Response to reviewer comments for the NHESS-Discussions article:
Review Article: Storm Britta in 2006: offshore damage and large waves in the North Sea

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Three online reviews were submitted for the article 'Storm Britta in 2006: offshore damage and large waves in the North Sea'. All the reviews raised important points, and I appreciate the new ideas that they introduced the analysis. I address the comments below, and introduced proposed revisions for the text. I have also prepared new and updated figures on the basis of the referee comments for inclusion in the revised manuscript:

Comments by Review 1: Prof. Ove. T. Gudmestad of the University of Stavanger

Review 1: This article by Kettle fulfills the objectives:
- *To review available data and reports*
- *To present a profile of the development and progression of the events.*

It is particularly important that this information be used for:
- *Design purposes of offshore structures and dykes (almost overtopped the dykes at Delfzijl)*
- *Operations (lifeboat was thrown around).*

Prof. Gudmestad points out that the article effectively reviews the available information for the storm and summarizes the progression of events, focusing mostly on the North Sea. He highlights that the information in the manuscript is important for design purposes and operations.

I propose changes to the last paragraph of the introduction to incorporate the comments:

The aim of this contribution is to review available reports and met-ocean data that were recorded during the storm and present a profile of the development and progression of events across the North Sea on 31 October–1 November 2006. It follows recommendations within the scientific community to document unusual wave events – rogue wave encounters – to establish database for subsequent investigation (Liu, 2007; Cavaleri and Bertotti, 2008; Nikolkina and Didenkulova, 2012). The understanding of storm surges and large waves is important for the design of coastal and offshore structures and for offshore operations.

Reviewer 1: The article also warn that the highest waves (rough waves) in a sample may not be predicted by statistics. This should influence design considerations for offshore facilities. Finally, it is suggested that events like this with proper analysis will improve the weather forecasting models for future benefits.

Prof. Gudmestad points out that engineers often use statistical extrapolation techniques based on Fisher-Tippet distributions that are meant to make estimates of the occurrence of freak waves based on a large database of smaller waves or events. The technique is outlined in textbooks, and Pugh (1987) gives a clear worked example. If underlying geophysical principles of met-ocean interaction change at high wind speeds, then the mathematical extrapolation technique becomes unsafe.

There have been publications highlighting altered met-ocean interactions at high wind speeds. For the North Sea Britta storm, Pleskachevsky et al (2012) point out that there may have been a close coupling and resonance between propagating atmosphere convection cells and rogue wave groups. This undermines the Fisher-Tippett statistical approach to estimate repeat periods of high waves. There is an extensive body of research on tsunamis from seismic events (e.g., Murty (1977), and this indicates a range of wave behavior based on wavelength, water depth, and crest height. In extreme conditions the wave field can alter to give solitary waves and bore events. This also means that the statistical approach to estimate large wave return periods breaks down.

I propose small modifications the last section of the conclusion:

… A climate link with the change in regional storm incidence is unclear, but there have been other climate-related changes in northern Europe especially over the last 50 years, and extreme weather events have led to damage on elements of societal infrastructure onshore (Hanssen-Bauer, 2009; Slingo et al., 2014). The evidence of rogue waves in several instrumental records from the southern North Sea highlights issues of the geophysical data that underpin design criteria for offshore structures. In particular, the indication of resonance coupling between propagating atmospheric convection cells and rogue waves (Pleskachevsky et al., 2012) suggests that the standard statistical extrapolations to estimate the occurrence of high waves may not be adequate. Faulkner (2002) and Smith (2007) have highlighted that the design criteria for offshore structures may not be equal to the challenge of the largest waves in the ocean. The 2006 Britta storm in the North Sea underlines the problem with a number of cases of large wave damage to ships and platforms, in addition to coastal damage.

Comments by Reviewer 2:

Reviewer 2: p5496, line 27: add the Draupner wave:
T.A.A. Adcock, P.H. Taylor, S. Yan, Q.W. Ma and P.A.E.M. Janssen (2011) Did the Draupner wave occur in a crossing sea? Proceedings of Royal Society A, 467 3004-3021C1899 or/and a line 10 of page 5501

The modified sentence at p.5496, line 27 in the updated manuscript would appear as:

… The issue of rogue waves in crossing seas had been previously identified by Klinting and Sand (1987) and Sand et al. (1990) in earlier instrument recordings of rogue waves at the Danish petroleum production platform Gorm. Adcock et al. (2011) identifies this as likely candidate mechanism for a rogue wave that was observed at the North Sea Draupner platform in 1995, and presents a review of other rogue wave incidents in crossing seas.

The reference in the manuscript to the Draupner wave has also been modified at p.5501, l.10:

…The New Year's Day storm of 1 January 1995 was associated with rogue waves that were observed in the northern North Sea at the Draupner offshore platform (Haver, 2004; Adcock et al., 2011) and a large car ferry travelling from Bergen to Newcastle (Sunde, 1995)….

Section 2: No mention is made of altimeter wave heights. It would be good to know whether or not the storm was observed by the altimeters see for instance http://globwave.ifremer.fr/

This is a good point. The Esurge website (http://www.storm-surge.info/sev-data-access?sev=/sears/SEV/11) gives a list of downloadable satellite altimeter overpass data from three satellites during the two days of the Britta storm. These satellites are ERS2, Envisat, and GFO; the Jason satellite did not have data over Europe during the Britta storm. I have used the online data viewer and identified 12 altimeter overpasses that went over some part of the Britta storm area in northwest Europe (ERS2: 4 images, ENVISAT: 4 images; GFO: 4 images).

The manuscript is a review of existing information about the Britta storm, and there has been no previous investigation of altimeter-derived significant wave height. On the basis of investigations of other storm events (Cavaleri and Bertotti, 2008; Hanafin et al., 2012), satellite altimeter information is likely to have good information to characterize the surface wave field for the Britta storm. I propose a modified paragraph to the existing manuscript to highlight this extra remote sensing information:

… The storm events in the North Sea were recorded by several satellites, and the full information from the Meteosat Second Generation (MSG-1) satellite platform to track cloud and visible surface features at 15 minute resolution has not yet been fully exploited. *As well, there is also information for significant wave height from the overpasses of three satellite altimeters during the course of the storm (http://www.storm-surge.info/sears-sev-list?aoi=/sears/AOI/AOI_010) with information to supplement point measurements at different locations in the North Sea.*

In the past I have obtained data Danish data
24023 Fjaltring KDI D. West Coast 56.47N 8.06E 3h Hs, Hm, T02, Tp, Mdir*
25077 Nymindegab KDI D. West Coast 55.81N 7.94E 3h Hs, Hm, T02, Tp, Mdir*
25138 Fanø Bugt KDI D. West Coast 55.35N 8.23E 3h Hs, Hm, T02, Tp, Mdir*
It would be good to check whether not these data were ever available.

I have contacted Soeren Bjerre Knudsen of the Danish coastal authority. He sent me processed wave buoy statistics for five waveriders on the west coast of Denmark for Oct-Nov, 2006: Hirthals, Hansholm, Fjaltring, Nymindegab, and Fano Bay. The maximum significant wave heights during the Oct.31-Nov.1, 2006 were 4.4m, 5.0m, 6.0m and 4.5m for Hirthals, Hansholm, Nymindegab, Fano Bay, respectively. Fjaltring has some data for these two months, but not for the two days of the Britta storm. I have not used this data in Figure 2, partly because the Danish stations are near the coast, and they are not located along the central axis of the wind field in the North Sea. I propose to modify the first paragraph in Section 2 to incorporate the referee comments:

The progress and development of sea state was recorded as summary statistics of significant wave height (Hs) from sea surface recorders and wave buoys from the Norwegian Sea to the southern North Sea. Significant wave height information is available for a number of coastal and offshore locations from government agencies and offshore platforms in Norway, the Netherlands, Germany, Denmark, the UK, and the Faroe Islands. Fig. 2 has been compiled from Norwegian, German, and Dutch sources to give information about the development of the storm wave field along the north-south axis of the North Sea. The data for most of the Norwegian platforms is from the Eklima database (http://eklima.met.no) of the Norwegian Meteorological Institute. For the Ekofisk platform, data was digitized from the monthly met-ocean data reports (Miros, 2006ab), available from the Miros and the Norwegian Meteorological Institute, and the time series trace in Fig. 2 is the upper envelope of three independent measurements systems on the platform. Near the southern North Sea coast, the data for FINO1 is from http://www.bsh.de/en/Marine_data/Projects/FINO/index.jsp, and the significant wave height for the Schiermonnikoog buoy has been calculated from a high resolution time series released by Rijkswaterstaat (Stoker, 2014).

The map shows that the low pressure center of storm passed across the northern part of the North Sea (Lefèbvre, 2007) through a group of Norwegian offshore petroleum production platforms…

Figure 2: why no show the time series at Schiermonnikoog mb -> hPa

This is a good suggestion. I have prepared another Figure 2 with the significant wave height of Schiermonnikoog (calculated from the high resolution data) and FINO1 on the same set of axes. The significant wave heights for the two stations are similar, which is expected from their close proximity. However, there are noteworthy features in the Schiermonnikoog data that reflect the fact that it is an unaltered original recording. The corrected Figure 2 has the atmospheric pressure of the travelling storm centre in hectopascals instead of millibars.

Ekofisk has 2 curves. Can you add the reason for having 2 curves and the implication on the error bars on the measurements.

The two curves for Ekofisk correspond to the minimum and maximum envelop curves of significant wave height recorded by three independent measurement systems within the Ekofisk production complex: Datawell Waverider buoy, and laser and radar altimeters at approximately 20-24m height on different connecting bridges between the platforms (see Miros (2006a,b) and Magnusson (2008) for photos of the layout of the Ekofisk complex). The Ekofisk measuring systems and data are described in Miros 2006a,b, which are available from Miros and met.no (Norwegian meteorological office). The data in the Ekofisk panel of Fig. 2 in the manuscript have been digitized from month time series data in Miros (2006a,b) using a processing program to analyze images at the pixel level. The pixel resolution of the images corresponds to a time resolution of ~15min, which is slightly better than the time interval used in the statistical analysis of the original data. The digitized Ekofisk data is the most accurate possible data reconstruction from the image in the original pdf file.

For uncertainty, the MIROS reports give a small range of maximum values for significant wave height among the three measurement systems between 8.7-13.1m for the evening of Oct. 31, 2006 and 9.0-12.5m for the early morning Nov. 1, 2006. The upper range in each case was recorded by the laser altimeter instrument. In calm conditions, the measurement systems tend to show good agreement.

In assessing the implications of these numbers, it is important to take account of how they were recorded, processed, and filtered. The laser and radar altimeters are mounted at 20-24m height on connection bridges between platforms and could not record the highest waves that were encountered during the storm. Both systems are affected by spray production during high wind events. Magnusson (2008) shows a photograph of a large wave encounter on the measurement platform location that illustrates the problem. Partly for these reasons, that raw wave height measurements at Ekofisk are subjected to a cleaning or filtering procedure. The data selection criteria and re-interpolation are not given, but they might be similar to the CEFAS procedure given at https://www.cefas.co.uk/cefas-data-hub/wavenet/qaqc-procedure/. The data cleaning procedure may remove quite a lot of points during the height of the storm. For example, the Miros report indicates that the Ekofisk waverider buoy had an almost 100% data capture rate raw data for October, but that the capture rate of approved data was 90.8%. In particular, there was a problem in the approved data during the two days of the storm. In this situation, it is better to trust the high range of reported significant wave heights. Media reports from Nov. 1, 2006 indicate that significant wave heights at Ekofisk were on the order of 12m. There was some damage on the decks of some platforms above 20m and this gives an indication of the highest waves.

For the amended manuscript, I propose to use only the upper envelope of significant wave height from Miros monthly data reports in the new version of Figure 2. The opening paragraph of Section 2 will be modified to give more information about the significant wave height in the surrounding panels (see above). The acknowledgements section will be modified to make reference to this online discussion.

for info: in the past I have also found the following sources of data quite useful (but not in Britta's case) the UK buoys ans platforms https://www.cefas.co.uk/publications-data/wavenet/ the Faroes: http://lv.fo/database

I have looked carefully at the CEFAS Wavenet network. Most of the waverider buoys on the East coast of the UK were placed after 2006. I have downloaded data for three Waverider buoys that were in operation during the Britta storm: Dowsing, Northwell, and West Gabbard. Of these, Dowsing has the most exposed northward exposure and showed significant wave heights up to 5m. I have not modified Figure 2 with extra panels to incorporate these UK waveriders. The main message of the figure is to show the development of the wave field through the middle of the North Sea.

I have contacted Bardur Niclasen at the University of Faroe Islands about the Waverider buoys around the Faroe Islands (identified at north, west, east, and south). He sent me processed wave parameters from the Faroe Islands instruments. I am still looking through this information, but the initial analysis shows that the patterns in Figure 2 are not changed by the Faroe Island data. There are unexpected challenges in working with this data (some instrument failures, nonstandard moorings with rigid lines instead of rubber cords, and very strong tidal currents). These are outlined in Niclasen and Simonsen (2007).

Comments by Reviewer 3

I am not used to review papers for NHESS and to write on this journal, so I lack the sensitivity to judge a proposed paper for it. So I will provide a general comment, a recommendation and let the editor judge for it. However, I wish to point out that some basic physical principles of the matter discussed should be taken into consideration, and this does not seem to be the case in this paper. Britta was certainly a remarkable storm, and a number of papers have been written about it. In practice the present paper is a short summary of the event, the reported damages, some (certainly remarkable, but debatable) measured data here reported without a criticism, a mention of the papers where the meteorological and oceanographic aspects have been analysed.

The referee summarizes the present review paper for consideration of publication in NHESS. The manuscript summarizes the Britta storm, bringing together available information to get a spatial and temporal overview of events. The referee feels that at a number of papers have been written about it. Actually, aside from a few reports by government meteorological and hydrological agencies that were written soon after the storm, there has been only one publication that focuses specifically on the Britta storm (Pleskachevsky et al, 2012). Only a portion of the available geophysical has been presented, and a complete listing of ship and platform damage has not appeared.

While for someone not in the field the whole looks impressive, for a professional reader of the field the natural comment is "so what? Thanks for the summary, but which is the information? All this was already known. Everything is simply mentioned, not discussed".

The importance of review summaries for storm and rogue waves has been highlighted in the NHESS articles by Didenkulova et al. (2006) and Nikolkina and Didenkulova (2011). Both articles assemble lists of rogue wave events from media sources that are difficult to locate. The final publications are well-regarded by the scientific community because to the density of information and emerging patterns. The present manuscript under review for NHESS follows the same pattern of bringing together information about the Britta storm to reveal the larger pattern of events.

Then, while looking at Figure 5 the first commet is "Wow!", this stops when reading the caption. If I am reading correctly, we are told that in 20 m depth (see caption) they recorded a >40 m high wave with a 20 m trough. Please note that this should have exposed the bare bottom. This requires some physical explanation. Panel b, a different episode, indicates a -22 m trough. I assume that in panels a and b the horizontal dotted line shows the bottom line. Does not this ring a bell? Similarly we are told (panel c) that in 30 m depth we had a group with a likely amplitude (not height) of 25 m, two consecutive waves exceeded 40 m height, with possible troughs at -25. I am not discussing here how these data were recorded (I do not have the material at hand), but I do not see how they can be physically true. In any case it is not acceptable to report data, although by other persons, that look absurd without a correspondingly suitable discussion and explanation. Therefore, mainly for this, but also for the lack of good and new information, I do not consider this paper suitable for publication.

The referee questions the quality of the instrument recording of the rogue wave events in Figure 5, based mainly the fact the height of the rogue waves is comparable with the water depth at the two sites. These data have been digitized and/or replotted from their original sources. Both rogue wave events have re-appeared multiple times in the scientific literature and online publications. The scientists who show the data usually comment on the remarkable size of the waves. Different lines of evidence support the recordings in Figure 5:

1. The reported ship and platform damage are consistent with the wave recordings. The cargo ship *Cementina* and rescue boat *Anna Margaretha* experienced rogue wave emergencies in the vicinity of Schiermonnikoog buoy during separate events. The recording shown in Figure 5a corresponds to the rogue wave that struck the *Cementina* from the north as the ship going to the east. This wave impact caused a large sideways roll, broke bridge windows, disabled the rudder (unclear if due to contact with the sea floor, which is normally at 20m at this site), and also disabled the anchor winch. A hole above the water line discovered during a ship survey the following day, but the survey report does not specify which side of the ship was damaged. The recording shown in Figure 5b corresponds to a three rogue wave group that capsized the *Anna Margaretha* rescue boat three times. Accounts of the event (Brinkman, 2007) are unclear if the boat made contact with the sea floor, but the radio aerials and searchlight were torn off the top of the boat. The recording shown in Figure 5c corresponds to a rogue wave event at the FINO1 platform that caused hand rail damage, broke instrument cables, and compressed a steel ladder up to the main deck at 20m. Neumann and Nolopp (2007) show a photo of this damage and comment on its significance. The physical damage is consistent with the wave heights shown in the digital recordings.
2. The wave recordings in Figure 5 were made with special Datawell Waverider buoys. The Datawell company developed the Waverider in the late 1960s, and the devices are considered an industry standard (Joosten, 2013). It is designed for North Atlantic winter deployments in coastal areas. The Waverider works by making fast recordings of acceleration and performing a double time-integration to give instantaneous wave height. The instrument flags bad data where the accelerations are too fast, for example from ship impact or unusual geophysical phenomena. The accelerations for the waves in Figure 5 are within the instrument safe limits, and are just very large. Because of the reputation of the Datawell Waverider, experienced scientists have been able to place their name behind these wave height recordings: Wolfgang Rosenthal, Susanne Lehner, as well as the Dutch team of Burgers et al. (2008).
3. One week after the Britta storm 2006, a fishing vessel *Hohe Weg* sank near the Alte Weser lighthouse in the Elbe estuary. When the wreck was discovered and raised, the bridge windows were broken and the evidence that the accident was caused by a very large wave. Different accident scenarios were explored, but all had the boat pinned to the sea floor in the bottom of a wave trough before being hit by following waves (BSU, 2008; see also Smith, 2007). The issue was discussed along with other severe storms in the winter of 2006-2007 during a review meeting of the German offshore wind energy community in Feb., 2007 (Lehner, 2007).
4. There is an extensive body of research based on tsunamis that waves can exhibit a range of behaviors based on wavelength, water depth, and crest height (Murty, 1977). Depending on conditions, the statistical wave field in deeper water can be transformed into solitary waves and bores. Murty (1977) presents a comprehensive overview of the subject, focusing on seismic sea waves, but describing laboratory and theoretical analysis of waves in general, including meteo-tsunamis. His review indicates that the large wave recordings in Figure 5 are within the range of current understanding of ocean wave phenomena. His analysis is valuable because is highlights the different ways that rogue waves in shallow water must be treated.

I propose modifications to the paragraph for background description of Figure 5:

The profiles of the rogue waves that caused platform and shipping damage near the North Sea coast were captured by two Waverider buoys at the Schiermonnikoog Nord and FINO1 sites (Fig. 5). The waverider instruments are produced by the Netherlands Datawell company with over 50 years of experience in the design of wave instruments for all-season North Sea deployments (Joosten, 2013), and the measuring buoys are considered an industry standard. The Schiermonnikoog buoy recorded two large wave groups separated by several hours. The buoy was located close to the two-ship emergency that is described in Brinkman (2007). The wave in Fig. 5a is close in time to first wave strike on the cement carrier *Cementina*, which broke bridge windows, disabled steering gear, and a caused a heavy roll. The wave group in Fig. 5b is close in time to the triple capsize of the Dutch rescue boat *Anna Margaretha*. Nearby gas production platforms were also damaged by waves during the early morning of Nov. 1, 2006, although the precise times are not known (Van Vliet, 2014). The physical profile of the wave that probably damaged the FINO1 platform has been shown in several sources (Herklotz, 2007; Hessner and Reichert, 2007; Pleskachevsky et al., 2012), and Fig.5c has been digitized from Pleskachevsky et al. (2012). The figure indicates that the maximum trough to peak wave height went off the instrument measuring scale for radio-transmitted data and exceeded a peak-to-trough height of 40m. However, the recorded accelerations during this time interval did not exceed the instrument limits, and the depicted wave group is considered a reliable portrayal of geophysical events (Pleskachevsky et al., 2012). For both the Schiermonnikoog and FINO1 sites, it is striking that the amplitude of the rogue waves is so large compared with the water depth. There are possible implications for ship damage in such cases, as pointed out by Pellika et al. (2014) in a discussion of Baltic Sea meteo-tsunamis. One week after Britta storm, the fishing vessel *Hohe Weg* sank at a nearby location near the Alte Weser lighthouse in a rogue wave incident (Smith, 2007), and it is thought that the boat was momentarily pinned on the sea bottom before having its bridge windows broken by a wave impact (BSU, 2008). The traces in Fig. 5 give insight into a dangerous storm-related phenomenon in the southern North Sea that is known locally as "ground sea".

There are open geophysical questions how to interpret and predict the frequency of such rogue wave events. The events recorded by the two Waveriders at FINO1 and Schiermonnikoog Nord were not from the same rogue wave groups, and the three rogue groups are distinct from one another. It is not clear how these waves may be linked with wave damage events that took place earlier in the northern and central North Sea. The review of Niclasen et al. (2010) clarifies that the simulation of such rogue wave events cannot be achieved with present wave forecasting models, and Murty (1977) places the observations within the range of the geophysical wave phenomena known as a bores, which are more akin to tsunamis coastal breakers, and beach run-up events. Pleskachevsky et al. (2012) highlights that such rogue wave structures are likely built up through close coupling with atmospheric convective systems that were passing across the North Sea; a type of resonance effect.

I proposed the following revised the Acknowledgements section for more information about the contributors and background information on the analysis:

Acknowledgements. I appreciate the information supplied by Gerda van Vliet of the Koninklijke Nederlandse Redding Maatschappij (KNRM); the results of an enquiry from 2006–2007 into the circumstances surrounding the triple capsize of a Dutch motor lifeboat Anna Margaretha on 1 November 2006. Stein Solberg (Chief Operations, JRCC Southern Norway, Stavanger, JRCC Stavanger) provided a list of air-rescue call-outs for the southern Norway district during the storm. Samuel J. Arnoldson of Thor Ltd. provided a copy of the accident report events surrounding the wave impact on the Thor Sentry. Konrad Ehrhardt (Head of Maritime Emergency Reporting and Assessment Centre, Central Command for Maritime Emergencies, Cuxhaven, Germany) sent press releases surrounding the rogue wave events on the Cementina and Anna Margaretha and rescue operations. Knut Iden of the Norwegian Meteorological Institute (DNMI) sent information about the Eklima archives of meteorological data from the Norwegian offshore production platforms, and also Miros monthly reports of Ekofisk met-ocean conditions. Erik Stoker of the Netherlands Datawell company sent raw data from Schiermonnikoog waverider buoy for the two days of the Britta storm (by permission of Rijkswaterstaat) and background information how to interpret it. Interested readers are referred to the NHESS online review discussions for more background on the analysis for this report. This work has been partially funded by the Norwegian Centre for Offshore the Wind Energy (NORCOWE) under Grant 193821/S60 from the Research Council of Norway (RCN).

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