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SEASAT Wave Height Measurement: A Comparison With Sea-Truth Data and a Wave Forecasting Model—Application to the Geographic Distribution of Strong Sea States in Storms

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The SEASAT altimeter derived wave height ('on-board' estimate) has been successfully compared with ship reports over the North Atlantic Ocean, for 163 passes of SEASAT, from September 15 to October 9, 1978. Satellite wave height measurements reveal features of great interest: first, SEASAT data are used to evaluate the spectral wave forecasting model, DSA 5, of the French Meteorological Office (La Météorologie Nationale). Then, the analysis of 26 SEASAT passes through low-pressure areas shows the geographic distribution of strong sea states in storms and the large variations of wave height over short distances, an important observation for wave modeling and ship routing.

INTRODUCTION

The radar altimeters of Skylab in 1973 and GEOS 3 in 1975 demonstrated that it is possible to estimate the significant wave height ($H_{1/3}$) from satellite measurements. Six algorithms have been developed for extracting $H_{1/3}$ from GEOS 3 data, and comparisons have shown a good agreement among them and with surface truth data [*Fedor et al.*, 1979]. SEASAT, launched on June 26, 1978, was equipped with a radar altimeter designed to give real time estimates of $H_{1/3}$ with a precision of $\pm 10\%$.

One of the objectives of satellite wave height measurements is to give across large areas in the oceans continuous sea state information that cannot be obtained with conventional ship and buoy measurements. Such information is very useful for oceanic wave modeling as well as knowledge of the distribution of strong sea states in storms.

The first part of this paper gives the results of a comparison between the real time SEASAT altimeter derived wave height and ship reports over the North Atlantic Ocean. Then, two applications of satellite measurements are shown: We first use SEASAT data to evaluate the wave forecasting model of the French Meteorological Office (La Météorologie Nationale); second, we show some features of the distribution of sea state in storms, emphasizing that the horizontal scale of large variations in wave height may be very short.

SEASAT ALTIMETER DATA

At the altitude of 800 km, the orbit of SEASAT is circular and nearly polar. The speed over the ground is about 6.6 km/s, and 14 revolutions are achieved every 24 hours. The altimeter, one of the five sensors onboard SEASAT, emits short (3 ns) electromagnetic pulses (13.5 GHz) at the rate of 1000/s. After specular reflection by the sea surface immediately below the satellite the pulse is transmitted back to the altimeter. The diameter of the area of interaction between the pulse and the sea surface increases from 2 to 12 km with increasing sea state. The effect of sea waves is to lengthen the leading edge of the altimeter return pulse, and $H_{1/3}$ is deduced from the mean shape of the return signal [*Barrick*, 1972; *Fedor et al.*, 1979]. Furthermore, the altimeter is equipped with a microprocessor, computing a real time estimate of $H_{1/3}$ at the rate of 10/s [*Townsend*, 1980].

SEASAT data used in this study originated from Interim Geophysical Data Records sent to the SEASAT Users Research Group of Europe by the Jet Propulsion Laboratory. It consists of an 'onboard' estimate of $H_{1/3}$, averaged over 1 s (≃6.6 km). A set of 163 passes of SEASAT over the North Atlantic Ocean (40°–70°N, 10°E–50°W), from September 15 to October 9, was investigated.

COMPARISON OF THE ALTIMETER-DERIVED WAVE HEIGHT WITH SURFACE DATA

The short life of SEASAT (≃3 months) allowed only a few comparisons with accurate surface data. The onboard estimate is in agreement with buoy measurements, as shown in Figure 1 [reproduced from the *SEASAT Gulf of Alaska Workshop II Report*, 1980]. At the higher wave height ($H_{1/3}$ > 3 m) the bias seems to increase but there is not enough data to establish precisely this trend.

To obtain a sufficient set of data, we used ship reports over the North Atlantic Ocean. Although visual ship observations of sea state are not very accurate, they can provide an idea of the altimeter-derived wave height accuracy for various sea states. When both swell (H_s) and wind wave (H_w) were reported, $H_{1/3}$ was obtained from $H_{1/3} = (H_s^2 + H_w^2)^{1/2}$. The data are separated into two categories according to the distance (D) from the SEASAT measurement to the ship observation points. The ship data is chosen such that the time difference with SEASAT data is less than 1 hour.

Figures 2 and 3 are scatter plots of ship $H_{1/3}$ versus SEASAT $H_{1/3}$, respectively, for $D < 50$ km and 50 km $< D <$ 100 km. The star symbol is used for the ocean weather stations L (57°N − 20°W) or M (66°N − 2°E), and data points are circled when the difference $\Delta = H_{1/3}$ ship $- H_{1/3}$ SEASAT is larger than 2 m. The statistics of the difference Δ are given in Table 1. The mean of Δ is less than 0.20 m, and, when excluding circled points, its standard deviation is about 0.80 m. The statistics in Table 2, illustrated by Figure 4, show that there is no bias in the data.

Anomalies noted by circled points on Figures 2 and 3 were examined, and it appears that some of them come from erroneous ship observations (points number 2, 4, 9, 10). It is difficult to explain anomalies 1, 3, and 13 because there are no other observations in the vicinity and the surface pressure

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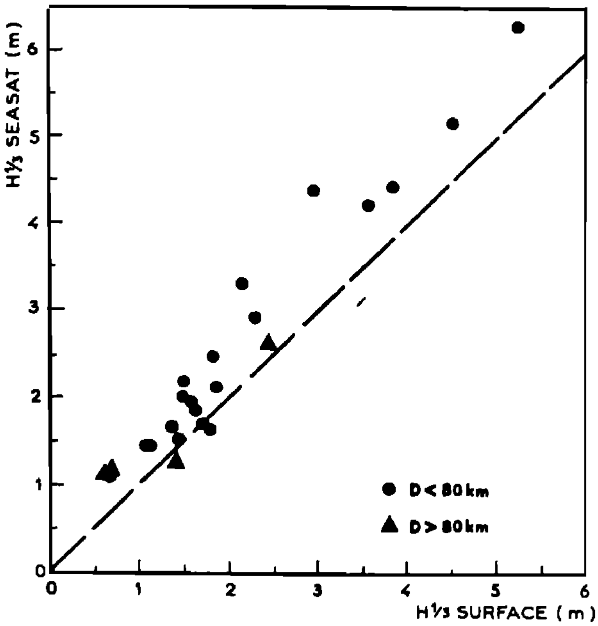

Fig. 1. Scatter diagram of buoys and station PAPA measurements versus SEASAT altimeter derived wave height (on-board estimate) [from the *SEASAT Gulf of Alaska Workshop II Report*, 1980].

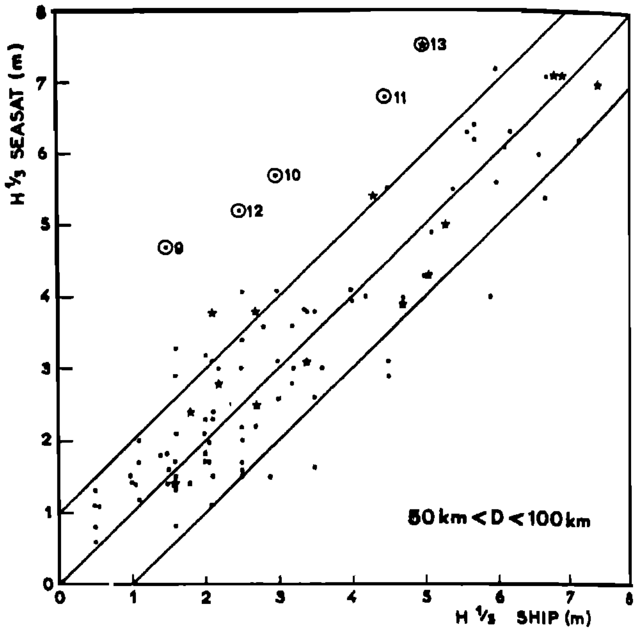

Fig. 3. Scatter diagram of ship wave height versus SEASAT altimeter wave height for 50 km < D < 100 km.

analysis charts are not sufficiently accurate for this calculation. On the other hand, it seems that anomalies 5, 6, 7 and 8, 11, 12 result from an overestimation of the 'onboard' estimate of SEASAT $H_{1/3}$.

Indeed these last anomalies occur for two passes of SEASAT. The first one is illustrated by Figure 5, showing the surface pressure analysis chart for 1200 UT, on which is reported the SEASAT ground track from 1209 UT to 1216 UT. The upper diagram indicates the SEASAT measured $H_{1/3}$ and ship reports, with the distance (in kilometers) from the track. Observations 5, 6, 7 are near the track (less than 20 km), and ship wave heights are about 2 m, while SEASAT indicates 5 m. Over the area limited by 37°–42°N and 20°–26°W, 11 ship reports are available at 1200 UT. Their distances from the track lie between 12 and 350 km (mean, 175 km; standard deviation, 127 km). The mean value of the heights reported by these ships is 3.6 m, with a standard deviation of 1.2 m, while the mean of the corresponding values measured by SEASAT is 5.0 m, with a standard deviation of 0.3 m.

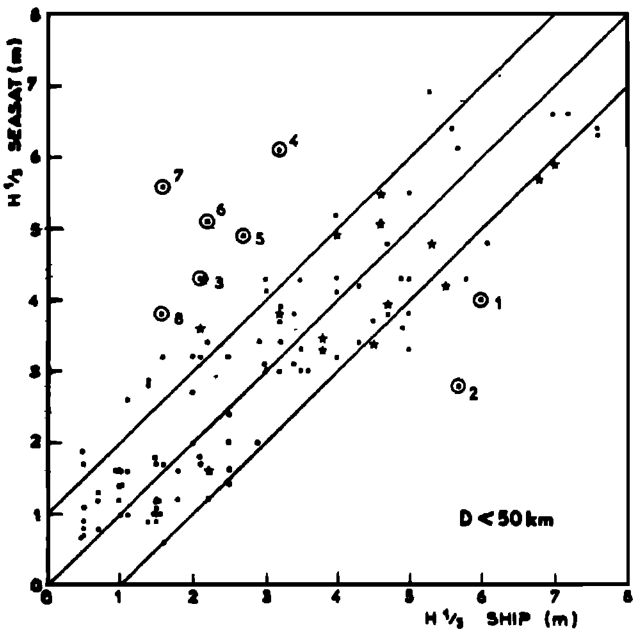

Fig. 2. Scatter diagram of ship wave height versus SEASAT altimeter wave height for D < 50 km. D = distance between ship and SEASAT data points. Points are circled when the difference between ship and SEASAT values is greater than 2 m. The star symbol is used for ocean weather station L or M.

The three other anomalies (8, 11, 12) are reported on Figure 6. There are 8 ship reports available, at 1200, over the area limited by 41°–49°N and 15°–21°W. The distances from the track lie between 15 km and 291 km (mean, 115 km; standard deviation, 82 km). The mean observed wave height is 4.3 m, with a standard deviation of 1.6 m, while the mean of the SEASAT values is 5.6 m, with a standard deviation of 1.3 m.

For these two passes, the onboard measured wave height is 1.4 m higher, on the average, than the available sea-truth data.

TABLE 1. Statistical Comparison of SEASAT Altimeter-Derived Wave Height (On-Board Estimate) and Ship Reports Over the North Atlantic Ocean

Category	D < 50 km		50 km < D < 100 km	
N	108	116	96	101
$\bar{\Delta}$ (m)	−0.002	0.11	−0.04	−0.17
σ (m)	0.80	1.06	0.75	0.93

N = number of data points; $\Delta = H_{1/3}$ ship − $H_{1/3}$ SEASAT; $\bar{\Delta}$ = mean value of Δ; σ = standard deviation of Δ. For each category (according to the distance D between SEASAT and ship data points), the two results are obtained, respectively, with and without data for which Δ is greater than 2 m.

TABLE 2. Statistical Comparison of SEASAT and Ship Wave Height for Various SEASAT Wave Height Classes

$H_{1/3}$ SEASAT	0–2 m	2–4 m	4–6 m	6–8 m
N	77	72	37	18
$\bar{\Delta}$ (m)	0.10	−0.19	−0.01	0.10
σ (m)	0.60	0.87	0.87	0.78

$\bar{\Delta}$ = mean value of $\Delta = H_{1/3}$ SEASAT − $H_{1/3}$ DSA; σ = standard deviation of Δ.

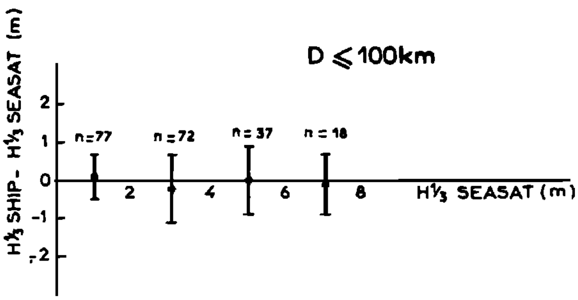

Fig. 4. Statistical comparison of ship reports and SEASAT altimeter wave height; plot of the mean value and standard deviation for each classe of SEASAT $H_{1/3}$ (a vertical segment represents twice the standard deviation).

EVALUATION OF A WAVE FORECASTING MODEL USING SEASAT DATA

The SEASAT wave height is used to evaluate the spectral model, DSA 5 ('Densités Spectro-Angulaires') of the French Meteorological Office. This model has been in routine operation since 1970 and is described by *Savina and Fons* [1966] and *Gelci and Devillaz* [1975].

The 12 hour forecast valid for 1200 UT, over the North Atlantic Ocean is broadcast daily. For comparison, only the SEASAT passes near 1200 UT (± 0300) are used. The forecast wave height value is linearly interpolated on the

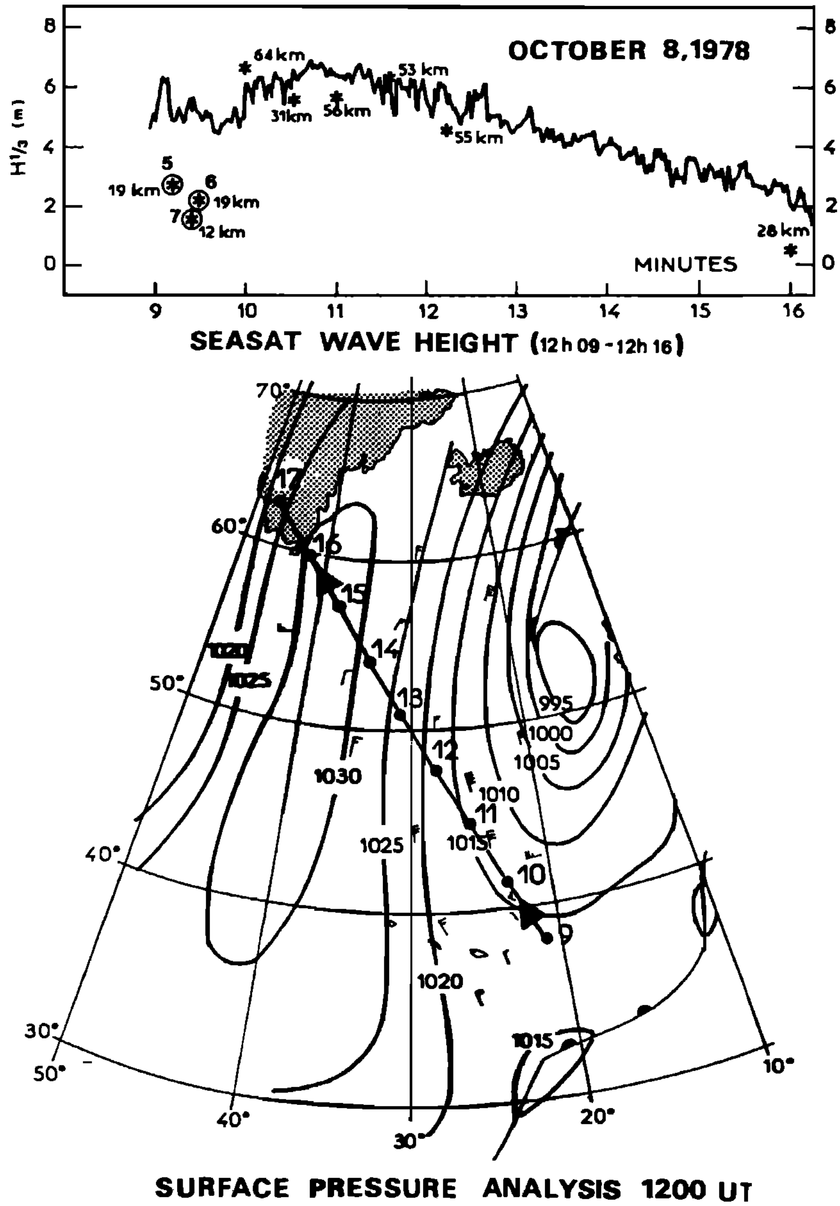

Fig. 5. Comparison of ship reports and SEASAT altimeter wave height, along one track. October 8, 1978.

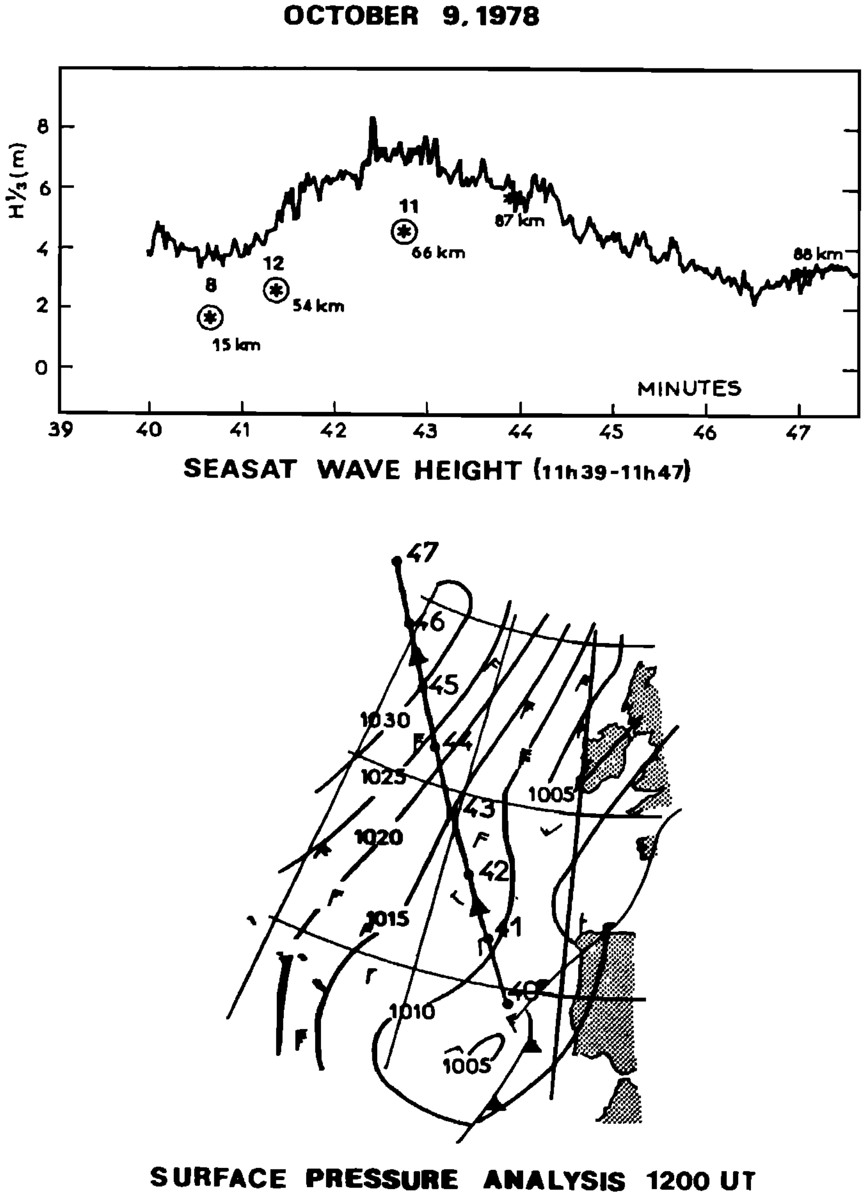

Fig. 6. Comparison of ship reports and SEASAT altimeter wave height, along one track. October 9, 1978.

forecast contour map, one point per minute (≃ 400 km) along the track (the size of the computing grid used by the model is about 160 km).

A set of 379 data points is obtained for 57 passes of SEASAT, over a period of 25 days (September 15 to October 9). As shown by Figure 7, the scatter in the data is important; the mean difference (DSA-SEASAT) is −0.3 m and the standard deviation about 1.3 m. In fact, these data points are not independent, and actually a comparison for each day is a better approach to the problem. The following examples show that the forecast may be very accurate.

The first example is for September 25. Figure 8 shows that the DSA forecast contour map for 1200 UT ($H_{1/10}$ in meters), on which is traced the SEASAT ground track from 1009 to 1016 UT; the surface pressure analysis chart for 1200 UT; the DSA and SEASAT wave height shapes. The conversion in $H_{1/10}$ is obtained from $H_{1/10} = 1.27\, H_{1/3}$ [*Longuet-Higgins*, 1952]. The last diagram shows relatively good agreement between the forecast and the measured values. The maxi-

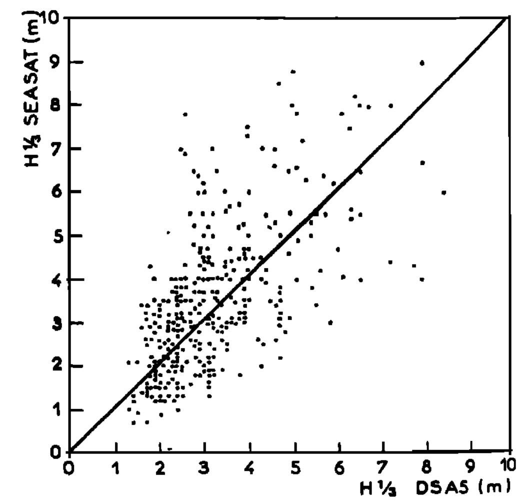

Fig. 7. Scatter diagram of the DSA forecast wave height versus SEASAT altimeter wave height.

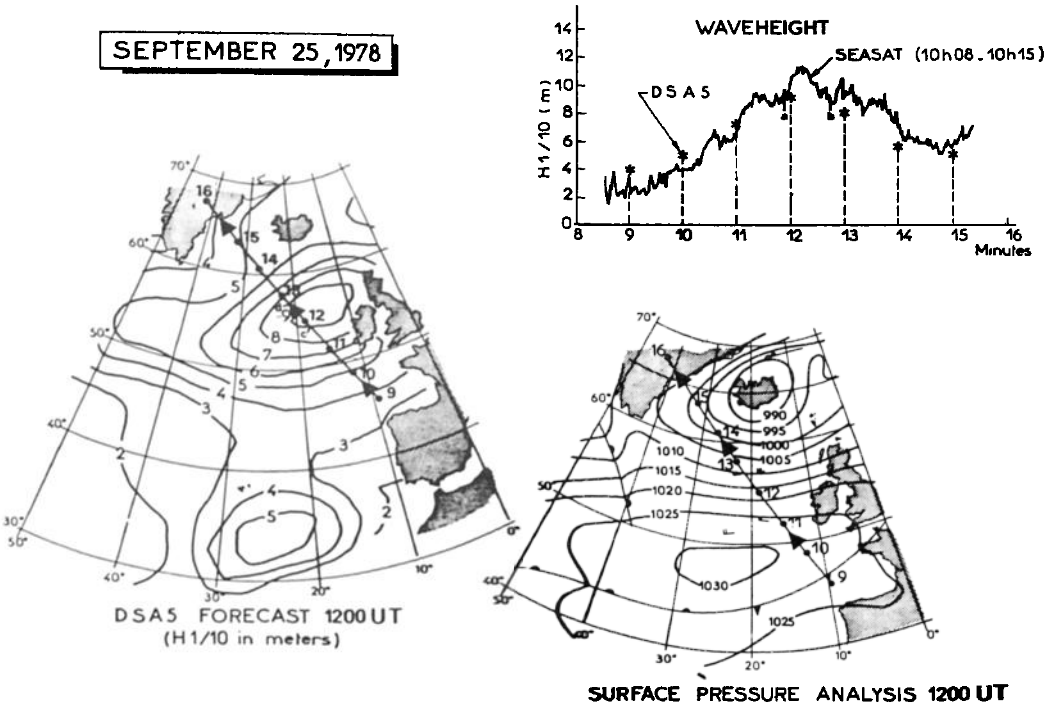

Fig. 8. Comparison of the DSA forecast wave height and SEASAT altimeter data for September 25, 1978. The DSA 5 forecast contour map 1200 UT, the surface pressure analysis 1200 UT, and the altimeter wave height.

mum wave heights are 10 m for DSA and 11 m for SEASAT.

A second example is given by Figure 9 (October 1), and the agreement is also good enough, though there is some lag in the position of the maximum. On the wave height diagram, we note that ship reports are in good agreement with SEASAT measurements.

The forecast is not always reliable, as shown by Figures 10 and 11. The first figure (September 24) indicates a lag of the two wave height shapes. The maximum as located by SEASAT is confirmed by the surface pressure analysis chart. The origin of this lag has to be sought in the forecast wind field used as input to the model.

The wave height diagram of Figure 11 (October 4) shows a large discrepancy between SEASAT and DSA. The maximum height measured by SEASAT ($H_{1/10} \simeq 9.5$ m) is in agreement with a ship report located at 10 nautical miles

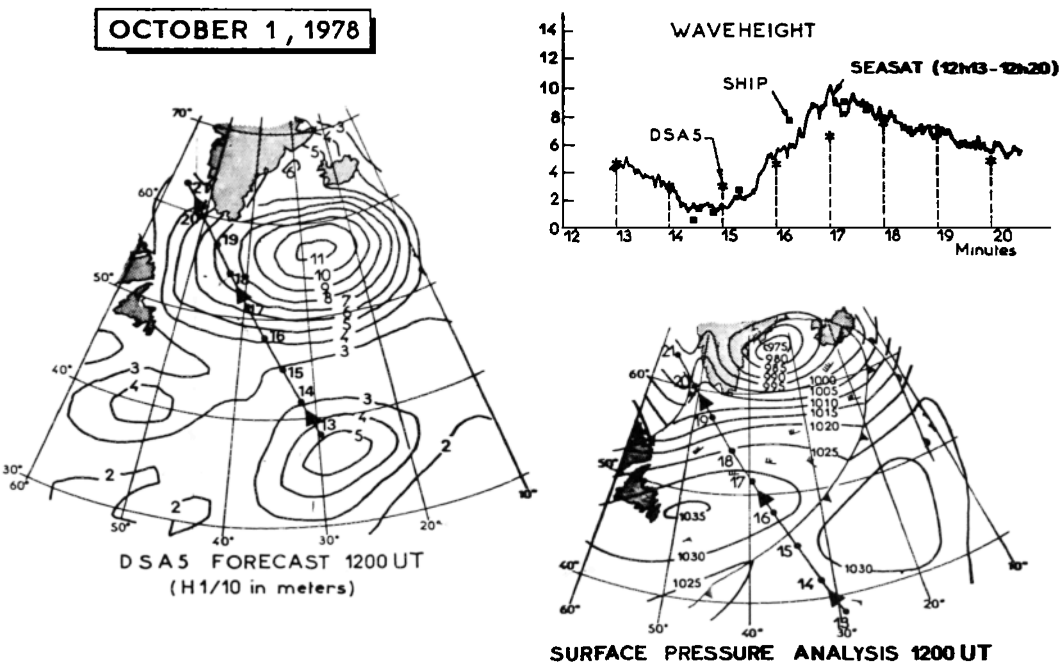

Fig. 9. Comparison of the DSA forecast wave height and SEASAT altimeter data. October 1, 1978.

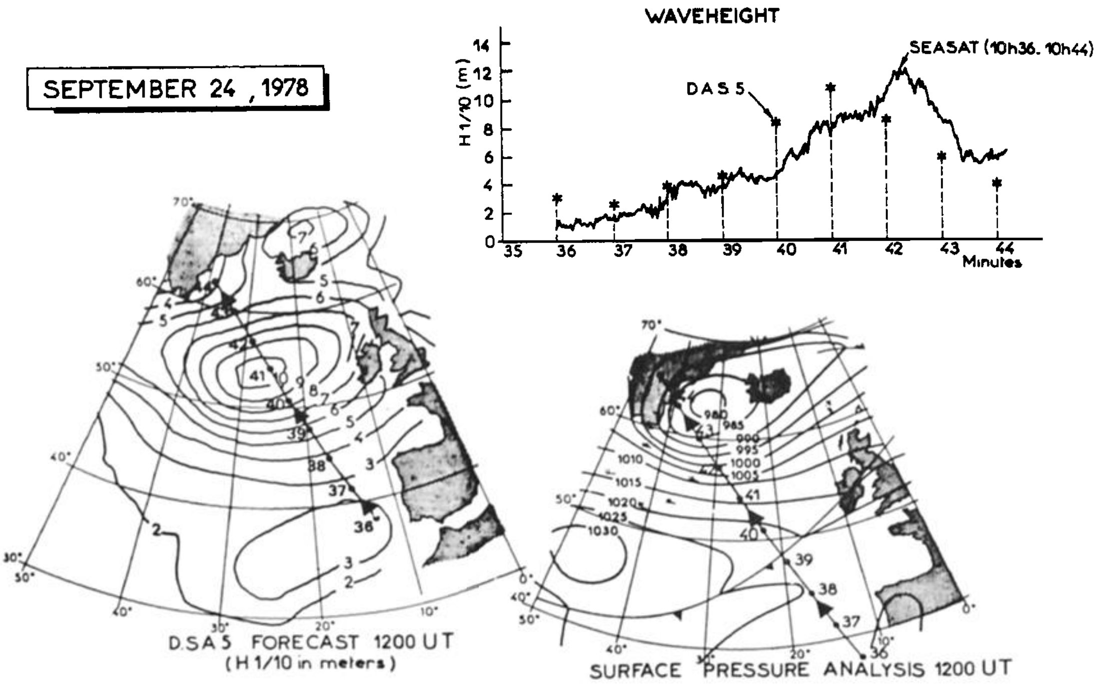

Fig. 10. Comparison of the DSA forecast wave height and SEASAT altimeter data. September 24, 1978.

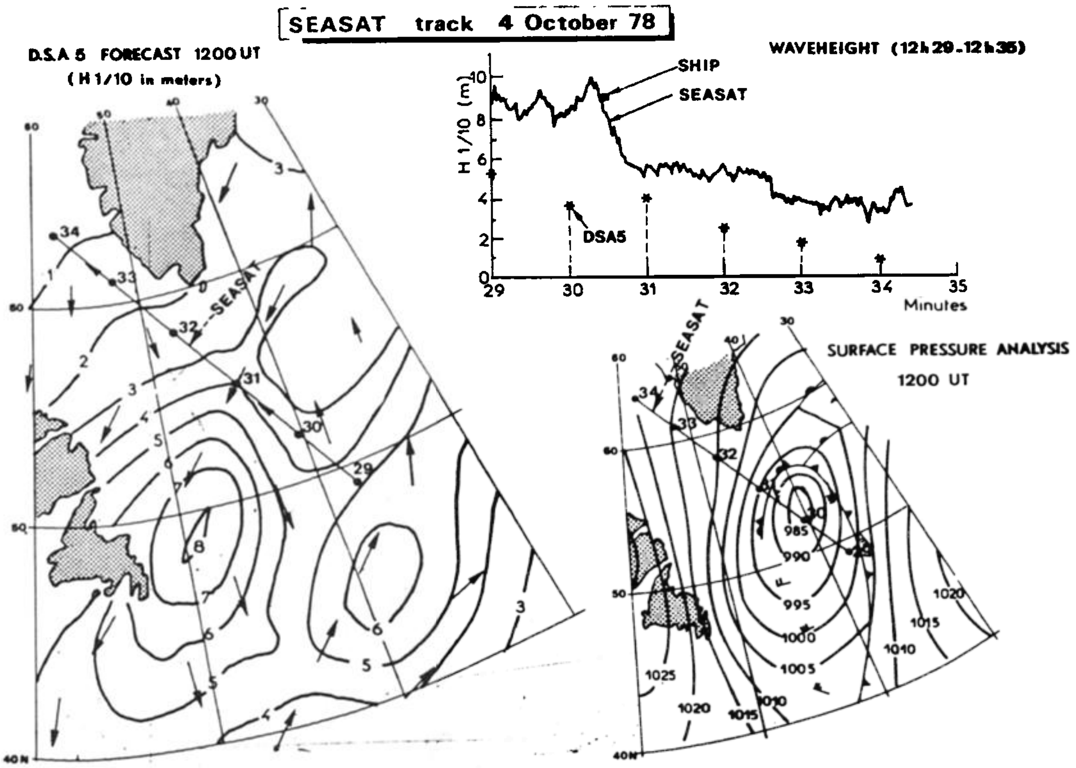

Fig. 11. Comparison of the DSA forecast wave height and SEASAT altimeter data. October 4, 1978.

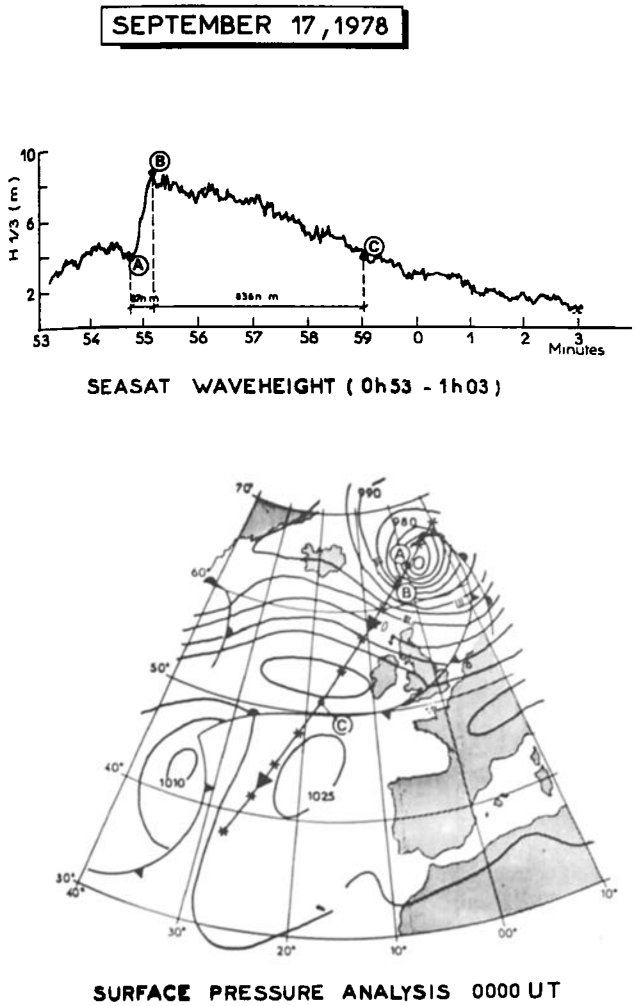

Fig. 12. An example of a sharp gradient in wave height measured by SEASAT on September 17, 1978.

from the track. On the other hand, the maximum DSA wave height, along the track, is only about 5 m. A strong sea state area was forecast by the model, to the SW, but this is not in close agreement with the pressure analysis. This can be explained by the fact that the computing time step is 3 hours, but the wind field is changed only in 6-hour time steps. If the pressure system moves rapidly, the forecast wave field may be slightly erroneous.

To sum up the comparison between model and altimeter data, we computed for each day the mean (Δ) and standard deviation (σ) of the differences between DSA and SEASAT values of $H_{1/3}$. The results are summarized in Table 3. We note that for 9 days (36%) the mean difference is less than 0.5 m and the standard deviation is less than 1 m.

TABLE 3. Comparison of the DSA Forecasting Wave Model and SEASAT Altimeter Data: Number of Occurrences for Classes of $\bar{\Delta}$ and σ for 25 Days of Data

	$\bar{\Delta}$ (m)		
σ (m)	0 – 0.5	0.5 – 1.0	1.0 – 1.5
0 – 1	9	2	1
1 – 2	6	3	4

N = number of data points; $\bar{\Delta}$ = mean value of Δ; $\Delta = H_{1/3}$ ship − $H_{1/3}$ SEASAT; σ = standard deviation of Δ.

DISTRIBUTION OF STRONG SEA STATES IN STORMS AS MEASURED BY SEASAT

The use of satellite measurements to construct contour maps of sea state for large regions of the oceans has been developed from GEOS 3 data [*Parsons*, 1979]. One difficulty arises when no satellite ground track lies through the real sea state maximum. The use of two or more satellites would certainly improve the method. As illustrated by the following four examples, SEASAT data show that sharp gradients in sea state may occur in low pressure systems.

On Figure 12 (September 17) the SEASAT track crosses a 960 mbar low-pressure center. The track is roughly oriented NE-SW, and on the upper diagram, the significant wave height is shown increasing from 4 m up to 8 m over a distance of 87 nautical miles (A–B), and then decreasing to 4 m over 830 miles (B–C). The strongest sea state is observed in the SW of the low pressure center, and the $H_{1/3}$ increase

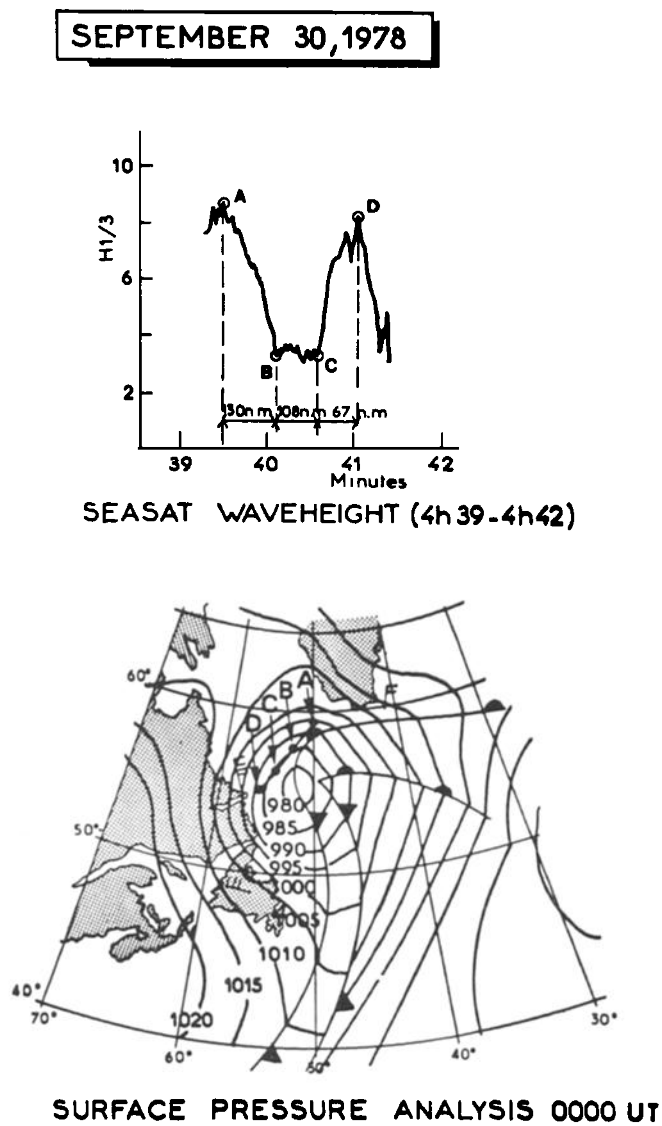

Fig. 13. An example of a sharp gradient in wave height measured by SEASAT on September 30, 1978 (0439 UT).

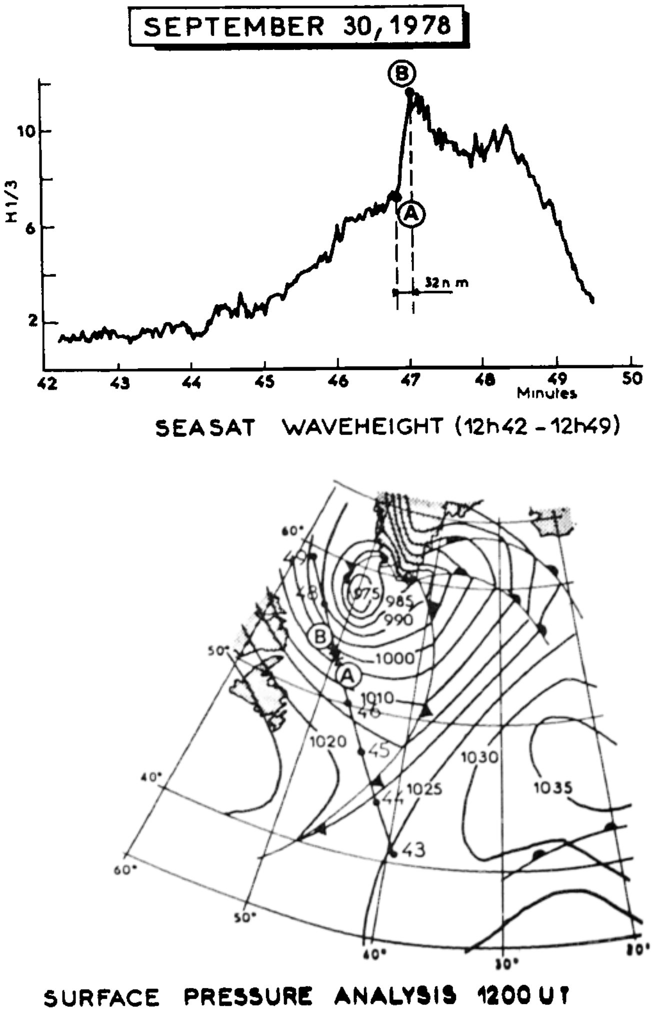

Fig. 14. An example of a sharp gradient in wave height measured by SEASAT on September 30, 1978 (1242 UT).

measured between A and B results from a strong pressure gradient over this area.

On Figure 13 (September 30), the track passes close to the center of a 980-mbar low pressure system. In the NE the wave height decreases from 8.5 m down to 3.5 m over 130 miles (A–B), it remains constant (3.5 m) near the center over 108 miles (B–C), and then increases toward the SW, up to 7.5 m over 67 miles (C–D). In this example, the observed symmetry of sea state is certainly due to the symmetry of the low pressure system.

The same system is shown, 12 hours later, on Figure 14, and SEASAT measurements indicate that $H_{1/3}$ is increasing from 7.5 m up to 11 m, over 32 miles (A–B). This variation is measured over an area of strong pressure gradient and large fetch.

The last example, Figure 15 (October 6), shows the transition from a strong wind and large fetch area to a high pressure center, which results in a rapid decrease of $H_{1/3}$ from 8 m down to 4 m, over 56 miles (AB).

Over the North Atlantic, from September 16 to October 9, we observed 13 situations like those described above. Over a distance of 50 nautical miles, wave height variations spread from 1.7 to 5.5 m. This happens generally in the south of low pressure systems, which can be explained by the asymmetry of these systems (the pressure gradient is generally stronger to the south) but also by its motion. The low pressure systems generally cross the North Atlantic Ocean from west to east, which implies that, in the south, the generated waves travel in the same direction as the system, the duration of wind action being longer than northward, where the opposite effect is observed. This last effect is difficult to detect with SEASAT measurements because of the influence of the orientation of tracks and their variable distance from the low pressure center.

However, from 26 tracks in the vicinity of low pressure systems, we obtained the mean position of strongest sea state areas relative to the storm center. For these tracks we also computed distances over which $H_{1/3}$ is equal to, or greater than, 50% of the maximum wave height. Tracks are roughly oriented NE-SW or SE-NW, and so we obtain distances in four directions. Results are shown in Figure 16. The mean position of the maximum is at about 300 miles ($\pm$175) to the S-SW (202° $\pm$ 53°) of the storm center, and distances over which $H_{1/3}$ is greater than 50% of the maximum are NE 230 miles, NW 340 miles, SW 550 miles, and SE 390 miles. Obviously, these results, from 25 days of data, are not climatologically significant but give an idea of the advantages that could be provided by real time altimeter measurements from two or more satellites similar to SEASAT.

CONCLUSIONS

The SEASAT real estimate of the significant wave height is in agreement with ship reports over the North Atlantic Ocean. The mean difference between the two data sets is less than 0.2 m, and the standard deviation is about 0.8 m, for sea states up to $H_{1/3}$ = 8 m. The remaining question is how accurate are visual ship reports? A comparison with Tucker records at ocean weather stations K (45°N – 16°W) and R (47°N – 17°W) [*Queffeulou*, 1980] shows that visually observed wave heights are greater than $H_{1/3}$ at the higher wave heights ($H_{1/3} > 4$ m), which would indicate that the SEASAT onboard wave height is slightly overestimated, as also shown in the *SEASAT Gulf of Alaska Workshop II Report* [1980]. This trend cannot be determined precisely because of a lack of accurate surface data. This suggests that long-term sea-truth experiments should be carried out at the beginning of a future satellite-borne altimeter flight. Interest in satellite measurements for sea state studies is considerable. Comparison of the SEASAT-derived wave height with the wave forecasting model, DSA, shows that the forecast is often satisfactory. It remains to be seen if the inaccuracy of the forecast wind field, used as input to the model, is the sole origin of some observed discrepancies. For this purpose, the SEASAT scatterometer-derived wind field would be useful.

Furthermore, SEASAT measurements in low-pressure systems have pointed out the effect of sharp gradients in sea state, features important for wave modeling and ship routing.

In the future, measurements obtained from a network of two or more satellites would allow an accurate study of sea state distribution in storms, effective ship routing, and improvement of initial conditions for wave forecasting models. Data stored by such a network for a long period could form the basis for climatological studies of sea states in the oceans.

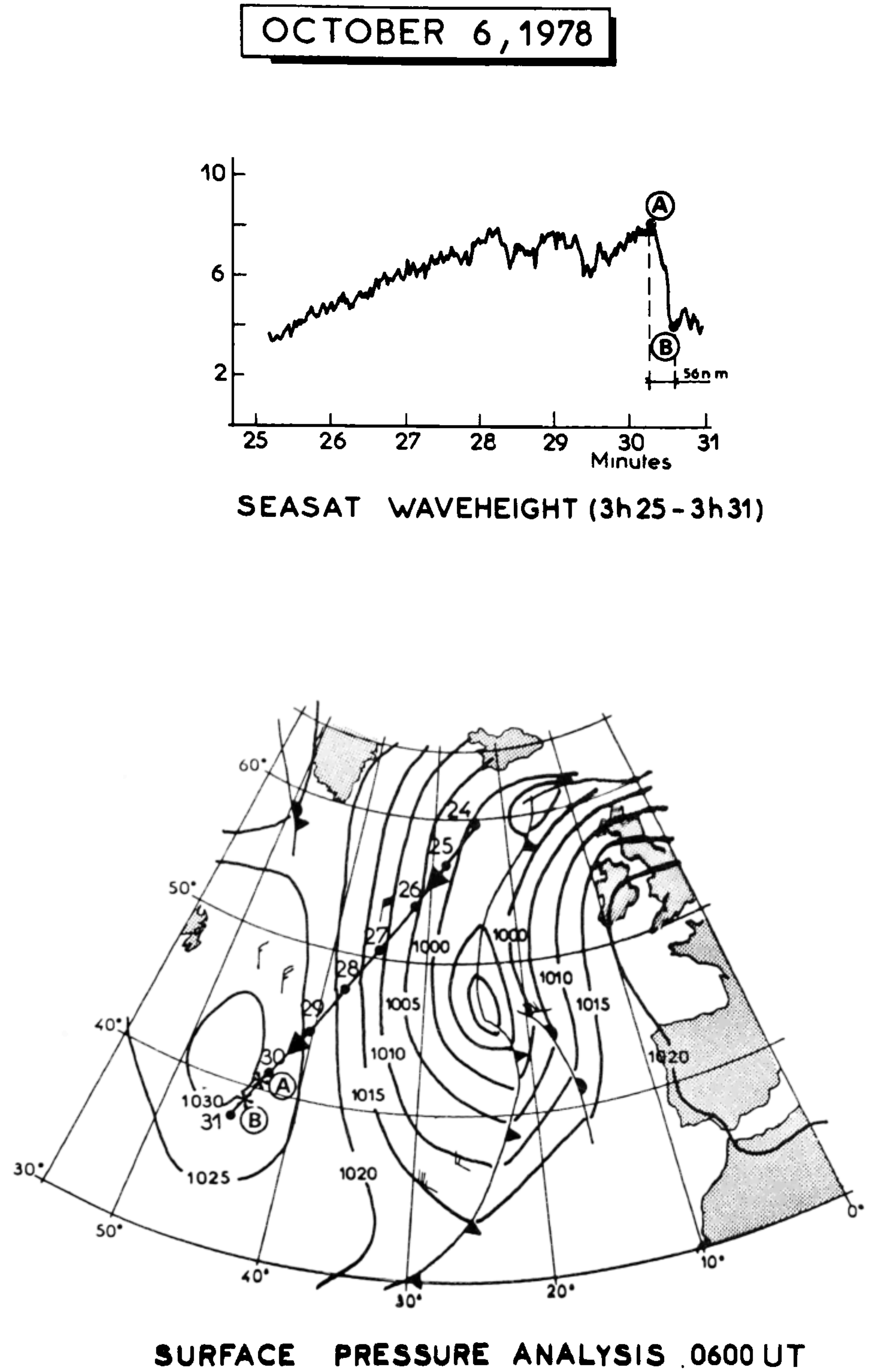

Fig. 15. An example of a sharp gradient in wave height measured by SEASAT on October 6, 1978.

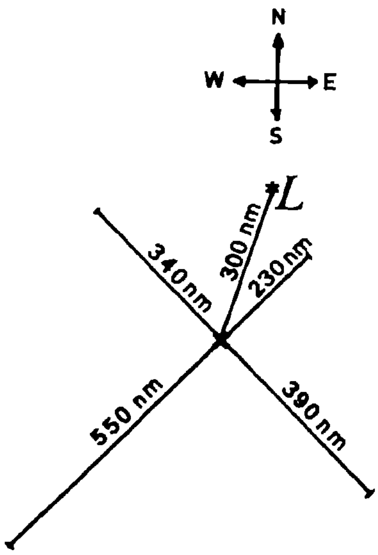

Fig. 16. Statistics on the distribution of strong sea states in storms as measured by SEASAT altimeter. The mean position of the maximum sea state is shown relative to the center of the low pressure system, and also the mean values of the distances (in nautical miles) over which $H_{1/3}$ is greater than 50% of the maximum wave height.

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