Nat. Hazards Earth Syst. Sci. Discuss., 3, 5493–5510, 2015
www.nat-hazards-earth-syst-sci-discuss.net/3/5493/2015/
doi:10.5194/nhessd-3-5493-2015

Natural Hazards and Earth System Sciences Discussions
Open Access

Review Article: Storm Britta in 2006: offshore damage and large waves in the North Sea

A. J. Kettle

Geophysical Institute, University of Bergen, P.O. Box 7803, Bergen, Norway

Received: 3 July 2015 – Accepted: 6 August 2015 – Published: 8 September 2015

Correspondence to: A. J. Kettle (ake043@gfi.uib.no)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Storm Britta in 2006: offshore damage and large waves in the North Sea

A. J. Kettle

Abstract

The Britta storm of 31 October–1 November 2006 was a severe autumn storm that was particularly damaging for shipping and coastal flooding from storm surge effects along the southern North Sea. The main low pressure of the storm propagated from Scotland to southern Norway on 31 October, leading to a system of strong north winds that moved southward across North Sea over an 18 h period. A progression of ship and offshore platform difficulties were registered from the northern part of the North Sea from late on 31 October and culminated near the coasts of Germany and the Netherlands early on 1 November with a series of ship emergencies linked with large waves. In two separate incidents, unusually high waves broke the bridge windows of ships and necessitated emergency rescues, and a Dutch motor lifeboat experienced a triple capsize. In the southern North Sea, several gas production and research platforms experienced wave impact damage. The FINO1 offshore research platform, near the Dutch–German border, experienced some of the worst storm conditions with some structural damage. Its meteorological and oceanographic instrumentation give a unique profile of the severe met-ocean conditions during the storm. Two Waverider buoys at FINO1 and the nearby Dutch coastal site of Schiermonnikoog recorded groups of large waves at different times during the storm. These reports give insight into a little-reported rogue wave phenomenon that sometimes accompanies the "ground sea" conditions of the worst storms of the area.

1 Introduction

The Britta storm of 31 October–1 November 2006 was particularly serious for offshore infrastructure and shipping in northern Europe. The autumn storm was characterized by a deep low pressure center that moved on a trajectory from north of Scotland to western Norway and then eastward through the Baltic Sea north of eastern Germany and Poland. Most of the damage in the North Sea and Baltic Sea was associated with strong north winds behind the propagating low pressure center. Severe flooding damage occurred in the Inner Danish Waters in the Baltic Sea outflow as the result of the meeting of wind-forced storm surges that pushed southward along the Kattegat and Baltic Sea. Storm surge damage also occurred in the southern North Sea and was particularly serious at the Netherlands city of Delfzijl near the Dutch–German border where coastal dykes were almost overtopped. Flooding occurred along the coast of the Netherlands and the center of Hamburg was flooded. In Denmark and certain sections of the North Sea coast of the Netherlands and Germany storm-surge sea levels were described as a 100-year event (Jorissen, 2006; Madsen et al., 2007; Woge Nielsen and Huess, 2008), and in some areas the water levels were the highest that had been recorded since the start of instrumental records in the 1800s. In addition to the storm surge, there were reports of unusually high waves both in the southern and northern North Sea. Wave measurements from satellites and offshore platforms show how the high wave field developed first in the northern North Sea and propagated southward under the influence of strong north winds with a long fetch.

There were a number of weather-related ship and platform incidents from the North Sea, which were in some cases associated with call-outs of emergency services. Figure 1 shows the locations reported marine damage and incidents during the storm and has been compiled from a number of sources (Lloyds Casualty Week, 2006; Cargolaw, 2006; Brinkman, 2007; Nikolkina and Didenkulova, 2012; Arnoldson, 2014; Van Vliet, 2014; Solberg, 2014) as well as newspaper reports. Many of these reports explicitly cite the occurrence of damage caused by very high waves occurring singly or in small groups – rogues. In addition to visual sightings, some of the extreme waves were also digitally recorded by national measurement networks that have been established for storm monitoring and damage assessment purposes. Descriptions of the met-ocean conditions during the storm were issued by the national meteorological and hydrographic agencies in the Netherlands (Jorissen, 2006; RWS-RIKZ, 2006; Zijderveld et al., 2007), Germany (Lefebvre, 2007), and Denmark (Woge Nielsen and Huess, 2008). The Netherlands national lifeboat institution (KNRM) published an

NHESSD
3, 5493–5510, 2015

account of the triple capsize of a rescue lifeboat in rogue waves near the Dutch coast that includes details of offshore events during the course of the storm (Brinkman, 2007).

In spite of the extent of the storm-related damage, there have been relatively few formal post-analysis reports about the Britta storm, and only a portion of the available met-ocean data has been collated to give a detailed overview of events during the storm. Burgers et al. (2008) cite the rogue wave events recorded by the Schiermonnikoog buoy as part of a larger investigation to assess model predictions of extreme wave height at different locations in the North Sea. The publication highlights the issue that instrumental recordings of ocean sea state are typically reported with the statistical summary parameter, significant wave height, and this imperfectly characterizes the highest (and most damaging) waves. Behrens and Günther (2009) present an overview of the characteristics of different types of severe winter storms that have impacted northern Europe in the recent period since 1999. They use Britta as the type specimen for a category of storms that move on a northern track across southern Scandinavia and cause severe maritime damage in the North Sea. This report emphasizes the wave damage to FINO1, a special highly instrumented offshore tower that was constructed to support the development of offshore wind energy in Germany. The issue is further elaborated by Emeis and Türk (2009) who clarify that winter storms passing eastward across the northern sections of the North Sea are particularly serious for marine infrastructure because the associated north winds have a long uninterrupted fetch that causes a high, well-developed wave field. They highlight that crossing seas associated with the swing of wind direction behind an eastward propagating low pressure centre may contribute to rogue wave formation, and this was supported in an investigation of the wave radar data by Hessner and Reichert (2007). 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.

Some remote sensing investigations have been carried out by the German space agency (DLR) focusing on the conditions during the Britta storm that led to damage on the FINO1 research platform. Brusch et al. (2008) highlight how satellite radar and visible images can be used synergistically to give insight into the structure of the atmosphere over the North Sea during overflight snapshots during the times of the strongest winds. A key result from this study is the description of southward-propagating convection cells across the North Sea, with convective cloud bands linked to surface roughness and swell features. Pleskachevsky et al. (2012) have expanded the satellite findings with model results that show how wind gusts with the propagating cloud convection cell augment the surface wave field with a resonant effect that could lead to the type of rogue wave events that were recorded at FINO1. The report emphasizes the serious nature of the event and questions the earlier analysis of Fischer et al. (2010). A number of coastal studies have developed modelling tools to characterize sedimentation dynamics in the German Wadden Sea. The Britta storm has been given particular attention for the types of changes that may occur in a single high-energy event (Bartholomä et al., 2009; Lettmann et al., 2009; Stanev et al., 2009; Grashorn et al., 2013), and there are possible implications about how the protective outer islands of the Waddensee would respond to future storms.

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; Bertotti and Cavaleri, 2008; Nikolkina and Didenkulova, 2012).

2 Development and propagation of the wave field across the North Sea

The progress and development of sea state was recorded as summary statistics of significant wave height (Hs) from sea surface recorders from offshore platforms and wave buoys from the Norwegian Sea to the southern North Sea (Fig. 2; compiled from http://eklima.met.no; http://www.bsh.de/en/Marine_data/Projects/FINO/index.jsp;

NHESSD
3, 5493–5510, 2015

Miros, 2006a, b). These give information about the development of the storm wave field in space and time. 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. The worst wave conditions in the northern North Sea took place when the low pressure center was moving between western Norway (12:00 UTC 31 October 2006) and the Skagerrak (18:00 UTC 31 October, 2006). The Norwegian production platforms in the Norwegian Sea at the north edge of the map were mostly not affected by the severe conditions that developed further south. Gullfaks in the northern North Sea is the first platform to experience large Hs with peak values at approximately 18:00 UTC on 31 October 2006. The region of high Hs passed by the line of the Norwegian offshore platforms Troll A–Heimdal–Sleipner–Ekofisk in sequence, and the maximum Hs was recorded at the coastal sites of Schiermonnikoog and FINO1 at between 04:00 and 04:30 UTC 1 November 2006. Ekofisk recorded the largest significant wave heights among the group of Norwegian production platforms, and the Valhall production platform nearby reported wave damage to its lifeboats. One of the three independent wave measuring systems on the Ekofisk production complex showed maximum wave heights reaching 22 m above mean sea level. The sensors indicated data quality issues in the sea level records at the time (Miros, 2006a, b), but this is not unexpected, and both Waverider buoys and radar instruments have difficulties at extreme sea states (Klinting and Sand, 1987; Baschek and Imai, 2011).

The Quikscat sun-synchronous satellite flew over the North Sea area twice in the early evening of 31 October and twice in the early morning of 1 November 2006, and this provides areal snapshots of the wind speed fields at 12.5 km resolution that are shown in Fig. 3 (see also Bancroft, 2007). The images strikingly illustrate how the wind storm propagated from the northern to southern North Sea over a 12 h period. The information shows broad agreement with the ship damage reports (Fig. 1) with most of the damage from the northern North Sea recorded on late 31 October 2006 and marine events near the Dutch and German North Sea coast following in the morning of 1 November. More detailed analysis of remote sensing information from other satellite platforms is presented in Brusch et al. (2008) and Pleskachevsky et al. (2012). 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 min resolution has not yet been fully exploited.

3 Instrumental Records: FINO 1 Research Tower and Waverider Buoys

The center of the wind storm moving southward across the North Sea passed close to the location of the FINO1 offshore meteorological tower near Borkum during the pre-dawn period of 1 November 2006. The met-ocean conditions were recorded by a suite of meteorological and oceanographic sensors. Figure 4 shows a subset of the most important storm-related geophysical parameters from this record over a 48 h period from the start of 31 October. The 10 min average wind speed (Fig. 4a) reached 32 $m\,s^{-1}$ (hurricane threshold) at the height of the storm, and wind speed gusts reached 40 $m\,s^{-1}$ in the original 1 Hz record. The atmospheric pressure record (Fig. 4b) showed one minimum in the early afternoon of 31 October and a second minimum value just after midnight on 1 November. These atmospheric pressure dips correspond to high water levels (Fig. 4c) for the ~ 12 h high tides and the coincident peak in the local storm surge in the early hours of 1 November. The significant wave height (Fig. 4d) approached 10 m at the time of the maximum storm surge.

The rogue wave event (described below) occurred at the same time, and broke the communications cables for the oceanographic instrumentation suspended below the main deck of the platform: water temperature and salinity (Fig. 4e) and also dissolved oxygen (Fig. 4f). The last records for these sensors give indications of how the bulk sea water properties were responding to the atmospheric forcing. Seawater temperature was decreasing rapidly from the cold air outbreak from the north. Salinity was increasing, and this may have been an advective effect from the powerful ocean currents generated during the storm, but it may have been partially due to enhanced sea spray evaporation previously described for another North Atlantic storm (Kettle and

NHESSD
3, 5493–5510, 2015

Turner, 2007). Oxygen supersaturation at 6 m reached levels over 60 %. While typical near surface oxygen saturations of a few percent are normal from a bubble injection process, a 60 % supersaturation (if accurate) would indicate a large entrainment of air bubbles at deep levels into the water column corresponding to an average excess pressure of ~ 0.6 atmospheres or ~ 6 m depth. The oxygen sensor at 25 m depth shows a normal expected value of 100 % saturation.

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 Schiermonnikoog buoy recorded two large wave groups separated by several hours (Stoker, 2014), and was linked with a serious two-ship emergency (Brinkman, 2007) and well as damage nearby production platforms (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 and exceeded 40 m. 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). 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 Waverider data gives a remarkable view of a storm-related phenomon known locally as “ground sea”.

4 Conclusions

The Britta storm of 31 October–1 November 2006 caused serious damage in the North Sea region, and was notable for the unusual incidence of very large coastal waves that were digitally recorded by coastal monitoring networks. A review of evidence indicates that this has been one of a similar series of powerful storms in the North Sea region since 1995. Behrens and Günther (2009) indicate that the decade starting from 1999 was particularly notable for severe winter storms in northern Europe, with a series of 10 storms in the North and Baltic Sea area that reached hurricane force. For maritime damage in the North Sea, certain years stand out with particularly severe autumn and winter storm events with reports in the popular and scientific press: 1995, 1999, 2006, 2007, and 2013. 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) and a large car ferry travelling from Bergen to Newcastle (Sunde, 1995). In the southern North Sea, a cargo ship sank (Sunde, 1995) and a German rescue cutter lost crewmembers overboard (Rosenthal and Lehner, 2007). For North Sea wind energy infrastructure, Storm Anatol on 3 December 1999 was noteworthy for unusually high waves that damaged the Horns Rev offshore meteorological mast in its first year of operation (Neckelmann and Petersen, 2000). After the Britta Storm, the FINO1 platform was damaged again by large waves during Storm Tilo on 9 November 2007 (Outzen et al., 2008) and Storm Xaver on 6 December 2013 (FINO1, 2014). 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 shipping and offshore petroleum and wind energy infrastructure (Faulkner, 2002).

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. 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).

References

Arnoldson, S. J.: HSEQ of Thor Ltd, Faroe Islands, email communication of damage report of Thor Sentry, 23 July 2014.

Bancroft, G. P.: Marine Weather Review–North Atlantic Area, September through December 2006, Mariners Weather Log, 51, no. 1, 2007.

Bartholomä, A., Kubicki, A., Badewien, T. H., and Flemming, B. W.: Suspended sediment transport in the German Wadden Sea – seasonal variations and extreme events, Ocean Dynam., 59, 213–225, doi:10.1007/s10236-009-0193-6, 2009.

Baschek, B. and Imai, J.: Rogue wave observations off the US West Coast, Oceanography, 24, 158–165, doi:10.5670/oceanog.2011.35, 2011.

Behrens, A. and Günther, H.: Operational wave prediction of extreme of extreme storms in Northern Europe, Nat. Hazards, 49, 387–399, 2009.

Bertotti, L. and Cavaleri, L.: The predictability of the "Voyager" accident, Nat. Hazards Earth Syst. Sci., 8, 533–537, doi:10.5194/nhess-8-533-2008, 2008.

Brinkman, K.: Capsize and survival, Report on lifeboat Anna Margaretha's capsizes, 1 November 2006, Koninklijke Nederlandse Redding Maatschappij (KNRM), 2007.

Brusch, S., Lehner, S., and Schulz-Stellenfleth, J.: Synergistic use of radar and optical satellite images to support severe storm prediction for offshore wind farming, IEEE J. Sel. Top. Appl., 1, 57–66, 2008.

Burgers, G., Koek, F., de Vries, H., and Stam, M.: Searching for factors that limit observed extreme maximum wave height distributions in the North Sea, in: Extreme Ocean Waves, edited by: Pelinovsky, E. and Kharif, C., Springer Netherlands, 127–138, 2008.

Cargolaw: http://www.cargolaw.com/presentation_casualties.06.html, last access: July 2014.
Emeis, S. and Türk, M.: Wave-driven heights in the German Bight, Ocean Dyn., 59, 463– 475, 2009.
Faulkner, D.: Shipping safety. A Matter of Concern, Ingenia (Marine Matters), Royal Academy of Engineering, London, 13, 13–20, 2002.
FINO1: http://www.fino1.de/meldungen/alle-meldungen/, last access: 22 August, 2015.
Fischer, J., Herklotz, K., Senet, C., Outzen, O., and Hahn, R.: Oceanographic observation at FINO-1 and the offshore windfarm "alpha ventus", Proc. German Wind Energy Conference DEWEK, Bremen, 2010.
Grashorn, S., Lettmann, K. A., Wolff, J.-O., Badewien, T. H., and Stanev, E.: East-Frisian Wadden Sea hydrodynamics and wave propagation in an unstructured grid model, Ocean Dynam., 65, 419–434, doi:10.1007/s10236-014-0807-5, 2015.
Hanssen-Bauer, I.: Klima i Norge 2100, Bakgrunnsmateriale til NOU Klimatilpasning, Norsk klimasenter, October 2009. (in Norwegian)
Haver, S.: A possible freak wave event measured at the Draupner jacket 1 January 1995, in: Proceedings, Rogue Waves 2004, edited by: Olagnon, M. and Previsto, M., Brest, France, 20–22 October 2004.
Herklotz, K.: FINO Sea state measurements at FINO1, in: 52nd IEA Topical Expert Meeting. Wind and Wave Measurements at Offshore Locations, Berlin, Germany, 20–21 February 2007, organized by TU Berlin and Germanischer Lloyd, edited by: Thor, S.-E., Vattenfall, 2007.
Hessner, K. and Reichert, K.: Sea surface elevation maps obtained with a nautical X-band radar – Examples from WaMoS II stations, 10th International Workshop on Wave Hindcasting and Forecasting and Coastal Hazard Symposium, North Shore, Oahu, Hawaii, 11–16 November 2007.
Jorissen, R. E.: Verslag van de stormvloed van 31 oktober en 1 november 2006 (SR84) Allerheiligenvloed 2006, Rikswaterstaat, RIKZ, 's-Gravenhage, November 2006, available at: http://repository.tudelft.nl/view/hydro/uuid3A56cbe951-8b26-4a0b-8816-a44a41e44994/, last access: 22 August 2015, 2006 (in Dutch).
Kettle, A. J. and Turner, S.: Upper ocean response to a summer gale south of Iceland: importance of sea spray in the heat and freshwater budget of storms, J. Geophys. Res., 112, C08011, doi:10.1029/2006JC004011, 2007.

NHESSD
3, 5493–5510, 2015

Storm Britta in 2006: offshore damage and large waves in the North Sea

A. J. Kettle

Klinting, P. and Sand, S.: Analysis of prototype freak wave, in Coastal Hydrodynamics, Proceedings of a conference sponsored by the waterway, port, coastal and ocean division of the American Society of Engineers, University of Delaware, Newark, Delaware, 28 June–1 July 1987, edited by: Dalrymple, R. A., ASCE, 618–632, 1987.

Lefebvre, C.: Orkan Britta am 31.10. und 01.11.2006 und seine Auswirkungen, Deutsche Wetterdienst (DWD), available at: http://beta.dwd.de/DE/leistungen/besondereereignisse/stuerme/deutschland/20061201_orkan_britta.html, last access: 22 August 2015, 2007 (in German).

Lettmann, K. A., Wolff, J.-O., and Badewien, T. H.: Modeling the impact of wind and waves on suspended particulate matter fluxes in the East Frisian Wadden Sea (southern North Sea), Ocean Dynam., 59, 239–262, doi:10.1007/s10236-009-0194-5, 2009.

Liu, P. C.: A chronology of freaque wave encounters, Geofizika, 24, 57–70, 2007.

Lloyd's Casualty Week: 3, 10, 17 November 2006.

Madsen, K. S., Hoyer, J. L., and Tschering, C. C.: Near-coastal satellite altimetry: sea surface height variability in the North Sea–Baltic Sea area, Geophys. Res. Lett., 34, L14601, doi:10.1029/2007GL029965, 2007.

MIROS: Monthly Report, October 2006, Ekofisk – Met-Ocean Data Recording, ND/1024/06/10, Miros AS, Norway, 7 November 2006a.

MIROS: Monthly Report, November 2006, Ekofisk – Met-Ocean Data Recording, ND/1024/06/11, Miros AS, Norway, 18 December 2006b.

Neckelmann, S. and Petersen, J.: Evaluation of the stand-alone wind and wave measurement systems for Horns Rev 150 MW offshore wind farm in Denmark, OWEMES (Offshore Wind Energy in Mediterranean and Other European Seas), ATENA, Rome, 17–27, 13–15 April 2000.

Nikolkina, I. and Didenkulova, I.: Catalogue of rogue waves reported in media in 2006–2010, Nat. Hazards, 61, 989–1006, 2012.

Outzen, O., Herklotz, K., Heinrich, H., and Lefebvre, C.: Extreme waves at FINO1 research platform caused by storm "TILO" on 9 November 2007, DEWI Magazin, No. 33, 17–23, August 2008.

Pleskachevsky, A. L., Lehner, S., and Rosenthal, W.: Storm observations by remote sensing and influences of gustiness on ocean waves and on generation of rogue waves, Ocean Dynam., 62, 1335–1351, 2012.

Rosenthal, W. and Lehner, S.: Individual wave height from SAR, Proceedings Envisat Symposium 2007, Montreux, Switzerland, 23–27 April 2007, ESA SP-636, July 2007.
RWS-RIKZ: Evaluatie Allerheiligenvloed 2006, Ministerie van Verkeer en Waterstaat, Rijkswaterstaat, Rijksinstituut voor Kust en Zee (RWS, RIKZ), Den Haag, 24 November 2006, available at: http://publicaties.minienm.nl/download-bijlage/17961/, last access: 26 August 2015, 2006 (in Dutch).
Sand, S. E., Ottesen Hansen, N. E., Klinting, P., Gudmestad, O. T., and Sterndorff, M. J.: Freak wave kinematics, in: Water Wave Kinematics, edited by: Tørum, A. and Gudmestad, O. T., Kluver Academic, Dordrecht, 535–549, 1990.
Slingo, J., Belcher, S., Scaife, A., McCarthy, M., Saulter, A., McBeath, K., Jenkins, A., Huntingford, C., Marsh, T., Hannaford, J., and Parry, S.: The recent storms and floods in the UK, Met Office, available at: http://www.metoffice.gov.uk/media/pdf/n/i/Recent_Storms_Briefing_Final_07023.pdf, last access: 27 August 2015, 2014.
Solberg, S.: Chief Operations, JRCC Southern Norway, Stavanger (JRCC Stavanger), email communication of callouts on Norwegian emergency services during 31 October–1 November 2006 storm, 5 November 2014.
Stanev, E. V., Grayek, S., and Staneva, J.: Temporal and spatial circulation patterns in the East Frisian Wadden Sea, Ocean Dynam., 59, 167–181, 2009.
Stoker, E.: Data provided by Datawell service department on permission of Rijkswaterstaat, email communication, 17 December 2014.
Sunde, A.: Kjempbølger i Nordsjoen (Extreme waves in the North Sea), Vaer & Klima, 1, 17–23, 1995 (in Norwegian).
Van Vliet, G.: secretariat, Koninklijke Nederlandse Redding Maatschappij (KNRM), email communication report of Dutch gas production platform operators, 15 August 2014.
Woge Nielsen, J. and Huess, V.: Stormfloden den 1. november 2006, available at: http://ocean.dmi.dk/case_studies/surges/01nov06.php, last access: 26 August 2015, 2008 (in Dutch).
Zijderveld, A., Voogt, L., den Heijer, F., Noort, J., Peters, H., de Grave, P., Oost, A., and Verlaan, M.: Allerheiligenvloed 2006, Achtergrondverslag van de stormvloed van 1 november 2006, Rijkswaterstaat Rijksinstituut voor Kust en Zee (RIKZ), 30 Juni 2007 (in Dutch).

NHESSD
3, 5493–5510, 2015

Storm Britta in 2006: offshore damage and large waves in the North Sea

A. J. Kettle

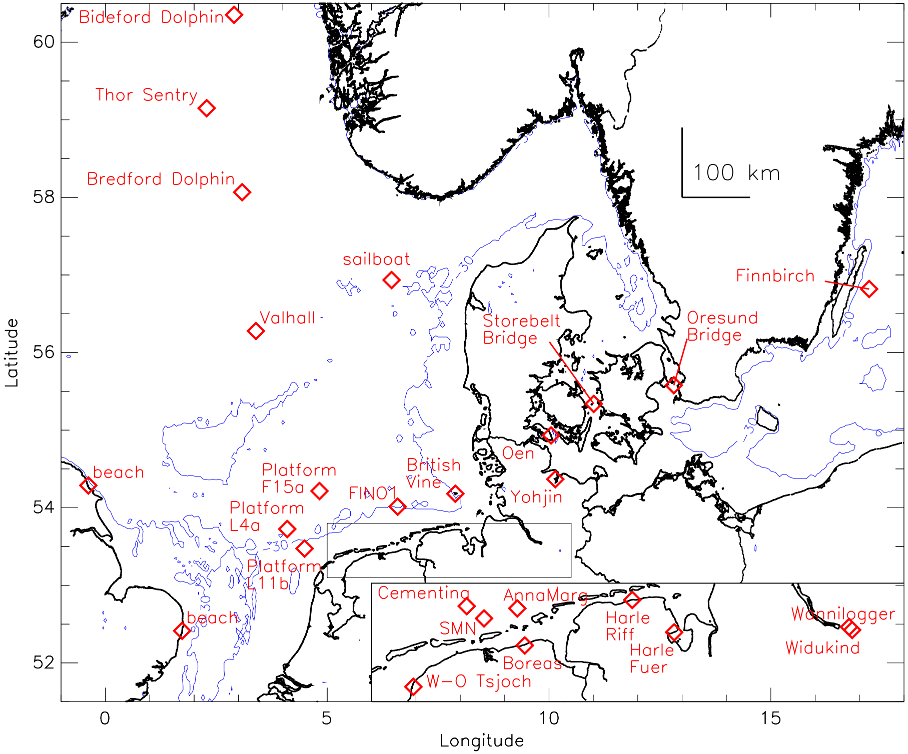

Figure 1. Marine shipping and coastal events associated with the Britta storm 31 October–1 November 2006. Incidents at the vessels *Thor Sentry*, *Cementina*, *Anna Margaretha* (denoted Annamarg on the diagram), and the beach events in the UK explicitly mention rogue wave events. Damage on the Valhall production platform (Norway), the Dutch production platforms, and the FINO1 tower in the southern North Sea were caused by high waves that reached over 15 m above average sea level.

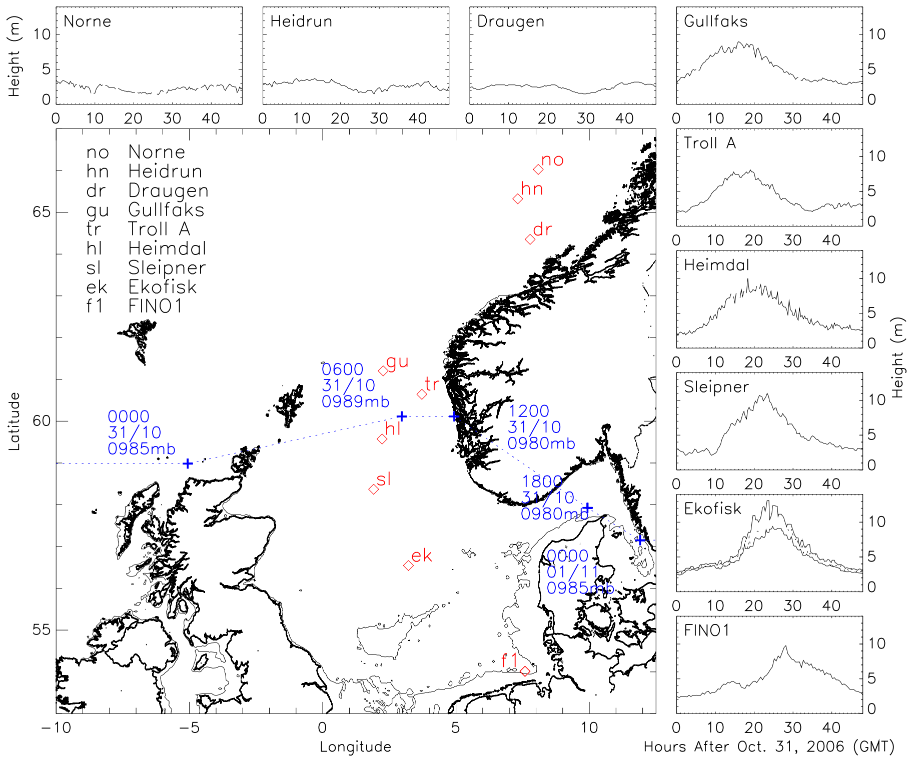

Figure 2. Time series of significant wave height during a 48 h period during the Britta storm 31 October–1 November 2006 from Norwegian offshore production platforms and the FINO1 tower in the German Bight. The track of the low pressure centre is in blue (Lefebvre, 2013).

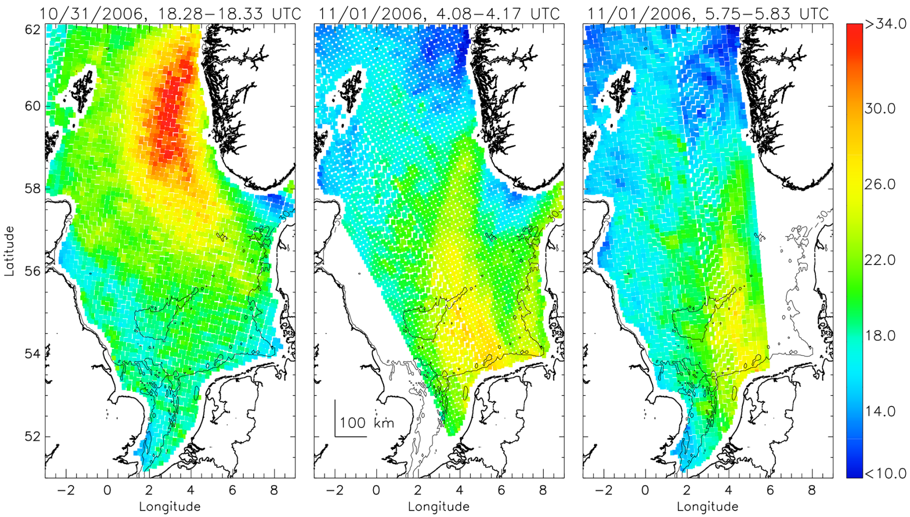

Figure 3. Three Quikscat images of surface wind speed (in $m\,s^{-1}$) from 31 October–1 November 2006. The scatterometer image sequence shows how the storm wind field moved from the northern to the southern part of the North Sea over ∼ 12 h. The North Sea is wholly or partially imaged during two consecutive overpasses of this sun-synchronous satellite in the morning and evening, giving a potential availability of four images per day or eight images over the storm period 31 October–1 November 2006.

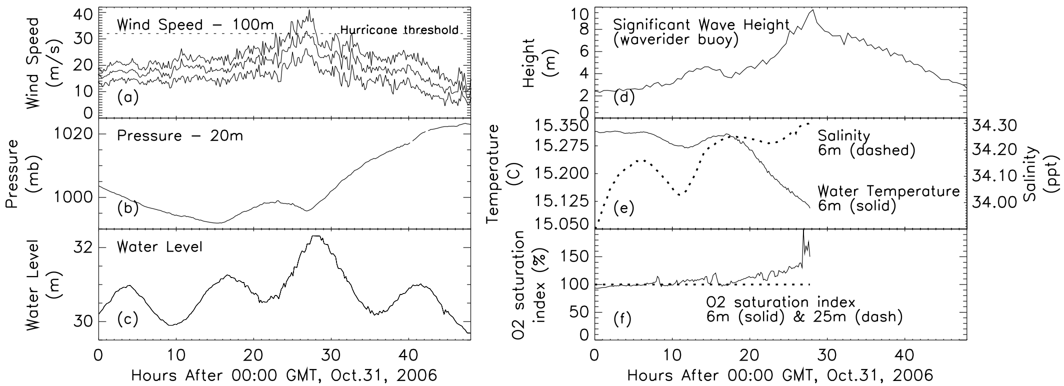

Figure 4. 48 h time series of important meteorological and oceanographic parameters recorded on the FINO1 tower during the Britta storm 31 October–1 November 2006: **(a)** wind speed at 100 m height (average, minimum, and maximum values of a 1 Hz series over 10 min intervals), **(b)** atmospheric pressure at 20 m height, **(c)** water level, **(d)** significant wave height, **(e)** water salinity and temperature at 6 m depth, **(f)** oxygen saturation at 6 and 25 m depth.

NHESSD
3, 5493–5510, 2015

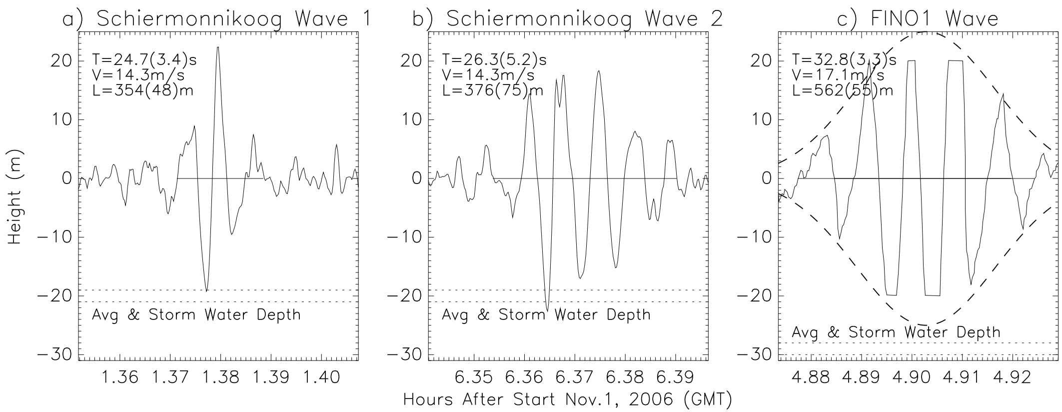

Figure 5. High-resolution time series of large waves during Britta storm recorded by Datawell waverider buoys at **(a, b)** Schiermonnikoog Nord (SMN; Stoker, 2014) and **(c)** FINO1 (Pleskachevsky et al., 2012). The wave incidents occurred during a high storm surge period. "T" denotes the average 0-crossing period with standard deviation, "V" denotes the phase velocity of shallow water waves at the sites calculated from the local water depth at the time (∼ 20 m for SMN and ∼ 30 m for FINO1), and "L" is the calculated wavelength. The SMN time series **(a)** and **(b)** are from an original data record archived internally in the waverider buoy and downloaded after instrument recovery soon after the storm (Zijderveld et al., 2007). The FINO1 time series **(c)** shows a rogue wave group whose peaks and troughs are truncated at the instrument measuring limits of ±20 m. The dashed lines show an approximate Gaussian envelope fit to the wave group with a trough-to-crest amplitude of 50 m and full-width at half-maximum of 70 s.