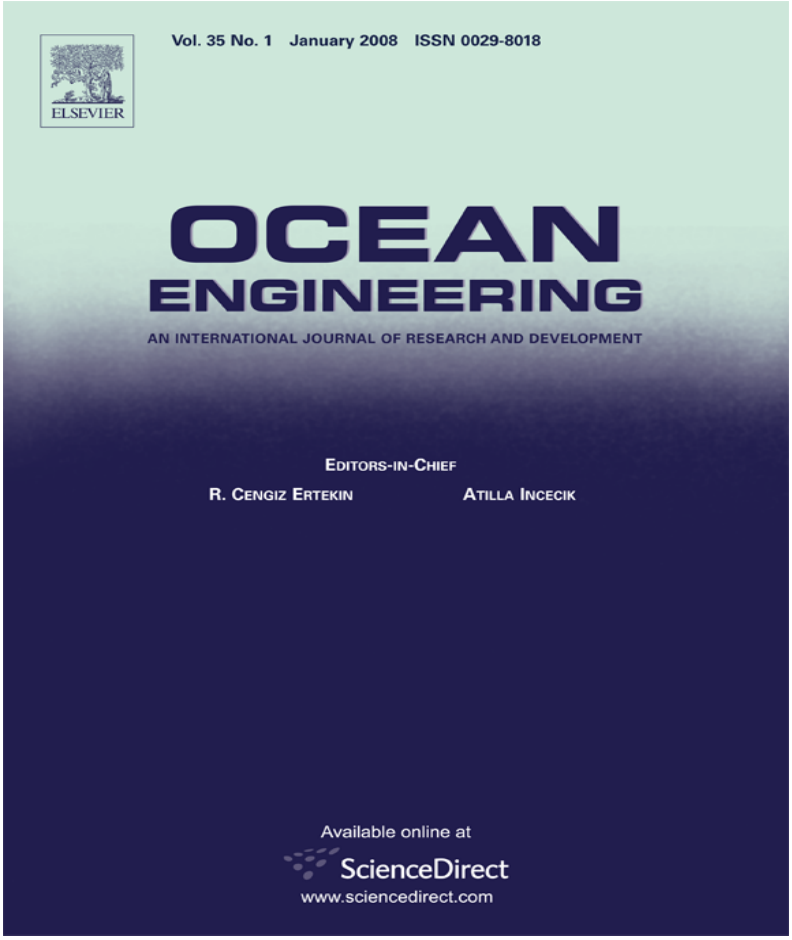
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# Analysis of the Voyager storm

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**Abstract**

We analyse the wind and wave conditions present in the Mediterranean Sea at the time and location when the cruise ship Voyager was reportedly hit by one or more big waves and suffered substantial damage. The analysis is done using wind and wave modelling supported by satellite and buoy wind and wave data. Granted the hindcast of the storm, we also analyse the local conditions for the possibility of freak waves.


*Keywords:* Wind; Waves; Storm; Hindcast; Wave height distribution; Freak waves

## 1. Preamble

On February 14, 2005 the cruise ship Voyager was on route from Tunis (Tunisia) to Barcelona (Spain) with about 800 people on board. Around 08 UTC the ship found herself in the middle of a severe mistral storm. Reportedly, a sequence of large waves up to 14 m height caused heavy damage to the communication and propulsion systems. After some time the crew managed to restart one of the engines, and, with only one propeller at work, the ship made her way to the harbour of Cagliari (Sardinia, Italy). A map of the area and the approximate position of the ship are given in Fig. 3.

Severe mistral storms, with northerly or north-westerly winds blowing from the French coast towards the Balearic Islands and Sardinia, are relatively common in the area (see, e.g., the Medatlas Group, 2004, for a related statistics). Our attention was attracted by the claims of "sudden lurching and shuddering". This is the typical consequences of the impact of a freak wave, i.e., of the appearance of a wave whose height exceeds the values reasonably expected from the Rayleigh distribution or modifications thereupon (see Longuet-Higgins, 1952, 1980, and Forristall, 1978). Therefore, we have hindcast the storm with the aim of obtaining the most reliable data in the area of the accident, especially about the wave heights.

The analysis of the wind and wave fields is described in Section 2. In Section 3, we discuss the possibility of freak waves at the time and location of the accident. Conclusions are drawn in the final Section 4.

## 2. The hindcast

The principle is to use a sequence of reliable wind fields to drive an advanced wave model, and to compare the results with the available measured data.

We have used two wind sources: the meteorological model of the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, UK) and COAMPS, a high-resolution model used at the Fleet Numerical Meteorology and Oceanography Center (FNMOC, Monterey, California, USA). At the time of the storm ECMWF used the T511 version of their meteorological model, with about 40 km resolution. The model is global and spectral, i.e. the fields are given as truncated time series of two-dimensional spherical Fourier components, the T-index representing the highest frequency considered. A full description of the model can be found in Simmons (1991), Simmons et al. (1995), and Simmons and Hollingsworth (2002). COAMPS, with 0.2° (about $22 \times 16$ km) resolution, is a limited area model nested in the coarser, but global, NOGAPS model. Both the models are operational at FNMOC. A good

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description of the models is given by Hogan and Rosmond (1991) and Hodur (1997).

Coupled to their meteorological model, ECMWF runs a global version of the advanced WAM wave model (see Komen et al., 1994 and Janssen et al., 2005), plus a so-called Mediterranean version (28 km resolution) that includes this sea. The 00, 06, 12, 18 UTC modelled wind and wave data are regularly stored in the local archive.

So, in principle the wind and, more importantly, the wave data we need are already available. However, Cavaleri and Bertotti (2004, 2006; see also Medatlas Group, 2004) have clearly shown how the ECMWF wind speeds, hence also the derived wave heights, are strongly underestimated in the inner seas, hence also in the Mediterranean basin. They also showed that the underestimate depends on the resolution of the meteorological model, expectably the quality of the results improving when increasing the resolution. At the time of the storm ECMWF was testing the new version, T799, of their meteorological model, with a series of trial analyses and forecasts run twice daily parallel to the operational T511 model. Therefore, we took advantage of these data to analyse the storm. However, the related analysis data were stored at 12 h intervals, hence not suitable for a rapidly varying wind field. Alternatively, we resorted to the use of the short-term forecasts, available at 3 h intervals. Out final sequence of wind fields was composed of the +3-+6-+9-+12 h forecasts starting at 00 and 12 UTC, in so doing obtaining an uninterrupted series of wind fields at 3 h interval. The short-term forecasts ensured the reliability of the fields. With the peak of the storm on February 14, we started our simulation on the 10th, allowing a 3 day warming up of the wave model, a more than sufficient period in an enclosed seas as the Mediterranean.

Cavaleri and Bertotti (2006) had previously quantified the improvement expected when using T799 with respect to T511, although still with values lower than the measured ones. A comparison with the measured data (see below) quickly confirmed this to be true also for the Voyager storm. A solution is to calibrate the wind fields in the area of interest and to run again the WAM model using as input the calibrated T799 wind fields. This calibration was achieved using the extensive coverage, typically twice a day, provided by the scatterometer of the QuikSCAT satellite. In the version we used these data are given as wind speed and direction at 25 km resolution. For the comparison, we chose the area between the Balearic Islands and Sardinia, and between France and the African coast, the one relevant for our present storm of interest. The modelled wind values were linearly interpolated at the time and position of the scatterometer data, and the co-located data analysed with a scatter diagram. The resulting symmetric best fit suggested a model underestimate of 14%. Therefore, we correspondingly increased the model wind speeds (the directions are very much correct) and ran the WAM model. These further runs were done with 0.25° ($28\times23$ km) resolution. Note that, as the calibration factors are location dependent (see the Medatlas Group, 2004, and Cavaleri and Sclavo, 2006) and we have used the same coefficient for the whole basin, our "calibrated" results are valid only for the area of interest. This is where we focus our attention.

These results were compared with the wave data available from the altimeter of the JASON and ENVISAT satellites. In particular, JASON made a descending path (see Fig. 1) right at or very close to the time of the accident (pass at 08.28 UTC, i.e., about half an hour after the accident), providing a nice section of the wind (speed) and wave (height) conditions along its ground track. It turned

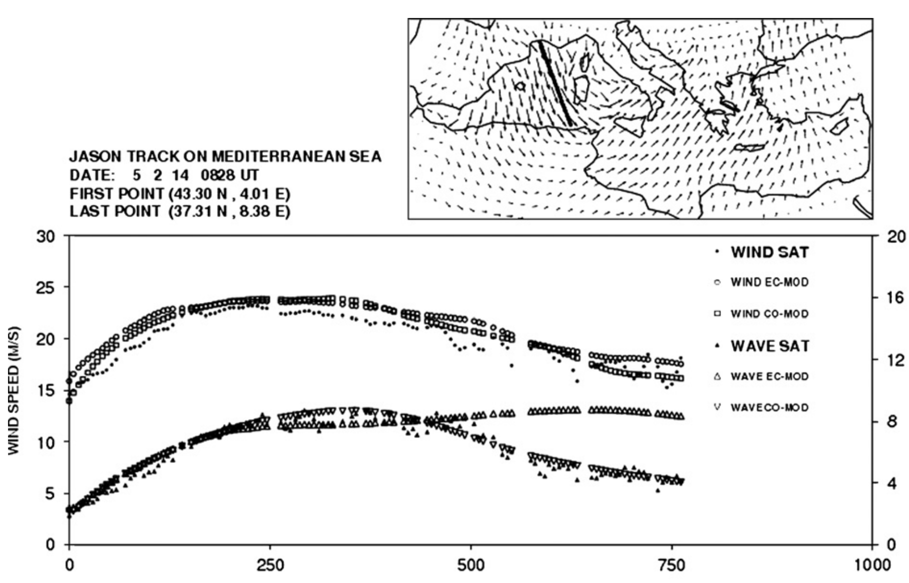


Fig. 1. Comparison between JASON altimeter wind speeds and wave heights and corresponding model results. EC-MOD = ECMWF and CO-MOD = COAMPS. The ground track and the overall wind field are shown in the smaller upper right figure.

out that the modelled wave heights were higher than the corresponding altimeter data by about 7%. Aiming at the best wave results, we correspondingly decreased the wind calibration coefficient to 1.10 and ran the WAM model again (a discussion on the 1.14 calibration coefficient is given in the final section). Fig. 1 provides a comparison between the final (calibrated) wind and wave modelled data (EC-MOD) with the corresponding JASON altimeter ones. There is a slight overestimate of the modelled wind speeds (this point too will be discussed in the final Section 4) and a very good fit of the modelled wave height values, at least till slightly above 39° latitude (southern end of Sardinia, about 450 km in the horizontal scale). The hindcast was repeated using as input the COAMPS winds (no calibration required). The results, for both wind and waves, are similarly reported in Fig. 1 (CO-MOD).

The two modelled wind sections are very similar. However, there is a substantial difference between the two wave results. South of 39° latitude, ECMWF indicates that the wave heights $H_s$ are still increasing while moving towards the African coast, while COAMPS places the maximum $H_s$ west of Sardinia, with substantially decreasing values when moving south. The reason for the different behaviour becomes evident if we analyse the corresponding wind (Fig. 2, at 03 UTC) and wave (Fig. 3, at 09 UTC) conditions. It is clear from Fig. 2 that the ECMWF winds

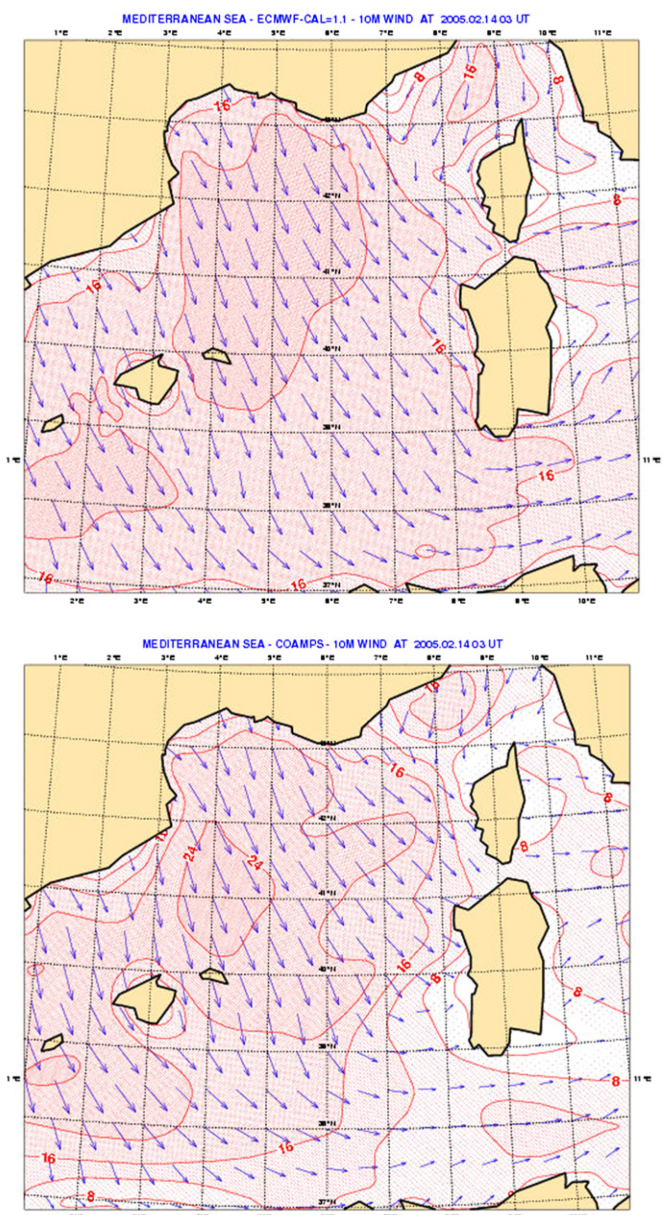


Fig. 2. Wind field at 03 UTC 14 February 2005. The area is the Western Mediterranean Sea. Isotachs at 4 m/s intervals. Arrows show wind speed and direction: (a) calibrated ECMWF and (b) COAMPS.

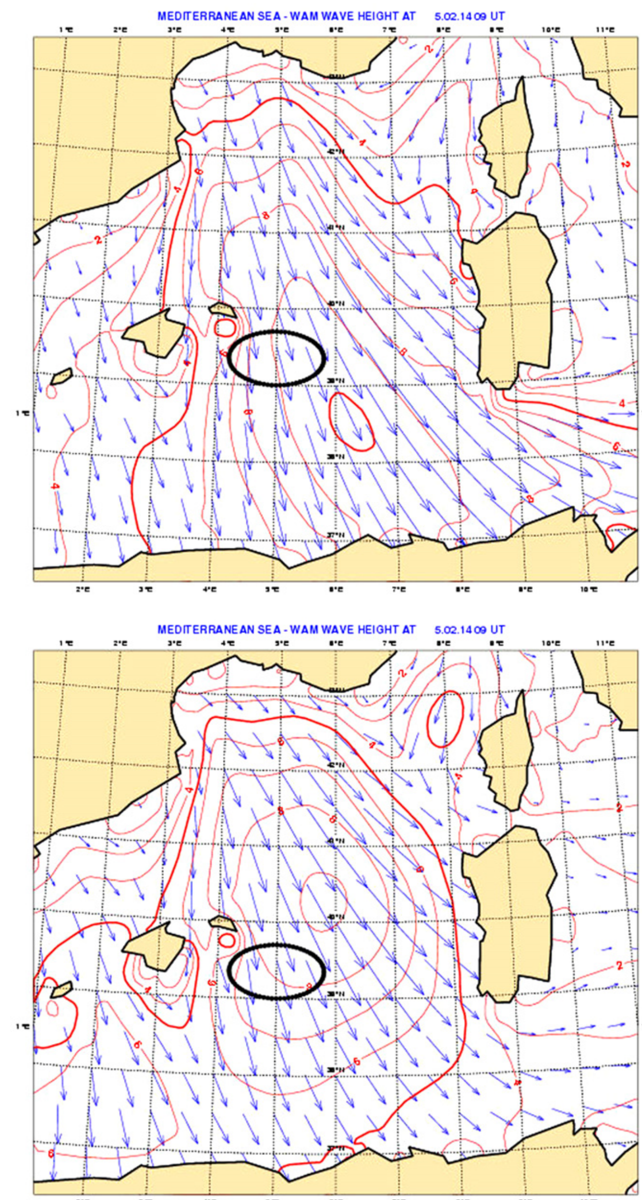


Fig. 3. Wave field at 09 UTC 14 February 2005. The area is the Western Mediterranean Sea. Isolines at 1 m intervals. Arrows show significant wave height and mean direction: (a) using calibrated ECMWF winds and (b) using COAMPS winds. The ellipse shows the approximate position of the cruiser Voyager at the time of the accident.

are "running ahead" with respect to COAMPS and, as it turns out, also with respect to the truth. This becomes evident when the model winds are compared with the data recorded on a meteo-oceanographic buoy off the west coast of Sardinia (not shown). Note the more extended area to the south by ECMWF where the wind speeds are larger than 16 m/s. The most evident feature is the position of the meteorological front, approximately identified in the figure by the position of the 16 m/s isotach where the wind vectors change abruptly direction. This has obvious consequences on the related wave fields in Fig. 3, with COAMPS placing the peak of the storm between the Balearic Islands and Sardinia, while ECMWF locates a larger than 10 m maximum only 150 km off the African coast.

The comparison in Fig. 1 clearly indicates the overall better and excellent quality of the COAMPS hindcast. Our further considerations are based on these results. In any case in the area of interest, the analysis was done with both the wind sources and led practically to the same results.

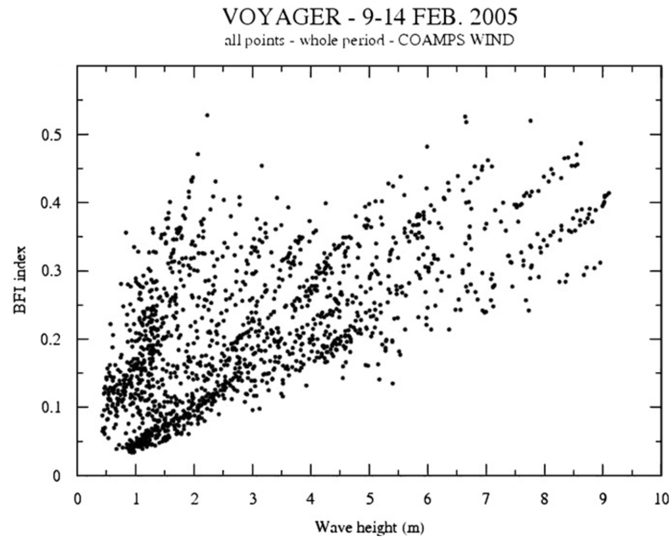


Fig. 4. Scatter diagram of the Benjamin–Feir instability indices vs. the corresponding significant wave heights in the area of the Voyager storm.

## 3. The probability of freak waves

Freak waves have received quite a bit of attention in recent years, mainly due to a detailed analysis of the many wave records available and to the fact that they seem not to be so rare as people used to think. Note that, defining a freak wave as an event higher than 2.2 times the significant wave height, "events" can be searched for in any wave condition. More interestingly, Osborne et al (2000) and Onorato et al. (2001, 2005) have recently clarified, first theoretically and than experimentally what is at least one of the mechanisms that lead to the formation of freak waves. Through a dimensional analysis of the nonlinear Schroedinger equation and through numerical simulations of the same equation, Onorato et al. (2001) managed to show that in certain conditions characterised by a large wave steepness ($H_s/L$, with $L$ the mean wave length), a modulation instability mechanism can arise as the result of a four-wave quasi-resonant interactions. This was then proved experimentally in a large wave channel (Onorato et al., 2005). What happens is that one wave starts borrowing energy from its neighbourhood companions, growing at their expenses. This makes the event even more spectacular, because the single freak wave is preceded and followed by much lower ones. The situation is transitory, as the large wave soon releases back the energy to its neighbourhoods, the process eventually repeating at different times and locations.

These findings found their way into operational applications with the work of Janssen (2003). Using the theory of weak turbulence and the concept of quasi-resonant interactions, he was able to derive analytically, under the hypothesis of narrow band spectra, a direct relationship between the kurtosis of the local wave spectrum and the Benjamin–Feir instability index (BFI), i.e., the parameter indicating the level of instability of specific wave conditions. It turns out that when BFI $>1$, the statistical distribution of the wave heights for a given spectrum is substantially modified. With respect to the Rayleigh distribution derived from the linear theory (Longuet-Higgins, 1952) and its modifications by Forristall (1978) and Longuet-Higgins (1980), there is a small decrease of the peak of the distribution and a substantial enhancement of the high value tail. This was clearly shown during the experiments by Onorato et al. (2005).

Out of the hindcast we have saved the wave spectra at a number of points, distributed throughout the area where the ship was located and, more in general, in the whole area with large significant wave heights. Then, we have evaluated the corresponding BFI values, shown in the scatter diagram of Fig. 4. Clearly all the BFI values are much lower than 1, with maxima around 0.5. According to the Janssen's approach, these values are too low to justify an enhanced probability of freak waves.

## 4. Discussion

According to the present theories, also validated by experimental results, the conditions present in the area of the Voyager at the time of the accident were not favourable to the formation of freak waves. Of course this does not exclude that a possibility, however slim, exists. On the other hand, the reported 14 m height does not seem so excessive also when considering the standard Rayleigh distribution, once the wave conditions in the area are taken into account. Looking in Fig. 3 at the significant wave heights present between the Balearic Islands and Sardinia (the two hindcasts are very similar in this area), we find $H_s$ between 8 and 10 m. With respect to these values, a 14 m height is 1.75 and 1.4 times larger, respectively. From the Rayleigh distribution these figures correspond to about one wave every 500 and 50 ones, i.e., one happening every more or less 1.5 and 0.18 hours (we have used 11 and 13 s peak periods, respectively, as derived from the hindcast).

Somehow, we feel uneasy with this result. Our wave results are quite robust, also confirmed by the altimeter data. Given the wave conditions at the time and location of the accident, we would expect much higher waves to hit the ship with respect to the 14 m reported as an exceptional event. The reports specifically talk about wave height. However, we hypothesise that it was a 14 m wave crest or so that hit the ship (this would explain breaking the window of the control room in the upper deck). Assuming a highly nonlinear wave of overall 18 m height, a repeated calculation leads to an expected return period of about 40 and 2 h, respectively. These sound like more realistic figures. Note anyhow that they are probably in excess, as, even without invoking a freak wave, these maxima seem to appear more frequently than indicated by the Rayleigh distribution. The statistics from the records obtained during severe storms or hurricanes (see, e.g., Osborne, 1982) steadily exceeds the Rayleigh expectations. Therefore, we conclude suggesting that the reports from the accident were inaccurate in their description, but that nevertheless the event lies well within the range of the practical possibilities.

Concerning the wind speeds, the results in Fig. 1 strongly suggest that a 14% model underestimate (see Section 2) derived from the comparison between the ECMWF and scatterometer data is indeed in excess. Ardhuin et al. (2006) argue about the quality of scatterometer data in the inner seas. From an extensive comparison between QuikSCAT scatterometer data in the Mediterranean Sea and accurate buoy-measured wind speeds, they report a consistent overestimate of the surface wind speed by the scatterometer. Our results lead to the same conclusion. However, there is another reason for the apparent strong underestimate of the ECMWF wind speeds. As Cavaleri and Bertotti (2004) have shown, the largest underestimate happens in the first 100–200 km off the coast (for offshore blowing winds). As we have derived a single calibration coefficient for the area covered by the storm, our estimate was biased towards lower model wind speeds.

The comparison with the altimeter data (see Fig. 1) indicates a positive difference, about 5%, between model and altimeter wind data. This is consistent with previous findings (see, e.g., the Medatlas Group, 2004 and Cavaleri and Sclavo, 2006) that the altimeter wind speeds are slightly underestimated in the inner seas. This is apparently connected to the more wind sea dominated conditions in these basins with respect to the oceans where the calibration of the instrument is usually carried out.

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Susanne Lenher pointed the storm to our attention.

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