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Ocean Wave Patterns Under Hurricane Gloria: Observation with an Airborne Synthetic-Aperture Radar

Abstract. *Surface imagery of ocean waves under Hurricane Gloria (September 1976) has been obtained with an airborne synthetic-aperture imaging radar. Observations were obtained over most of the area within a radius of 150 kilometers around the center of the eye. These direct observations made it possible to derive the wave patterns in the region around a hurricane eye.*

Observations of ocean wave patterns near a hurricane center are practically nonexistent. High-altitude aircraft observations with cameras are not generally possible because of extensive cloud cover. Flights at very low altitude with laser profilometer observations have been conducted on some occasions (*1, 2*); however, they are limited to a very small coverage along the aircraft track and contain no directional information. Direct surface measurements by ships near the eye are few because of the sea conditions, and they are limited in coverage. Pore (*3*) has collected a large number of visual ship reports in a variety of hurricanes and studied the spatial distribution of wave properties. However, most of the reported observations were at a distance greater than 130 km from the hurricane's center. There also have been a few surface point measurements of hurricane waves from offshore platforms (*4*) and from instrumented buoys (*5*).

Recently, high-resolution imagery of ocean waves and surface patterns obtained with airborne radar systems has been reported (*1, 6*). The direction and wavelength of the ocean waves can be directly determined from the radar image. However, the relationship between the radar signature and the wave characteristics, such as the directional energy spectrum, is not well understood and is an area of active research. One major advantage of the imaging radar is that, with the proper selection of frequency, it is insensitive to cloud cover. Another is that it does not require sun illumination. A further key factor is that, if operated in a coherent synthetic-aperture mode, it can obtain high-resolution imagery from high-altitude airborne or spaceborne platforms.

These considerations led us to conduct an experiment to observe the ocean surface under hurricanes Emmy, Frances, and Gloria in the summer of 1976. The aircraft used was the National Aeronautics and Space Administration Ames CV-990 jet, which flew over these hurricanes at altitudes ranging from 8,000 to 13,000 m. The aircraft was equipped with the Jet Propulsion Laboratory synthetic-aperture, multifrequency-imaging radar, which was operated at 1.2 and 9.6 Ghz. The inherent resolution of the system is between 25 and 50 m, depending on the "look" angle. Thus, only waves of wavelengths equal to or larger than about 75 m can be clearly imaged with this sensor. Continuous imagery, with a 10-km swath, was obtained on two perpendicular legs centered at the eye and extending radially to approximately 150 km to each side of the eye. Imagery was also obtained along two octagonal flight lines centered at the eye with average radii of about 50 and 140 km.

The data discussed in this report were obtained on 30 September 1976, during Hurricane Gloria. At the start of the observations (at 1600 G.M.T.), the hurricane center was located 650 km northeast of Bermuda at 58°00′W, 32°40′N and was moving with a speed of 28 km/hour in a northeasterly direction. The maximum surface wind, reported by a low-flying National Oceanic and Atmospheric Administration (NOAA) aircraft, was 60 m/sec, and the radius to maximum wind was approximately 60 km. The observation period lasted about 4 hours.

The wind field was counterclockwise with a slight inward spiral, as is typical for hurricanes in the Northern Hemisphere. The wind field was stronger on the right side of the storm, as seen facing the direction of storm movement. This is also typical; for, if a hurricane is to remain an organized unit, the winds must blow faster in the direction of storm travel than against it. This leads to a substantial asymmetry in the wave field under a

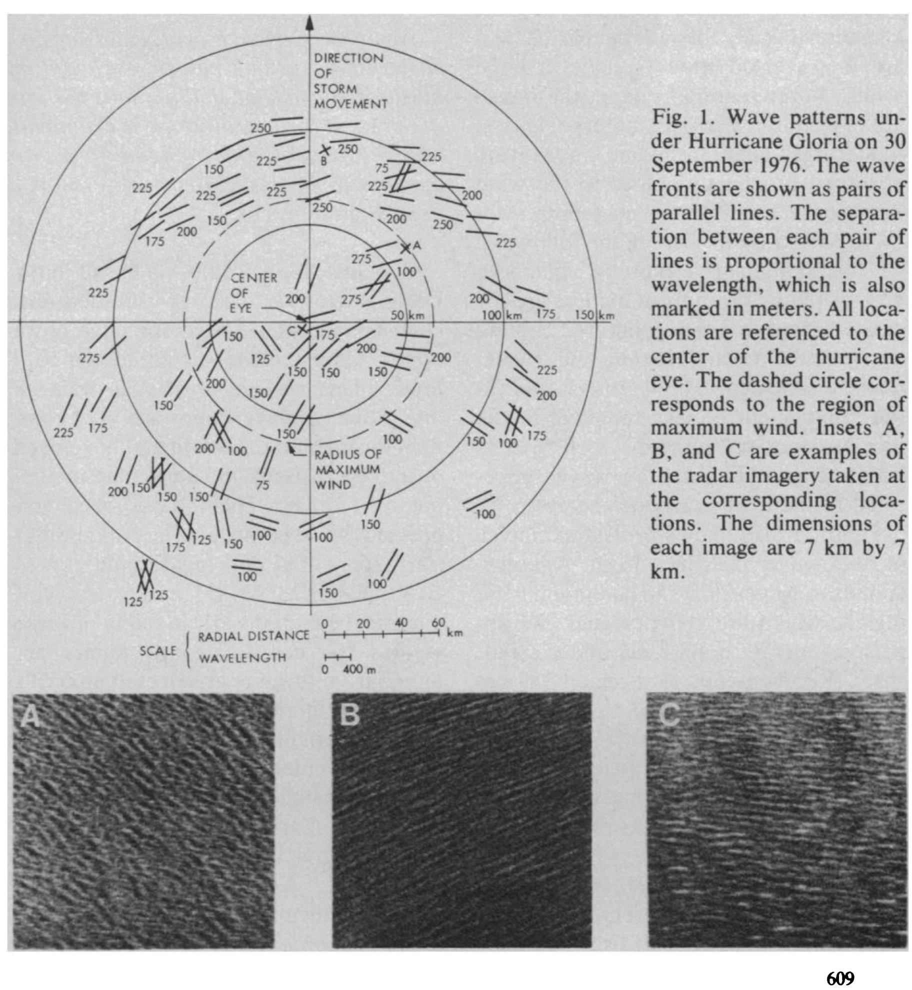

Fig. 1. Wave patterns under Hurricane Gloria on 30 September 1976. The wave fronts are shown as pairs of parallel lines. The separation between each pair of lines is proportional to the wavelength, which is also marked in meters. All locations are referenced to the center of the hurricane eye. The dashed circle corresponds to the region of maximum wind. Insets A, B, and C are examples of the radar imagery taken at the corresponding locations. The dimensions of each image are 7 km by 7 km.

hurricane. The waves on the right side are not only generated under a higher wind but also stay under the influence of the wind field longer since they are moving with it. Therefore, the waves moving out in front of a storm are much larger than those propagating out from the rear. During the observation period, Hurricane Gloria was traveling as fast as a 150-m wave (10-second period) would propagate; thus, only waves of longer wavelengths (that is, traveling faster) would propagate ahead of the storm.

Figure 1 shows the wave pattern of the dominant waves obtained from the L-band (1.2 Ghz) imagery. Sections of the radar imagery in three different locations are also shown (Fig. 1, insets A through C). The radar imagery makes it possible to determine the waves' direction (with 180° ambiguity) and wavelength. The data obtained show several interesting features. Around the area of maximum wind, the wave direction is close to the wind direction; the wavelengths range from 100 m (behind the eye) to 275 m (at the right front of the eye). In the eye region, the waves are frequently of a long period and are short-crested (that is, have a short crest length). Away from the eye, the waves in the front half region appear to be propagating in the radial direction, which is roughly perpendicular to the local wind. They are characteristically of a long period and are long-crested (that is, have a large swell). In the rear half region, the waves are of a shorter period, and, especially in the left rear quadrant, some waves were observed propagating close to the wind direction. Possible explanations for these observations include the following: (i) the dominant waves at distances greater than 100 km from the eye are the ones that have been generated around the maximum wind region and subsequently propagated outward (*7*); and (ii) the radar might be less sensitive to the locally generated waves, which tend to be more chaotic than the waves generated farther away, around the eye.

Figure 1 also shows typical examples of the wave imagery. Inset A corresponds to waves near the maximum wind region, which are short-crested and appear to contain both a sea and a swell. Inset B corresponds to a region 149 km away from and ahead of the eye. The waves there are well organized and long-crested (have a swell). Inset C corresponds to a region near the center of the eye, where the crestedness of the waves is in between that of cases A and B.

We also calculated the average wave period for the four different quadrants: right front, right rear, left front, and left rear, using the deep water dispersion relation for gravity waves. The values obtained were 11.2, 9.2, 10.9, and 9.5 seconds, respectively. These values are, on the average, larger than those reported by Pore (*3*) for the waves at distances greater than 130 km from the eye.

More observations are required before it will be possible to derive general conclusions on the behavior of waves around the center of a hurricane. More airborne observations are planned for 1977 and 1978, and spaceborne observations are to be made in 1978. These observations should lead to a better understanding of the statistical behavior of waves in the eye region of hurricanes.

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Slope Profiles of Cycloidal Form

Abstract. *Concave profiles of basalt hills in the Darling Downs area of southeastern Queensland can be cycloidal or exponential in form. Where the complete hillslope consists of shallow soils the form is cycloidal. Where colluvial lower slopes are present the overall slope is exponential but the upper, dominantly sedentary portion is cycloidal. The cycloidal form, which corresponds to the curve of least time, appears to be associated with erosional processes and the exponential form with depositional processes.*

Concave slope profiles on basalt in the Darling Downs area of southeastern Queensland extend from the edge of an upper, almost plane surface down to a lower plane surface or a local drainage line. Such concave slopes are very common throughout the world and have been described in terms of particular mathematical forms. They have been expressed as binomials (*1*), polynomials (*2*), exponential and logarithmic curves (*3, 4*), power curves (*5*), and a variety of empirical equations (*6*). In many of these studies the coordinates of points obtained from leveling at selected intervals have been fitted statistically to the various mathematical curves. Ruhe and Walker (*4*) noted that toe and foot slopes could be matched by one of their equations, but that the curve of the back slope was too steep for the same equation.

One mathematical curve with interesting properties that has been neglected in slope analysis is the common cycloid. This curve arises as a solution to the brachistochrone problem of J. Bernoulli and is the least time path by which frictionless particles may move under gravity from one point to another not immediately beneath it. Another property is that several such particles released simultaneously anywhere on a cycloid slope will reach the lower extremity at the same time. A hillslope with such a profile would have the ideal shape for the most rapid disposal of water provided friction was not important. King (*7*) has attributed this property to the pediment, a landform common on the hills of the Darling Downs.

Six Darling Downs slope profiles have been tested against cycloid and exponential curves and the fits compared. The exponential curve appears to have been accepted (*5*) as an adequate model for many concave profiles. "True" curves of the slopes were obtained from en-