18th International Ship and Offshore Structures Congress (ISSC 2012) - W. Fricke, R. Bronsart (Eds.)

18th INTERNATIONAL SHIP AND
OFFSHORE STRUCTURES CONGRESS

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VOLUME 1

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

Chairman: Elzbieta M. Bitner-Gregersen
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KEYWORDS

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

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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 of the Committee membership.

The mandate of the 2009 ISSC I.1 Committee has been adopted and extended. 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 operations and prediction of operability. Also in accordance with the ISSC mandate, this Committee has reported on the resources available for design and the operational environment. Additionally, in what represents an extension of the 2009 ISSC I.1 mandate, the Committee has initiated cooperation with the corresponding ITTC Committees.

The Committee consisted of members from academia, an oil company, research laboratories and classification societies. The Committee met three times: in Paris (24–26 February 2010), Madras (10–11 January 2010) and in St. Johns' (17–19 October 2011). Committee members also met on an ad hoc basis at different scientific conferences and industrial workshops. The Paris meeting was combined with a Fatigue Workshop organized by Ifremer and the oil company Total to which all Committee members were invited. A further meeting was arranged with the ISSC 2012 I.2 (Loads) Committee together with the ITTC Seakeeping and Ocean Engineering Committees in Portsmouth, 26 November 2010, which was attended by the Chairman and one Committee member. The Committees' reports were exchanged and it was agreed to hold a joint workshop on "Uncertainty Modelling for Ships and Offshore Structures" taken place 8 September 2012. The content of the ITTC reports was discussed at the ISSC 2012 Committee I.1 meetings.

The organisation of this report is an evolution of the outline used by the preceding Committee in their report to the 17th ISSC. Section 2 focuses on sources of environmental data for wind, waves, current, sea water level and ice. Section 3 addresses modelling of environmental phenomena, while Section 4 discusses some selected special topics. The design and operating environment is presented in Section 5. The most significant findings of the report are summarised in Section 6.

Furthermore three areas were considered as particularly important fields at the present time and were selected for special attention: climate change and variability, Computational Fluid Dynamics (CFD) applied to met-ocean modelling and statistical approaches.

Rogue waves have been a topic of increasing interest over the past two decades, and two international projects dedicated to these waves have been initiated by the industry CresT/ShortCresT and EXTREME SEAS during the period of the 2012 ISSC I.1 Committee. Following the previous Committee 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 28th–30th International Offshore Mechanics and Arctic Engineering (OMAE) conferences held

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in Honolulu (2009), Shanghai (2010) and in Rotterdam (2011), the 19th - 21st International Offshore and Polar Engineering (ISOPE) conferences held in Osaka (2009), Beijing (2010) and Maui, Hawaii (2011). Also of great interest to the Committee were the 11th and 12th International Workshop on Wave Hindcasting and Forecasting held in Halifax, Canada (2009) and Hawaii (2011) respectively, the MARSTRUCT (International Conference on Marine Structures) conference which took place in Lisbon (2009) and in Hamburg (2011), the EUG (European Geosciences Union) conference in Vienna (2011), WISE (Waves in Shallow Water Environment) in Mexico (2009), Brest (2010) and Qingdao (2011), POAC (Port and Ocean Engineering under Arctic Conditions) in Luleå (2009) and in Montréal (2011), IWMO (International Workshop on Modelling the Ocean) in Qingdao (2011), and MARTECH (International Conference on Marine Technology and Engineering) conference in Lisbon (2011). Papers from those sources have been reviewed and those of particular relevance are cited here.

Success of the global and basin-scale ocean models development with data assimilation under the GODAE (Global Ocean Data Assimilation Experiment) program opened a new era of operational oceanography. GODAE ended in 2008 and continues as GODAE Ocean View: https://www.godae-oceanview.org/

A number of Joint Industry Projects (JIPs) are also contributing to the world's knowledge base on the met-ocean 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: CresT and EXTREME SEAS (both on extreme and rogue waves), HAWAII and LoWish (both on shallow water), SAFE OFFLOAD (LNG terminals) and NavTronic (ship routing). A number of hindcast projects have also been in operation, notably CASMOS (Caspian Sea), NAMOS (NW Australia), SNEXT (North Sea), SEAFINE (SE Asia), BOMOS (Brazil, Atlantic waters) and a Chinese national project in the South China Sea. The present status of the GlobWave project initiated by ESA in 2008, making satellite derived data more widely available, is also reviewed here.

Climate change has also been a topic of continuing worldwide interest. The previous Committee reviewed this subject as a special topic and the current Committee has also done so, in Section 4. The present report makes an attempt to provide ISSC with the most up-to-date information from leading scientists on the main climate change issues of relevance to those working on the seas: storm intensity and frequency, sea-level rise, sea ice extent, and the debate on the contribution of natural variability to climate change. Particular attention is given to the Arctic environment and to tropical and extra-tropical hurricanes. The studies carried out by the Intergovernmental Panel on Climate Change have got particular focus, IPCC (2011).

Enhancing safety at sea through specification of uncertainties related to environmental description is also dealt with in the report. Uncertainty is being increasingly recognized by the shipping, offshore and emerging renewable energy industries.

Given such 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. The Chairman endorses the work of the Committee members and has the pleasure to recommend this report for the consideration of Congress.

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2 SOURCES OF ENVIRONMENTAL DATA

This section addresses the sources of data for environmental descriptions. The nature and uses of the data are left to other sections.

Sea waves, wind, current, sea water level and ice conditions vary geographically and in time. Their variability can be approximated by physical and probabilistic models. If long records of measurements are available then the statistical procedures can be used to describe variability of met-ocean conditions. The issue of data ownership remains a general problem; 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.

Whilst the advantages of having data freely available to academia and industry are clear, the commercial sensitivity of some data sets is recognized. However, it is possible for organizations to make data available without compromising their confidentiality. An example of this is the SIMORC URL data base: http://www.simorc.org/, administered by the University of Southampton, as noted in the last report.

2.1 Wind

New needs for a detailed description of wind profiles and turbulence at regional and local scales, mostly required by the developing wind off-shore industry, appear to play a major role in the development of new sensors as well as the implementation of downscaled numerical models. The offshore wind industry especially not only needs data on suitable locations for the installation, but also on the changes in the wind profile. The wind profile in the large range from sea level to heights of more than two hundred metres will be important but as of now this type of data are not available.

2.1.1 Locally Sensed Wind Measurements

Meteorological data of good quality are important for understanding both global and regional climates. Local measurements, traditionally at $10\,m$ height, 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 has allowed for much more detailed descriptions of wind in the offshore environment: large areas can be scanned yielding a more refined image of the environmental data.

Great efforts have been made to evaluate records of locally recorded environmental data. Jiménez *et al.* (2010) summarize the evaluations made to date of the quality of wind speed and direction records acquired at 41 automated weather stations in the northeast of the Iberian Peninsula. Observations were acquired from 1992 to 2005 at a temporal resolution of 10 and 30 minutes. A quality assurance system was imposed to screen the records for manipulation errors associated with storage and management of the data, consistency limits to ensure that observations are within their natural limits of variation, and temporal consistency to assess abnormally low/high variations in the individual time series. In addition, the most important biases of the dataset are analysed and corrected wherever possible. A total of 1.8 % wind speed and 3.7 % wind direction records were assumed invalid, pointing to specific problems in wind measurement. The study contributes to the science with the creation of a wind dataset of improved quality, and it also reports on potential errors that could be present in other wind datasets.

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Shimada *et al.* (2009) analyse long-term wind measurements made at the research platform of Shirahama Oceanographic Observatory, located $2\,km$ off the coastline in Tanabe Bay, Japan. Based on measurements of a propeller anemometer at $23\,m$ height, the authors describe annual- and monthly-mean wind speeds and directions, frequency distribution of wind speed, wind rose, energy density, atmospheric stability and turbulence intensity.

Similarly, Türk and Emeis (2010) evaluate data recorded at the offshore measuring platform FINO1 in the German Bight (Forschung in Nord- und Ostsee 1). They obtained the dependence of turbulence intensity on the wind speed from four years of 10-minute mean wind data. The investigated dataset is unique in so far as no high quality long-term measurements with a height resolution of $10\,m$ at heights between 33 and $103\,m$ and a minimum distance to the coast of $45\,km$ have been available so far. Wave height and therefore sea surface roughness and turbulence intensity increase with increasing wind speed. Türk and Emeis show how the influence of the surface roughness decreases with height and compare their findings with previous results.

A method for prediction of wind speed at a selected location based on the data collected at neighboring locations is described by Kusiak and Li (2010). The affinity of wind speeds measured at different locations compared with the location of interest is defined by Pearson's correlation coefficient. Five turbines with similar wind conditions are selected among 30 wind turbines for in-depth analysis and the wind data from these turbines are used to predict wind speed at a selected location. A neural network ensemble is used to predict the value of wind speed at the turbine of interest. The results demonstrate that a higher Pearson's correlation coefficient between the wind speeds measured at different turbines has produced better prediction accuracy for the same training and test scenario.

2.1.2 Remotely Sensed Wind Measurements

Past and present satellite programs dedicated to wind measurement using scatterometers, radiometers, altimeters and Synthetic Aperture Radars were described in the 2009 ISSC I.1 report where accuracy of satellite data was also reported. Since then new or updated surface wind data were made available. Most recent developments include improvement of high wind speed estimation and grid refinement of wind fields, using multiple mission observations.

The Remote Sensing Systems (RSS) QuikSCAT data have been completely reprocessed using a new Geophysical Model Function referred to as Ku-2011 (V4 QuikSCAT) (Ricciardulli and Wentz, 2011). The new processing has improved quality of high wind speeds (previously overestimated for winds greater than $20\,m/s$) and wind directions (especially at very low ($< 5\,m/s$) and high wind speeds ($> 15\,m/s$). A better agreement between radiometer and scatterometer winds in typically high wind speed regions is also pointed out.

A new model was proposed (Quilfen *et al.*, 2011) for estimation of near-surface wind speed in high wind conditions. The model was built using coincident observations made by instruments on board QuikSCAT and Jason during orbits crossovers and allows estimates of wind speed for values above $18\,m/s$.

Daily wind fields from Metop/ASCAT scatterometer retrievals are produced in near real-time over the global ocean with a spatial resolution of 0.25° from April 2007 to present, using the 'objective method' (Bentamy and Croize-Fillon, 2011). Data and documentation are available at CERSAT, the ERS data archive centre in Brest, France.

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In the framework of the MyOcean program, a data base of Global Blended Mean Wind Fields was also developed for the global ocean. Data include wind components (meridional and zonal), modulus of wind stress vector as well as associated error estimates. Evaluated from joint satellite observations (QuikSCAT and ASCAT scatterometers and SSM/I radiometers) and ECMWF operational wind analysis data, this data base offers a refined horizontal resolution of 0.25×0.25 degrees with a 6-hour time step for more than five years, starting from 1st April 2004 up to 22nd November 2009 (also available at CERSAT).

2.1.3 Numerical Modelling to Complement Measured Data

Numerically generated wind data are still commonly used in design and marine operations and for some ocean areas they are the only data available. They 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 (see DNV, 2010, 2011).

The recently updated or new developed met-ocean data bases like: ERA-Interim, NORA10, HIPOCAS, ARGOSS and Fugro-OCEANOR include information about both wind and waves and are discussed in detail in Section 2.2.3. Below only some additional information not given in Section 2.2.3 is provided.

Young *et al.* (2011) used a 17-year wind data base (1991-2008) of calibrated and validated satellite altimeter measurements and compare them with 12 deep-water buoys and numerical model predictions from NCEP (National Centre for Environmental Protection). The results are qualitatively consistent and are showing that the mean wind speed has stayed similar over the investigated period while the extreme wind speed has increased (see also Section 2.2.3 and 4.1.2).

Bertotti *et al.* (2011) have compared the model wind speeds (seven forecast systems were considered) versus the available measured values from scatterometer and found some inconsistencies in the results, model wind data were on average larger than the measured ones. Limited amount of data available and its different times and positions, at and off the centre of the storm, impede the drawing of any definite conclusion in this respect.

With increased interest in developing the offshore wind power plant, numerical studies have been conducted to estimate the wind speed profile and variability. Based on satellite derived surface wind (QuikSCAT), objectively analysed air-sea flux (OAFLUX) and reanalysis (NCEP-DOE AMIP-II), Capps and Zender (2009) extrapolated the surface wind speed to 80 m altitude incorporating stability effect. Such estimates are further combined with practical turbine characteristics and sitting to estimate the ocean wind power potential (Capps and Zender, 2010). The Wind Challenger Project is a joint industry project in Japan designing a bulk carrier propelled by hard wing sail. In this project, Nishida *et al.* (2011) has estimated the velocity profiles of the marine boundary layer based on downscaled NWP (numerical weather prediction) output. The study suggests shortage of in-situ observation.

A comprehensive review of offshore wind resource assessment was outlined by Sempreviva *et al.* (2008). The process involves site selection based on resource evaluation by models, and in-situ evaluation of wind climatology, vertical profile and turbulence. Recently, numerical models are becoming available tool for assessing wind profiles (e.g. Pushpadas *et al.*, 2010).

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2.2 Waves

Wave data from hindcast studies, discussed in Section 2.2.3, are the choice data sets for development of design criteria. However, measured wave data either locally (Section 2.2.1) or remotely (Section 2.2.2) remain important for development, calibration, and validation of numerical models, baselining, and specification of more detailed wave descriptions such as spectra and individual wave heights and crest elevations. This is particularly important in coastal areas where the prediction of waves is further complicated by shallow-water and coastal boundary effects.

2.2.1 Locally Sensed Wave Measurements

The status quo has essentially been maintained with respect to the collection of in-situ wave data, with most measurements undertaken as a part of on-going national coastal wave monitoring and by oil companies, particularly in more remote areas in support of exploration for new oil and gas fields. In the remote areas, wave buoys remain the instrument of choice, while wave radars are the choice instrument for permanent facilities with platforms for mounting the radars.

Measurements of significant wave height beyond $16\,m$ have been recorded both in deep as well as shallow water. The UK Met Office operating a network of marine Automatic Weather Stations (MAWS) around the UK has reported from the moored buoys (open-ocean deep water locations) west off Ireland and outside the Bay of Biscay (two buoys are operated jointly with Meteo-France) the maximum significant wave heights of $18.3\,m, 17.2\,m, 16.6\,m, 16.0\,m$ and $13.8\,m$ in the period from 7th to 10th December 2007; Turton and Fenna (2008). Babanin *et al.* (2011a) present the wave conditions in Typhoon Krosa prior to touching Taiwan in October 2007. The maximum wave height $H_{max} = 32\,m$ with significant wave height $H_s = 24\,m$ were measured at the water depth of $h = 38\,m$. The authors conclude that the measurement does not appear faulty and is physically realistic.

An extensive review of the performance of platform-mounted wave sensors was undertaken during the industry-sponsored CresT (Cooperative Research on Extreme Seas and their impacT) Joint Industry Project (JIP). The JIP had access to a very large dataset of water surface elevation measurements from various installations across the globe, provided by the participants in the JIP. The sensors were fixed-platform, absolute surface elevation measuring devices, including wave radars, a wave staff, optical lasers, and a step gauge, and some from floating systems. The vast majority of the data was from Saab wave radars, and the study concluded that this instrument also provided the most reliable data (Christous and Ewans, 2011).

Measurements made from floating systems require compensation for the vessel motions, and therefore involve a significant source of uncertainty, particularly in the case of ships, where the demand for accurate onboard wave measurements remains strong. In this respect, Simos *et al.* (2010) analysis of experimental data performed with a small-scale model of an FPSO platform under a wide range of sea state conditions is encouraging. Results showed that the sea conditions could be estimated with good precision.

Fu *et al.* (2011) gave an overview of ship borne systems and techniques, including a shipboard array of ultrasonic distance sensors for measuring directional wave spectra, a 'Commercial Off The Shelf' (COTS) wave radar system, and a COTS scanning LIDAR system. It was concluded that using ship-mounted LIDAR is a viable approach to measuring wave displacements from underway, high-speed vessels, but LIDAR performance is highly dependent on the wind and sea conditions. It was further concluded,

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in general, that the systems worked well for a fixed platform with a fixed incidence angle, but ship motion and a changing ambient environment present additional difficulties, and that Dynamic methods that perform real-time calibration of the systems may be required.

Fu *et al.* (2011) also trialed a WaMoS II X-band marine radar wave measurement system by OceanWaves GmbH, and concluded that such systems provide reasonable directional wave spectra when mounted at fixed sites, but exhaustive validation studies of the shipboard installations where the changing environment and ship motions need to be taken into account remains to be done. Story *et al.* (2011) discussed existing limitations with commercial incoherent navigation radar systems. Poor measurements resulted when there is little to no wind. Uncertainty with line-of-sight shipboard-based measurements effects due to low grazing angles effects, and limitations of wave radar in the cross-range direction, were also highlighted, associated with polarization effects. Additional limitations in sea states where nonlinear effects, such as wave breaking, and non-uniform surface wind drifts, were also mentioned, but these limitations are also common to other wave measuring devices.

Story *et al.* (2011) conclude that commercial systems require calibration of each installation in order to determine the correct values for these constants based on empirical data for height/incidence angle and hardware installation, and without them the wave height measurements perform poorly. Much of the validation data show that for a fixed platform in perfect conditions, wave radar can provide estimates of the frequency, direction, and wave height with an accuracy of around 10 %. Wave height values are significantly less reliable from shipboard platforms than those from fixed platforms. Advanced techniques addressing the impact ship motion has on these analysis techniques should be pursued further.

Wave measurement using stereo-photogrammetry type techniques continues to be the subject of much active research. Fedele *et al.* (2011a) present results from measurements with a Wave Acquisition Stereo System (WASS) deployed at the oceanographic tower Acqua Alta in the Northern Adriatic Sea, off the Venice coast in Italy. Their results produced accurate estimates of the sea state surface dynamics and associated directional spectra and produced wave surface statistics that agreed well with theoretical models. Bechle and Wu (2011) report the development of a virtual wave gauge (VWG) technique for processing stereo imaging data. Improved efficiency compared with traditional methods is demonstrated, and it is concluded that VWG has the potential to make real-time remote stereo imaging wave measurements a reality. de Vries *et al.* (2011) obtained good validation of stereo-photogrammetry measurements in both the laboratory with a pressure sensor and at a coastal location with buoy data.

Work continues on understanding the limitations of HF radar measurements and how these can be improved. In particular, Wyatt *et al.* (2011) identify aspects of measurements made at three coastal stations that require further improvement. These include modifications to the underlying theory particularly in high sea states, identification and removal of ships and interference from the radar signals before wave processing and some form of partitioning to remove these from the wave spectrum. The need to match the radio frequency to the expected wave peak frequency and wave height range, with lower radio frequencies performing better at higher wave heights and lower peak frequencies and vice versa, was also demonstrated.

The WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) continues to make progress in the Pilot Project on Wave measurement

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Evaluation and Test (www.jcomm.info/WET), which arose from the JCOMM/OGP workshop in New York, October 2008. In particular the collection and analysis of data from co-deployments of wave sensors continues. This has been undertaken at two Canadian sites and at locations in India, Korea and Australia. Efforts are underway in the USA in support of the Pilot Project, including the planned co-deployment of a directional waverider in Monterey Canyon, with the longer term goal of establishing a deep water evaluation test bed at that location, with a shallow water test bed at Duck, North Carolina.

2.2.2 Remotely Sensed Wave Measurements

The GlobWave project (www.globwave.org) is an interesting initiative funded by the European space Agency (ESA) to service the needs of satellite wave product users. A web portal provides a single point of reference for satellite wave data and associated calibration and validation information. A consistent set of satellite wave data from all available satellite altimeter data and from ESA synthetic aperture radar data is made available. The historical archive contains altimeter data from 8 satellites, ranging from Geosat (operating between 1985 and 1989) through to Envisat, Jason-1 and Jason-2. The historical data is continuous in time from 1991 to 2009, and near real-time data is made available from Envisat, Jason-1 and Jason-2 within a few hours of measurement time.

Some additional products are also made available, such as altimeter crossovers, computed for each pair of satellites, when crossing of their respective tracks is possible, providing a comprehensive dataset of coincident measurements that can be used to monitor the quality of each sensor and improve their calibration. Also made available are matching measurements between satellite and in-situ buoys, computed for various pairs of buoy networks and satellites providing a comprehensive dataset to assess, monitor and intercompare the accuracy of each of these sources of measurements.

For detailed description of satellite data accuracy reference is made to the ISSC 2009 I.1 Committee report.

2.2.3 Numerical Modelling to Complement Measured Data

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. Hence hindcast data (or corrected hindcast) are often used and they remain to be the main source of met-ocean data for establishing joint environmental description as well as for design and operational planning. 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. In Mackay (2011) a deconvolution algorithm has been presented which reduces bias if the error CDF (Cumulative Distribution Function) is known.

The advantage of hindcast data is that they can be generated for a specific location world-wide and for a required time period, and three dimensional (frequency-direction) wave spectra as well as information on a spatial grid can be provided. Numerical wave models used for forecasting or building hindcast data bases are under constant evolution. In recent years attention has been given to improving resolutions of wave spectral models, implementing new or modified wind input and wave dissipation functions and including energy dissipation through wave breaking.

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Recently various hindcast and satellite data bases have emerged and the work of comparing and of assessing differences and uncertainty level involved in their use is not yet properly explored, although significant progress has been achieved for some data bases. The previous I.1 Committee report noted a lack of validation of numerical wave models with instrumented data beyond 12 metres, but some studies have included such extreme data since that time. Cardone and Cox (2011) demonstrated that the current 3G (3rd generation) models are capable of accurately hindcasting significant wave heights above 14 metres in very extreme storms. Similar studies are carried out at different met-offices world-wide.

Young *et al.* (2011) used a 23-year data base of calibrated and validated satellite altimeter measurements on a global scale and compare them to the 12 deep-water buoys and NCEP (National Centre for Environmental Protection) numerical model predictions. The results are qualitatively consistent and are reported in more details in Section 4.1.3.

ERA-Interim is the latest global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA-Interim project was conducted to prepare for a new atmospheric reanalysis to replace ERA-40, which will eventually extend the data base back to the early part of the twentieth century. The main improvement is the quality of data assimilation. ERA-Interim currently covers the period from 1st January 1979 onwards, and continues to be extended forward in near-real time. Gridded data products include a large variety of 3-hourly surface parameters, describing weather as well as ocean-wave and land-surface conditions, and 6-hourly upper-air parameters covering the troposphere and stratosphere.

The Norwegian data base NORA10 for wind and waves in the North Sea and Norwegian Sea, and the North Atlantic, has been developed at the Norwegian Meteorological Institute, with major support from a consortium of oil companies known as The Norwegian Deep Water Programme, see e.g. Aarnes *et al.* (2011). The NORA10 data base was validated extensively against satellite and buoy observations and gives higher spatial resolution than ERA40 from ECMWF albeit over a smaller area.

Campos and Guedes Soares (2011) have compared the HIPOCAS data base (44 years, covering the North Atlantic and the European seas) with NOAA/NCEP data for the whole North Atlantic. HIPOCAS is a result of the wave model WAM-cycle4 forced by REMO ((REgional Model) surface wind fields. The wave data set of NOAA/NCEP is a forecast that has been continually performed by WAVEWATCH III since 1997, forced by GFS surface wind fields. Small divergences between the two data sets are identified in standard weather conditions in the North Atlantic. Differences dependent on longitude were observed in both wave and wind fields.

In order to increase accuracy of wind and waves data bases the offshore industry has updated hindcast data sets for several basins, within proprietary joint industry projects, since the last reporting period.

The wind and wave hindcast data for the southern North Sea were updated in the Southern North Sea Extremes (SNEXT) JIP in 2009. This data set includes a 20-year hindcast with model grids to a resolution of 3 km and 1 km for resolving shallow water effects, (http://www.oceanweather.com/metocean/next/index.html).

A wind and wave hindcast for the Northwest of Australia was provided in 2010. The NAMOS (The North Australia Metocean Study Tropical Cyclone Wind and Wave Extremes) JIP provided estimates of wind and wave extremes based on new hindcasts

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of historical tropical cyclones affecting exploration and production areas offshore north Australia. This data base was updated under Phase 2 of the JIP, including data from analysis of an expanded historical tropical cyclone population.

The SEAFINE (SEAMOS-South Fine Grid Hindcast) JIP have commissioned an update to the current hindcast for the South China Sea, following a one year evaluation run of an improved current modelling scenario. The update will include an 18-year continuous production run, with results available in 2010.

The ARGOSS and Fugro-OCEANOR global wind and wave data bases described in the previous report are under continuous improvement. The new features of the ARGOSS data base (the version "15 June 2011") are reported on the ARGOSS website: http://www.waveclimate.com/clams/redesign/html/newfeatures.html. They include, between others, extension of the data up to 2010, updated and improved model calibration, directional roses and a more sophisticated shallow water model. The Fugro-OCEANOR databasis (http://www.oceanor.com/) includes new products like: a complete data-base/software package for providing wave climate data and statistics including full directional spectra time series anywhere globally both in deep and shallow waters at any time in the last 50+ years and right up to date, a modern-day Worldwide Wave Statistics (WWWS) equivalent of the old long standing volume Global Wave Statistics (GWS) atlas (British Maritime Technology, 1986), and wind and waves energy mapping (Barstow *et al.,* 2009).

Wave modelling tools are essential to assess energy generation resources. A nationwide survey of Australia was conducted by Hughes and Heap (2010) using the 3G wave model. Likewise a survey was made along the Spanish coast by Iglesias and Carballo (2009) and the information was further refined with coastal high resolution wave model (Iglesias *et al.,* 2010).

It should be noticed that the significant wave height provided by numerical wave models is calculated from the zero-spectral moment and is a slightly biased estimator of the one obtained from a sea surface time series as it includes an assumption of linearity of sea surface.

Further, when using wave model data a resolution of the model from which data are generated as well as an approach adopted for data calibration will decide the exact type of significant wave height the data represent, e.g. a 20-minute, 1-hour or 3-hour significant wave height; the topic remains insufficiently discussed in the literature.

2.2.4 Wave Description from Measured Ship Motions

Onboard sea state estimation based on ship motions, particularly when combined with other measurements with 'fusion' techniques, is becoming increasingly practical, for example the Decision Support System (DSS). It was introduced in the 2009 Committee report and it has seen further development: Nielsen *et al.* (2011), Nielsen and Jensen (2011). Wave description from measured ship motion utilises the analogy between a ship and a wave rider buoy, although the ship is moving with a forward speed. Using this methodology it is possible to obtain an estimate of the wave spectrum at the location of an advancing ship by processing its wave-induced responses in a similar way as for the traditional wave rider buoy. For a review on this development see e.g. Nielsen and Stredulinsky (2012). In this paper the authors compare 'wave buoy analogy' derived data from a large set of full-scale ship motion measurements with simultaneoss waverider buoys' measurements and wave radar system measurements. They found fairly accurate estimates of integrated sea state parameters when compared

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to corresponding estimates from the buoys, although there was poorer agreement of energy spectra. The wave buoy analogy, for the data considered, was said to provide, on average, slightly better sea state estimates than the wave radar system.

2.3 Current

Developments within renewable energy have brought the need for new current measurements as well as numerical current data. Several studies showing how tidal energy can be utilized can be found in the OMAE 2011 and ISOPE 2011 Conference Proceedings for example.

2.3.1 Locally Sensed Current Measurements

Not much work has been done in this area since 2009. Acoustic measurement techniques (both coherent and incoherent) for in-situ sensing of ocean current offer an excellent space-time resolution of the velocity profile. Another type of in-situ measurement of ocean current profile is based on autonomous underwater gliders. Accuracy of these in-situ measurements is discussed in the previous Committee report.

A joint effort between the USA's Minerals Management Service's (MMS) and Mexico's Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE) to understand more on the dynamics of the Loop Current as it enters the Gulf through the Yucatan Channel was initiated in 2009. The particular objective is to measure currents in the Yucatan-Campeche area to provide data about the upstream conditions in the Loop Current and help improve forecasting of Loop Current eddy shedding and intrusions. CICESE has deployed eight moorings in Mexican waters east of the Yucatan Peninsula, where the Yucatan Current is found. The moorings will gather measurements and data in water depths up to $3{,}000\,m$ for two years.

The utilisation of the Kuroshio Current power is being studied in Japan and Taiwan (e.g. Falin, 2010). Observational study was conducted at the Miyake Island south of Japan for selecting potential sites for the power generation. Kodaira *et al.* (2011) 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.

2.3.2 Remotely Sensed Current Measurements

Retrieving of currents features from remote sensing is mostly based on observation of Sea Surface Height (SSH) and requires cross-analyses with other parameters or data sources. Remote sensing also provides interesting data bases for identification of current structures and eddies and validation of models.

Hansen *et al.* (2010) use the European Space Agency (ESA) Advanced Synthetic Aperture Radar (ASAR) Doppler grid information to analyse the main current regimes in Norwegian waters. They show that in spite of the low velocity of the circulation, the method allows identification of patterns of the ocean currents driven by the topography in that area to be identified. They also show that the large scale circulation pattern obtained with high resolution current mapping compares qualitatively well with patterns obtained by other means (drifters).

The quality of remotely sensed SSH measurement has been enhanced by some researchers by combining the remote data with data from instrumented measurements. Focusing on the northern California current system, Saraceno *et al.* (2008) show that it is possible to improve the quality of the SSH in the coastal area (within $\sim 40\,km$

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from shore), poorly estimated by remote sensing, hence the assessment of geostrophic alongshore currents, by mixing offshore gridded SSH fields with time series of SSH measured by coastal tide gauges. Le Hénaff *et al.* (2011) use reprocessed Topex/poseidon altimetric data combined with sea surface temperature data to assess the interannual variability of the Navidad current along the Spanish coast.

2.3.3 Numerical Modelling to Complement Measured Data

An overview of the GODAE (Global Data Assimilation Experiment) project and the various products were introduced in the previous Committee I.1 report. In this report, we will introduce examples of numerical downscaling and the application of the GODAE products for ocean renewable energy and tracer tracking.

Ocean basin scale wind-driven ocean circulation is known to be most intense at the western boundary of the basin. The Kuroshio Current and the Florida Current (at the boundary of the Pacific and Caribbean Sea respectively) are considered to possess potential for hydro-kinetic power of the order of 20–30 GW. A number of numerical simulations have been conducted to estimate the available power resources, the velocity structure and temporal variations, at specific sites. Duerr and Dhanak (2010) have analysed the Hybrid Co-ordinate Ocean Model (HYCOM) reanalysis but had to adjust the transport to match the observed value. Often, the Global Circulation Models fail to reproduce the structure of the current that is locally modified by topographic effects and by local winds. The Kuroshio Current power is estimated based on numerical models and are reported as a government document and Japanese conference papers (e.g. Nishida *et al.*, 2011). Various other numerical studies about the estimation of ocean currents and tidal currents were reported at the 9th European Wave and Tidal Energy Conference which took place at the University of Southampton, UK, 4–9 September 2011.

An example of downscaling is the JCOPE2 (Japan Coastal Ocean Predictability Experiment); the reanalysis product is based on a nested Princeton Ocean Model (POM), downscaling from the Pacific model (1/4 degree resolution) to the 1/12 degree model near Japan (Miyazawa *et al.*, 2009). Isobe *et al.* (2010) further downscaled from the JCOPE2 reanalysis using the Finite Volume Coastal Ocean Model (FVCOM) to model the swift current at the Bungo channel between the Honshu Island and the Shikoku Island. The model successfully reproduced the rapid current called the Kyucho that branches off from the Kuroshio Current. The sensitivity of such downscaling techniques to the initial and boundary conditions were evaluated by simulating the Florida Current using the Hybrid Coordinate Ocean Model (HYCOM) (Halliwell *et al.*, 2009). The current field locally driven by wind was not influenced by the choice of the outer model whereas the alongshore current related to the Loop Current was sensitive to its realization in the outer model. Inter-comparisons among global models at different resolutions and nested regional models were conducted simulating the circulation in the Philippine Archipelago (Hurlburt *et al.,* 2011).

Ocean model outputs have been utilised 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. The oil was observed by satellites and the image showed an interesting pattern of stretching and advection by the Loop Current. The chaotic nature of the oil movement is described by Mezić *et al.* (2010) based on the diagnosis of fluid flows with invariant attracting and repelling manifolds. The motion of the debris from the disaster sites in Japan after the March 2011 tsunami was

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studied using both statistical ocean model and the satellite derived ocean current fields (Maximenko and Hafner, 2011). A number of studies have been made using various numerical models tracing the radioactive materials from the Fukushima Nuclear Power Plant but are not published.

We can also mention the Maximenko Hafner (2011) work in other current section 2.3.1.

2.4 Sea Water Level

Sea water level measurements have received special attention due to the ongoing debate about climate change. Section 4.1.4 summarised the main findings associated with climate change projections. Attention has been given to extreme sea levels caused by severe storms such as tropical or extratropical cyclones. An obvious source of error of long-term sea level trends from in-situ measurements is the change of the terrestrial reference frame.

Archiving of historical data sets, their quality control, and statistical analyses are the essential ingredients of the analysis of long-term sea level variations. A status report of the Global Sea Level Observing System (GLOSS) and community recommendation for the future role of GLOSS were given as a community white paper at OceanObs'09 (Merrifield *et al.*, 2009). The GCN (GLOSS Core Network) stations are being developed to have real-time distribution capability in view of flood warnings from storm surges and tsunamis.

The Australian Baseline Sea Level Monitoring Project (ABSLMP) collected and analysed the monthly sea level data up to June 2011 in the 16 locations around Australia. The quality-controlled data are available in electronic form from the Bureau of Meteorology website.

According to Cavaleri *et al.* (2010) current meteorological and oceanographic numerical systems for generating sea water level are able to predict satisfactorily severe sea water level events due to surge.

2.5 Ice

In recent years, changes in the Arctic Ocean weather as well as changes in Antarctica have received widespread attention. Sea ice constitutes a critical element of the arctic marine environment stability and any changes to the global sea ice regime result in changes to ocean ecosystem. This further influences global weather patterns, which will affect Arctic and Antarctic ice packs as well as intensity, frequency and duration of storms.

From the engineering point of view sea ice characteristics such as concentration, extent and thickness as well as physical-mechanical properties, age of ice and type of ice (level ice, broken ice) are important. Sea ice appears in many forms affecting ship, offshore structures and more recently offshore wind energy turbines.

Sea ice can be characterized by its age (from new, young, first year to multi-year ice), concentration (% of water surface coverage) and form. Sea ice can be found as level ice or broken ice in form of ridges, hummock field and landfast ice. In the marine environment there is also the problem of icing caused by sprayed or shipped seawater due to wind, ambient and seawater temperature.

Sea ice properties are determined by a number of factors. A number of studies have addressed sea-ice conditions and its variability, e.g. Fissel *et al.* (2009). The interannual variability of ice conditions in the Canadian Beaufort Sea was found by the authors

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to be very large, which leads to statistical uncertainties in the statistical significance of the derived trend results.

Marine icing is getting increasing attention. An ongoing research project MARICE (Marine icing), sponsored by the Norwegian Research Council and the offshore industry, and coordinated by DNV, is dedicated to this topic. Some project results can be found in Kulyakhtin and Løset (2011).

2.5.1 Locally Sensed Ice Measurements

Sea trials, field and site measurements still provide the most reliable data on ice properties that could be used for climatological predictions and/or as engineering design parameters.

Ice thickness, ice coverage and extent, its growth and melting rates in specific geographic locations could be used for estimates and predictions of local or global weather/climate changes, to validate and calibrate numerical predictions models as well as design arctic structures and projection of availability of shipping routes.

Physical and mechanical properties of sea ice such as compressive strength, tensile/flexural strength, fracture toughness, friction, shear strength, elastic modulus and density, as well as, loads and local ice pressures could be used as engineering parameters in predictions of ice-structure interaction scenarios and establishing ice failure criteria, and in verification and validation of numerical tools. Those measurements can be carried out by various means from moving ships or submarines, by drill-hole techniques from stationary ice stations or by long-term measurements and observations from permanent structures.

The geometry of a ship hull and employed propulsion system constitutes its signature for operations in level ice that is expressed by the curve of level ice thickness vs. ship speed (h-v curve). The h-v characteristics could be used to determine level ice thickness from ship speed. In order to test the h-v relationship von Bock and Oilach (2010) performed full-scale trails aboard of MV Aranda. To determine and validate ice thickness obtained from the resultant ship velocity other ice properties possibly affecting ice resistance such as bending strength, crushing strength, ice temperature and salinity, were also measured at three stationary camps along the vessel trail path. The resultant ice thicknesses obtained from Aranda trials were very scattered and affected by the other measured ice properties. In the final conclusions the authors were skeptical if the employment of a vessel as a level ice thickness measuring sensor is feasible.

Indirect measurements of sea ice thickness from a moving vessel are presented by Suyuthi *et al.* (2010). The paper demonstares application of an electromagnetic device installed on both sides of a ship hull to measure ice thickness during operations in ice infested waters. The device is a part of the Ice Loads Monitoring (ILM) system that normally is used to collect information for prediction of extreme ice loads acting on the ship hull for short time duration. Similar technology was used by Lee and Jeong (2011). The electromagnetic induction instrument EM31-MK2 and updated the Cold Region Research and Engineering Laboratory (CRREL) empirical formula was used to obtain the ice thickness. The used updated formula was validated against drilled samples. The measured ice thickness was between 1.0 to 3.5 m.

Su *et al.* (2010) present an upward looking sonar (ULS) mounted on a submarine to observe ice thickness of ice less than 0.5 m. The technology is known and successfully

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employed to measure ice thickness since the 1990's, however; its application to measuring thin ice is relatively new. The system was validated and calibrated using digital camera images. Various types of flat jacks have been employed in destructive strength and non-destructive mechanical properties measurements for many years. They have been extensively used for in-situ fracture testing of sea ice in Arctic and Antarctica. Pennington and Dempsey (2011) investigated effects of initial pressure and opening distance on measured load when using a kevlar flat jack. The authors concluded that a single calibration factor cannot be assumed as it depends highly on the separation distance between loading surfaces and applied pressure. The calibration factor decreases as the distance increases, and appears asymptotic with increasing pressure.

Barrault and Strub-Klein (2009) investigated propagation of stress in ice in the Barents Sea by measuring the stress in six locations using stress sensors frozen in ridged ice. A borehole jack placed at known distances from sensors generated the stress. The observed stress propagation was inversely proportional to the distance from the source and decayed 4 metres from the source. Hutchings *et al.* (2010) conducted analysis of the relationship between internal ice strain-rate, stress and thickness redistribution of Arctic pack ice. The ice deformation observations were conducted using an ice drifting buoy instrumented with GPS. The trials were conducted in the Beaufort Sea. In-situ ice loads from fast and moving ice for design of wind-power generator foundations in ice-infested waters were investigated by Fransson and Bergdahl (2009). The authors noticed that the design effective pressure and compressive strength were independent of ice thickness, but design pressure was increasing with the ice drift speed.

Application and usefulness of conventional marine radars for ice detection has been recognised for some time. They are helpful in detection of multi-year ice and fragments of icebergs, but their range very often does not exceed one kilometre. Digitally enhanced radars can deliver higher resolution images allowing for better identification of ice characteristics allowing for avoidance of hazardous ice in the path of operating vessels. O'Connell (2011) presents a development of high-speed, cross-polarized, marine radar that will be able to make a distinction between various types of ice and enhance detection of smaller dangerous pieces in heavy see conditions. Gignac *et al.* (2011) applied high resolution radar data to assess ice conditions during freeze-up and break-up periods of 2009–2011 near the villages of Nunavik, Quaqtag and Umiujaq. The authors utilized RADARSAT-2 fine ($9\,m$) and ultra-fine ($3\,m$) images that were processed using the Multivariate Iterative Region Growing using Semantics technique. The resultant maps show ice formations classified as brash ice, multiyear ice, first year ice and open water. The results were validated against ground and air photos showing promising accuracy.

2.5.2 Remotely Sensed Ice Measurements

Sensors on board satellites (radiometers, scatterometers) allow a global and daily monitoring of various ice parameters such as: ice cover, ice concentration, ice thickness and ice drift.

Remotely sensed ice data is now regularly assimilated in ocean models such as TOPAZ (Nansen Environmental and Remote Sensing Center, Norway), FOAM (UK MetOffice), Mercator-Ocean (France), NCEP (USA), LIM (Belgium).

New data bases were recently made available. The United States NOAA's National Snow and Ice Data Center provides a data base of sea ice concentrations in daily time series from 9 July 1987 through to 31 December 2007. Sea Ice concentrations are obtained from gridded brightness temperatures from the Defense Meteorological

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Satellite Program (DMSP) series of Special Sensor Microwave Imager (SSM/I) passive microwave radiometers and are gridded on the NSIDC polar stereographic grid with $25 \times 25\,km$ grid cells. A data base covering 18 winters of ice drift was also made available at CERSAT.

Tournadre *et al.* (2008) developed an automated process for small iceberg detection from Jason's altimeter high rate wave form data. The large number of detected icebergs (up to 8000 for the year 2005, south of 45°S) appeared to be strongly correlated with sea ice extent.

Using this process and a six year data base of fields of small icebergs built from Jason-1 archive data (2002–2008) Ardhuin *et al.* (2011b) investigated, by comparison with wave model data, the influence of such icebergs fields on wave propagation. They find that in the southern ocean, icebergs distribution patterns appear strongly correlated with wave model error and propose a simplified parameterization of wave blocking by icebergs which induces a correction of the model's major errors.

Evolution of the sea ice extent is one of the major concerns of the studies related to climate change. Projections obtained from different models predict a possible total loss of sea ice cover in the arctic around 2030 (Wang and Overland, 2009). The September 2007 minimum sea ice extent was largely discussed and studied; Kauker (2009), Graversen *et al.* (2010), Giles *et al.* (2008).

Derivation of sea ice thickness from remote sensing alone appears not to be totally satisfactory. Ice thickness assessment requires simultaneous measurement of sea ice freeboard, snow cover and the densities of snow, ice and water (Kurtz *et al.*, 2009). These parameters are not always simultaneously available with homogeneous spatial resolution. Farrell *et al.* (2009) propose a new detection algorithm for the retrieval of altimeter sea surface height in the Arctic Ocean; they describe a procedure to calculate sea ice freeboard based on data from the Geoscience Laser Altimeter System (GLAS) onboard the ICESat mission. The authors produce a five years time series of freeboard elevation in the arctic, which in spite of uncertainties in snow thickness, indicates that overall sea ice freeboard has decreased during the considered observation period.

Based on the analysis of ICEsat data, Kwok *et al.* (2009) indicate that over the 2003-2008 period, an important decrease in volume and thickness of the multi-years ice cover over the Arctic Ocean could be observed.

Prinsenberg *et al.* (2011b) utilized three independent systems installed beneath of a helicopter to describe snow, and land-fast and mobile ice characteristics along the Labrador Shelf. The authors used a Ground-Penetrating Radar (GPR) to obtain the thickness of the snow layer on the ice and thickness of low salinity ice. The Electromagnetic-Laser (EM) system was applied to obtain ice thickness and surface roughness. The Video-Laser recorded the flight path. In their conclusions the authors indicate that the GPR and EM complement each other in interpreting ice and snow characteristics.

Johnston and Haas (2011) validated helicopter-base electromagnetic induction (HEM) system for measurement of ice thickness against drill-hole measurements of very thick ice. The measurements were taken in an area where drill-hole measurements are available for comparison. The HEM underestimated the average ice thickness on three floes by up to $1.9\,m$, and by as much as $3.1\,m$ on the fourth one. The authors finally indicate that application of HEM for measurement of very thick ice could be limited and suggest development of correction factors for future HEM applications.

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2.5.3 Numerical Modelling to Complement Measured Data

Numerical modelling based directly on measured data links the development of sensing-technology with sea-ice models. Such techniques are applied not only for the hindcast of sea-ice conditions for past decades, when relatively little measured data were available, they also give short-term predictions for sea ice build-up and prognoses for sea-ice extent under the influence of global warming.

Martin (2007) derives sea-ice ridges quantities from laser altimeter and airborne electromagnetic measurements. He then develops different numerical algorithms for the representation of ridges in a large-scale sea ice model. His study of sea ice drift focuses on the comparison of different sea ice-ocean coupled models and the validation with buoy and remotely sensed data from the period 1979–2001 on the basis of monthly averages. Martin found that all investigated models are capable of producing realistic drift pattern variability although differences are found between models and observations. He considers different causes for the discrepancies, which may lie in the wind stress forcing as well as sea ice model characteristics and sea ice-ocean coupling. Three different approaches to the simulation of pressure ridge formation are introduced and tested in idealised experiments and for realistic Arctic conditions. The model results show that the ridge density is mainly related to the sea ice drift whereas the mean sail height relates to the parent ice thickness. Most deformation occurs at coastlines. In general, all of the proposed algorithms produce realistic distributions of ridges.

Notz and Worster (2008, 2009) focus on the salinity of sea ice. They present data from in-situ measurements of the salinity evolution. The measured bulk salinity profiles show that during ice growth, sea-ice salinity is continuous across the ice-ocean interface and that there is no instantaneous loss of salt at the advancing front. The bulk salinity within the ice decreases continuously with time from the ocean water salinity. The findings showing that gravity drainage occurs for a critical Rayleigh number of around 10 are in close agreement with earlier theoretical and experimental studies. The authors also re-examine five processes that have been suggested to be important for the loss of salt from sea ice. These processes are the initial fractionation of salt at the ice-ocean interface, brine diffusion; brine expulsion, gravity drainage, and flushing with surface melt water. Their results from analytical and numerical studies, as well as from laboratory and field experiments, show that, among these processes, only gravity drainage and flushing contribute to any measurable net loss of salt. It should be mentioned that the salinity affects the ice mechanical properties and also the freezing/melting of ice and therefore it is important for ships and offshore structures.

3 MODELLING OF ENVIRONMENTAL PHENOMENA

The environmental description often employs a mixture of mathematical, probabilistic, empirical and statistical models. The following “decoupling” approach is commonly used.

One assumes that for a limited period of time and in a particular geographical region met-ocean conditions vary in a stationary way called sea state. Met-ocean 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.

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3.1 Wind

Modelling the wind speed data has important implications in wind studies, providing valuable insight and parametric quantities for further engineering analysis. Wind not only acts on offshore and ship structures directly; it also constitutes the main driving force for waves, influences currents and also the drift of sea-ice. The classical modelling approach is to fit the probability distribution to a known model and estimate statistical parameters like mean and variance. Wind modelling considering multiple time scales is performed for different purposes. On long time intervals, the atmospheric circulation and embedded storm cells are affected by global warming. The long term predictions of extreme events give valuable information for the construction especially of fixed offshore structures. In the shorter term, wind forecasts for a few days are needed for operational planning, when steps in construction require calm weather conditions or a strait is unsafe to pass under strong winds. In the context of the increase of offshore wind energy, reliable forecasts of the order of hours or minutes are also become increasingly important since the complex electrical networks are sensitive to large fluctuations, which may occur at the onset of a storm.

The reports by Monteiro *et al.* (2009a, 2009b) give an overview of the activities with respect to wind energy in different parts of the world. Many countries and regions are introducing policies aimed at reducing the environmental footprint from the energy sector and increasing the use of renewable energy.

3.1.1 Analytical and Numerical Description of Wind

Wind power forecasting (WPF) is frequently identified as an important tool to address the variability and uncertainty in wind power and to more efficiently operate power systems with large wind power penetrations. In general, wind power forecasting can be used for a number of purposes, such as: generation and transmission maintenance planning, determination of operating reserve requirements, unit commitment, economic dispatch, energy storage optimization (e.g., pumped hydro storage), and energy trading. Monteiro *et al.* (2009a, 2009b) review and analyze state-of-the-art wind power forecasting models and their application to power systems operations. They give a detailed description of the methodologies underlying state-of-the-art models. The physical approach, which consists of several submodels, which together deliver the translation from the weather prediction forecast at a certain grid point and model level, to power forecast at the considered site and at turbine hub height. Every submodel contains the mathematical description of the physical processes relevant to the translation. They also consider the statistical approach which is emulating the relation between meteorological predictions, historical measurements, and generation output through statistical models whose parameters have to be estimated from data, without taking any physical phenomena into account.

Costa *et al.* (2008) give a brief review on 30 years of history of the wind power short-term prediction, since the first ideas and sketches on the theme to the current state of the art on models and tools, giving emphasis to the most significant proposals and developments. The two principal lines of thought on short-term prediction (mathematical and physical) are indistinctly treated because a standard for measurement of performance is still not adopted.

Most models are based on a combination of a numerical description of the underlying physical process or a statistical approach and external data from remote or local measurements. The models may apply iltering for a better prediction of wind speeds. For

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example, Louka *et al.* (2008) study the application of Kalman filtering as a post processing method in numerical predictions of wind speed. Two limited-area atmospheric models are employed, with different options/capabilities of horizontal resolution, to provide wind speed forecasts. The application of Kalman filter to these data leads to the elimination of any possible systematic errors, even in the lower resolution cases, contributing further to the significant reduction of the required CPU time. The authors show the potential of this method for wind power applications.

The work of Kavasseri and Seetharaman (2009) makes use of fractional-ARIMA or f-ARIMA models to describe, and forecast wind speeds on the day-ahead (24 h) and two-day-ahead ($48\,h$) horizons. Results indicate that significant improvements in forecasting accuracy are obtained with the proposed models compared with the persistence method.

Since wind speed has a huge impact on the dynamic response of wind turbines, many control algorithms use a measure of the wind speed to increase performance, e.g. by gain scheduling and feed forward. As accurate measurements of the effective wind speed are in general not available from direct measurements, wind speed must be estimated in order to make such control methods applicable in practice. The technique described by Østergaard *et al.* (2007) estimates the rotor speed and aerodynamic torque by a combined state and input observer. These two variables combined with the measured pitch angle are then used to calculate the effective wind speed by an inversion of a static aerodynamic model.

A significant number of papers address the problem of the quality of high wind within tropical cyclone structures.

Hurricane Katrina of 2005 has been subject to deep analysis. Gathering and analysing an extensive multi-platforms observations data set, Powell *et al.* (2010) built a data base allowing a description with a 3 hours time step of Katrina's wind field evolution as the hurricane was travelling across the Gulf of Mexico. Therefore, the hurricane wind analysis system H*Wind was used which permits creating composite snapshots of the wind field based on all available observations over a given time window. Furthermore, the H*Wind fields were blended with peripheral data, using the IOKA system, then interpolated to the grids so as to provide forcing for the storm surge (ADCIRC) and wave models (WAM, Wave Watch, SDWave).

Based on analysis of observation data of wind fields measured for several days during seven hurricanes as well as on theoretical considerations, Stern and Nolan (2009) revisit some commonly accepted results regarding the vertical structure of tangential winds in tropical cyclones. Confirming previous studies, they show that the outward slope of the radius of maximum winds linearly increases with radius. On the other hand, they suggest that the slope of the radius of maximum speed is not related to intensity as was usually considered. This discrepancy seems to be mostly explained by the coarse sampling and data quality in previous studies.

Using a high resolution model (WRF), Uhlhorn and Nolan (2011) attempt to quantify the error made in estimating cyclone intensity as the maximum observed wind. They simulate the Hurricane Isabel of 2003 and reconstruct an observation data base as if measurement were made by a virtual aircraft equipped with a stepped frequency microwave radiometer flying a standard pattern. Analysis of the data suggests that the maximum observed surface wind typically underestimates the tropical cyclone maximum 1-minute sustained wind speed by about 7 to 10 %, on average whereas

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underestimation of the 10-minute averaged maximum wind speed is only about 1 to 3 %.

A large number of studies are dedicated to the development and analysis of regional models which allow assessment of smaller scale phenomena using higher resolution models by focussing on reduced areas. Leduc and Laprise (2009) investigate sensitivity of a regional climate model to the size of the numerical domain while Winterfeldt and Weisse (2009) assess the improvement in quality of the marine wind field induced by regional models when compared with those of a global reanalysis (NRA-R1) and point out interesting added value in coastal areas with complex topography.

3.1.2 Experimental Description of Wind

The experimental testing of structures in wind is often performed with scale models in wind tunnels. These tests are strongly linked to a specific structure. The geometry and the local installation need to be known in order to generate meaningful results in such experiments.

A method for modal wind load identification from across-wind load responses using Kalman filtering is presented by Hwang *et al.* (2011). They verify their findings using the wind tunnel test data.

Plain-air experiments, which are not focused on the wind forces on a specific structure often focus on certain weather phenomena. Choi (2004) investigates the variation of wind velocity with height during thunderstorms at five levels on a 150 m tall tower. Velocity profiles for more than 50 thunderstorms are studied and classified into four types according to the profile shape and the height of the highest wind speed. It is observed that wind profiles during thunderstorms are affected by several factors with the major ones being distance from the thunderstorm cell centre, intensity of the storm and ground roughness. Experimental studies on the simulation of thunderstorm wind using an impinging jet are also carried out to further investigate the effect of these parameters.

Cao *et al.* (2009) analyse the wind characteristics of Typhoon Maemi (2003) on the basis of 10-minute wind speed samples. The wind speeds were measured simultaneously by nine vane and seven sonic anemometers at a height of about 15 m. Turbulence intensity and scale, gust factor, peak factor, decay factor of the coherence function, probability distribution function, power spectrum, and their variations with wind speed are obtained. Wind-direction-dependent analysis is conducted on the wind characteristics. Turbulence intensity decreases with wind speed and remains almost constant when the wind speed becomes high. The averaged values of gust factor and peak factor are 1.6 and 3.3, respectively. The spatial cross correlation and decay factor of the coherence function increase slightly with wind speed. The probability density function of fluctuating wind speed of a strong typhoon follows a Gaussian distribution, and the power spectrum of strong wind can be expressed by a Karman-type spectrum at low frequency. The wind characteristics of the typhoon are shown to be very similar to those of non-typhoon winds.

The classical statistical description techniques have some drawbacks. They lack the time variation properties and ignore cross-dependencies between other meteorological data. Hocaoglu *et al.* (2010) developed a procedure to model the wind speed data using a dependent process of atmospheric pressure in the form of hidden Markov models. Consequently, the inherent dependencies between the wind speed and pressure are exploited. The models relate the two quantities in a framework which eliminates

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the necessity of direct sample-wise correlations, and avoid direct time-series analysis complications of the stochastic wind speed data at a marginal expense of easy pressure measurements. The experimental data were obtained from recordings of hourly atmospheric pressure and wind speed values for two cities in Turkey, namely Izmir and Kayseri.

3.1.3 Statistical and Spectral Description of Wind

To the Committee knowledge no changes to the statistical and spectral description of wind took place since 2009. Wind models commonly applied can be found in DNV RP-C205 (DNV, 2010) and DNV-OS-J101 (DNV, 2011). A joint fit of significant wave height and wind speed for the NW Australia location is presented in Bitner-Gregersen (2010) using the Conditional Modelling Approach (CMA) while for the Brasilian location by Sagrilo *et al.* (2011) applying the Nataf model.

3.2 Waves

Accuracy of the wave spectral models is under continuous improvement. The GlobWave project initiated by ESA in 2008 to improve the uptake of satellite-derived wind-wave and swell data is still continuing. A draft version of the GLOBWAVE Data Handbook is now available on the project web site (http://www.globwave.org/) and user feedback is requested.

The knowledge of extreme and rogue waves has significantly advanced recently. The predictions made by theoretical and numerical models compare well with experimental results.

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 characteristics.

3.2.1 Analytical and Numerical Description of Waves

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. 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.

Since 2009 intercomparison among different forecast systems, i.e. meteorological model and wave model have been carried out. Bertotti *et al.* (2011) compared the model results versus the available measured wave data from altimeters and a small number of buoys and showed that on average model wave heights were lower than the measured ones; it was difficiult to reach firm conclusions however.

WAVEWATCH III^{TM} version 3.14 (Tolman, 2009) was delivered in which some source term options for extremely shallow water (surf zone) have been included, as well as wetting and drying of grid points. A multi-grid or wave model driver was developed allowing the full two-way interaction between all grids at the time step level. Additionally, spectral partitioning was made available for post-processing of point output, or for the entire wave model grid (Hanson and Phillips, 2001). Spectral partitioning, allows identification of the various wave systems (swells and wind sea). This is useful for wave resource assessment and for design.

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Major contribution to the improvement of wave models based on the radiative transfer equation (RTE) is the development of new modified wind input and wave dissipation functions based on more physical description of the transfer mechanisms.

Recent developments with input (wind) and dissipation source terms have been made by Banner and Morison (2010). Babanin *et al.* (2010) (see also Babanin *et al.*, 2011b) proposed a new formulation for dissipation by breaking, based on observations that wave breaking only happens after an average background steepness exceeds a threshold value and that breaking probability depends on the excess of the mean steepness above this threshold. Other proposals for such semi-empirical dissipation functions were made and implemented in operational versions of WAVEWATCH III^{TM} (Ardhuin *et al.*, 2011a). Filipot *et al.* (2010) also propose a common parameterization of breaking wave height distribution which may be used from deep to shallow water.

One major interest in the implementation of these new dissipation terms is that these are based on observations and allow introduction of a more consistent description of the physics of the wind-wave interactions whereas previous approaches were mostly based on more parametric descriptions relying on the tuning of the various source terms to reproduce observed trends.

Tamura *et al.* (2010) studied the impact of non-linear energy transfer on realistic wave fields of the Pacific Ocean using the Simplified Research Institute of Applied Mechanics (SRIAM) model, which was developed to accurately reproduce non-linear source terms with lower computational cost than more rigorous algorithms, and the widely used Discrete Interaction Approximation (DIA) method. Comparison of the model with buoy observations revealed a negligible difference in significant wave heights but pronounced bias in peak frequency with DIA. The analysis of spectral shape indicated that the SRIAM method can quantitatively capture the overshoot phenomena around the spectral peak during wave growth.

Varieties of wind input source terms and dissipation source terms are implemented in operational wave models. One of the issues under debate is to set a cap on each source term rather than tuning the model so that the sum of input and dissipation source is realistic. Examples of implementations were presented at the 12th International Workshop on Wave Hindcasting and Forecasting held in Hawai (2011) and the nonlinear source term was discussed there.

Recently, in an attempt to improve the upper ocean mixing, various parameterization based on the concept of "wave induced turbulence" have been suggested; see Babanin *et al.* (2009), Dai *et al.* (2010). A number of works related parameterisation schemes such as BV parameterisation (Huang *et al.*, 2011), Stokes production term (Huang and Qiao, 2010), and modified K-profile parameterization (Qiao *et al.*, 2010), were presented. The wave induced turbulence is still under debate and active discussion supported by presentations took place in the WISE meeting at Qingdao in June 2011.

Classical topics of radiation stress and wave induced mixing are being revisited to improve the modeling of direct coupling of surface waves and ocean current. Different choice of the treatment of the free surface boundary condition and the coordinate system gives a different expression of the depth dependent radiation stress (Ardhuin *et al.*, 2008). Mellor (2008) corrected for some errors in the expression given in his 2003 paper which validity is being debated in the paper by Bennis and Ardhuin being in press. The issue was discussed in the WISE meeting in Brest, April 2010 and an attempt to include such effects in actual wave-current coupled model was presented

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at the International Workshop on Modelling the Ocean (IWMO) at Qingdao in June 2011 e.g. Tamura *et al.* (2010).

Dumont *et al.* (2011) consider the wave-ice interactions and their effects on sea ice–ocean models. The role of sea ice as a dampener of wave energy and the wave-induced breakup of ice floes are investigated. These two processes act in concert to modify the incident wave spectrum and determine the main properties of the marginal ice zone. The model predicts a sharp transition between fragmented sea ice and the central pack.

The code SWAN is commonly utilised to deal with shallow water wave climate. To describe wave transformations from deep water to shallow water depth the combined effect of the wave refraction, diffraction and reflection on the wave transformation has been considered by using the Mild-Slope Equation (MSE). Liau *et al.* (2011) proposed MSE including the higher-order bottom slope terms and ambient current effects into the wave action balance equation.

There has been further impetus to push exclusively non-stationary models such as WAM and WAVEWATCH-III closer to shore (e.g. Tolman, 2009) since this avoids 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.

A major initiative to improve wind wave predictions was launched under the umbrella of the National Oceanographic Partnership Program (NOPP) in 2009 (http://www.nopp.org/). The initiative is a four-year programme funded by the Office of Naval Research (ONR), the US Army Corps of Engineers (USACE), the National Oceanic and Atmospheric Administration (NOAA), and the Minerals Management Service (MMS). For some publications regarding improvement of the source terms in contemporary ocean wave models reference is made to the 12th International Workshop on Wave Hindcasting and Forecasting (http://www.waveworkshop.org/12thWaves/).

Wave models in deep and finite water describing short-term variations of water surface may be categorized into four classes: linear wave models, the Boussinesq, Kadomtsev–Petviashvili (KP) and the Korteweg-de Vries (KdV) models, second order wave models, and higher-order wave models. For extreme waves in extremely shallow water, the Boussinesq equation model (or KdV model, or its generalisation the KP equation) or its higher order extension is usually adopted with a relevant non-dimensional number, say Ursell number (ratio of wavelength, wave amplitude and water depth). For intermediate water depths the 2nd order shallow water theory is applicable whilst in deep water the 2nd order deep water theory may be applied; higher order theories may be needed for extraordinarily steep sea states. Nonlinear Schrödinger Equations (NLS), Modified Nonlinear Schrödinger Equations (MNLS), HOSM (Higher Order Spectral Method) have all been used to provide estimates of rogue waves.

Linear and second order wave models (e.g. the 2nd order Sharma and Dean finite-water wave theory) are well established and have commonly been used in design in the last years. Since 2009 increasing focus has been given to description of rogue waves (also called freak or abnormal waves) in shallow, intermediate and deep water.

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 two models has been pointed out by the ISSC 2009 I.1 discusser Prof. H. Tomita, see the ISSC 2009 Congress Proceedings Vol. III.

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A number of physical mechanisms to explain the extreme and rogue wave phenomena have been suggested in the last decade; these include: linear Fourier superposition (frequency or angular linear focussing), crossing wave systems, wave-current interactions, quasi-resonant interaction (modulational instability) and shallow water effects. Since 2009 there has been increasing focus on further explanation of these mechanisms, development of numerical codes for description of extreme and rogue waves, as well as on comparison and validation of numerical nonlinear wave models with experimental and field data.

Three important review publications have been issued recently: Dysthe *et al.* (2008), Kharif *et al.* (2009) and Osborne (2010), gathering significant findings within the field of extreme and rogue waves. The paper of Pelinovsky *et al.* (2011) is also a valuable reference.

Didenkulova and Pelinovsky (2011) studied the formation of rogue waves in the framework of nonlinear hyperbolic systems with an application to nonlinear shallow water waves. It is shown that rogue waves can appear in nonlinear hyperbolic systems only as the result of non-linear wave–wave or/and wave–bottom interaction.

The transformation of a random wave field in shallow water of variable depth has been analysed by Sergeeva *et al.* (2011) within the framework of the variable-coefficient Korteweg-de Vries equation. It is shown that the characteristic wave height varies with depth according to Green's law, and this follows rigorously from the theoretical model.

Much attention has been given to quasi-resonance (modulation instability), one of the intermediate and deep water mechanisms responsible for generation of rogue waves. Wave breaking is not typically included in these studies except by simple parameterization e.g. Babanin (2011), and work continues in this area.

The deterministic theory of ocean waves, formulated as a nonlinear Schrödinger equation, has been shown to reproduce observed rogue waves very accurately when properly calibrated. The equations have also successfully been used to generate rogue waves, in a numeric and physical wave tanks, e.g. Babanin *et al.* (2011b), Toffoli *et al.* (2010a, 2010b), Slunyaev *et al.* (2011, 2012).

Toffoli *et al.* (2010b) have compared numerical simulations of a Boundary Modified Nonlinear Schrödinger equations (BM-NLS) and the potential Euler equations solved by Higher Order Spectral Method (HOSM) for long-crested and short-crested waves with different directional wave spreading and for the JONSWAP spectral parameter γ=3 and γ=6. Both models have provided similar results despite the bandwidth constraint of BM-NLS.

Mori *et al.* (2011) demonstrated by Monte-Carlo simulation of the NLS with various spectral geometries that the maximum attainable kurtosis as a result of quasi-resonance depends both on the frequency band-width and directional spreading. The result agreed well with the earlier experimental investigations by Waseda *et al.* (2009a, 2009b), and Onorato *et al.* (2006) showing increased occurrence of freak waves as the directional spectrum narrows.

Strongly nonlinear and fully nonlinear simulations of extreme wave events have been performed by Shemer *et al.* (2010a, 2010b) and Slunyaev (2010). In particular, the conformal 2D code has been employed for basic wave tests resulting in generation of steep and breaking waves. HOSM with the nonlinearity parameter M = 6, which corresponds to practically fully nonlinear wave simulations, was used to simulate 2D

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waves. Ruban (2010) investigated the formation of rogue waves in sea states with two close spectral maxima using a completely nonlinear numerical model for long-crested surface waves.

The Hilbert transform is a primitive method for obtaining the wave envelopes, which disregard wave nonlinearity, which is crucial when rogue waves are considered. Slunyaev (2009) examined different approaches and tested versus application to the in-situ data: 2-order and 3-order bound (Stokes) waves' consideration in a narrow-band assumption, and the Creamer transform approach. Although the difference in the surface elevation profile between the different envelope approaches is not visible, the distinctions between the vertical velocities and spectral tails are obvious.

Numerical simulations by using HOSM for solving the Euler equations have indicated that the number of extreme events increase when an angle between the two interacting wave systems was around 30–40 degrees, Toffoli *et al.* (2011b). This finding is supported by recent theoretical investigations of Onorato *et al.* (2010).

Impact of current in modifying the quasi-resonant wave evolution has been studied by Onorato *et al.* (2011a, 2011b) and Toffoli *et al.* (2011a, 2011c). A condition of partial opposition has been considered. The studies have shown that the current can trigger the formation of large amplitude waves. This conclusion has been confirmed by Hu and Ma (2011) who have shown that the physical properties of rogue wave are influenced significantly by the velocity of current. The authors established a spatial domain model of current modified nonlinear Schrödinger (NLSC) equations in one horizontal dimension for describing the deep-water wave trains in a prescribed stationary current field.

Some interesting developments have taken place on direct and indirect evidence on the specific meteorological conditions leading to the formation of narrow directional wave fields and occurrence of rogue waves, Waseda *et al.* (2011). Met-ocean conditions associated with occurrence of rogue waves were also studied, Bitner-Gregersen and Toffoli (2012). Rozhkov (2009) proposed a mechanism of generating a giant rogue wave in mid-ocean. The swell (steady wave) is the initial condition for the wave evolution at the beginning of which the wave is driven by the gust of wind, and then the wave runs free up to its overturning and may become huge. The time of the evolution is less than half of the swell period. In the course of the free evolution the wave height may also oscillate creating the "Three Sisters" effect.

A general consensus on the ultimate shape of waves has not been achieved yet due to the complexity of the breaking mechanism. A review book on breaking waves by Babanin (2011) outlines the state-of-the-art in understanding of wave breaking and presents the main outstanding problems. Dao *et al.* (2011) using an advanced numerical method, the Smoothed Particle Hydrodynamics enhanced with parallel computing, reproduced well the extreme waves and their breaking process. Babanin *et al.* (2011b) relate the wave breaking in oceanic conditions to features of two-dimensional breaking waves due to modulational instability. The authors argue that the physics of rogue waves is defined by the same processes as those leading to the onset of breaking with surface waves.

3.2.2 Experimental Description of Waves

Laboratory tests have been conducted world-wide to investigate extreme and rogue wave events, primarily through changing various wave spectral parameters and utilising a directional wave generator.

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An interesting study with similar wave experiments conducted independently in two different facilities, the MARINTEK ocean basin (Norway) and the directional wave basin at the Australian Maritime College (AMC), is reported by Toffoli *et al.* (2011a). Although those facilities have different sizes and are equipped with different wave makers, the results obtained are very consistent. The modulational instability process is quenched when short-crested waves are considered.

Laboratory measurements of nonlinear wave group dynamics collected in the experiments in the Large Wave Channel (GWK) in Hannover have been carried out by Shemer *et al.* (2010a, 2010b) and compared with numerical simulations of the spatial version of the Dysthe model. Similar simulations within the spatial version of the NLS equation exhibit much worse agreement with the measured waves and thus the NLS equation is not efficient for this kind of modelling.

Cherneva and Guedes Soares (2010, 2011) have compared the results of experiments carried out in the DHI and MARINTEK basin and have shown that the observed maximum wave steepness systematically decreases with the band wide parameter.

An extensive investigation of the wave crest carried out in the MARIN basin is reported by Buchner *et al.* (2011). Particular attention in the experiment was the study of very steep crests. The study has confirmed earlier investigations; wave directionality suppressed nonlinear effects.

Latheef and Swan (2011) have performed an experimental study of wave properties in different sea states in the Imperial College facilities in order to study statistics of wave crest and height.

Investigation of crossing-wave systems has been carried by Toffoli *et al.* (2011b). HOSM was used for solving the Euler equations. Both numerical simulations and experimental data indicate that the number of extreme events depends on the angle between the two interacting wave systems.

Laboratory experiments of the wave field traversing obliquely an ambient current were carried out in the MARINTEK tank by Toffoli *et al.* (2011c). Tests on regular waves have shown that the current can trigger the formation of large amplitude waves. However, for the sea states considered this has resulted only in a weak deviation from the statistical properties observed in absence of a current.

Toffoli *et al.* (2010c) analysed a large sample of individual wave steepness data collected from measurements of the surface elevation in laboratory facilities and the open sea under a variety of sea state conditions. Observations reveal that waves are able to reach steeper profiles than the Stokes' limit for stationary waves. Direct measurements of instability-caused breaking in a directional wave tank with directional spread are discussed also by Babanin *et al.* (2011b).

Dai *et al.* (2010) have investigated mixing induced by nonbreaking surface waves in a wave tank by measuring the thermal destratification rate of the water column without waves and when waves are present. The study demonstrates that the mixing induced by nonbreaking waves may add an important contribution to the vertical mixing process in the upper ocean and suggests a way to parameterise wave-induced mixing in numerical ocean models.

The nonlinear dynamics of surface gravity is today reasonably understood, the focus is now on forcing terms like wind and current and wave breaking.

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3.2.3 Statistical and Spectral Description of Waves

Short-term statistics. For Gaussian seas the crest distribution is often approximated by Rayleigh cumulative distribution function (CDF). For severe seas the Rayleigh CDF has been corrected in various ways often employing a Weibull distribution with empirically fitted parameters to capture very high crest heights.

Another approach to estimate the crest height is to employ a non-Gaussian model for waves and compute the crest height in the model. Normalized crossing intensity, given by the Rice formula, is often used to estimate of the crest height distribution. It is also a conservative estimate that fits well to the tail of the distribution. A new approach on evaluation of the Rice formula for second order wave models, based on a saddle point approximation, was presented in Butler *et al.* (2009). Further Laplace distributed processes have been used to model waves at fixed location, see Åberg *et al.* (2009). In Galtier (2011) an estimation method of crossing intensity for the Laplace process was given. Lindgren *et al.* (2010) give means to evaluate Rice's formula for Lagrange waves.

In Lindgren *et al.* (2010) the authors review work on a a spatio-temporal stochastic Lagrange wave model (an alternative to the Gaussian linear model) and give means to compute theoretical distributions of some wave characteristics, e.g. wave slope, see also Lindgren (2009).

Romero and Melville (2010) have studied spatial wave statistics, e.g. wave steepness and length of the crest extracted from LIDAR data and compared those with the theoretical distributions derived for Gaussian (linear) models. They concluded that the observed characteristics differ from the theoretical ones.

Several authors have studied extreme and wave rogue statistics in shallow, intermediate and deep water. Suggested simplified definitions of rogue waves, not sufficiently reflecting the physics of rogue waves, were noted in the previous Committee report. Recently Gemmrich and Garrett (2010) have proposed using an "unexpected wave", such as a wave twice as high as any of the preceding 30 waves, when studying extreme waves.

Sergeeva *et al.* (2011) have shown within the framework of the variable-coefficient Korteweg-de Vries equation that the skewness and kurtosis increase when the depth decreases, and simultaneously the wave state deviates from the Gaussian. The slope of the bottom influences the results. If the random wave field is represented as a soliton gas a number of large-amplitude (rogue) solitons increases when water becomes shallower.

Didenkulova (2011) has studied statistics of wave height in shallow water. Wave heights with high crests and deep troughs have been observed. The occurrences of rogue waves with high crests have been correlated with significant wave height when deep troughs were not present.

Latheef and Swan (2011) have performed a large experimental study of wave properties in different sea states. They compared observed crest and wave height with the models proposed in the literature and concluded that so called Glukhovskiy distribution gives the best fit; this confirms earlier findings.

Toffoli and Bitner-Gregersen (2011) have used the potential Euler equations to investigate comprehensively the effect of modulational instability on statistical properties of surface wave characteristics like water surface elevation, wave crest, wave trough, wave height, skewness and kurtosis in directional wave fields. The effect of modulational

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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.

The statistics of wave height and crest based on numerical simulations carried out with 2D and 3D HOSM models, Boundary Modified-NLS (BM-NLS) model and the laboratory data have been compared with the 2nd order crest and height Tayfun distributions and the Rayleigh distribution by Toffoli *et al.* (2010b). There is good qualitative and quantitative agreement between the numerical and experimental statistics also regarding of the maximum kurtosis (important for practical applications), except for very narrow directional waves.

Several authors have pointed out that the kurtosis can be regarded as a suitable parameter to identify the presence of a rogue event in a short-term wave records, see e.g. Toffoli *et al.* (2011b), Mori *et al.* (2011). Toffoli *et al.* (2011b) found higher kurtosis values when analysing waves in bimodal sea states, with higher occurrences when there were directional differences between 20 and 40 degrees. Further investigations are needed to conclude whether the two peaks spectrum has larger impact on occurrence of rogue waves than the spectrum bandwidth and directional spreading.

It has been verified both theoretically and experimentally that the kurtosis depends on the square of the BFI (Benjamin Fair Index), Onorato *et al.* (2006). Mori *et al.* (2011) present two-dimensional Benjamin Fair Index (BFI-2D) and express the kurtosis as a function of it. Random waves are expected to become unstable when BFI>0.6, provided the wave field is long crested (i.e. unidirectional wave propagation); e.g. Toffoli and Bitner-Gregersen (2011).

Zakharov and Shamin (2010) studied the statistics of the occurrence of rogue waves on a surface of an ideal heavy liquid arising in the course of evolution of a statistically homogeneous random Gaussian wave field. The mean steepness of initial data varies from small to moderate values. The frequency of the occurrence of extreme waves decreases with an increase in the spectral width of the initial distribution, but remains relatively high even for broad spectra.

Results of an extensive tank investigation on the wave crest distribution at fixed location were reported in Buchner *et al.* (2011). The conclusion was that wave crests are higher than predicted by linear (Gaussian) sea models, and second- and third-order corrections are needed to better describe the crest height variability. The Forristall second order distribution was recommended as the model that most adequately fits the tank data but not the field data.

In Petrova *et al.* (2011) statistical properties of wave crest, height and trough were investigated using experiments in deep water basin with bimodal crossing seas. The observed distributions differed significantly from the theoretical one derived for Gaussian seas and the second-order corrected distributions. Modifications of parameters were proposed.

Gemmrich and Garrett (2011) showed that the occurrence rate of extreme wave crests can be displayed effectively by plotting ln(-lnP), where P is the probability of the wave or crest height exceeding a particular value, against the logarithm of that value.

The studies of wave statistics are mostly centered on individual waves, often extreme, however in many safety applications the properties of wave groups are at least as or even more important, as reported by Clauss *et al.* (2011a, 2011b). A review of work on wave groups in oceanography is given by Bassler *et al.* (2010). In this work several

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statistics of observed envelope properties are presented. Similarly in Cherneva and Guedes Soares (2011), the observed deep water basin wave group characteristics are compared with the theoretical crossing distributions derived for Gaussian processes. Their findings confirmed results, presented by many authors, that wave group dynamics are nonlinear, making the wave group process significantly non-Gaussian. Theoretical results on distributions of wave group characteristics for non-Gaussian waves or Gaussian spatio-temporal fields are as yet very limited; see e.g. Podgorski and Rychlik (2008) for some theoretical results on the envelope of Gaussian wave fields.

Somewhat different results were reported in Forristall (2011), where the author compared theoretical spatial distribution for crest height of a Gaussian wave field due to Piterbarg (1996) with measurements in the MARIN Offshore Basin and reported good agreement between measurements and the theoretical distribution.

A number of investigations have attempted to find relations between individual wave parameters and sea state characteristics identifying occurrence of rogue waves but have not succeeded in finding any strong correlation (see, e.g. Christou and Ewans, 2011a, 2011b). Recently Waseda *et al.* (2011) used the number of records containing a freak wave per certain time window as a proxy to estimating the enhancement of the tail of the probability density function. The authors have found that there is a notable increase of the probability of occurrence of freak waves when the sea level pressure gradient is strengthened and the directional wave spectrum is relatively narrow (directional spread about 30 degrees). Bitner-Gregersen and Toffoli (2012) demonstarte how sea state duration affects probability of occurrence of rogue waves.

A fundamental but often tacitly assumed condition upon which short-term characteristics are based is that sea states are stationary. Sea state stationarity was addressed by Ewans (in prep.) in the Safe Offload project who investigated the temporal behaviour of swell using the wavelet transform for Directional Waverider buoy data from Duck, North Carolina. It was shown that non-stationary sea states were usually associated with local wind-sea growth rather than significant changes in the swell component, which could be considered stationary for at least as long as the 160-minute records.

Long-term statistics. Computation of extreme wave parameters are often performed by a two-level procedure which requires a model for long term variability of sea states and a distribution of a wave parameter during a sea state. The long term variability of sea states can be specified by a long term CDF (Cumulative Distribution Function) of spectral parameters.

Fedele *et al.* (2010) employed the technique for studying the extreme wave amplitude in sea storms at a fixed point with attention to modeling storm shapes. Gaussian wave amplitudes were modelled by means of the Rayleigh CDF. The authors focused on extreme wave crests occurring in some region and time period in sea storms. The waves were Gaussian and for a fixed sea state Rice's method in three dimensions was employed, see Azaïs and Wschebor (2009), for theory behind of the method.

In Mao and Rychlik (2012) the spatio-temporal model of significant wave height due to Baxevani *et al.* (2008) combined with a transformed Gaussian model was used to estimate extreme ship response when sailing on a North Atlantic route.

In recent years increasing attention has been given to the importance of including wind sea and swell components in a joint environmental description. Olagnon and Guédé (2010) show how to model several swell components. Bitner-Gregersen (2010) demonstrates that two approaches suggested for joint modelling of wind sea and swell

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can give significantly different predictions of extreme swell values. Sagrilo *et al.* (2011) have shown, using Brazilian data, applicability of the Nataf transformation to describe joint probabilities for wave (wind sea and swell), wind and current parameters with direction The treatment of directional data using wrapped normal distributions is an innovative contribution to research on joint probabilities.

Liu *et al.* (2010) studied joint variability of significant wave height and wind speeds in the Bohai Sea.

Extremes in significant wave height from the NORA10 data were estimated by Aarnes *et al.* (2011) using the Generalized Extreme Value distribution and Generalized Pareto distribution/Peak Over Threshold model.

In Baxevani *et al.* (2009) a spatio-temporal model for significant wave height was presented; an improved model to the one given in Baxevani *et al.* (2008) and fitted to the satellite data. The model was used in Rychlik *et al.* (2010) to estimate the 100 years return value worldwide. Alliot *et al.* (2011) generalised the model of Baxevani *et al.* (2009) and fitted the model to hindcast data validated by satellite altimeter data and buoy measurements. Further generalization of the model is presented in Baxevani *et al.* (2011) where a general class of spatio-temporal models is introduced which may lead to new developments.

The Baxevani *et al.* (2009, 2011) approach to define spatio-temporal fields is convenient for generalizations of non-Gaussian spatio-temporal models, since the dynamics can be added to any significant wave height spatial surface. In Åberg and Podgorski (2011) a new class of Laplace distributed fields, which can be horizontally and vertically asymmetrical, has been proposed. By introducing movements to the field a spatio-temporal model can be obtained. Further research is needed to check the usefulness of Laplace fields to model space time variability of significant wave heights.

In Ailliot *et al.* (2011) the velocity field is modelled by hidden Markov chain estimated from meteorological data. In Schlather (2010) a related class of Gaussian fields with non-separable covariance structure has been presented.

Vanem (2011) gives a literature survey on different sea state modelling approaches, particularly about spatio-temporal models, citing 211 references. In Vanem *et al.* (2011) a Bayesian hierarchical model in space and time is fitted to hindcast data for significant wave height in an area in Northern Atlantic. It is a non-Gaussian model developed to study climatic changes in significant wave height. Further research is needed to improve effectiveness of the model. The model has been adapted to monthly maxima in Vanem and Bitner-Gregersen (2012).

Due to the spatial size considered for the significant wave heights field, the efficiency of simulations of spatio-temporal models is an important issue. In Lindgren *et al.* (2011) algorithms for efficient computations and simulations of Gauss-Markov fields were presented. The fields are useful tools for modelling of quantities varying in a non-homogenous way over large areas. The authors also derived a new class of random field models using nested stochastic partial differential equations (SPDE).

Loffredo *et al.* (2009) show that the main drawback of the Hanson and Phillips (2001) approach commonly used in design for splitting the 3D wave spectrum into separate peaks is when there are fully developed wind seas with small wind decay but still in the same direction of the wave field. If the wave systems under examination cannot satisfy the formulation adopted by Hanson and Phillips (2001), the old wind sea will be treated as swell and the new wind sea set to zero. This will have impact on statistics of wind sea and swells (Bitner-Gregersen, 2010).

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There are statistical techniques available that could be used to determine statistically similar ocean areas which have not been applied because of the low spatial resolution nature of the data available. Lucas *et al.* (2011) explore the capabilities of regional frequency analysis, which provides an appropriate statistical based method to deal with this problem.

Spectral description. The 2009 Committee I.1 reported that the Pierson-Moskowitz and JONSWAP spectra are most well known and widely applied along with wave spreading according to frequencies. This situation remains. Increasing attention has been given since 2009 to describe bi- and multi-model seas; wind sea and swell (or several swell components). In Norwegian waters, the Torsethaugen bi-modal spectrum suggested in 1993 and simplified in 2004 by Torsethaugen and Haver is the most common for design purposes.

Methods for partitioning of directional spectra into wave systems, such as the one proposed by Hanson and Phillips (2001), are now widely used and even implemented in wave models such as WAVEWATCH III$^{\text{TM}}$ (Tolman 2009). The splitting of complex sea-states into their constituting wave systems, swells and wind-sea, allows a more accurate description of the energy distribution in the spectro-directional referential which is adequate for refined wave climate statistics (Saulnier *et al.,* 2011) and of major interest for resource assessment as described in the protocols for resource assessment provided by the EU funded project EQUIMAR (Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact - http://www.equimar.org).

Bitner-Gregersen and Toffoli (2009) have compared the wind sea and swell components predicted according to the Torsthaugen partitioning procedure with the ones given by the hindcast data from three locations: West Shetland, NW Australia and off the coast of Nigeria. The results indicate that the Torsethaugen spectrum should be used with care outside the Norwegian waters. The Torsethaugen partitioning procedure is sensitive to inaccuracy in H_s and T_p (spectral peak period) estimates for the total sea. Uncertainties related to these estimates may result in predicting an incorrect sea state type (e.g. a wind dominated sea instead of a swell dominated sea) when the Torsethaugen model is applied.

Traditionally, the directional distribution of ocean waves has been regarded as unimodal, with energy concentrated mainly on the wind direction. However, numerical experiments and field measurements have demonstrated that the energy of short waves tends to be accumulated along two off-wind directions, generating a bi-modal directional distribution. Toffoli *et al.* (2010a) have used numerical simulations of the potential Euler equations to investigate the temporal evolution of initially unimodal directional wave spectra. The approach adopted does not include external forcing such as wind and breaking dissipation, thus spectral changes are only driven by nonlinear interactions. Simulations show that the nonlinear interactions spread energy outwards from the spectral peak along two characteristic directions in qualitative agreement with a simplified narrow-banded model proposed by Longuet-Higgins (1976). According to the latter, the energy redistributes on directions forming angles of ± 35.5 degrees about the dominant wave direction. As a result, the directional distribution develops a bimodal form as the wave field evolves. The results are somewhat consistent with the parametric empirical bimodal directional model proposed by Ewans (1998). For a fairly long crested wave field, the simulations fit the Ewans model. However, as waves become shorter crested, the side lobes tend to slightly concentrate over broader directions with a consequent deviation from the aforementioned bi-modal directional

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model. Toffoli *et al.* (2010a) have provided a parameterisation for the lobe amplitude derived directly from the parametric bimodal directional model of Ewans.

3.3 Current

Success of the global and basin-scale ocean models with data assimilation under the GODAE program opened a new era of operational oceanography. It needs to be mentioned that 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.

The regional and coastal models can be forced by both astronomical tides and the basin-scale circulation. Therefore, phenomena related to external tides, storm surges, river plumes, coastal topographic waves, upwelling, downwelling and alongshore currents, mesoscale instability eddies and contour currents and standing meanders are in settlements, leaving the internal tides, surface fronts and submesosclae vortices, wakes and littoral currents as frontier phenomena (McWilliams, 2009). To best resolve these phenomena, modelling efforts are made at high-resolution, with wave-current interaction, and with realistic coastal and bottom topography. Operational ocean models need still improvements as they can fail to reproduce observed surface currents in the open ocean and particularly nearshore, see e.g. Breivik *et al.* (2011).

3.3.1 Analytical and Numerical Description of Current

The three dimensional hydrodynamic model COHERENS (COupled Hydrodymamic and Ecological REgioNal Shelf seas) http://www.mumm.ac.be/~patrick/mast/ is a multi-purpose numerical model for coastal seas which can consider the effect of waves on current through introducing wave radiation stress. Recently, a coupled model COHERENS-SWAN was adopted to simulate tidal current distribution under waves. The current velocities and surface elevation are calculated simultaneously. In the coupled model COHERENS-SWAN (Zhang *et al.,* 2009), the mutual influence of wave and current are included through exchange of data of each model. SWAN is introduced into COHERENS as a subroutine. COHERENSE gets wave height, period and direction through calling SWAN. SWAN gets current velocity and surface elevation from COHEERENS to account for their effects on wave simulation. The effects of non-uniform currents on wave propagation and wave blocking are investigated by Zhan *et al.* (2010) using a new Boussinesq model, in which the non-linear interaction of wave and current are taken into account.

Hao *et al.* (2009) presented the numerical results of wind-driven current in a lake using the Princeton Ocean Model (POM) and showed that the orthogonal curvilinear the grid in horizontal plane and the sigma coordinate in vertical plane are most effective. Shan *et al.* (2010) modelled the current generated in the deep water offshore basin at Shanghai Jiao Tong University using unsteady Reynolds Averaged Navier-Stokes (RANS) code and compared the numerical results with experiments. Based on measured full-depth deepwater current data in the South China Sea (offshore from Borneo), Sheikh *at al.* (2010) analysed the current speeds using Empirical Orthogonal Functions (EOFs) and their extreme profiles derived using the inverse First Order Reliability Method (FORM).

High resolution submesoscale-eddy-resoving models are being developed and are applied to, for example, processes relevant to larval transports in regions connecting open ocean and coastal seas (Mitarai *et al.*, 2009). With further refinement of the model approaching the coast, the wave-driven current field plays a significant role interacting with submesoscale current variations e.g. Uchiyama *et al.* (2009). The so-called

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vortex-force formulation which is an alternate expression for the classical radiation stress of the nonlinear coupling of waves and currents was successfully implemented in this modelling. Uchiyama *et al.* (2010) further downscaled to resolve the surf zone dynamics where both vortex force and non-conservative wave effect on current due to breaking were significant in resolving the under-toe.

Schaeffer *et al.* (2011) investigate dynamics of mesoscale anticyclonic eddies identified by mean of HF radars in the Gulf of Lions in the Mediterranean Sea. The authors focus on identification of physical mechanisms for the generation of such eddies and especially the influence of wind forcing. Numerical studies point out two mechanisms for eddy generation which correspond to two identified meteorological conditions.

Considering the case of mesoscale eddies generation around the Hawaiin archipelago, Kersalé *et al.* (2011) assess the sensitivity of an ocean model to forcing and especially wind forcing. The study shows that in order to correctly reproduce the oceanic circulation, multiple combined forcing (wind, inflow topography) must be implemented. It also shows that the Quik-SCAT wind data, with higher spatial resolution captures the complexity of the atmospheric flow in the different channels between the islands and allows a more accurate reproduction of the oceanic circulation.

3.3.2 Statistical and Spectral Description of Current

Not much progress can be reported since 2009. Statistical properties of surface current have been investigated for three locations in the EC project SAFE OFFLOAD. Some results are presented in Bitner-Gregersen (2010). Modelling of vertical profiles of large ocean currents is discussed by Jonathan *et al.* (2011b). Statistics of wave–current interaction are reported in Section 3.2.3.

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. Conclusions of these investigations are summarized in Section 4.1.4.

Assessment of the performance of state-of-the-art meteorological and oceanographic numerical systems in predicting the sea state (including surge) in the Adriatic Sea during intense storms has been carried out by Cavaleri *et al.* (2010). Two major storms that affected Venice are presented in the study. The results indicate the surge model should provide users with valuable forecasts.

3.5 Ice

Information about sea ice processes can come from field camps or aircraft and satellites, but data from these sources are limited. Sensors cannot account for all characteristics of sea ice anytime and anywhere. Furthermore, the record of sea ice data has a limited history. Satellite observations date back only to the mid-1970s; other observations, such as ship records, may go back as far as the late 19th Century, but they are sparse. Moreover, these data cannot predict the future of sea ice extent.

Sea-ice models allow for the reconstruction of historical patterns of sea ice and the prediction of future changes. Polar Regions are particularly sensitive to small changes in climate, and sea-ice models have undergone a significant development throughout recent years. Depending on the purpose of modelling, sea-ice models are used for short-term operational forecasts (one to five days) for ocean vessels in sea ice-covered regions, as well as for seasonal forecasts (one to three months) to aid in planning.

The dynamics equations take into account winds, currents, and other forces that influence sea ice motion. They consider air and ocean temperatures, albedo, and other forces that influence the growth and melt of sea ice.

3.5.1 Analytical and Numerical Description of Ice

Timmermann *et al.* (2009) describe a global Finite Element Sea Ice–Ocean Model. The ocean component is based on the Finite Element model of the North Atlantic but has been substantially updated and extended. A finite element dynamic-thermodynamic sea ice–model has been developed and coupled to the ocean component. Sea ice thermodynamics have been derived from the standard Alfred Wegener Institute for Polar and Marine Research (AWI) sea ice model featuring a prognostic snow layer but neglecting internal heat storage. The dynamic part offers the viscous-plastic and elastic-viscous-plastic rheologies. The coupled model is run in a global configuration and forced daily atmospheric reanalysis data for 1948–2007. Results indicate that many aspects of sea ice distribution and hydrography are found to be in good agreement with observations.

Although most of the solar radiation is reflected back into the atmosphere by the sea ice, part of it is absorbed, and the rest heats the surface sea water by penetrating through the sea ice. Cao *et al.* (2011) consider the resulting Near Sea-surface Temperature Maximum, which appears at a depth of less than $40\,m$ in the Arctic sea ice covered region. Most of the heat in the sea water diffuses back upwards due to the existence of the pycnocline forming a temperature peak just above it. By heating the water below the sea ice, the heat accelerates the melting of sea ice. A thermodynamic coupled sea ice-upper ocean column model was used by the authors in order to examine the relationship between the solar radiation flux penetrating through the sea ice and maximum temperature of the Near Sea-surface Temperature Maximum.

The work of Gödert and Suttmeier (2009) presents a phenomenological constitutive flow model for polar ice derived from so-called mesoscopic considerations and its consistent implementation into an appropriate finite element scheme. A systematic investigation of the development of texture in isothermal polar ice is presented. From the viewpoint of numerics the flow of ice is considered as a stationary free surface Stokes flow fully coupled with the development of its texture. Boundary conditions at the free surface are accommodated in the course of the computation to the actual flow situation. It turned out that the choice of the velocity boundary conditions at the bottom (bed-rock) is the crucial point in modelling induced anisotropy of free surface flow.

The marginal ice zone is the boundary between the open ocean and ice-covered seas, where sea ice is significantly affected by the onslaught of ocean waves. Waves are responsible for the breakup of ice floes and determine the extent of the marginal ice zone and floe size distribution. When the ice cover is highly fragmented, its behaviour is qualitatively different from that of pack ice with large floes.

Ice loads have traditionally been estimated using empirical data and "engineering judgment". On the other hand, it is believed that computational mechanics and advanced computer simulations of ice-structure interaction play an important role in developing safer and more efficient structures, especially for irregular structural configurations. The work by Bergan *et al.* (2010) explains the complexity of ice as a material in computational mechanics terms. The paper points towards the use of advanced methods like the Arbitrary Lagrangian-Eulerian (ALE) formulations, meshless methods, particle methods, the Extended Finite Element Method (XFEM), and

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multi-domain formulations in order to deal with these challenges. Much research is still needed to achieve satisfactory reliability and versatility of these methods.

Ahlkrona (2011) addresses the topic of ice sheet modelling. It involves describing a system including the ice sheet, ice shelves and ice streams, which all have different dynamical behaviour. The governing equations are non-linear, and to capture a full glacial cycle more than 100,000 years need to be simulated. To reduce the problem size, approximations of the equations are introduced. The most common approximation, the Shallow Ice Approximation (SIA), works well in the ice bulk but fails elsewhere e.g. the modelling of ice streams and the ice sheet/ice shelf coupling. In recent years more accurate models, so-called higher order models, have been constructed to address these problems.

Modelling of the internal pressure field and effects of a finite ice strength on a new model for sea ice dynamics, based on a global optimisation problem, rather than a local rheology, are examined by Huntley *et al.* (2007) and Huntley and Tabak (2007). In both references the pressure is seen as emerging not from an equation of state but as a Lagrange multiplier that enforces the ice's resistance to compression while allowing divergence. This formulation leads to an analytic description that is also easily implemented in a numerical code, which exhibits marked stability and is suited to capturing discontinuities. In order to investigate the behaviour of the model under ice yielding, the equations are cast in an Eulerian framework, now allowing for variable thickness. The model is first tested under conditions of infinite ice strength, to ensure that the numerics behave as desired. A finite ice strength is incorporated into the model as a second optimisation step, minimising the change in ice thickness necessary to satisfy the upper bound on the pressure, whereby ice strength is taken to be a linear function of thickness, following typical parameterisations in the literature.

The Jacobian-free Newton-Krylov method is implemented by Lemieux *et al.* (2010) to solve the sea ice momentum equation with a viscous-plastic formulation. This method has many advantages: the system matrix (the Jacobian) does not need to be formed and stored, the method is parallelizable and the convergence can be nearly quadratic in the vicinity of the solution. The convergence rate is characterized by two phases: an initial phase with slow convergence and a fast phase for which the residual norm decreases significantly from one Newton iteration to the next. Because of this fast phase, the computational gain of the Jacobian-free Newton–Krylov method over the standard solver used in existing viscous-plastic models increases with the required drop in the residual norm (termination criterion). The method is between 3 and 6.6 times faster (depending on the spatial resolution and termination criterion) than the standard solver using a preconditioned generalized minimum residual method.

The growth of sea ice and the associated loss of salt are addressed by Notz (2005) experimentally as well as numerically. His findings show that in winter salt is only lost from sea ice by so-called gravity drainage and that the bulk-salinity and solid-fraction fields are continuous across the ice–ocean interface during ice growth. The concept of an effective distribution coefficient is therefore not warranted in the context of sea ice. It is further shown that so-called brine expulsion does not lead to any net loss of salt from sea ice, and that flushing with melt water during summer is the only other process that has any impact on the salinity evolution of sea ice. These results are obtained theoretically, using the so-called mushy-layer equations and an enthalpy-based numerical model. The theoretical predictions are confirmed by laboratory and field experiments, using a new instrument developed in this study, which allows the

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in situ measurement of the salinity distribution in growing sea ice with a very high temporal and spatial resolution.

A numerical dynamic-thermodynamic sea-ice model for the Baltic Sea is used to analyze the variability of ice conditions in three winter seasons by Herman *et al.* (2011). The modelling results are validated with station (water temperature) and satellite data (ice concentration) as well as by qualitative comparisons with the Swedish Meteorological and Hydrological Institute ice charts. Analysis of the results addresses two major questions. One question concerns the effects of meteorological forcing on the spatio-temporal distribution of ice concentration in the Baltic. Patterns of correlation between air temperature, wind speed, and ice-covered area are demonstrated to be different in larger, more open sub-basins e.g. Bothnian Sea than in the smaller ones e.g. Bothnian Bay. Whereas the correlations with air temperature are positive in both cases, the influence of wind is pronounced only in large basins, leading to increase/decrease of areas with small/large ice concentrations, respectively. The other question concerns the role of ice dynamics in the evolution of the ice cover. By means of simulations with the dynamic model turned on and off, the ice dynamics is shown to play a crucial role in interactions between the ice and the upper layers of the water column, especially during periods with highly varying wind speeds and directions. In particular, due to the fragmentation of the ice cover and the modified surface fluxes, the ice dynamics influences the rate of change of the total ice volume, in some cases by as much as $1\,km^3$ per day. As opposed to most other numerical studies on the sea-ice in the Baltic Sea, this work concentrates on the short-term variability of the ice cover and its response to the synoptic-scale forcing.

Liu *et al.* (2011) present a fine-resolution coupled ice-ocean model configured for the Bohai Sea and North Yellow Sea. Seasonal simulations were made from the winters of 1997/1998 to 2008/2009. By comparing of the simulation results and the remote sensing images, the ice-ocean coupled model reasonably reproduces the seasonal variations of the sea ice conditions in the Bohai Sea and North Yellow Sea. The predicted ice-freezing date, ice-ending date and ice periods are in fairly good agreement with observations, and some are even identical to measurements. The simulated maximum of the sea ice extent date and the observations match well. Normally, the sea ice thickness of the west part in Liaodong bay is less than that of the east part, which can be reproduced well by the ice-ocean coupled model.

Ji *et al.* (2011) modified a discrete elemental model (DEM) for sea ice dynamics based on granular material rheology. In the model, a soft particle is used with ability of self-adjusting its size. Each particle is treated as an assembly of ice floes characterised by adjustable ice concentration and thickness applying conservation of mass rule. The contact forces between ice floes are calculated using a viscous-elastic-plastic model and shear forces are obtained from the Mohr-Coulomb friction law. The model allows the simulation of ice piece dynamics in a channel and in an open domain with a vortex wind and current effects. The authors claim that the simulations show promising results.

Improvements to the sea ice forecasting tools are welcomed by the shipping and offshore engineering communities. All forecasts start from the observed initial conditions of ocean, land and atmosphere. Models are typically sensitive to the initial conditions, which are usually not known accurately, due to limited number of observing stations, imperfections of used instruments and other errors. Models are also sensitive to model formulations.

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The UK Met Office, Peterson *et al.* (2011), has recently upgraded its seasonal prediction system GloSea4 by implementing initialisation of the observed sea ice component in the forecast model HadGEM3/CICE. The upgrade improves the Arctic atmosphere locally near the ice edge and provides better forecast of ice extent in summer (minimum) and winter (maximum). The winter ice edge is particularly well predicted in Greenland, Norwegian and Barents Seas. Other areas like Labrador Sea, Bering Sea and Okhotsk Sea are less accurately forecasted. Further development is expected to include enhancement to the system horizontal resolution together with the ocean and sea ice assimilation scheme, and better quality of assimilated observations.

Increasing economic activities in ecologically sensitive Polar Waters increase the possibility of a devastating industrial pollution incident in these areas. An oil spill could be one of the possible disasters. Karlsson *et al.* (2011) conducted laboratory investigation of oil spills behaviour in the presence of sea ice in order to improve strategy of responses to oil spills in ice. The authors studied entrainment and upward migration of oil through the ice during growth and melt. They found that the oil can reach several centimetres into the ice through discrete brine channels where porosity is between 8 and 15 % even in the cold ice. The amount of oil absorbed by the ice will also depend on ice temperature.

Modern anisotropic plasticity ice dynamics models allow explicit descriptions of the formation and evolution of leads, rafts and ridges. The presence of these kinematic parameters can be very important for offshore operators. Pritchard and Tremblay (2011) present a preliminary idea for a new ice dynamic numerical model that describes the velocity and stress discontinuity explicitly. The analysis is limited to a quasi-static behaviour, for which temporal changes are resolved to a day or longer. Thus time does not appear in the momentum and constitutive equations at each time step. The scheme integrations are conducted along characteristic directions, so discontinuities appear naturally. So far, the authors use a new meshless model and have an anisotropic continuity law that describes lead formation and evolution, and derived the governing equation in characteristic coordinates. A numerical code is planned which will begin by solving the one dimensional problem.

3.5.2 Experimental Description of Ice

Full scale trials and model experiments are still the most reliable sources of information on ice properties and ice-structure interaction for designers and operators of offshore fixed and floating polar structures.

Two large ice model test campaigns were performed in the period 2007–2010 and are presented by Bruun *et al.* (2011) as a part of a Joint Industry Project. The objectives of the project were to investigate different floater geometries and ice model test set-ups e.g. with the model fixed to a carriage and pushed through the ice versus ice pushed towards a floating model moored to the basin bottom, also their influence on the ice failure mode and structure responses in the various tested ice conditions. This paper presents the objectives and motivations for the project, the models tested, the target test set-up for the various tested configurations and the test matrix. Initial results from a fixed model tested in three first-year ice ridges with similar target ice properties are also presented and compared.

Lee *et al.* (2011), Choi *et al.* (2011) and Lee and Jeong (2011) present results of the sea ice trails conducted with a Korean built icebreaker. The trials of the first Korean icebreaker "ARAON" were conducted in the Arctic Ocean in July–August 2010. Sea ice concentrations at the Arctic sea were 4/10 to 10/10 and sea ice thicknesses were

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roughly 1.0 to 3.5 m. During the trials characteristics and physical properties of sea ice and snow were measured, as well, icebreaking performance of the vessel in various ice and snow coverage conditions was evaluated. In situ measurements of the sea ice thickness distributions at the ice floe were conducted using drilling and electromagnetic induction instrument, EM31-MK2. Conductivity of the ice floes was measured and sea ice thickness was estimated applying empirical formula developed at the Cold Regions Research & Engineering Laboratory, CRREL. The results of sea ice thickness derived with the EM31-MK2 were compared with observations results and a new empirical formula for estimation of sea ice thickness through the analysis of apparent conductivity data is suggested.

One of the tasks when evaluating performance of ice class vessels and Arctic offshore structures in an ice model basin is to prepare a proper model of the ice with correct scaling of natural sea ice properites. Every ice model basin in the world has individually developed their own ice modelling technique and methodology. The EG/AD/S model ice which is a diluted aqueous solution of ethylene glycol, aliphatic detergent and sugar, may provide for the correct scaling of mechanical properties of columnar sea ice. The MOERI (Maritime & Ocean Engineering Research Institute) ice model basin of Korea which opened 2009, adopts the EG/AD/S type model ice, in collaboration with the IOT (Institute for Ocean Technology), Canada. Cho *et al.* (2009) presents a study that focuses on the evaluation of mechanical properties of the EG/AD/S model ice for the possible use in the new MOERI ice model basin.

Model tests on the Shoulder Ice Barrier (SIB) were performed in the large ice tank of the Hamburg Ship Model Basin (HSVA) during July 2007 as part of HYDRALAB III and are presented by Gürtner (2010). The main goal was to investigate the conceptual design of the SIB and assess ice forces and ice rubble build-up. Model test results showed that the SIB potentially could be utilised as an ice protection structure for future shallow water application. Based on the model tests performed a computational model for simulating ice-SIB interactions was developed. This computational ice-structure interaction model involves the simulation of ice rubble accumulations and accordingly the ice forces exerted on the structure.

3.5.3 Statistical and Spectral Description of Ice

Bekker *et al.* (2010a, 2010b) present a study where the problems of a statistical modelling of ice loads from drifting hummocky features and level ice fields on the reinforced gravity based structures in the Piltun-Astohsky and Lunsky fields offshore Sakhalin, north east Russia, are investigated.

Data collected by the Upward Looking Sonar (ULS) during a 5000 km submarine voyage between the Chukchi Sea, Beaufort Sea and North Pole are reported by Marcellus *et al.* (2011). They present a statistical approach used to extract key ice characteristics from ULS data that could be used in development of safe shipping routes in Polar Regions. The ice properties include floe size and thickness and ice ridge geometries for first year and multiyear ice.

4 SPECIAL TOPICS

4.1 Climate Change and Variability

The Intergovernmental Panel on Climate Change (IPCC) ARA5 report is under development (some members of the ISSC I.1 Committee have been reviewers of this report) and is planned to be issued in 2013/2014. The IPCC SREX "Summary for Policymakers" report was issued in November 2011 while the whole SREX (Special

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Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation) report will be available in 2012.

Climate differs with geographic location and is influenced by amongst other factors latitude and distance from the open oceans. Climate has always changed over time, and the variations observed today are due to: natural variability (originating from the internal dynamics of the Earth's ocean and atmospheric system and occurring usually on time scales a few years from decadal to multi-decadal, but much longer cycles due to movement of poles may also occur, e.g. 23000 year cycles); climate change due to external forcing (such as changes in solar radiation and volcanic activity, varying on time scales from years to millennia); and anthropogenic climate change (caused by human activities, which takes place over a few decades to centuries), as stated by, for example, Bitner-Gregersen and Eide (2010).

The AR4 report (IPPC, 2007) concluded that there is very high confidence that the net effect of human activities since 1750 has contributed significantly to the global warming. This conclusion remains in 2012. It is pointed out by IPCC (2011) that assigning "low confidence" in a specific extreme on regional or global scale neither implies nor excludes the possibility of changes in this extreme. Many uncertainties remain in modern climate change projections.

Multi-decadal natural variability of climate (see ISSC 2009 I.1 report) due to the Earth's system dynamics, short term externally forced climate changes and short term changes (10–12 years) in solar radiation to some extend have been taken care of in design of marine structures by considering sufficiently long met-ocean data records (typically much longer than 10 years). Climate change due to long term external forcing such as solar radiation and caused by changes in the Earth's orbit is neglected in a design process because of the large time scale of its occurrence.

It is, however, important to be aware that the natural climate variability can be of the same order of magnitude as the anthropogenic climate change and may mask it for several years to come. Further, the anthropogenic climate change is affecting the natural climate modes. Palmer (2008) suggests that changes due to natural mode swap could be much larger than anthropogenic changes. Therefore the next 30–100 years' climate statistics may be affected strongly by it.

The Climate Change Conference which took place in Copehnagen in December 2009 raised climate change policy to the highest political level. It should also be mentioned that the credibility of the IPCC has been publicly called into question during the period of this Committee, in particular following mistakes in the AR4 glacial retreat projections.

4.1.1 Temperature

According to the IPCC SREX (2011) it is "virtually certain" ($> 99\,\%$ probability of occurrence) that increases in the frequency and magnitude of warm daily temperature extremes and decreases in the magnitude of cold extremes will occur in the 21st century on the global scale. The 20-year return period daily temperature will "likely" ($> 90\,\%$ probability of occurrence) increase by about 1–3 ^oC by the mid-21st century and by about 2–5 ^oC by late the 21st century, depending on the region and emission scenario (based on the B1, A1B and A2 scenarios, see ISSC I.1, 2009). The expected increase of the average Earth surface temperature will be twice as high in the Arctic compared to other parts of the Earth (IPCC, 2007).

Over the last two years, the Berkeley Earth Surface Temperature Project chaired by Prof. Richard Muller has deeply studied changes in global temperature. The changes

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at the locations investigated have shown warming typically between 1–2 ^oC, much greater than the IPCC's (2007) average of 0.64 ^oC (http://www.berkeleyearth.org/).

The Copenhagen Climate Change Conference 2009 obtained strong convergence of the views of governments on the long-term goal of limiting the maximum global average temperature increase to no more than 2 degrees Celsius above pre-industrial levels, being subject to a review in 2015. No agreement on how to do this in practical terms, however, was reached. The 2011 UN Climate Change Conference held in Durban, South Africa, from 28 November to 9 December 2011 has agreed, however to prolong the Kyoto Agreement until 2015.

4.1.2 Wind

The review of the observed and projected changes of wind activities until 2010 is given by Bitner-Gregersen and Eide (2010). The IPCC SREX report (2011) concludes that average tropical cyclone maximum wind speed is "likely" to increase, although increases may not occur in all ocean basins. It is "likely" that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. Further, there is "medium confidence" (about 5 out 10 chance) that there will be a reduction in the number of extra-tropical cyclones averaged over each hemisphere. There is "low confidence" (about 2 out of 10 chance) in the detailed geographical projections of extra-tropical cyclone activity while there is "medium confidence" in a projected poleward shift of extra-tropical storm tracks. "Low confidence" is associated with projections of small spatial-scale phenomena such as tornadoes and hail.

The recent study of Young *et al.* (2011) based on a 17-year satellite data base (1991-2008) shows, however, a clear global increase in the monthly mean, 90th-, and 99th-percentile values of wind speed for $2° \times 2°$ regions. The study reports that the mean and 90th percentile wind have increased by at least 0.25 to 0.5 % per year with stronger trend in the Southern than in the Northern Hemisphere, apart from the central north Pacific. At the 99th percentile extreme wind speeds are increasing over the majority of the word's oceans by at least 0.75 % per year.

4.1.3 Waves

The review given by Bitner-Gregersen and Eide (2010) identified that the global climate models in IPCC AR4 did not include wave conditions. Available studies have used statistical relationships between wave heights and sea level pressure (statistical downscaling) or the winds from the global models to run wave models (dynamic downscaling) in order to predict the future wave climate and uncertainties are related to these predictions. This situation remains.

Studies carried out before 2009 have reported increases of 0.35–1.15 m in the seasonal maxima of H_s by 2080 and of 0.2–0.8 m in the 20-year H_s in the 50-year period (2001–2050) in the northeast North Atlantic. These positive trends have also been confirmed by later studies, e.g., Dragani *et al.* (2009), Wang *et al.* (2009), and Dodet *et al.* (2010).

Several investigations have also shown an increase in extreme H_s in the North and Norwegian Sea, however, this is very regionally dependent. Grabemann and Weisse (2008) found increases in the 99 % percentile of the long-term H_s as an average over four climate model/emission scenario combinations to be 0.25–0.35 m from the present to the end of the 21st century in the North Sea. However, the range for the northern North Sea varied from 0.10 m to 0.6 m and the authors assign an uncertainty to the mean value of 0.6–0.7 m. Debernard and Røed (2008) found that the annual 99-percentiles of significant wave height increase 6–8 %, and 4 % or less in the North and

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Norwegian Seas and west of the British Isles by the end of the 21st century (2071–2100). The results indicate also more frequent strong wind and wave events in the future with higher extreme surge but high uncertainty is attributed in these estimates.

Young *et al.* (2011) have found using the 23-year (1985–2008) data base of calibrated and validated satellite altimeter measurements a general global trend of increasing values of wave height over this period, but to lesser degree than wind speed. Large regions of the north Pacific and north Atlantic show a weak negative trend (0.25 % per year), as do much of the equatorial regions of all oceanic basins. However, the southern hemisphere has a consistent weak positive trend of approximately 0.25 % per year. The 90th percentile and the 99th percentile wave height trends are progressively more positive, with the higher latitudes (greater than 35°) of the both hemispheres showing positive trends of approximately 0.25 % per year at the 90th percentile and 0.50 % at the 99th percentile. The buoy and wave model data support these conclusions.

Vanem and Bitner-Gregersen (2012) using the Bayesian-Hierarchical model and the North Atlantic C-ERA-40 data (1958–2002), have predicted an increase of the significant wave height up to 2.0 m by the end of the 21st century.

Babanin *et al.* (2009) and Dai *et al.* (2010) have shown, based on the concept of "wave induced turbulence", how to improve climate change predictions by improving the upper ocean mixing modeling.

4.1.4 Sea Water Level

A new climate model (ECHAM5/MPL-OM1) considering changes of sea level due to increased CO2 in the atmosphere and developed for IPCC AR4 has been applied to simulate the climate changes under different increased CO2 scenarios (Mu *et al.*, 2010). The sea surface temperature and salinity structure, the sea level variation and the changes of sea ice in the northern hemisphere have been analysed.

The degree to which climate models (Global Climate Model, GCM, or Regional Climate Model, RCM) have sufficient resolution and/or internal physics to realistically capture the meteorological forcing responsible for storm surges is regionally dependant. For example current GCMs are unable to realistically represent tropical cyclones

According to IPCC SREX (2011) it is "very likely" that mean sea level rise will contribute to upward trends in extreme coastal high water levels in the future but they will be geographically non-uniform. Changes of sea water level remain as reported by IPCC (2007); on average up to 0.5 m of sea level rise can be expected by the end of 2100 although some recent investigations seem to indicate that these numbers can be higher.

Sea level variations due to surge and tide in future climate have been investigated by several researchers, e.g. Debernard and Roed (2008), Sterl *et al.* (2009), Harper *et al.* (2009). Harper *et al.* (2009) studying tropical cyclones off the east coast Australia have shown that there is a relatively small impact of 10 % increase in tropical cyclone intensity on the 100-year storm tide.

Taking into consideration the change of the terrestrial reference frame, Collileux and Wöppelmann (2010) reported a bound of 1.2 to 1.6 $mm/year$ global sea level rise for the past century whose upper bound is slightly lower than the IPCC AR4 estimates of 1.8 $mm/year$. The geodetic requirements to improve the prediction of the sea level rise and its variability is reviewed by Blewitt *et al.* (2010). For example, Wu *et al.* (2011) have estimated the earth radius expansion rate to be 0.2 $mm/year$.

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Based on global tide gauge records, Merrifield *et al.* (2009) estimated an acceleration of sea level rise since 1990 as $3.2 \pm 0.4\,mm\ yr^{-2}$, higher than the average values of 1.5 $\pm$ $0.5\,mm\ yr^{-2}$ in 1962–90. Ray and Douglas (2011) have shown the large sea-level trends of the satellite era (post-1992) may not be unique. However, Woodworth *et al.* (2011) provided evidence of a century of sea-level-rise acceleration which is still under debate (Bojannowski, 2011, Rahmstorf and Veermeer, 2011, Houston and Dean,2011). Church and White (2011) updated their earlier analysis and estimated a statistically significant acceleration of $0.009 \pm 0.003\,mm\ yr^{-2}$ and $0.009 \pm 0.004\,mm\ yr^{-2}$ since 1880 and 1900 respectively.

Gu and Li (2009) show with long-term tide gauge records that decadal sea level oscillations along the Pacific coast are significantly affected by the Pacific Decadal Oscillation with a 2–3 year lag and its variation may influence long-term trends. Menendez and Woodworth (2010) analysed worldwide tide gauge data and have shown that a trend in extreme sea levels globally is more pronounced since the 1970's. This is supported by Haigh *et al.* (2010).

Merrifield (2011) showed that strengthening of the trade wind contributed to the sea level rise of the tropical Pacific since the early 1990s. Influence of natural climate variability such as an Indian Ocean Dipole has been observed as well (Han *et al.*, 2010; Dunne *et al.,* 2011). Recent regional decadal trends are largely due to wind pattern change (Timmermann *et al.*, 2010).

4.1.5 Ice

Sea ice characteristics such as concentration, extent and thickness are considered to have a profound impact on global climate. Sea ice in the Arctic has shown dramatic changes over the last 30 years. The extent of summer ice (September) has declined by 8.9 % per decade between 1979 and 2009 and the winter ice (March) by 2.5 % per decade. September 2007 had the smallest ice extent on record (see e.g. Budikova, 2009) but although the extent and area increased through 2008 and 2009 it is likely that the total Arctic sea ice volume had its minimum in 2009. The decrease of sea ice (http://arctic.atmos.uiuc.edu/cryosphere/) and resulting unusual conditions, such as the North-East and the North-West Passage being open simultaneously for the first time in recorded history in August 2008, has raised alarm.

Some model projections predict a possible total loss of sea ice cover (at a September datum) in the Arctic around 2030 (Wang *et al.*, 2009) while other ones show seasonal ice coverage of Arctic by the end of 21st century. Recent observations indicate, however, that the simulation models under predict the Arctic ice decline (Budikova, 2009).

Golubeva and Platov (2009) based on model calculations show a significant reduction of the ice area in the Canadian waters. Stroeve *et al.* (2011) show how a range of climate models project future September ice extent in the Arctic Ocean, along with observed ice extent. Note that the models do not reproduce the historic ice data well. The study indicates that the ice cover in summer may practically disappear before 2050 (before 2020 has even been suggested by some investigations). However, an ice free Arctic winter is not predicted by any model, though the ice may be limited to first year ice and, therefore a likely maximum thickness of 2.0–2.5 m.

The EC project Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies (DAMOCLES, 2010) suggests that the Arctic Ocean could be ice-free in summer in as little as 10 to 15 years from now, much sooner than had been predicted by most of the IPCC models.

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4.2 CFD

CFD (Computational Fluid Mechanics) methodology is getting increasing attention in modelling of water waves and it is expected that this will continue.

As opposed to the analytical description of wave fields, another approach is the discretised space and time method of Computational Fluid Dynamics. Commercially available suites with turbulence based on Reynolds Averaged Navier Stokes (RANS) methods have dominated the maritime market, but open source packages such as OpenFOAM are beginning to find some acceptance. Although the idea of the 'Numerical Towing Tank' including ship-wave interaction has been suggested for many years, CFD work requiring high power computing was typically limited to very localised flows and short time frames. Sufficient processing power is now much more affordable so that many research centres have multiple processor facilities available and limited scope studies may even be performed with desktop computers. The EU '6th Framework' project VIRTUE (www.virtual-basin.org) adopted a co-operative approach.

Typically CFD has been applied to specific fluid-structure interaction problems. There has been limited focus on the wind-wave interaction and wave propagation modelling. Wu and Oakley (2009) presented a study on the generation and evaluation of progressive regular waves with the commercial code STAR-CCM+. Virtual wave gauges at several locations in the numerical tank were compared with first and second order Stokes waves; they found that the dissipation of wave amplitude down the tank was higher than observed in experiments, but lower than had been shown by other researchers. They were able to show wave profiles that were close to 1st and 2nd order Stokes descriptions, with 2nd order fitting better for higher amplitude (steeper) waves. The behaviour of the CFD waves could have been higher order still. Denchfield *et al.* (2010) compared numerical and physical tank realisations of superposed regular wave trains with the aim of creating 'rogue' waves; success was limited, but the CFD was restricted to a laminar flow model which clearly did not capture breaking mechanisms observed in the tank. Clauss has presented several papers in this area, for example Clauss *et al.* (2008). The authors discuss methods for numerically reproducing nonlinear waves by physical tank methods with both potential flow and RANS codes. Using several different scenarios such as regular and irregular long crested waves with embedded wave packets, they show the importance of a nonlinear approach to accurately produce the desired wave and thus the fluid-structure loads.

Choi and Yoon (2009) developed an internal wave generation scheme using momentum source to produce the target waves. The scheme was applied to the RANS equation model in the CFD code FLUENT. Ko *et al.* (2011) continued the study on internal wave generation by combining the previous approach with the VOF scheme of the Lin and Liu one of 1999. The numerical experiments were applied with the aid of the CFD code Flow3D.

The application of CFD models was not restricted during the reporting period only to gravity waves. A relevant example is the work of Das *et al.* (2009) who followed numerically the generation of a tsunami wave using two different approaches, namely a RANS and a VOF method as well as a numerical model based on the so-called Smoothed Particle Hydrodynamics (SPH).

Indeed the methods for studying wave generation and propagation problems are characterized by diversity. This is manifested by the existence of alternative to CFD models. Indicative examples are the work of Kim *et al.* (2006) who developed techniques for the generation of random waves by solving the so-called mild-slope equations of

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Suh *et al.* (1997) and the study of Kim and Lee (2011) that was based on the Control Volume Approach.

Despite increasing interest, RANS CFD methods cannot rival the flexibility of analytical approaches in representing high order and non-linear waves, and are therefore not favoured by the leading edge wave dynamics researchers. Neither do they yet rival the established potential flow based ship/marine structure wave response models. Nevertheless, this kind of CFD offers a conceptually straightforward way to approach the wave-structure interaction that is becoming much more accessible to the engineering community and may be the only choice for modelling particularly complicated situations.

4.3 Statistical Approaches

Publication of statistical and artificial intelligence methods especially for predicting ocean waves has accelerated over recent years. These are the so-called soft computing techniques, which do not assume any mathematical model *a priori*. Such methods are based on analysis of recent historical data, to make predictions about the future, and in this respect are dependent on the availability of recent and accurate time series estimates of the parameters concerned. By comparison dynamical models are based on predictions based on an understanding of the physics and an implementation of these into a numerical model. The publications reported work involving the application and validation of various methods for the prediction of meteorological and oceanographic parameters. Londhe (2008) provides a good summary of these methods, and a number of recent papers are summarized in this section.

Recent examples of the application of various soft computing approaches in terms of wave parameter predictions are given by Reikard and Rogers (2011), Malekmohamadi (2011), Özger (2010), Herman *et al.* (2009), Cañellas *et al.* (2010), Sylaios *et al.* (2009), and Etemad-Shahidi and Mahjoobimodel (2009), and Mahjoobi and Mosabbeb (2009). All showed reasonable success, primarily for relatively short projection periods. Golestani and Zeinoddini (2011) also showed that these methods could also accurately fill data gaps in wave parameters and also to predict wave spectra.

An interesting use of Artificial Neural Network (ANN) for transferring pressure transducer measurements to surface elevation is given by Tsai and Tsai (2009). They employed ANN to convert the pressure signal into significant wave height, significant wave period, maximum wave height, and spectral peakedness parameter using data obtained from underwater ultrasonic acoustic transducer measurements at various water depths. Their results showed that, for water depths greater than $20\,m$, the wave parameters obtained from the ANN were significantly closer to those obtained by the acoustic measurements recorded by using a linear pressure transfer function. This was not the case for wave heights greater than a significant wave height $4\,m$, but improvement was expected when the training data set contained more records with large wave heights.

Wahle *et al.* (2009) discuss work involving a novel approach to parameterising the exact nonlinear interaction source (Snl) term for wind wave spectra. They mapped discrete wave spectra directly onto the corresponding Snl-terms using a neural net (NN), training the NN with modelled wave spectra varying from single mode spectra to highly complex ones. They found that the NN approach performed well in mapping the wave spectra onto the corresponding Snl-terms, emulating the WRT-method calculations of the exact nonlinear interaction source terms for single and multi-mode wave spec-

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tra with a much higher accuracy then the approximations implemented in present operational wave-models.

Delavari *et al.* (2011) used Fuzzy Inference System (FIS) and Adaptive Neuro-Fuzzy Inference System (ANFIS) methods to estimate breaking wave height and the water depth at the breaking point, finding that the ANFIS model to provide more accurate and reliable estimation of breaking wave height, compared with semi-empirical equations, but that some semi-empirical equations provided better predictions of water depth at the breaking point compared to the ANFIS model.

Aydogan *et al.* (2010) predicted vertical current profiles in the Strait of Istanbul. The used an artificial neural network (ANN) model built on thousands of hours of concurrent measurements of current profiles, meteorological conditions, and surface elevations. The model predicted 12 outputs of East and North velocity components at different depths in a given location. Predictions from the model had an average root mean square error of $0.16\,m/s$ when compared with observations. They also found good overall agreement with observations when used to predict current velocities 1–12 h into the future, and concluded that the technique can be used as a reliable tool for forecasting current profiles in straits.

Neural Networks have also been used to estimate regional and global sea level variations through the 20th century, based on long-term tide gauge records (Wenzel and Schröter, 2010). The neural network technique is used to connect the coastal sea level with the regional and global mean via a nonlinear empirical relationship, solving the difficulties with both the vertical movement of tide gauges over time and the problem of choosing the weighting function for each individual tide gauge record. Neural networks are also used to fill data gaps in the tide gauge records. The global mean sea level for the period January 1900 to December 2006 is estimated to rise at a rate of $1.56 \pm 0.25\,mm/yr$ which is reasonably consistent with earlier estimates, but no significant acceleration was detected. While most of the basins showed a sea level rise of varying rate, a mean sea level fall in the southern Indian Ocean was found. No significant trends were found for the tropical Indian and the South Atlantic, but they were the only basins to show significant acceleration. At shorter timescales, oscillations with periods of 25 years and between 50–75 years were found to be dominant and consequently there were strong rise rate correlations (but with phase lags) between the different basins.

To conclude this section, it is clear from the summary that there exists a host of soft computing techniques, with wide application although most effort appears to be focused on wave predictions. Data gap filling and short-term prediction appear obvious applications. The success of various techniques in terms of forecasts is largely only for short projection times; so it is the relatively short computation time associated with these techniques, where the major advantage over traditional, physics-based approaches lies. This would suggest an operational application, but much more experience is needed with these techniques before they could be applied in critical operational situations.

5 DESIGN AND OPERATIONAL ENVIRONMENT

5.1 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

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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. 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. Although environmental wave data and models are not explicitly used by classification society rules for general ship design they are used 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 use of wave climate 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 met-ocean 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.

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.

5.1.1 Met-Ocean Data

Visual observations of waves collected from ships in normal service and summarized in the BMT Global Wave Statistics (GWS) atlas (British Maritime Technology, 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 design.

The necessity of replacing that historic, (essentially subjective) observation based wave data base 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, which has intensified because of the climate change debate. Predictions of extreme met-ocean parameters based on the new wave data bases have shown large discrepancies making still difficult reaching firm conclusions, as discussed by Bitner-Gregersen and Skjong (2011).

The offshore industry uses location specific data in specification of design and operation criteria and generally regards instrumentally recorded data as superior to model derived data. However, due to limited availability of instrumental data, hindcasts are also commonly used. Increasing attention has been given since 2009 to the uncertainties in hindcasts, and in particular to energy partitioning procedures used to separate wind sea and swell contributions e.g. Loffredo *et al.* (2009), Bitner-Gregersen

(2010). The offshore companies are following the met-ocean research findings on climate change, but as with the shipping industry there have been no changes in the standards as a consequence so far.

Since the last reporting period, both research organisations and the offshore industry have updated wind and waves hindcast data sets for several basins, within proprietary joint industry projects (see Section 2.2.3).

5.1.2 Design Environment

In the design process, international standards are followed to calculate ship structural strength and ship stability during extreme events, with an occurrence of once every 20 years - the Ultimate Limit State, ULS, corresponding to the maximum load carrying resistance. Recently, an increase in the return period to 25 years has been adopted by IMO. 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 (NORSOK Standard, 2007) take into account extreme severe wave conditions by requiring that a 10000-year wave does not endanger the structure integrity (ALS).

Long-term distributions of sea states are often employed in the prediction of met-ocean characteristics or various responses that a marine structure will experience. It is recognized that uncertainties/errors in the estimated long-term distributions often leads to gross errors in the predictions. Hence, since 2009 a lot of research effort has been put into refining models and estimation procedures of the long-term sea state description.

Joint long-term environmental models are required for a 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 can be found in Bitner-Gregersen (2012). The joint met-ocean statistical models were originally developed for design purposes but Bitner-Gregersen (2010) has proposed a procedure allowing also application of these models to operational conditions. Utilisation of a joint fit for fatigue calculations is given by Olagnon and Guédé (2010).

Joint met-ocean models are commonly used with the environmental contour concept due to Winterstein *et al.* (1993), IFORM, (see also Haver and Winterstein, 2009; DNV, 2010) for specification of design criteria. Recently, Jonathan *et al.* (2011a) have proposed an alternative technique based on the 'Heffernan and Tawn 2004' approach to modelling conditional extremes and demonstrated its use for hindcast data from the Northern North Sea, the Gulf of Mexico and the North West Shelf of Australia. An advantage of this technique is that it does not depend on an a priori model for the joint distribution, it can easily be extended to multi-dimensions (e.g., Jonathan *et al.*, 2011a), and it offers flexibility in the specification of the form of the probability contours (Jonathan *et al.*, 2011a). Comparison with the IFORM concept and a discussion of uncertainties related to both approaches needs still further investigations.

In Hagen *et al.* (2010) wave storm history combined with Weibull distributed wave heights was used to derive the long term CDF of wave heights acting on an offshore structure.

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Since 2009 increasing attention has been given to directional effects and combined seas (see Bitner-Gregersen, 2011; Loffredo *et al.*, 2009). Consensus has still not been reached within the industry concerning directional criteria. For reliability calculation the Forristall procedure is recommended to be used by DNV RP-C205 (2010).

Effort continues relentlessly in the quest to reduce the uncertainties associated with the estimation of extreme environmental parameters for design, mainly through improvements in the extremal modelling. In recognition of this, Mackay (2011) proposes a method for correcting bias in return values of wave heights caused by hindcast uncertainties. Gibson *et al.* (2009) demonstrate uncertainties related to extreme crest predictions. Forristall (2011) has proposed a procedure for correction of extreme wave crest due to spatial variability of seas surface in a sea state. Applications for design are reported by e.g. Bitner-Gregersen (2011).

Jonathan and Ewans (2011a) describe the application of a spatial model for establishing extreme wave conditions in the Gulf of Mexico. The model allows for dependency between adjacent locations and allows for a natural variation of the extremes in space. It is an alternative, and perhaps a superior approach, to site averaging in which data from surrounding locations are pooled on the assumption that the extreme climate is homogeneous over the pooling space.

Recognition of the consideration of the spatial variation in extreme value analysis is an example of the need to consider covariates when performing analysis. The importance of this with specific examples for seasonality is shown by Jonathan and Ewans (2011b) and is also emphasized by Menéndez *et al.* (2009).

Vanem and Bitner-Gregersen (2012) suggest how to link the Bayesian hierarchical space-time model allowing projections of future climate changes to a joint met-ocean model.

The Peaks Over Threshold (POT) method is probably the most widely used approach to calculating extremes, for which the Generalized Pareto Dstribution (GPD) asymptotic distribution. A problem with the method is the need to set a threshold which needs to be high enough in order to justify use of the GPD, but low enough so that enough data remain for analysis. This is discussed by Mazas and Hamm (2011). MacDonald *et al.* (2011) describe an extreme value mixture model combining a non-parametric kernel density estimator with an appropriate tail model. Thompson *et al.* (2009) propose an automatic approach to threshold selection. Næss (2011) recommends using the upcrossing rate methodology instead of POT in design.

Mackay *et al.* (2011) evaluate the performance of several estimators for the parameters of the GPD from Monte Carlo simulations and conclude that the likelihood-moment (LM) estimator is close to the lowest bias and variance over a wide range of sample sizes investigated.

Gaussian models to describe met-ocean phenomena are still used in applications. If the observed Probability Density Function (PDF) differs significantly from the Gaussian model then some researchers transform the data so that the observed CDF matches the transformed Gaussian CDF, see e.g. Azaïs *et al.* (2011a) and references therein. An application of such an approach for the estimation of extreme responses of a container ship is presented in Mao *et al.* (2012). Another interesting approach to compare more complex properties of waves with those predicted by an adopted model is presented in Ortega *et al.* (2011).

For design for ice operations, satellite Earth Observation (EO) are expected to being play a more and more important role in the future as discussed by Partington *et al.*

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(2011). Adoption of the International Standards Organization (ISO) standard number 19906 – Arctic Offshore Structures standards for cold regions, which has a probabilistic approach, requires quantification of ice environment behaviour in probabilistic maner.

ISO 19906 presents recommended procedures on protection of people, environment and property when operating in polar conditions. The standards were developed by the ISO Technical Committee 67 (TC67), Sub-Committee 7 (SC7 – Offshore Structures), Working Group 8, and approved by ISO member countries in December 2010. Spring *et al.* (2011) present history of standards development, editing and review process as well as its acceptance by ISO and participating members. ISO 19906 standards constitute unification and harmonization of existing local national codes into a single international standard.

Moslet *et al.* (2011) present ISO 19906 related projects at DNV in Norway. DNV is managing two related JIP projects, Barents2020 and IceStruct. The Barents2020 project focuses on Russian-Norwegian development of common rules for safe exploration in the area of Barents Sea; the goal of the IceStruct project is to help a non-specialist designer to comply with the normative provisions of ISO 19906 and address design issues not covered by the standard.

5.1.3 Design for Climate Change and Rogue Waves

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 met-ocean 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 Bitner-Gregersen and Eide (2010).

The marine industry has initiated studies on potential impact of climate change on design of marine structures, e.g. Bitner-Gregesen *et al.* (2011), Bitner-Gregersen and Skjong (2011), Vanem and Bitner-Gregersen (2011); others still not publicly available.

Observed and projected changes in waves and wind climate are expected to have the largest impact on marine structure design in comparison with other environmental phenomena. Changes in sea level combined with storm surge have little potential to affect ship design directly but may impact offshore and coastal installations, depending on how significant they are. Secondary effects, such as changes in sea level range, harbour depths and offloading heights may need to be taken into account. The predicted increase in marine growth may increase loads on marine structures in some ocean regions, e.g. the Baltic Sea.

It is also important to be aware that changes, like increase in storm activity (note intensity, duration and fetch) in some regions (still low confidence in these projections, IPPC, 2011), may lead to secondary effects such as increased frequency of occurrence of extreme wave events. The frequency of occurrence of combined wave systems like wind sea and swell/swells may increase also in some ocean areas due to the increase of storm intensity and change of storm tracks. This may consequently lead to more frequent extreme events (Toffolli *et al.,* 2011).

The risk associated with rogue waves has attracted the attention of the shipping and offshore industry, which has recently initiated two international research projects: the JIP project CresT (Cooperative Research on Extreme Seas and their impact) coordinated by MARIN in The Netherlands, and its second phase ShortCresT, and the EC project EXTREME SEAS (Design for Ship Safety in Extreme Seas) coordinated

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by DNV of Norway. Rogue waves are not explicitly included in classification societies' rules and offshore standards today due to lack of consensus about their definition and probability of occurrence.

Some recent investigations regarding probability of occurrence of extreme and rogue waves e.g. Baschek and Imai (2011), Rozhkov (2009), Bitner-Gregersen and Toffoli (2012) seem to indicate, however, that rogue waves may need to be considered by ship and offshore standards; although further investigations are still called for to reach firm conclusions.

5.2 Operations

Marine operations require more detailed description of sea state variability than long-term sea state distributions used for design can provide, e.g. optimal ship routing Mao *et al.* (2010a), estimation of variance in accumulated fatigue damage Mao *et al.* (2010b), construction of warning systems for high sea levels, extreme waves and planning of marine operations. These applications use correlations between sea state parameters at different locations and moments in time. Such information is often a part of spatio-temporal models of sea state variability.

Signing of the delimitation treaty between Norway and Russian Federation in September 2010, has opened new opportunities for the shipping and offshore industry in the Barents Sea and brought the need for further research of met-ocean and ice conditions in the Arctic regions.

5.2.1 Planning

The EC SAFE OFFLOAD project has proposed a procedure utilising information about wind sea and swell in specification of a risk-based approach for safety of offloading operations from the LNG terminals to shuttle gas tankers.

McGonigal *et al.* (20011) show results of JIP investigating the presence of EIFs (Extreme Ice Features) in the area between Ellesmere Island and Prince Patrick Island. The data was collected in August 2008 from satellite images. Roughly 200 EIFs were identified, including 40 ice islands, 93 ice island fragments and 67 multi-year hummock fields. Ice island fragments were defined as less than $1\,km$ in the longer dimension, ice islands had an average diameter between 1.6 and $5.2\,km$, and multi-year hummock fields between 1.7 and $13.8\,km$.

Mudge *et al.* (2011) analysed Canadian Ice Service (CIS) records from 1982 to 2010 and studied two passages of Viscount Melville Sound (VMS) by CCGS Amundsen in order to assess feasibility of navigation if Canadian Arctic. The authors observed a high degree of spatial and temporal variability in ice conditions in the area of Northwest Passage with large seasonal variations. The study indicates the importance of timely and accurate ice information in making the Northwest Passage feasible for trade as numerical models are not inaccurate.

5.2.2 Warning Criteria and Decision Support Systems

Several authors have studied relations between spectral parameters and occurrence of extreme or rogue waves and the topic is also investigated in the EC EXTREME SEAS project. Mori *et al.* (2011) have used Monte Carlo simulations on the Nonlinear Schrödinger equation in two horizontal dimensions and found that increasing directional spread decreases kurtosis, a parameter accepted to be related to higher probability of rogue wave occurrences. On the other hand Toffoli *et al.* (2011b) found

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higher kurtosis values when analysing waves in bimodal sea states, with higher occurrences when directional differences were between 20 and 40 degrees.

The distribution of encountered wave slope was used to predict risks for capsizing of vessels, see Leadbetter *et al.* (2011) and Åberg *et al.* (2008) for the theoretical background of the method.

The development of decision support systems remains in focus. As proposed by Nielsen *et al.* (2011) and Nielsen and Jensen (2011), they require the collection of relevant data e.g. met-ocean, ship response, on board. These types of data can also be used for self learning (see the EC project NavTronic for example).

Search and Rescue operations require specific decision support systems. Their planning relies on accurate forecasting of the drift of objects under search. The most widely used approach for drift assessment is based on the Leeway method in which Leeway coefficients taking into account combined action of wind and waves are experimentally identified for various classes of objects allowing assessment of drift velocity and direction as a function of wind speed. Breivik *et al.* (2011) propose a standardised method for assessment of Leeway coefficients from field experiments. Uncertainties in forcing fields (wind and currents) as well as other information such as initial date and location of the drift are accounted for when introducing a stochastic approach used a on MonteCarlo technique for the computation of an ensemble of equally probable perturbed trajectories (Breivik *et al.*, 2008).

Accuracy of drift prediction is highly dependent on the quality of the forecasting of environmental data. It was pointed out during the 4th International Workshop on Technologies for Search And Rescue and other Emergency Marine Operations (2011, Brest, France) that the use of HF-radar and Lagrangian floats (SLDMBs) data for assimilation or correction of current can provide efficient improvement of the accuracy of the drift prediction.

Iyerusalimskiy *et al.* (2011) present state-of-the-art ice load monitoring and alarm system that was installed on a large icebreaking tanker operating between the Barents Sea and Murmansk. The system is designed to measure and record in real time the ice pressure and loads and calculates structural responses in selected locations on the hull.

6 CONCLUSIONS AND RECOMMENDATIONS

Accuracy of wind and waves hindcast data bases for several ocean basins has been improved since 2009. The issue of met-ocean data ownership remains a general problem. Whilst the advantages of having data freely available to academia and industry are clear, the commercial sensitivity of some data sets is recognised. However, it is possible for organizations to make data available without compromising their confidentiality. An example of this is the SIMORC URL data base administered by the University of Southampton, as noted in the last Committee report.

Owing to many research efforts, the occurrence of rogue waves, their mechanism, and detailed dynamic properties are now becoming clear. The state of the art development on rogue waves are well summarised at three Rogue Wave Conferences, held in 2000, 2004, and 2008 by Ifremer, and the publications reviewed in Section 3.2. Consistency between numerical models and experimental data has been documented. The focus is now on forcing terms like wind and current and wave breaking that are not typically included.

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Despite recent achievements, consensus on the definition of rogue waves and particularly their probability of occurrence has not been reached yet. Such consensus, however, is essential for the evaluation of possible revision of offshore standards and classification society rules, which currently do not include rogue waves explicitly. The Norwegian offshore standards take into account severe wave conditions by requiring that a 10000-year wave does not endanger the structure integrity (Accidental Limit State, ALS). But it still lacks guidelines for model predictions of extreme and rogue waves and design scenarios to be included in a possible ALS procedure. Recent investigations seem to indicate that rogue waves may well need to be considered by ship and offshore standards. However, further investigations regarding the probability of occurrence of rogue waves and their impact on marine structure responses are still called for before firm conclusions can be drawn.

Attention has been given to accounting for directional effects, modelling of wind sea and swell, seasonality, spatial and non-stationary statistics and their applications in design. The importance of these effects on extreme met-ocean statistics has been demonstrated.

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.

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, the increased intensity of tropical cyclones has caused devastating damage to the offshore industries in the Caribbean in the past 8 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 for some locations. It is noted that there is large uncertainty associated with the projections.

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. Not many publications are written from the viewpoint of the designer; too often they focus on too low return periods.

Economic markets and environmental changes in northern areas give projections of further and progressive availability of Arctic seas. Decreasing ice cover extent and thickness will allow pioneers to operate closer to calving glaciers but also increases the probability of encountering icebergs, bergy bits and other ice formations in areas where they were not previously experienced.

6.1 Advances

Utilisation of wave information collected by satellites in wave models has increased significantly through the GlobWave project initiated by the ESA in 2008. Access to wind and waves remote sensing data bases has improved.

A major improvement of wave models based on the radiative transfer equation (RTE) is the development of new modified wind input and wave dissipation functions (for

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breaking) based on more physical description of the transfer mechanisms. A common parameterisation of breaking wave height distribution which may be used from deep to shallow water has been proposed. Exclusively non-stationary models such as WAM and WAVEWATCH-III have been pushed closer to shore.

The knowledge of extreme and rogue waves has significantly advanced since 2009 and the nonlinear dynamics of surface gravity is now reasonably understood. The predictions made by theoretical and numerical models compare well with experimental results. New investigations include the effect of current and wave breaking. Indirect evidence on the specific meteorological conditions leading to the formation of narrow directional wave fields has been shown.

Significant 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. But 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.

As the effects of global warming have been closely monitored, results from a variety of local and remote ice measurements are available, ranging from satellite data on the extent of ice, ice thickness from moving vessels to various mechanical properties obtained from ice probes.

The observed trends and projected climate changes have been used to demonstrate their impact on marine structure responses.

6.2 Recommendations

The need for improving the availability, quality and reliability of met-ocean data bases was reported by the previous Committee. This situation is unchanged, and any effort to address this concern is recommended. Further utilisation of remote sensing data by the marine industry should continue.

The importance of including wave breaking and external forcing (wind) when modelling rogue waves requires increasing attention. 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. Further, a consistent approach combining new information about extreme and rogue waves in a design perspective needs to be proposed.

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 as well as modelling of wind sea and swell for design and operational purposes.

Work on enhancing safety at sea through specification of uncertainties related to the environmental description should continue. The shipping industry lags the offshore industry in these studies but has made significant progress since 2009. Further development of decision support systems should support this work.

The 2012 ISSC I.1 Committee recognises the significance of the IPCC (2007, 2011) findings and the conclusions drawn by the Panel. However, as pointed out by the IPCC Panel (2011), there are still significant uncertainties associated with climate change projections making it difficult to drawn firm conclusions. Reducing these uncertainties requires attention. The adaptation process to climate change should continue by the shipping and offshore industry. The projected climate changes 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 met-ocean and ice data, and models.

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