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COMMITTEE I.1
ENVIRONMENT

COMMITTEE MANDATE

Concern for descriptions of the ocean environment, especially with respect to wave, current and wind, in deep and shallow waters, and ice, as a basis for the determination of environmental loads for structural design. Attention shall be given to statistical description of these and other related phenomena relevant to the safe design and operation of ships and offshore structures. The committee is encouraged to cooperate with the corresponding ITTC committee.

COMMITTEE MEMBERS

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KEYWORDS

Environment, ocean, wind, wave, current, sea level, ice, deep water, shallow water, data source, modelling, rogue waves, climate change, design condition, operational condition, uncertainty.

CONTENTS

1. INTRODUCTION

This report is built upon the work of the previous Technical Committees in charge of Environment. The aim is to review scientific and technological developments in the field since the last Committee, and to set them in the context of the historical developments, in order to give a practicing engineer a balanced, accurate and up to date picture about the natural environment as well as data and models which can be used to approximate it in the most accurate way. The content of the present report also reflects the interests and fields of competence of the Committee membership.

The mandate of the 2012 ISSC I.1 Committee has been adopted. It accords ice an equal status with traditional interests such as wind, wave, current and sea water level, and recognizes the importance of environmental data to the planning of marine operations and prediction of operability. Also in accordance with the ISSC I.1 mandate, this Committee has reported on the resources available for design and the operational environment. Additionally, the Committee has continued the initiated in 2010 cooperation with the corresponding ITTC Committees.

The renewable energy installations are not mentioned explicitly in the Committee I.1 mandate as the ISSC 2015 Committee V.4 Offshore Renewable Energy is addressing the topic. However, the increased use of renewable energy sources has encouraged the Committee I.1 to put some attention to these issues, focusing on metocean description only. The Committee I.1 would like to suggest extending, in communication with the Committee V.4, the I.1 mandate in the future by giving renewable energy installations an equal status with ships and offshore structures.

The Committee consisted of members from academia, research organizations, research laboratories and classification societies. The Committee met four times: in Lisbon (18–19 February 2013), Shanghai (9–10 December 201), San Francisco (8 June 2014) and in Høvik (13–14 November 2014). Committee members also met on an ad hoc basis at different scientific conferences and industrial workshops. The Committee I.1 contributed, together with the ISSC 2015 I.2 (Loads) Committee and the ITTC Ocean Engineering Committee, to the organized by the ITTC Seakeeping Committee the 2nd ITTC-ISSC Joint Workshop on uncertainty modelling which took place 30 August 2014 in Copenhagen.

The organisation of this report is an evolution of the outline used by the preceding Committee in their report to the 18th ISSC Congress. Section 2 focuses on sources of environmental data for wind, waves, current, sea water level and ice (including snow). Section 3 addresses modelling of environmental phenomena while Section 4 climate change. Section 5 discusses some selected special topics. The design and operating environment is presented in Section 6. The most significant findings of the report are summarised in Section 7.

Three areas are considered as particularly important fields at the present time and have been selected for special attention: hurricanes, wave-current interaction and resource assessment.

Rogue waves have been a topic of increasing interest over the past two decades. Two international projects ShortCresT and EXTREME SEAS dedicated to these waves have been completed during the period of the 2015 ISSC I.1 Committee. Following the two previous Committees this Committee felt that the rogue waves could be adequately dealt with inside the normal wave sections: the wave data section (2.2) and wave modelling section (3.2).

Major conferences held during the period of this Committee include the 31st–33th International Ocean, Offshore and Arctic Engineering (OMAE) conferences held in Rio de Jainerio (2012), Nantes (2013), San Francisco (2014), and the 22nd–24th International Offshore and Polar Engineering (ISOPE) conferences held in Rhodes (2012), Alaska (2013) and Busan (2014). Also of great interest to the Committee were: the 13th International Workshop on Wave Hindcasting and Forecasting held in Banff (2013), the MARSTRUCT (International Conference on Marine Structures) conference which took place in Espoo (2013), the EUG (European Geosciences Union) conference in Vienna (2012, 2013, 2014), WISE (Waves in Shallow Water Environment) in Washington (2013) and Reading (2014), COST (Predictive Power of Marine Science in a Changing Climate) in Sopot (2014), the European Safety and Reliability conference (ESREL) in Amsterdam (2013) and Wroclaw (2014), POAC (Port and Ocean Engineering under Arctic Conditions) in Espoo (2013), IWMO (International Workshop on Modelling the Ocean) in Yokohama (2012) and Bergen (2013), respectively, TRA (Transport Research Area) in Paris (2014), MARTECH (International Conference on Marine Technology and Engineering) conference in Lisbon (2014) and the U.S. Department of Energy Wave Energy Converter Extreme Conditions Modeling (ECM) Workshop in Albuquerque, NM (2014). Works on resource assessment for Marine Renewable energy were reported at EWTEC 2013 (European Wave and Tidal Energy Conference) in Aalborg (2013). Papers from those sources have been reviewed and those of particular relevance are cited here. The articles published in journals and conference proceedings not available to the Committee in the final forms by March 2015, are not covered by the present review.

A number of Joint Industry Projects (JIPs) are also contributing to the world's knowledge base on the metocean environment, with results released publicly in the form of academic papers. Several EU, JIP and ESA (European Space Agency) projects have reported during the course of this Committee, including: EXTREME SEAS, ShortCresT (both on extreme and rogue waves), HAWAII and LoWish (both on shallow water), NavTronic (ship routing), SAFE OFFLOAD (LNG terminals), SHOPERA (energy efficient safe ship operations) and DeepStar (metocean processes). A number of hindcast projects have also been in operation or results from them have been reported during the period of this Committee, notably GROW2012 (global), GROW-Fine Northern Indian Ocean, GROW-Fine Mediterranean Sea, GROW-Fine Sea of Okhotsk, the GROW Fine Caribbean (Caribbean Sea), the GROW Fine North Atlantic Basin, NAMOS (NW Australia), SNEXT (North Sea), SEAFINE (SE Asia), BOMOSHU (Brazil, Atlantic waters), WASP (WesT Africa Swell Project), and a Chinese national project in the South China Sea. The present status of the ESA GlobWave project, making satellite derived data more widely available, is also reviewed; a summary of services can be found on http://globwave.ifremer.fr /Products/Summary-of-Services.

Success of the global and basin-scale ocean models development with data assimilation under the GODAE (Global Ocean Data Assimilation Experiment) program, initiated some years ago, opened a new era of operational oceanography. This program ended in 2008 and has continued as GODAE OceanView (https://www.godae-oceanview.org/). The 5 years' of GODAE OceanView progress and priorities were presented at the GODAE OceanView Symposium in Baltimore in 2013.

Climate change has also been a topic of continuing worldwide interest both regarding mitigation as well as adaptation process. It has had impact on research activities within the shipping, offshore, emerging renewable energy and coastal engineering industry sectors and the need to adaptation to climate changes is getting increasing recognition within these sectors. The previous Committee reviewed this subject as a special topic while the current Committee has addressed it in a separate Section 4 on climate change. During the period of the 2015 ISSC I.1 Committee the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC. 2013) has been issued and is reviewed herein. The present report makes an attempt to provide the ISSC Congress with the most up-to-date information from leading scientists on the main climate change issues of relevance to those working on the seas: temperature, sea ice extent, sea-level rise and storm intensity and frequency. Particular attention is given to the Arctic environment and to tropical and extra-tropical hurricanes and related wave climate.

Enhancing safety at sea through specification of uncertainties related to environmental description is being increasingly recognized by the shipping, offshore, emerging renewable energy and coastal engineering industries. Organization of the 2nd ITTC-ISSC Joint Workshop on uncertainty modelling is confirming the importance of the topic. Generally, uncertainty related to wave description may be divided into two groups: aleatory (inherent, intrinsic) uncertainty and epistemic (knowledge based) uncertainty (Bitner-Gregersen et al., 2014a). Aleatory uncertainty represents a natural randomness of a quantity, also known as intrinsic or inherent uncertainty, e.g. the variability in wave height over time. Aleatory uncertainty cannot be reduced or eliminated. Epistemic uncertainty represents errors which can be reduced by collecting more information about a considered quantity and improving the methods of measuring it. Recent scientific and technological developments in the field of environment are presented in the report in the perspective of these uncertainties.

The report is covering a wide ranging subject area and limited space as well as the boundaries presented by the range of specialisms and competencies of the Committee members, this Committee report cannot be exhaustive. However, the Committee believes that the reader will gain a fair and balanced view of the subjects covered and we recommend this report for the consideration of the ISSC 2015 Congress.

2. ENVIRONMENTAL DATA

Wind, ocean waves, current, sea water level, ice and snow conditions vary geographically and in time. Physical, probabilistic and statistical models can approximate this variability. Environmental data represent an important contribution to modelling of environmental phenomena. They can be collected by in-situ instruments, remote sense techniques and/or generated by a model. Environmental data are affected by measurement, statistical (sampling variability) and model uncertainties (Bitner-Gregersen et al., 2014a), which are not fully quantified today. A question getting increasing attention in the last years is: Are these measurements actually ground truth? This question was also raised up during the 13th International Workshop on Wave Hindcasting and Forecasting and 4th Coastal Hazards Workshop taken place in Banff, Canada (Jensen et al., 2013), but a final answer to it still does not exist.

The issue of data ownership remains a general problem (ISSC, 2009, ISSC, 2012, Bitner-Gregersen et al., 2014a) even though some progress regarding access to the environmental data has been made since 2012. This makes work on comparison of different data sources and specification of uncertainties related to them difficult, and consequently specification of the ground truth even more challenging. The data are often of proprietary nature–for example, oil companies, ship owners, and agencies usually keep their data confidential. In some cases, government agencies make data freely available in the public domain, such as the NOAA, NIBCO data sources, but this is the exception rather than the rule. An example of making data available without compromising their confidentiality is the SIMORC URL data base: http://www.simorc.org/, administered by the University of Southampton (ISSC, 2012).

Also in 2010 TOTAL Oil & Gas Operator launched a project to give remote and public access to real-time wind, current and wave, or other metocean data monitored from many oil and gas platforms offshore West and Central Africa (from Nigeria to Angola). Since 2013, with the support of the French Meteorological Office Météo-France, the data from half dozen platforms offshore Nigeria, Congo and Angola have become available on the World Meteorological Organization's (WMO) Global Telecommunication System (GTS). (Quiniou-Ramus et al., 2013) present the type of metocean stations that are part of this network (MODANET), the IT architecture that was selected to send the data out of the TOTAL Company's network, the quality control undertaken by Météo-France before sending the data to the GTS, and discuss future possible use of the data that are envisaged.

The stationarity and homogeneity assumption of measurements is obviously questionable and likely not valid in some circumstances. It is getting increasing focus in academia and the marine and renewable energy industries, e.g. (Ewans, 2014). The need to account for non-stationarity and non-homogeneity of environment data is expected to continue, particularly because of changing climate but also due to needs of engineering applications. Although several data uncertainties have been reported during the period of the ISSC 2015 Committee I.1 a systematic investigation of them still is lacking.

2.1 Wind

Meteorological data of good quality are important not only for understanding of global and regional climates but also for specification of design and operational criteria of ship, offshore and renewable energy structures. Local measurements of the wind, traditionally at 10 m height above the sea surface, have been the standard way to record wind characteristics for decades and remain important particularly for verification of data from other sources. But as suitable measurement sites are scarce, and it is not possible to enlarge this number significantly, the advent of remote measurement techniques and numerical simulations has allowed for much more detailed descriptions of wind in the offshore data.

Apart from wind speed also wind direction, wind profile (describing variations of the mean wind speed with height above the ground or above the sea water level), gust, wind spectrum and squalls represent important characteristics of a wind field which can be determined from wind data, see (DNV, 2014).

2.1.1 Locally sensed wind measurements

Large and meso-scale wind fields have been studied for years leading to a wide variety of wind field data. These measurements have been either focused on short term detailed observations with attention on specific meteorological and oceanographic mechanisms or on longer term measurements of statistical behavior and have been used to support weather forecasting. More recently with the increased activity in coastal regions a number of efforts have established offshore observation capability providing a valuable source of environmental data of all types. The U.S. Department of Commerce's National Oceanographic Data Center (NODC) is one of the national environmental data centers operated by the National Oceanic and Atmospheric Administration (NOAA). They are part of the World Data Center System initiated in 1957 to provide a mechanism for data exchange, and they operate under guidelines issued by the International Council of Scientific Unions (ICSU). There are three World Data Centers for Oceanography:

- World Data Center, Silver Spring, Maryland, United States
- World Data Center, Moscow, Russia
- World Data Center, Tianjin, People's Republic of China

In-situ wind measurements are collected by buoys, ships and platforms. Perhaps the most well-known organization collecting wind data is the U.S. National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) (www.ndbc.noaa.gov). As a part of the National Weather Service (NWS), the center designs, develops, operates, and maintains a network of approximately 90 data collecting buoys and 60 Coastal Marine Automated Network (C-MAN) stations. For each of these buoys and C-MAN stations the NDBC provides hourly observations from a network of all stations measuring wind speed, direction, and gust; barometric pressure; and air temperature. In addition, all buoy stations, and some C-MAN stations, measure sea surface temperature and wave height and period. Conductivity and water current are also measured at selected stations.

The wind is often assumed to be stationary over one-hour, and relationships between specific parameters, such as the ratio of the maximum 1-minute mean wind speed in the hour, are required to be specified. Recommended relationships are available in codes, such as (ISO, 2012, DNV, 2014).

Muyau et al. (2014) investigated short-term effects in wind data, sampled at 1 Hz off the west coast of Borneo, including mainly monsoon conditions. Their data set consisted of 5952 1-hour records collected at three offshore locations and one onshore location. Using the stringent run test, they found none of their 1 Hz data records to be stationary over one hour, and even when the 1 Hz data were averaged over longer intervals, no records of 3-second means were found to be stationary, and only 14% of the records of 1-minute means were found to be stationary. The authors concluded that the run test was not reliable for the 10-minute mean wind speeds over the one hour, due to the small data set. The results for the original data set and other averaging intervals, which were almost entirely non-stationary over one hour for their data sets, indicate that the application of fixed short-term wind relationships is questionable.

The lack of stationarity in the wind measurements has long been recognised for highly transient wind events, such as squalls. Bitner-Gregersen et al. (2014b) show the wind speeds measured during a “major” North Atlantic Storm and the other during a squall event demonstrating clearly the transient nature of the squall wind speeds.

Within the 15-year JIP DeepStar project all available hurricane wind data sets made in and around the Gulf of Mexico since 1998 have been collected, quality control, and then analyzed (Cooper et al., 2013). The data sets included offshore platform anemometer records, measurements from National Oceanic and Atmospheric Administration (NOAA) buoys, Coastal-Marine Automated Network (C-MAN), Automated Surface Observing System (ASOS), and National Ocean Service (NOS) stations, tower arrays of anemometers deployed along the coast, coastal weather radars, and dropsonde observations made by hurricane hunter aircraft. The aim of these investigations has been improving modelling of hurricanes based on the historiocal data with reasonable statistical uncertainty (see also Section 6.1.2).

New needs for a detailed description of wind profiles and turbulence at regional and local scales, mostly required by the developing wind offshore industry, appear to play a major role in the development of new sensors today as well as the implementation of downscaled numerical models. The offshore wind industry needs data on suitable locations for the installation and changes in the wind profile (beyond 200 m) as well as spatial distribution of wind characteristics. These data are still very spare today.

2.1.2 Remotely sensed wind measurements

Remotely sensed surface wind data is available from the U.S. National Oceanic and Atmospheric Administration’s (NOAA) Center for Satellite Applications and Research (STAR). Both active (radar) and passive (radiometer) microwave sensors are capable of retrieving ocean surface wind speed, and with active microwave instruments being used to also retrieve the wind direction. The development and refinement of instrumentation and algorithms for ocean surface wind retrieval is an ongoing process being conducted in both the active and passive remote sensing areas. STAR’s Ocean Surface Winds Team (OSWT) web site (http://manati.star.nesdis.noaa.gov/products.php) provides: wind vector fields and wind speed fields. Additionally the STAR’s web site provides rain, sea ice, SST and water vapor data.

Information on specific storms as well as storm forecast data can be found at http://www.nrlmry.navy.mil/tc_pages/tc_home.html. The web page was created to provide remote sensing imagery and data sets derived from both geostationary and polar orbiter sensors. The limitation of the data sets from the web site is that the data sets are updated automatically in near real-time generating the data products, updating storm positions, adding new storms and deleting storms that have decayed and are no longer active. The available data is global in nature and includes the standard visible/IR and water vapor geostationary imagery in addition to passive and active microwave data.

Various remote sensing databases have been updated and made available at CERSAT (http://cersat.ifremer.fr/) thanks to the new cloud computing facility Nephelae.

The complete ERS-1 & ERS-2 altimeter data archive from 1991 to 2003 has been reprocessed in the context of ESA REAPER project. The ERS-1/2 REAPER Altimeter dataset is composed of the following three product types which are freely accessible: GDR, the RA Geophysical Data Record product containing radar range, orbital altitude, wind speed, wave height and water vapor from the ATSR/MWR as well as geophysical corrections; SGDR, the RA Sensor Geophysical Data Record (SDGR) product containing all of the parameters found in the REAPER GDR product (ERS_ALT_2_) with the addition of the echo waveform and selected parameters from the Level 1b data; and the RA Meteo product containing only the 1 Hz parameters for altimeter (surface range, satellite altitude, wind speed and significant wave height at nadir) and ATSR/MWR data (brightness temperature at 23.8 GHz and 36.5 GHz, water vapor content, liquid water content) used to correct altimeter measurements. It also contains the full geophysical corrections. Major improvements with respect to the previous ESA RA products format (OPR–Ocean Product–and WAP–Waveform product) have been implemented (e.g. the 4 Envisat RA-2 retrackers, RA calibration improvement, new reprocessed Precise Orbit Solution, ECMWF ERA-interim model, NICO09 ionospheric correction until 1998, GIM ionospheric correction up to 2003, new SSB, etc.). The assessment of the REAPER data quality versus the ERS OPR and WAP data shows a clear improvement in terms of accuracy over the tandem periods between ERS-1, ERS-2 and Envisat missions (currently assessed periods). However, the REAPER dataset presents some limitations (such as the use of poor MWR Wet tropospheric correction, out of range PTR corrections, etc.) that are fully described in the Product Handbook.

Gridded daily wind vector and wind stress fields, estimated over global ocean from QuikSCAT scatterometer (referred as DQSCAT) data, have been updated in 2013. Their spatial resolution is 0.25° in longitude and in latitude. They are produced from the new QuikSCAT wind retrievals indicated as QuikSCAT *V3* (ftp://podaac.jpl.nasa.gov/OceanWinds/ quikscat/preview/ L2B12 /v3/). Wind retrievals are provided over QuikSCAT swath at Wind Vector Cell (WVC) of 12.5km spatial resolution. The new scatterometer product is assumed improving wind speed performance in rain and at high wind conditions. The calculation of daily gridded wind fields from scatterometer wind observations is performed using same objective method used for the estimation of daily ASCAT wind fields (DASCAT) (Bentamy et al., 2011). The resulting wind field accuracy is investigated trough the comparisons with daily-averaged winds from moored buoys. The overall statistics indicate that the daily scatterometer wind fields compare well to daily-averaged buoy data. The rms differences do not exceed 2m/s and 20° for wind speed and direction, respectively. Despite of difference in buoy and scatterometer sampling schemes used for the estimation of daily winds, correlation values attest that satellite daily winds reproduce fairly well in-situ estimates.

Analyzing a 5-year dataset collected over two surface current and meteorological moorings, Plagge et al. (2012) investigated the influence of surface currents on satellite scatterometer and altimeter ocean winds. Comparing wind residuals between Ku-band Quick Scatterometer (QuikSCAT) and buoy measurements they observed that scatterometer winds and buoy wind direction differences due to currents were negligible for the range of surface velocities encountered and the length scales observed by QuikSCAT. As a consequence; at length scales of 10 km and longer the scatterometer wind can be considered to be current relative and not earth relative. Observed differences between earth-relative and current-relative winds of order 10%–20% of the wind velocity are not uncommon in the considered area and other ocean regions and this study more fully validates that microwave remote sensing winds appear to respond to wind stress even in the presence of larger-scale currents.

For further discussion of accuracy of satellite data see also (ISSC, 2009).

2.1.3 Numerical modelling to complement measured data

Numerically generated wind data are still commonly used in design and marine operations as well as renewable energy applications. For some ocean areas they are the only data available. Although the number of remote sense data is increasing (e.g. the GlobWave database) they not always exist for a location considered in an engineering application. The numerical data refer usually as the 10-minute average wind speed at the 10 m height above the ground or the still water level and include also wind direction. The wind data can be converted to a different averaging period as well as to the different heights by appropriate commonly used expressions; e.g. (DNV, 2014).

The recently updated or new developed metocean data bases such as: ERA-Interim (European Reanalysis), http://www.ecmwf.int/en/research/climate-reanalysis, ERA-Clim (European Reanalysis of Global Climate Observations) http://www.ecmwf.int/en/research/projects/era-clim, CFSR (Climate Forecast System Reanalysis), https://climatedataguide.ucar.edu/climate-data /climate-forecast-system-reanalysis-cfsr, NORA10 (Aarnes et al., 2012), HIPOCAS (www. mar.ist.utl.pt/hipocas/members_details.as), BMT-ARGOSS (http://www.bmtargoss.com/met ocean-web-portals/wwwwaveclimatecom/) and Fugro-OCEANOR (http://www.oceanor.no/ Services/Worldwaves/WW_database) include information about both wind and waves. Further progress aiming at enhancing accuracy of these databases and/or extension of the time period they covered has taken place since 2012. The improvement includes higher resolution, better quality-control of assimilated data and/or improvement of validation procedures, see e.g. (Cardone et al., 2014).

2.2 Waves

Observations of waves in the open ocean still represent a challenge and they are limited. Most of wave recordings take place in coastal areas. Therefore wave data from hindcast studies are the choice data sets for development of design criteria of marine structures. However, measured wave data either locally or remotely remain important for development, calibration, and validation of numerical wave models used for generating hindcasts, particularly in coastal areas due to shallow-water aspects of wave dynamics. The measured data are also important for providing description of individual wave characteristics in the open ocean and coastal waters as well as validation of nonlinear short-term wave models. During the period of the

Committee new instrumental data sets including extreme waves have been collected/reported and further improvements of hindcasts have taken place.

With the increased need and use of ocean wave measurements the question that remains to be addressed is: Are these measurements actually ground truth? What are the uncertainties and limitations of the various measurement systems? Apart from instrumental errors wave data are affected by statistical uncertainty due to limited duration of wave records and model uncertainty associated with a method used for derivation/generation of wave parameters. Additionally, whenever observations of the ocean wave environment are made, the questions of stationarity and ergodicity need to be addressed.

Wave characteristics commonly used in applications include significant wave height, spectral (or zero-crossing) wave period, wave spectrum and wave directional spreading, see (DNV, 2014).

2.2.1 Locally sensed wave measurements

Wave buoys, a wave staff, radars, lasers, LASAR and a step gauge remain the most important sources of in-situ measurements. Specific issues for the most common wave measurement systems include:

- Lidar–Fixed point measurements need to consider instrumentation accuracy in the range estimate provided by the instrument. The absorption of water also needs to be accounted for. For free surfaces with low void fraction this error is likely less than any uncertainty in the along range resolution. Typical range resolutions are around +/–2.5 cm and thus would likely only be of concern in very low sea states.
- Buoy–Uncertainties in significant wave height H_s seem to be associated mostly with a question how well the buoy tracks the free surface and whether non-linear effects are accurately measured. Additionally issued related to specific installations may also be present. The buoy may "cut" the top of the wave off, particularly if it is moored. One area that remains to be opened is what uncertainty exists in estimation of wave direction. The accuracy is dependent on the number of degrees of freedom and how the 2D spectrum is derived. Three DOF buoys have difficulty resolving directional wave energy due to the poor directional resolution (again dependent on the processing method). While they likely get the dominant wave direction, they will tend to smear energy in a given frequency band if there are multiple systems that propagate at similar headings.
- X-Band Radar–The dominant source of uncertainty for these systems comes from the calibration. If there is an assumed linear relationship between H_s and the square of SNR (Signal-to-Noise Ratio), then an issue is how is the spread in the fit applied to the measured H_s data? A universal uncertainty cannot be applied for all radars since it is so dependent on the actual data used during calibration. Nieto-Borge et al. (2008) shows a typical calibration curve. At a SNR of 1.5 the H_s values ranged from 2.5–4 m. So while period and direction may be easily obtained from these systems, accurate H_s measurements is still a topic for further research.

Significant wave height H_s and spectral (or zero-crossing) wave period T_p (T_z) represent important parameters for design and operations of ships and offshore structures. They are used for validation of wave models, wave climate studies and calculations of extremes for weather forecasting purposes. Whether significant wave height H_s is determined using directly time series ($H_{1/3}$), 4*standard deviation (std) of the free surface or via calculation of the zeroth moment of the spectrum (M_0) there are closed form expressions for the statistical uncertainty that should be accounted for (Bitner-Gregersen and Hagen, 1990, Bitner-Gregersen and Magnusson, 2014). Also H_s computed via 4*std or by 4*sqrt(M_0) won't necessarily be equal due to windowing/overlapping of segments during calculation of the spectrum. Each system has a specific frequency bandwidth it is able to measure, and no single system can measure the entire wave spectrum. Further, as pointed out by (Bitner-Gregersen and Hagen, 1990) H_s computed via 4*std is only equal to the one calculated via 4*sqrt(M_0) if the sea surface is a narrow-banded Gaussian process.

In September 2013, a U.S. Office of Naval Research funded, nine-day experiment was conducted aboard the research vessel R/V Melville, where the statistical and phase-resolved wavefield were measured using a shipboard radar, airborne lidar, wave buoys, and a bow mounted lidar (Merrill et al., 2014). The measurement area was just west of Southern California and around San Clemente Island and the Channel Islands (Figure 1). The local wave field was measured using the OceanWaves WaMoS® II wave radar system coupled using a post-processing routine developed by Scripps Institute of Oceanography (SIO) to obtain phase-resolved results from the WaMoS radar intensity maps. Point measurements of the wave field were provided by SIO miniature wave buoys and Datawell III Waverider buoys, both of which were modified to record buoy motions at 1.0 Hz in addition to their normal statistical parameters. During three separate periods of the cruise, an airborne lidar system provided five kilometer box sweeps of the wave field in the vicinity of the ship. An experimental bow mounted wave measuring lidar system developed by SIO to record the wave height in the vicinity of the ship (but outside of the ship generated wake) was also deployed. A small boat with a wave measuring ultrasonic array system was also used when conditions allowed.

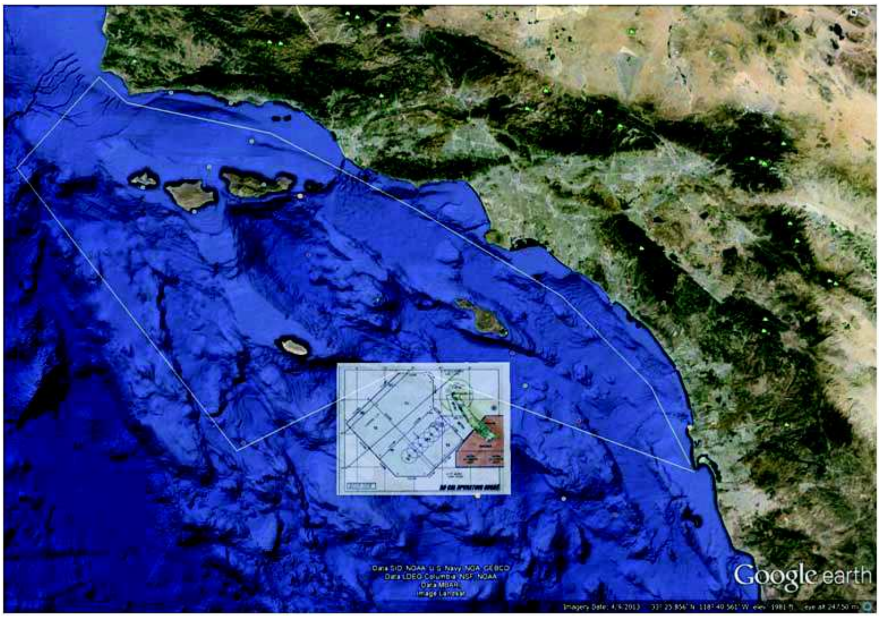

Figure 1. The R/V Melville operational area for the September 2013 field experiment.

Merrill et al. (2014) compare the wave measurements made from the various instrumentation systems and notes that while comparison of the wave statistics shows that each system is correctly capturing the generalized wavefield behavior, it also shows that significant work still needs to be done in regards to the measurement of phase-resolved wave fields where much of the uncertainty due to registration in both time and space is present.

Wave measuremets recorded by buoy and radar installed 6 km apart in a deep water region offshore northeast Brazilian shelf were compared by Ribeiro et al. (2013). Differences in wave directional spectral parameters calculated by both equipments were found. The H_s correlation was 91% and bias 0.06 m. The radar H_s compared to the buoy H_s was overestimated in high sea states and underestimated in low ones. The T_p correlation was 69% and bias 0.02 s. The peak direction was the worst correlated, 60% correlation was found for E-ESE directional band. Time series matched each other showing the typical regional wave climate for the area.

A new wave data processing system allowing deeper evaluation of the information that was stored inside a wave buoy and was not transmitted in real-time was presented by Pereira et al. (2012). The main aims of this study has been to increase the reliability of real-time data transmitted by heave-pitch-roll buoys and verify the efficiency of a single board computer to execute the traditional wave processing including automatic quality control.

Gemmrich and Garrett (2012) investigated the influence of inertial current on sea-states from offshore buoy measurement pointing out that wave-current interaction is inducing wave height modulation. They suggest that these interactions be taken into account in hindcast wave models.

An interesting element regarding wave measurement is the development of video processing techniques which provide new and interesting insight in the assessment of wave characteristics and breaking.

Fedele et al. (2013) use stereo imaging techniques to identify the space-time evolution of the sea surface. Creating data series of sea surface maps they analyze the characteristics of large waves. This study revealed that the maximum wave surface height over an area during a given duration (space–time extreme) is larger than that expected at a given point in space (time extreme). If the area is large enough compared to the mean wavelength, a space–time extreme most likely coincides with the crest of a focusing wave group that passes through the area.

Schwendeman et al. (2014) investigated energy dissipation in young wind sea by mean of in-situ measurement. Their main conclusions are that there is a strong correlation between wave breaking dissipation and the mean square slope of the waves, both of which increase along fetch. Video-derived breaking rates and breaking crest distributions also increase with mean square slope. Conducting error analysis they suggest that many bulk breaking parameter values from various recent field experiments are likely biased by subtleties of video collection and processing.

A number of efforts have focused on improving the performance of wave radars. This work has concentrated on both improved accuracy in measuring wave spectra and in measuring phase resolved wave fields. Although techniques to extract wave parameters from radar measurements have been evolving over the past several decades (Young et al., 1985, Nieto-Borge et al., 2008) along with our understanding of the scatterers that contribute to sea clutter (Long, 2001), they still have limited accuracy and reliability even under idealized conditions (Johnson et al., 2009). The primary reason is due to the large number of factors that sea clutter depends on, both radar parameters as well as sea characteristics.

A number of these efforts have examined the use of coherent radar systems. These systems include both high transmit power systems capable of long range and coherence to allow for Doppler processing and systems that transmit non-coherently but are coherent on receive. Smith et al. (2013) describes the development of a low cost, high power coherent on receive radar for making sea surface measurements. Hacket et al. (2014) compare wave field measurements from incoherent and coherent measurements from a dual-polarized pulse-Doppler X-band radar to examine the sensitivity of the extracted wave parameters to the characteristics of the radar and the scatterers. These experiments were performed offshore of the Scripps Institution of Oceanography pier in July 2010. Radar measurements in low wind speeds were performed with dual-polarized high-resolution X-band pulse-Doppler radar at low grazing angles along with two independent measurements of the surface waves using conventional sensors, a GPS-based buoy and an ultrasonic array.

Comparison between radar cross section (RCS) and Doppler modulations show peak values occurring nearly in-phase, in contrast with tilt modulation theory. Spectral comparisons between Doppler-based and RCS-based spectra show that Doppler-based spectra demonstrate a greater sensitivity to swell-induced modulations, while RCS-based spectra show greater sensitivity to small-scale modulations (or generally have more noise at high frequency), and they equally capture energy at the wind wave peak. Doppler estimates of peak period were consistent with the conventional sensors, while the RCS differed in assignment of peak period to wind seas rather than swell in a couple cases. Higher-order period statistics of both RCS and Doppler were consistent with the conventional sensors. Radar-based significant wave heights are lower than buoy-based values, and contain nontrivial variability of ~33%. Comparisons between HH and VV polarization data show VV data more accurately represents the wave field, particularly as the wind speeds decreases.

It is interesting to note that new very high significant wave heights have been registered/reported since 2012, see (Cardone et al., 2014). The K-5 buoy in the eastern North Atlantic recorded a new high measurement of H_S = 19.0m on 4 February, 2013. The authors report in addition several cases of satellite altimeter estimates of H_S ~20 m in the North Atlantic and the North Pacific.

Several rogue waves recorded in the ocean have also been reported in the period of this Committee. During the Andrea storm, which crossed the central part of the North Sea on November 8th-9th, 2007 storm, on November 9th, 2007 a rogue wave called Andrea was measured at the Ekofisk field (Magnusson and Donelan, 2013). This wave is comparable in characteristics to the well-known New Year wave (called also the Draupner wave) recorded by Statoil at the Draupner platform the 1st January 1995, see Table 1. C_{max} in Table 1 denotes the maximum crest height in the wave record, H_{max} the maximum zero-downcrossing wave height with the crest C_{max}, CF is the maximum crest factor (crest criterion), HF is the maximum height factor (height criterion). CF>1.3 (or >1.2 as suggested by Haver and Anderson (2000) and HF> 2 within a 20-minute wave record represent simplified definitions of a rogue wave, see e.g. (Bitner-Gregersen and Toffoli, 2012a). If both criteria are fulfilled a rogue wave can be classified as a double rogue wave (Krogstad et al., 2008). As seen in Table 1 both the New Year wave as well as the Andrea wave can be called the double rogue wave. Note that both waves are recorded in the North Sea at the platforms located in the water depth of ca. 75 m.

Table 1. Characteristics of the Andrea and New Year waves derived from the ca. 20-minute wave records.

Wave parameters	Andrea wave	Draupner wave
H_s	9.2 m	11.9 m
T_p	13.2 s	14.4 s
C_{max}	15.0 m	18.5 m
$CF=C_{max}/H_s$	1.63	1.55
H_{max}	21.1 m	25.0 m
$HF=H_{max}/H_s$	2.3	2.1

Waseda et al. (2014) have reported extreme waves registered in 2009, 2012 and 2013 by point-positioning GPS-based wave measurements conducted by deep ocean (over 5,000 m) surface buoys moored in the North West Pacific Ocean. Two large rogue (freak) waves exceeding 13 m in height were observed in October 2009 and three extreme waves around 20 m in height were observed in October 2012 and in January 2013. These extreme events are associated with passages of a typhoon and a mid-latitude cyclone.

The two rogue waves recorded on 26 and 27 October 2009 had distinct directional characteristics, former being narrow and latter being broad. On October 4, 2012, extreme waves of 22.8 m ($H_{1/3}$ = 13.4 m), and 17.3 m wave height ($H_{1/3}$ = 10.3 m) were registered during passage of typhoon while on January 14, 2013, an extreme wave height 17.7 m ($H_{1/3}$ = 10.0 m) was observed during passage of a bomb cyclone. These three waves were not rogue waves with regard to maximum height factor criterion (HF > 2), the wave crest criterion is not reported by Waseda et al. (2014). Up to 6% of observations collected in a few months in 2009, 2012 and 2013 represented rogue waves, but they were recorded in the intermediate sea states (the average $H_{1/3}$ = 2.7–5.6 m). The authors suggest that a direct measurement of extreme wave by GPS sensor might become an attractive alternative for observing extreme waves offshore. The accuracy of such measurement depends on how well the platform follows the wave motion.

Rogue waves have been also recorded by the wave buoy SBF3-1 in the sea area of mainland Jiangsu, China (Wang et al., 2014) but the wave heights have not been high.

Wave records are often limited to 20-minutes and therefore parameters derived from these records are affected by sampling variability, the statistical uncertainty due to limited number of observations. Bitner-Gregersen and Magnusson (2014) have provided estimates of sampling variability associated with significant wave height and zero-crossing wave period based on measurements from the Ekofisk field in central North Sea. The calculated sampling variability shows the same trend as the theoretical values due to (Bitner-Gregersen and Hagen, 1990). The sampling variability is higher in H_s than in T_z and both increase with increasing H_s and T_z. It is anticipate that sampling variability depent on the shape of a wave spectrum; the JONSWAP spectrum gives higher variability than the Pierson-Moskowitz spectrum. The authors demonstrated the impact of intrinsic and sampling variability on short-term and long-term description of ocean waves as well as validation of wave spectral models. The intention of the study has been to put again attention to intrinsic and sampling variability and to remind practitioners that sampling variability must be taken into account for accurate use of wave measurements.

The limited duration of wind and waves time series has allowed adopting an assumption of stationarity on which most of wind and waves models is based today. However, conditions such as e.g. wind-sea developing as rapidly-moving tropical cyclones or hurricane passes will not be stationary (Ewans, 2014, Bitner-Gregersen et al., 2014b). Ewans (2014) examined the stationarity (determined from the run test) of 12-months' Directional Waverider data recorded at the US Corp of Army Engineers' Field Research Facility at Duck, North Carolina. He found the vast majority of the records were stationary up to 160 min. Non-stationary records have been generally associated with changing wind-sea conditions occurring with local wave growth.

2.2.2 Remotely sensed wave measurements

Investigations aiming at providing satellite wave products for users are continuously going on. The GlobWave project (www.globwave.org), reported in the previous Committee I.1 Report, has been an interesting initiative funded by the European Space Agency (ESA) to service the needs of satellite wave product users.

Work was conducted over the years at CERSAT so as to provide relevant validated altimeter data sets. As a major outcome of this work, altimeter significant wave height (SWH) measurements are presently available almost continuously over a 20-year time period from the eight altimeter missions ERS-1&2, TOPEX-Poseidon, GEOSAT Follow-On (GFO), Jason-1, Jason-2, ENVISAT and CryoSat. Each altimeter data product has specific characteristics (format, flags), and in order to facilitate the access to SWH altimeter measurements and the use of this long time series, data were extracted from the original products, screened according to quality flag values, corrected and gathered into homogeneous daily data files (Queffeulou, 2013).

SWH data from the CryoSat-2 IGDR data sets produced and provided by the NOAA Laboratory for Satellite Altimetry (ftp://ibis.grdl.noaa.gov/pub/cs2igdr/), both low rate mode (LRM) and Pseudo LRM were validated using comparisons with collocated altimeter measurements from Jason-1, Jason-2 and ENVISAT RA-2. They were implemented in the data base. Additionally, preliminary results of the validation work of the SARAL AltiKa, launched in February 2013, are provided by the author, showing a very high accuracy of the AltiKa SWH (Significant Wave Height) measurement.

A well-known interest of remote sensing is the ability it offers to assess wave trains propagation across oceanic basins. For instance Young et al. (2013) analyzed altimeter data from transects across the Southern Ocean to determine the decay of oceanic swell. They observed that the decay rate is shown to be proportional to wavenumber squared and swell amplitude cubed, confirming previous work by Ardhuin (2009) and Babanin (2012). This decay relationship is consistent with turbulent interaction with the background, either in the air or water and is in agreement with the limited previous studies. It presents a source term suitable for use in wave prediction models.

However, coverage offered by satellite altimeters and space-borne Synthetic Aperture Radars is still sparse and spectrally limited. In order to compensate for this, various authors investigate the possibility of extracting relevant information from seismic noise data to complement the remote sensing information(Ardhuin et al., 2012). Especially, Husson et al. (2013) analyze the signature of one swell event in the seismic noise recorded all around the Pacific and show that it is a natural complement to the global coverage provided by the Synthetic Aperture Radar wave mode data from ENVISAT. The great sensitivity of seismometers to very long waves allowed revealing the presence of swell forerunners when arriving to the coast, which by default are not detected by the SAR.

Analysis of the available SAR archives allows assessment of various specific features affecting wave propagation. Using an archive of satellite ENVISAT ASAR images acquired for a period of about five years, 2007–2011, over the White Sea and during periods when the water column was thermally stratified, Koslov et al. (2014) identified and analyzed internal waves having a variety of spatial scales, propagation directions and interpacket distances. Assumption that observed nonlinear internal waves group (IWs) are generated at the consequent tidal cycles by the interaction of relatively strong barotropic tidal flow with the frontal area located over the bank in the SW Gorlo Strait seems to be confirmed by the results of the numerical model used to calculate the propagation of NIW packets generated in the SW Gorlo Strait which agrees with the SAR observations and confirms the strong influence of M2 tidal cycles.

Using airborne and spaceborne interferometric synthetic aperture radars (InSARs) allowing surface velocity measurements at very high spatial resolutions over a large area, Hwang et al. (2013) investigated the breaking process over a coastal zone. Breaking can be detected by mean of various methods among which the analysis of surface roughness decorelation. They show that the breaking fraction is strongly correlated to the wind sea mean square slope, in agreement with previous observations showing that the breaking length scale is considerably shorter than the dominant wavelength.

The 2013 Ocean Surface Topography Science Team (Willis and Bonnefond, 2013). Meeting was held in Boulder, CO on October 8-11. The primary objectives of the OSTST Meeting were to provide updates on the status of Jason-1 and OSTM/Jason-2, conduct splinter meetings on the various corrections and altimetry data products, and discuss the science requirements for future altimetry missions.

2.2.3 Numerical modelling to complement measured data

Numerical wave models used for forecasting or building hindcast databases are under constant evolution (see Section 3.2.3). Hindcast data (or corrected hindcast) are often used and they remain to be the main source of metocean data for design and operational planning as well as for establishing joint environmental description. Locations where high quality in-situ data are available are sparsely distributed, since buoy and platform data are geographically limited, and though satellite observations offer global coverage, they suffer from temporal sparsity and intermittency, making estimation of long term distributions and extreme analysis difficult. The corrected hindcast may be unbiased on average but still can be corrupted by other types of errors, which introduce a bias in the estimated return values of extreme sea states.

The limitation of the hindcast data has been for some time a lack of validation of numerical wave models with instrumented data of significant wave height beyond 12 meters, but such data have started to exist and used in the validation work recently. They confirm that 3rd Generation wave models are capable of accurately hindcasting significant wave heights also in very extreme storms, see e.g. (ISSC, 2012, Cardone et al., 2014).

As mentioned in Section 2.3.1 the recently updated or new developed metocean databases such as: ERA-Interim, ERA-Clim, CFSR, NORA10, GROW12, HIPOCAS, BMT-ARGOSS and Fugro-OCEANOR include information about both wind and waves and quality of these data bases is under continuous improvement. ERA-Interim, ERA-Clim and CFSR databases have higher resolution and improved forcing with better quality-control of assimilated data, see e.g. (Aarnes et al., 2012, Cardone et al., 2014). In the extra-tropics these hindcasts can be expected to provide good estimates of the wave climate, especially for the highest waves, whereas ship observations (collected since 1854) of the highest waves are notoriously unreliable, and may be subject to some fair-weather bias (ship observations are discussed in Section 6.1 Design). The hindcast models are somewhat less reliable in the tropics, but for tropical storms the waves are less extreme and do not define the design criteria for a sailing ship but may define design criteria for offshore structures. Some recent result showing accuracy of hindcast models in extratropical storms is presented e.g. by Ponce de Leon and Guedes Soares (2014) and in Ponce de Leon et al. (2014).

It is expected that hindcast data compare more satisfactory with measurements in conditions which are lower than the design metocean conditions. Further, predictions giving by different metocean databases may also be more consistent in these conditions but this is not sufficiently documented yet and new investigations are called for.

Due to development of computers wave frequency-directional wave spectra have started to be archived by met-offices opening new possibilities for environmental modelling as well as design and marine operations.

2.2.4 Wave description from measured ship motions

Nielsen and Stredulinsky (2012) showed that it is possible to estimate the wave spectrum at the location of an advancing ship by processing its wave-induced responses similar to the situation of a traditional wave rider buoy. The study utilized a large set of full-scale motion measurements and the authors were able to compute fairly accurate estimates of integrated sea state parameters when compared to corresponding estimates from real wave rider buoys. The complete distribution of wave energy was also compared and showed poorer agreement. The authors compared also their ship motion based estimates to observations obtained from a commercial wave radar and showed that for the studied data set, the motion based estimate provided, on average, slightly better sea state estimates than the wave radar system.

2.3 Current

Current data are important for studying ocean dynamics but also for the marine structure design and operations. Information about current profile and velocities is of particular interest for structures that are sensitive to currents, such as e.g. risers, riser towers, export lines, pipelines and umbilicals, especially in connection with possible occurrences of vortex-induced-vibration (VIV) effects. Developments taken place within renewable energy have brought the need for new current measurements as well as numerical current data. Several studies showing how current energy can be utilized can be found e.g. in the OMAE 2012, OMAE 2013 and OMAE 2014 Conference Proceedings. The most common categories of ocean currents are: wind generated currents, tidal currents, circulational currents, loop and eddy currents, soliton currents, longshore currents (DNV, 2014). Important characteristics of current field include mean current speed, eddies, variations of current with water depth and current direction.

2.3.1 In-situ current measurements

Acoustic measurement techniques (both coherent and incoherent) for in-situ sensing of ocean current offer an excellent space-time resolution of the velocity profile (Bitner-Gregersen et al., 2014a).

Ocean current observations can be found at a number of web-sites. NOAA's National Oceanographic Data Center (NODC), http://www.nodc.noaa.gov/, provides current data from a number of sources as does the Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency), http://www.bsh.de/en/index.jsp, of the German Federal Ministry of Transport, Building and Urban Development. The Southern Oscillation Index/El Nino web site, http://www.pmel.noaa.gov/tao/elnino/nino-home.html provides access to a number of links to a number of data products including surface currents.

The utilisation of the Kuroshio Current power has initiated several measurements campaigns in Japan and Taiwan. Kodaira et al. (2013) conducted an Acoustic Doppler Current Profiler (ADCP) measurement around the island that revealed enhanced current speed of the Kuroshio Current under topographic influences. Concurrent measurement by SAR revealed strong radar scatter where the current shear is strong.

Studies of the Loop Current carried out in the JIP DeepStar included the first measurements of the loop inflow and turbulence and evaluation of existing numerical models, (Cooper et al., 2013). The Loop Current is a strong permanent current that flows through the Yucatan Straits, loops northward, and then exits through the Florida Straits where it is renamed as the Gulf Stream. In DeepStart the first time focus was given on measuring the flow of the Loop through the Yucatan Straits providing fundamental information that had never been gathered. The investigations showed that many of the models used were much worse than simply assuming that the loop current remained unchanged (persistence). Further, it was documented that the models were primarily limited by the accuracy of their initial conditions. These findings have been utilized in other marine industry efforts to improve forecast models.

New measurements of current in the Brazilian waters have been reported during the term of the Committee. Current data measured by an instrumented mooring line deployed at the Santos Basin, in a water depth of 2200 m, show a mean velocity of 0.20 m/s with no preferential direction, (Andrioni et al., 2012). Peak velocities 3–4 times higher than the average in a 3-year time series measured at the Santos Basin, on Lula field have been identified associated with the passage of eddies dipoles. Current speeds up to 1.2 m/s at the first hundred meters of the water column have been generated.

Ceccopieri and Silveira (2012) used 2-year recorded current data series from an oceanographic mooring array (F2200) at Lula Field to study the vertical variability of the ocean flows in this area. This variability represents essentially the 1st baroclinic mode and a large part of it occupies the first 400–600 m water depth, with no predominant direction. It has been observed that the significant directional variability over the São Paulo Plateau occurs far away from the mean current jets that flow parallel to the continental shelf geometry. Further, significant seawater column seasonal stratification has been found.

2.3.2 Remotely sensed current measurements

Near-realtime global ocean surface currents derived from satellite altimeter and scatterometer data can be found at NOAA's Ocean Surface Current Analyses–Real Time (OSCAR) web site (http://www.oscar.noaa.gov/index.html). The data is validated against moored and floating buoy data, and the method to derive surface currents with satellite altimeter and scatterometer data is the outcome of several years NASA sponsored research.

2.3.3 Numerical modelling to complement measured data

Ocean model outputs have been used after the incident at the Deepwater Horizon platform in April 2010 in the Gulf of Mexico to trace spilled oil in the Gulf Stream, and to trace debris and radioactive materials after the earthquake and tsunami incidents on 11 March 2011 in north east Japan, see e.g. (Aoyama et al., 2012), (Tsumune et al., 2012), providing promising results. In Massonnet et al. (2013) comparison of predictions of five ocean models can be found.

2.4 Sea water level

Sea level variations have got special attention in the last decade due to the ongoing debate about climate change. The sea level changes have been geographically non-uniform in the past and climate projections show that they will be also in the future (see Section 4.1.4). They have little effects on ship design directly but have impact on design and operations of offshore and coastal installations and may influence ship operations (e.g. due to changes of harbour depth).

Sea level variations are collected by gauges, remote sensing techniques or generated by numerical models.

2.4.1 Locally sensed sea water level measurements

Sea level observations by tide gauges are restricted to the coastal region and because of the natural geographical inhomogeneity of the sea level rise; the global average sea level estimates become erroneous. An obvious source of error of long-term sea level trends from in-situ measurements is the change of the terrestrial reference frame which needs always to be checked.

2.4.2 Remotely sensed sea water level measurements

Satellite altimetry provides a means to measure directly the global sea surface topography and its accuracy depends on the spatial scale. Although altimetry is not able to provide local short scale sea level monitoring, it provides the long-term mean sea level change at global scale.

2.4.3 Numerical modelling to complement measured data

Numerical modelling can provide historical data sets which are essential for the analysis of long-term sea level variations for marine and renewable energy applications.

Several studies have been carried out to project future sea water level changes using GCM (Global Climate Model) or RCM (Regional Climate Model) models (see Section 4.1.4). The degree to which GCM, or RCM, have sufficient resolution and/or internal physics to realistically capture the meteorological forcing responsible for storm surges is regionally dependent.

2.5 Ice and snow

Trends in the Arctic and Antarctic regional climate are largely investigated as they are considered markers of global climate change. Ice and snow melting conditions are analyzed mostly from remote sensing and in-situ data. Sea ice evolution is also widely studied and large efforts have been made to develop and validate coupled ice-ocean models. Changes of ice conditions are reported in Section 4.1.3.

2.5.1 Locally and remotely sensed ice and snow measurements

Barrand et al. (2013) used a data set combining in situ meteorological observations, spaceborne scatterometer data (QuickScat), together with output from simulations of a regional climate model, RACMO2, to analyze the melting conditions on the Antarctic Peninsula. Trends of the positive degree day (PDD) sum were found largely positive at most stations. QuickScat data analysis showed that melt was typically more variable over ice shelves than grounded ice but that no evident link was identified between early melt season onset and ice shelf retreat or breakup events. However ice-shelf break-up or retreat events were found to coincide with longer melt season durations. Finally QSCAT melt extent in the Antarctic Peninsula was shown to be strongly correlated with the October–January averaged SAM index, linking AP melt trends to large-scale (global) modes of atmospheric variability.

Using CryoSat-2 data acquired between November 2010 and September 2013 and adapting a repeat-track method, McMillan et al. (2012) produced the first altimeter-derived estimates of volume and mass change for the entire Antarctic ice sheet. Based on analysis of this new data set that provides near-continuous (96%) coverage of the entire continent, extending to within 215 km of the South Pole and leading to a fivefold increase in the sampling of coastal regions, the authors estimate that, since 2010, the average Antarctic ice sheet contribution to global sea level rise has been 0.45 ± 0.14 mmyr^{-1}, a value, which is more than twice as large as the 20 year mean determined from an ensemble of geodetic techniques.

Comiso and D.K. (2014) provide a general assessment of the current state of the Arctic climate as derived from historical satellite and in-situ data, as reflected in its major components, temperature, sea ice cover and snow cover. They indicate that warming in the Arctic has been amplified, as expected from ice-albedo feedback and other effects and as predicted by models, with a rate of warming increasing of about 0.6^{o}C/decade in the Arctic during the period 1981 to 2012. They also list some requirements for future observations, as for instance ice thickness and snow cover as well as for the development of numerical models incorporating the physics of the system and able to simulate the observed variability and trends of the various parameters in the system.

Low-resolution remotely sensed sea ice drift products are widely used for various purposes such as validation of coupled ocean-sea ice models, model parameter estimation and data assimilation in the Arctic Ocean. Sumata et al. (2014) made an intercomparison of four different Arctic Ocean low-resolution ice-drift products derived from satellite observations, and also examined their differences to buoy drift data. The products are inferred from different sensors with different time and space scales, and different motion-tracking algorithms so that the data was processed to monthly mean vectors so as to standardize the temporal representation. This comparison provides practical information to data users as well as uncertainty estimates. Even though the transpolar drift speed differs among the products by 13% on average and differences among the products are not spatially uniform, all the products are considered by the authors as practical and useful for model validation and data assimilation, providing that the uncertainty and error statistics are given in a proper way.

CERSAT provides a new database, Altiberg, which contains the small iceberg (<3km in length) detected by altimeters using the high resolution waveforms. The level 2 products are the individual detected iceberg files. The level 3 product contains Antarctic polar stereographic 100 km resolution grids of monthly volume of ice, probability of presence of icebergs and mean iceberg area. The database is also available for other several altimeter mission (ERS-1, ERS-2, Jason-1, Jason-2, CryoSat-2, Topex, Envisat, AltiKa). A merged product combining all the available altimeters is also provided.

2.5.2 Numerical modelling to complement measured data

As important decreases in Arctic sea ice are predicted by some climate models it is critical to assess the accuracy and reliability of high-latitude climate forecasts. This requires a better understanding of sea ice dynamics and thermodynamics through the proper simulation of sea ice and its responses to atmospheric forcing across a range of temporal and spatial scales. Johnson et al. (2012) assessed the ability of six coupled Arctic Ocean Model Intercomparison Project (AOMIP) models to simulate sea ice thickness and to identify trends. Sea ice thickness from six AOMIP models was compared with thickness across the Arctic basin from various remote and in-situ measurement data sets. Authors indicate that on the one hand the models overestimate thickness of ice thinner than 2 m, which is problematic for forecasting areas of open water and perhaps the timing of the seasonal cycle, and on the other hand they underestimate the thickness of measured ice thicker than 2 m possibly hindering long-term forecasts where the proper role of multi-year ice is critical.

With about the same objective, Lindsay et al. (2013) evaluated seven different atmospheric reanalysis in the Arctic regions and compared four data sets for use in simulating past sea ice conditions. Sea ice thickness and total ice volume were computed with the PIOMAS coupled ice–ocean model. Obtained results are broadly similar even though one atmospheric model provided a better agreement than the others with submarine ice draft measurements.

Wave propagation through ice and in ice covered waters is rather intensively investigated. Campbell et al. (2014) used a stereo imaging system to analyze propagation of waves interacting with three different types of ice. Alteration of the frequency content of the wave spectra together with the damping of the energy flux is found to be ice quality dependent. It is also noted that wave reflection is observed at the boundary of each ice layer.

Meylan et al. (2014) analyzed wave propagation in the Antarctic marginal ice zone (MIZ) from in situ measurements of ocean surface wave spectra. Analysis of the measurements provided by an array of five wave sensors shows significant wave heights and peak periods do not vary appreciably in approximately the first 80 km of the ice-covered ocean where dominant floe sizes are less than 6 m and ice concentrations are relatively low. Beyond this region, where dominant floe sizes are greater than 10 m and concentrations are higher, significant wave heights is found to decay whilst peak periods increase. Attenuation rates are investigated and found to be insensitive to amplitudes for long-period waves but to increase with increasing amplitude above some critical amplitude for short-period waves. They also decrease with increasing wave period. Further, for long-period waves the decrease is shown to be proportional to the inverse of the period squared. This relationship can be used to efficiently implement wave attenuation through the marginal ice zone in ocean-scale wave models.

Unlike the rapid sea ice losses reported in the Arctic, satellite observations show an overall increase in Antarctic sea ice concentration over recent decades. However, observations of decadal trends in Antarctic ice thickness, and hence ice volume, do not currently exists. Holland et al. (2014) use a model of the Southern Ocean and its sea ice, forced by atmospheric reanalysis to assess 1992–2010 trends in ice thickness and volume. The model successfully reproduces observations of mean ice concentration, thickness, and drift, and decadal trends in ice concentration and drift, imparting some confidence in the hindcasted trends in ice thickness. The small overall increase in modeled ice volume is actually the residual of much larger opposing regional trends. Even though the reasons these regional patterns of changes that produces the overall increase in ice cover are not well known and proposed drivers are numerous, the model results presented by the authors reproduce observations of mean ice concentration, drift, and thickness, as well as trends in ice concentration and drift. Additionally, the simulated ice thickness trends also agree with those of Masumoto et al. (2012), which can be regarded as a best estimate because of their use of data assimilation.

3. ENVIRONMENTAL MODELS

The environmental description often employs a mixture of mathematical, probabilistic, empirical and statistical models. The following “decoupling” approach is commonly used. It is assumed that for a limited period of time and in a particular geographical region metocean conditions vary in a stationary way called sea state. Metocean conditions in a sea state can be described by means of mathematical models depending on a number of characteristic parameters. Changes of sea state parameters, which vary much slower than sea waves, wind, currents, sea water level and some ice characteristics, are modelled by means of probabilities. The final description of environmental conditions is obtained by combining the models for sea states evolution with the description of sea waves, wind, current, sea water level and ice in a sea state.

The increasing awareness of importance of environmental uncertainties for safety at sea is contributing to increased number of benchmark studies where performance of different models is compared and evaluated (e.g. the 2nd ITTC-ISSC Workshop). Both academia and industry is participating in these studies. However, specification of model uncertainty is not an easy task. Model uncertainty is due to imperfections and idealisations made in physical process formulations as well as in choices of probability distribution types and fitting techniques applied for estimation of distribution parameters, see (Bitner-Gregersen et al., 2014a). Several errors can contribute to model uncertainty each defined as the ratio between the true quantity and the quantity as predicted by the model. A mean value not equal to1.0 expresses a bias. The standard deviation expresses the variability of the predictions by the model. Experimental tests, field tests or the average values of recognized models (or weighted models) are used often as a reference value (the true value).

Most of the probabilistic and hybrid models are based today on the assumption of stationarity and homogeneity which can be questioned in certain conditions (see Section 2) and may have significant impact on model predictions. Attention to this model uncertainty has been given in the course of the Committee, e.g. (Bitner-Gregersen et al., 2014b).

3.1 Wind

The classical modelling approach for engineering applications is to fit the probability distribution to a known model and estimate statistical parameters such as the mean and variance. The common statistical description techniques have some drawbacks as they lack the time variation properties and ignore cross-dependencies between other meteorological data. No important changes to the statistical and spectral description of wind have taken place in recent years. Wind models commonly applied can be found, e.g. in Legacy DNV RP-C205 (DNV, 2014) and Legacy DNV-OS-J101 (DNV, 2011). The importance of accounting for non-stationarity have been stressed during the period of the Committee. Also the homogeneity assumption needs to be revisited in the future, particularly due to renewable energy installations. CFD (Computational Fluid Dynamics) methodology is getting increasing attention in modelling of wind conditions.

3.1.1 Analytical description of wind

As a result of social awareness of air emission due to use of fossil fuels, the utilization of the natural wind power resources becomes an important option to avoid the dependence on fossil resources in industrial activities. For example, the maritime industry, which is responsible for more than 90% of the world trade transport, has already started to look for solutions to use wind power as auxiliary propulsion for ships. The practical installation of the wind facilities often requires large amount of investment, while uncertainties for the corresponding energy gains are large. Therefore a reliable models to describe the variability of wind speeds in time and large geographical regions are needed to estimate the expected available wind power, coefficient of the variation of the power and other statistics of interest, e.g. expected length of the wind conditions favourable for the wind-energy harvesting.

Most models considers time series of wind data at fixed locations or in space keeping the time fixed. Modelling spatial and temporal dependence of wind speed U_w, is a very complex problem. Often one proposes to use the transformed Gaussian model, which assumes that there exists a deterministic function G, possibly dependent on location, such that $X = G(U_w)$ has Gaussain CDF. In Ailliot and Monbet (2012) a switching Markov model has been used to describe the dependence structure of wind speed data. The advantage of the model is that it uses a number of typical weather conditions to include meteorological information into the description wind speed variability. The limitation is the complexity of the model which limits its applicability to relatively small regions. In Rychlik and Mustedanagic (2013) a global non-stationary model for wind speeds variability has been proposed. In this work the transformed wind speed $X = G(U_w)$ is a non-stationary and non-homogeneous Gaussian field. The model is defined by means of its mean values, variances and the covariances. The global covariances depends on local parameters which are covariances of wind speeds gradient. The model was applied in Rychlik and Mao (2014) to describe statistical properties of wind speeds encountered by vessels along commercial routes. Measured wind speeds on-board Wallenius Lines AB ships were used to validate the model.

Installations of wind-harvesting equipment's on-board of a vessel raise a question of structural safety. In order to analyse the relevant loads both wind speed and wind direction is needed. Modelling wind velocity in time and space is much harder problem than considering just wind speed. The reason is the complex dependence between wind speed and the direction which cannot be described using the transformed Gaussian models. In Ailliot et al. (2014) a spatio-temporal model for wind velocities has been proposed. It is a generalization of the model proposed in Ailliot and Monbet (2012) and hence also limited to small geographical regions.

The parameters in models presented in Ailliot and Monbet (2012), Rychlik and Mustedanagic (2013), Rychlik and Mao (2014) and Ailliot et al. (2014) are all estimated using ERA-Interim data Dee et al. (2011) produced by European Centre for Medium-Range Weather Forecasts.

Muyau et al. (2014) have investigated wind data sampled at 1 Hz from three offshore locations off the west coast of Borneo and one onshore location (see Section 2.1.1) which included mainly monsoon conditions. The data set analysed consisted of 5952 1-h records. The authors have found that none of their 1 Hz data records was stationary over one hour, and even when the 1 Hz data were averaged over longer intervals, no records of 3-second means were found to be stationary, and only 14% of the records of 1-min means were found to be stationary. The results indicate that application of fixed short-term wind relationships is questionable.

3.1.2 Statistical and spectral description of wind

Wind, waves and current are the most important environmental loads that act on ships and offshore structures. Statistical descriptions of the loads are often used in evaluation of reliability of structures details as well as safety of marine activities. A standard model of the loads assumes that those are stationary for a period of time lasting from 10 minutes to several hours. During such periods properties of loads (time series) are described by means of their average values and power spectral densities (PSD). A Gaussian, or transformed Gaussian, model is commonly used. This is convenient since the loads are then uniquely defined by the mean, PSD and transformation, if the transformed Gaussian model is employed.

Several parametric families of PSD, i.e. functions of sea state parameters like; significant wave height H_s; peak period T_p, some parameters that describing waves directional spreading, average wind speed U_w, turbulence intensity, gust factor and other, exist. Means to simulate Gaussian time series are well established. The simulated time series of artificial loads are then used to study responses of structures, ships etc. During the period 2012–2014 there were a number of papers published presenting studies of responses of offshore located wind mills, mooring lines etc. to the combine wind and wave loads. In several papers one was choosing some typical values of sea states and wind parameters focusing mostly on derivation of responses. Those papers will not be included in the present summary of the research on environmental conditions.

The stationarity periods are very short compared to length of maritime operations or life of a structure details. Consequently the parameters defining PSD forms time series that long-term variability needs to be appropriately modelled. While marginal models for sea states or winds parameters are well established the multivalued models for joint sea-states wind parameters variability are still under development. Two types of applications are commonly met in the literature; reliability assessments or estimation of available energy at offshore located wind mills and safety of structures or maritime operations. In the first type of problems the general variability of environmental loads are of interest including both common and rare values of parameters. In the second type of problems the focus is on extreme cases which can lead to failures and for "safe" structures or operations are rarely encountered.

In Li et al. (2013) the authors have presented a model for the joint PDF (Probability Density Function) of mean wind speed U_w, significant wave height H_s and peak period T_p. The long-term PDF of U_w was assumed to be Weibull, the conditional PDF of H_s given U_w were also Weibull with parameters being a polynomial functions of the mean wind speed. Finally, the conditional distribution of T_p given U_w and H_s was lognormal with parameters dependent on the mean wind and significant wave heights. The joint PDF were fitted to the 10 years of hindcast data in several locations in Atlantic Ocean along European coast. For extreme responses analysis the authors proposed to use the 50-year contour surfaces of the fitted joint PDF. Another approach was presented in Tao et al. (2013b). In that work the authors proposed to use copulas to model the joint PDF of U_w and H_s. This is an approach to introduce dependence between non-Gaussian variables when marginal PDFs are known. Basically one is first specifying marginal PDFs for U_w and H_s and then the joint PDF for the parameters is modelled by means of an appropriately chosen function (copula) of the marginal PDFs.

Finding an appropriate model for a joint PDF of extreme parameter values is a difficult problem. First of all data are sparse and has to be gathered over long time periods. Secondly the data may not be stationary or homogeneous. Modelling multivalued extremes is an active research field in statistics. One way to model variability of extreme values, e.g. having 100 years return, when there are not sufficiently many observations is to fit a joint PDF to the available data and extrapolate PDF to the regions were data are missing. This approach was used in Li et al. (2013) and Tao et al. (2013b). The method relies on assumptions that a chosen PDF fits correctly data both in central region, dominating the fit, and in tails for which there are often only few observation available. This may not be the case and hence if distribution of extreme values are of major interest, then one should look for the tailored models, valid solely in the tails.

One often taken approach is to select "extreme episodes", for example severe storms, and propose a PDF for the observed environmental parameters. Such an approach was taken in Towe et al. (2013) where one was modeling variability of extreme H_s and U_w values. In the paper the authors assumes that the marginally H_s and U_w have extreme value distribution (Fréche). Then means to model and estimate dependence measures for bivariate extremes were presented. The analysis was further generalized by introducing covariates which allows to deal with the cases when data are not stationary (homogeneous). The method was validated using the hindcast data at three locations in North Sea. It was shown that storm direction is important covariate and that extreme wind speed and significant wave height are dependent.

Another modelling approach was presented in Naess and Karpa (2013). In that paper the authors extended the ACER method (Naess and Karpa, 2013) to estimate the extreme quantiles to cover the bivariate data. Wind speed and significant wave height data were considered. The hindcast at some location close to Norway coast were used for validation. The method applies to time series and no extraction of storms is needed. Finally the estimates of ACER empirical surface was extrapolated to very high quantiles by means of a fit of a parametric function to the empirical ACER.

All the work discussed above used hindcast or buoys to study the distributions of wind speed or significant wave height. The hindcast or reanalysis do not represent actual measurements of quantities but extrapolations to the grid locations based on simulations from complex dynamical models. It is defined on regular grids in time and space and hence convenient to use. Often the data has to be calibrated using in situ measurements before these can be used. In Young et al. (2013) the satellite measurements of wind speed and significant wave height were used to estimate the 100 years return wind speeds and significant wave heights. The trends in these values were also identified and used in prediction of the future return values over the globe.

The practical installation of the wind facilities often requires large amount of investment, while uncertainties for the corresponding energy gains are large. Therefore a reliable models to describe the variability of wind speeds in time and large geographical regions are needed to estimate the expected available wind power, coefficient of the variation of the power and other statistics of interest, e.g. expected length of the wind conditions favourable for the wind-energy harvesting.

Roughly the average available wind power during a stationarity period is proportional to average wind speed raised to power three hence an accurate long-term distributions of wind speed at one or simultaneously at several positions are of interest. There exists several complex numerical programs to reconstruct wind fields using ocean-atmosphere models based on large-scale meteorological data, called hindcast or reanalysis. In Salvacao et al. (2013) the authors presented a study in which results derived by means of the mesoscale model WRF, a regional non-hydrostatic model and ERA-Interim data (Dee et al., 2011), were calibrated using some buoy measurements. The method was validated and shown to be useful to derive the long-term distributions of wind speeds and directions along the Portuguese coast. In the calibration process a relation between the average wind speeds and height above the ground is needed. In Babanin and McConochi (2013) wind measurements near surface of waves was studied and the accuracy of the relation was investigated. The conclusion was that one needs to be cautious when extrapolating the wind speeds measured by buoys to e.g. 10 meters. For example if the logarithmic law is used then U_{10} could be overestimated. In Trombe et al. (2013) results of an experiment where weather radars were used for monitoring the weather at the Horns-Rev offshore wind farm, in the North Sea were presented. Use of the weather radar enabled the collection of meteorological observations at high spatio-temporal resolutions for enhancing the understanding of meteorological phenomena that drive wind fluctuations. The measured environment provided relevant inputs to prediction systems for anticipating changes in the wind fluctuation dynamics, generating improved wind power forecasts.

In the field of energy production prediction models of wind vector characteristics are needed in order to supervise and optimize the electricity generation and planning. Prediction by means of time series of wind speeds have been extensively studied in the literature. For example a model for very short-term probabilistic forecasts (essential for an optimal management of wind generation) was presented in Pinton (2012). The author used mixtures of generalized Lognormal distributions combined with autoregressive and conditional parametric autoregressive models to predicts wind speeds. Another innovative approach was presented in Stefanakos et al. (2014) where fuzzy time series techniques were applied to forecast wind speeds. The efficiency of the method has been compared with the forecasting using more traditional ARIMA models.

3.2 Waves

The wave spectral models remain being continuously developed. The GlobWave project initiated by ESA in 2008 to improve the uptake of satellite-derived wind-wave and swell data is still on going. The present status of the ESA GlobWave project making satellite derived data more widely available is on http://globwave.ifremer.fr/Products/Summary-of-Services and the GLOBWAVE Data Handbook on the project web site (http://www.globwave.org/).

The knowledge of extreme and rogue waves has advanced since the 2012. The predictions made by theoretical and numerical models compare well with experimental results. Attention has been given during the period of the Committee to including forcing sources such as wind and wave breaking in nonlinear wave models and to studying wave-current interaction. Scale effects in model tests of extreme waves has been in increasing focus.

Some progress has been made on long-term description of sea states, particularly on directionality of several wave systems and spatial-temporal models of sea surface characterists. Also shallow water effects are getting increasing attention due to the needs of renewable energy industry and adaptation to climate change.

3.2.1 Analytical and numerical wave models

The WAM model and the WAVEWATCH-III model are the most generalized and tested wave prediction models used for both hindcasting and forecasting purposes. Although both WAM and WAVEWATCH-III are 3rd generation (3G) wave models, they now differ in a number of physical and numerical aspects and may give different predictions. This is an indication that a single “best” solution has not yet been accepted. The SWAN model remains to be used with shallow water wave climate. The quality of numerical wave and surge hindcasts for offshore and coastal areas depends to a large extent on the quality and the accuracy of the upper boundary conditions, i.e. in particular on the quality of the driving wind fields. Recent progress on wave modelling has been presented at the 13th International Workshop on Wave Hindcasting and Forecasting & 4th Coastal Hazard Symposium, taken place 27 Oct.–1 Nov. 2013 in Banff, Canada (http://www.waveworkshop.org/13thWaves/index.htm). Selected papers presented are published in the 2014 Special Issue of Ocean Dynamics.

Efforts to push exclusively non-stationary models such as WAM and WAVEWATCH-III closer to shore reported in ISSC 2012 I.1 Report (ISSC, 2012) have continued during the period of this Committee, e.g. (Tolman, 2013). This development is motivated to avoid learning, maintaining, and running multiple wave models at a given operational centre. Continuous attempts are made also to establish a stronger interaction between the wave and the circulation modelling community important for future development of the wave and circulation models.

Wave models have largely improved over the recent years thanks to new developments in both parameterization, introducing more consistent description of the physics based on observations, and numerical choices. Roland and F. (2014) summarize the most important aspects of these improvements, including the introduction of currents, coastal reflection, and bottom sediment types which are of prime interest for modeling in coastal waters. Most of these improvements were implemented in a new version (4.18) of the code WaveWatch III® which was released in March 2014 by NOAA/NCEP allowing the use of unstructured grids and introducing new parameterizations for wave dissipation together with new parameterizations for bottom friction including movable bed roughness (Tolman and group, 2014). Details on the parameterization and physics that were implemented can be found in earlier papers.

Ardhuin et al. (2012) investigated the description of wave-current interaction in models considering also conditions with strong currents. They showed that including currents in the model resulted in error reductions by up to 30% on the evolution of the significant wave height; even at locations where currents are relatively weak but which are located down-wave of strong current gradients that cause large refraction effects. Leckler et al. (2013) proposed an improved parameterization of energy dissipation by whitecapping taking into account the physical relationship intrinsically linking spontaneous breaking dissipation with dissipation induced by breaking waves.

In parallel to this effort for improvement of the models, operational services were developed and hindcast databases were implemented (see Section 2.2.3).

The National Centers for Environmental Prediction (NCEP) (Chawla et al., 2012) implemented a new global forecast operational system using the third public release of WAVEWATCH III (3.14). This new multi-grid system was designed to provide the National Weather Service (NWS) and NCEP centers with model guidance of suitable resolution for all areas where they have the responsibility of providing gridded forecast products. New important features include two-way nesting between grids and carving out selected areas of the computational domain. This allowed increasing spatial resolution and extending the global domain closer to the North Pole, while at the same time optimizing the computational cost. A spectral partitioning algorithm was also implemented to separate individual sea states from the overall spectrum, thus providing additional products for multiple sea states. This modeling system has been validated against data using a multiyear hindcast database as well as archived forecasts.

A thirty one year wave hindcast (1979–2009) was implemented by Chawla et al. (2012) using NCEP's latest high resolution Climate Forecast System Reanalysis (CFSR) wind and ice database. This hindcast has been generated using the third generation wind wave model WAVEWATCH III (3.14) with a mosaic of 16 two-way nested grids having a resolution ranging from 1/2 to 1/15. Validation made for bulk significant wave height H_s and 10 m (above Mean Sea Level) wind speeds U_{10} comparing with both altimeter records and NDBC buoys showed the general ability of the database to correctly representing the wave climate. Agreement is excellent at most buoys between model and data out to the 99.9th percentile but of better quality at the offshore buoys than at the coastal buoys because of unresolved coastal features (topographic/ bathymetric) as well as issues related to interpolating wind fields at the land-sea margins. It should be noted though that the authors point out some concerns about the wave climate in the Southern Hemisphere due to the over prediction of winds (early part of the database) as well as the lack of wave blocking due to icebergs (in the model).

Another 20 year multi-scale global hindcast database of global wave parameters has been produced, (Rascle 2013), using WaveWatch III with a new parameterization for wave, and forcing from a combination of ECMWF analysis and CFSR reanalyzes, sea ice from CFSR and ECMWF and icebergs from CERSAT. Validation of this database against altimeters and buoys pointed out different features, especially related to wind forcing and in agreement with conclusions by Chawla et al. (2013). CFSR winds were found anomalously high in the Southern Ocean for the years 1991–1993, compared to following years, resulting in anomalous high biases for these years, including off the U.S. West coast. CFSR and NCEP analyses are found to have systematically higher values than ECMWF analyses of the wind speed, especially for the highest speed range.

Even if a simple calibration of the wind wave growth parameter corrected the average to high wave heights, modeled wave heights are found to still be too low for the highest values (Hs > 12 m), likely due to an underestimation of the winds in these conditions. The new parameterization implemented in the model also allowed a more accurate estimation of parameters derived from spectral moments, including the surface Stokes drift and mean square slopes that are relevant for wave–current interactions modeling and remote sensing, and also spectra of seismic noise sources. However air-sea fluxes of momentum and energy are found to be not very realistic and will require adjustments of the future generation and dissipation parameterizations.

As pointed out in the previous papers, quality and accuracy of the wind forcing is important for wave modeling, especially in complex coastal areas. Bricheno et al. (2013) investigated the influence of the accuracy of representation of wind forcing and mean sea level pressure on waves and surges modeling. Running the Weather Research and Forecasting (WRF) model at 12-, 4-, and 1.33-km resolution for a storm event over the Irish Sea they used the outputs to force the coupled hydrodynamic and the Proudman Oceanographic Laboratory Coastal Ocean Modeling System (POLCOMS)–Wave Model (WAM) so as to assess the effect of the forcing on storm surge and waves. They observed an improvement of the wind speed estimation when moving from 12- to 4-km resolution but going to the 1.33 km resolution showed no further significant improvement. Implementing the atmospheric model results at 12 and 4 km as input to the ocean model, wave direction was seen to improve with increased ocean model resolution, and higher-resolution forcing was found to generally increase the wave height over the Irish Sea by up to 40 cm in places. Improved clustering of wave direction was observed when 4-km meteorological forcing was used. Large differences were seen in the coastal zone because of the improved representation of the coastline and, in turn, the atmospheric boundary layer. Hence, the combination of high-resolution atmospheric forcing and a coupled wave–surge model gave the best result.

The effect of the grid resolution on modelling of fetch-limited wave growth has been studied using wave model WAM by Touboul and Pelinovsky (2014). Three different methods to compile a grid for a wave model in the case of an irregular shoreline were discussed. The effect of grid resolution on the growth rate of the wave energy at short fetch was relatively large.

Fan et al. (2012) described a 29-yr (1981–2009) global ocean surface gravity wave simulation generated by a coupled atmosphere-wave model using NOAA/GFDL's High-Resolution Atmosphere Model (HiRAM) and the WAVEWATCH III. The comparisons with satellite altimeter measurements indicated that the significant wave height (SWH) low bias in ERA-40 reanalysis had been improved in these model simulations.

For several decades, the Discrete Interaction Approximation (DIA) for nonlinear resonant four-wave interactions has been the engine of third-generation wind-wave models. Tolman (2013) presented a Generalized Multiple DIA (GMD) which expands upon the DIA by (i) expanding the definition of the representative quadruplet, (ii) formulating the DIA for arbitrary water depths, (iii) providing complimentary deep and shallow water scaling terms and (iv) allowing for multiple representative quadruplets. The GMD is rigorously derived to be an extension of the DIA, and is backward compatible with it. The free parameters of the GMD have been optimized holistically, by optimizing full model behavior in the WAVEWATCH III wave model (Tolman and Grumbine, 2013). The results showed that in deep water, GMD configurations can be found which remove most of the errors of the DIA. The two-scale approximation (TSA) to the full Boltzman integral representation of quadruplet wave-wave interactions has recently been presented as a new method to estimate nonlinear transfer rates in wind waves, and has been tested for idealized spectral data, as well as for observed field measurements (Willis and Bonnefond, 2013). TSA has been implemented in WAVEWATCH III and shown to perform well for wave spectra from field measurements, even for cases with directional energy shearing, compared to the DIA.

Gramstad and Babanin (2014) has made an attempt to include quasi-resonance interaction in the wave model. The results are preliminary but promising and call for further investigations.

A semi-empirical determination of the spectral dependence of the energy dissipation due to surface wave breaking has been studied by Romero et al. (2012) and then used to propose a model for the spectral dependence of the breaking strength parameter *b*, defined in the O.M. Phillips's statistical formulation of wave breaking dynamics. Numerical investigations based on full dynamic equations for wave breaking have been studied by Chalikov and Babanin (2012) in a one-dimensional environment with a wave spectrum. Besides, the role of breaking in an evolving wave field has been studied by Schwendeman et al. (2014).

Importance of high frequency tail in third generation wave models, SWAN and WAVEWATCH-III, has been studied by Siadatmousavi et al. (2012) with different assumptions for high cut-off frequency used to evaluate the interaction of low and high frequency components in wave spectral evolution. The results showed that WAM Cycle 3 was more sensitive to cut-off frequency as well as to the exponent used in the expression for the frequency tail, than other formulations in SWAN. Wang and Jiang (2012) proposed a new spectral dissipation source term which comprises saturation based dissipation above two times of peak frequency and improved whitecapping dissipation at lower frequency spectrum. The reciprocal wave age was involved into the whitecapping model to adjust dissipation rate at different wind speed. The Phillips higher frequency saturation parameter in the saturation-based dissipation was no longer taken as a constant, but varies with wave age. In addition, limiters based on the CFL criteria have been proposed for the spectral propagation velocities in SWAN (Dietrich et al., 2013). These limiters prevented the excessive directional turning and frequency shifting of wave energy and improve accuracy by reducing local errors that would otherwise spread throughout the computational domain. Rascle and Ardhuin (2013) presented a multi-scale global hindcast of ocean waves which covered the years 1994–2012, based on improved source term parameterizations for wind sea and swell dissipation (Ardhuin et al., 2010).

Waves propagating in shallow water dissipate energy in a thin, turbulent boundary layer near the bottom experience friction. This friction can be estimated with a simple quadratic friction law scaled with an empirical coefficient. Two values of this coefficient have been recommended by previous studies (for sandy bottoms): a high value for waves in a storm and a low value for swell. However, the review of a large number of more recent observations by Zijlema et al. (2012) gave a new wind drag parameterization with lower values. Using this lower value also improved the estimates of wave growth in shallow water and of low frequency wave decay in a tidal inlet, independent of the wind drag. Besides, modification of the STWAVE bottom friction coefficients and boundary forcing conditions has been studied on the STWAVE model (Christopher et al., 2013). The results indicated good agreement with the measured nearshore wave data for an open water Manning '*n*' bottom friction coefficient equal to 0.03 s/m$^{0.33}$, and good agreement with the measured inshore wave data with Manning '*n*' bottom friction coefficients equal to values derived from land classification data and applied in the ADCIRC model.

The effect on waves of the Wave-Current Interaction (WCI) process has been studied for wave simulation. Nearshore propagation of cyclonic waves have been simulated (Panigrahi et al.) using state-of-art SWAN model coupled with hydrodynamic model POM (Princeton Ocean Model). Ardhuin et al. (2012) did a study on performance of numerical models in conditions with strong currents. The results showed that wave models can reduce the errors on significant wave heights by more than 30% in some macrotidal environments, such as the coast of Brittany, in France. The structured grid circulation model ROMS has been coupled with the unstructured grid Wind Wave Model II (Dutour-Sikiric, 2013). The chosen models and coupling approach allowed the grids of both models to be chosen independently. In addition, the unstructured-mesh SWAN spectral wave model and the ADCIRC shallow-water circulation model have been integrated into a tightly-coupled SWAN+ADCIRC model (Dietrich et al., 2011). (Dietrich et al., 2012) examined the SWAN+ADCIRC model applied to a high-resolution, 5M-vertex, finite-element SL16 mesh of the Gulf of Mexico and Louisiana. Performance and validation of ADCIRC+SWAN model were also studied by Prasad et al. (2013) and Choi et al. (2013). Their study signified the importance of coupled parallel ADCIRC+SWAN model for operational needs during extreme events.

The University of Miami has presented a Fully Coupled Atmosphere-Wave-Ocean Modeling system (UMCM). The UMCM includes three model components: atmospheric, surface wave, and ocean circulation models. Chen et al. (2007) gave a brief introduction to UMCM and an overview for the coupled modeling effort in the Coupled Boundary Layer Air-Sea Transfer (CBLAST)-Hurricane program. Chen et al. (2013) described the results of a new directional wind–wave- coupling parameterization in a fully coupled model developed based on the CBLAST-Hurricane observations and laboratory measurements. Currently, UMCM can be configured with two different options in terms of component models: 1) coupled with the fifth-generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5), a third generation wave model (WAVEWATCH III), and the three-dimensional Price-Weller-Pinkel (3DPWP) upper ocean model (UMCM-MWP); and 2) coupled with the Weather Research and Forecasting Model (WRF), the University of Miami Wave Model, UMWM, (Donelan et al., 2012), and the Hybrid Coordinate Ocean Model (HYCOM) (UMCM-WMH).

In addition, Li et al. (2012) did an investigation of the effects of wave state and sea spray on an idealized typhoon using an air-sea coupled modeling system. The coupling between atmosphere and sea surface waves considered the effects of wave state and sea sprays on air–sea momentum flux, the atmospheric low-level dissipative heating, and the wave-state-affected sea spray heat flux. Smith et al. (2013) examined tropical cyclone ocean-wave model interactions using an ESMF (Earth System Modeling Framework) based tropical cyclone (TC) version of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). The Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system was used to investigate Semi-enclosed Gulf of Venice (Benetazzo et al., 2013). The results revealed that, when applied to intense storms, the effect of coupling on waves results in variations of significant wave height up to 0.6 m, with some areas experiencing significant increase/decrease of wave spectral energy for opposite/following currents respectively.

Pleskachevsky et al. (2012) investigated the impact of the gustiness on surface waves under storms in the North Sea, focusing on the appearance of wave groups with extreme high amplitude and wavelength. Optical and microwave satellite data were used to connect mesoscale atmospheric turbulences and extreme waves measured near the German coast. Moving atmospheric open cells are observed to produce a local increase in the wind field at the sea surface, moving as a consistent system with a propagation speed near to swell wave-traveling speed which is showed to be the cause for the variability in height and length for wave groups and the probability for individual high waves.

Output from the wave models provides sea state description in a form of the two-dimensional wave spectrum but does not give any information about the instantaneous position of the sea surface in a given sea state. To obtain the latter numerical wave models describing short-term variations of water surface elevation need to be applied. A review of these models for deep, intermediate and shallow water has been presented by the previous Committee I.1 (ISSC, 2012, Bitner-Gregersen et al., 2014a). Further, a recently issued valuable book on wave modelling of Massel (2013) provides an overview of existing wave models. In the present report we concentrate on modelling of extreme and rogue waves.

Extreme and rogue (called also freak or abnormal) waves have been studied extensively in the past few decades and attention to these waves has remained also during the period of this Committee. Osborne, (2010) and Osborne (2013) suggested to group nonlinear waves to:

- Population I–Stokes waves, nonlinear and steep
- Population II–Unstable packets, steep with a narrow band wave spectrum being able to be indetified by the Benjamin-Feir Index, BFI, see (Onorato et al., 2006a).

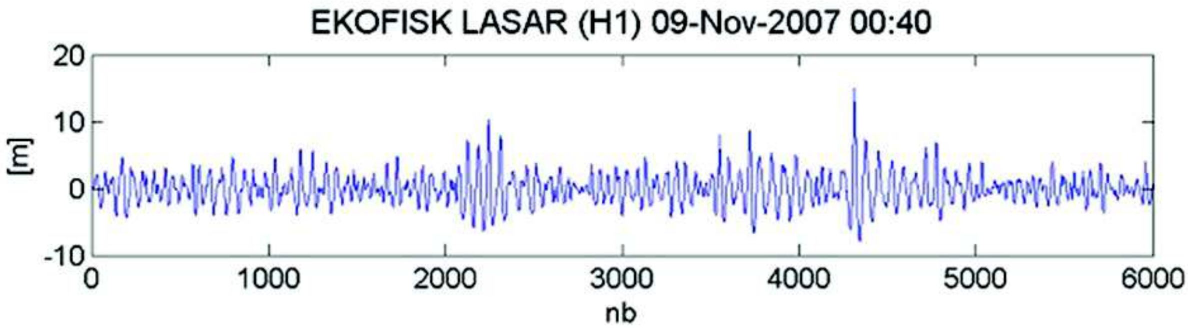

Figure 2. The wave profile time series during the Andrea storm as measured by the laser within 20 min with 5 Hz sampling frequency at the Ekofisk field 9 November 2007, after (Magnusson and Donelan, 2013).

Sea states responsible for formulations of these unstable packets and occurrence of abnormal waves are characterized by large steepness and a narrow wave spectrum, both in frequency and direction. An example of an abnormal wave, being much higher and steeper than the surrounding waves in the record is shown in Figure 2.

A number of studies addressing rogue waves have been conducted theoretically, numerically, experimentally and based on field data. The occurrence of rogue waves, their generation mechanism, and detailed dynamic properties are now becoming clear. The recent state-of-the-art review on mechanisms responsible for generating of these waves can be found in (Onorato et al., 2013), see also e.g. (Bitner-Gregersen et al., 2014c). They can be classified as follows:

- linear Fourier superposition (frequency or angular linear focussing)
- wave–current interactions
- crossing seas
- quasi-resonance nonlinear interactions (modulational instability)
- shallow water effects
- wind.

As demonstrated in the EC EXTREME SEAS project (EXTREME-SEAS, 2013) the numerical codes used satisfactory for description of rogue waves today include: NLS (NonLinear Schrödinger) equation [2D, 3D], Dysthe model [2D, 3D], HOSM (High-Order Spectral Method) [2D, 3D] and Conformal Method [2D] (Figure 3). These codes have been applied and enhanced in EXTREME SEAS and validated towards field and laboratory data. Numerical wave data generated by them compare well with the model test data, e.g. (Toffoli et al., 2011a), (Slunyaev et al., 2012), (Oberhagemann J, 2012), (Bitner-Gregersen and Toffoli, 2012a) and they are capable to reproduce the field data, e.g. (Bitner-Gregersen et al., 2014c). It needs to be mentioned that forcing sources such as wind and wave breaking are not included in the codes presented in Figure 3.

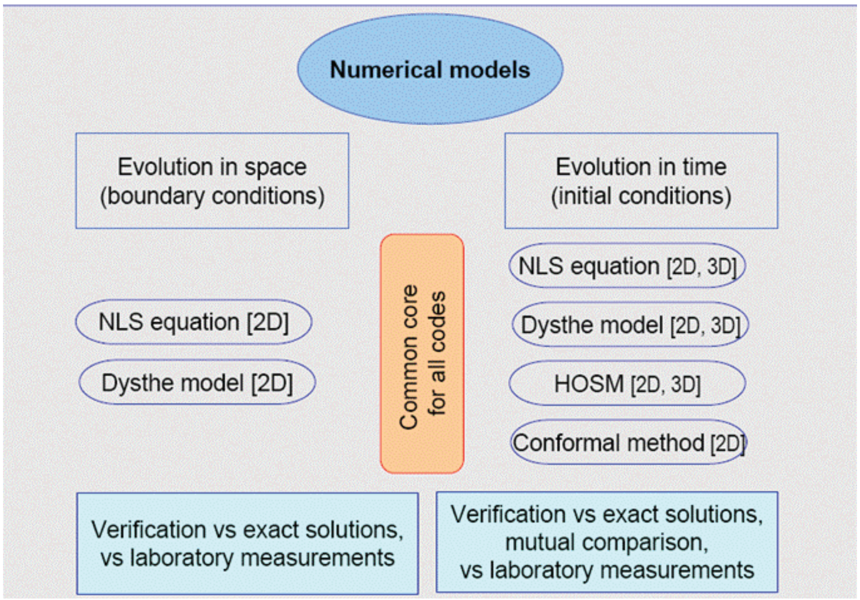

Figure 3. The flowchart of nonlinear wave models, after Slunyaev, (EXTREME-SEAS, 2013).

In the last decade most of the attention was given to the formation of rogue waves due to quasi-resonance nonlinear interactions referred to as modulational instability. It has been shown that sea states responsible for occurrence of modulational instability in deep water are characterized by high steepness and a narrow wave spectrum, both in frequency and direction, and can be identified by the Benjamin Feir Index, BFI, (see e.g. (Onorato et al., 2013)). Such sea states can be addressed as *Rogue Sea States (*M. Onorato, pers. comm*.,* (EXTREME-SEAS, 2013)). The BFI is a measure of the relative importance of nonlinearity and dispersion. It can be defined as BFI = $(k_pH_s/2)/(\Delta\omega/\omega_p)$, where $k_pH_s/2$ is the wave steepness (k_p is the wavenumber at the spectral peak) and $\Delta\omega/\omega_p$ is the frequency spectral bandwidth ($\Delta\omega$ is the halfwidth at half-maximum of the spectrum and ω_p is the spectral peak frequency). It should be noted that the above definition of BFI is valid for stationary conditions *(*A. Slunyaev, pers. comm*.,* (EXTREME-SEAS, 2013)). Provided the wave field is sufficiently steep, narrow banded and unidirectional, random waves are expected to become unstable when BFI = O(1). This results in increased probability of occurrence of rogue waves associated with an enhancement of non-Gaussian properties of the surface elevation, as shown by several authors, e.g. (Onorato & Proment, 2012), (Xiao et al., 2013). Since 2012 several studies bringing further insight in the physics of rogue waves have been carried out.

Stochastic numerical simulations (unidirectional, strongly nonlinear) of sea states characterized by the JONSWAP spectrum have been conducted within the strongly nonlinear approach by Sergeeva and Slunyaev (2013). The dominating horizontal asymmetry of rogue waves is obtained in severe situations: the rare slope is usually higher than the front slope. The geometry of maximum wave shapes is analyzed by the authors with the focus on issue how the extreme waves look like.

Slunyaev and Shrira (2013) have studied the nonlinear stage of modulational instability in detail by means of fully nonlinear numerical simulations. The maximum attainable wave crest amplification (for particular initial conditions, the cases leading to breaking are not concerned) is found to be about 4.2, wave trough amplification slightly exceeds 3, and wave height amplification is slightly less than 3. The universal maximum wave and wave group are formulated, and peculiarities of the wave shape are calculated and analyzed.

Within the weakly nonlinear theory the nonlinear stage of the modulational instability has been described by analytic breather solutions of the nonlinear Schrödinger equation (Chabchoub et al., 2012, Slunyaev et al., 2013d). These solutions (single and many co-phased modes of the modulational instability) are tested in the laboratory tank, and satisfactory agreement is obtained between the measurements and the theory. The strongly nonlinear simulations of potential hydrodynamic equations exhibit very good agreement with the measurements while the weakly nonlinear theory (nonlinear Schrödinger equation) is a reasonable first approximation for nonlinear wave groups.

A few rogue wave events, which have been registered in-situ (the North Sea) by means of time-series of surface displacement, have been reconstructed with help of numerical simulations of approximate asymptotic equations by Slunyaev et al. (2014). The reconstruction procedure has been verified implicitly by means of strongly nonlinear simulations. It is shown that the reconstruction may be reliable for the period of about 10 min.

It is established that the directional spreading of wave energy weakens effects related to modulational instability when one wave system is present, for references see e.g. (ISSC, 2012). Onorato et al., (2006b) and Osborne (2010) have shown that the modulational instability and rogue waves can be triggered by a peculiar form of directional sea state, where two identical, crossing, narrow-banded random wave systems interact between each other. Such results have been confirmed through recent numerical simulations of the Euler equations and experimental work carried out at the MARINTEK Laboratories (Toffoli et al., 2011b). It was observed that extreme events are more likely to occur when $40^o < \beta < 60^o$ confirming the findings of Onorato et al. (2006b).

The study of Bitner-Gregersen and Toffoli (2014) based on hindcast data and numerical simulations carried out by the HOSM method show that rogue-prone crossing sea states can occur in the ocean. Further, the authors demonstrate that although directionality has an effect on occurrence of extreme waves in crossing seas, extreme waves can occur not only for narrow-banded wave directional spreading but also when it is broader. The most critical condition for occurrence of rogue waves in crossing seas is associated with energy and frequency of two wave systems while the angle between the wave systems and directional spreading will decide how large extreme waves will grow. The 40 degree angle and narrow-banded directional spreading is generating the largest waves. It is interesting to note, that wind sea and swell wave systems registered during the Louis Majesty accident Cavaleri et al. (2012) had approximately the same wave energy and frequency but a typical wave directional spreading.

The accident to the Louis Majesty ship took place in the Mediterranean Sea on March 3, 2010 (Cavaleri et al., 2012). The ship was hit by a large wave that destroyed some windows at deck number five and caused two fatalities. Using the WAM wave model, driven by the COSMO-ME winds, a detailed hindcast of the local wave conditions has been performed. The results have revealed the presence of two comparable wave systems characterized by almost the same frequency (around 0.1Hz) and significant wave heights of approximately 3.5 m. The total significant wave height, H_{m0}, at the time of the accident was estimated around 5 m. These sea state conditions are discussed by the authors in the framework of a system of two coupled Nonlinear Schrödinger (CNLS) equations, each of which describe the dynamics of a single spectral peak. Even though, due to the lack of measurements, it is impossible to establish the nature of the wave that caused the accident, it has been shown that the angle between the two wave systems during the accident is close to the condition for which the maximum amplitude of the breather solution is observed ($40^o < \beta < 60^o$).

Waseda et al. (2013) have revisited a well-studied marine accident case in Japan in 1980 (Onomichi–Maru incident) and hindcasted the sea states using both the DIA and SRIAM nonlinear source terms in the wave spectral model. The findings indicate that the temporal evolution of the 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 authors show 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. The unimodal wave system grew under strong influence of local wind with a peculiar energy transfer. This conclusion contradicts the marine inquiry report speculating that the two swell systems crossed at the accident site.

When studying rogue waves the information given by the hindcast and the higher order solutions can be utilized and their use is encouraged. The complementary nature of the two types of models has been pointed out by the ISSC 2009 I.1 Official Discusser Prof. H. Tomita, ISSC (ISSC, 2009). As discussed by Bitner-Gregersen et al. (2014c) a spectral wave model (e.g. a WAM-like model) provides sea state description only in a form of the two-dimensional wave spectrum withbout giving any information about the instantaneous position of the sea surface in a given sea state. Note also that it accounts for wind forcing and resonant wave interactions but not for quasi-resonant interactions, which are responsible for occurrence of modulational instability and hence rogue waves (Onorato et al., 2013). Phase resolving wave models, on the other hand, provide the water surface elevation from which statistical properties of individual waves can be extracted and include quasi-resonant interactions. Further, these nonlinear wave models allow simulation of a wave record for a required time duration and by repeating the 17-30 minute simulations sufficient number of times significant reduction of sampling variability in estimated sea surface characteristics and their probability of occurrence can be achieved.

Bitner-Gregersen et al. (2014c) have applied coupling of the wave spectral model WAM and the numerical nonlinear wave model based on the Euler equations, solved with the HOSM method, proposed in West et al. (1987), to investigate statistical properties of surface oscillations during the particularly severe Andrea storm, which crossed the central part of the North Sea on November 8th–9th, 2007. The analysis shows that when the Andrea storm is passing the North Sea rogue waves can be expected in several locations, not only at Ekofisk where the Andrea wave was recorded. Rogue waves are deducted during the storm development; when storm builds up and when it decades, in the location considered by the study. They are not observed when the storm reaches the largest H_s. The proposed approach for coupling the wave spectral model with the nonlinear phase resolving model can be considered to be used for forecasting purposes. Although these models are computationally intense, the great advance in enhancing computer power has made the coupling between them feasible.

Spatial variation of nonlinear wave groups with different initial envelope shapes has been theoretically studied by Zhang et al. (2014a). The results have confirmed that the simplest nonlinear theoretical model is capable of describing the evolution of propagating wave packets in deep water. Further, three groups of laboratory experiments run in the CEHIPAR wave basin have also been investigated and systematically compared with the numerical simulations of the nonlinear Schrödinger equation. A small overestimation has been detected, especially in the set of experiments characterized by higher initial wave steepness but generally the numerical simulations show a high degree of agreement with the laboratory experiments confirming again that the nonlinear Schrödinger equation catches the essential characteristics of the extreme waves and provides an important physical insight into their generation.

Forcing sources such as wind and wave breaking have started to be included in the numerical codes. Onorato and Proment (2012) considered the effect of the wind and the energy dissipation on the nonlinear stages of the modulational instability by mapping the forced/damped nonlinear Schrödinger equation into the standard NLS with constant coefficients. The results give some insights on the effects of wind and dissipation on the formation of rogue waves. The authors show that the effect of wind/dissipation has an impact on the modulational instability; in particular, an initially stable (unstable) wave packet could be destabilized (stabilized) by the wind (dissipation). Xiao et al. (2013) proposed the energy dissipation model in HOSM which is based in a low-pass filter in the wavenumber space. The energy dissipation process due to breaking is simulated by filtering the frequencies higher than the frequencies given by the two filter parameters established by comparison the HOSM simulations with measurements.

CFD (Computational Fluid Dynamics) methodology is getting increasing attention in modelling of water waves, particularly extreme waves and wave breaking. The numerical simulation of multiphase and multicomponent fluid flows is a challenging task in CFD. Iafrati et al. (2013) use direct numerical simulation of the Navier-Stokes equations for a two-phase flow (water and air) to study the dynamics of the modulational instability of free surface waves and its contribution to the interaction between the ocean and atmosphere. The study shows that if the wave steepness of the initial wave exceeds a threshold value, wave-breaking events are observed and the formation of large-scale dipole structures in the air. In the case of breaking due to modulational instability the dissipation of the energy is mostly concentrated in the air side. Simulations carried out correspond to the propagation of waves without the presence of external wind; the consequences of wind on the generation of vorticity during breaking event are under investigation.

Chella et al. (2013) investigated the wave breaking process over a submerged reef. They use a two-phase numerical model, which solves the flow problem for air and water simultaneously. The Navier-Stokes equations are solved on uniform Cartesian grids in two dimensions. A staggered grid is used for the computation with the velocities defined at the cell edges and the pressure at the cell centres. The study focused on simulating breaking waves over a submerged reef with differnt slope and on determining the breaker depth and breaker height indices for various values of wave steepness and crest submergence. Examination of the wave profile during wave breaking has shown that most of the energy is concentrated at the crest of the breaking wave. The numerical results of the study are in reasonable agreement with the experimental results and are consistent with the principles of wave hydrodynamics.

A new Lattice Boltzmann method (LBM) has been developed by Banari et al. (2013) in order to simulate efficiently multiphase flows with high density ratios and to study complex air-sea interaction problems, such as wind wave breaking and related sea-spray generation. The method is only currently implemented in a two-dimensional (2D) framework but can be extended to 3D.

Toffoli et al. (2013a) present a laboratory experiment in a large directional wave MARINTEK basin carried out to investigate the instability of a plane wave to oblique side band perturbations in finite water depth. Experimental observations are supported by numerical simulations and confirm that a carrier wave becomes modulationally unstable even for relative water depths $k_p h < 1.36$ (with k the wavenumber of the plane wave and h the water depth), when it is perturbed by appropriate oblique disturbances. The authors state that the results present evidence that the underlying mechanism is still a plausible explanation for the generation of rogue waves in finite water depth. These findings are confirmed by Fernandez et al. (2014) using direct numerical simulations of the Euler equations (HOSM) but the results, nonetheless, indicate that modulational instability cannot sustain a substantial wave grow for $kh < 0.8$.

Using a Boussinesq model with improved linear dispersion, Gramstad et al. (2013) showed numerical evidence that bottom non-uniformity can provoke significantly increased probability of rogue waves as a wave field propagates into shallower water, in agreement with the earlier experimental results.

Kinematics of extreme waves has been compared versus extreme kinematics of all waves and with predictions of 3-order and 5-order asymptotic nonlinear theory by Sergeeva and Slunyaev (2013). Though in general the significant amount of data well correspond to each other, some difference between kinematics of extreme waves and extreme kinematics is emphasized. Rogue waves are typically characterized by large values of velocities, but high velocities do not necessarily correspond to rogue waves.

Toffoli et al. (2012) have carried out a detailed analysis of the surface wave kinematics of random directional waves using HOSM. A number of sea states with different wave steepness, spectral bandwidth and directional spreading were considered to address the combined effect of high order nonlinearity and directional spreading on wave kinematics. Because the model is not capable to model breaking effects, input sea states were defined so that an individual wave does not overcome the steepness for breaking onset. Despite this limitation, the numerical simulations offer a complete overview of the velocity field with the possibility to investigate the statistical properties of the orbital motion. The simulations revealed that the growth of large amplitude waves as an effect of modulational instability leads to a significant departure of the horizontal velocity from linear predictions which increased up to 60% of the initial (linear) condition for unidirectional wave field. As short directional spreading increases, departure from the Gaussian distribution gradually diminishes and eventually vanishes for sufficiently broad directional spreading.

The wave runup in narrow bays leads to larger runup heights than in the situation of a plane geometry. This natural observation is confirmed and described theoretically by Rybkin et al. (2014). Touboul and Pelinovsky (2014) have shown that the bottom pressure distribution is much improved (with respect to linear description) using the Green–Naghdi model. Solitonic waves, travelling or fully reflected at a wall have been considered as a particular case in the study. The fully nonlinear potential equations are used to control the efficiency of the description. The Green–Naghdi model is found to predict well the bottom pressure distribution, even when the quantitative representation of the runup height is not satisfactorily described.

The interest in polar regions has brought attention to wave–ice interactions. Massel and Przyborska (2013) proposed theoretical models of the surface waves generated by calving glaciers. Four case studies of the ice blocks falling into water, representing selected “modes” of the glacier calving, and corresponding water surface oscillations have been studied. The “modes” included: cylindrical ice block of small thickness impacting on water, ice column sliding into water without impact, large ice block falling on water surface with pressure impulse and ice column detaching from the glacier wall and falling on water surface. The carried out calculations show that the glacier calving with pressure impulse creates higher oscillations than the case of calving with ice column sliding into water. High waves are also generated when ice column detaches from the glacier wall and impact on water surface. The developed models can be useful for estimation of the wave amplitude as a function of distance from the glacier wall as well as a function of time from the impact at a given location.

Wave-current interaction is reported under special topics in Section 5.2.

3.2.2 Experimental description of waves

Extensive laboratory tests of extreme and rogue waves have been carried out by two research projects, EC EXTREME SEAS and ShorCresT JIP (continuation of the CresT JIP), and the EC-Hydralab IV program. Some tests of the EC-Hydralab IV program were utilised by EXTREME SEAS.

In (EXTREME-SEAS, 2013) the model tests have been carried out in the tank of Technische Universität Berlin (TUB) and the Spanish basin Canal de Experiencias Hidrodinamicas de El Pardo (CEHIPAR). The project utilized also model tests data from experiments carried out world-wide in which the project partners had participated. The first phase of the tests consisted of generating the target deterministic wave sequences with inserted extraordinarily large waves and irregular waves with rogue waves (unidirectional and with varying directional spreading). Measurments, apart from water surface, recorded also kinematic characteristics of these waves. In the second phase of the model tests ship behaviour in extreme and rogue waves have been studied. Four ships have been investigated by the project: the LNG Tanker, Product/Chemical Tanker, Cruise Ship and Large Container Ship. The ships were instrumented to measure motions and wave induced loads. Both extraordinary rogue waves: the Draupner wave and the Andrea wave have been reproduced in the model tanks, the Draupner wave in the TUB tank while the Andrea wave (see Figure 2) in the CEHIPAR basin. At the Technical University of Berlin breather solutions of the Nonlinear Schrödinger (NLS) equation have been successfully produced with help of the University of Torino and used for the first time in sea-keeping tests (Clauss et al., 2012), opening up new perspectives in the methodology of examining offshore structures and ships against rogue waves.

Model tests in the CresT and ShortCresT JIP projects have been carried out in the MARIN and Imperial College basins and were addressing offshore structures. The ShortCresT investigations included long crested and short crested waves (short crested waves at different scales) and frequency spectra of field and basin waves. Buchner and Forristal (2012) observed in ShortCresT that short crested basin waves and field waves show very similar behaviour. ShortCresT investigations of nonlinear waves are generally confirming the findings of EXTREME SEAS. The final results of the ShortCresT project will be published in the OMAE 2015 Conference Proceedings. A summary of the findings is given by Hennig et al. (2015).

Short intense long-living nonlinear wave groups (with steepness up to $ka = 0.3$ and a couple of oscillations in the group) have been shown to exist in laboratory conditions (unidirectional propagation, deep water flume), (Slunyaev et al., 2013b). They are the strongly nonlinear analogue of the envelope solitons of the integrable nonlinear Schrodinger equation. The measured groups agree very well with the strongly nonlinear simulations of the potential equations of hydrodynamics. It is found that the nonlinear rise of the solitary group velocity is even larger than one of the uniform Stokes wave. These nonlinear groups form extreme wave patterns.

The space-time evolution of high wave groups in crossing seas have been investigated in the MARINTEK basin by Santoro et al. (2013). The experimental data have been supported by applying Quasi-determinism theory of Boccotti given that a high crest takes place in a fixed point in the basin. It is observed that the high waves group is given by the superposition of two wave groups, associated, one with the low-frequency component of the frequency spectrum, and the other with the high-frequency one. Further, it is shown how in crossing seas the change in direction of one system affects the evolution of the related group, without any influence on the evolution of the other one. The effect of the change in the wave spectrum on wave profiles have also been analysed.

Yan et al. (2013) performed a laboratory experiment on the instability of Stokes wave trains with large steepness in finite water depths. Two class instabilities of Stokes wave, quartet interaction and quintet interaction, were observed. It is found that the evolution of crescent wave pattern is affected by the development of quintet interaction. The larger the relative water depth, the more quickly the growth of the instability is observed. The impact of wave steepness for the occurrence of the competition is examined by applying linear instability analysis of a Stokes wave. The results show that the observed Benjamin-Feir instability is two dimensional.

The dependence of runup heights on the incident wave shape (sinusoidal wave or solitary wave, particular polarity and wave asymmetry) has been studied. The theoretical formulas obtained in Didenkulova et al. (2014) and Rybkin et al. (2014) have been confirmed in experiments in the large wave tank of the Hannover University and in the wave facility of the Caen University (Ezersky et al., 2013a, Ezersky et al., 2013b).

Results of model tests carried out in the MARINTEK model basin and used to establish statistics of wave parameters are reported in Section 3.2.3. Several experiments addressing wave-current interaction have taken place since 2012 and are reported in Section 5.2 (Special topics).

One of the main issue when performing experiments is reduction of sampling variability, the uncertainty due to limited number of data. Sampling variability is an epistemic uncertainty and can be reduced opposite to the intrinsic uncertainty of sea surface elevation which is always present. For stationary meteorological conditions, due to randomness of sea surface, wave parameters derived from a wave record will depend on which part of a wave record is used in an analysis as well as on the length of a wave record (Bitner-Gregersen and Hagen, 1990, Bitner-Gregersen and Magnusson, 2014). An error introduced by the limited length of a wave record is an epistemic uncertainty and can be reduced by increasing duration of wave measurements/numerical simulations. Ideally a wave record should be infinite to eliminate sampling variability. Numerical simulations of water surface represent a good support to field and model tests as they allow reducing sampling variability by increasing duration of simulations when wave input is kept constant and intrinsic variability accounted for. This is more difficult in nature, where stationarity of sea states is an issue, and in model tests due to the costs associated with repeated model test runs.

Model tests need to be repeated a sufficient number of times to reduce sampling variability otherwise bias results maybe obtained, does not matter how accurate instruments used in an experiment are, see (Bitner-Gregersen et al., 2014b, Bitner-Gregersen and Magnusson, 2014). Inaccuarcy introduced in test results due to the limited number of data can be accounted for in load and response analysis in terms of distribution functions or standard deviations. The bootstrapping technique can be used to establish these uncertainties.

It needs also to be mentioned that to reflect intrinsic variability of linear and nolinear numerical simulations of surface elevation as well as waves generated in model basins, wave models and laboratory wave makers have to account for random ampliture and phase of a wave field. Further, modulational instability occur typically after 10-30 wave lengths from a wavemaker thus a scale of model tests should to be considered carefully to be able to generate abnormal waves in a basin.

3.2.3 Statistical description of waves

Wave height and wave crest are ones of the most important wave characteristics for engineering applications. A recent review of wave crest distributions can be found in Bitner-Gregersen et al. (2014b).
Comparisons of individual wave height and crest distributions with the distributions of laboratory data for a wide range of conditions, including highly nonlinear steep sea states and sea states with extensive and intensive wave breaking have been conducted as part of the EC EXTREME SEAS and ShorTCresT JIP projects. It has been demonstrated that linear and second-order models are not able to capture very nonlinear waves like rogue waves. Some recent papers from these projects, developed since 2012, are reviewed below. The review includes also investigations carried outside the projects.

In Petrova and Guedes Soares (2014) statistical properties of wave crest, height and trough are investigated using experiments generated in the deep water MARINTEK basin with mixed crossing seas. The findings are compared with the previous results from the same experiment. Waves have been generated using bimodal spectra following the model of Guedes Soares (1984). The observed statistics and probabilistic distributions exhibit, in general, increasing effects of third-order nonlinearity with the distance from the wavemaker. However, this effect is less pronounced in the wave systems with two following wave trains than in the crossing seas with identical initial spectral characteristics.

Deep-water waves with different initial steepness able to trigger modulational instability and measured in the MARINTEK wave basin have been studied by Cherneva et al. (2013). The authors compare the statistics of wave heights, crest and trough amplitudes observed in the basin with a variety of theoretical approximations based on Gram–Charlier expansions. The results indicate that the theoretical approximations describe the empirical distributions reasonably well, for the most part. The study also shows that the zero-up- and zero-down crossing heights of the largest waves observed in the tests do not exceed Miche–Stokes type upper limits.

Zhang et al. (2013a), using the NLS equations and experimental data from the CEHIPAR wave basin, have confirmed the early findings, the occurrence of the modulation instability resulted from the quasi-resonant four wave interaction in a unidirectional sea state in deep water, can be indicated by the coefficient of kurtosis. The latter has shown correlation with the extreme wave height. The modified Edgeworth-Rayleigh distribution has been used to approximate the wave heights. The authors have related also some statistical properties of the maximum wave heights in different sea states with the initial Benjamin-Feir Index.

Having in mind engineering applications (Bitner-Gregersen and Toffoli, 2012b) proposed a 2-parameter Weibull crest distribution derived based on experimental directional wave data (included rogue waves and wave breaking) collected in the MARINTEK basin. The analysis has been supported by HOSM numerical simulations. The related parameters have been parameterised as a function of a general version of the Benjamin-Feir Index for directional sea states. On the whole, the proposed distribution captures better the tail of the crest distribution than the (Forristall, 2000) crest distribution.

In the ShortCresT JIP, departures from the Forristall crest distribution were also found for steep sea states by comparison with crest distributions from measured waves in the laboratory at Imperial College; and a new parameterization that accounts for the additional nonlinear effects, including breaking has been developed (Swan and Latheef, 2014).

Statistics of new field measurements of wave height and crest elevation measured in the North Sea during a storm in December 2012 are presented by Gibson et al. (2014). The water surface elevation was recorded by Saab WaveRadar REX instruments mounted on eight fixed-jacket platforms in addition to a Datawell Directional Waverider buoy. 19 freak waves, following the definition of Haver and Anderson (2000), occurred during this storm. An easterly sea state which peaked well in excess of the 100-year wave height has been generated by the storm. The study shows that the significant steepness and spectral bandwidth during the storm remain almost constant and the measured crest elevations and wave heights are in good agreement with the Forristall and Boccotti distributions. However, for the wind-speed larger than 25 m/s the measured crest elevation lies above the second-order Forristall distribution.

Christou and Ewans (2014) took advantage of the development of a large in-situ measurement wave database to jointly analyze sea-state parameters, environmental conditions and local characteristics so as to provide an insight into the behaviour of rogue waves. The database, constructed using data sets of quality-controlled measurements from fixed sensors mounted on offshore platforms, mostly located in the North Sea, contains 122 million individual waves, of which 3,649 are rogue waves. Analysis of sea-states parameter showed that rogue-waves induced an increase of the kurtosis value. Examination of metocean conditions for each sea-state suggested that there was not any particular combination of wind-sea, swell, wind or current that is particularly conducive to the formation of rogue waves. Finally, a wavelet analysis conducted on the rogue wave samples presented evidence to suggest that rogue waves are merely extraordinary and rare occurrences of the normal population that are caused by dispersive focusing.

It is interesting to note that the analyses carried out by Christou and Ewans (2014) of measured data from the Kvitebjørn platform did not find a link between low spreading and the occurrence of rogue waves in the measured data. Opposite, Waseda et al. (2011) provided evidence of an increased likelihood of rogue waves at the Kvitebjørn platform in the North Sea when directional spreading was relatively low (approximately 7.6 degrees narrower compared to observations without rogue waves present), and this corresponded to a wave spreading of 30 degrees.

Wang et al. (2014) analysed preliminary one year observed wave data from Jiangsu (coastal water), China. The horizontal symmetry, vertical symmetry, wave steepness, kurtosis and the BFI index have been studied. Most of the rogue waves, which are not high, are present in 5 intermediate water depth what results in the obscure correlation between BFI and rogue waves. The authors postulate that two different types of rogue waves are present in the considered area.

The statistics of the elevation estimated by Waseda et al. (2014) from the buoy position record of the JKEO (Jamstec Kuroshio Extension Observatory), NKEO (New Kuroshio Extension Observatory) observation sites and the Hiratsuka observation tower has shown that the probability density function (PDF) is nearly Gaussian, and the PDF of the extremum is well approximated by the analytical formula of Cartwright and Longuet-Higgins (1956).

Babanin (2012) argues that different scenarios of wave evolution should be represented by different wave height/crest probability distributions. Otherwise, the residual scatter is inevitable and will not be improved even when the databases are enhanced and measurement accuracy is improved. Selection of such scenarios needs to be based on the understooding of wave physics.

It is well recognized today that the effect of modulational instability is gradually suppressed when the wave energy spreading increased and the second order wave theory is adequate to describe the statistical behaviour of ocean waves up to a particular probability level (ISSC, 2012).

Stansberg (2012) applied a Hilbert envelope approach (energy envelope) to describe the wave groups and showed that the sampling variability of the extreme energy envelope is much higher than for linear phenomena, due to the quadratic nature. Note, that the Hilbert transform disregard wave nonlinearity, being crucial when rogue waves are considered, see (ISSC, 2012).

The nonlinear and nonstationary properties of a special field wave record have been analysed by Cherneva and Guedes Soares (2014) with the Wigner spectrum with the Choi–Williams kernel. The wave time series including the Andrea rogue wave recorded at the Ekofisk field has been used in the study. The ability of the Wigner spectrum to reveal the wave energy distribution in frequency and time is demonstrated. The results are compared with previous investigations for different sea states and also the state with Draupner's abnormal "New Year" wave.

Despite these recent achievements regarding dynamic properties of rogue waves a consensus on probability of occurrence of rogue waves has not been achieved yet. Probability of occurrence of rogue waves is related to mechanisms generating them. Since 2012 occurrence of rogue waves due to some of these mechanisms have been studied.

To investigate the frequency of occurrence of seas states which may trigger the modulational instability in deep water in the North Atlantic, Bitner-Gregersen and Toffoli (2012a) have used hindcast data from a few North Atlantic locations generated by Oceanweather Inc. and European Centre for Medium-Range Weather Forecast (ECMWF). The Oceanweather Inc. hindcast wind and wave covered the period 1988–1998 and were sampled every 3 h. Data have been post-processed by Shell using the program APL Waves Hanson and Phillips (2001) for the partitioning of 3-D spectra (i.e. directional wave spectra) into separate peaks. The ECMWF wind and wave data covered the period 2001–2009 and were archived at a sampling frequency of 6 h. Results revealed rogue-wave-prone sea states can occur in the North Atlantic (the North Atlantic wave climate is used for design of ships) more often than once in the 20/25-yr return period. Also the highest sea state within the 10-yr time period analysed (H_s > 15 m) is characterised by $k_pH_s/2$ = 0.13, the conditions which may trigger the modulational instability.

Also, as shown by Bitner-Gregersen and Toffoli (2014), rogue-prone crossing wave systems responsible for the generation of abnormal waves can occur more often than once in the 20/25-yr return period in the North Atlantic and the North and Norwegain Sea, primarily in low and intermediate sea states. Their occurrence is location specific, depending strongly on local features of wave climate. This type of sea states have not been found in locations where wind sea and swell components, or several swell components, are well separated, characterized by significantly different spectral periods.

Nikolkina and Didenkulova (2012) divide the area of occurrence of rogue events into three zones: deep water area, shallow-water regions and the coast. The shallow water zone is defined as the sea areas with depths <50 m while deep waters are associated with water depths exceeding 50 m. The coastal rogue events include unexpected and hazardous waves of extreme height or run-up that occurred at the shoreline. The list of rogue and rogue-like events has been completed based on the literature review, existing databases and information published in the media. The validity of the event (true or possible), its classification in terms of its location (shallow, deep water or coast zone) and estimated H_s are given in the list developed by the aurhors. The investigations have shown that observed rogue waves are widely spread around the World, however, some regions seem to be more affected. The great number of rogue wave observations in shallow waters (51% for all observed events and 38.5% for the selection of true events only) and at the coast (40% for all observed events and 50% for the selection of true events only) can be explained by the dense population in these areas and/or a heavy marine traffic in coastal waters. The annual variability of rogue wave changes significantly from year to year.

On the basis of available information about eyewitness observations of rogue waves it is found later by Didenkulova et al. (2013c) that the rogue waves occur with similar probability in situations when the longitudinal modulational instability is efficient or inable (deep or shallow waters). The relative threshold depth which splits the situations to ‘shallow’ and ‘deep’ water is about 20 m. Opposite, Wang et al. (2014) found that in coastal waters of Jiangsu, China, the occurrence probability of rogue waves is similar to the one predicted by the Rayleigh distribution.

Oh and Jeong (2013) have studied the maximum significant wave heights and periods observed at the nine measurement stations at the Korean coast of the East Sea. The aim of the study has been identifying meteorological conditions which in several recent years generated extremely high waves at the Korean coast of the East Sea causing severe coastal disasters almost every winter season. The authors found that the reason for appearance of the high waves were extra-tropical low pressure systems that had been rapidly developing in the East Sea. The study has contributed to better understanding of mechanism forming such strong low pressure systems and spatial evolution of them. To enhance predictability of these systems further investigations are needed.

Aarnes et al. (2012) investigated the 100-yr return value estimates of significant wave height using the recent Norwegian Reanalyzes 10 km (NORA10) hindcast database developed by the Norwegian Meteorological Institute and covering the northeast Atlantic. They considered three different stationary models commonly applied in extreme value statistics: the generalized extreme value (GEV) distribution, the joint GEV distribution for the largest-order statistic (LOS), and the generalized Pareto (GP) distribution. In general, the H_s 100-yr return value estimates differ by less than ±5%, with local discrepancies peaking around 20%. In these areas the annual maximum and the peaks-over-threshold methods were found to outperform the largest-order statistics. However, no model has been found to be superior in all cases.

Extreme metocean conditions occur simultaneously in a storm process. Different techniques for modelling simultaneous data have been investigated recently. Based on a bivariate equivalent maximum entropy distribution, Dong et al. (2013b) estimated joint extreme parameters of the concomitant wave height and wind speed at a site in the Bohai Sea. Tao et al. (2013b) hindcasted by a numerical model the annual extreme wave height and corresponding wind speed at a platform in Bohai Bay for the period 1970 to 1993. Bivariate normal copula and Frank copula are utilized to construct joint distribution of these two random variables. Applicability of copula models to estimate joint probabilities needs still further investigations.

3.2.4 Spectral description of waves

Wave spectra represent a key input to the design process. Empirical formulations of waves spectra were used extensively in engineering applications and this situation remains. Typical forms for the frequency spectrum (see e.g. (Amurol et al., 2014)) are modified versions of the Pierson and Moskowitz (PM) spectrum and the JONSWAP spectrum for unimodal conditions (one wave system), and the (Ochi and Hubble, 1976) and (Torsethaugen, 1993, Torsethaugen, 1996) spectrum for bimodal sea states (two wave systems present), see (DNV, 2014). The two wave system wave spectrum of Guedes Soares (1984) can also be used.

The maritime industry has used traditionally the PM spectrum but recently also other empirical spectra have started to be applied like the JONSWAP spectrum and a double peak spectrum particularly for evaluation of ship operational criteria. The choice of formulation depends on the site and the conditions being represented; for example, when the spectrum is being defined for extreme sea states for design, a unimodal description will usually be most representative. It should be noted that the choice of spectral form has implications for the spectral levels above and below the spectral peak. There is still uncertainty about the form of the decay in the high frequency tail–the (modified) PM and JONSWAP formulae have an f^5 tail decay, while the Torsethaugen (1993) spectrum had originally the f^4 tail which later was modified (Torsethaugen, 1996) to become a function of H_s and is ranging from f^4 to f^5 (for details see e.g. (Bitner-Gregersen et al., 2014b)).

Waseda et al. (2014) analysing buoys' deep water data in the North West Pacific Ocean in 2009, 2012, and 2013 have shown that the tail of the averaged spectrum follows the frequency tail f^4, and the significant wave height and period satisfies the Toba's 3/2 law. The observations compare well with a numerical wave hindcast.

The universal power law for the spectrum of one-dimensional breaking Riemann waves in shallow water is justified by Pelinovsky et al. (2013). The spectrum of spatial amplitudes at the breaking time has an asymptotic decay of $k^{-4/3}$, with corresponding energy spectrum decaying as $k^{-8/3}$. This result remains valid for arbitrary nonlinear wave speed and may be important for interpretation of measured spectra and construction of theoretical model spectra of essentially nonlinear waves.

Shell Global Solutions, in association with Ifremer and Oceanweather, formed a Joint Industry Project WASP (West Africa Swell Project), to analyze and compare the available data on swell and its spectral description. Measurements were obtained from Shell, Ifremer, Chevron and Marathon. Hindcast data came from Oceanweather and the NOAA WAVEWATCH model. Sites ranging from Nigeria to Namibia were considered. The project was initiated in 2001 and has permitted improvement in the knowledge of swell climatology in West Africa. The full description of the project is given by Olagnon et al. (2004). Some project results were presented in the OMAE 2013 Conference (Forristall et al., 2013, Olagnon et al., 2013, Prevosto et al., 2013).

Swell events show a large variety of configurations when they arrive at sites off West Africa after generation and propagation of waves across the Atlantic Ocean (Prevosto et al., 2013). Within the West Africa Swell Project (WASP JIP), these different configurations have been described and discussed and the ability of numerical models to reproduce faithfully their properties has been assessed from comparisons with in-situ measurements. The numerical wave models were not, at the time of the project, of sufficient quality to accurately track all the swell events, but the models provided better information on superposition of multiple swell systems than directional buoys. Since the end of the project the hindcast models have been improved by the integration of new dissipation and nonlinear interaction source functions and also by the addition of buoy and altimeter data assimilation. Therefore the comparison of the numerical model prediction and buoy data is not conclusive. Analyses of some shallow water measurements have indicated the presence of low-frequency components that could be due to the presence of infra-gravity waves but further investigations are needed to use these results in engineering applications.

Modeling the dispersion of swell over long distances has indicated that the resulting power spectrum will have a triangular or lognormal shape (Forristall et al., 2013). Sampling variability makes it difficult to distinguish between those shapes or JONSWAP or Gaussian forms, but lognormal spectra generally provided good fits. The models also indicate that the width of the spectrum in both frequency and direction should be inversely related to the peak frequency.

3.3 Current

The ISSC 2009 I.1 Committee (ISSC, 2009) reported on success of the global and basin-scale ocean models development with data assimilation under the GODAE (Global Ocean Data Assimilation Experiment) which opened a new era of operational oceanography. GODAE ended in 2008 and continues as GODAE Ocean View: https://www.godae-oceanview.org/ (see ISSC, 2012). The 5 years of GODAE OceanView progress and future priorities were presented at the GODAE OceanView Symposium in Baltimore, Maryland, 4–6 November 2013.

As pointed out by the previous I.1 Committee (ISSC, 2012) the GODAE product is global and it provides boundary conditions for regional and high-resolution models. It does not aim at covering all time-scales that are required for engineering.

3.3.1 Analytical description of current

Ocean model outputs have been used after the incident at the Deepwater Horizon platform in April 2010 in the Gulf of Mexico to trace spilled oil in the Gulf Stream as well as to trace debris and radioactive materials after the earthquake and tsunami incidents on 11 March 2011 in north east Japan, see e.g. (Aoyama et al., 2012, Tsumune et al., 2012). The results are promising, showing that numerical ocean models can be utilized in these type of analyses although they may give different predictions. In Masumoto et al. (2012) comparison of predictions of five ocean models can be found when data around Japan are used.

Ocean current models such as HYCOM are used increasingly for engineering applications and have recently been assessed using data at the location offshore West Africa by Jeans et al. (2013). Jeans and Wade (2013) have shown that the HYCOM model does not represent dominant features of the local current regime in the region offshore Namibia. This region is subjected to relatively strong diurnal sea breezes, which can drive nearly resonant inertial responses in the ocean, which can, in turn, dominate the current regime. The spatial resolution of the wind field used to drive the global HYCOM model is insufficient to resolve this critical wind forcing, so the resulting model currents cannot represent the dominant features.

Utilization of current by energy devices has been presented at e.g. the OMAE 2013 and 2014 conferences.

3.3.2 Statistical and spectral description of current

(Jones et al.) has proposed a Monte Carlo simulation method for combining different independent current components such as tide, through-flow, surge and high-frequency currents which are present in the Singapore Straits. The suggested model is expanding the horizon of available measured and modelled data and is facilitating the definition of design current speeds. The number of random picks from the non-exceedence probability distributions of the surge, through-flow and high-frequency components in a given year for each component is defined by assuming its occurrence rate to be Poisson-distributed around a known annual mean value. The method gives a reduction in design current when compared to values derived by multiplying the exceedence probabilities of varying independent contributions directly. The Kuroshio current is a major global current that flows near the east coasts of Taiwan and Japan. It is a relatively strong current with typical speeds of 3 to 5 knots at the water surface. Agarwal and McNeill (2013) present the derivation of extreme two-dimensional (i.e., directional) and planar profiles for Kuroshio currents at a site in Nankai Trough, Japan; water depth is almost 2000 m. Totally about 6000 currents profiles measured over six months in 2010 by JAMSTEC have been used in the study. The inverse first-order reliability method (inverse FORM) and proper orthogonal decomposition (POD) techniqve have been employed to preserve the directionality in extreme currents. A set of a limited number of extreme N-year current profiles is derived using the proposed methodology. The introduced methodology for deriving extreme directional current profiles from measured data seems to give promising results.

Ceccopieri and Silveira (2012) successfully applied statistical and dynamical orthogonal modes in order to study the vertical variability pattern of the oceanic flows of the São Paulo Plateau of Brazil.

3.4 Sea water level

Several studies have been carried out to project future sea water level changes using GCM (Global Climate Model) or RCM (Regional Climate Model) models. The findings are summarised in Section 4.1.4. The degree to which GCM, or, RCM have sufficient resolution and/or internal physics to realistically capture the meteorological forcing responsible for storm surges is regionally dependent. For example current GCMs are unable to realistically represent tropical cyclones.

3.5 Ice and snow

Ice and snow models are discussed in Section 4.1.3 dedicated to climate change. Changes in the Arctic Ocean and Antarctica weather have received widespread attention. The projected climate changes in these regions are opening new opportunities for the marine industry. Potential seasonal shipping on the Northern Sea Route, the Northwest Passage and maybe a Transpolar Route, will improve access to many offshore resources in the Arctic region (see Section 6.2).

4. CLIMATE CHANGE

During the course of the ISSC 2015 Committee I.1 the Fifth Assessment Report (AR5) summarising the latest scientific findings regarding climate change has been issued by (IPCC, 2013). A significant development has taken place since the issue of the Fourth Assessment Report (AR4) (IPCC, 2007), particularly in the increased use of quantitative statistical measures simplifying synthesis and visualization of model performance (see e.g. Sahany et al., 2012).

AR5 is confirming the conclusion of AR4, the observed climate changes are due to human activities. Further, there are large regional variations in observed and projected climate driven changes in environmental conditions. As in AR4, temperature, sea water level and ice has got more attention in the AR5 report in comparison to wind and waves, but it is the first time the IPCC is providing an assessment of wave models. The main uncertainties in the understanding of the climate system and the ability to project changes in response to anthropogenic influences identified by IPPC (2013) include: uncertainties in observation of changes in the climate system, uncertainties in drivers of climate change, uncertainties in understanding the climate system and its recent changes, uncertainties in global and regional climate change models.

It can be mentioned that in December 2014 a global climate conference has been held in Lima where the participating nations agreed to collaborate to mitigate climate changes.

4.1 New IPPC Scenarios and climate models

The IPCC Fifth Assessment Report (IPCC, 2013) uses four scenarios to describe past and future driving forces, called Representative Concentration Pathways (RCP). These can be described as four possible trajectories for future greenhouse gas concentrations in the atmosphere. They include emissions of greenhouse gases and land cover/use but not socio-economic, technology, demographic and other aspects as the Fourth IPPC Assessment Report forcing covered. Each scenario leads to a certain change of average global temperature over the next century (or more).

The four RCPs lead to radiative forcing levels of 8.5, 6.0, 4.5 and 2.6 W/m^2, by 2100 and they are named according to it, i.e. RCP 8.5, RCP 6, RCP 4.5 and RCP 2.6, which has been estimated based on the forcing of greenhouse gases and other forcing agents. Each of the RCPs covers the 1850–2100 period and together they cover the range of forcing found in literature; they are sufficiently separated to allow distinguishable climate results (about 2 W/m^2 was found to satisfy this) and the number of RCPs are manageable. They include one mitigation scenario leading to a very low forcing level (RCP 2.6), two medium stabilization scenarios (RCP 4.5/RCP 6) and one very high baseline emission scenario (RCP 8.5).

The main characteristics of four RCPs are summarized by van Vuuren and al. (2011a), Meinshausen and al. (2011) and Moss and al. (2010), and they are described in more details by Riahi and al. (2011), Masui and al. (2011), Thomson and al. (2011), Dutour-Sikiric (2013) and van Vuuren and al. (2011b). The scenario RCP 4.5 is expected to achieve the political target of a maximum global mean temperature increase of 2°C while the scenario RCP8.5 is close to "business as usual» and believed to give a temperature rise of 4°C or more.

Projections of changes in the climate system are made by (IPCC, 2013) using a hierarchy of climate models ranging from simple climate models, to models of intermediate complexity, to comprehensive climate models, and Earth System Models (ESMs). These models based on the set of new scenarios of anthropogenic forcing have been used for the new climate model simulations carried out under the framework of the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the World Climate Research Programme. A large number of comprehensive climate models and ESMs have participated in CMIP5, they form the core of the climate system projections.

Most modes of interannual to interdecadal variability are now capture by the climate models. As in the AR4 Report, their assessment presents a varied picture and the CMIP5 models only show a modest improvement over CMIP3 (Coupled Model Intercomparison Project Phase 3), mostly due to fewer poor-performing models (IPCC, 2012, IPCC, 2013). New since the AR4 process-based model evaluation, is now helping identify sources of specific biases, although the observational record is often too short or inaccurate to offer full specification of model uncertainty.

Confidence in climate model projections in AR5 is based on physical understanding of the climate system and its representation in climate models, and on a demonstration of how well models represent a wide range of processes and climate characteristics on various spatial and temporal scales (Knutti et al., 2010). A climate model's credibility is increased if the model is able to simulate past variations in climate, such as trends over the 20th century and palaeoclimatic changes.

Longer-term climate change projections are outside the range of historical observations making assessment of models' accuracy difficult. A frequently used approach to improve the climate model projection is the re-calibration of model outputs to a given observed value, e.g. (Wang and Overand, 2012), (Mahlstein and Knutti, 2012). Some studies explicitly formulate a statistical frameworks that relate future observables to climate model output (reviewed in (Knutti et al., 2010) and (Stephenson et al., 2012). Such frameworks not only provide weights for the mean response to forcing scenarios but also allow the uncertainty in the predicted response to be quantified (Bracegirdle and Stephenson, 2012).

The following terms have been used by (IPCC, 2013) to indicate the assessed likelihood of climate projections: *virtually certain* (99–100% probability), *very likely* (90–100% probability), *likely* (66–100% probability), *about as likely as not* (33–66% probability), *unlikely* (0–33% probability), *very unlikely* (0–10% probability), *exceptionally unlikely* (0–1% probability). Additional terms *extremely likely* (95–100% probability), *more likely than not* (>50–100% probability), and *extremely unlikely* (0–5% probability) have been introduced.

4.1.1 Temperature

The observational record of 20th century changes in global surface temperature has been compared to that simulated by each CMIP5 and EMIC model and the respective multi-model means. For the CMIP5 models, interannual variability in most of the simulations is qualitatively similar to that observed although there are several exceptions. The gradual warming evident in the observational record, particularly in the more recent decades, is also evident in the simulations, with the multi-model mean tracking the observed value closely over most of the century, and individual model results departing by less than about 0.5°C.

The observed global mean surface temperature (GMST) has shown a much smaller increasing linear trend over the past 15 years than over the past 30 to 60 years. Depending on the observational data set, the GMST trend over 1998–2012 is estimated to be around one-third to one-half of the trend over 1951–2012. The reduction in observed GMST trend is most marked in Northern Hemisphere winter. However, the decade of the 2000s has been the warmest in the instrumental record of GMST.

In the AR4 (IPCC, 2007) it was noted that the largest errors in SST (Sea Surface Temperature) in CMIP3 were found in mid and high latitudes. While this is still the case in CMIP5, there is marginal improvement with fewer individual models exhibiting serious bias. The inter-model zonal mean SST error standard deviation is significantly reduced at all latitudes north of 40°S, even though the multi-model mean is only slightly improved.

The globally averaged combined land and ocean temperature data as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06] °C, over the period 1880–2012, when multiple independently produced datasets exist, about 0.89 [0.69 to 1.08] °C over the period 1901–2012, and about 0.72 [0.49 to 0.89] °C over the period 1951–2012 when based on three independently-produced data sets. Sea surface temperatures have also increased. Intercomparisons of new SST data records obtained by different measurement methods, including satellite data, have resulted in better understanding of errors and biases in the records. For average annual NH temperatures, the period 1983–2012 was very likely the warmest 30-year period of the last 800 years (high confidence) and likely the warmest 30-year period of the last 1400 years (medium confidence). This is supported by comparison of instrumental temperatures with multiple reconstructions from a variety of proxy data and statistical methods, and is consistent with AR the results.

It is virtually certain that the upper ocean (above 700 m) has warmed from 1971 to 2010, and likely that it has warmed from the 1870s to 1971. It is likely that the ocean warmed between 700-2000 m from 1957 to 2009, based on 5-year averages. It is also likely that the ocean warmed from 3000 m to the bottom from 1992 to 2005, while no significant trends in global average temperature were observed between 2000 and 3000 m depth from circa 1992 to 2005. Below 3000 m depth, the largest warming is observed in the Southern Ocean.

These findings strengthens the conclusions from both AR4 (2007) and SREX, Risk of Extreme Events and Disasters to Advance Climate Change Adaptation, (IPCC, 2012) that it is now very likely that anthropogenic forcing has contributed to the observed changes in the frequency and intensity of daily temperature extremes on the global scale since the mid-20th century. In terms of historical trends, CMIP3 and CMIP5 models generally capture observed trends in temperature extremes in the second half of the 20th century (Sillmann et al., 2013) and there is high agreement that the global distribution of temperature extremes are represented well by CMIP3 and CMIP5 models. Studies with fixed ice-sheet topography indicate the increase of SST is greater than 2°C but less than 4°C (medium confidence) of global mean surface temperature rise with respect to the pre-industrial level.

It is *likely* that the GMST anomaly for the period 2016–2035, relative to the reference period of 1986–2005 will be in the range 0.3°C to 0.7°C (medium confidence). It is *very likely* that globally averaged surface and depth-averaged temperatures averaged for 2016–2035 will be warmer than those averaged over 1986–2005. According to (IPCC, 2013) global mean temperatures will continue to rise over the 21st century under all of the RCPs. From around the mid-21st century, the rate of global warming begins to be more strongly dependent on the scenario. GMSTs for 2081–2100, relative to 1986–2005 will *likely* be in the 5 to 95% range of the CMIP5 models; 0.3°C to 1.7°C (RCP2.6), 1.1 to 2.6°C (RCP4.5), 1.4°C to 3.1°C (RCP6.0), 2.6°C to 4.8°C (RCP8.5). The Arctic region is projected to warm most (very high confidence). It is *virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase. Increases in the frequency, duration and magnitude of hot extremes along with heat stress are expected; but occasional cold winter extremes will continue to occur.

Over the course of the 21st century, the global ocean will warm under all RCP scenarios. The strongest ocean warming is projected for the surface in subtropical and tropical regions. At greater depth the warming is projected to be most pronounced in the Southern Ocean. Best estimates of ocean warming in the top one hundred metres are projected to be 0.6°C (RCP2.6) to 2.0°C (RCP8.5), and 0.3°C (RCP2.6) to 0.6°C (RCP8.5) at a depth of about 1 km by the end of the 21st century. Due to the long time scales of this heat transfer from the surface to depth, ocean warming will continue for centuries, even if GHG emissions are decreased or concentrations kept constant.

4.1.2 Ice and snow

Realistic historical sea ice represent an important input to climate models (Wang and Overand, 2012), (Massonnet et al., 2013), (Stroeve et al., 2012), (Massonnet et al., 2013), (Wang and Overand, 2012), (Overland and Wang, 2013). (IPCC, 2013) reports that most of arge-scale sea ice processes, such as basic thermodynamics and dynamics, are well understood and well represented in models. However, there are still challenges in modelling important details of sea ice dynamics and deformation, particularly in small scales, see e.g. (see e.g. (Hutchings et al., 2011). Currently, sea ice model development is focusing primarily on more precise descriptions of physical processes including biological and chemical species.

Snow model development for sea ice has lagged behind terrestrial snow models. Lecomte et al. (2013) introduced vertically varying snow temperature, density and conductivity to improve vertical heat conduction and melting in a 1D model intended for climate simulation. The model has, however, limitations, many physical processes affecting the evolution of the snow pack, such as redistribution by wind, moisture transport (including flooding and snow ice formation) and snow grain size evolution, still are not included in most climate models.

Evaluation of sea ice performance requires accurate information on ice concentration, thickness, velocity, salinity, snow cover and other factors. The most reliably measured characteristic of sea ice remains sea ice extent (usually understood as the area covered by ice with a concentration above 15%). Caveats, however, exist related to the uneven reliability of different sources of sea ice extent estimates (e.g., satellite vs. pre-satellite observations), as well as to limitations of this characteristic as a metric of model performance, see (Notz and Marotzke, 2012).

As in AR4, there is very high confidence that the Arctic sea ice extent (annual, multi-year and perennial) decreased over the period 1979–2012. The average decrease was likely between 1.3 m and 2.3 m. The rate of the annual decrease was *very likely* between 3.5 and 4.1% per decade (range of 0.45 to 0.51 million km^2 per decade). The average decrease in decadal extent of annual Arctic sea ice has been most rapid in summer and autumn (high confidence), but the extent has decreased in every season, and in every successive decade since 1979 (high confidence). The extent of Arctic perennial and multi-year ice decreased between 1979 and 2012 (very high confidence). The rates are *very likely* 11.5 [9.4 to 13.6]% per decade (0.73 to 1.07 million km^2 per decade) for the sea ice extent at summer minimum (perennial ice) and *very likely* 13.5 [11 to 16] % per decade for multi-year ice. There is medium confidence from reconstructions that the current (1980–2012) Arctic summer sea ice retreat was unprecedented and SSTs were anomalously high in the perspective of at least the last 1,450 years.

It is *likely* that the annual period of surface melt on Arctic perennial sea ice lengthened by 5.7 [4.8 to 6.6] days per decade over the period 1979–2012. There is high confidence that in the Arctic, where the sea ice thickness has decreased, the sea ice drift speed has increased. There is very high confidence that, during the last decade, the largest contributions to global glacier ice loss were from glaciers in Alaska, the Canadian Arctic, the periphery of the Greenland ice sheet, the Southern Andes and the Asian mountains (80% of the total ice loss). It is *very likely* that the annual Antarctic sea ice extent increased at a rate of between 1.2 and 1.8% per decade (0.13 to 0.20 million km^2 per decade) between 1979 and 2012 (very high confidence).

It is *very likely* that the Arctic sea ice cover will continue shrinking and thinning year-round in the course of the 21st century as GMST rises. At the same time, in the Antarctic, a decrease in sea ice extent and volume is expected, but with low confidence. The CMIP5 multi-model projections give average reductions in Arctic sea ice extent for 2081–2100 compared to 1986–2005 ranging from 8% for RCP2.6 to 34% for RCP8.5 in February and from 43% for RCP2.6 to 94% for RCP8.5 in September (medium confidence). A nearly ice-free Arctic Ocean (sea ice extent less than 106 km^2 for at least five consecutive years) in September before mid-century is *likely* under RCP8.5 (medium confidence). There is little evidence in global climate models to a seasonally ice-free Arctic Ocean beyond which further sea ice loss is unstoppable and irreversible. In the Antarctic the CMIP5 multi-model mean projects a decrease in sea ice extent that ranges from 16% for RCP2.6 to 67% for RCP8.5 in February and from 8% for RCP2.6 to 30% for RCP8.5 in September for 2081–2100 compared to 1986–2005 (low confidence).

There is very high confidence that snow cover extent has decreased in the NH (Northern Hemisphere), especially in spring. Satellite records indicate that over the period 1967–2012, snow cover extent *very likely* decreased; the largest change, –53% [–40 to –66%], occurred in June. No month had statistically significant increases. In the Southern Hemisphere (SH), evidence is too limited to conclude whether changes have occurred.

It is *very likely* that NH snow cover will reduce as global temperatures rise over the coming century. Global model projections show that by the end of the 21st century a decrease of the NH spring snow covered area will be 7 [3 to 10] % (RCP2.6) and 25 [18 to 32] % (RCP8.5); there is medium confidence in these numbers. Further, by the end of the 21st century, projected near-surface permafrost area is projected to decrease by between 37% (RCP2.6) to 81% (RCP8.5) (medium confidence).

Some recent references addressing climatic changes of ice include: (Box, 2013), (Box and Colgan, 2013), (Winkelmann et al., 2012), (Franco et al., 2013), (Fettweis et al., 2013), (Little et al., 2013.).

4.1.3 Sea water level

Both tide gauge and satellite altimetry data show that the GMSL (Global Mean Sea Level) has continued to rise, relative to 1961–1990, (IPCC, 2013). Although the increase is fairly steady, observational records show short periods of either no change or a slight decrease. The observed estimates of the GMSL increase lie within the envelope of all the projections except perhaps in the very early 1990s. The sea level rise uncertainty due to scenario-related uncertainty is smallest for the most recent assessments (AR4 and AR5) and observed estimates lie well within this scenario-related uncertainty. It is *virtually certain* that over the 20th century sea level rose. The mean rate of sea level increase was 1.7 mm yr^{-1} with a *very likely* range between 1.5 to 1.9 between 1901 and 2010 and this rate increased to 3.2 with a *likely* range of 2.8 to 3.6 mm yr^{-1} between 1993 and 2010.

According to IPCC (2013) it is *very likely* that the rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971–2010 for all RCP scenarios due to increases in ocean warming and loss of mass from glaciers and ice sheets. Model projections of sea level rise are larger than reported in the AR4 (2007), primarily because of improved modeling of land-ice contributions. For the period 2081–2100, compared to 1986–2005, global mean sea level rise is *likely* (medium confidence) to be in the 5 to 95% range of projections from process-based models, which give 0.26 to 0.55 m for RCP2.6, 0.32 to 0.63 m for RCP4.5, 0.33 to 0.63 m for RCP6.0, and 0.45 to 0.82 m for RCP8.5. For RCP8.5, the rise by 2100 is 0.52 to 0.98 m with a rate during 2081–2100 of 8 to 16 mm yr^{-1}.

Based on current knowledge, only the collapse of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century (medium confidence). It is *virtually certain* that global mean sea level rise will continue beyond 2100, with sea level rise due to thermal expansion to continue for many centuries but the amount is dependent on future emissions. The available evidences today indicate that sustained global warming greater than a certain threshold above pre-industrial would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea level rise of about 7 m. It is *very likely* that there will be a significant increase in the occurrence of future sea level extremes in some regions by 2100, with a *likely* increase in the early 21st century. Sea level rise of 1 to 3 m per degree of warming is projected if the warming is sustained for several millennia.

According to IPCC (2013) there is low confidence in region-specific projections of storminess and associated storm surges.

Some recent references addressing sea level changes include: (Jevrejeva et al., 2012b), (Jevrejeva et al., 2012a), (Gillet-Chaulet and al., 2012), (Gehrels et al., 2012), (Gillet-Chaulet and al., 2012), (Bamber and Aspinall, 2013), (Dutton and Lambeck, 2012).

4.1.4 Wind and waves

The two last Assessment Reports (AR) form IPCC (2007) and IPCC (2013) are based on results from the Coupled Model Intercomparison Project (CMIP) studying the output of climate models (CMs). The CMIP was established by the Working Group on Coupled Modelling (WGCM) of the World Climate Research Programme (WCRP) in 1995 and provides a community-based infrastructure in support of climate model diagnosis, validation, and intercomparison.

CMIP has gone through five phases. The fifth phase, CMIP5, has provided a framework for assessments in the Fifth IPCC Assessment Report (AR5) but so far only a limited number of wind and wave studies are based on CMIP5 models (http://cmip-pcmdi.llnl.gov), and most post-AR4 wind and wave studies are based on CMIP3 (http://cmip-cmdi.llnl.gov/cmip3_overview.html). A comprehensive summary of characteristics and performance of climate models is given by IPCC (2013).

Storms can be classified into two groups: extra-tropical cyclones (regular storms) and tropical cyclones (hurricanes and typhoons). IPCC (2013) reports that there is low confidence in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. Increases in the frequency and intensity of the strongest storms in the North Atlantic are robust (very high confidence) but the cause of this increase is debated (the relative importance of internal variability and anthropogenic and natural forcings). The model projections indicate that it is *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, with a *likely* increase in both global mean tropical cyclone maximum wind speed and rainfall rates, however, there is lower confidence in region-specific projections of frequency and intensity. Because of improvements in model resolution and downscaling techniques, it is *more likely than not* that the frequency of the most intense storms will increase substantially in some basins under projected 21st century warming. The scientific community is in agreement that the global number of extratropical cyclones is *unlikely* to decrease by more than a few per cent.

Recent investigations continue to support the findings of the AR4 and SREX, it is a *likely* poleward shift of storm tracks since the 1950s (both in NH and SH). Storm track biases in the North Atlantic have been improved slightly. There is low confidence in the magnitude of regional storm track changes, and the impact of such changes on regional surface climate.

It is *likely* (medium confidence) based on reanalysis forced model hindcasts and ship observations that mean significant wave height has increased since the 1950s over much of the North Atlantic north of 45°N, with typical winter season trends of up to 20 cm per decade. It is also *likely* (medium confidence) that annual mean significant wave heights will increase in the Southern Ocean as a result of enhanced wind speeds. Swells generated in the Southern Ocean are likely to affect heights, periods, and directions of waves in adjacent basins. It is *very likely* (medium confidence) that wave heights and the duration of the wave season will increase in the Arctic Ocean as a result of reduced sea-ice extent. In general, there is low confidence in region-specific projections due to the low confidence in tropical and extratropical storm projections, and to the challenge of downscaling future wind fields from coarse-resolution climate models.

The CMIP3 results of Hemer et al. (2012) and Hemer et al. (2013), Fan et al. (2013), Mori et al. (2012), Semendo et al. (2013), support the earlier studies reviewed by Bitner-Gregersen et al. (2013a), i.e. negligible changes in the projected mean SWH (Significant Wave Height) in all ocean basins except the Southern Ocean and the South Pacific. Both Mori et al. (2013) and Hemer et al. (2013) found that the variance of wave-climate projections associated with wave downscaling methodology dominated other sources of variance within the projections, e.g. the climate scenario or climate model uncertainties. Further, Mori et al. (2013), Hemer et al. (2013) and Fan et al. (2013) found some changes in wave periods and wave direction in the 21st century. Wave periods were found to increase over the eastern Pacific and decrease in the North Atlantic. Wave directions exhibit clockwise rotation in the tropics.

Wind and wave projections using CMIP5 models are limited. de Winter et al. (2013) compared the Gumbel probability density functions (PDFs) for the annual maximum wind speed for 12 models for RCP4.5 and RCP8.5. The chosen regions were the southern and the northern North Sea and the time period 2050–2100. The distributions show significant variability between the 12 models with respect the mean values and standard deviations. It is particularly noteworthy that the 100 year wind speed for the northern North Sea varied from around 24 m/s to 34 m/s, an extremely large deviation seen from an engineering point of view.

Few similar studies appear to have been made on wave heights. Dobrynin et al. (2012) used one wave model (WAM) forced by winds from one CM (EC-Earth) to study the evolution of the global wave climate over 250 years (1850–2100) in terms of the mean projected SWH, using RCP4.5 and RPC8.5. On a global scale only minor changes were detected in the mean projected wave height, 0.05 m from 1850 to 2010. Between 2010 and 2100 the change was found to be an increase of 0.03 m for RCP8.5 and a decrease of 0.005 m for RCP4.5, respectively. The anomaly in Norwegian waters appears to have been close to 0%.

Uncertainties associated with wind and waves projections are presented in a flowchart in Figure 4.

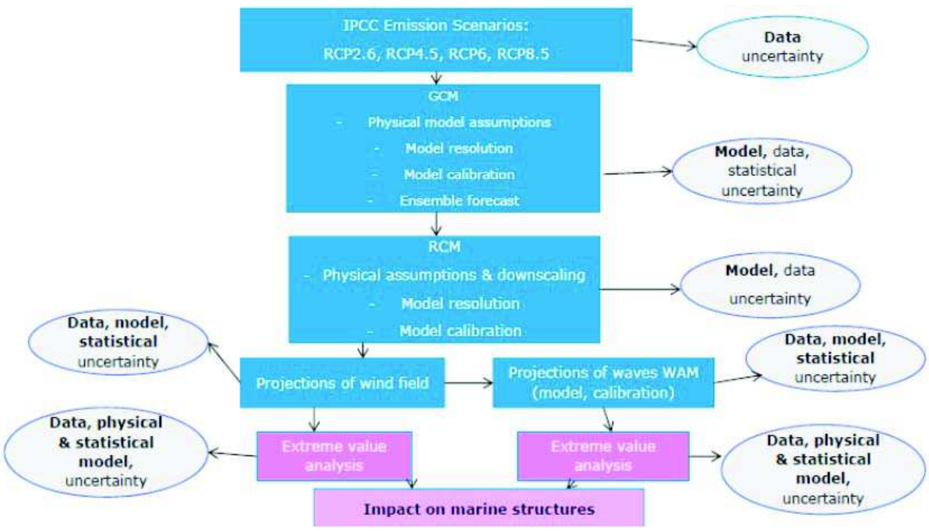

Figure 4. Uncertainties associated with wind and waves projections.

4.1.5 Ocean circulation

The movement of fresh water between the atmosphere and the ocean can also influence oceanic salinity, which is an important driver of the density and circulation of the ocean. It is *very likely* that changes in the mean surface waters salinity have taken place since the 1950s (IPCC, 2013). The mean contrast between high- and low-salinity regions increased by 0.13 [0.08 to o.17] from1950 to 2008. The Atlantic has become saltier and the Pacific and Southern Ocean freshened. There is high confidence in this assessment. According to IPCC (2013) it is *likely* that salinity will increase in the tropical and especially subtropical Atlantic, and decrease in the western tropical Pacific over the next few decades. Overall, it is *likely* that there will be some decline in the Atlantic Meridional Overturning Circulation by 2050 (medium confidence). However, the rate and magnitude of weakening is very uncertain and decades when this circulation increases are also to be expected. These changes are expected to have impact on the ocean current patterns.

5. SPECIAL TOPICS

5.1 Hurricane

Modelling of hurricanes has got increasing attention in the scientific community and media due the extreme weather events reported in the last decade and projected climate changes. Reasons for occurrence of the hurricanes is still a topic of discussion. It is interesting to note that the API (American Petroleum Institute) hurricane metocean conditions in the Gulf of Mexico were revised some years ago to account for effects of recent major hurricanes as well as changes in understanding regarding occurrence of hurricanes

Hurricane or typhoon (tropical cyclones) originate over tropical oceans in the latitudes between 5° to 20° from the equator where the surface water temperature is sufficiently warm. A strong low pressure pumps up a large amount of air from just above the sea surface rises in spiral fashion and condenses to from clouds and precipitation in the upper atmosphere. A large amount of latent heat energy is released into the atmosphere generating strong winds Hurricane or typhoon frequently causes serious damage to marine structure or navigating vessels. Wind wave modeling is essential method to predict wave height. High accurate model plays an important role for disaster prevention.

Forecasting of wave heights is essential for planning and operation of maritime activities. Traditionally, wave heights have been predicted using physics-based models, which rely primarily on the energy balance equation. More recently, soft computing techniques such as Artificial Neural Network, Genetic Programming (GP) have been used to generate forecasts with leads time from a few hours to several days. Nitsure et al. (2012) improved the forecast of wave heights with lead times of 12 h and 24 h using GP. The results were satisfactory, especially for the peak wave heights formed by the extreme events like hurricanes. Besides, a spherical multiple-cell (SMC) grid was installed in a global wave model by Li et al. (2012) to overcome the polar wave problems. A 2nd order upstream non-oscillatory advection scheme and a rotation scheme for wave spectral refraction were used. The unstructured SMC grid allows time step to be relaxed and land cells to be removed, saving over 1/3 of the total computation time in comparison with the original latitude-longitude grid model. In addition, a quadtree-adaptive model was applied by Tsai et al. (2013) for prediction of waves generated by tropical cyclones. The quadtree grid system can be adapted to the vicinity of the hurricanes and/or some prescribed regions of interest which require higher resolutions, so that the quadtree grid system can move with the hurricanes.

The University of Miami has presented a Fully Coupled Atmosphere-Wave-Ocean Modeling system (UMCM). The UMCM includes three model components: atmospheric, surface wave, and ocean circulation models. Chen et al. (2007) gave a brief introduction to UMCM and an overview for the coupled modeling effort in the Coupled Boundary Layer Air-Sea Transfer (CBLAST)–Hurricane program. Chen et al. (2013) described the results of a new directional wind–wave-coupling parameterization in a fully coupled model developed based on the CBLAST-Hurricane observations and laboratory measurements. Currently, UMCM can be configured with two different options in terms of component models: 1) coupled with the fifth-generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5), a third generation wave model (WAVEWATCH III), and the three-dimensional Price-Weller-Pinkel (3DPWP) upper ocean model (UMCM-MWP); and 2) coupled with the Weather Research and Forecasting Model (WRF), the University of Miami Wave Model, UMWM, Donelan et al. (2012) and the Hybrid Coordinate Ocean Model (HYCOM) (UMCM-WMH).

In addition, Liu et al. (2012) did an investigation of the effects of wave state and sea spray on an idealized typhoon using an air-sea coupled modeling system. The coupling between atmosphere and sea surface waves considered the effects of wave state and sea sprays on air–sea momentum flux, the atmospheric low-level dissipative heating, and the wave-state-affected sea spray heat flux. Smith et al. (2013) examined tropical cyclone ocean-wave model interactions using an ESMF (Earth System Modeling

Framework) based tropical cyclone (TC) version of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). The Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system was used to investigate semi-enclosed Gulf of Venice Benetazzo et al. (2013). The results revealed that, when applied to intense storms, the effect of coupling on waves results in variations of significant wave height up to 0.6 m, with some areas experiencing significant increase/decrease of wave spectral energy for opposite/following currents respectively.

The features of typhoon such as occurrence time, location, tracks and intensity have much uncertainty, and corresponding probability research have a great development recently. Zhang and Xu (2005) proposed a Modified Maximum Entropy Distribution (MMED) with four unknown parameters which can cover different kinds fitting curves for extreme environmental elements. (Dong et al., 2013b) proposed maximum likelihood method to estimate uncertain parameters, and compared it with method of moment and empirical curve fitting method. Dong et al. (2013a) introduced Poisson-MMED to consider typhoon occurrence numbers and process extreme values, and adopted it in the long-term extreme value calculations of storm surges based on the data from Japan and North Sea. Ocean environmental elements such as wind, wave and current induced by typhoon are generally statistically related. Dong (2013c) selected annual extreme significant wave heights and corresponding peak periods based on storm process data firstly, then constructed bivariate equivalent MMED to study the joint probability of these two elements. Tao et al. (2013a) proposed several Poisson bivariate MMEDs by using four common-used copulas and Poisson distribution (which fits the storm occurrence numbers), and established a Joint Tide-Wave Impact Grade to judge the typhoon storm surge intensity passed Qingdao of China. For marine engineering designs, Dong et al. (2012) presented interval estimations of return wave heights based on MMEDs while Tao et al. (2013b) gave the joint design parameters of wave height and wind speed by using bivariate MMEDs, and by taking account of typhoon occurrence frequency, the corresponding Poisson compound extreme value distributions can also be used for designs. Figure 5 shows a flowchart of the hurricane or tyhpoon hindcast model and statistical model used when diriving extremes.

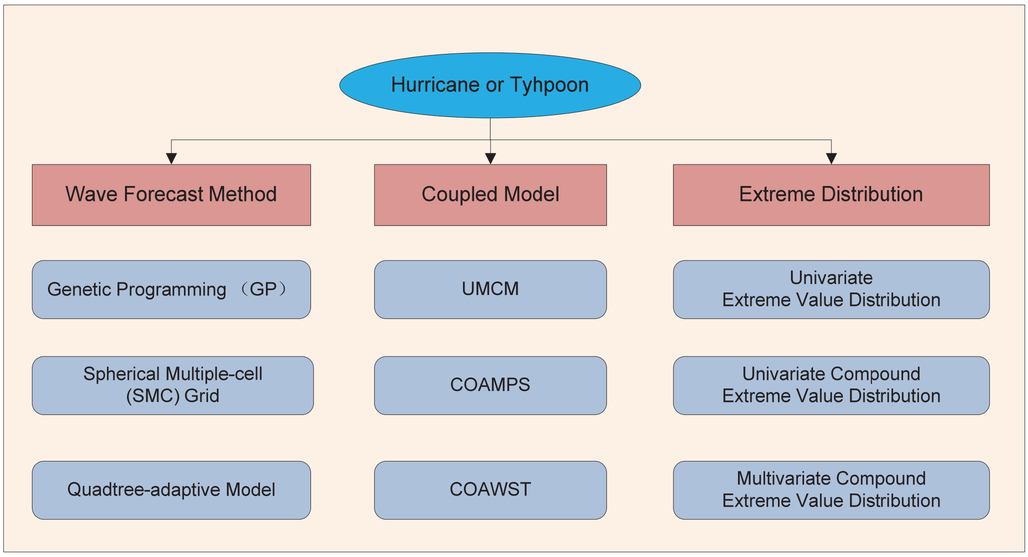

Figure 5. Hurricane or tyhpoon hindcast model and statistical model.

5.2 *Wave current interaction*

Wave-current interaction is a common phenomenon in the ocean. It affects wave parameters, the shape of a wave spectrum and has impact on the flow field of current. Consequently it influences the response and safety of marine structures. The subject got increasing attention in the last decade due to the debate about rogue waves and recently also climate change as well as the renewable energy needs.

In the present section the latest trend of investigations dedicated to wave-current interaction are reviewed for the period 2009–2014, given main focus on the years 2012–2014.

5.2.1 Wave-current Interaction Model

Based on intensive former research, Smith (2006) summarized the energy, momentum, and mass-flux changes between surface wave and underlying Eulerian mean flows. Besides classical wave “radiation stress”, other various terms are identified with, for example, the integrated “CL vortex force” implemented. They focused on interpreting these terms in term of physical mechanism and permitting reasonable estimates of the associated dependency. Lane et al. (2007) compared the vortex-force representation of the wave-averaged effects on currents with the radiation-stress representation in a region that is proper for coastal and shelf waters.

Mellor (2011) presented surface wave equations appropriate to three-dimensional ocean model by assuming that the depth dependence of wave motions is provided by linear theory. Expressions for vertically dependent radiation stress and a definition of the Doppler velocity for a vertically dependent current field are obtained. The momentum and wave energy equations included other quantities such as vertically dependent surface pressure forcing and terms representing the production of turbulence energy by currents and waves. This research provided sound base for three-dimensional ocean models that treat surface wave and wind- and buoyancy-driven currents simultaneously. Later, Ardhuin et al. (2008a) criticized this paper of inadequate approximations of the wave motion. They showed these equations are not consistent in the simple case of shoaling waves without current. The modification needs a numerical evaluation of the wave-forcing terms. Mellor (2011) revised their work, abandoning the a priori use of sigma coordinates as characterization of waves derived for a flat bottom can be misunderstood in the sigma domain. Only the depth-dependent stress radiation terms are added to the momentum equation to incorporate them into three-dimensional circulation models. It is also believed that transport of the surface stress into the water column is supported by pressure and turbulence instead of turbulence alone as described in former studies.

On the other hand, Ardhuin et al. (2008b) utilized the generalized Lagrangian mean theory to find exact equations for three-dimensional wave-turbulence-mean flow interactions. To close their equations, they specify the wave forcing terms under the hypotheses of small surface slope, weak horizontal gradients of water depth and mean current, and weak curvature of the mean current profile, yielding analytical expressions for the mean momentum and press forcing terms related to the wave spectrum. Furthermore, *glm2z*-RANS equations with non-divergent mass transport in Cartesian coordinate are obtained by applying a vertical change of coordinate. Their approximation provides an explicit extension of known wave-averaged equations to short scale variations of the wave field and vertically varying currents. The underlying exact equations can provide a natural framework for extensions to finite wave amplitudes and any realistic conditions. Meanwhile, Bennis and Ardhuin (2011) thought that work of Mellor (2011) is not consistent with the known depth-integrated momentum balance in the presence of a sloping bottom. Unrealistic surface elevations and currents can be produced by a numerical integration of the equations in the absence of dissipation. It seemed to them that the inconsistency is caused by a different averaging for the pressure gradient term and the advection terms of the same equation. Nevertheless, work of Mellor (2011) can produce large errors for continental shelf applications such as the study of cross-shore transports outside the surf zone. They recommended equations for the quasi-Eulerian velocity (McWilliams et al., 2004, Ardhuin et al., 2008b) which is free from such problems. Mellor (2011) replied to this criticism, stating that it is only partially correct but fallacious for the most part.

Hasanat Zaman and Baddour (2011) reported a study of three-dimensional interaction of a current-free monochromatic surface wave field with a wave-free uniform current field under the assumption of irrotational and inviscid flow. Particularly, the wave and current fields are not necessarily collinear with each other. They also developed the expressions to describe the characteristics of the interacting flow by mass, momentum and energy transport conservation. They used parameters such as the surface disturbance amplitude and length, mean water depth, mean current-like parameter and direction of the combined flow to illustrate the wave-current field after interaction.

Wave breaking influences wave-current interactions in real sea. Whitecapping affects the Reynolds stresses. Restrepo et al. (2011) modified a model (McWilliams et al., 2004) for the conservative dynamics of waves and currents to include the averaged effect of multiple, short-lived, and random wave-breaking events on large spatio-temporal scales. They treated whitecapping by parameterizing stochastically as an additive uncertainty to the fluid velocity. They coupled it to the Sokes drift as well as to the current velocity in the form of nonlinear momentum terms in the vortex force and the Bernoulli head. They discussed whitecapping’s effect on tracer dynamics, mass balance and boundary conditions.

Aiki and Greatbatch (2012) investigated the residual effect of surface gravity waves on mean flows in the upper ocean by thickness-weighted mean (TWM) theory in a vertically Lagrangian and horizontally Eulerian coordinate system. They derived depth-dependent equations for the conservation of volume, momentum and energy, which allow for (i) finite amplitude fluid motions, (ii) the horizontal divergence of currents, and (iii) a concise treatment of both kinematic and viscous boundary conditions at the sea surface.

Chen and Chen (2014) presented a three-dimensional Lagrangian solution up to the fifth-order found for the Boundary Value Problem (BVP) of irrotational, progressive water waves propagating in the presence of uniform current in water of constant depth. They embedded wave-current interaction in the Lagrangian velocity potential assuming that pressure is not affected by current in the wave-current field. Further, they also presented motion properties of particles such as the particle motion period, drift velocity, the Lagrangian mean level and the 3D particle trajectory and streamline. The numerical results were in good agreement with experiments (Chen et al., 2012). When currents vanish, the present solution deduces to the solution of the progressive wave propagation (Chen et al., 2010).

5.2.2 Numerical and Analytical Method

Rusu and Guedes Soares (2011) investigated wave-current interaction using SWAN model, which is a state-of-art spectral model for the wave transformations. They explained the theoretical background of the wave-current interactions, including the transformation of the wave spectrum and breaking waves due to currents. Generally, their experimental data and the simulations had good agreement. Moreover, Rusu et al. (2011) studied the wave propagation and the consequences of the influence of currents on waves in an estuary. They evaluated the effects of the wind and local currents on the incoming waves by performing SWAN simulations with and without considering the tide level and tide induced currents. The model results were also compared with measurements to validate the results of the wave prediction system developed. Bratland et al. (2011) described the calculation of wave elevations in higher order unidirectional, irregular waves with a uniform current in deep water.

Markus et al. (2013) using unsteady RANS equations simulated the flow field of a nonlinear wave in combination with a non-uniform current. The methodology combines a non-linear wave model with a VOF calculation to generate an unsteady sea state. A simulation strategy that focuses on capturing wave-current interaction is introduced and is validated with respect to fluid particle kinematics.

Ardhuin et al. (2012) reviewed the performance of numerical models in conditions with strong current with respect to currents effects on waves. Their analysis was supported by experiments and real sea measurements. They showed that using different parameterizations with a dissipation rate proportional to some measure of the wave steepness to the fourth power, the results deviate significantly, none being fully satisfactory. So they called for experiments data with higher spatial resolution to better resolve the full spatial evolution of the wave fields and to validate the parameterizations.

Moreira and Peregrine (2012) investigated numerically effects of nonlinearity on a linear water wave train in deep water with underlying currents by using a boundary-integral method. Their research included a 'slowly' varying current and a 'rapidly' varying current (see Figure 6). Especially, they paid attention to wave breaking and blocking and qualitatively explained former experimental observation.

Teles et al. (2013) evaluated wave-current interactions by an advanced CFD solver based on RANS equations. First, changes in the mean horizontal velocity and the horizontal velocity amplitude profiles and the influence of various first and second order turbulence closure models were studied. The results of the numerical simulations were compared to the experimental data from former studies. Secondly, they conducted more detailed study of the shear stresses and the turbulence viscosity vertical profile changes.

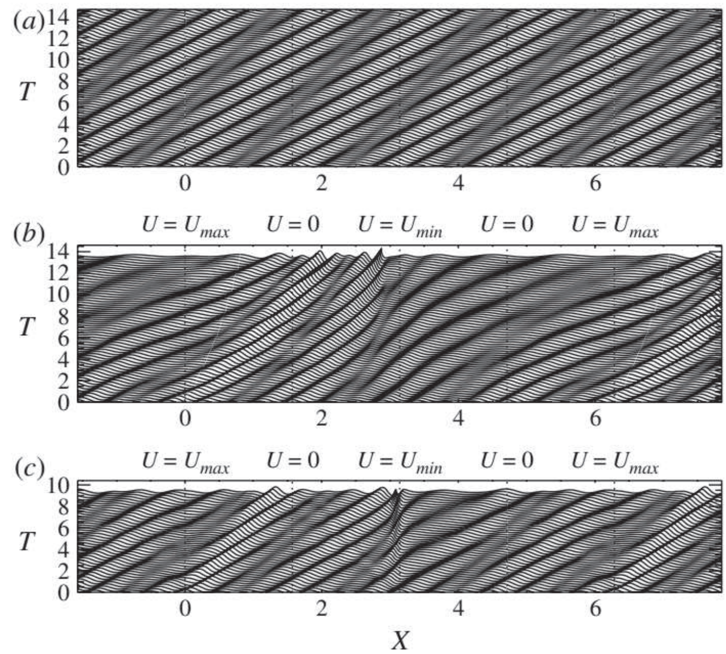

Figure 6. Fully nonlinear results obtained for wave groups propagating over (a) still water, (b) a 'slowly' varying current and (c) a 'rapidly' varying current, (Moreira and Peregrine, 2012).

Zou et al. (2013) formulated a new Boussinesq-type equations for wave-current interactions. They included the mean water depth change caused by the presence of current and wave–current interaction. Both strong and moderate current were considered. They revealed the effect of the current on the vertical distributions of the wave velocity and the pressure. They performed numerical simulation to show the effect of the mean water depth change, caused by the presence of current, on wave motions.

Zhang et al. (2014b) utilized RANS equations, with k_t-ε turbulence model (k_t denotes the turbulent kinetic energy and ε is the dissipation rate) and VOF method to capture free surface, to study wave-current interactions. They referred to work by Lin and Liu (1999) and used a inertia wave generator in the middle of numerical tank. The generation of current was realized by setting boundary conditions. So they studied the wave in following and opposing current simultaneously (see Figure 7). They validated their velocity profiles by comparing with experimental work by Umeyama (2011). Furthermore, they discussed the effects of wave periods and current velocity on regular wave-current induced water surface profile and velocity distribution. Finally, they studied the propagation of a solitary wave traveling with a following/opposing current numerically.

Myrhaug and Holmedal (2014) provided a simple analytical tool to calculate the wave-induced current beneath long-crested (2D) and short-crested (3D) random waves. As an example, they calculated the significant values of the Stokes drift and transport in deep water and in finite water depth.

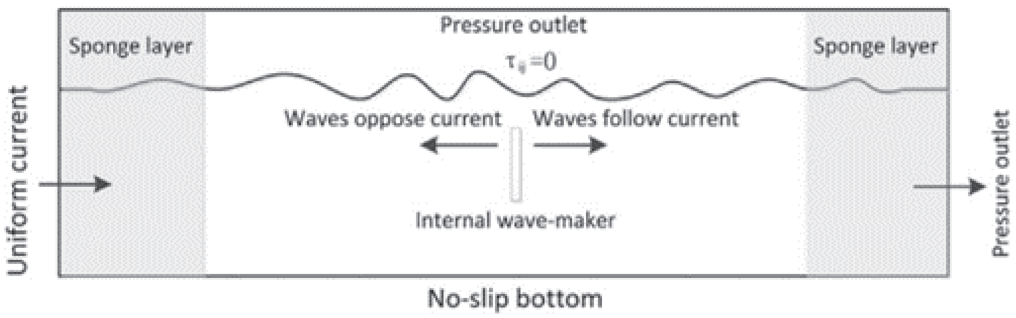

Figure 7. An illustrative sketch of computational domain and boundary conditions for modeling wave–current interaction, Zhang et al. (2014).

Wave-current interaction could affect the wave focusing and freak wave in the ocean. Hu and Ma (2011) investigated the influence of wave-current interaction on freak waves based on modified Nonlinear Schrödinger Equations (NLS). Peng et al. (2013) developed a numerical wave tank by high order spectrum method (HOSM) and simulated nonlinear wave-current interactions. Peng et al. (2013) investigated similar issue by a RANS simulation taking viscous effect into consideration.

5.2.3 *Experiments and Measurements*

Umeyama (2009) investigated the turbulence intensities of the interaction between nonbreaking waves with varying periods and uniform current in a two-dimensional water flume. The prediction of the Eulerian mean velocity was discussed in following and opposing current. Furthermore, Umeyama (2009) conducted intensive experiments under different wave parameters such as the ratio between wave height and wavelength or that between particle velocity and depth-averaged velocity. He looked into the phase-averaged turbulent intensities, wave-current Reynolds stress, and velocities for variable wave or hydraulic characteristics such as wave height, period, direction, and water depth. This study also made up for the data lacking an aspect of phase-averaged velocity and lateral turbulence in former study. Recently, Umeyama (2011) employed Laser Doppler anemometer (LDA) and coupled Particle Image Velocimetry(PIV) and particle tracking velocimetry (PTV) measurements to study kinetic aspects of surface waves propagating with or without a current in a constant water depth. Physical properties of the velocity and trajectory of a water particle during one wave cycle were investigated experimentally.

Ma et al. (2010) conducted a laboratory observation of the nonlinear evolution of waves propagating on a spatially varying opposing current in a 2D wave-current flume. A frequency downshift was found in opposing currents. The ultimate frequency downshift increases as increase initial steepness enhances. The evolution of frequency modulation was observed using the instantaneous frequency extracted by the Morlet-wavelet transform. Wave blocking in strong current could increase the asymmetric modulation and accelerate the effective frequency downshift.

Gemmrich and Garrett (2012) examined long records of surface wave heights from buoy observations in the northeastern Pacific Ocean. Their findings showed the effect of near-inertial currents on surface waves.

The result had implications for wave forecasting and provided valuable information on the frequency, strength, and intermittency of the associated near-inertial motions.

Toffoli et al. (2013b) performed experiments in two independent wave tanks and showed experimentally that a stable wave propagating into a region characterized by an opposite current may become modulationally unstable. The experimental results supported the recent conjecture based on a current-modified nonlinear Schrödinger equation which establishes that rogue waves can be triggered by a nonhomogeneous current characterized by a negative horizontal velocity gradient.

Robinson et al. (2013) provided a first insight into the dynamics of dense saline gravity currents moving beneath regular progressive free-surface water waves. After the initial collapse, the gravity currents propagated horizontally with two fronts, one propagating in the wave direction and the other against the wave direction. The overall length of the gravity current, the position of the gravity current center, the shape of the two leading profiles and an asymmetry in the shape of the upstream and downstream current heads have been discussed in the paper.

Wijesekera et al. (2013) deployed several acoustic Doppler current profilers and vertical strings of temperature, conductivity, and pressure sensors on and around the East Flower Garden Bank (EFGB) (180-km southeast of Galveston, Texas) to examine surface wave effects on high-frequency flows over the bank and to quantify spatial and temporal characteristic of these high-frequency flows.

Ma et al. (2013) carried out systematic experiments focusing on the evolution of wave trains with initially sidebands on uniform currents in a wave-current flume.

The linear modal theory for waves on opposite jet current is given by Shrira and Slunyaev (2014a). It is based on the approximate variable separation for transverse modes. The resulting one-dimensional boundary-value problem allows one to perform theoretical analysis of waves on currents, and to employ a series of analytic solutions. The Agulhas current represents of order 100–1000 trapped wave modes. Shrira and Slunyaev (2014b) has formulated also the weakly nonlinear equation for modes of waves trapped by an opposite jet current. The mode evolution against the current is described by the nonlinear Schrödinger equation with reduced nonlinear term. The weakly nonlinear solutions are verified by means of strongly nonlinear simulations. The occurrence of localized breaking events from smooth initial conditions is shown. The 3D intense solitary wave patters are shown to exist. The 3D problem corresponds to effectively unidirectional dynamics, and thus the probability of rogue waves in the field of trapped waves is much higher.

5.3 Wave and wind energy resource assessment

With the development of Marine Renewable Energy, a significant effort is made on resource assessment. Objectives of resource characterization include not solely wind, wave or tidal current power assessment but also an accurate description of the environment for the purpose of engineering applications such as design and optimization of marine devices and marine operations. As a consequence, a refined characterization of the space and time variability of the various relevant parameters is requested, especially in coastal areas, and adapted analysis tools are to be developed.

Especially for the case of wave energy extraction there exists a strong demand for high resolution wave hindcast databases allowing regional or site climatology assessment.

Boudiere et al. (2013) developed a sea-states hindcast database for the assessment of sea-states climatologies that fulfills such requirements for MEC design and optimization. This database, covering the Channel and Bay of Biscay over a 19 years period from 1994 to 2012 was built running an up-to-date configuration of the WaveWatch III® wave model on a refined unstructured grid with mesh size ranging from about 200 m in coastal areas to about 10 km offshore. The wave model is forced by the wind field from the CFSR reanalysis (Climate Forecast System Reanalysis) that was produced at NCEP (National Centre for the Environmental Prediction) in 2010. Tidal currents and water levels were derived from atlases of tidal harmonics obtained from the MARS 2D (Model for Applications at Regional Scale) hydrodynamic model. Outputs include a large set of parameters relevant to marine energy applications at each point of the computational grid together with directional spectra at over 4000 locations. Model data was validated against in-situ (buoy), remote sensing measurement data as well as another hindcast database and proved to be of good quality.

Combining the WAVEWATCH III and SWAN wave models, Garcia-Medina 2013 built a 7 year hindcast at a 30 arc-second resolution along the coast of Oregon and southwest Washington, USA.The hindcast accuracy was validated against buoy data and was used to analyze the alongshore variability of the resource over the continental shelf. Beyond the classical general power decay with depth related to wave refraction and shoaling, specific local features of the power distribution are identified. For instance due to wave refraction, areas off the central and southwest Oregon coast are identified that show increased wave power at 50 m of water in comparison with the 250 m value. It is also observed that areas with preferentially narrower wave spectra in both frequency and direction are identified off southwest Oregon. However, it is also pointed out that a near shore wave energy resource characterization for Oregon and Washington, in water depth lesser than 50 m, may necessitate even higher-resolution assessments.

Influence of tide on wave propagation, hence on wave energy resource is worth being evaluated. Using a non-linear coupled wave-tide model SWAN-ROMS (Hashemi and Neill, 2014) assessed the impact of tides on the wave energy resource of the northwest European shelf seas. Comparing one month of wave power computed using the SWAN model alone, that is without current, and the SWAN-ROMS coupled results they show that the impact of tides is significant, and can exceed 10% in some regions of strong tidal currents (e.g. headlands). Results also show that the effect of tidal currents on the wave resource is much greater than the contribution of variations in tidal water depth, and that regions which experience lower wave energy (and hence shorter wave periods) are more affected by tides than high wave energy regions.

Even though the Mediterranean Sea is usually considered as a basin with limited wave resource, significant number of studies are conducted to provide high resolution assessment of the wave energy resources in that area.

Using a parallel version of the WAM wave model Cycle 4.5.3 Liberti et al. (2013) built a ten year hindcast data base of the entire Mediterranean basin on a 1/16° resolution grid to assess the wave energy resource. Analysis of the model results allows the characterization of the regional distribution of the resource. For instance, the western Sardinia coast and the Sicily Channel are found to be among the most productive areas in the whole Mediterranean. Additionally, simulation results show the presence of significant spatial variations of wave power availability even on relatively small spatial scales along these two coastlines, confirming the needs for high resolution resource assessment. Seasonal variability is also investigated and large amplitude seasonal variation range is observed in some areas.

Combining wave buoy data and a 22 year hindcast data set provided by ECMWF, Vicinanza et al. (2013) assessed the power resource off the coast of Sardinia (Italy) in the Mediterranean Sea. The annual offshore wave power was found to range between 8.91 kW/m and 10.29 kW/m, the bulk of which is provided by north-westerly waves. They also studied the nearshore energetic patterns by means of a numerical coastal propagation model (Mike21 NSW). The analyses highlight two “hot spots” in which, practically, the energy dissipation appears to be compensated for by natural phenomena of energetic refraction and wave reflection due to seabed interaction and where the wave power is respectively 9.95 and 10.91 kW/m.

Even though regional and local studies are a mandatory requirement for resource assessment, global characterization of the available resource should also be considered as it presents some economical and industrial interest. Using six years (2005–2011) of a hindcast database provided by NOAA and built using WAVEWATCH III at a spatial resolution of 30 arc-minutes and a temporal resolution of 3 hours, Gunn and Stock-Williams (2012) estimated from global parameters the wave power along the world’s oceanic coastline. Introducing the Pelamis P2 power matrix they also estimated the extractable power for an array of such wave energy converter (WEC). Beyond a quantitative description of the available power around the world, this work allows to point out an interesting qualitative result as it reveals that the best areas for wave power generation may not be exactly correlated with the best areas for raw resource.

Using a more general approach valid for any device to be installed at a specific site and focusing on other parameters than the sole available power, namely the energy spread in frequency and direction, and the seasonality, Portilla et al. (2013) show that other areas than the most energetic ones (located in the storm-belts) can be similarly attractive simply because the lower energy level is compensated by a greater potential efficiency due to wave characteristics more uniform in time and to the lack of severe conditions.

As for waves, tidal current resource assessment requires an accurate characterization of the available power on rather high resolution grids but covering large areas over which tidal turbines are likely to be deployed in arrays. It is also of prime importance to characterize the variability of the flow and therefore to provide parameters, metrics and methodologies that are suitable for engineering applications. Even though numerical modeling is the most widely used approach, there are still strong requirements for in-situ measurement capacity, especially to contribute to the assessment of the turbulent features of the flows in the highly energetic areas considered for the deployment of tidal turbines.

Presenting results of a measurement campaign conducted at two energetic sites, Thomson et al. (2012) discuss the development of a set of metrics for describing the turbulence together with the utility of ADCP measurements for observing turbulence at tidal energy sites These results provide some of the first realistic conditions for estimating the fatigue loads and the performance of tidal turbines as only very few measurement campaigns at energetic sites have been conducted and little data is available.

A comprehensive methodology for the validation of numerical models in two and three dimensions is presented by Gunn and Stock-Williams (2013) and discussed. Especially they present novel extended methods for the validation of 3D data and use Acoustic Doppler Profiler data for a case study validation of a specific energetic site and finally provide interesting guidelines for model validation purpose.

6. DESIGN AND OPERATIONAL ENVIRONMENT

6.1 Design

New designs and operational decisions must be assessed/made relative to recognised codes and standards, for which the responsible authority, perhaps a classification society or the user himself, will depend on the design and its application. To achieve recognition, an environment parameter's climatology must be demonstrated as robust and of adequate accuracy and consequently such codes and standards may lag behind the state-of-the-art.

The majority of ocean-going ships are designed currently to the North Atlantic wave environment, which is regarded as the most severe. It is interesting to note that recent investigations of global wind and wave conditions are confirming the latter, see (Cardone and Cox, 2011, Cardone et al., 2014). The traditional format of classification society rules is mainly prescriptive, without any transparent link to an overall safety objective. In 1997 and 2001 IMO has developed Guidelines for use of the Formal Safety Assessment (FSA) methodology in rule development which will provide risk-based goal–oriented regulations (IMO, 1997, IMO, 2001). Although environmental wave data and models are not explicitly used by classification society rules for general ship design they are needed in rule calibration when FSA methodology is applied. For some less typical designs, classification society rules require or recommend some type of dynamic load analysis that makes also use of metocean data.

Classification rules, in fact, permit the design of ships for restricted service (in terms of geographical zones and the maximum distance the ship will operate from a safe anchorage); in which case reduced design loads apply. Many aspects of the design, approval and operation require a detailed knowledge of local weather conditions. While in principle open to all ship types, the use of such restricted service is in practice mainly confined to high speed vessels.

Unlike ship structures, offshore structures normally operate at fixed locations and often represent a unique design. As a result, platform design and operational conditions need to be based on location specific metocean climate. Note that Floating Production Storage and Offloading (FPSO) systems are designed for the North Atlantic wave environment if location specific wave climate cannot be proved more appropriate.

Even though the same basic principles prevail for hydrodynamic loads on ships and offshore structures, actual problems and methods for assessing these loads in the design stage are quite different. Further, to some extent different wave models are used for defining design and operational conditions for these two types of structures.

In the comparatively nascent field of operational analysis techniques, it is more frequently the responsibility of the user to select a climatology that they feel is most suitable to the task. Such decisions are taken based on a risk assessment.

6.1.1 Met-Ocean Data

Visual observations of waves collected from ships in normal service and summarized in the British Maritime Technology Global Wave Statistics (GWS) atlas (BMT, 1986) are still used for ship design and operations. The average wave climate of four ocean areas in the North Atlantic, with some correction introduced due to inaccuracy of zero-crossing wave period (Bitner-Gregersen et al., 1995), is recommended by the International Association of Classification Societies (IACS 2000) for ship design.

The visual BMT data represent a sufficiently long observation history to provide reliable global climatic statistics over much of the global ocean. Wind speeds (Beaufort Scale) and directions, and wave heights in a coarse code have been reported since 1854. Observations of wave height, period, and direction have been collected from ships in normal service all over the world since 1949, and are made in accordance with guidance notes from the World Meteorological Organisation (WMO, 2001, WMO, 2003). These data include some bad weather avoidance as ships try not to sail into storms; today many ships receive weather forecast from meteorological offices. Thus this database is probably biased towards lower wave heights, see e.g. (Bitner-Gregersen et al., 2014d). Note also that the GWS Atlas was published in 1986 thus the last 28 years is missing which has impact on extreme wave heights; the 100-year H_s reported by Grigorieva and Gulev (2006) is beyond 18-19 m in the North Atlantic.

The utility of visual observations depends on appropriate calibration versus accurate measurements of the wave characteristics. BMT (1986) compared the GWS marginal distributions for wave heights and wave periods with instrumental Shipborne Wave Recorder and National Oceanic and Atmospheric Administration

(NOAA) buoy data for different locations and concluded that the wave heights and periods for which statistics were given corresponded to measured values. However, the accuracy of the GWS data has been questioned in the literature since the 90-ties, especially concerning the wave period as discussed, e.g. by Wing and Johnson (2010), Bitner-Gregersen et al. (2014b) and Bitner-Gregersen et al. (2014d).

Apart from uncertainties associated with the GWS data and missing the last 28 years, the limitation of these data is lack of information about directional wave spectrum, as pointed out by Wing and Johnson (2010) and Bitner-Gregersen et al. (2014b). Wing and Johnson (2010) have shown that wave directionality have quite an unpredictable effect on the long term ship motions and loads.

The necessity of replacing that historic, (essentially subjective) observation based wave database for ship design with instrumentally collected (objectively measured) data bases, or by a combination of numerical and measured data, has become a subject of increasing discussion within classification societies in recent years. This discussion has intensified because of routing systems with which some ships are equipped and the climate change debate. Currently, two other sources of global metocean climate are available in addition to the ship observations. These are data from numerical wave prediction models and satellite data (e.g. the GlobWave database). Predictions of extreme metocean parameters based on these new wave databases have shown large discrepancies making still difficult reaching firm conclusions, as discussed by Bitner-Gregersen et al. (2013a) and Bitner-Gregersen et al. (2014d). Some descripancies between different data bases predictions will need to be recognised and accepted but they need to be further documented.

Further, there is an ongoing discussion within the shipping industry how to account in ship design for wave climate which sailing ships experience during their lifetime; can wave climate derived from ship motions and marine radar be utilized in this process? The technology for deriving wave heights from marine radars has not yet been demonstrated in a satisfactory approach. Such approach is being under development within the JCOMM Wave measurement and Evaluation (WET) project (www.jcomm.info/WET). It is interesting to note that the recent investigations of Cardone et al. (2014) based on GlobWave and GROW2012 data show that a vessel is more exposed to encounter dangerous sea states along mid and high latitude NH (Northern Hemisphere) routes.

The offshore industry uses location specific data in specification of design and operation criteria. Traditionally instrumentally recorded data were regarded as superior to model derived data. However, due to limited availability of measurements and improved hindcasts, the latter have become increasingly used in design in the last decade. New improved global wave hindcasts (e.g. ERA-Interim, ERA-Clim, CFSR) are continuously developed, see e.g. (Cardone et al., 2014). In the extra-tropics these hindcasts can be expected to provide good estimates of wave climate, especially for the highest waves, whereas ship observations of the highest waves are notoriously unreliable, and may be subject to some fair-weather bias. The hindcast models are somewhat less reliable in the tropics, but for tropical storms the waves are less extreme and do not define the design criteria for a sailing ship but will effect offshore structure design. Note that a coarse resolution of a wave model may give up to a few meters lower H_s extremes than a high resolution.

Since the last reporting period, research organisations as well as the offshore industry have updated wind and waves hindcast data sets for several basins, within proprietary joint industry projects (see Section 2.1.3 and 2.2.3). Increasing attention has also been given to the uncertainties in hindcasts, and in particular to energy partitioning procedures used to separate wind sea and swell contributions (Kpogo-Nuwoklo et al., 2014, Bitner-Gregersen et al., 2014b).

The shipping and offshore industries, e.g. (Bitner-Gregersen et al., 2013a, Vanem et al., 2014, Bitner-Gregersen et al., 2014d), (Hagen et al., 2013), follow research findings on climate change, but so far effects of climate change on metocean conditions have not been introduced in the standards due to large uncertainties related to climate change projections.

6.1.2 Design Environment

In the design process, international standards are followed to calculate ship structural strength and ship stability during extreme events with a return period of 20/25 years; the Ultimate Limit State (ULS) check corresponding to the maximum load carrying resistance. Checks in the Accidental Limit State, ALS, (corresponding to the ability of the structure to resist accidental loads and to maintain integrity and performance due to local damage or flooding) cover grounding, collision, and fire and explosion. An extreme weather event check is not included in ALS.

Offshore structures (including FPSOs) follow a different approach to ship structures and are designed for the 100-year return period (ULS). The Norwegian offshore standards, being now under updating, NORSOK (2012) take into account extreme severe wave conditions by requiring that a 10000-year wave does not endanger the structure integrity (ALS).

Further, the shipping industry is commonly using the linear regular and irregular waves as input to numerical codes for calculations of ship loads and responses while the 2nd order irregular waves are currently applied by the offshore industry when analysing structural loads and responses. Both linear and second order wave models are not able to capture very steep waves such as rogue waves (called also abnormal or freak), see Section 3.2. Recently, an increasing use of CFD tools in analysis of marine structures has taken place requiring a proper description of sea states as well as extreme and very steep waves.

The prediction of horizontal velocities underneath measured irregular wave surface elevations is addressed by Birknes et al. (2013) using a simple case of unidirectional waves in deep water. The results from three commonly used methods for calculating the crest kinematics (two second order wave models and the Wheeler stretching, see (DNV, 2014)) are compared with the model test results. All three methods show a reasonable agreement with model test results although the second order models are clearly superior to the Wheeler method. However, when wave breaking is present the second order model is expected to underestimate the kinematics at the very top of the crest and the velocities can exceed the phase velocity. To obtain satisfactory prediction of wave kinematics higher order potential theory's solutions (e.g. HOSM) and CFD methods need still further exploration (see Section 3.2.1), particularly for very steep and breaking waves.

Very steep and breaking waves are getting growing attention in the shipping and offshore industry because their impact on loads and responses of marine structures. They have been addressed by the EXTREME SEAS and ShortCresT projects, and in MARINTEK where combination in a consistent manner of CFD and model tests has intensively been studied in the last years, e.g. (Pakozgi et al., 2012; Stansberg et al. 2012). Commonly, extreme random wave events identified from numerical simulations or model tests are isolated and modelled by CFD. This methodology is in development and attention to it will grow in the future.

Platform decks cover a reasonably large area compared to the size of a wave crest and when waves propagate, their crest heights change. Forristall (2015) investigated this change using measurements from the MARIN wave basin and numerical linear simulations. The second order enhancement of crest is accounted for by factoring the Gaussian maximum. Empirical fits to the simulations have been proposed that can be used for most practical problems.

Stansberg (2012) recommends to explore further random wave groups as they are of importance for the slowly varying motions of large floating structures.

Research efforts regarding refining models and estimation procedures of the long-term sea state description continues, given particular focus to the associated uncertainties. see e.g. (Bitner-Gregersen et al., 2014a, Bitner-Gregersen et al., 2014b, Bitner-Gregersen, 2015). Long-term distributions of sea state parameters are representing an important input to loads and response calculations of marine structures. They are also required for the level III reliability analysis (Madsen et al., 1986).

A review of joint long term probabilistic modelling of wind, waves, and current and sea water level and associated uncertainties can be found in Bitner-Gregersen (2012) Bitner-Gregersen (2015) with particular attention given to the Conditional Modelling Approach (CMA). It is pointed out that the Nataf model needs to be use with care because it can give bias results. Recently attention has been given to use of multivariate copulas in establishment of joint probabilities. Tao et al. (2013b) utilized bivariate normal copula and Frank copula to construct joint distribution of two random variables; extreme wave height and concomitant wind speed, and applied it to calculate the maximum base shear of the on-site fixed jacket platform. The results show that the joint probability models constructed by the bivariate copulas result in lower design environmental parameters due to consideration of correlation between random variables instead of assuming extreme wind and waves occurring simultaneously. Based on a bivariate equivalent maximum entropy distribution, Dong et al. (2013b) estimated joint design parameters of the concomitant wave height and wind speed at a site in the Bohai Sea for the exploitation of marginal oil field. A systemic comparison of approaches applied today for description of joint probabilities, including copulas models, using data from several ocean regions is still lacking and needs attention. Note that copula models do not utilize the complete probabilistic information obtained from simultaneous observations.

It is interesting to note that also metocean parameters describing the typhoon event and used in design can be determined under multivariate extreme ocean environmental conditions, as illustrated for the exploitation of marginal oil field by Dong et al. (2007).

Modelling of wind sea and swell remains an important topic for engineering applications. Several conventional partitioning exist, see (ISSC, 2012). Kpogo-Nuwoklo et al. (2014) has proposed a new method to identify temporal sequences of wave systems parameters, consistent with respect to the meteorological events that are the sources of the phenomena. This method is based on the watershed algorithm which is directly applied to the whole time-history of wave spectra. Using appropriate criteria, the identified events are classified into swell or wind sea events. The approach is validated using field data from West Africa and hindcast data from the Iroise Sea. The results show a good identification of wave systems events with a good correlation between wind sea events and wind characteristics.

Effects associated with the variability of the probability of extremes as a function of season and of direction are shown by Feld (2014). There are statistically significant differences between return values for different directions and seasons.

Keef et al. (2013a) propose a variant of the conditional extremes model in which marginal transformation to Laplace rather than Gumbel scale is performed. (Keef et al., 2013b) propose additional constraints within the conditional extremes model formulation, particularly relevant for negatively associated variables. Gillet-Chaulet et al. (2012) use the conditional extremes model to estimate joint extremes of large-scale indicators for severe weather.

Jonathan et al. (2013) incorporated the effect of covariates in the conditional extremes model of Heffernan and Tawn (2004), which has been further extended to involve a common general-purpose penalised spline representation of model parameters with respect to multidimensional covariates, see (Jonathan et al., 2014). An example of the application of the method for estimating conditional extremes with covariate for hindcast storm peak significant wave height and associated spectral period in the northern North Sea are reported by Ewans and Jonathan (2014). The objective is to model the distribution of spectral period for large storm peak significant wave height as a function of storm direction. The study shows the influence of longer fetches on extremes.

Muyau et al. (2014) found poor agreement between the current ISO wind gust factors and their measurements. The measurements of wind profiles showed more shear than the ISO profiles. Further, the ISO spectrum has not provided a good description of the spectra of the measured data. The extreme winds in tropical areas are usually associated with squalls. A Joint Industry Project was initiated to examine squalls of West Africa. The investigations carried out have shown significant differences between (ISO, 2012) gust to mean wind speed ratios and wind speed coherence relationships and those derived for measurements made by the JIP. Alternative relationships have been proposed from the squall data acquired during the JIP (Santala et al., 2014). The DeepStar project has validated the equations for hurricane winds recommended by the American Petroleum Institute (API, 2012). The recent findings have revealed that the present industry standards for hurricane wind spectra, profiles, and gusts can be improved (Cooper et al., 2013); revisions are planned to be adopted.

Dong et al. (2012) has shown that joint occurrence period of wind speed and wave height (or other metocean parameters), important for design and marine operations, can be estimated based on both service term and risk probability.

The marine industry uses commonly joint metocean models with the environmental contour concept due to Winterstein et al. (1993), IFORM, (see also (DNV, 2014)) for specification of design criteria. The concept and associated uncertainties have been recently discussed by Haver et al. (2013) using the North Sea and the Gulf of Mexico as examples. The authors underline that the contour concept is an approximate method. Further, they point out that for a broad range of problems, long term q-probability extremes can be estimated by finding the worst sea state along the q-probability contour for a response considered, and by estimating 0.9-percentile of the 3-hour extreme value for this sea state. In the North Sea/Norwegian Sea, the choice of 0.9-percentile will often give a reasonable, but may not necessarily, a perfect estimate. For the Gulf of Mexico q-probability extremes have been estimated by identifying the most unfavourable combination of hurricane peak characteristics along the q-probability contour and then finding the 0.95-percentile of the 30-minute extreme value for this hurricane peak event. The authors have stressed that they have little experience with using the method to hurricane governed areas therefore the results for the Gulf of Mexico should be regarded as an example.

An alternative approach for establishing the environmental contour lines in the original environmental space has been suggested by Huseby et al. (2013) by utilizing Monte Carlo simulations of the joint environmental probability. Comparison of this approach with the IFORM concept is presented by Vanem and Bitner-Gregersen (2014) and discussed in view of engineering applications. The new procedure although theoretically consistent is not able to estimate non-convex contours and therefore may give unrealistic values of sea state parameters in some cases.

The joint metocean statistical models were originally developed for design purposes. Bitner-Gregersen (2015) has proposed an approach allowing use of these models also for marine operations; for illustration of its application see (Hagen et al., 2015). Hagen and Solland (2013) discusses how weather criteria for platforms that are unmanned during storms can be calculated to ensure an acceptable safety for personnel. The study briefly discussed how forecast uncertainty can be accounted in a consistent manner.

More recently, the concept of “scenario” of wave weather has been revisited (Degtyarev, 2005). When applied to design, the key idea behind this concept is that an uncountable infinite set of wave conditions may be replaced by a countable finite set of discrete situations (scenarios).

6.1.3 Design for Climate Change and Rogue Waves

Global warming and extreme weather events reported in the last years have attracted a lot of attention not only in academia and media but also in the shipping and offshore industry. Three important questions are in focus: will occurrence of extreme weather events increase in the future, which geographical locations will be most affected, and to what degree will climate change affect future ship traffic and design of marine structures? Observed and projected changes in wave conditions are expected to have the largest effect on ship and offshore structure design and operations in comparison to other environmental phenomena while for offshore platforms changes in sea water level are also crucial. Potential changes in ocean current and their impact on design and marine operations need also attention.

It is also interesting to note that climate changes resulting in some ocean regions in growth of storm activity (intensity, duration and fetch) and changes of storm tracks may result in secondary effects such as increased frequency of occurrence of abnormal waves, also called rogue or freak waves, see e.g. (Cavaleri et al., 2012), (Bitner-Gregersen and Toffoli, 2014).

To be able to design for climate change time-dependent statistical descriptions need to be adopted. Statistical extreme value analysis, as currently used in the metocean community, has to be upgraded to take into account the non-stationary character of current climate, in terms of both climate change trends and natural variability cycles. These changes need to be incorporated in the risk based approach used currently in design as proposed by e.g. (Bitner-Gregersen et al., 2013a, Bitner-Gregersen et al., 2014d).

At present climate change and rogue waves are not explicitly included in classification societies' rules and offshore standards due to lack of sufficient knowledge about uncertainties associated with climate change projections and a consensus reached about probability of occurrence of rogue waves. Significant uncertainties associated with climate change projections are remaining and further research is needed to quantify them and to propose how to account for them in design. Further, open access to field wave data, including rogue waves, and more detailed information about wave conditions when marine accidents occur in accident databases are also called for.

The risk associated with climate change and rogue waves has been recognized, however, by the shipping and offshore industry and an adaptation process to climate change and rogue waves has started. The oil company STATOIL has already introduced an internal requirement accounting in a simplified way for rogue waves; a structure shall not be put at risk even if it is hit by a wave crest height 10% larger than the crest height predicted by the second order wave model, see (ISSC, 2013). This is to account for a number of uncertainties and not only possible rogue wave developments. This requirement is now under discussion for possible implementation in a revised version of the Norwegian standard NORSOK. How to account for climate change is also discussed.

The marine industry has initiated several studies to quantify potential impact of climate change on current design (e.g. (Bitner-Gregersen et al., 2013a, Vanem et al., 2014, Bitner-Gregersen et al., 2014d, Hagen et al., 2013). Also the international project dedicated to rogue waves, EC project EXTREME SEAS (Design for Ship Safety in Extreme Seas), and coordinated by Legacy DNV of Norway, and the JIP project ShortCresT (Effect of Short-CresTedness on extreme wave impact) coordinated by MARIN in The Netherlands, had been initiated and completed during the period of the ISSC 2015 I.1 Committee. The ongoing Research Council of Norway (RCN) project ExWaCli (Extreme Waves and Climate Change Accounting for uncertainties in design of marine structures), coordinated by Legacy DNV of Norway, aims at understanding impact of climate change on wave conditions in the northern areas in the 21st century, identifying uncertainties associated with the predicted changes and demonstrating their consequences for design and operations of marine structures (Bitner-Gregersen et al., 2013b). There are also other research activities dedicated to rogue waves and climate change going on within the marine industry but still not publically available. How to account for climate change and rogue waves in current design practice for tankers (and marine structures in general) is presented by Bitner-Gregersen et al. (2013a) and Bitner-Gregersen et al. (2014d) and for offshore platforms by Hagen et al. (2013).

The observed increase of ocean temperature will also be a challenge for the marine and renewable energy industry in the future. Increase of marine growth leading to increase of loads on marine and renewable energy structures maybe expected in some ocean regions. A lack of marine growth data for design remains a problem. The photosynthesis occurs only down to about 100–200 m, and sunlight disappears altogether at 1000 m or less, while the ocean descends to a maximum depth of about 11 000 m. Thus it is not expected seeing marine growth below 500 m or 1000 m. Until recently the deep sea was largely unexplored, therefore more investigations dedicated to deep sea are needed.

It is interesting to mention that assessments of climate change hazards to electric power infrastructure such as the Sandy hurricane and flooding of habours and towns have been carried out by the Classification Society DNV GL (Quan Luna et al., 2014, Yates et al., 2014).

6.2 Operations

The reduction of emissions of greenhouse gas (GHG) has become an urgent global task for the prevention of global warming. In order to reduce the GHG emissions from the international maritime sector ahead of the other sectors, amendments to MARPOL ANNEX VI making “Energy Efficiency Design Index (EEDI)” and “Ship Efficiency Management Plan (SEEMP)” mandatory were adopted at the 62nd session of Marine Environment Protection Committee (MEPC 62) held in July 2011, and have entered into force on 1 January 2013.The EEDI is used as an index to assess the energy efficiency of a new ship. On the other hand, the SEEMP is a management plan for implementing energy efficiency improvement measure (for example, slow steaming, optimum ship routing, just in time arrival, speed optimization, optimum trim and appropriate hull maintenance, etc.) during actual operation in an organized and efficient manner. The SEEMP is to be prepared by the ship owner. IMO has issued guidelines to develop the SEEMP (Resolution MEPC.213(63), (IMO, 2012)), and the guidelines require at least the following items to be described in the SEEMP:

(1) Energy efficiency improvement measures
(2) Monitoring procedure for energy efficiency
(3) Measureable goal for energy efficiency improvement
(4) Procedure for evaluating the energy efficiency improvement being implemented

SEEMP Guidelines require that energy efficiency is improved by repetitive implementation of the cycle consisting of “Planning”, “Implementing”, “Monitoring” and “Self-evaluation and Improvements”. That is, each ship has to implement the planned efficiency measures by periodic self-monitoring of the energy efficiency (the fuel consumption, etc.) and evaluate these results so that they can be fed back to the next efficiency improvement plan. However, the purpose of the SEEMP requirement is to only independently promote the implementation of efficiency improvements. Therefore, the detailed content of the efficiency improvement measures to be used or the results (goal attainment level of efficiency improvements) are not looked into by the third party. In accordance with the SEEMP requirement, ship owners and operators are required to operate the ships from a viewpoint of environment as well as safety. Especially, accurate weather forecast is important for the eco-efficiently ship operations. This is because the optimum ship routing depends on the weather forecast significantly.

At the early stage of deliberations on the EEDI regulation in IMO, there was concern that ships with excessively small propulsion power would be constructed just for the purpose of improving the EEDI value. Therefore, discussions on minimum propulsion power in adverse weather condition were started in IMO. Consequently, for ships which comply with EEDI requirements, it was required that the installed propulsion power shall not be less than the propulsion power needed to maintain the maneuverability of the ship in adverse conditions as defined in guidelines developed by IMO. As the result of subsequent deliberations in IMO, “2013 Interim Guidelines for Determining Minimum Propulsion Power to Maintain the Maneuverability of Ships in Adverse Conditions” were developed and adopted as “Resolution MEPC.232(65)” (IMO, 2013). The “2013 interim minimum power guidelines” are applicable only to bulk carriers, tankers and combination carriers of 20,000DWT or above to which compliance with required EEDI is required during phase 0 (from 2013 to 2014) of the EEDI implementation. In this context, the final guidelines applicable to ships in phases 1, 2 and 3 are to be developed by IMO at a later stage. The applicable ships are required to fulfil either of the two assessment levels in accordance with the “2013 Interim Minimum Propulsion Power Guidelines”. If a ship does not satisfy the criteria of a level-1 assessment, a level-2 assessment is to be considered.

Table 2. Required minimum propulsion power.

Type of ship	Minimum Propulsion Power (kW)
Bulk Carrier	0.0687 x DWT + 2924.4
Tanker/Combination Carrier	0.0689 x DWT + 3253.0

For the level-1 assessment, minimum power lines for each ship type are calculated using formula as a function of deadweight shown in Table 2. Installed propulsion power is not to be less than power calculated using the formula.

The level-2 simplified assessment is an indirect assessment procedure based on an assumption that, in adverse condition, if a ship has sufficient installed power to move with a certain advance speed in head waves and wind, and if it is lower than the torque limit within the operating range of the installed engine, the ship can also be expected to maintain course in waves and wind from any other direction. In the “2013 Interim Minimum Power Guidelines”, adverse conditions used for the level-2 assessment are defined as shown in Table 3.

Table 3. Adverse conditions.

Ship length Lpp (m)	Significant wave height (m)	Peak wave period (s)	*Mean wind speed (m/s)*
Lpp＜200	4.0		15.7
200≦Lpp＜250	*	7.0 to 15.0	*
Lpp≧250	5.5		19.0

(* Linearly interpolated value depending on ship's length)

The maneuverability in waves are stricter in coastal waters than in the open sea: while in the open sea, it is sufficient to keep a favorable heading with respect to wind and waves, and some drifting with wind and waves is acceptable, in coastal waters, due to navigational restrictions, the ship might need to keep a prescribed track irrespective of the direction of waves and wind. On the other hand, ships are not supposed to be in coastal areas in very severe weather conditions, and should leave to the open sea before the weather conditions become too severe. Thus, the weather conditions used in the assessment procedure can be relaxed in comparison with the worst possible weather conditions expected in unrestricted service. In order to determine the adverse condition, comprehensive assessments were carried out using numerical simulations. North-Atlantic scatter table from IACS Recommendation 34 (IACS, 2000) was used as a seaway climate used for comprehensive assessments. Moreover, JONSWAP sea spectrum with the peak parameter of 3.3 was considered for coastal waters. The results of the comprehensive assessments were compared with the results of the statistical approach (Level-1 assessment). Consequently, the adverse conditions used for level-2 assessment were determined taking into consideration both results of the comprehensive assessments and the statistical approach.

Hereafter, the adverse conditions specified in "2013 Interim Minimum Power Guidelines" are validated by new research projects on the minimum propulsion power such as the EC project SHOPERA (Energy Efficient Safe SHip OPERAtion), (Papanikolaou et al., 2014) and a new Japanese R&D project (MEPC67/INF.22, 2014).

6.2.1 Planning and executing marine operations

Operators are normally required to plan the efficiency operations in advance. In case of ships, as mentioned above, the plans are developed in accordance with the SEEMP requirement. Studies of weather forecast, hindcast and window analysis are important for planning the efficiency operations of offshore structures as well as ships.

In order to operate and maintain offshore marine renewables, a device will have to be accessible for a certain period of time. This will require a weather window consisting of a consecutive period of wave heights low enough and long enough for the device to be accessed. O'Connor et al. (2013) presented the results of a weather window analysis of wave data from the west coast of Ireland and the Atlantic coast of Portugal in order to quantify the levels of access to ocean energy renewables, which may be deployed there, for operation and maintenance activities. The results indicate that the levels of access off Ireland and Portugal are far below those observed at other marine renewable locations, and at the lower wave height access limits, there are very few suitable weather windows and considerable winter waiting periods between these windows. The implications of these low levels of access suggest that maintaining wave energy converters, off the west coast, may not be feasible and devices will need to be brought ashore for operation and maintenance activities.

Walker et al. (2013) conducted a similar weather window assessment with application to transit and deployment operations in the southwest UK, applying a Weibull persistence model to a large wave model database. The method, which allows computation of access and waiting times requires high quality and high quantity datasets so as to cover a sufficiently large area to account also for transit times. The specific study conducted in southwest UK also shows that the level of access to a local marine renewable testing site is highly dependent to seasonal variability and can be highly reduced in winter.

Numerical forecasts of weather and oceanography are increasingly common in the field of ship operations due to advances in computer science. However, in some situations, the accuracy of forecasts is too unreliable to ensure safe operations. Sasa et al. (2013) presented current situation and difficulty of wave forecast from viewpoint of ship management by using a nationwide questionnaire. They recommend improving wave forecasts from the viewpoint of ship operations. As a result, Sasa et al. (2014) carried out feasibility study for improving the forecasting of wave growth pattern from the viewpoint of safe ship operation. It was pointed out that the further study is necessary in the future.

Oil offloading from Spread Mooring System (SMS) FPSO is usually done by means of a dynamically positioned shuttle tanker (DPST) in tandem configuration. The ST receives the oil pumped by the FPSO from a bow or stern offloading station, and the operation may take up to 3 days. In order to minimize the risks associated with the operation, the shuttle tanker (ST) should be kept within a safety zone with respect to the FPSO, which is usually given as a minimum distance between the two ships and an aperture angle from the FPSO centerline. In order to guarantee the tanker position during the whole operation, the operation must be performed with tankers provided with DP (dynamic positioning) systems. Since SMS FPSOs may be not aligned to the environmental forces, keeping the shuttle tanker in position may be a hard task for the DP system, depending on the environmental conditions. There are non-rare situations in which the ST must be disconnected and the operation interrupted. Corrêa et al. (2013) presented a methodology based on static calculation of DP capacity for evaluating the downtime of offloading operation in Brazilian waters. Three generations of DP tankers applied in Brazilian waters were considered. Santos and Campos Basin long-term (8-year) environmental conditions were used in the downtime calculation. The results indicated that due to the large variation of wave-wind conditions along the year, both offloading stations are indeed necessary, since the ST can avoid the conditions in which it is pushed towards the FPSO. The results also indicated that incrementing the angle that defines the green-zone substantially decreases the offloading downtime and the number of disconnections required. The risk analysis is beyond the scope of the present work. The DP power specified for the ST generations II (for Campos Basin) and III (for Santos Basin) are shown to be quite adequate, since it is demonstrated that increasing this power will not lead to a substantial reduction in the downtime.

Also the EC project SAFE OFFLOAD (coordinated by Shell) was dedicated to specification of operational criteria for limiting metocean conditions for LNG terminals. The project has shown that for the specified target failure probability, the maximum allowable metocean conditions can be determined for a given operational strategy. When developing acceptance criteria for LNG terminals (which are transferred to operational criteria), planning as well as carrying out offloading operations both a threshold for significant wave height (and/or associated metocean parameters) and a required weather window for carrying out offloading represent important characteristics. They need to be included in a joint metocean description to allow utilizing it for operational purposes (see (Hagen et al., 2015), (Bitner-Gregersen, 2015)). As demonstrated by Hagen et al. (2015) wind-sea and swell govern the criteria for LNG terminals. Thus particular attention should be given to data uncertainty related to estimation of these wave components as well as models adopted to describe them.

The U.S Office of Naval Research has been developing an Environmental and Ship Motion Forecasting (ESMF) system capable of real-time predictions of future ship motions that utilizes a Doppler radar to determine the wave field surrounding the ship; nonlinear wave theory to propagate the wave field forward in time; and ship seakeeping theory to predict the future ship motions. The ESMF system was designed to provide real-time environmental data and wave and ship motion forecasts over three time scales: detailed phase-resolved wave and ship motion time series over 30 seconds, envelopes of the wave and ship motion time series over 5 minutes, and statistically-averaged parameters characterizing the sea state and ship motions over 24-48 hours. An ESMF system prototype was tested aboard the R/V Melville during the two week sea trial in September 2013. Alford et al. (2014) describes the ESMF system with special emphasis placed on the techniques used to analyze and to predict the future waves at the ship, the real time computations of the ship motions, and the preliminary results of the sea trials.

6.2.2 Northern Sea Route, Weather routing, Warning Criteria and Current

Changing climate gives potential opportunities for seasonal shipping on the Northern Sea Route, the Northwest Passage and a potential for Transpolar Route, improving access to many offshore resources in the Arctic region.

Using monthly and daily CCSM4 sea ice concentration and thickness simulations for different scenarios covering different periods along the 21st century and considering various radiating forcing, Stephenson et al. (2013) investigate the technical shipping accessibility for various navigation routes in the arctic. Their projections, based on capabilities of Polar Class 3, Polar Class 6 and Open Water vessels show that new areas of the Arctic will become accessible to these classes of vessels. In spite of regional discrepancies all areas will see their period of access lengthening. For instance along the Northern Sea Route, July-October navigation season length averages ~120, 113, and 103 days for PC3, PC6, and OW vessels, respectively by late-century.

Smith and Stephenson (2013) show the ATAM-derived optimal September navigation routes for hypothetical ships seeking to cross the Arctic Ocean between the North Atlantic (Rotterdam, The Netherlands and St. John’s, Newfoundland) and the Pacific (Bering Strait) during consecutive years 2006–

2015 (A and C) and 2040–2059 (B and D) as driven by ensemble-average GCM projections of sea ice concentration and thickness assuming RCPs 4.5 (A and B; medium-low radiative forcing) and 8.5 (C and D; high radiative forcing) climate change scenarios. Red lines indicate fastest available trans-Arctic routes for PC6 ships; blue lines indicate fastest available transits for common open-water ships. Where overlap occurs, line weights indicate the number of successful transits using the same navigation route. Dashed lines indicate national 200-nm EEZ boundaries; white backdrops indicate period-average sea ice concentrations in 2006–2015 (A and C) and 2040–2059 (B and D).

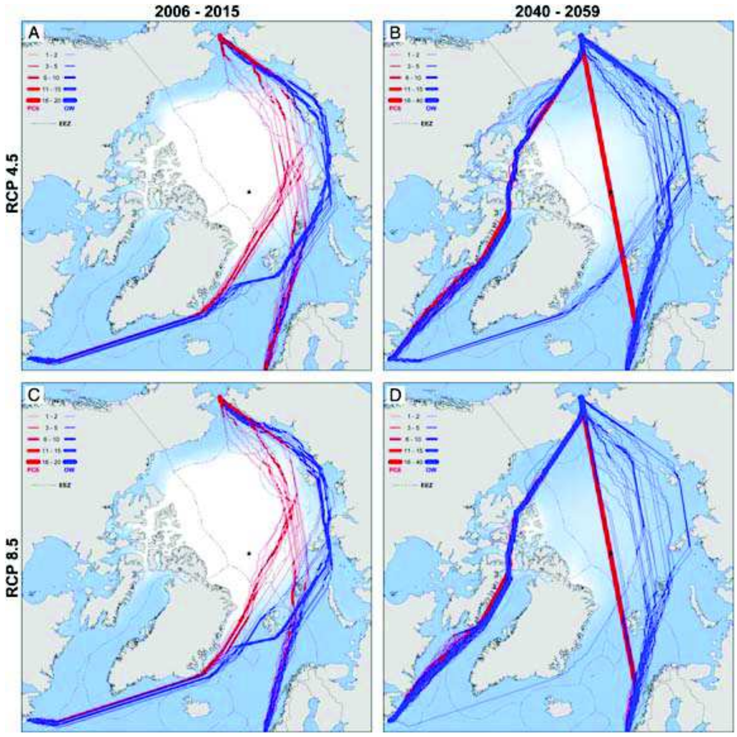

Figure 8.

Stephenson et al. (2013) used the Arctic Transportation Accessibility Model (Stephenson et al., 2011) with individual and ensemble-averaged datasets of projected sea ice thickness and concentration from seven climate models: the Australian Community Climate and Earth-System Simulator versions 1.0 and 1.3 (ACCESS1.0, ACCESS1.3), the Geophysical Fluid Dynamics Laboratory version CM3 (GFDL-CM3), the Hadley Global Environment Model 2 Carbon Cycle (HadGEM2-CC), the Institute Pierre Simon Laplace medium resolution coupled ocean–atmosphere model (IPSL-CM5A-MR), the Max Planck Institute for Meteorology Earth System Model (MPI-ESM-MR) and the National Center for Atmospheric Research (NCAR) Community Climate System Model version 4 (CCSM4), assuming two different climate change scenarios and two vessel classes, to assess future changes in September Arctic shipping potential (see Figure 8). They found that by midcentury, changing sea ice conditions will enable:

- Expanded September navigability for common open-water ships crossing the Arctic along the Northern Sea Route over the Russian Federation.
- Robust new routes for moderately ice-strengthened (Polar Class 6) ships over the North Pole.
- New routes through the Northwest Passage for both vessel classes.

The limitation of the Northern Sea Route not sufficiently discussed is the water depth on parts of the route. This limitation may require that ships will need to sail farther from the coast where ice coverage is larger.

The development of decision support systems remains a focus. Application of such systems require collection of relevant data such metocean conditions and ship response, on board. The recently completed EC project NavTronic has demonstrated that these types of data can also be used for self-learning.

Several authors have studied relations between spectral parameters and occurrence of extreme and rogue waves and the topic is still under development. It has also been investigated in the EC EXTREME SEAS project in collaboration with the the European Centre for Medium-Range Weather Forecast. Recently an approach for coupling the wave spectral model with the nonlinear phase resolving model has been proposed by Bitner-Gregersen et al. (2014d) for use in forecasting of these abnormal waves; the results are promising.

6.2.3 Eco-Efficiency Ship Operation

In order to reduce the GHG emissions from international maritime sector, the International Maritime Organization (IMO) requires to promote higher efficiency of ship operations using energy efficiency improvement measures such as optimum ship routing and just-in-time speed operation of ships. As a result, shipping companies is required to promote higher efficiency of ship operation and also to evaluate effect of the operation in accordance with the SEEMP requirement. The purpose of classical weather routing is to search the best route based on the existing weather/current forecast data from the aspect of safety first and economy. On the other hand, for the reason of the SEEMP requirement as well as rising cost of fuel, latest optimum ship routing is carried out based on various data such as weather/current forecast, operation schedule, fuel consumption, speed, trim, ship characteristics and real time monitoring etc. in order to achieve a good balance between safety and environment. The objective is not to avoid all adverse weather but to find the best balance to minimize transit time and fuel consumption without placing the vessel at risk to weather damage or crew injury. Therefore, there have been so many studies on the optimum ship routing to achieve further eco-efficiency ship operation. To seek the good balance between safety and environment is core challenges for today’s ship owners and operators.

Lin and Fang (2013) proposed a ship weather-routing algorithm based on the composite influence of dynamic forces, i.e. wind, wave and current forces, for determining the optimized transoceanic voyages. The developed routing algorithm, three-dimensional modified isochrones (3DMI) method, utilized the recursive forward technique and floating grid system for both the east- and west-bound ship routes in the North Pacific Ocean. In order to achieve the goals of minimized fuel-consumption or the maximized-safety routes for the transoceanic voyages, two sailing methods were applied as the prerequisite routes in the earth coordinate systems. The proposed calculation was verified to be effective for the optimized sailings by adjusting the weighting parameters in the objective functions.

Chu et al. (2013) assessed the impact of METOC ensemble forecast systems on optimal ship route. Evaluation of a weather routing decision aid for operational fleet use and concept of operations were also conducted for the USS Princeton guided missile cruiser (CG)-59 in a sea trial test following the 2012 Rim of the Pacific exercises. They were able to assess the impact and sensitivity of the SVPDA modeling to METOC input parameters. Environmental model uncertainties were quantified through ensemble modeling. It was found that the SVPDA model was very sensitive to: location, direction, seasonal synoptic/mesoscale weather, hull/propulsion type and condition, route length, specific model improvements, and ensemble methods. The possibility of significant fuel cost reduction was also identified by utilizing the best ensemble member with the maximum fuel-saving of 20%.

Recently Essig et al. (2013) described the development of the Smart Voyage Planning Decision Aid (SVPDA) from discovery to possible implementation in the context of a Maritime Energy Portfolio Tool focused on providing the necessary data needed for evaluating energy saving initiative implementation and operational strategies that optimize mission capability, energy savings, and return on investment.

On-board measurement of fuel consumption of a ship has been carried out in a relatively severe sea condition. In the full scale experiment, the ship traveled on several courses to investigate the change of fuel consumption relative to the encounter wave angle. The result shows that the wave direction has a great influence on the main engine horse power and fuel consumption, and also shows a possibility of fuel efficiency prediction. In order to develop an eco-friendly navigation support system, Iseki and U.D. (2013) applied results of Bayesian wave estimation to fuel efficiency prediction, since the Bayesian method does not require wave measurements but needs only ship motion data as input and the method is suitable for on-site wave estimation. It was shown that the proposed concept of an eco-friendly navigation system is effective and worth further investigation.

During these times of fluctuating freight rates and oversupply, selection of optimum speed will give an operator a crucial advantage. Until the recession, the emphasis has always been on larger capacity and higher speed. Now, design innovation and slow steaming are becoming important. Khor et al. (2012) showed that an optimum speed can be selected at design stage through a combined revenue-cost and propulsion analysis. New software was set up to assist speed optimization process for large container ships. The software was used both propulsion and revenue-cost analysis with an ultra-large container ship model of 20,000 TEU as a case study to derive the most profitable speed. The results showed that 19.5 knots is the optimum speed which is a departure from current trend of 25 knots but supporting the concept of slow steaming.

Speed optimization schemes face challenges in daily vessel operations due to very strict constraints imposed by itinerary and due to limited accuracy of available weather and sea current forecasts. Since fuel-optimal routing is highly sensitive to constraints such as just-in-time arrival, one high speed leg can wipe out the accumulated savings of an entire voyage. Ilus and Heikkinen (2012) presented an approach to optimal speed estimation which is based on statistical route forecasts based on historical data measured on specific routes. Simulation was used to provide alternative and improved energy efficient speed profiles. The simulation of optimal speed profiles suggested possible 3 ± 1% energy savings.

As of today vessels have and will in future have even more possibilities to affect the ship's overall energy balance. These possibilities are enabled for example with diesel electric configurations, waste heat recovery units, trim variations, operational profiles, alternative fuels and hull cleaning schedules. Unfortunately all this flexibility comes with certain problems as the system complexity grows beyond human understanding. Finding and especially operating constantly at the optimum point is significantly more challenging with all these variables. Even if one or two specific areas can be efficiently optimized by for example a dedicated chief engineer, the full potential of comprehensive optimization is often left unused. Ignatius et al. (2014) took an insight into a holistic performance management and optimization system for any type of vessel. It not only takes in account energy efficiency but also the availability and safety of the vessel and fleet. The system produces a comprehensive optimization and monitoring framework for overall energy efficiency of basically any process, and gives clear decision support both to the users onboard and also for the management ashore.

Shipping companies seek to promote higher efficiency of ship's operation and also to evaluate effect of the operation. Just-in-time speed operation holds the prospective effect of major greenhouse gas (GHG) reduction. However, the methodology to evaluate the effectiveness by using these services has not confirmed. Kano and Namie (2014) introduced the outline of Eco shipping support system for the navigation plan an optimal speed voyage by taking into account wind, wave and current forecasts. And the estimation methodologies of amount of GHG emission reductions by the speed planning from the System and applicability to RORO ship were confirmed.

Development and decrease cost of onboard sensor technology, data collection systems and satellite internet connections have opened new possibilities to collect extensive datasets of the performance related information from vessels. Analyzing this performance related data is challenging because the performance of a ship is affected by many complex factors such as wind, waves, currents, shallow water and often the ship's operating condition has significant impact to performance such as variety of displacements in operation. Therefore normalization methods are required for making the performance readings measured and collected from a ship comparable. Normalization in this means evaluating the effect of these different factors affecting ship's performance during the time of measurement and correcting then the result to given baseline condition which can for examples be calm water, design draft and speed condition or the average operation condition of the ship. Kariranta (2012) showed to utilize normalized performance data for ship operations and design. The normalization was carried out by using hydrodynamic functions and statistical approach. Direct commercial use of such normalized data could be sharing the profit of a shipping pool based on the real performance of the ships in it and for example making "virtual arrival" calculations more exact. It also gives good input for the design stage of the ship by allowing the designers to take a look on real operation conditions that the ships are in for example for calculating the required sea margin more accurately, use the "virtual voyage" as design criteria instead of only using one design speed and draft and give feedback how different hull shapes react for wave loads.

In general, the speed power performance of ships is optimized for design speed and draught in accordance with the contract condition. But, the contract condition may not be always the same as the actual operating condition. Therefore, in order to reduce the fuel consumption practically, it is necessary to optimize the performance under various conditions considering the actual voyage. This is the reason that the trim optimization covering various operating profiles becomes the main issue in reducing fuel oil consumption. Lee et al. (2014) carried out a numerical study to optimize trim conditions through the computational evaluation system with variation in draught, ship speed and voyage trim. The results of the trim optimization performed numerically are well-matched with the towing test result. It is confirmed that the computational evaluation system is a useful and efficient tool for trim optimization and the provided optimum trim will be able to contribute to fuel savings under the operating conditions.

7. CONCLUSIONS

The issue of metocean data ownership remains a general problem even though access to new databases has become available since 2012 (e.g. MONET, (Quiniou-Ramus et al., 2013)) and awareness of its importance has increased. Whilst the advantages of having data freely available to academia and industry are clear, the commercial sensitivity of some data sets is recognised. An example of making data available without compromising their confidentiality is the SIMORC URL database: http://www.simorc.org/, administered by the University of Southampton.

A question raised today is: Are the metocean measurements actually the ground truth? An answer to it still does not exist. There are several uncertainties related to field and remotely sensed data and complete knowledge about them is lacking. The stationarity and homogeneity assumption of measurements is obviously questionable and likely not valid in some circumstances. The topic requires attention.

Development and decrease cost of onboard sensor technology, data collection systems and satellite internet connections have opened new possibilities to collect extensive datasets of the performance related information from vessels, offshore platforms and renewable energy installations. These so-called Big Data include information about load and response conditions of structures and related metocean climate. A methodology for utilization this information is still under development and both academia and industry is interested in it.

Accuracy of wind and waves hindcast databases for several ocean basins has improved since 2012 through improved understanding of the physics of metocean phenomena. Validation of these databases against field measurements and remotely sensed data for significant wave beyond 14 m is still too limited.

Many research efforts in the last decade have contributed to understanding of mechanisms generating rogue waves and their detailed dynamic properties. The state of the art development on rogue waves are well summarised at three Rogue Wave Workshops, held in 2000, 2004, and 2008 by Ifremer, and the publications reviewed by the previous and present ISSC I.1 Committee. Consistency achieved between numerical models and experimental data has been documented. Since 2012, the focus has been given on forcing terms like wind, current and wave breaking that are not typically included. Several photos of rogue waves observed in the nature have been collected in a book of Olagnon and Kerr (2015) which may encourage to new research findings.

Simplified definitions of rogue waves such as the wave height and crest criteria are commonly applied. Despite recent achievements, a consensus on the probability of occurrence of rogue waves has not been reached yet. Such consensus, however, is essential for a systematic evaluation of possible revision of classification society rules and offshore standards, which currently do not include rogue waves explicitly. The EC EXTREME SEAS project has contributed to new findings on probability of occurrence of rogue waves which need to be further explored. It is worth to mention that the oil company STATOIL has already introduced an internal requirement accounting in a simplified way for rogue waves, see (ISSC, 2013). This requirement is now under discussion for possible implementation in the revised version of the Norwegian standard NORSOK.

Attention to directional effects, modelling of wind sea and swell, seasonality, spatial and non-stationary statistics continues. New studies documenting the importance of these effects on extreme metocean statistics have been carried during the period of the Committee.

With the increase of offshore wind energy installations, reliable forecasts of the order of hours or minutes are also becoming increasingly important since the complex electrical networks are sensitive to large fluctuations, which may occur at the onset of a storm. In addition, more information on the wind profile in the lower atmospheric layer is needed for the design and analysis of these structures. Long-term trends, not only in the occurrence of extreme events but also other statistical properties will remain an important research topic in wind analysis in forthcoming years. Further, non-stationarity and non-homogeneity of the wind field needs to be accounted for.

CFD (Computational Fluid Dynamics) methodology is getting increasing focus in modelling of metocean phenomena but it is still in development. Attention to it will grow in the future.

The Fifth Assessment Report (IPCC, 2013) is confirming the conclusion of the Fourth Assessment Report (IPCC, 2007); the observed climate changes are due to human activities. Climate change projections show that ice, sea water level, wind, waves and ocean circulations will be affected by global warming but this will be much regional dependent. Extreme value estimates of wind and waves needed for design work may be more affected by climate changes than the average values although there are some examples where they were less affected. Too little attention has been given in AR5 to wind and waves and too few publications are written from the viewpoint of the designer, focusing often on too low return periods. However, a significant development has taken place since AR4 in the increased use of quantitative statistical measures simplifying synthesis and visualization of models' performance.

On a positive note for the marine community is the emergence of potential opportunities for seasonal shipping on the Northern Sea Route, the Northwest Passage and a potential Transpolar Route, improving access to many offshore resources in the Arctic region. On the negative side increases of probability of encountering icebergs, bergy bits and other ice formations in some areas maybe expected where they were not previously experienced. The increased intensity of tropical cyclones has caused devastating damage to the offshore industries in the Caribbean in the past 11 years; the link with the warming climate is debatable but if so these effects would be anticipated to continue as warming continues. The observed trends and projected climate changes indicate that significant impact on marine structure design may be expected in some ocean regions. It is noted that there is large uncertainty associated with the climate projections.

Awarness of importance of accounting for uncertainties associated with environmental description in risk assessment of ship, offshore and renewable energy structures is continuously increasing within the marine and renewable energy industry. Although several data, statistical and model uncertainties have been reported during the period of the ISSC 2015 Committee I.1 a systematic investigation of them is still lacking. To increase further awareness of a role uncertainties have in design work the 2nd ITTC-ISSC Joint Workshop on uncertainty modelling took place 30 August 2014 in Copenhagen. The Worshop was organized by the ITTC Seakeeping Committee with contribution from the ISSC 2015 Committee I.1, the ISSC 2015 I.2 (Loads) Committee and the ITTC Ocean Engineering Committee.

Operational aspects of ships have got a lot of attention in the report as they are reflecting topics being under discussion in IMO such as energy efficiency, ship maneuverability in weather conditions and of reduction of pollution from ships.

The needs of the renewable energy industry as well as climate change have strong impact on research directions within metocean description and this trend is expected to continue.

7.1 Advances

New metocean databases have been opened for the users. Access to wind and waves remote sensing databases is continuously improving. Utilisation of wind and wave information collected by satellites in wave models is increasing, particularly due to the GlobWave project initiated by the ESA in 2008.

Wave models have largely improved over the recent years thanks to new developments in parameterization, introducing more consistent description of the physics based on observations, and numerical choices, introduction of currents, coastal reflection, and bottom sediment (prime interest for modeling in coastal waters) in the models. Most of these improvements were implemented in a new version (4.18) of the code WaveWatch III® that was released in March 2014 by NOAA/NCEP allowing the use of unstructured grids and introducing new parameterizations for wave dissipation together with new parameterizations for bottom friction including movable bed roughness. An attempt has also been made to include quasi-resonance interaction in the wave model lacking today.

Due to development of computers wave frequency-directional wave spectra have started to be archived by met-offices opening new possibilities for environmental modelling and design and operation work.

The knowledge about extreme and rogue waves has advanced since 2012; the nonlinear dynamics of surface gravity waves is now reasonably understood. The predictions made by theoretical and numerical models compare well with experimental results. Progress has been taken place regarding inclusion of forcing terms such as wind, current and wave breaking. Indirect evidence on the specific meteorological and oceanographic conditions leading to the formation of rogue waves has been strengthened by new field observations.

The first more systematic investigations of extreme and rogue waves and ship behaviour in these waves were carried out in the EC ERXTREME SEAS project, while behaviour of offshore platforms in these waves was investigated by the JIP Crest/ShortCrest project; both projects were completed in the period of the Committee.

The importance of accounting for non-stationarity and non-homogeneity of environment data and models has been demonstrated by examples. Also further progress has been made on development of spatial and temporal models. Recognition of the need to consider covariates when performing extreme value analysis has been shown.

The increased use of renewable energy sources, especially offshore wind energy, has triggered many new research activities. With the limited number of profitable locations came a trend towards higher structures up to some two hundred metres. However, it is not the wind energy industry alone that focuses on more accurate wind data in lower layers of the atmosphere; both academia and others industrial sectors are also interested in it. The trends in the development of new sensors and data acquisition techniques are expected to continue.

The issue of the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC, 2013) is an important milestone in climate change research. A variety of model predictions of metocean phenomena is available now to the users. The Coordinated Ocean Wave Climate Project (COWCLIP) has found that the variance of wave-climate projections associated with wave downscaling methodology dominated other sources of variance within the projections, e.g. the climate scenario or climate model uncertainties, but that needs further exploration.

7.2 Recommendations

The need for improving the availability, quality and reliability of metocean databases was reported by the previous ISSC I.1 Committees. This situation is mostly unchanged, and any effort to address this concern is recommended. Further utilisation of remote sensing data by the marine industry needs to continue. A lack of marine growth data for design remains a problem. In a case of ocean temperature's increase marine growth will be a challenge in some ocean regions.

A question “Are the metocean measurements actually the ground truth?” needs further exploration. Whenever observations of metocean conditions are made, stationarity and ergodicity needs to be addressed. A consistent methodology for handling Big Data is called for. Development of it will require collaboration between academia and industry. Some initiatives for establishing such collaboration have already taken place. A remaining question is: how to utilize Big Data in design and operation work?

Studies dedicated to including wave breaking and external forcing (wind) when modelling rogue waves should continue. Detailed investigations of meteorological and oceanographic conditions in which extreme and rogue waves occur together with analyses of field wave time series (uncertainty due to sampling variability may be a problem here) are needed to reach a consensus about probability of occurrence of rogue waves; this being mandatory for evaluation of possible revision of classification society rules and offshore standards. Such studies should focus on metocean conditions during storm growth and decade, crossing seas as well as presence of current. Further, a consensus needs to be reached on how combining new information about extreme and rogue waves in design and operation work. The effect of modulational instability (one of the mechanisms responsible for generation of rogue waves) is gradually suppressed, when the wave energy spreading increases. This needs to be reflected in possible revisions of rules and offshore standards.

Inclusion of nonlinear and rogue waves in commonly used codes for analyses of wave-structure interaction is strongly recommended. This has been initiated in the EC EXTREME SEAS project for ships and in the JIP CresT/ShortCrest project for offshore structures, but further investigation is still called for. Rogue waves affect not only local loads but also global loads.

Focus needs to be given to properly accounting for directional effects in design, assuring consistency between omnidirectional and directional criteria, to seasonality, spatial and non-stationary statistics, and current profile as well as modelling of wind sea and swell for design and operational purposes. Utilization of frequency-directional wave spectra, archived by met-offices today, in this work is strongly recommended.

Studies contributing to a systematic quantification of uncertainties of metocean description should continue both in academia and industry. It is also recommended to agree on common definitions of uncertainties within academia and industry.

The 2015 ISSC I.1 Committee recognizes the significance of the IPCC (2013) findings and the conclusions drawn by the Panel. There are still significant uncertainties associated with climate change projections. Identification and reduction of these uncertainties as well as consistently combining them requires attention. That is of crucial importance for the shipping, offshore, renewable energy and coastal engineering industry. Both the mitigation as well as the adaptation process to climate change should continue within the industry. The climate changes caused damages but also open new opportunities for Arctic development and challenges when shipping the goods to main economic centers. To take advantage of these opportunities new technologies will be required to safely operate in polar ice environments which need to be based on reliable metocean and ice data, and models. Attention needs be given not only to the Arctic regions but also to the Antarctic waters.

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REFERENCES

Aarnes, O. J., Breivik, O. & Reistad, M. 2012. Wave Extremes in the Northeast Atlantic. *Jouranl of Climate,* 25**,** 1529–1543.

Agarwal, P. & Mcneill, S. Extreme directional and planar profiles for Kuroshio current using Inverse Form and proper orthogonal decomposition. Proc. OMAE 2013, 9–14 June 2013 Nantes, France.

Aiki, H. & Greatbatch, R. J. 2012. Thickness-Weighted Mean Theory for the Effect of Surface Gravity Waves on Mean Flows in the Upper Ocean. *Journal of Physical Oceanography,* 42(5), 725–747.

Ailliot, P., Bessac, J., Monbet, V. & Péne, F. 2014. Non-homogeneous hidden Markov-switching models for wind time series *HAL,* hal-00974716, hal.archives-ouvertes.fr.

Ailliot, P. & Monbet, V. 2012. Markov-switching autoregressive models for wind time series. *Environmental Modelling and Software*, 92–101.

Amurol, S., Ewans, K. & Sheikh, R. Measured wave spectra offshore Sabah & Sarawak, Malaysia Proceedings of OTC-Asia, March 26–28 2014 Kuala Lumpur, Malaysia.

Andrioni, M., Lima, J.A.M., Guerra, L.A., Ribeiro, E.O., Nunes, L.M.P., Ceccopieri, W., de Souza Rego, V. & de Oliveira, S.M. 2012. Ocean Eddies' Influence on Lula Field, Santos Basin, Brazil. Proceedings of the OMAE 2012 Conference, 1–6 July 2012b Rio de Janeiro, Brazil.

Aoyama, M., Tsumune, D., Uematsu, M., Kondo, F. & Hamajima, Y. 2012. Temporal variation of 134 Cs and 137 Cs activities in surface water at stations along the coastline near the Fukushima Dai-ichi Nuclear Power Plant accident site, Japan. *Geochemical Journal* 46, 321–325.

API (American Petroleum Institute). 2012. Derivation of metocean design and operating conditions, API RP 2MET, First Edition.

Ardhuin, F., Chapron, B., Collard, F. 2009. Observation of swell dissipation across oceans. *Geophysical Research Letters,* 36.

Ardhuin, F., Jenkins, A. D. & Belibassakis, K. A. 2008a. Comments on "The Three-Dimensional Current and Surface Wave Equations". *Journal of Physical Oceanography,* 38 (6), 1340–1350.

Ardhuin, F., Rascle, N. & Belibassakis, K. A. 2008b. Explicit wave-averaged primitive equations using a generalized Lagrangian mean. *Ocean Modelling,* 20(1), 35–60.

Ardhuin, F., Rogers, E., Babanin, A. V., Filipot, J.-F., Magne, R., Roland, A., Van Der Westhuysen, A., Queffeulou, P., Lefevre, J.-M., Aouf, L. & Collard, F. 2010. Semi-empirical dissipation source functions for wind-wave models: Part I. Definition, calibration and validation. *J. Phys. Oceanogr.,* 40(9), 1917–1941.

Ardhuin, F., Roland, A., Dumas, F., Bennis, A.-C., Sentchev, A., Forget, P., Wolf, J., Girard, F., Osuna, P. & Benoit, M. 2012. Numerical wave modeling in conditions with strong currents: Dissipation, refraction, and relative wind. *J. Phys. Oceanogr.,* 42, 2101–2120.

Babanin, A. Swell Attenuation due to Wave-induced Turbulence. Proceedings of the OMAE 2012 Conference, 1–6 July 2012 Rio de Jainerio, Brazil.

Babanin, A. V. & Mcconochi, J. Wind measurements near the surface of waves. Proc. OMAE 2013, 9–14 June 2013 Nantes, France.

Bamber, J. L. & Aspinall, W. P. 2013. An expert judgement assessment of future sea level rise from the ice sheets. *Nature Clim. Change,* 3, 424–427.

Banari, A., Grilli, S. T. & Janssen, C. F. Two phase flow simulation with Lattice Boltzmann method: application to wave breaking. Proc. OMAE 2013 Conference, 9–14 June 2013 Nantes, France.

Barrand, N. E., Vaughan, D. G., N., S., M., T., Kuipers Munneke, P., Van Den Broeke, M. R. & Hosking, J. S. 2013. Trends in Antarctic Peninsula surface melting conditions from observations and regional climate modeling. *Journal of Geophysical Research: Earth,* 118 315–330.

Benetazzo, A., Carniel, S., Sclavo, M. & Bergamasco, A. 2013. Wave-current interaction: Effect on the wave field in a semi-enclosed basin. *Ocean Modelling* 70, 152–165.

Bennis, A.-C. & Ardhuin, F. 2011. Comments on 'The Depth-Dependent Current and Wave Interaction Equations: A Revision. *Journal of Physical Oceanography,* 41(10), 2008–2012.

Birknes, J., Hagen, Ø., Johannessen, T.B. & Nestegård, A., 2013. Second-Order Kinematics Underneath Irregular Waves. Proceedings OMAE 2013, 9–14 June 2013, Nantes, France.

Bitner-Gregersen, E. M. 2012. Joint long-term models of met-ocean parameters. *In:* Carlos Guedes Soares, Y. G., N. Fonseca, A.P. Texeira (ed.) *Marine Technology and Engineering: CENTEC Anniversary Book.* London, UK: CRC Press, A. A. Balkema, Taylor and Francis.

Bitner-Gregersen, E. M. 2015. Joint met-ocean description for design and operations of marine structures. *Applied Ocean Research,* In press.

Bitner-Gregersen, E. M., Bhattacharya, S. K., Chatjigeorgiou, Y. K., I., E., Ellermann, K., Ewans, K., G., H., Johnson, M. C., Ma, N., C., M., Nilva, A., I., R. & Waseda, T. 2014a. Recent developments of ocean environmental description with focus on uncertainties. *Ocean Engineering,* 86 (2014), 26–46.

Bitner-Gregersen, E. M., Cramer, E. H. & Korbijn, F. Environmental Description for Long-term Load Response of Ship Structures. Proceedings of ISOPE-95 Conference, 11–16 June 1995 The Hague, The Netherlands.

Bitner-Gregersen, E. M., Eide, L. I., Hørte, T. & Skjong, R. 2013a. *Ship and Offshore Structure Design in Climate Change Perspective*, Springer.

Bitner-Gregersen, E. M., Eide, L. I., Hørte, T. & Vanem, E. Impact of Climate Change and Extreme waves on Tanker Design. Proceedings of the SNAME Conference, 23–25 October 2014d Houston, USA.

Bitner-Gregersen, E. M., Eide, L. I., Reistad, M. & Huseby Bang, A. ExWaCli: Extreme waves and climate change: Accounting for uncertainties in design of marine structures. Proceedings of the13th International Workshop on Wave Hindcasting and Forecasting, 27 October–1 November 2013b Banff, Alberta, Canada.

Bitner-Gregersen, E. M., Ewans, K. C. & Johnson, M. C. 2014b. Some uncertainties associated with wind and waves description and their importance for engineering applications. *Ocean Engineering,* 86 (2014), 11–25.

Bitner-Gregersen, E. M., Fernandez, L., Lefevre, J.-M. & Toffoli, A. 2014c. The North Sea Andrea storm and numerical simulations. *Natural Hazards and Earth System Sciences,* 14.

Bitner-Gregersen, E. M. & Hagen, Ø. 1990. Uncertainties in Data for the Offshore Environment. *Struct. Safety,* 7, 11–34.

Bitner-Gregersen, E. M. & Magnusson, A. K. 2014. Effect of intrinsic an sampling varaibility on wave parameters and wave statistics. *Ocean Dynamics,* 64(11), 1643–1655.

Bitner-Gregersen, E. M. & Toffoli, A. 2012a. On the probability of occurrence of rogue waves. *Natural Hazards and Earth System Sciences,* 12 751–762.

Bitner-Gregersen, E. M. & Toffoli, A. A semi-empirical wave crest distribution of random directional wave fields. Proceedings of the OMAE 2012 Conference, 1–6 July 2012, Rio de Janeiro, Brazil.

Bitner-Gregersen, E. M. & Toffoli, A. 2014. Probability of occurrence of rogue sea states and consequences for design of marine structures. *Ocean Dynamics,* 64, 1457–1468.

Bitner-Gregersen, E. M. 2015. Joint met-ocean description for design and operations of marine structures. *AOR*, http://dx.doi.org/10.1016/j.apor.2015.01.007

Bmt 1986. British Maritime Technology (Primary Contributors: Hogben N., Da Cunha L.F., Oliver H.N.) Global Wave Statistics. *Atlas.* London, England: Unwin Brothers Limited.

Boudiere, E., Maisondieu, C., Ardhuin, F., Accensi, M., Pineau-Guillou, L. & Lepesqueur, J. 2013. A suitable metocean hindcast database for the design of Marine energy converters. *International Journal of Marine Energy*, 3–4, e40–e52.

Box, J. E. 2013. Greenland ice sheet mass balance reconstruction. Part II: Surface mass balance (1840–2010). *J. Climate,* 26, 6974–6989.

Box, J. E. & Colgan, W. 2013. Greenland ice sheet mass balance reconstruction. Part III: Marine ice loss and total mass balance (1840–2010). *J. Clim.,* 26, 6990–7002.

Bracegirdle, T. J. & Stephenson, D. B. 2012. Higher precision estimates of regional polar warming by ensemble regression of climate model projections. *Clim. Dyn.,* 39, 2805–282.

Bratland, A. K., Børresen, K. & Berntsen, P. I. B. Higher Order Wave-Current Elevations in Deep Water. 30th International Conference on Ocean, Offshore and Arctic Engineering, 19–24 June 2011 Rotterdam, The Netherlands. 1–9.

Bricheno, L. M., Soret, A., Wolf, J., Jorba, O. & Baldasano, J. M. 2013. Effect of high-resolution meteorological forcing on nearshore wave and current model performance. *J. Atmos. Oceanic Technol.,* 30, 1021–1037.

Buchner, B. & Forristal, G. Are basin wave different from field waves? (First investigations during 'CREST' JIP). Proc. 31st Int. Conf. on Ocean, Offshore and Arctic Eng. OMAE 2012, 1-6 July 2012, Rio de Janeiro, Brasil.

Campbell, A. J., Bechle, A. J. & Wu, C. H. 2014. Observations of surface waves interacting with ice using stereo imaging. *J. Geophys. Res. Oceans,* 119, 3266–3284.

Cardone, V. J., Callahan, B. T., Chen, H., Cox, A. T., Morrone, M. A. & Swail, V. R. 2014. Global distribution and risk to shipping of very extreme sea states (VESS). *International Journal of Climatology.*

Cardone, V. J. & Cox, A. T. Modelling Very Extreme Sea States (VESS) in real and synthetic design level storms. Proceedings of the OMAE2011 Conference, 2011 Rotterdam, The Netherlands.

Cartwright, D. E. & Longuet-Higgins, M. S. 1956. Statistical distribution of the maxima of a random function. *Proc., Roy. Soc. A,,* 237, 212–232.

Cavaleri, L., Bertotti, L., Torrisi, L., Bitner-Gregersen, E., Serio, M. & Onorato, M. 2012. Rogue waves in crossing seas: The Louis Majesty accident. *Journal of Geophysical Research,* 117.

Ceccopieri, W. & Silveira, I.C.A. 2012. Is the Vertical Variability of the Ocean in Santos Bight, Brazil, Dominated by the Western Boundary Current Meanders? Proceedings of the OMAE 2012 Conference, 1–6 July 2012, Rio de Janeiro, Brazil.

Chabchoub, A., Hoffmann, N., Onorato, M., Slunyaev, A., Sergeeva, A., Pelinovsky, E. & Akhmediev, N. 2012. Observation of a hierarchy of up to fifth-order rogue waves in a water tank. *Phys Rev E* 86.

Chalikov, D. & Babanin, A. V. 2012. Simulation of wave breaking in one-dimensional spectral environment. *J. Phys. Oceanogr.,* 42, 1745–1761.

Chawla, A., Spindler, D. & Tolman, H. L. 2013. Validation of a thirty year hindcast using the climate forecast system reanalysis wind. *Ocean modeling,* 70, 189–206.

Chawla, A., Tolman, H. L., Gerald, V., Spinler, D., Spindler, T., Alves, J.-H., Cao, D., Hanson, J. & Devaliere, E.-M. 2012. A multigrid wave forecasting model: A new paradigm in operational wave forecasting. *Weather and Forecasting,* 28.

Chella, M. A., Bihs, H., Kamath, A. & Muskulus, M. Numerical modelling of breaking waves over a reef with a level-set based numerical wave tank. Proceedings of the OMAE 2013 Conference, 9–14 June 2013 Nantes, France.

Chen, S. S., Price, J. F., Zhao, W., Donelan, M. A. & Walsh, E. J. 2007. The CBLAST-Hurricane program and the next-generation fully coupled atmosphere-wave- ocean models for hurricane research and prediction. *Bull. Amer. Meteor. Soc.,* 88, 311–317.

Chen, S. S., Zhao, W., Donelan, M. A. & Tolman, H. L. 2013. Directional wind-wave coupling in fully coupled atmosphere-wave-ocean models: Results from CBLAST-Hurricane. *J. Atmos. Sci.,* 70, 3198–3215.

Chen, Y.-Y. & Chen, H.-S. 2014. Lagrangian solution for irrotational progressive water waves propagating on a uniform current: Part 1. Fifth-order analysis. *Ocean Engineering,* In press.

Chen, Y.-Y., Chen, H.-S., Lin, C.-Y. & Li, M.-S. 2012. Lagrangian Solution for an Irrotational Progressive Water Wave Propagating on a Uniform Current. *Journal of Atmospheric and Oceanic Technology,* 30(4), 825–845.

Chen, Y.-Y., Hsu, H.-C. & Chen, G.-Y. 2010. Lagrangian experiment and solution for irrotational finite-amplitude progressive gravity waves at uniform depth. *Fluid Dynamics Research,* 42(4).

Cherneva, Z. & Guedes Soares, C. 2014. Time–frequency analysis of the sea state with the Andrea freak wave. . *Nat. Hazards Earth Syst. Sci.,* 14, 3143–3150.

Cherneva, Z., Tayfun, M. A. & Guedes Soares, C. 2013. Statistics of waves with different steepness simulated in a wave basin. *Ocean Engineering,* 60 (2013), 186–192.

Choi, B. H., Min, B. I., Kim, K. O. & Yuk, J. H. 2013. Wave-tide-surge coupled simulation for typhoon Maemi. *China Ocean Eng.,* 27(2) 141–158.

Christopher, B., Smith, J. M., Kenney, A. & Jensen, R. 2013. STWAVE simulation of hurricane Ike; Model results and comparison data. *Coastal Eng.,* 73, 58–70.

Christou, M. & Ewans, K. 2014. Field measurements of rogue water waves. *J. Phys. Oceanogr.,* in press.

Chu, P. C., Miller, S. E. & Hansen, J. A. 2013. Fuel-saving ship route using the Navy's ensemble meteorological and oceanic forecasts. *Journal of Defense Modeling and Simulation: Applications, Methodology, Technology,* 201X, Vol XX(X), 1–16.

Clauss, G., Klein, M., Dudek, M. & Onorato, M. Application of Breather Solutions for the Investigation of Wave/Structure Interaction in High Steep Waves. 31th OMAE–International Conference on Ocean, Offshore and Arctic Engineering, 1–6 July 2012 Rio de Janeiro, Brazil.

Comiso, J. C. & D.K., H. 2014. Climate trends in the Arctic as observed from space. *WIREs Clim Change 2014,* 5, 389–409.

Cooper, C., Mitchell, T., Forristall, G. & Stear, J. 2013. DeepStar Metocean Studies: 15 years of Discovery. *Marine Technology Society Journal*, 47(3), 19–26.

Corrêa, D. C., Oliveira, A. C., De. Tannuri, E. A. & Sphaier, S. H. Comprehensive Dowtime Analysis of DP-Assisted Offloading Operation of Spread Moored Platforms in BraziWian waters. 32nd International Conference on Ocean, Offshore and Arctic Engineering OMAE 2013, 9–14 June 2013 Nantes, France.

De Winter, R. C., Sterl, A. & B.G., R. 2013. Wind extremes in the North Sea Basin under climate change: An ensemble study of 12 CMIP5 GCMs. *Journal of Geophysical Research: Atmospheres* 118 1601–1612.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., Van De Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., Mcnally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., De Rosnay, P., Tavolato, C., Thépaut, J. N. & Vitart, F. 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society,* 137., 553–597.

Degtyarev, A. B. New approach to wave weather scenarios modelling. Proceedings of the 8th International Ship Stability Workshop, 6–7 October 2005 Istanbul, Turkey.

Didenkulova, I., Nikolkina, I. & Pelinovsky, E. 2013c. Rogue waves in the basin of intermediate depth and the possibility of their formation due to the modulational instability. *JETP Letters* 97, 194–198.

Didenkulova, I., Pelinovsky, E. N. & Didenkulov, O. I. 2014. Run-up of long solitary waves of different polarities on a plane beach. *Izvestiya, Atmospheric and Oceanic Physics* 50, 532–538.

Dietrich, J. C., Tanaka, S., Westerink, J. J., Dawson, C. N., Luettich Jr., R. A., Zijlema, M., Holthuijsen, L. H., Smith, J. M. & Westerink, J. J. 2012. Performance of the unstructed-mesh, SWAN+ADCIRS model in computing hurricane waves and surge. *J. Scientific Computing* 52, 468–497.

Dietrich, J. C., Zijlema, M., Allier, P.-E., Holthuijsen, L. H., Booij, N., Meixner, J. D., Proft, J. K., Dawson, C. N., Bender, C. J., Naimaster, A., Smith, J. M. & Westerink, J. J. 2013. Limiters for spectral propagation velocities in SWAN. *Ocean Modelling* 70, 85–102.

Dietrich, J. C., Zijlema, M., Westerink, J. J., Holthuijsen, L. H., Dawson, C. N., Luettich, R. a. J., Jensen, R. E., Smith, J. M., Stelling, G. S. & Stone, G. W. 2011. Modeling hurricane waves and storm surge using integrally-coupled, scalable computations. *Coast. Eng.,* 58, 45–65.

Dnv, L. 2011. Design of offshore wind turbine structures.

Dnv, L. 2014. Environmental Conditions and Environmental Loads. *In:* Dnv, L. (ed.). Høvik, Norway.

Dobrynin, M., Murawsky, J. & Yang, S. 2012. Evolution of the global wind wave climate in CMIP5 experiments. *Geophysical Research Letters* 39.

Donelan, M. A., Curcic, M., Chen, S. S. & Magnusson, A. K. 2012. Modeling waves and wind stress. *J. Geophys. Res. Oceans,* 117.

Dong, S., Fan, D.-Q. & S.-S., T. 2012. Joint occurrence period of wind speed and wave height based on both service term and risk probability. *Journal of Ocean University of China,* 11(4), 488–494.

Dong, S., Liu, W., Zhang, L. & Guedes Soares, C. 2013a. Return value estimation of significant wave heights with maximum entropy distribution. *Journal of Offshore Mechanics and Arctic Engineering* 135.

Dong, S., Tao, S. S., Lei, S. H. & Guedes Soares, C. 2013b. Parameter estimation of the maximum entropy distribution of significant wave height. *Journal of Coastal Research* 29(3), 597–604.

Dong, S., Wang, L. & Fu, X.-Y. Design parameter estimation under multivariate extreme ocean environmental conditions in the Bohai Sea. Proc. of International Conference on Ocean, Offshore and Arctic Engineering, 2007 San Diego, California, USA.

Dong, S., Wang, N.N., Liu, W. & Guedes Soares, C. 2013c. Bivariate maximum entropy distribution of significant wave height and peak period. *Ocean Engineering,* 59(1), 86–99.

Dutour-Sikiric, M.-A. 2013. Regional Ocean Modelling System and Wind Wave Model. *Ocean Modelling,* 72, 59–73.

Dutton, A. & Lambeck, K. 2012. Ice volume and sea level during the last interglacial. *Science,* 337, 216–219.

Ewans, K. C. 2014. Temporal characteristics of swell and a wavelet-based test for swell stationarity. *Applied Ocean Research,* In press.

Ewans, K. C. & Jonathan, P. 2014. Evaluating environmental joint extremes for the offshore industry. *J. Marine Systems,* 130, 124–130

Extreme-Seas 2013. Design for Ship Safety in Extreme Seas (EXTREME SEAS) Europe: EC Grant Agreement no.:234175, http://cordis.europa.eu/result/rcn/55382_en.html, (see also http://www. mar.ist.utl.pt/ extremeseas/), Coordinated by Legacy DNV, Norway. Contact: Elzbieta.Bitner-Gregersen@dnvgl.com

Ezersky, A., Abcha, N. & E., P. 2013a. Physical simulation of resonant wave run-up on a beach. *Nonlinear Processes in Geophysics* 20, 35–40.

Ezersky, A., Tiguercha, D. & Pelinovsky, E. 2013b. Resonance phenomena at the long wave run-up on the coast. *Natural Hazards and Earth System Sciences* 13, 2745–2752.

Fan, Y., Held, I. M., Lin, S. J. & Wang, X. L. 2013. Ocean warming effect on surface gravity wave climate change for the end of the 21st century. *J. Clim.,* 26, 6046–6066.

Fan, Y., Lin, S.-J., Held, I. M., Yu, Z. & Tolman, H. L. 2012. Global ocean surface wave simulation using a coupled atmosphere-wave model. *J. Climate* 25, 6233–6252.

Fedele, F., Benetazzo, A., Gallego, G., Shih, P., Yezzi, A., Barbariol, F. & Ardhuin, F. 2013. Space–time measurements of oceanic sea states. *Ocean Modelling,* 70, 103–115.

Feld, G., Randell, D., Wu, Y., Ewans, K.C. & Jonathan.P. Estimation of storm peak and intra-storm directional-seasonal design conditions in the North Sea. Proc. 33nd Conf. Offshore Mech. Arct. Eng., 7–14 June 2014 San Francisco, USA.

Fernandez, L., Onorato, M., Monbaliu, J. & Toffoli, A., 2014. Modulational instability and wave amplification in finite water depth. Nat. Hazards Earth Syst. Sci., 14, 705–711.

Fettweis, X., Franco, B., Tedesco, M., Van Angelen, J. H., Lenaerts, J. T. M., Van Den Broeke, M. R. & Gallee, H. 2013. Estimating Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric model MAR. *Cryosphere,* 7, 469–489.

Forristall, G. Z. 2000. Wave Crest Distributions: Observations and Second-Order Theory. *J. Phys. Ocean.,* 30, 931–1943.

Forristall, G. Z. Laboratory measurements compared to theory. Proceedings of the OMAE 2015 Conference, 31 May–5 June 2015 St. John’s, Newfoundland, Canada.

Forristall, G. Z., Ewans, K., Olagnon, M. & Prevosto, M. The WesT Africa Swell Project (WASP). Proceedings of the OMAE 2013 Conference, 9–14 June 2013 Nantes, France.

Franco, B., Fettweis, X. & Erpicum, M. 2013. Future projections of the Greenland ice sheet energy balance driving the surface melt. *Cryosphere,* 7, 1–18.

Gehrels, W. R., Balouin, Y. & Certain, R. 2012. Nineteenth and twentieth century sea-level changes in Tasmania and New Zealand. *Earth Planet. Sci. Lett.,* 315, 94–102.

Gemmrich, J. & Garrett, C. 2012. The Signature of Inertial and Tidal Currents in Offshore Wave Records. *Journal of Physical Oceanography,* 42(6), 1051–1056.

Gibson, R., Christou, M. & Feld, G. 2014. The statistics of wave height and crest elevation during the December 2012 storm in the North Sea. *Ocean Dynamics,* 64, 1305–1317.

Gillet-Chaulet, F. & Al., E. 2012. Greenland ice sheet contribution to sea-level rise from a new-generation ice-sheet model. *Cryosphere,* 6, 1561–1576.

Gramstad, O., Zeng, H., Trulsen, K. & Pedersen, G. K. 2013. Freak waves in weakly nonlinear unidirectional wave trains over a sloping bottom in shallow water. *Physics of Fluid*, 25, 122103.

Gramstad, O. & Babanin, A. Implementing nonlinear term in third generation models. Proceedings of the OMAE2014 Conference, 9–14 June 2014 Nantes, France.

Grigorieva, V. & Gulev, S., 2006. Extreme wind waves worldwide from the VOS data and their changes over the last 50 years. ftp://ftp.wmo.int/Documents/PublicWeb/amp/mmop/documents/JCOMM-TR/J-TR-34-9th-waves-workshop/Papers/Gulev.pdf

Guedes Soares, C. 1984. Representation of double-peaked sea wave spectra. *Ocean Engineering,* 11, 185–207.

Gunn, K. & Stock-Williams, C. 2012. Quantifying the global wave power resource. *Renewable Energy,* 44(2012), 296–304.

Gunn, K. & Stock-Williams, C. 2013. On validating numerical hydrodynamic models of complex tidal flow. *International Journal of Marine Energy,* 3–4, e82–e97.

Hacket, E. E., Fullerton, A. M., Merrill, C. F. & Fu, T. C. 2014. Comparison of incoherent and coherent wave field measurements using dual-polarized pulse-Doppler X-band radar. *IEEE Transactions on Geosciences and Remote Sensing* In press.

Hagen, Ø., Falkenberg, E. & Bitner-Gregersen, E. M. 2015. Reliability Based Approach for Offloading Operation Related to Motion of Two Side-by-Side Moored LNG Carriers. *Applied Ocean Research,* In press.

Hagen, Ø., Garrè, L. & Friis-Hansen, P. DNV-ADAPT framework for risk-based adaptation: a test case for the offshore industry. Proc. 11th International conference on Structural Safety and Reliability (ICOSSAR), June 2013 2013 New York, USA.

Hagen, Ø. & Solland, G. On Safety and reliability for platforms that are unmanned during severe storms. Proceedings of the OMAE 2013 Conference, 9–14 June 2013 Nantes, France.

Hanson, J. L. & Phillips, O. M. 2001. Automated analysis of ocean surface directional wave spectra. *Journal of Atmospheric and Oceanic Technology* 18, 277–293.

Hasanat Zaman, M. & Baddour, E. 2011. Interaction of waves with non-colinear currents. *Ocean Engineering,* 38(4), 541–549.

Hashemi, M. R. & Neill, S. P. 2014. The role of tides in shelf-scale simulations of the wave energy *Resource, Renewable Energy* 69.

Haver, S. & Anderson, O. J. Freak waves: Rare realizations of a typical population or typical realizations of a rare population. Proceedings of the 10th International Offshore and Polar Engineering (ISOPE) Conference, 28 May–2 June 2000 Seattle, USA.

Haver, S., Bruserud, K. & Baarholm Sagli, G. Environmental contour method: An approximate method for obtaining characteristic response extremes for design purpose. Proceed. the 13th International Workshop on Wave Hindcasting and Forecasting & 4th Coastal Hazard Symposium, 27 Oct.–1 Nov. 2013 Banff, Canada.

Heffernan, J. E. & Tawn, J. A. 2004. A conditional approach for multivariate extreme values. . *J. R. Statist. Soc.,* B 66.

Hemer, M. A., Fan, Y., Mori, N., Semedo, A. & Wang, X. L. 2013. Projected changes in wave climate from a multi-model ensemble. *Nature Climate Change* 3 471–476.

Hemer, M. A., Wang, X. L., Weisse, R. & Swail, V. R. 2012. Advancing Wind-Waves Climate Science: The COWCLIP Project. *Bulletin of the American Meteorological Society* 93, 791–796.

Hennig, J., Scharnke, J., Swan, C., Hagen, Ø., Ewans, K., Tromans, P. & Forristall, G. Z. Effects of short-crestedness on extreme wave impact–A summarey of findings from the Joint Industry project ShortCresT. Proceedings of the OMAE 2015 Conference, 31 May–5 June 2015 St. John's, Newfoundland, Canada.

Holland, R., Bruneau, N., Enright, C., Losch, M., Kurtz, N. T. & Kwok, R. 2014. Modeled trends in Antarctic sea ice thickness. *Journal of Climate,* 27, 3784–3801.

Hu, H. H. & Ma, N. Numerical simulation on nonlinear evolution of rogue waves on currents based on the NLS equation. 30th International Conference on Ocean, Offshore and Arctic Engineering OMAE 2011, June 2011 Rotterdam, The Netherlands.

Huseby, A. B., Vanem, E. & Natvig, B. 2013. A new approach to environmental contours for ocean engineering applications based on direct Monte Carlo simulations. *Ocean Engineering,* 60.

Husson, R., Ardhuin, F., Collard, F., B., C. & Balanche, A. 2013. Revealing forerunners on Envisat's wave mode ASAR using the Global Seismic Network. *Geophysical Research Letter,* 39.

Hutchings, J. K., Roberts, A., Geiger, C. A. & Richter-Menge, J. 2011. Spatial and temporal characterization of sea-ice deformation. *Ann. Glaciol.,* 52, 360–368.

Hwang, P. A., Toporkov, J. V., Sletten, M. A. & Steven, P. M. 2013. Mapping Surface Currents and Waves with Interferometric Synthetic Aperture Radar in Coastal Waters: Observations of Wave Breaking in Swell-Dominant Conditions. *Journal Of Physical Oceanography,* 43, 563–582.

Iacs 2000. Standard Wave Data. *In:* Iacs (ed.) *Recommended Practice.*

Iafrati, A., Babanin, A. & Onorato, M. 2013. Modulational Instability,Wave Breaking, and Formation of Large-Scale Dipoles in the Atmosphere. *Physical Review Letters,* 110.

Ignatius, J., Räsänen, J.-E., Tervo, K. & Ellis, T. A Comprehensive Performance Management Solution. 13th International Conference on Computer and IT Applications in the Maritime Industries (COMPIT'14), 2014 Redworth, UK. 558–568.

Ilus, T. & Heikkinen, A. Challenges in Vessel Speed Optimization. 11th International Conference on Computer and IT Applications in the Maritime Industries (COMPIT'12), 2012 Liege: Belgium., 284–296.

Imo 1997. Interim Guidelines for the Application of Formal Safety Assessment (FSA) to the IMO Rule Making Process. *Maritime Safety Committee, 68th session June 1997; and Marine Environment Protection Committee, 40th session, September 1997.*

Imo 2001. Guidelines for Formal Safety Assessment for the IMO Rule Making Process. *IMO/Marine Safety Committee 74/WP.19.*

Imo 2012. 2012 Guidelines for the development of a ship energy efficiency management plan (SEEMP). *Resolution MEPC.213(63).*

Imo 2013. 2013 Interim guidelines for determining minimum propulsion power to maintain the manoeuvrability in adverse conditions. *Resolution MEPC.232(65).*

Ipcc 2007. The Fourth Assessment Report: Climate Change (AR4): The AR4 Synthesis Report, the Working Group I Report: The Physical Science Basis (ISBN 978 0521 88009-1 Hardback; 978 0521 70596-7 Paperback), the Working Group II Report Impacts: Adaptation and Vulnerability, the Working Group III Report: Mitigation of Climate Change. *AR4.* UN.

Ipcc 2012. The IPCC SREX: Summary for Policymakers. Report. *SREX.* UN.

Ipcc 2013. The Fifth Assessment Report: Climate Change (AR5): The AR5 Synthesis Report. *AR5.* UN.

Iseki, T. & U.D., N. Study on a Method for Estimationing Fuel Consumption in a Seaway. 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2013), 9–14 June 2013 Nantes: France.

Iso 2012. Petroleum and natural gas industries— specific requirements for offshore structures—part 1: metocean design and operating conditions. International Organization for Standardization.

Issc. ISSC 2009 Committee I.1 Environment Report. Proceedings ISSC 2009, August 2009 Seoul, Korea. 1–126.

Issc. ISSC 2012 Committee I.1 Environment Report ((Bitner-Gregersen, E.M. (chairman), Bhattacharya S. K., Chatjigeorgiouc, I.K, Eames, I., Ellermann, K. Ewans, K. Hermanski, G., Johnson, M.C., Ma, N., Maisondieu, Ch, Nilva, A., Rychlik, I., Waseda, T). Proceedings ISSC 2012, 9–13 September 2012 Rostok, Germany.

Issc. ISSC 2012 Committee I.1 Environment Reply to Discussers (Bitner-Gregersen, E.M. (chairman), Bhattacharya S. K., Chatjigeorgiouc, I.K, Eames, I., Ellermann, K. Ewans, K. Hermanski, G., Johnson, M.C., Ma, N., Maisondieu, Ch, Nilva, A., Rychlik, I., Waseda, T). Proceedings ISSC 2012 9–13 September 2013 Rostok, Germany.

Jeans, G., Harrington-Missin, L., Calverley, M., Maisondieu, C., Herry, C. & Quiniou, V. Deepwater Current Profile Data Sources for Riser Engineering Offshore West Africa. Proceedings of the 32nd International Conference on Ocean, Offshore and Arctic Engineering, 9–14 June 2013 Nantes, France

Jeans, G. & Wade, I. Simulation of strong intertial currents to support preliminary engineering offshore Namibia. Proceedings of the OMAE 2013 Conference, June 9–14 2013 Nantes, France.

Jensen, R. E., Swail, V. & Hesser, T. J. What is the ground truth? Proceedings of the 13th International Workshop on Wave Hindcasting and Forecasting and 4th Coastal Hazards Workshop, 27 October–1 November 2013 Banff, Canada.

Jevrejeva, S., Moore, J.C & Grinsted, A. 2012b. Potential for bias in 21st century semiempirical sea level projections. *J. Geophys. Res.,* 117.

Jevrejeva, S., Moore, J. C. & Grinsted, A. 2012a. Sea level projections to AD 2500 with a new generation of climate change scenarios. *Global Planet. Change,* 80–81, 14–20.

Johnson, J. T., Burkholder, R. J., Toporkov, J. V., Lyzenga, D. R. & Plant, W. J. 2009. A numerical study of the retrieval of sea surface height profiles from low grazing angle radar data. *IEEE Trans. Geosci. Remote Sens.,* 47, 1641–1650.

Jonathan, P., Ewans, K. C. & Randell, D. 2013. Joint modelling of environmental parameters for extreme sea states incorporating covariate effects. *Coastal Eng.,* 79, 22–31.

Jonathan, P., Randell, D., Wu, Y. & Ewans, K. 2014. Return level estimation from non-stationary spatial data exhibiting multidimensional covariate effects. *Ocean Eng.,* In press.

Jones, O., Ewans, K. & Chuah, S. A Monte Carlo approach for estimatiing extreme currents in the Singapore Straits. Proceedings of the OMAE 2013 Conference, 9–14 June Nantes, France.

Kano, T. & Namie, S. A Study on Estimation of GHG Emission for Speed Planning Operation Using Energy Efficiency Index and Time-Series Monitoring Data. 13th International Conference on Computer and IT Applications in the Maritime Industries (COMPIT'14), 2014 Redworth, UK. 167–180.

Kariranta, R.-J. Utilization of performance data collection and normalization for ship operations and design. 11th International Conference on Computer and IT Applications in the Maritime Industries (COMPIT'12), 2012 Liege, Belgium. 438–448.

Keef, C., Papastathopoulos, I. & Tawn, J. A. 2013a. Estimation of the conditional distribution of a vector variable given that one of its components is large: additional constraints for the Heffernan and Tawn model. *J. Mult. Anal.,* 115, 396–404.

Keef, C., Tawn, J. A. & Lamb, R. 2013b. Estimating the probability of widespread flood events. *Environmetrics,* 24, 13–21.

Khor, Y. S., Døhlie, K. A., Konovessis, D. & Xiao, Q. Optimum Speed Analysis for Large Containerships. 11th International Conference on Computer and IT Applications in the Maritime Industries (COMPIT'12), 2012 Liege:, Belgium. 121–131.

Knutti, R., Furrer, R., Tebaldi, C., Cermak, J. & Meehl., G. A. 2010. Challenges in Combining Projections from Multiple climate Models. *Journal of Climate* 23 2739–2758.

Kodaira, T., Waseda, T., Nakagawa, T., Isoguchi., O. & Miyazawa, Y. 2013. Measuring the Kuroshio Current Around Miyake Islands, a Potential Site for Ocean-Current Power Generation. *Int. J. Offshore Polar Eng.,* 23(4)**,** 272–278.

Kpogo-Nuwoklo, K. A., Olagnon, M. & Gue'd´E, Z. Wave spectra partitioning and identification of wind sea and swell events. Proceedings of the OMAE 2014 Conference, 8–13 June 2014 San Francisco, California, USA.

Krogstad, H. E., Barstow, S. F., Mathiesen, L. P., Lønseth, L., Magnusson, A. K. & Donelan, M. A. Extreme waves in the long-term wave Measurements at Ekofisk. Proc. Rogue Waves 2008 Workshop, 23–33 October 2008 Brest, France.

L., L., A., C. & G., S. 2013. Wave energy resource assessment in the Mediterranean, the Italian perspective. *Renewable Energy* 50, 938–949.

Lane, E. M., Restrepo, J. M. & Mcwilliams, J. C. 2007. Wave–Current Interaction: A Comparison of Radiation-Stress and Vortex-Force Representations. *Journal of Physical Oceanography,* 37(5), 1122–1141.

Leckler, F., Ardhuin, F., Filipot, J.-F. & Mironov, A. 2013. Dissipation source terms and whitecap statistics. *Ocean Modelling,* 70, 62–74.

Lee, J. Y., C.S., S., Kim, H., Hong, C. & Seo, J. Development and Application of Trim Optimization and parametric Study using an Evaluation System (SoLuTion) based on the RANS for Improvement of EEOI. 33nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2014), 8–13, June 2014 San Francisco, USA.

Li, J.-G. 2012. Propagation of ocean surface waves on a spherical multiple-cell grid. *Journal of Computational Physics,* 231(24), 8262–8277.

Li, J.-X., Liu, D.-Y. & Liu, S.-X. 2012. Numerical Investigation of the Effect of Current on Wave Focusing. *China Ocean Engineering,* 26(1), 37–48.

Li, L., Gao, Z. & Moan, T. Joint environmental data at five European offshore sites for design of combined wind and wave energy devices. Proceedings of the ASME 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2013), 9–14June 2013 Nantes, France.

Lin, P. & Liu, P. 1999. Internal Wave-Maker for Navier-Stokes Equations Models. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 125(4), 207–215.

Lin, Y. H. & Fang, M.-C. The ship-routing optimization based on the three-dimensional modified isochrones method. 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2013), 1–6 July 2013 Nantes, France.

Lindsay, R., Wensnahan, M., Schweiger, A. & Zhang, J. 2013. Evaluation of Seven Different Atmospheric Reanalysis Products in the Arctic. *Journal of Climate,* 27, 2588–2606.

Little, C. M., Oppenheimer & Urban, N. M. 2013. Upper bounds on twenty-first-century Antarctic ice loss assessed using a probabilistic framework. *Nature Clim. Change,* 7, 654–659.

Liu, B., Guan, C., Xie, L. & Zhao, D. 2012. An investigation of the effects of wave state and sea spray on an idealized typhoon using an air-sea coupled modeling system. *Advances in Atmospheric Sciences* 29(2), 391–406.

Ma, Y., Dong, G. & Ma, X. Investigations of the Effetcs on Benjamin-Feir Instability by Uniform Currents. 33nd International Conference on Ocean, Offshore and Arctic Engineering, 9–14 June 2013 Nantes, France.

Ma, Y., Dong, G., Perlin, M., Ma, X., Wang, G. & Xu, J. 2010. Laboratory observations of wave evolution, modulation and blocking due to spatially varying opposing currents. *Journal of Fluid Mechanics,* 661, 108–129.

Madsen, H. O., Krenk, S. & Lind, N. C. 1986. *Methods of Structural Safety*, Prentice-Hall, Enlewood Cliffs.

Magnusson, A. K. & Donelan, M. A. 2013. The Andrea wave. Characteristics of a measured North Sea rogue wave. *JOMAE*.

Mahlstein, I. & Knutti, R. 2012. September Arctic sea ice predicted to disappear for 2oC global warming above present. *J. Geophys. Res. Atmos.,* 117.

Markus, D., Hojjat, M., Wüchner, R. & Bletzinger, K. U. 2013. A CFD approach to modeling wave-current interaction. *International Journal of Offshore and Polar Engineering,* 23(1), 29–32.

Massel, S. 2013. *Ocean Surface Waves: Their Physics and Prediction*, World Scientific.

Massel, S. & Przyborska, A. 2013. On the surface waves generation due to glacier calving. *Oceanologia,* MS No 40/2012.

Massonnet, F., Mathiot, P., Fichefet, T., Goosse, H., Konig Beatty, C., Vancoppenolle, M. & Lavergne, T. 2013. A model reconstruction of the Antarctic sea ice thickness and volume changes over 1980–2008 using data assimilationc. *Ocean Modelling* 64, 67–75.

Masui, T. & Al., E. 2011. An emission pathway for stabilizing at 6 Wm-2 radiative forcing. *Climatic Change* 109, 59–76.

Masumoto, Y., Miyazawa, Y., Sumune, D., Kobayashi, T., Estournel, C., Marsaleix, P., Lanerolle, L., Mehra, A. & Garraffo, Z. D. 2012. Oceanic dispersion simulation of Cesium 137 from Fukushima Daiichi Nuclear Power Plan. *Elements,* 8, 207–212.

Mcmillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., Hogg, A. & Wingham, D. 2012. Increased ice losses from Antarctica detected by CryoSat-2. *Geophys. Res. Lett.,* 41, 3899–3905.

Mcwilliams, J. C., Restrepo, J. M. & Lane, E. M. 2004. An asymptotic theory for the interaction of waves and currents in coastal waters. *Journal of Fluid Mechanics,* 511, 135–178.

Meinshausen, M. & Al., E. 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* 109, 213–241.

Mellor, G. 2011. Reply. *Journal of Physical Oceanograph,* 41(10), 2013–2015.

Mellor, G. L. The Depth-Dependent Current and Wave Interaction Equations: A Revision. *Journal of Physical Oceanography,* 38(11), 2587–2596.

Mepc67/Inf.22 2014. Japanese activity on "Minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions. *MEPC 67/INF.22.* Submitted by Japan to IMO.

Merrill, C. F., Geiser, J., Pfitsch, D., Fu, T. C., Terrill, E., Depaolo, T., Cook, T., Lenain, L., Richer, S. & Fullerton, A. M. Simultaneous ship motions and ocean waves measured in the time domain. 30th Symposium on Navaly Hydrodynamics, 2–7 Nov. 2014 Hobart, Australia.

Meylan, M., Bennetts, L. G. & Kohout, A. L. 2014. In situ measurements and analysis of ocean waves in the Antarctic marginal ice zone. *Geophys. Res. Lett.,* 41, 5046–5051.

Moreira, R. M. & Peregrine, D. H. 2012. Nonlinear interactions between deep-water waves and currents. *Journal of Fluid Mechanics,* 691, 1–25.

Mori, N., Shimura, S., Nakajo, T., Yasuda, T. & (2012), A. H. M. Multi-model ensemble projection of future coastal climate change Coastal Engineering Proceedings, 2012.

Mori, N., Shimura, T., Nakajo, S., Ysujio, D., Yasuda, T., Mase, H. & Suh, K. D. Projection of future wave climate change and application to coastal structure design. Proceedings of Breakwater Conference, 2013 Edinburgh, UK.

Moss, R. H. & Al., E. 2010. The next generation of scenarios for climate change research and assessment. *Nature,* 463, 747–756.

Muyau, J., Ewans, K. C. & Jonathan, P. Short-term variability of wind measurements in South China Sea. OTC-24904. Proceedings OTC-Asia, 26–28 Marchx 2014 Kuala Lumpur, Malaysia (submitted for publication).

Myrhaug, D. & Holmedal, L. E. 2014. Wave-induced current for long-crested and short-crested random waves. *Ocean Engineering,* 81(0), 105–110.

Naess, A. & Karpa, O. Statistics of extreme wind speeds and wave heights by the bivariate acer method Proceedings of the 32nd International Conference on Ocean, Offshore and Arctic Engineering OMAE 2013, 9–14 June 2013 Nantes, France.

Nielsen, U. D. & Stredulinsky, D. C. 2012. Sea State Estimation from an Advancing Ship–A Comparative Study using Sea Trial Data. *Applied Ocean Research,* 34, 33–44.

Nieto-Borge, J. C., Hessner, K. & Mata-Moya, D. D. 2008. Signal-to-noise ratio analysis to estimate ocean wave heights from X-band marine radar image time series. IET Radar. *Sonar and Navigation,* 2(1), 35–41.

Nikolkina, I. & Didenkulova, I. 2012. Catalogue of rogue waves reported in media in 2006–2010. *Nat. Hazards Earth Syst. Sci.,* 61.

Nitsure, S. P., Londhe, S. N. & Khare, K. C. 2012. Wave forecasts using wind information and genetic programming. *Ocean Engineering* 54 61–69.

Norsok 2012. Action and action effects. *In:* Directorate, T. N. O. (ed.). Norway.

Notz, D. & Marotzke, J. 2012. Observations reveal external driver for Arctic sea-ice retreat. *Geophys. Res. Lett.,* 39.

O. Lecomte, 1 T. Fichefet, M. Vancoppenolle, F. Domine, 4, F. Massonnet, 1p. Mathiot, S. Morin & 2013.Barriat, P. Y. 2013. On the formulation of snow thermal conductivity in large-scale sea ice models. *Journal of Advances in Modelling Earth Systems,* 5, 1–16.

O'connor, M. L., Lewis, T. & Dalton, G. Weather Window Analysis of Irish and Portuguese Wave Data with Relevance to Operations and Maintenance of Marine Renewables. 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2013), 9-14 June 2013 Nantes, France.

Oberhagemann J, L. J., & El Moctar O., 2012. Prediction of ship response statistics in severe sea conditions using RANSE. Proc. of ASME 2012 31th Int. Conf. on Ocean, Offshore and Arctic Engineering, 1-6 July 2012 Rio de Janeiro, Brazil.

Ochi, M. K. & Hubble, E. N. On six-parameters wave Spectra. Proceedings of 15th Coastal Engineering Conference, 1976. 301–328.

Oh, S.-H. & Jeong, W.-M. 2013. Characteristics of high waves observed at multiple stations along the east coast of Korea. *Nat. Hazards Earth Syst. Sci.,* 13, 3503–3514.

Olagnon, M. & Kerr, J. 2015. *Anatomie curiese des vagues scélérates.* Editions Quæ (in French).

Olagnon, M., Prevosto, M., Van Iseghem, S., Ewans, K. & Forristall, G. Z. 2004. WASP–West Africa Swell Project – Final report and Appendices.

Olagnon, M., Ewans, K., Forristall, G.Z. & Prevosto, M. West Africa swell spectral shapes. Proceedings of the OMAE 2013 Conference, 9–14 June 2013 Nantes, France.

Onorato, M., Osborne, A., Serio, M., Cavaleri, L., Brandini, C. & Stansberg, C. 2006a. Extreme waves, modulational instability and second order theory: wave flume experiments on irregular waves. *European Journal of Mechanics–B/Fluids,* 25, 586–601.

Onorato, M. & Proment, D. 2012. Approximate rogue wave solutions of the forced and damped nonlinear Schrödinger equation for water waves. *Physics Letters A,* 376 (2012), 3057–3059.

Onorato, M., Residori, S., Bortolozzo, U., Montina, A. & Arecchi, F. T. 2013. Rogue waves and their generating mechanisms in different physical contexts. *Physics Reports,* 528**,** 47–89.

Onorato, M. A., Osborne, A. & Serio, M. 2006b. Modulation instability in crossing sea states: A possible mechanism for the formation of freak waves. *Phys. Rev. Lett.,* 96.

Osborne, A. 2010. *Non-linear Ocean Waves and the Inverse Scattering Transform*, Academic Press.

Osborne, A. 2013. Classification of Rogue Wave Solutions of the Nonlinear Schroedinger Equation. *EGU General Assembly Geophysical Research 2013, NH5.2.* Vienna, Austria.

Overland, J. E. & Wang, M. 2013. When will the summer arctic be nearly sea ice free? *Geophys. Res. Lett.*

Pakozdi, C., Kendon, T. E. and Stansberg, C. T., 2012. A numerical study of a focused wave packet near the surf zone. Proceedings of the OMAE 2012 Conference, 1–6 July 2012, Rio de Janeiro, Brazil.

Panigrahi, J. K., Umesh, P. A., Padhy, C. P. & Swain, J. Nearshore propagation of cyclonic waves. *Nat Hazards,* 60, 605–622.

Papanikolaou, A., Zaraphonitis, G., Bitner-Gregersen, E., Shigunov, V., El Moctar, O., Guedes Soares, C., Reddy, D. N. & Sprenger, F. Energy Efficient Safe Ship Operation (SHOPERA). Proceedings RINA Conference, 24–25 Sept. 2014 London, UK.

Peng, B., Ma, N. & Gu, X. C. Study on Influence of Wave-current Interaction on Prediction of Rouge Wave Taking Viscous Effect into Account. 32nd International Conference on Ocean, Offshore and Arctic Engineering, 9–14 June 2013 Nantes, France.

Pereira, H.P.P., Ribeiro, C.E.P, Carvalho, F.N., Moraes, L.F. & Campos, R.M. 2014. Improvement of Directional Wave Information and Quality Control Before Real-Time Telemetry of Heave-Pitch-Roll Metocean Buoys. Proceedings Oceans–St. John's, 2014, 14–19 Sept. 2014, IEEE, St. Johns'. NL, DOI: 10.1109/OCEANS.2014.7003276

Petrova, P. G. & Guedes Soares, C. 2014. Natural Hazards and Earth System Sciences. *Natural Hazards and Earth System Sciences,* 14, 1207–1222.

Pinton, P. 2012. Very short-term probabilistic forecasting of wind power with generalized logit-Normal distributions. *Journal of the Royal Statistical Society,* 61(4), 555–576.

Plagge, A. M., Vandemark, D. & Chapron, B. 2012. Examining the Impact of Surface Currents on Satellite Scatterometer and Altimeter Ocean Winds. *Journal of Atmospheric And Oceanic Technology,* 29, 1776–1793.

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

Ponce De Leon, S., Gomez, J., Sanchez-Arcilla, A. & Guedes Soares, C. Comparison of extreme storms in the North Atlantic and Mediterranean. 3rd IAHR Europe Congress, 14–16 April 2014 Porto, Portugal.

Ponce De Leon, S. & Guedes Soares, C. 2014. Extreme wave parameters under North Atlantic extratropical hurricanes. *Ocean Modelling,* 81, 78–88.

Portilla, J., Sosa, J. & Cavaleri, L. 2013. Wave energy resources: Wave climate and exploitation. *Renewable Energy,* 57, 594–605.

Prevosto, M., Ewans, K., Forristall, G. Z. & Olagnon, M. . Swell genesis, modelling and measurements in West Africa. Proc. 32nd Int. Conf. on Offshore Mech. and Arctic Eng., 9–14 June 2013 Nantes, France.

Ribeiro, E.O., Ruchiga, T.S. & Lima, J.A.M. 2013. A Brazilian Northeast Coast Wave Data Comparison: Radar vs Buoy. Proceedings OMAE 2013, Nantes, France.

Quan Luna, B., Garrè, L. & Friis Hansen, P. 2014. Risk based adaptation of infrastructures to floods and storm surges induced by climate change. *Proc. EGU 2014, abstracts and presentations.* Vienna, Austria.

Queffeulou, P. Merged Altimeter Wave Height Database. An Update. Proc. 'ESA Living Planet Symposium 2013, 9–13 September (ESA SP-722, December 2013) 2013 Edinburgh, UK.

Quiniou-Ramus, V., Estival, R., Venzac, P. & Cohuet, J.-B. Resl-time of weather and ocean stations: public-private partnership on in-situ measurements in the Gulf of Guinea. Proceedings of the OMAE 2013 Conference, 9–14 June 2013 Nantes, France.

Rascle, N. & Ardhuin, F. 2013. A global wave parameter database for geophysical applications. Part 2: Model validation with improved source term parameterization. *Ocean Modelling* 70, 174–188.

Restrepo, J. M., Ramíírez, J. M., Mcwilliams, J. C. & Banner, M. 2011. Multiscale Momentum Flux and Diffusion due to Whitecapping in Wave--Current Interactions. *Journal of Physical Oceanography,* 41(5), 837–856.

Riahi, K. & Al., E. 2011. RCP 8.5–A scenario of comparatively high greenhouse gas emissions. *Climatic Change* 109, 33–57.

Ribeiro, E.O., Ruchiga, T.S. & Lima, J.A.M. 2013. A Brazilian Northeast Coast Wave Data Comparison: Radar vs Buoy. Proceedings OMAE 2013, 9–14 June 2013, Nantes, France.

Robinson, T. O., Eames, I. & Simons, R. 2013. Dense gravity currents moving beneath progressive free-surface water waves. *Journal of Fluid Mechanics,* 725, 588–610.

Roland, A. & F., A. 2014. On the developments of spectral wave models: numeric and parameterization for the coastal ocean. *Ocean Dynamics,* 64 833–846

Romero, L., Melville, W. K. & Kleiss, J. M. 2012. Spectral energy dissipation due to surface wave breaking. *J. Phys. Oceanogr.,* 42, 1421–1444.

Rusu, L., Bernardino, M. & Guedes Soares, C. 2011. Modelling the influence of currents on wave propagation at the entrance of the Tagus estuary. *Ocean Engineering,* 38(10), 1174–1183.

Rusu, L. & Guedes Soares, C. 2011. Modelling the wave–current interactions in an offshore basin using the SWAN model. *Ocean Engineering,* 38(1), 63–76.

Rybkin, A., Pelinovsky, E. N. & Didenkulova, I. 2014. Nonlinear wave run-up in bays of arbitrary cross-section: generalization of the Carrier-Greenspan approach. *J. Fluid Mechanics* 748, 416–432.

Rychlik, I. & Mao, W. 2014. Probabilistic model for wind speed variability encountered by a vessel. *Natural Resources,* In press.

Rychlik, I. & Mustedanagic, A. 2013. A spatial-temporal model for wind speeds variability Department of Mathematical Sciences Division of Mathematical Statistics, Chalmers, University of Technology, University of Gothenbourg.

Salvacao, N., Bernardino, M. & Guedes Soares, C. Validation of a regional atmospheric model for assessing the offshore wind resources along the Portuguese coast. Proceedings of the32nd International Conference on Ocean, Offshore and Arctic Engineering OMAE 2013, 9–14 June 2013 Nantes: France.

Santala, M. J., Calvery, M., Taws, S., Grant, H., Watson, A. & Jeans, G. Squall Wind Elevation/Gust Factors and Squall Wind Coherence. Proceedings Offshore Technology Conferencex, 5–8 May 2014 Houston, Texas, USA.

Santoro, A., Guedes Soares, C. & Arena, F. Analysis of experimental results on the space evolution of wave group in crossing sea, . Proceedings of the OMAE 2013 Conference, June 9–14 2013 Nantes, France.

Sasa, K., Chen, C., Shiotani, S., Ohsawa, T. & Terada, D. Numerical Anaølysis of Failed Forecasts of Waves under Low Pressures from Viepoint of Ship Operation. 33nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2014), 8–13 June 2014 San Francisco, USA.

Sasa, K., Terada, D., Shiotani, S., Wakabayashi, N. & Ohsawa, T. Current Situation and Difficulty of Wave Forecast from Viwepoint of Ship Management. 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2013), 9–14 June 2013 Nantes, France.

Schwendeman, M., Thomson, J. & Gemmrich, J. R. 2014. Wave breaking dissipation in a young wind sea. *J. Phys. Oceanogr.,* 44, 104–127.

Semendo, A., Weisse, R., Behrens, A., Sterl, A., Bengstsson, L. & Gunther, H. 2013. Projection of Global Wave Climate Change toward the End of the Twenty-First Century. *Jounal of Climate,* 36.

Sergeeva, A. & Slunyaev, A. 2013. Rogue waves, rogue events and extreme wave kinematics in spatio-temporal fields of simulated sea states. *Nat. Hazards Earth Syst. Sci.,* 13, 1759–1771.

Shrira, V. I. & Slunyaev, A. V. 2014a. Nonlinear dynamics of trapped waves on jet currents and rogue waves. *Phys. Rev.,* E 89, 1–5.

Shrira, V. I. & Slunyaev, A. V. 2014b. Trapped waves on jet currents: asymptotic modal approach. *J. Fluid Mech.,* 738, 65–104.

Siadatmousavi, S. M., Jose, F. & Stone, G. W. 2012. On the importance of high frequency tail in third generation wave models. *Coastal Engineering* 60, 248–260.

Sillmann, J., V., Kharin, V., Zhang, X., Zwiers, F. W. & Bronaugh, D. 2013. Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. *J. Geophys. Res. Atmos.,* 118, 1716–1733.

Slunyaev, A., Clauss, G. F., Klein, M. & Onorato, M. 2013b. Simulations and experiments of short intense envelope solitons of surface water waves. *Phys. Fluids.,* arXiv:1302.4531.

Slunyaev, A., Pelinovsky, E. & Guedes Soares, C. 2014. Reconstruction of extreme events through numerical simulations. *Journal of Offshore Mechanics and Arctic Engineering,* 136.

Slunyaev, A., Pelinovsky, E., Sergeeva, A., Chabchoub, A., Hoffmann, N., Onorato, M. & Akhmediev, N. 2013d. Super rogue waves in simulations based on weakly nonlinear and fully nonlinear hydrodynamic equations. *Phys. Rev.,* E 88.

Slunyaev, A. V., Sergeeva, A. V. & Pelinovsky, E. N. 2012. Modelling of deep-water rogue waves: different frameworks. *In:* Carlos Guedes Soares, Y. G., N. Fonseca, A.P. Texeira (ed.) *CENTEC Anniversary Book. Marine Technology and Engineering.* london, UK: Taylor & Francis Group, 199–216.

Slunyaev, A. V. & Shrira, V. I. 2013. On the highest non-breaking wave in a group: fully nonlinear water wave breathers vs weakly nonlinear theory. *J. Fluid Mech.,* 735, 203–248

Smith, J. A. 2006. Wave–Current Interactions in Finite Depth. *Journal of Physical Oceanography,* 36(7), 1403–1419.

Smith, L. C. & Stephenson, S. R. New Trans-Arctic Shipping Routes Navigable by Midcentury. PNAS, March 4 2013. E1191-E1195.

Smith, T. A., Chen, S., Campbell, T., Martin, P., Erick Rogers, W., Gaberšek, S., Wang, D., Carroll, S. & Allard, R. 2013. Ocean-wave coupled modeling in COAMPS-TC: A study of Hurricane Ivan (2004). *Ocean Modelling* 69, 181–194.

Stansberg, C. T. 2012. Random wave groups and nonlinear extreme platform responses in model testing. *SOBENA Journal of Marine Systems and Ocean Technology*, 7(2).

Stansberg, C. T., Berget, K., Graczyk, M., Muthanna, C. & Pakozdi, C., 2012. Breaking wave kinematics and resulting slamming pressures on a vertical column. Proceedings of the OMAE 2012 Conference, 1–6 July 2012, Rio de Janeiro, Brazil.

Stefanakos, C. N., Schinas, O. & Eidnes, G. Application of fuzzy time series techniques in wind and wave data forecasting. Proceedings of 33nd International Conference on Ocean, Offshore and Arctic Engineering OMAE 2014, 8–13 June 2014 San Francisco, USA.

Stephenson, D. B., Collins, M., Rougier, J. C. & Chandler, R. E. 2012. Statistical problems in the probabilistic prediction of climate change. *Environmetrics* 23, 364–372.

Stephenson, S. R., Smith, L. C., Brigham, L. W. & Agnew, J. A. 2013. Projected 21st-century changes to Arctic marine access. *Climatic Change*.

Stephenson, S. R., Smith, L. C. & J.A., A. 2011. Divergent long-term trajectories of human access to the Arctic. *Nat Clim Change,* :156–160, :156–160.

Stroeve, J. C., Serreze, M.C., Holland, M. M., Kay, J. E., Meier, W. & Barrett, A. P. 2012. The Arctic's rapidly shrinking sea ice cover: A research synthesis. *Clim. Change,* 110, 1005–1027.

Sumata, H., Lavergne, T., Girard-Ardhuin, F., Kimura, N., Schdi, M. A., Kauker, F., Karcher, M. & Gerdes, R. 2014. An intercomparison of Arctic ice drift products to deduce uncertainty estimates. *J. Geophys. Res. Oceans,* 119, 4887–4921.

Swan, C. & Latheef, M. 2014. Nonlinear wave amplification and the effect of wavebreaking., ShorTCresT Joint Industry Report (Work Package 1.2). London, UK.

Tao, S. S., Dong, S., Wang, N. N. & Guedes Soares, C. 2013a. Estimation storm surge intensity with Poisson bivairate maximum entropy distribution based on copulas. *Natural Hazards,* 68.
Tao, S. S., Dong, S. & Xu, Y. H. Design parameter estimation of wave height and wind speed with bivariate copulas. The Proceedings of 32nd International Conference on Offshore Mechanics and Polar Engineering, 9–14 June 2013b Nanes, France.
Teles, M. J., Pires-Silva, A. A. & Benoit, M. 2013. Numerical modelling of wave current interactions at a local scale. *Ocean Modelling,* 68(0), 72–87.
Thomson, A. M. & Al., E. 2011. RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change* 109, 77–94.
Thomson, J., Polagye, B., Durgesh, V. & Richmond, M. C. 2012. Measurements of Turbulence at Two Tidal Energy Sites in Puget Sound, WA, IEEE. *Journal Of Oceanic Engineering,* 37 (3).
Toffoli, A., Bitner-Gregersen, E. M., Osborne, A. R., Serio, M., Monbaliu, J. & Onorato, M. 2011a. Extreme Waves in Random Crossing Seas: Laboratory experiments and numerical simulations. *Geophys. Res. Lett,* 38, L06605.
Toffoli, A., Bitner-Gregersen, E. M., Osborne, A. R., Serio, M., Monbaliu, J. & Onorato, M. 2011b. Extreme Waves in Random Crossing Seas: Laboratory experiments and numerical simulations. *Geophys. Res. Lett.,* 38.
Toffoli, A., Bitner–Gregersen, E. M. & Onorato, M. Statistics of wave orbital velocity in deep water random directional wave fields. Proceedings of the OMAE 2012 Conference, 2–6 July 2012 Rio de Janeiro, Brazil.
Toffoli, A., Fernandez, L., Monbaliu, J., Benoit, M., Gagnaire-Renou, E., Lefevre, J.M., Cavaleri, L., Proment, D., Pakozdi, C., Stansberg, C.T., Waseda, T. & Onorato, M., 2013a. Experimental evidence of the modulation of a plane wave to oblique perturbations and generation of rogue wavse in finite water depth. *Physics of Fluids*, 25, 091701.
Toffoli, A., Waseda, T., Houtani, H., Kinoshita, T., Collins, K., Proment, D. & Onorato, M. 2013b. Excitation of rogue waves in a variable medium: An experimental study on the interaction of water waves and currents. *Physical Review E,* 87(5).
Tolman, H. L. 2013. A Generalized Multiple Discrete Interaction Approximation for resonant four-wave interactions in wind wave models. *Ocean Modelling* 70, 11–24.
Tolman, H. L. & Group, T. W. I. D. 2014. User manual and system documentation of WAVEWATCH III® version 4.18.
Tolman, H. L. & Grumbine, R. W. 2013. Holistic genetic optimization of a Generalized Multiple Discrete Interaction Approximation for wind waves. *Ocean Modelling* 70, 25–37.
Torsethaugen, K. A two-peak wave spectral model. Proceedings of the 12th International Conference on Offshore Mechanics and Arctic Engineering (OMAE 1993), 20–24 June 1993 Glasgow, UK.
Torsethaugen, K. 1996. Model for Double Peaked Wave Spectrum. SINTEF Civil and Environmental Engineering. Trondheim, Norway.
Touboul, J. & Pelinovsky, E. 2014. Bottom pressure distribution under a solitonic wave reflecting on a vertical wall. *European Journal of Mechanics B/Fluids* 48, 13–18.
Towe, R., Eastoe, E., Tawn, J., Wu, Y. & Jonathan, P. The extremal dependence of storm severity, wind speed and surface level pressure in the Northern North Sea. Proceedings of the 32nd International Conference on Ocean, Offshore and Arctic Engineering OMAE 2013, 9–14 June 2013 Nanes, France.
Trombe, P.-J., Pinson, P., Bovith, T., Cutululis, N. A., Draxl, C., Giebel, G., Hahmann, A., Jensen, N. E., J., B.P., Le, N. F., Madsen, H., Pedersen, L. B., Sommer, A. & Vincent, C. L. 2013. Weather radars–The new eyes for offshore wind farms. *Wind Energy,* 17(11), 1767–1787.
Tsai, C.-C., Hou, T.-H., Popinet, S. & Chao, Y. Y. 2013. Prediction of waves generated by tropical cyclones with a quadtree-adaptive model. *Coastal Engineering* 77, 108–119.
Tsumune, D., Tsubono, T., Aoyama, M. & Hirose, K. 2012. Distribution of oceanic (137) Cs from the Fukushima Dai-ichi Nuclear Power Plant simulated numerically by a regional ocean model. *Journal of Environmental Radioactivity,* 111, 100–108.
Umeyama, M. 2009. Changes in Turbulent Flow Structure under Combined Wave-Current Motions. *Journal of Waterway, Port, Coastal and Ocean Engineering,* 135(5), 213–227.
Umeyama, M. 2011. Coupled PIV and PTV Measurements of Particle Velocities and Trajectories for Surface Waves Following a Steady Current. *Journal of Waterway, Port, Coastal and Ocean Engineering,* 137(2), 85–94.
Van Vuuren, D. & Al., E. 2011b. RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change,* 109, 95–116.
Van Vuuren, D. P. & Al., E. 2011a. The representative concentration pathways: an overview. *Climatic Change,* 109, 5–31.
Vanem, E. & Bitner-Gregersen, E. M. Alternative environmental contours for marine structural design–a comparison study. Proceedings of the OMAE 2014 Conference, 8–15 June 2014 San Francisco, USA.
Vanem, E., Bitner-Gregersen, E. M., Eide, L. I., Garrè, L. & Friis Hansen, P. Uncertainties of Climate Modeling and Effects on Wave Induced Bending Moment. Proceedings of the SNAME Conference, 23–25 October 2014 Houston, USA.
Vicinanza, D., Contestabile, P. & Ferrante, V. 2013. Wave energy potential in the north-west of Sardinia (Italy). *Renewable Energy,* 50.
Walker, R. T., Vannieuwkoop-Mccall, J., Johanning, L. & Parkinson, R. J. 2013. Calculating weatherwindows: Applicationtotransit,installation and the implications on deployment success. *Ocean Engineering,* 68**,** 88–101.

Wang, M. & Overand, J. E. 2012. A sea ice free summer Arctic within 30 years: An update from CMIP5 models. *Geophysical Research Letters* 39.

Wang, Y. & Jiang, X. 2012. Improvement and application of a saturation based wave dissipation function in SWAN model. *Acta Oceanol. Sin.,* 31(1), 24–32.

Wang, Y., Tao, A. F., Zheng, J. H., Doong, D. J., Fan, J. & Peng, J. 2014. Preliminary investigation on the coastal rogue waves of Jiangsu. *Nat. Hazards Earth Syst. Sci.*.

Waseda, T., Hallerstig, M., Ozaki, K. & Tomita, H. 2011. Enhanced freak wave occurrence with narrow directional spectrum in the North Sea. *Geophysical Research Letters,* 38.

Waseda, T., Sinchi, M., Kiyomatsu, K., Nishida, K., Takahashi, S., Asaumi, S., Kawai, Y., Tamura, H. & Miyazawa, Y. 2014. Deep water observations of extreme waves with moored and free GPS buoys. *Ocean Dynamics,* 64, 1269–1280.

Waseda, T. K., In, K., Kiyomatsu1, K., Tamura, H., Miyazawa, Y. & Iyama1, K. 2013. Predicting freakish sea state with an operational third generation wave model. *Nat. Hazards Earth Syst. Sci. Discuss.,* 1**,** 6257–6289.

West, B. J., Brueckner, K. A., Jand, R. S., Milder, D. M. & Milton, R. L. 1987. A new method for surface hydrodynamics. *J. Geophys. Res.,* 92, 11803–11824.

Wijesekera, H. W., Wang, D. W., Teague, W. J., Jarosz, E., Rogers, W. E., Fribance, D. B. & Moum, J. N. 2013. Surface Wave Effects on High-Frequency Currents over a Shelf Edge Bank. *Journal of Physical Oceanography,* 43(8), 1627–1647.

Willis, J. & Bonnefond, P. 2013. Report of the Ocean Surface Topography Science Team Meeting. *In:* Boulder, C. (ed.). USA.

Wing, D. A. & Johnson, M. C. Ship operability predicted from long term directional wave records. *In:* Architects, R. I. O. N., ed. The William Froude Conference–Advances in Theoretical and Applied Hydrodynamics, Past and Future, November 2010 Portsmouth, UK. 24–25.

Winkelmann, R., Levermann, A., Martin, M. A. & Frieler, K. 2012. Increased future ice discharge from Antarctica owing to higher snowfall. *Nature,* 492, 239–242.

Winterstein, S. R., Ude, T. C., Cornell, C. A., Bjerager, P. & Haver, S. Environmental parameters for extreme response: Inverse FORM with omission factors. Proceedings of ICOSSAR'93, 1993 Innsbruck, Austria.

Wmo 2001. Guide to Marine Meteorological Services. Geneva, Switzerland: World Meteorological Organization.

Wmo 2003. Manual on the Global Observing System. Geneva, Switzerland: World Meteorological Organization.

Xiao, W. Y., Liu, Y., Wu, G. & Yue, D. K. P. 2013. Rogue wave occurrence and dynamics by direct simulations of nonlinear wave-field evolution. *J. Fluid Mech.,* 720, 357–392.

Yan, K., Zou, Z. & Zhou, Y. Competition of class I and II instabilities in evolution of crescent waves. Proceedings of the OMAE 2013 Conference, 9–14 June 2013 Nantes, France.

Yates, D., Quan Luna, B., Rasmussen, R., Bratcher, D., Garre, L., Chen, F., Tewari, M. & Friis-Hansen, P. 2014. Stormy Weather: Assessing Climate Change Hazards to Electric Power Infrastructure: A Sandy Case Study. *Power and Energy Magazine, IEEE.*

Young, I. R., Babanin, A. V. & Zieger, S. 2013. The decay rate of ocean swell observed by altimeter. *Journal of Physical Oceanography,* 43, 2322–2333.

Young, I. R., Rosenthal, W. & Ziemer, F. 1985. A three-dimensional analysis of marine radar images for the determination of ocean wave directionality and surface currents. *Journal of Geophysical Research,* 90(C1), 1049–1059.

Zappa G., Shaffrey, L. C., Hodges, K. I., Sansom, P. G. and Stephenson, D. B. "A Multimodel Assessment of Future Projections of North Atlantic and European Extratropical Cyclones in the CMIP5 Climate Models." *J. Climate*, 26 (2013):5846–5862. doi: http://dx.doi.org/10.1175/JCLI-D-12-00573.1

Zhang, H., Cherneva, Z., Guedes Soares, C. & Onorato, M. Comparison of Distributions of Wave heights from Nonlinear Schrödninger Equations Simulations and Laboratory Experiments. Proceedings OMAE 2013 Conference, 9–14 June 2013a Nantes, France.

Zhang, H., Guedes Soares, C. & Onorato, M. 2014a. Modelling of the Spatial Evolution of Extreme Laboratory Wave Heights with the Nonlinear Schrödinger and Dysthe Equations. *Ocean Engineering,* 89, 1–9.

Zhang, J. S., Zhang, Y., Jeng, D. S., Liu, P. L. F. & Zhang, C. 2014b. Numerical simulation of wave–current interaction using a RANS solver. *Ocean Engineering,* 75(0), 157–164.

Zhang, L. & Xu, D. 2005. A new maximum entropy probability function for the surface elevation of nonlinear sea waves. *China Ocean Eng.,* 19(4), 637–646.

Zijlema, M., Van Vledder, G. P. & Holthuijsen, L. H. 2012. Bottom friction and wind drag for wave models. *Coastal Engineering* 65, 19–26.

Zou, Z. L., Hu, P. C., Fang, K. Z. & Liu, Z. B. 2013. Boussinesq-type equations for wave–current interaction. *Wave Motion,* 50(4), 655–675.