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Predicting freakish sea state with an operational third generation wave model

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Abstract

Understanding of freak wave generation mechanism has advanced and the community has reached to a consensus that spectral geometry plays an important role. Numerous marine accident cases were studied and revealed that the narrowing of the directional spectrum is a good indicator of dangerous sea. However, the estimation of the directional spectrum depends on the performance of the third generation wave model. In this work, a well-studied marine accident case in Japan in 1980 (Onomichi–Maru incident) is revisited and the sea states are hind-casted using both the DIA and SRIAM nonlinear source terms. The result indicates that the temporal evolution of the basic parameters (directional spreading and frequency bandwidth) agree reasonably well between the two schemes and therefore most commonly used DIA method is qualitatively sufficient to predict freakish sea state. The analyses revealed that in the case of Onomichi–Maru, a moving gale system caused the spectrum to grow in energy with limited down-shifting at the accident site. This conclusion contradicts the marine inquiry report speculating that the two swell systems crossed at the accident site. The unimodal wave system grew under strong influence of local wind with a peculiar energy transfer.

1 Introduction

A number of ship accidents in the North West Pacific Ocean, especially in the sea east of Japan, were reported from decades ago. The mysterious sea is coined “the Dragon’s Triangle” mimicking the famous “Bermuda Triangle” in the Atlantic Ocean (Berlitz, 1989). During the World War II, Admiral Halsey and his fleet had sailed into the heart of Typhoon Cobra in the North Pacific, and lost three destroyers (Drury and Clavin, 2007). Recently Atsukawa (1999) had analysed the meteorological conditions during this incident and suggested that the vessel might have encountered a wave over 30 m in height (Fig. 1). Although this description is rather speculative, Atsukawa did make numerous interesting observations: the ship had encountered waves over 30 m

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which is followed by 28 m wave; the Kuroshio Current is present; the bow of the ship had surfaced. These observations are related to the formation of wave group, wave-current interaction and slamming load. Undoubtedly, Atsukawa's observation is influenced by the well-known and well-studied marine accident near Japan, the Onomichi–Maru incident (Yamamoto et al., 1983). The incident is memorable because of the famous picture of her without the bow (Fig. 2). Because of lack of knowledge about freak/rogue waves at that time, the cause of the incident was mistakenly attributed to a high wave called the Sankaku-nami in Japanese or triangular wave, which suggest a crossing of large swells. We will show in this study that this was not the case and the directional spectrum was uni-modal at the time of the incident.

Historical incidents of the freak wave or the rogue wave are well documented in the text book by Kharif, Pelinovsky and Sulnyev (2010). The large waves that appear in the ocean unexpectedly are named differently each representing one of the characters of the freak wave; giant wave, mad-dog wave, wall of water, holes in the sea, three sisters, pyramidal waves, etc. Scientists and engineers define them as wave which is “higher than twice the significant wave height” and is “isolated”. For linear and narrow banded random wave, the distribution of wave height is approximately Rayleigh (Longuet-Higgins and Cart-Wright, 1953) and therefore appearance of waves over twice the significant wave height is about once every 3000 waves. Inevitably, the encounter of ships with the freak and giant waves is rare, but Kharif and Pelinovsky (2003) reports that during 1969–1994 twenty-two super-carrier ships and 525 lives in total may have been lost due to freak waves in the Atlantic and the Pacific Ocean. Nine of the accidents occurred in the Dragon's Triangle, including the two Japanese large carrier ships, the Bolivar–Maru and the Onomichi–Maru. More recent incidents of fishing boats, ferry boat and Onomichi–Maru are documented in Waseda et al. (2012). Out of 7 incidents, five occurred when the directional spectrum narrowed. None of the incidents had direct evidence of the ship encountering the freak wave, but the freakish sea index which maps the dimension of the directional spectrum indicated a dangerous sea state for those cases.

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The freakish sea index maps the trajectory of the directional spreading (σ_θ) and frequency bandwidth (Q_p) and was successfully used in the study of Suwa–Maru incident by Tamura et al. (2009) and of Onomichi–Maru incident by In et al. (2009). What the freakish sea index indicates is the temporal change of the geometry of the directional spectrum. In most of the incidents studied by Waseda et al. (2012), the freakish sea index was changing rapidly in time. Furthermore, in some cases, the incidents occur exactly when the freakish sea index indicated narrowest directional spectrum.

Numerous “freak wave indices” are suggested. Attributing the modulational instability of the long crested waves for the formation of large amplitude waves, Onorato et al. (2001) and Janssen (2003) independently introduced a parameter that compares the relative magnitude of nonlinearity and dispersion. Those parameters were called the Ursel number and the Benjamin–Feir Index respectively. The latter terminology is used more often in recent literatures. These studies were experimentally extended to include the effect of directional spreading of the wave spectrum by Waseda (2006). However, earlier works already indicated evidences that for realistic directional spreading, the occurrence probability of freak waves is small (Onorato et al., 2002; Soquet-Juglard et al., 2005). In turn, the freak wave occurrence becomes high when the bandwidth of wave spectrum is narrow (Toffoli et al., 2008; Onorato et al., 2009a; Waseda et al., 2009; Onorato et al., 2009b; Mori et al., 2011; Xiao et al., 2013). The conclusion deduced from these experimental works were validated by observation indicating that under certain meteorological condition the probability of freak wave occurrence will increase (Waseda et al., 2011).

In this paper, the wave field during the time of the accident of the Onomichi–Maru will be hind-casted with an operational wave model (WAVEWATCH III). The comparison of the model results with the sea states described in the official report of the marine accident inquiry were presented earlier by In et al. (2009). A brief overview of the Onomichi–Maru incident and the hind-cast simulation will be provided in Sect. 2. The comparison of the spectral evolution and the deduced freakish sea index will be compared between DIA simulation and SRIAM simulation in Sects. 3 and 4. Possi-

ble cause of the freakish sea state under moving gale condition will be discussed in Sect. 5. Conclusion follows.

2 Hind-cast simulation of Onomichi–Maru accident

The Japanese bulk carrier Onomichi–Maru was built in 1965 (200 m, 60 000 t). On 30 December 1980, during a voyage carrying fully loaded coal from the United States to Japan, she encountered an extremely high wave, and as a result of slamming impact, lost her bow. The fact that a supper-carrier ship over 200 m was split into two bodies by the force of wave impact came to a shock for the Japanese Ministry of Transportation. A committee was organized to investigate the cause of the accident, concurrently with the marine accident inquiry. The committee concluded that the impact of the slamming was too strong for her body to remain intact and the Onomichi–Maru was broken into two (Yamamoto et al., 1983). The estimated height of the wave was about 20 m. The committee reported that at the time of the accident, steady swell came from the west with 8 ~ 9 m significant wave height and 12 s wave period, and another relatively unsteady swell came from the west-northwest with 3.8 ~ 6.2 m significant wave height and 12 s wave period. The committee concluded that the former steady swell caused the pitching motion of the ship, and an unlucky superposition of the second swell made an extreme wave which caused severe slamming. However, our simulation result shows that this was not the case.

We conducted a three-tiered nested wave hind-cast simulation covering the period from 1 December of 1980 to 10 January of 1981 by an operational third generation wave model WAVEWATCH III (Tolman, 2002). The first level (nest1) covers the whole Pacific Ocean at 1° resolution (95° E–70° W, –75° S–75° N), the second level (nest2) covers the north-west Pacific Ocean with 0.25° resolution (135–180° E, 22–47° N), and the last level (nest3) covers an area around the accident site with 0.125° resolution (150–160° E, 26–36° N). The topography of each area was specified by ETOPO2 (NOAA). As the wind data, we used the JRA-25 (Japanese Re-Analysis 25 yr) data

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of the Japan Meteorological Agency, which is 1.25° resolution at 3 h interval covering most area of the globe. The model setting is detailed in In et al. (2009) and will be briefly summarized here: the number of directions was set to 24 (by 15°) for SRIAM and 36 (by 10°) for DIA; the number of frequencies was set to 25 levels, with the increment factor of 1.1 in the frequency range 0.0412–0.4056 Hz, or 1.08 in the range of 0.0412–0.2611 Hz. The source terms of the WAVEWATCHIII (Tolman–Chalikov source terms) were selected by benchmarking the model setting against the fetch law with an ideal wind condition (Iyama, 2007).

The nonlinear wave-wave interaction term (Snl) is calculated by both the discrete interaction approximation method (DIA method, Hasselmann et al., 1985) and the SRIAM method (Komatsu and Masuda, 1996). The SRIAM method approximates the Hasselmann’s collision integral (Hasselmann, 1963) with 20 optimized combinations of resonant quartets instead of one in DIA. The SRIAM method was implemented in realistic simulations for the first time by Tamura et al. (2008, 2009 and 2010), demonstrating that the directional spectrum under rapidly changing wind condition and the spectral tail are better resolved by SRIAM method. In Tamura et al. (2009), spectral evolution of swell and wind-wave interaction was hind-casted for the Suwa–Maru No.58 incident (June 2008) using SRIAM Snl. In this study, we have made hind-cast simulation with both DIA and SRIAM Snl and compared the spectral evolutions. These model results were validated by Iyama (2007) and In (2009) with observational data of NOWPHAS (Nation Wide Wave Information Network for Ports and Harbors, Port and Airport Research institute in Japan) and the drifting GPS buoy (Japan Meteorological Agency).

The sea states during the accident and the particulars of Onomichi–Maru from the marine inquiry report are summarized in Table 1. Swells 1 and 2 were suggested to be the main cause of the accident. The committee report states that the swell 1 from the west caused the pitching motion of the ship, and an unlucky superposition of the swell 2 from west-north-west made an extreme wave of 20 m which caused severe slamming. However, from the wave field map of Otsubo (1983), the main locations of these swells seem distant away from the actual accident site (Fig. 3 left). This historical hand-drawn

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wave field map is likely based on the second generation wave model, which was most reliable at that time (Tomita, 2009). The swell 1 is indicated by horizontal arrow and the swell 2 by oblique arrow in the south. The accident location is marked by the cross.

These swell systems are indeed well resolved in our simulation (Fig. 3). In the north of the accident cite (solid square), the wave (12–12.5 s) which might correspond to swell 1 is propagating from the west, and in the south-west of the accident site, the wave (11.5–12 s) which might correspond to swell 2 is propagating from the west-north-west. At the accident location, a wave (12.41 s, 8.22 m) was propagating eastward, slightly oriented towards the south (rotated 5.36° to the south, Fig. 3). In an area south of 35° N, the directions of wind and wave (swell 1) are almost the same (Fig. 4). Along the latitude of the accident site (31° N), the wave directions are nearly constant (eastward) and the peak period becomes longer as the waves propagate to the east. The westerly winds have sustained for about 5 days before the time of the accident.

The significant wave height and the three parameters relevant for freak wave prediction are mapped in Fig. 5. A region with high nonlinearity (steepness), narrow directional spreading and reduced dispersion (narrow frequency bandwidth) is found in a large area stretching from east to west in which the accident site is located in the centre¹. The area represents where the probability of freak wave occurrence is high. The temporal evolution of the wind speed, significant wave height, spectral peak period, steepness, frequency bandwidth Q_p and directional spreading σ_θ , are plotted in Fig. 6. A gale over 14 ms⁻¹ started on 27 Decemeber and reached the maximum when

¹Wave Steepness (ak): $ak = \frac{\pi}{\sqrt{2}} \times \frac{H_s}{L_m}$

Frequency Peakedness (Q_p) (Goda, 1970):

$$Q_p = 2m_0^{-2} \int_0^\infty d\sigma \sigma \left[\int_0^{2\pi} F(\sigma, \theta) d\theta \right]^2 \text{ where } m_0 = \int_0^{2\pi} \int_0^\infty F(\sigma, \theta) d\sigma d\theta$$

Directional Spreading (σ_θ) (Kuik et al., 1988):

$$\sigma_\theta = \left[2 \left\{ 1 - \left(\frac{a^2 + b^2}{m_0^2} \right)^{\frac{1}{2}} \right\} \right]^{\frac{1}{2}}$$

$$\text{where } a = \int_0^{2\pi} \int_0^\infty \cos(\theta) F(\sigma, \theta) d\sigma d\theta \quad b = \int_0^{2\pi} \int_0^\infty \sin(\theta) F(\sigma, \theta) d\sigma d\theta$$

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the accident occurred on 30 Decemeber. The Q_p increased within a day before the accident, and σ_θ reduced continuously during the gale condition. Despite ak remained relatively unchanged, the directional spectrum narrowed and became most narrowest when the accident occur. Therefore, the Onomichi–Maru may have sailed right in the centre of a dangerous sea where the freak wave occurrence is high. Furthermore, the evolution of the directional spectrum reveals that the coexistence of the two swell systems, as suggested by the inquiry committee, is highly unlikely at the accident location (Sect. 3).

3 Spectral evolution

The spectral evolution at the test site will be investigated based on the third generation wave model outputs. Evolution of the directional spectrum will be described for both DIA and SRIAM computations (Sect. 3.1). In Sect. 3.2, the source terms will be studied in detail comparing the two schemes.

3.1 Directional spectrum

The wave energy density at the time of the accident is unimodal and is unequivocally reproduced by both DIA and SRIAM hindcast simulations (Figs. 7 and 8, lower left). The two swell systems as indicated by the incident report are not present in these simulation results. The projection of the directional spectrum to the frequency and directional

frequency spectrum is even narrower with SRIAM. Comparing the frequency spectra 48 h before and after the accident, the rapid narrowing of spectral bandwidth in just a few days is rather remarkable.

Overall, we can conclude that there were only one wave system at the accident site and is strongly influenced by the local wind. Because the value of the directional spreading σ_θ , was minimum at the accident time (Fig. 6), the sea condition was likely not a crossing-sea as conjectured in the accident report. With a relatively narrow directionality and frequency bandwidth, the possibility of freak wave occurrence might have increased, and caused the accident.

3.2 The source functions

As the wind-sea grows under constant wind forcing, the energy is transferred from the waves in the frequency range higher than the peak of the spectrum, to the frequency range lower than the peak and to the spectral tail (Hasselmann et al., 1985). As a result, the spectral peak downshifts. The transfers of energy among spectral components occur due to four-wave resonant interactions and the shape of the transfer function depends on the spectral geometry. The growth of fetch-limited or duration-limited wind-sea under constant wind forcing is thus characterized by this typical nonlinear transfer function S_{nl} and the associated self-similar spectrum.

However, under changing wind condition, directional spectrum deviates from the standard self-similar spectral shape and likewise the S_{nl} . Rapid narrowing of the frequency spectrum with limited spectral peak downshifting is a remarkable feature during the Onomichi–Maru accident (Figs. 7 and 8). Thus a peculiar shape of S_{nl} is expected. The temporal evolution of S_{nl} in frequency domain is depicted in Fig. 9. From 72 h to 48 h before the accident, the peak of the spectrum gradually downshifts (Figs. 7 and 8) and so is the peak of the S_{nl} . However, from 24 h before the accident, the energy level of the peak builds up while the peak of the S_{nl} is more or less fixed in frequency. Another notable feature of the S_{nl} is the large negative value in the range of around 0.075 Hz and 0.18 Hz (1 to 2.5 times the spectral peak frequency) and the large positive

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value in the range of around 0.18 Hz to 0.3 Hz (2.5 to 4 times the spectral peak frequency). Thus, a large part of the spectral energy is transferred to both the peak of the spectrum and to the tail of the spectrum as a result of nonlinear wave–wave interaction.

On the other hand, the spectral shape at frequencies higher than twice the peak (~ 0.15 Hz) remains more or less unchanged. Tamura et al. (2010) has shown that in operational wave model, the nonlinear source term annuls the imbalance of the energy input and dissipation and therefore the equilibrium spectral tail remains unchanged. Therefore, the large S_{nl} values at frequency ranges higher than twice the spectral peak is not necessarily an indication of spectral change. Indeed a large part of the wind input energy is redistributed elsewhere by nonlinear transfer (Fig. 10). Most apparently, the energy is transferred to the frequency range of the spectral peak, but at oblique angles. The tendency to broaden the spectrum at the peak is more prominent with the SRIAM computation (compare Figs. 7 and 8). The spectrum is quite narrow in frequency but relatively broad in direction. This broadening is a consequence of active energy transfer among spectral components. Therefore it is apparent that the wave system is not a simple linear superposition of the two swell systems. A few days before the accident, the wave field was more or less bimodal (note the two wave systems are different from swell 1 and 2). As the gale system developed, the unimodal directional spectrum developed around 0.1 Hz and gradually downshifted to around 0.07 Hz where the spectral energy developed rapidly. The spectral geometry will be characterized by two parameters, directional spreading and frequency bandwidth, i.e. the freakish sea index, in the next section.

4 Freakish sea index

In the case of the Onomichi–Maru accident, the directional spectrum rapidly narrowed in frequency and direction in 24 h. A number of marine accidents occur in similar situations in which the sea states rapidly changed. Those incidents are described in Waseda et al. (2012) and Tamura et al. (2009). None of these marine accidents have

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solid evidence of freak wave occurrence but these case studies suggest that operational wave model is useful in providing a warning criterion for ships navigating in open ocean. A visualized risk index of freak wave will be useful and we proposed to use the Joint–Probability–Density–Function (JPDF) of the directional spreading Q_p and the frequency peakedness σ_θ as an indicator of the likelihood of freak wave (In et al., 2009; Tamura et al., 2009). The idea of the freakish sea index is to visualize the development of spectrum in the Q_p and σ_θ domain. In the case of Suwa–Maru incident, Tamura et al. (2009) showed nicely that the spectrum narrowed rapidly in less than 6 h as a result of interaction of background swell and wind-sea. The spectrum thus developed from a bimodal state to unimodal state. In the case of Onomichi–Maru, the rapid change of Q_p was associated with local development of the wave system.

These spectral developments might be affected by the setting of the operational model. In the case of Onomichi–Maru incident, both the DIA and SRIAM nonlinear source terms were used. As illustrated in Sect. 3, the use of SRIAM method slightly broadened the spectrum in direction but narrowed the spectrum in frequency. Let us now compare the performance of DIA and SRIAM simulations in expressing the freakish sea index (Fig. 11). Apparently, the timing of the accident is unequivocally represented at the turning point of the Q_p and σ_θ trajectory; i.e. both simulations commonly indicate that the accident occur when the directional spectrum was narrowest within the 4 days. The values of both Q_p and σ_θ are about the same despite the subtle difference in the directional distribution at the peak frequency (Figs. 7 and 8). At other times, the SRIAM simulation tends to show slightly broader spectrum in direction but the frequency bandwidth seem to agree. Qualitatively, the two diagrams convey the same message that the accident occur at the turning point of the Q_p and σ_θ trajectory. For operational use, DIA is 20 times faster than SRIAM. Our comparison suggests that the DIA simulation is sufficient to provide qualitatively correct information useful for the warning criterion.

5 Wind-sea development under changing wind field

The change of the wave spectrum in time observed at a fixed location is determined by not only the source functions but also the propagation term. Classical fetch-laws are obtained only for those cases that either the tendency term can be neglected (fetch-limited) or the propagation term can be neglected (duration-limited). In realistic cases, wind fields are changing in both time and space so that both the tendency and the propagation terms are important. It is therefore not surprising if the overall change in the spectral shape deviates from ideal cases of fetch- or duration-limited wind-sea. Nevertheless, it is of interest to find out how the wind field changed in the Onomichi–Maru accident case.

The wind speed and wind vectors of 29 December, 12:00 UTC and 30 December, 00:00 UTC are presented in Fig. 12. A strong gale system with maximum velocity close to 20 ms^{-1} covered a large area East of Japan (3000 km by 1000 km) and moved 1000 km to the East in 12 h. The gale system itself is strengthening and the change of wind speed observed at the accident location can be attributed to its eastward movement. Therefore, initially the wind speed is decaying to the east along the 31° N (28 December, 06:00 UTC) but as the gale system moves towards the east, the wind speed is increasing to the east along 31° N (29 December, 18:00 UTC); Fig. 13. When the accident occur (30 December, 06:00 UTC), the peak of the gale system reached the accident location and the highest wind speed was recorded. Evolution of the wave spectrum under such condition is not straightforward and it is likely that the wind speed, the propagation speed and the spatial scale of the gale system coincidentally matched to enhance the freakish sea state at the accident location.

6 Conclusions

The direct cause of the marine accident often remains unexplained. However, marine accidents do occur under certain sea states (e.g. Toffoli et al., 2005). As demonstrated

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in previous studies, a number of marine accidents were associated with narrowing of the directional spectrum (Tamura et al., 2009; In et al., 2009 and Waseda et al., 2012). The narrowing of the spectrum can be visualized in a diagram of the directional spreading σ_θ and frequency peakedness Q_p . Marine accidents tended to occur in the turning point of the trajectory in this domain. We called the Q_p and σ_θ diagram the freakish sea index. In this study, we have shown that the dangerous sea state can be well predicted with both DIA and SRIAM simulations. The response of the directional spectrum to changing wind condition is sensitive to the accuracy of the nonlinear interaction source term (Tamura et al., 2008). However, for operational use, still the DIA is most commonly used. Therefore, the finding that the freakish sea index is equally well predicted with DIA and SRIAM is good news for operational purpose. Of course, both are model results and ought to be validated by observation. However, the observation in this region is rather limited. The hindcast simulations of the Pacific Ocean with SRIAM and DIA were validated against available buoy observations by Tamura et al. (2010); it was shown that the energy is reproduced equally well while the peak period was better reproduced by SRIAM. Apart from such difference between models, common shortage of the models is that the directional spectrum tends to be much broader than observation (Babanin et al., 2010). Therefore, the numerous freak wave indices are quantitatively inaccurate when estimated from the wave model. What the Q_p and σ_θ diagram indicates is a much larger change of the spectral geometry as a result of meteorological forcing. On the physical aspect, the case study of the Onomichi–Maru incident revealed that a moving gale system is associated with the development of the freakish sea. While the spectral peak period remained relatively unchanged, the energy increased. As a result, the spectrum narrowed. The dynamics of such spectral development is yet to be understood and left for future study.

The wind-waves under influence of local wind is considered to be in “local equilibrium” and, as proposed by Toba (1973), satisfies the following relationship:

5 $\left(\frac{gH_s}{u_*^2}\right) = B^{1/2} \left(\frac{gT}{u_*}\right)^{3/2}$. The Toba’s 3/2 law corresponds to the fetch laws: $\left(\frac{gH_s}{u_*^2}\right) \propto \left(\frac{gF}{u_*}\right)^{1/2}$ and $\left(\frac{gH_s}{u_*^2}\right) \propto \left(\frac{gF}{u_*}\right)^{1/3}$. It is known that the observed fetch laws do not necessarily have the same exponents (e.g. Lamont-Smith and Waseda, 2009 and references therein). Recently, in the framework of weak turbulence theory, the exponents of these relationships were shown to vary depending on the regimes of the fetch-limited growth

10 (Gagnaire-Renou et al., 2011; Badulin et al., 2007). It is therefore not surprising that in an unstationary wind condition or when fetch is not well defined, the windsea does not satisfy the conventional laws. The exponent $\left(\frac{gH_s}{u_*^2}\right) = B^{1/2} \left(\frac{gT}{u_*}\right)^\alpha$ was estimated assuming constant drag coefficient 0.002 and $B = 0.062$ (Fig. 14). Apparently, the exponent α is highly variable in time and depends largely on wind speed. The exponent α has

15 increased within 12 h before the accident. The implication of this result, according to Gagnaire-Renou et al. (2011), maybe that the windsea before the accident tended to be “under-saturated”. More work is vital.

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Table 1. Summary of conditions of the Onomichi–Maru accident from the marine accident inquiry report.

The detail of the accidents				
Date	30 Dec 1980 14:30 (JST)			
Locale	156°11′ E, 31°0′ N			
The particulars of Onomichi–Maru				
Length	216.40 m			
Breadth	31.7 m			
Draft	17.3 m			
The sea states				
	Height	Period	length	Dir.(from)
Swell 1	8–9 m	12 s	150–180 m	W
Swell 2	4–6 m	12 s	225–284 m	WNW
Wind wave	4 m	8 s	no data	WSW
Wind	Lv.8 Beaufort rank ⇒ 17.2–20.7 ms ⁻¹			WSW

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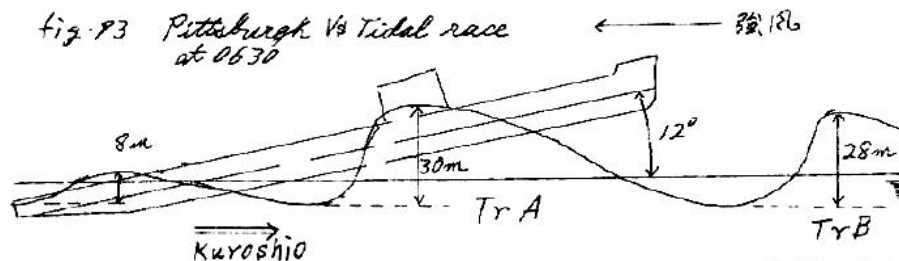


Fig. 1. A schematic of Pittsburgh encountering giant wave of 30 m (reproduced from Atsukawa, 1999).

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Fig. 2. An image of Onomichi-Maru without a bow.

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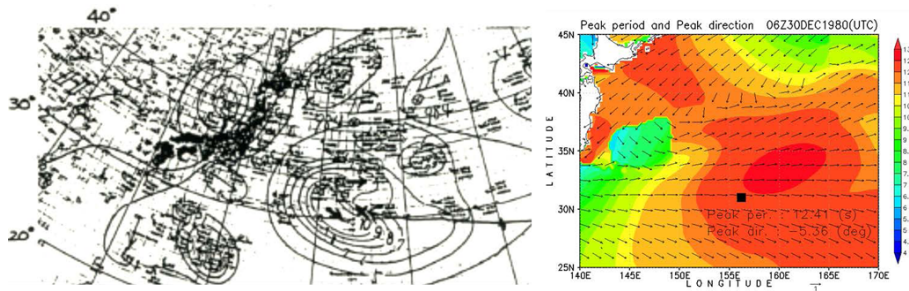


Fig. 3. The historical wave field map (contours are significant wave height, arrows indicate direction of waves, and cross marks the accident location) reproduced from Otsubo (1983) (left figure), and the peak period and direction from this simulation (right figure, colour shading is the peak period, and the arrow showing the wave propagation direction).

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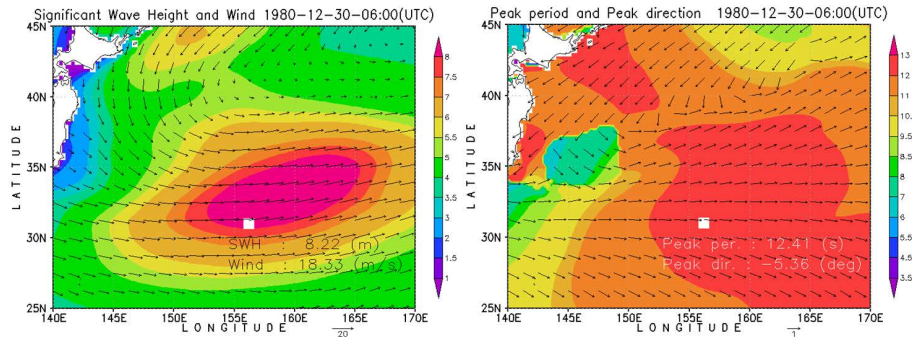


Fig. 4. (left figure) The field data of significant wave height (H_s , contour) and wind speed vector when the accident occurred. White square is the accident site. The data is from the second level field (nest2). Wind vectors are sub-sampled at every 5 grids. (right figure) The field data of peak period (contour) and peak direction (arrows) when the accident occurred. White square is the accident site.

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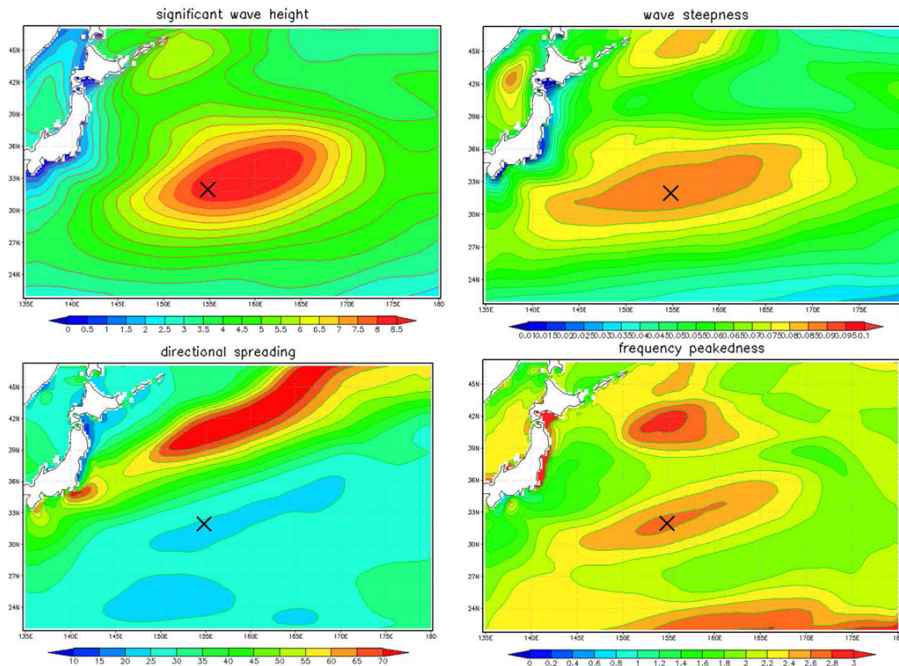


Fig. 5. Significant wave height (top left), wave steepness (top right), directional spreading (bottom left) and frequency peakedness (bottom right) at the time of the Onomichi–Maru accident (30 December 1980). The crosses denote accident location.

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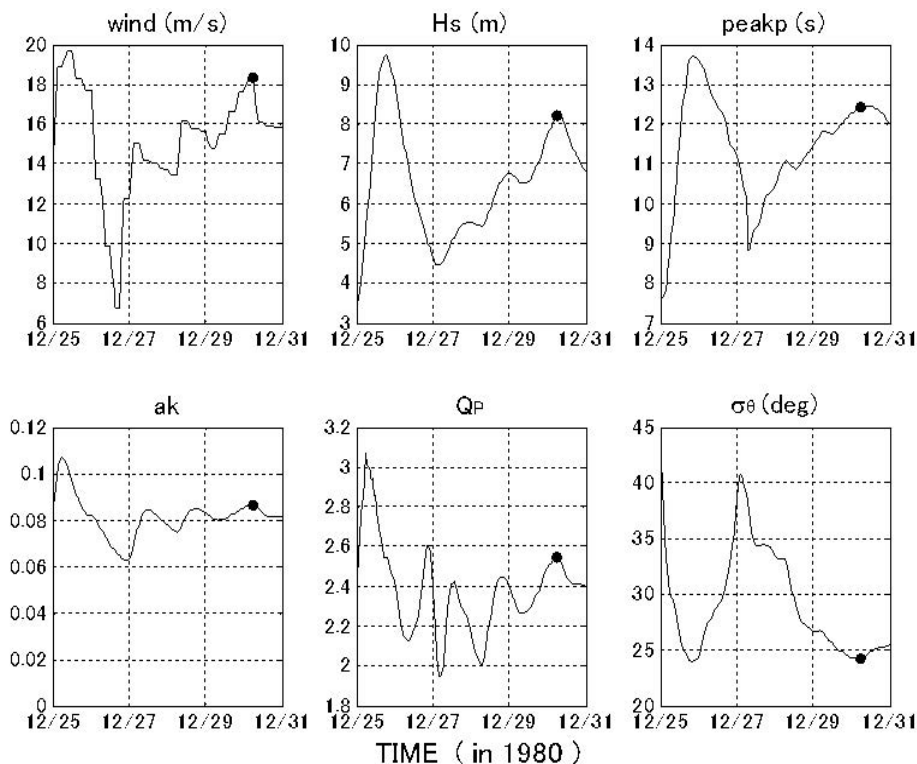


Fig. 6. Time series of sea state parameters from 25 December to 31 December in 1980 at the accident site (156.1° E, 31.0° N); wind speed, significant wave height (H_s), wave steepness (ak), peak period ($peakp$), frequency peakedness (Q_p), and directional spreading (σ_{θ}). The black dot marks the accident time.

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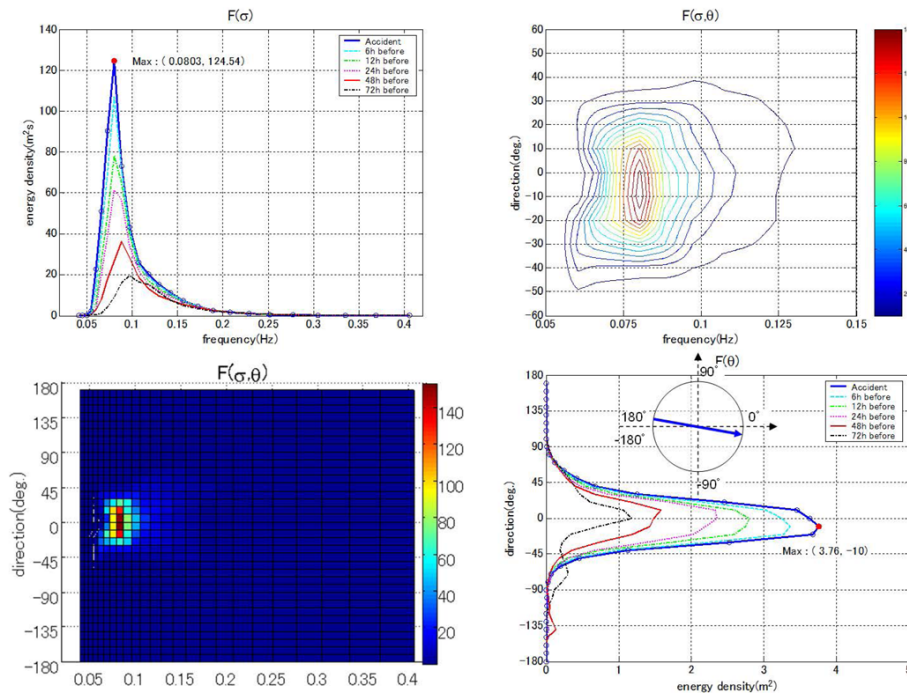


Fig. 7. Directional spectrum at the time of the accident (lower left) and the spectrum enlarged around the peak (upper right). The evolution in time of the spectrum projected on the frequency domain (upper left) and on the directional domain (lower right) are shown from 3 days before the accident to the time of the accident. The simulation was made using DIA.

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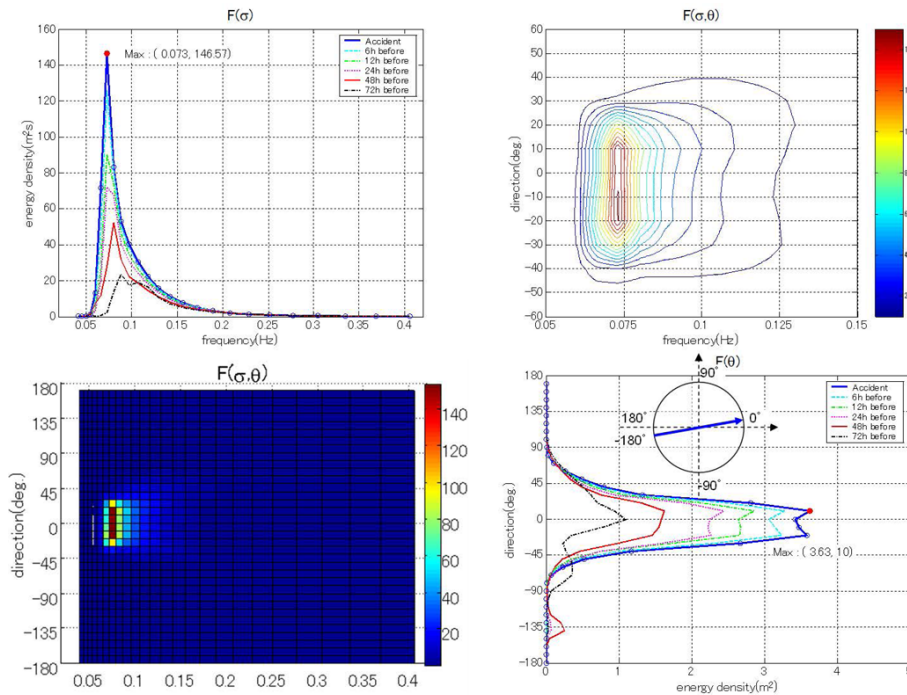


Fig. 8. Same as Fig. 7 but for the simulation made using SRIAM.

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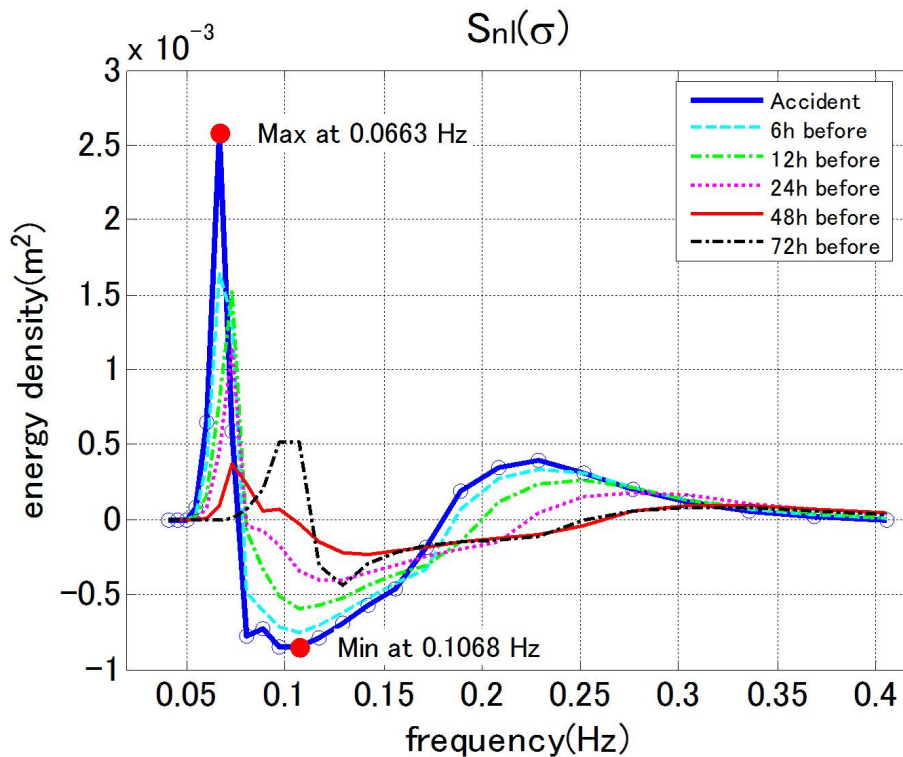


Fig. 9. The nonlinear transfer function corresponding to the SRIAM simulation result shown in Fig. 8. Shown are for 72, 48, 24, 12, 6 h before the accident and at the time of the accident.

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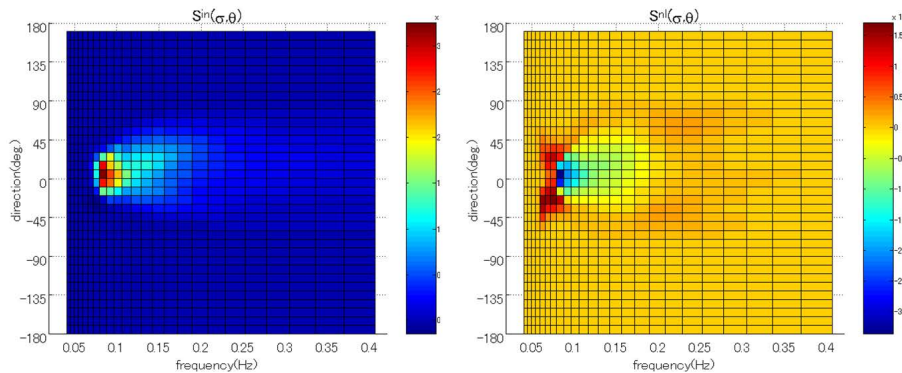


Fig. 10. The wind input source function (left) and the nonlinear transfer function of the SRIAM simulation (right) at the time of the accident.

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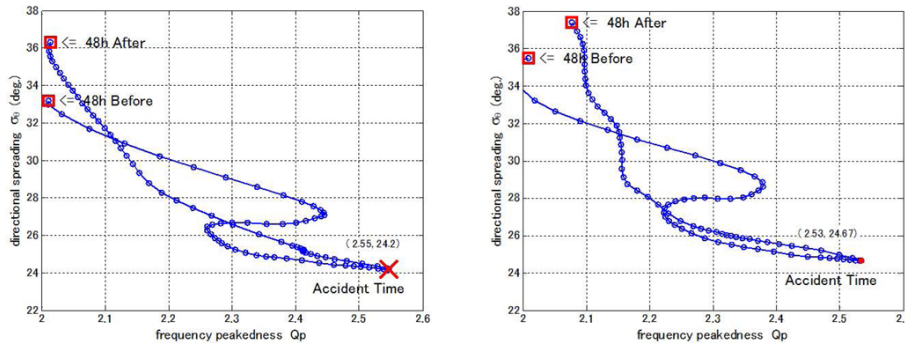


Fig. 11. 2-D scatter plot of frequency peakedness and directional spreading by 1 h interval for 48 h before and after the accident (left DIA, right SRIAM). Red cross and red point indicate the accident time.

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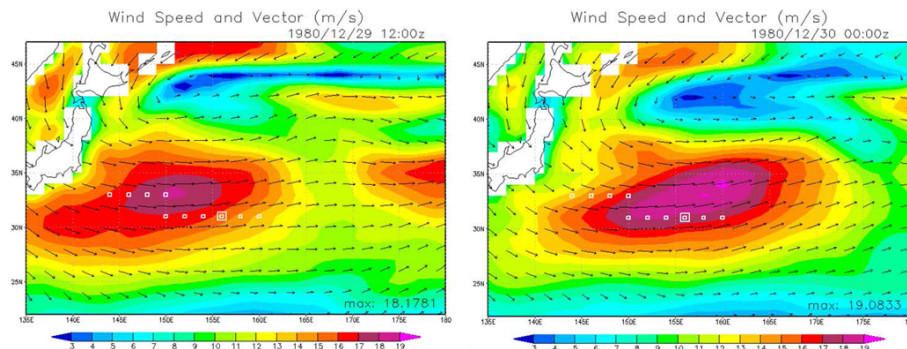


Fig. 12. Wind field evolution: 12 h before the accident (left) and at the time of the accident (right). The contour shading is the wind speed and the arrows indicate wind direction.

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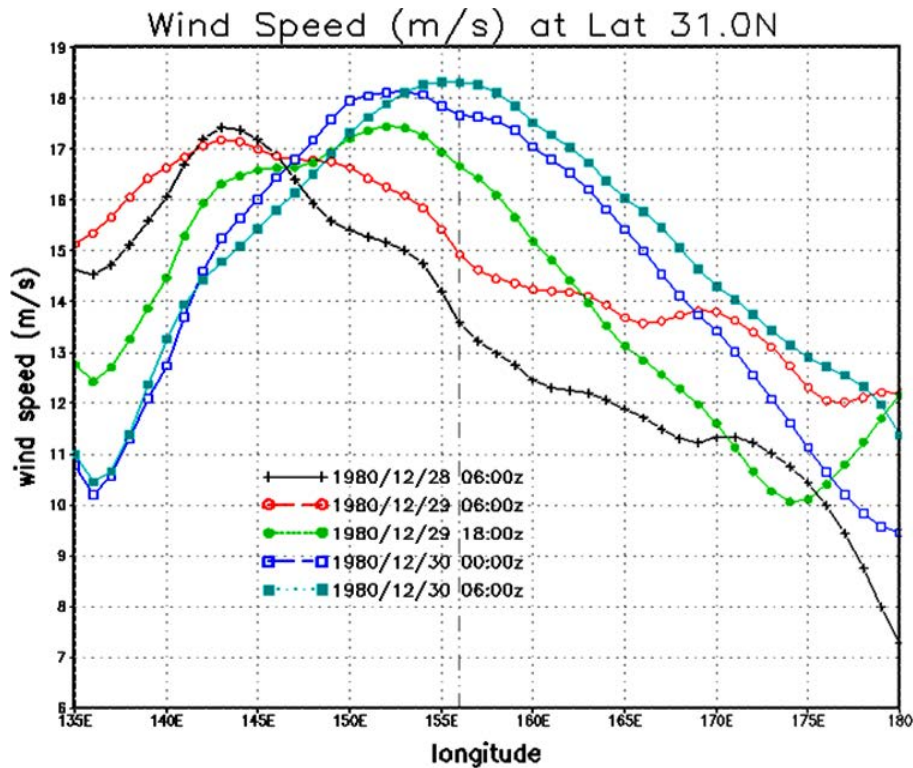


Fig. 13. Wind speed sections along 31° N from 135° E to 180° E from 28 December, 06:00 z to 30 December, 06:00 z.

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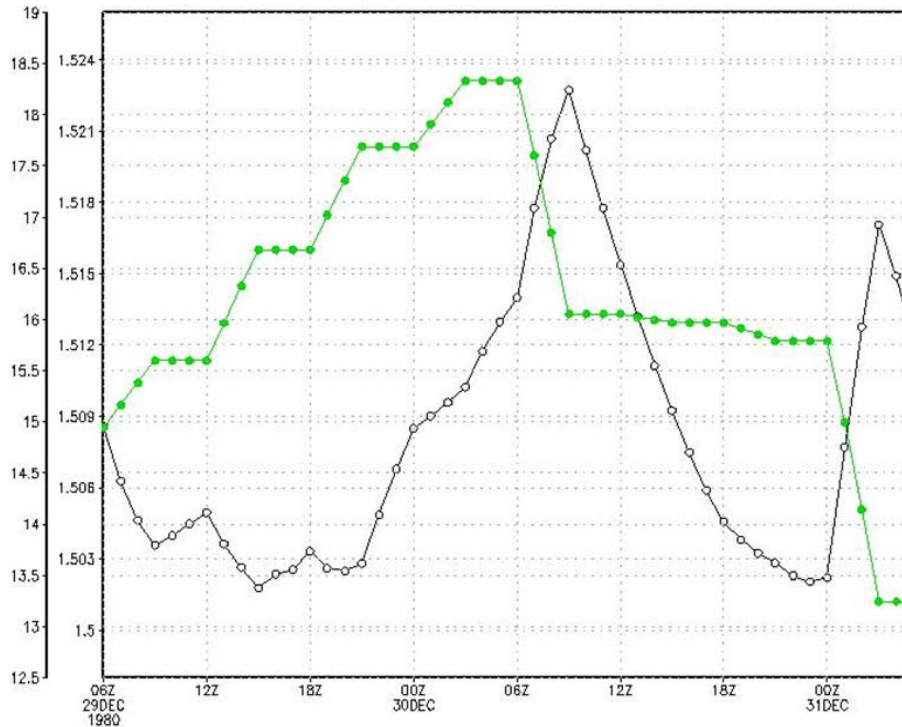


Fig. 14. Evolution of the exponent α (black line) and the wind speed (green line) 24 h before and after the accident. The horizontal axis is time in UTC and the vertical axes are the exponent α (ranging from around 1.5 to 1.525) and the wind speed (ranging from around 12.5 ms^{-1} to 19 ms^{-1}).

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