Were extreme waves in the Rockall Trough the largest ever recorded?

Naomi P. Holliday,[1] Margaret J. Yelland,[1] Robin Pascal,[1] Val R. Swail,[2] Peter K. Taylor,[1] Colin R. Griffiths,[3] and Elizabeth Kent[1]

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[1] In February 2000 those onboard a British oceanographic research vessel near Rockall, west of Scotland experienced the largest waves ever recorded by scientific instruments in the open ocean. Under severe gale force conditions with wind speeds averaging 21 ms^{-1} a shipborne wave recorder measured individual waves up to 29.1 m from crest to trough, and a maximum significant wave height of 18.5 m. The fully formed sea developed in unusual conditions as westerly winds blew across the North Atlantic for two days, during which time a frontal system propagated at a speed close to the group velocity of the peak waves. The measurements are compared to a wave hindcast (AES40, Swail and Cox, 2000) which successfully simulated the arrival of the wave group but underestimated the most extreme waves. **Citation:** Holliday, N. P., M. J. Yelland, R. Pascal, V. R. Swail, P. K. Taylor, C. R. Griffiths, and E. Kent (2006), Were extreme waves in the Rockall Trough the largest ever recorded?, *Geophys. Res. Lett.*, *33*, L05613, doi:10.1029/2005GL025238.

1. Introduction

[2] Extreme values of individual (H_{max}) and significant wave height (H_s) are important for ocean engineering applications, but are rarely measured in situ and difficult to accurately predict. Measurements of extreme events are unusual because of the very low spatial coverage of buoys and under-sampling by satellite altimeter data [*Alves and Young*, 2003]. Modern wave prediction models are known to significantly under-predict extreme sea states for H_s above 12m [*Cardone et al.*, 1996; *Resio et al.*, 1999] and so measurements of extreme waves are important for the validation of models and calibration of satellite wave sensors. Here we present wind and wave data recorded by high quality instruments on RRS *Discovery*, propose a hypothesis for the formation of the extreme waves, suggest that the waves experienced were the largest ever recorded in the open ocean, and reveal a shortcoming in wave hindcasting.

2. Data and Methods

[3] The data were collected on cruise 245 on RRS *Discovery* (January–February 2000). The cruise was funded by the UK's Natural Environment Research Council with the scientific mission to occupy a hydrographic section between Scotland and Iceland (the extended Ellett line [*Ellett et al.*, 1986; *Holliday et al.*, 2000]). The data are part of a time series of deep ocean measurements that began in 1976. Figure 1 shows the location of RRS *Discovery* on 8 February, overlying the satellite-derived wind speeds for that day.

[4] The wave data were collected by a Shipborne Wave Recorder MkIV (SBWR). The SBWR is a very reliable system for measuring waves on the deep sea by ship; it was the first instrument to measure deep ocean waves during storms and has been in use since the 1950s. The instrument has been developed over time, but the principles of operation are unchanged and described by *Tucker and Pitt* [2001]. Two pairs of accelerometers and pressure sensors are mounted port and starboard on the ship's hull below the waterline, approximately amidships. The port and starboard instrument pairs are combined to eliminate effects of ship roll, and the accelerometer signal is double-integrated with respect to time to generate ship heave. The pressure sensors provide a wave height signal additional to the heave, so after allowance has been made for ship response, the two are combined to calculate in-situ sea surface height variability (i.e., the wave height). Sections of the wave height signal are used to derive energy spectra which are used to calculate various statistical parameters including significant wave height (H_s, four times the standard deviation of sea surface elevation). Individual wave height is defined as the zero-upcrossing wave height, which is the range of elevations (difference between highest crest and lowest trough) between two successive upcrossings of the mean water level, i.e., the vertical distance between a wave crest and the preceding or following wave trough. The SBWR was recording data continuously throughout the cruise, with a one-second sampling rate and a 10 minute break every 8 hours while data were saved.

[5] The SBWR on RRS *Discovery* was calibrated in September 2000 and found to be accurate within ±1%. A comparison with wave height data from a satellite overpass provides confidence in the accuracy of results from the shipborne measurements; on 9 February 2000 at 22:10 TOPEX was directly over the location of RRS *Discovery* and recorded significant wave height of 10.5m (within the region of the satellite footprint) while the SBWR recorded H_s of 11.3 m (over a 30 minute period).

[6] The local wind speed data were obtained using an R2 Solent sonic anemometer, mounted in the bows of the ship on the foremast platform at a height of 18 m above sea level. The anemometer sampled at 56 Hz and output data at 21 Hz. The 10 minute mean wind speed data were corrected for the ship's speed over the ground, the effect of the ship distorting the flow of air to the sensor, instrument height and atmo-

[1] National Oceanography Centre, Southampton, University of Southampton, Southampton, UK.
[2] Climate Research Division, Environment Canada, Downsview, Ontario, Canada.
[3] Scottish Association for Marine Science, Dunstaffnage Marine Laboratory, Oban, UK.

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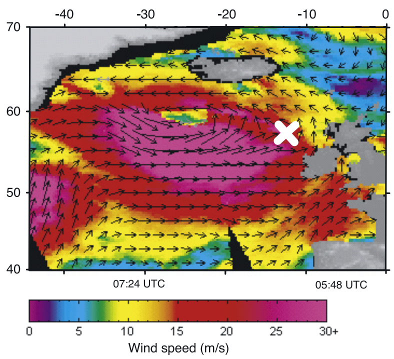

Figure 1. The location of RRS *Discovery* on 8 February 2000 (white cross), overlying the satellite-derived wind speeds for that day (QuikScat morning pass wind vectors). QuikScat data are produced by Remote Sensing Systems and sponsored by the NASA Ocean Vector Winds Science Team. Data are available at http://www.remss.com (2005). Grey shading is land; black shading represents no data.

spheric stability to give the equivalent 10 m neutral wind speed (U_{10n}). Data used in the analysis were obtained when the ship was pointing into the wind, within ±30 degrees.

3. Results

[7] On 8 February 2000, the RRS *Discovery* was caught in a developing storm at 57.5°N, 12.7°W, just east of Rockall and some 250 km west of Scotland [*Holliday and Griffiths*, 2000]. The strong winds and high seas meant that the ship had no option but to remain hove to as conditions worsened. The largest waves arrived some 12 hours after the local wind speed rose above 20 ms^{-1}, with H_s rapidly increasing in magnitude from midday to early evening of 8 February, peaking around midnight, and reducing well before the wind speed dropped below 20 ms^{-1} again late in the morning of 9 February (Figures 2 and 3). The largest individual waves occurred in a 12 hour period between mid-afternoon on 8 February and mid-morning of 9 February,

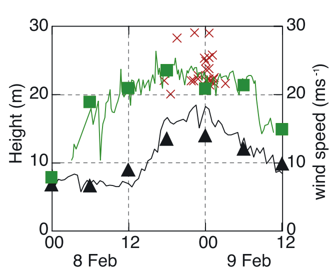

Figure 2. Extreme wind and waves recorded by RRS *Discovery* on 8–9 February 2000 at 57.5°N 12.7°W. Black line is significant wave height (defined as four times the standard deviation of sea surface elevation). Green line is wind speed when the wind direction was within ±30° of the bow (10 minute averages of true wind corrected for stability and at a height of 10 m). Red crosses are individual wave heights that exceeded 20 m. AES40 hindcast data for the same period at 57.5°N 12.5°W are given as black triangles (significant wave height) and green squares (neutral wind speed at 10 m).

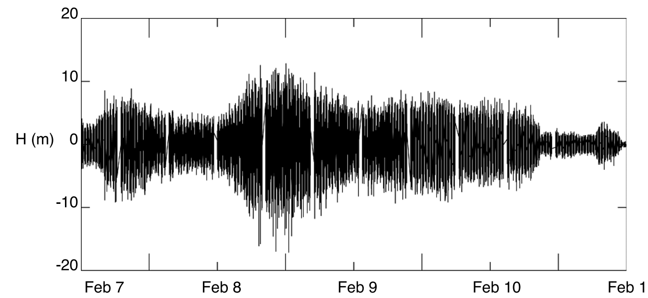

Figure 3. The individual wave record for 7–11 February 2000. Data recorded at 1 second intervals with 10-minute breaks every 8 hours while data were saved.

when 23 waves over 20 m were recorded, the highest wave reached 29.1 m from crest to trough, and H_s reached 18.5 m (Figure 4). The wind speed at the time of the maximum H_s was constant at around 21 ms^{-1} (a maximum 10 minute average of 24 ms^{-1}), the equivalent of a severe storm on the Beaufort scale. For a fully developed sea and U_{10n} = 23 ms^{-1}, H_s values of about 13 m [*Tucker*, 1991] or 14 m [*Resio et al.*, 1999] would be expected, implying some propagation of swell into the area.

[8] The Rockall region of the north-east Atlantic is renowned for frequent strong winds since it lies within the storm track. The region is also known for high seas, and the previous highest instrument-recorded wave in this region was 26.3 m (H_s = 15.7 m) measured in December 1972 by the Ocean Weather Ship *Weather Reporter* at 59°N 19°W [*Draper*, 1986]. Since observations like those are sparse, data from a wave hindcast model can provide insight into historical wind and wave conditions of the region. The AES40 hindcast uses rigorously kinematically re-analysed wind fields which gave improved wave heights over NCEP-NCAR reanalysis wind data [*Swail and Cox*, 2000]. The hindcast data reveal the measured winds to be severe but not exceptional, whereas the wave data were both extreme and exceptional. In the 50-year period covered by the AES40 hindcast (1954–2004), wind speeds of >20 ms^{-1} occurred every year at the closest grid point (57.5°N 12.5°W); a total of 486 different occasions. Most were in January and February, but 2 or more events occurred in every month except July. Wind speeds of >23.5 ms^{-1} occurred in 81 events in the hindcast. The 100 year return period wind speed value at that location is 31.4 ± 2.4 ms^{-1}. The maximum H_s given by the hindcast at that grid point was

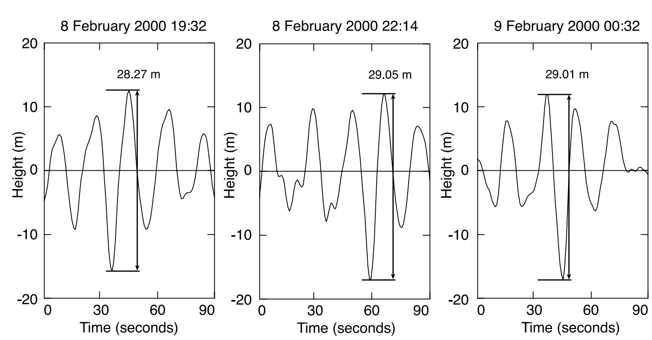

Figure 4. The wave records for the three largest measured individual waves.

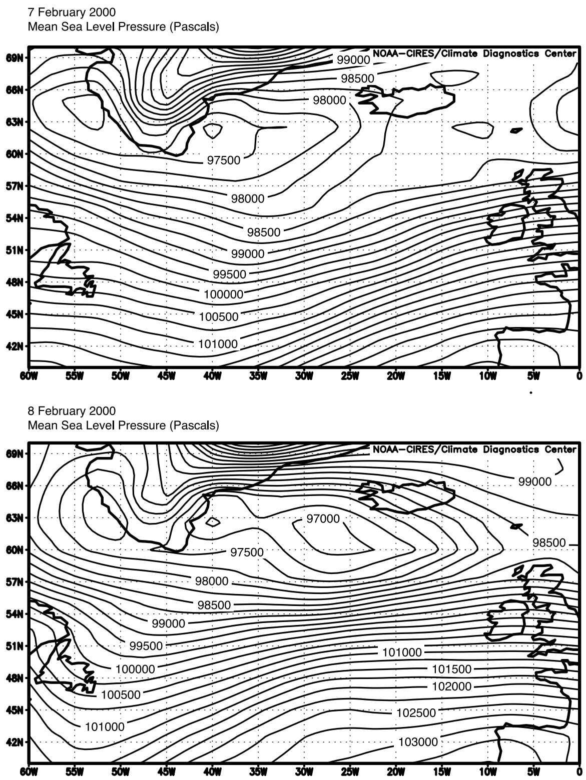

Figure 5. Daily average mean sea level pressure maps for 7 and 8 February 2000. Images provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their Web site (http://www.cdc.noaa.gov/).

15.5 m; only 6 events had $H_s > 15.0$ m. The 100-year maximum wave height for that location is 30.7 m; the 100-year return period for H_s is 16.6 ± 0.9 m.

[9] The AES40 wind speeds for February 9 2000 match the measured winds well (23.5 m s^{-1}). Figure 2 shows that the AES40 wave hindcast also matched the measured significant wave height very well in timing and magnitude, except for the peak of the measurements. While the SBWR measured H_s = 18.5 m, the hindcast produced a maximum of 14.0 m. The AES40 wave heights for the February 2000 storm were exceeded in the hindcast record on 14 different occasions, though none had $H_s > 15.5$ m, indicating a possible shortcoming in the hindcast approach under these specific conditions. The AES40 hindcast simulated the December 1972 conditions rather better; the hindcast wind speeds were considerably higher than the February 2000 values at 31.6 ms^{-1} over a wide area, and the H_s at grid point 59.4°N 18.3°W was 14.6 m (with a maximum H_s = 15.1 m at 16.7°W).

[10] We hypothesise that the extreme waves developed under resonant conditions whereby high winds propagated at the same speed as the wave group. The highest wind speeds were recorded on 7 February, but the largest waves occurred during the night of 8–9 February. This corresponded to the approach of a frontal system with strong warm sector winds which propagated at about 18 m s^{-1}. Since this speed was close to the group velocity of the peak waves there was the potential for the wind sea to have been continually built by this system as they crossed the ocean together. The rapid increase in wave height at the beginning of the event supports the hypothesis, and synoptic pressure charts for February 2000 show how the conditions may have occurred. Figure 5 shows not a "typical" scenario of a train of depressions separated by small regions of high pressure, but a complex deep low near Iceland and strong westerly airflow across the entire North Atlantic for two consecutive days. The result was a long fetch capable of allowing a fully developed sea to evolve. The fetch is critical in determining the wave height. For example, 25 ms^{-1} wind blowing for 50 hours across the deep ocean with a fetch of 1100 km, would result in a fully developed sea with H_s = 15.4 m, wave period of 19.2 s, and wave speed of 30 m s^{-1} [*Tucker*, 1991] or H_s = 17.2 m [*Resio et al.*, 1999]. The ability of the model to simulate the rapid increase in wave height but not the measured maximum may suggest a problem with the time evolution of the hindcast wind field; in trapped fetch conditions, getting the translation speed of the synoptic feature precisely correct is critical.

4. Discussion and Conclusions

[11] The significant wave height of 18.5 m is greater than any previously published wave data, and the maximum individual wave height of 29.1 m is amongst the largest. Waves recorded during Hurricane Ivan in 2004 reached H_s = 17.9 m and H_{max} = 27.7 m [*Wang et al.*, 2005]. Some of the largest waves have been recorded by Canadian buoys in the western North Atlantic under extreme wind conditions, for example H_s of 17.3 m and H_{max} of 30 m during the "Halloween Storm" of 1991 [*Cardone et al.*, 1996] and H_s of 17.1 m and H_{max} of 30 m during the 1995 Hurricane Luis [*Perrie and Long*, 2002]. An H_{max} of 30 m represents the maximum possible height allowed by the range set for the buoy mounted wave recording system. Unlike other extreme waves however, the waves recorded in the Rockall Trough in 2000 were not generated by exceptional winds, but by weather conditions that led to a long fetch across the North Atlantic, and a peak wave group travelling across the ocean at a similar velocity to a strong wind feature.

[12] It seems likely that there have been other cases of resonant wave growth in this area which have gone unrecorded because of a lack of open ocean wave measurements and the failure of wave hindcast models to simulate these conditions. Satellite altimeter data has been shown to underestimate extreme wave heights, so there is clearly a need for more direct deep ocean wave measurements by buoys and ships. In addition further development of wave hindcast models is required to better simulate resonant wave growth. The establishment of an international data resource for high quality extreme wave events would aid future analysis and model improvement.

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C. R. Griffiths, Scottish Association for Marine Science, Dunstaffnage Marine Laboratory, Oban PA37 1QA, UK.

N. P. Holliday, E. Kent, R. Pascal, P. K. Taylor, and M. J. Yelland, National Oceanography Centre, Southampton, University of Southampton, Waterfront Campus, Southampton SO14 3ZH, UK. (nph@noc.soton.ac.uk)

V. R. Swail, Climate Research Division, Environment Canada, 4905 Dufferin Street, Downsview, ON, Canada M3H 5T4.