Rogue waves: rare but damaging

A recent incident highlights the danger of large waves propagating in a direction different from the mean wind and wave direction. What is the probability of encountering such waves?

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On January 14, 2010, the crab fishing vessel *Early Dawn* was hit by a very large wave coming from an unexpected direction when fishing near St. Paul, Alaska. According to the Captain, the rogue wave was at least twice as high as the rest of the waves, if not 2.5 times as high. The Captain first saw the wave at a distance of approximately 100 metres, and immediately warned the crew with a buzzer. Three crew members were able to get to safety, while one crew member working at the stern of the vessel was injured by the wave. According to the Captain, the rogue wave was also observed from a distance shortly after the incident by a partner vessel fishing in the same area.

When the wave struck at 23:45 AKST, the *Early Dawn* was at 56°N 44'30", 172°W 42'32". She was fishing on a downwind set on a heading of 255° and a ship's speed of 7-8 knots, in a depth of approximately 145 metres. The waves came from a direction of 85°, ie 10° to the port side of the stern, with no obvious cross seas. The rogue wave which struck the vessel was estimated to be 30-35 feet high (9.1-10.7 metres), about twice the observed significant wave height of 4.8 metres. The direction of the wave was estimated to be at a 45-50° angle to the North of the predominant wave direction, i.e. coming from a direction of 35-40° (Figure 1).

According to the Captain, the wave was first seen when it was approximately 100 metres away. At an average wave period of 7.8 seconds this translates to a travel speed of 12.1 metres per second. Given that the vessel was moving away from the rogue wave at about 2.5 metres per second, this results in a warning time of approximately 10 seconds before the wave hit the vessel.

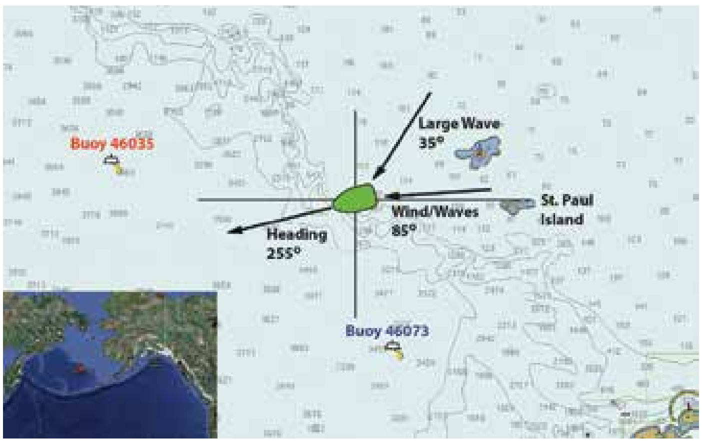

Figure.1: Wave and wind directions related to the rogue wave incident near St. Paul, Alaska (Bering Sea), and the positions of the *Early Dawn* and the two meteorological buoys nearby.

What is a rogue wave?

Although 'rogue wave' is a popular term for an unusually large ocean wave that can cause damage to ships or endanger people, some media accounts of rogue waves really just refer to very rough seas. In scientific terms, a 'rogue wave' refers to waves with height H, from trough to crest, such that $H/H_s \geq \alpha$, where the significant wave height H_s is the average height of the highest one-third of the waves, and the multiplier α is commonly chosen as either as 2.0 or 2.2.

Under maritime law, a rogue wave falls into the category of 'perils of the sea', which has been defined as 'those perils which are peculiar to the sea, and which are of an extraordinary nature or arise from irresistible force or overwhelming power, and which cannot be guarded against by the ordinary exertions of human skill and prudence'. Similarly, an Act of God has been defined as 'a natural phenomenon of such unanticipated force and severity as would fairly preclude charging the carrier with responsibility for damage occasioned by its failure to guard against it'.

Background conditions

The Bering Sea is well known for rough sea state conditions, particularly during the autumn and winter months. However, the occurrence of extreme individual waves can only be predicted in a statistical sense. Furthermore, the directionality of this wave made it more unusual while increasing the potential for injuries and damage to the ship. Here, we examine the probability of encountering such waves.

The weather conditions during the incident were accurately predicted by the National Weather Service in Anchorage, Alaska, more than a day in advance. It is therefore likely that the Master anticipated the observed significant wave height of 4.8 metres. The wave that hit the *Early Dawn* on January 14, 2010, qualifies as a rogue wave according to the scientific definition given above. With a return period of 28 hours, the wave height of twice the significant wave height was not extraordinary. What makes this wave unusual is the angle of approach relative to the direction of the predominant waves. Under the circumstances of the incident, the likelihood that a rogue wave approaches the vessel at an angle consistent with the observations is only 1%, resulting in a total return period of about 120 days. This is equivalent to a likelihood of 1/500 or 0.2% of encountering such a rogue wave within a 6-hour shift.

Weather and wave conditions

The marine forecast issued on January 13, 2010, at 04:00 AKST by the US National Weather Service Anchorage, Alaska, predicted that a low pressure system of 949 millibars near 47°N and 163°E would move to 49°N and 178°E by the afternoon of January 14, and to 49° N 180°E by the afternoon of January 15, while slightly weakening to 955 millibars.

The forecast issued a gale warning with easterly winds increasing from 20 knots (10 metres per second) on January 13 to 45 knots on January 14 and throughout the following night. Wave height was predicted to increase from 2.7 metres to 6.7 metres (9 feet to 22 feet).

The accuracy of the forecast was confirmed by local wave buoy observations, available from the US National Data Buoy Center. Buoy 46073 is located at 55°N 6'36" and 171°W 58'52" at a distance of 207 kilo metres to the south of the location of the incident. At 23:00 AKST, the data show a significant wave height of 4.8 metres and a wind speed of 37 knots with gusts up to 47 knots coming from a direction of 80°. The wind speed and wave height had been increasing significantly over the course of the day.

Buoy 46035, located at 57°N 4'1", 177°W 45'0", 303 kilometres to the West of the location of the incident, reported an even higher significant wave height of more than 8 metres. The buoy did not report wind direction, but it showed that the sea had been calm for several days and the wind picked up only about 24 hours prior to the rogue wave incident (Figure 2).

These observations confirm the sea state and wind conditions estimated by the Captain.

The buoys did not provide directional data for the waves, but the frequency spectra consistently show a narrow single peak while the wind speed and wave height increased in response to the storm (Figure 3). This suggests the absence of a second set of large waves coming from a direction other than the predominant wave direction (ie across sea). We conclude that, as reported by the Captain, the direction of the predominant waves was the same as that of the wind, which blew consistently from a direction of 80° to 120°.

Likelihood of occurrence

The large wave that hit the *Early Dawn* qualifies as a rogue wave according to the scientific definition. Its likelihood of occurrence is determined by its height H relative to the significant wave height H_S, as well as its direction relative to the predominant wave direction. We take $H/H_S = 2.0$ and the wave direction relative to the predominant wave direction to be 50°, as reported by the Captain.

The likelihood of occurrence of a rogue wave is commonly calculated with the so-called Tayfun distribution. It yields an occurrence rate of 1 in 1.3 $\times 10^4$ waves for a wave with $H/H_S \geq 2.0$. With an average wave period of 7.8 seconds, as reported by buoy 46073, this is equivalent to a return period of only 28 hours.

The likelihood that the direction of a rogue wave is at a certain angle relative to the predominant wave direction in uni-directional seas in the open ocean is known from a total of 7,157 rogue waves observed in 80 years of wave data off the US West coast, from buoys that could resolve the direction of individual waves. No such directional records exist from the Bering Sea, but there is no scientific reason to expect different statistics for the directional distribution of rogue waves in the Bering Sea.

The relative direction of the large wave was estimated as 45°-50°, which is 35°-40° off the stern of the *Early Dawn*. The impact on a vessel is usually larger when a wave approaches from the side. We calculate the likelihood of a rogue wave hitting the vessel at an angle larger than 35° from the bow or stern, on either the port or starboard side of the vessel. Given that the waves were coming from an angle of 10° to the port side of the stern, this is equivalent to a rogue wave direction relative to the predominant wave direction of 45-155° on the starboard side and 25-135° on the port side. The resulting cumulative likelihood in uni-directional seas is 1.21%. If on the other hand we take 50° as the relative direction of the large wave, the corresponding likelihood of a rogue wave hitting the vessel at an angle larger than 40° from the bow or stern is 0.93%. We therefore take 1% as the likelihood for a rogue wave hitting the vessel at an angle at least as large as that observed.

The resulting total return period of a rogue wave with $H/H_S \geq 2.0$ travelling at an angle that could have impacted the vessel is therefore 28 hours/1% = 117 days. This return period is valid for this particular wave direction, and for any given significant wave height. The damage caused by a wave coming from an unusual angle also depends on its absolute height and the design of the vessel.

Rough seas occur when strong winds blow for a long time over large distances, and when the waves then move into shallow water or are refracted and amplified in currents. In a given sea state, 'rogue ' waves with a wave height greater than the average by a factor of 2 or 2.2 seem to occur with a frequency that is in reasonable accord with

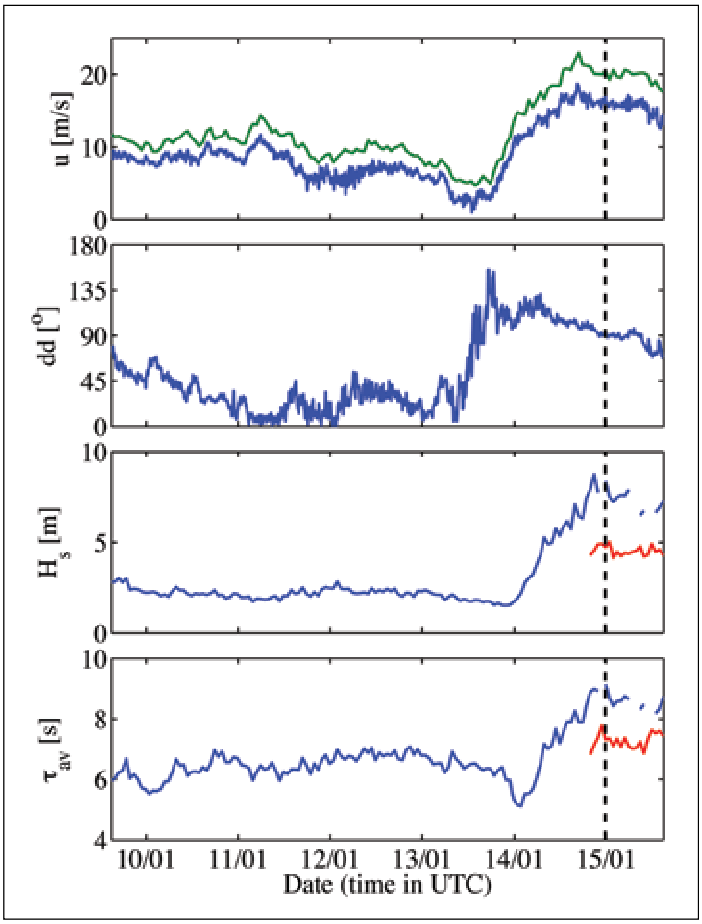

Figure 2: Wind speed *u* (blue), gusts (green), and wind direction *dd* at buoy 46073. Significant wave height H_S and average wave period t_{av} at buoy 46073 (blue) and 46035 (red). The dashed lines indicate the time of the rogue wave incident.

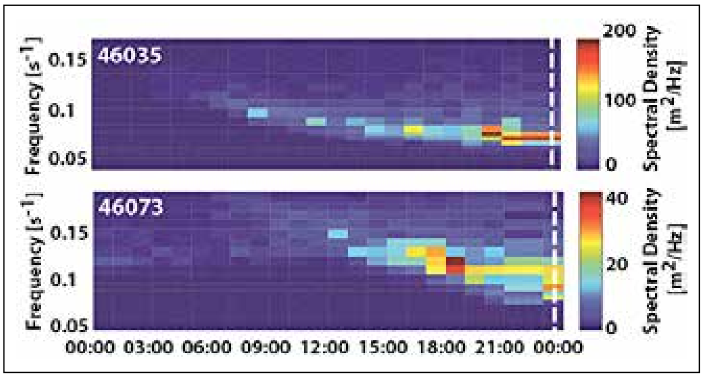

Figure 3: Wave energy spectra at buoy 46035 (top) and 46073 (bottom) on 14 January 2010. The dashed lines indicate the time of the rogue wave incident.

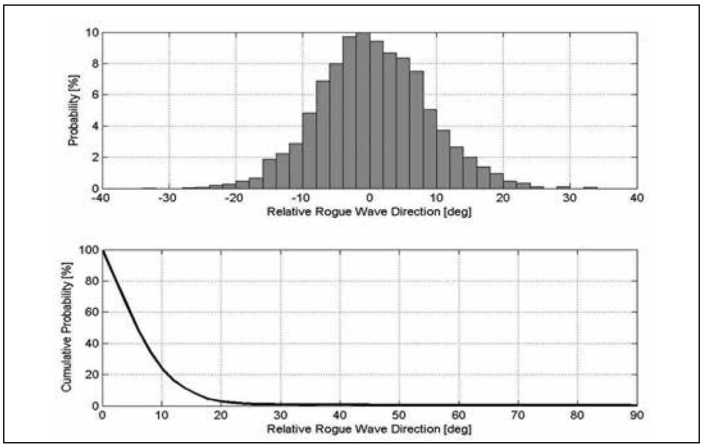

Figure 4: Likelihood (upper panel) and cumulative likelihood (lower panel) that a rogue wave approaches from a certain angle relative to the direction of the predominant waves.

simple theoretical expectations. Though good observations are lacking, the rare waves that are even larger may occur more frequently than predicted by simple theories. Some studies suggest that the cause may be associated with a change of shape of large waves, in particular due to the tendency of large waves to develop sharp crests. Further observations are required. The persistence of individual extreme waves is also unknown.

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Chris Garrett is an emeritus professor of ocean physics at the University of Victoria, but is still involved in issues of ocean waves, ocean mixing, tides, and marine renewable energy. He is a Fellow of the Royal Society of London and a Foreign Associate of the US National Academy of Sciences.