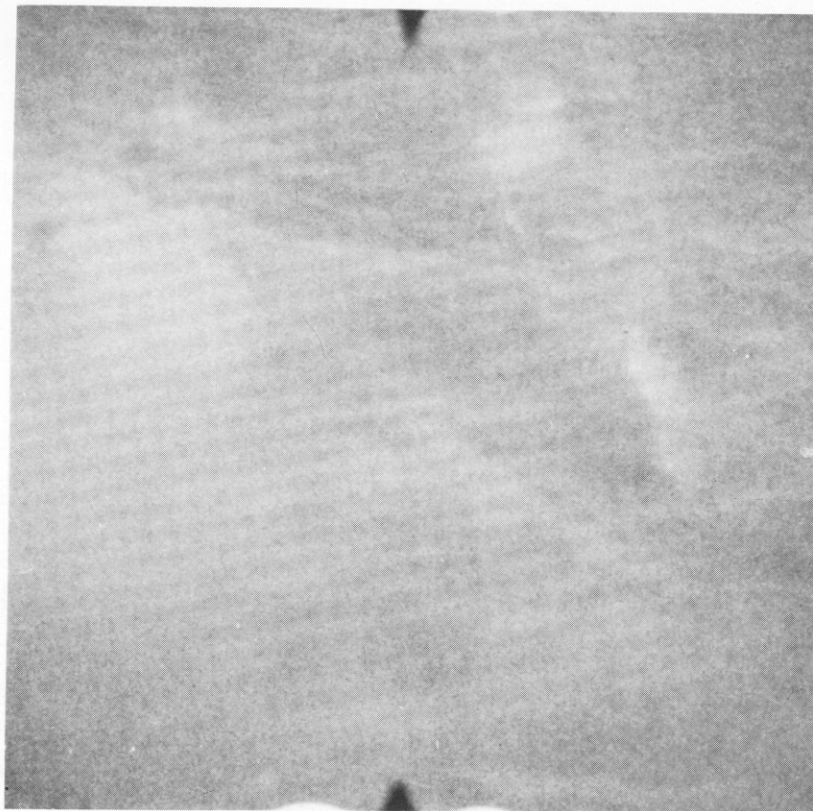
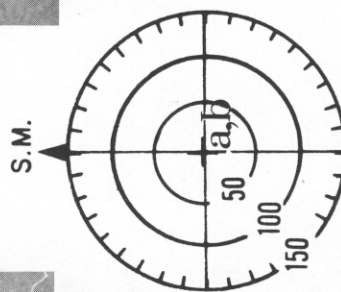
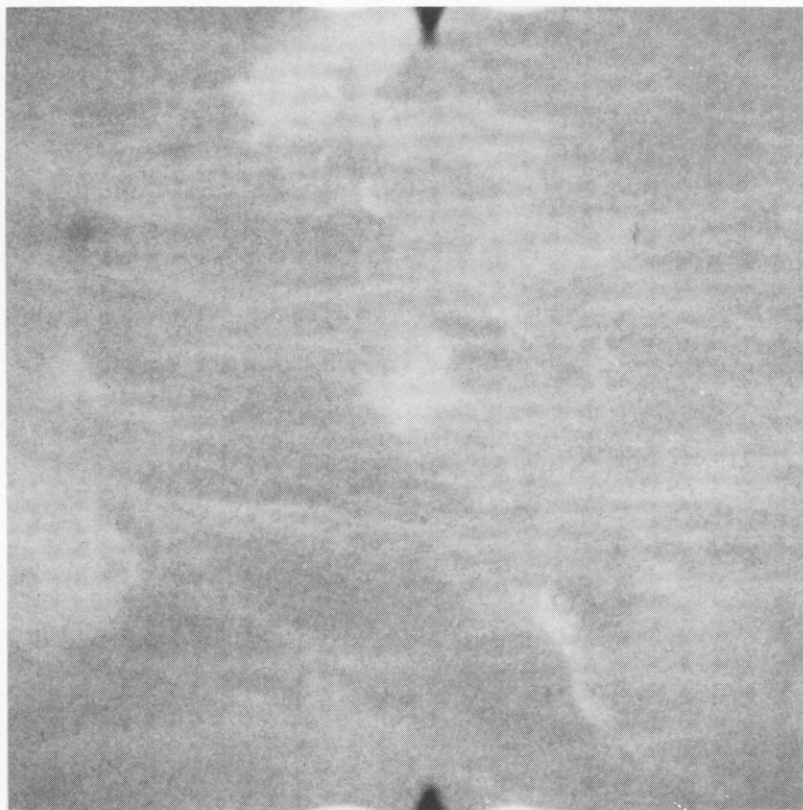


Figure 16b. Flight 790830I, David.
RA = 1469 ft. Flight level wind 61.7 m s^{-1}

49 m s^{-1} B18H 95 kt (107 kt)

Beaufort 18 (90-96 kt mean; 102-108 kt sustained). Cloud, spray and foam patches merge into large, white, undefinable areas historically referred to as "white sheets." Surface features have only rough boundary definition.



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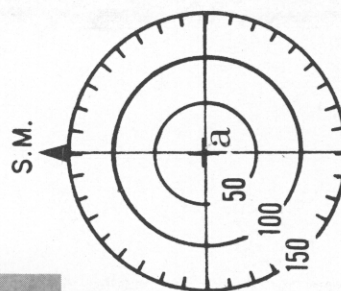


Figure 17a. Flight 790830I David
RA = 1489 ft. Flight level wind 63.0 m s^{-1}

50 m s^{-1} B19L 97 kt (110 kt)

Beaufort 19(96-102 kt mean; 108-115 kt sustained). Isolated large, white puffs. Only strongest features of previously seen thick streaks remain observable giving impression of only a very few widely scattered, non-parallel streaks or wide bands. Surface 100% covered by whiteish and greenish cast.

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